Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 47 No. 3 September 2016 ISSN 0046-5828

Subsea Horizontal Directional Coring (HDC)

C. K. Tsang[1], S. F. Chau[2] and Jimmy Chan[3]
[1,2,3]*AECOM Asia Co. Ltd., Hong Kong*
[1]*E-mail*: ck.tsang@aecom.com

ABSTRACT: The Tuen Mun – Chek Lap Kok Link comprises a 9 km long dual 2-lane carriageway between Tuen Mun and North Lantau, with approximately 5 km long sub-sea tunnel between Hong Kong Boundary Crossing Facilities and Tuen Mun. This is a major highway infrastructure constructed to alleviate the increase in cross boundary traffic due to projected developments in the Northwest New Territories and North Lantau in Hong Kong, including the Airport developments and the Hong Kong-Zhuhai-Macao Bridge. The proposed subsea tunnel is to be constructed by large diameter Tunnel Boring Machines (TBM) which will bore underneath two sets of existing submarine power cables providing power supply to the Hong Kong International Airport. Ground investigation using conventional vertical marine drillholes is not allowed within the cable protection zone with the considerations of the potential risk of damaging the power cables. To provide sufficient ground information for the design of the proposed TBM tunnel, Horizontal Directional Coring (HDC) with a total length of 660m was proposed at the invert level along the tunnel alignment. It was anticipated that the HDC would go through rock, soil or soil/rock interface and terminate at interface of soft / mixed ground. The HDC works has been completed in mid-2013. This paper describes the design considerations and the trajectory planning of the HDC work, with construction of a marine platform (of size 15m x 20m to facilitate the installation of the HDC). The difficulties and problems encountered during the subsea horizontal drilling is also discussed.

1. INTRODUCTION

Horizontal Directional Coring (HDC) is an advanced ground investigation technique aimed at obtaining continuous sampling along the tunnel alignment. This is analogous to drilling a "pilot tunnel" with a very small diameter along the tunnel alignment to investigate the anticipated ground conditions to be encountered. . The technique has become increasingly popular for tunneling projects in Hong Kong and has been applied successfully in Eagle's Nest Tunnel, Po Shan Drainage Tunnel and Harbour Area Treatment Scheme (HATS) 2A Tunnels. Despite the cost for HDC being comparatively higher than conventional vertical drilling, it allows geologists and engineers to have a full review of the ground and geo-hydrological conditions along the tunnel alignment, which is of vital important for successful planning of the tunneling works.

For Tuen Mun – Chek Lap Kok Link (TM-CLKL) Project, a 660m long subsea HDC at the invert level along the centre of the twin tunnel alignments was proposed to collect ground information underneath the cable protection zone where conventional marine vertical drilling was not allowed during the initial ground investigation (GI) stage, thus enables ground information to be obtained in the cable protection zone.

This paper presents details of the design considerations and trajectory planning of the subsea HDC installation work, the difficulties and problems encountered during the construction and the associated remedial solutions.

2. PROJECT BACKGROUND

2.1 TM-CLKL Subsea Tunnel

The proposed TM-CLKL comprises a 9 km long dual 2-lane carriageway between Tuen Mun and North Lantau. The alignment commences at a connection with the NLH at Tai Ho of Lantau. It heads northwest on a 1.6 km long sea viaduct to the proposed Hong Kong Boundary Crossing Facilities (HKBCF) near the Hong Kong International Airport (HKIA). After landing on the eastern edge of the proposed HKBCF, the alignment turns north and heads into a 5km long sub-sea tunnel, which is to be constructed by large diameter TBMs under the Urmston Road. After crossing the Urmston Road, the alignment daylights at a reclamation just east of the Tuen Mun River Trade Terminal and then heads eastward on an elevated structure over Lung Mun Road, before joining a proposed toll plaza in Tuen Mun Area 46. The project includes three main civil works contracts: Contract I – Southern Connection Viaduct Section, Contract II – Northern Connection Sub-sea Tunnel Section, and Contract III – Toll Plaza and Associated Connection. The layout plan of TM-CLKL project is shown in Figure 1. At the date of this paper being prepared, the three civil works contracts are in progress.

The subsea tunnels passes through several important facilities: a) submarine power cables and telecommunication cables, which are the only power and telecommunication supply to the airport; b) Urmston Road, which is one of the busiest marine navigational channels in Hong Kong; and c) marine borrow area, mud disposal ground and contaminated mud pits located nearby the project area. The site constraints are shown in Figure 1.

Immersed tunnel was originally proposed for the TM-CLKL subsea tunnel based on the past experiences of cross harbour tunnels constructed in Hong Kong. However, dredging for the tunnel trench is required for immersed tunnel construction and it would cause significant impacts to the environment and marine ecology particularly in the active zone of Chinese White Dolphins within project site area. In addition, diversion of the submarine power cables is required which would cause significant delay for the implementation of the project. With detailed study and assessment, large diameter TBM bored tunnels were eventually proposed to resolve the impacts associated with immersed tunnel scheme. On the other hand, the proposed TBM bored tunnels need to tackle technical challenges of being the biggest and deepest subsea TBM tunnels to be constructed in Hong Kong. The main subsea tunnels will employ two large diameter (approx. 14m) TBMs designed to overcome mixed ground conditions at about 60m below the existing sea level.

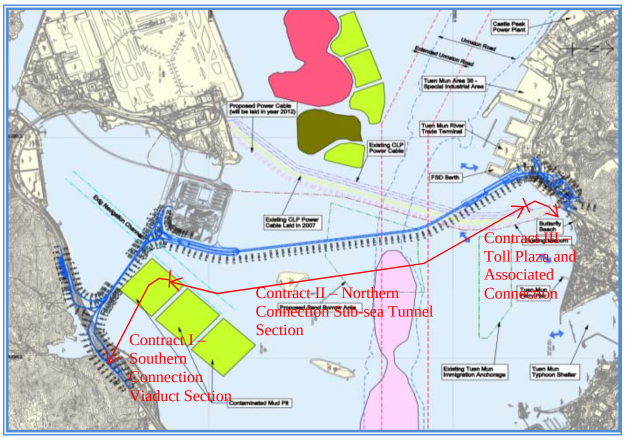

Figure 1 Layout plan and site constraints of TM-CLKL project

2.2 Ground Investigation and Geological Conditions

Extensive ground investigation including marine vertical drillholes, marine inclined drillholes, marine CPTs, geophysical surveys and subsea HDC were carried out along and in the vicinity of the TBM tunnels to confirm the geological stratification. More than 200 numbers of existing marine drillholes and the land drillholes were carried out during the design stage. Locations of the marine GI stations are shown in Figure 2. Geophysical seismic reflection profiling survey with line spacing of 20m x 50m was carried out within a 200m corridor along the tunnel alignment. In the region of tunnels pass underneath the submarine cable protection zone (area of 200m x 800m), swath bathymetry, marine magnetic and seismic profiling survey with grid line spacing of 25m were carried out.

The geological conditions along TM-CLKL subsea tunnels have been reviewed based on the published records, available GI records, GI works under Investigation Assignment and Design & Construction Stage. The findings of the marine GI works are generally in line with the published geological information. The inferred geological longitudinal section is shown in Figure 3. The sub-surface profile along the proposed tunnel alignment consists of marine deposit overlying alluvium, which is underlain by completely decomposed granite (CDG) and bedrock.

The proposed TBM tunnels will generally pass through a thick layer of alluvium with local presence of marine deposits at the southern section (1950m). Subsequently in the middle section (1700m), completely decomposed rock is expected to be encountered while the alluvium becomes thinner. At the northern section (850m) including the submarine cable protection zone (540m), the tunnel is likely to encounter rock where the rockhead levels intercept the lower portion of the tunnel. Since permission to carry out drillholes within the submarine cable protection zone was not allowed in the design stages, the rockhead profile along this section was based on the interpreted rockhead levels from the geophysical survey data.

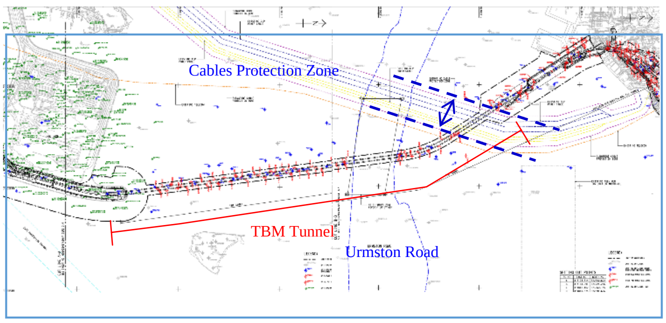

Figure 2 Ground investigation plan

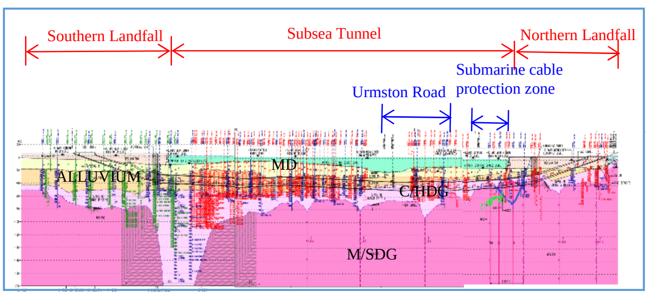

Figure 3 Inferred geological longitudinal section along tunnel alignment

3. HORITONTAL DIRECTIONAL CORING (HDC)

In order to collect more reliable ground information particularly the soil and rock interface in the cable protection zone for the design of TBM, HDC is considered to be proposed in marine condition for TM-CLKL project. HDC employs a steerable drilling bit allowing the core to follow a pre-planned alignment. The HDC system comprise 3 main components: 1) Steerable drilling – using steerable directional core barrel; 2) borehole surveying – using a miniature electronic multishot (EMS) instrument; and 3) windows software package for the planning and plotting of the borehole trajectory. There are normally two types of core hole size for HDC operation, "N" size unsteerable coring (in straight section) and "D" size steerable (in curve section) coring, giving a core diameter of 47 mm and 31.5 mm for the straight section and curved section respectively. The maximum bending angle of HDC shall be 9 degree per 30 m, which gives the minimum bending radius of about 180 m. The maximum core-run is 3m in curved section and 6 m in straight section. The essential elements of the HDC system and operation principle have been discussed by Lam et. al., 2008, and Cunningham & Tam 2012.

The stages of HDC operation usually include: 1) insert casing into rock head; 2) steer HDC down and level out to tunnel horizon; 3) drill out horizontal coring in 50m stages with specialist steering and with pump down packer water inflow testing if required; 4) complete horizontal coring through expected geological feature and to investigate along tunnel alignment; 5) complete water absorption testing with double packer along selected lengths of HDC hole; and 6) grout and backfill HDC hole.

HDC is generally used for rock tunnel projects and had been successfully employed in providing useful geological and geo-hydrological information for tunnel design and geological risk control in several tunnel projects in Hong Kong. A summary of HDC in previous tunnel projects carried out in Hong Kong is shown in Table 1.

Table 1 Summary of HDC in Previous Tunnel Projects

Project	HDC Information				In-situ test
	HDC	**Length (m)**	**Duration (months)**	**Geology**	
Po Shan Tunnel (Lam et al. 2008, Lo et al. 2010)	HDD1	252	1	Grade II/III Tuff	Impression packer test, water absorption test, groundwater inflow monitoring
	HDD2	310	1.5	Grade I/II Tuff	
HATS 2A Tunnels (Cunningham et al. 2012a, Cunningham et al. 2012b)	HD01	1250	10	Grade III/II Granite	Impression packer test, water absorption test, groundwater inflow monitoring
	HD02	610	5	Grade III/II Granite	
	HD03	655	6	Grade III/II Granite	
	HD03a	795	5	Grade III/II Granite	
	HD04	1085	8	Grade III/II Granite	
	HD05	700	5	Grade III/II Tuff	
Eagle's Nest Tunnel (Lo & Cheuk 2006)	NP/1	1152	6	Grade II/III Granitic rock	groundwater inflow monitoring
	SP/1	550	2	Grade II/III Granitic rock	

4. DESIGN OF THE SUBSEA HDC

4.1 Design Considerations

The subsea tunnels will pass underneath the CLPP submarine cable protection zone with length of about 540m. Liaison with CLP and telecom cable company concluded that the telecom cable was abandoned and the protection zone for CLP cables was agreed at 100m from both sides the outermost cable. Conventional marine drillhole between the cables was not allowed at the design stage with the consideration of potential risks of damaging the cables which are the only power supply to the HKIA. Thick layer of soft soil and high water depth (over 20m) is anticipated at the southern side of the submarine cable zone, as a result starting the HDC from the northern side (with water depth of about 15m) of the cable protection zone was proposed.

The total length of the proposed HDC was about 660m. The proposed alignments of the HDC were shown on Figures 4 and 5. The main purpose of the HDC was to identify the ground conditions and collect rock sample for testing along the tunnel alignment within the cable protection zone. In order to prevent the risk of leaving any obstacle of HDC equipments in the tunnel bore, HDC was planned to be drilled at the invert level along the centre of the twin tunnels. Based on the available GI information and the inferred geological longitudinal section, it was anticipated that the HDC would go through the rock, soil or soil/rock interface and be terminated at the interface of soft / mixed ground..

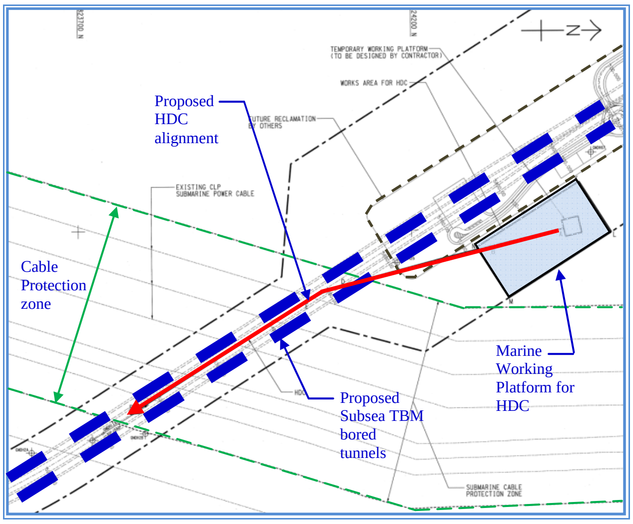

Figure 4 Layout plan of the proposed HDC

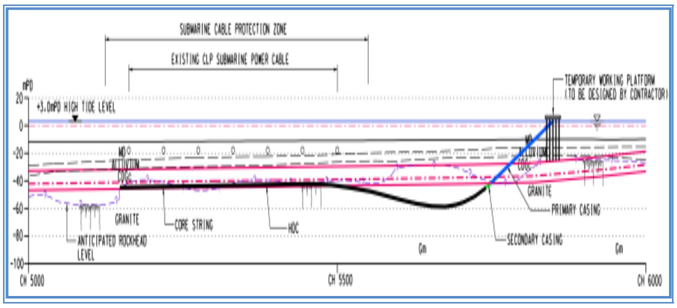

Figure 5 Longitudinal section of the proposed HDC

The HDC operation in marine condition can be carried out from a jack-up barge or a marine working platform located outside the submarine cable protection zone. In order to carry out the inclined drillhole and HDC, a stable working platform with the following pre-requisites are required:

- Sufficient leg length of the platform to cope with the water depth and seabed conditions;
- Able to resist lateral reaction from inclined drillhole / HDC;
- Sufficient working area for set up of drilling rig and storage of ancillary equipment; and
- Sufficient stability to withstand typhoon and other adverse weather conditions.

The biggest jack-up barge available in Hong Kong is with maximum leg length of 35m and plan dimension of 12m x 19.5m. The operating water depth is acceptable however the jack-up barge is not designed to withstand lateral reaction. Besides, the working area available on the jack-up barge was considered insufficient for the HDC set up. In case of typhoon, the jack-up barge has to be towed to typhoon shelter. Therefore, jack-up barge was considered not feasible for the HDC works and a tailor-made marine working platform supported by pile foundation was provided. According to the specifications provided by the specialist contractor, a minimum working area of 15m x 20m should be provided for HDC set up and operations.

4.2 Trajectory Planning of the HDC

To ensure the HDC to arrive at the invert level along the centre of the twin tunnels within the CLPP submarine cable protection zone, the starting point was planned at about 300m from the interface between tunnel alignment and the edge of CLPP submarine cable protection zone with offset of about 150m east to the tunnel alignment. The curved section of HDC should run at a detour route and pass underneath the south-bound tunnel. The lowest level shall be about 20m below the tunnel invert level to ensure the minimum turning radius of 180m is not breached. Thereafter, the trajectory of HDC should be adjusted both horizontally and vertically to a direction parallel to the tunnel alignment and at the target location before entering the CLPP cable protection zone.

The trajectory was planned and developed in 3-dimensional space and the corresponding radius of curvature for the initial section was planned to be 200m. There were 6 control points with coordinates and elevation of the proposed HDC trajectory and tolerance envelope of drilling to govern the drilling specialist to plan the coring path with preset bending and roll angles. The control points included the starting point, the end point of the inclined straight section entering bedrock, the anticipated lowest point of steerable coring, the control point below the first tunnel section, the adjusted point with corrected direction before entering the target position of CLPP submarine cable protection zone, and the end point of the trajectory. The vertical and horizontal tolerances of the directional core hole were +/- 5m from the planned trajectory. Figures 4 and 5 showed the projected views of the 3-dimensional trajectory on plan and tunnel longitudinal section.

In order to allow the HDC to start from steering within the rock mass, an initial section of inclined drillhole with casing from a working platform was constructed down to the rockhead level. Thereafter, the HDC equipments were inserted within the casing of the inclined drillhole for directional coring. For the rock sections, "D" size steerable coring was used. It was anticipated that CDG/HDG ground may be encountered within the rock section along the planned trajectory. With the consideration of more than 25m overburden at the coring level and the ground is expected to be very dense. "N" size non-steerable coring (a straight section) is used for these sections. In order to pass through the soft ground, grouting works and casing may be necessary during drilling operation. In addition, core loss is expected in the soft ground resulting in no information can be recovered by the wire-line core recovery barrel. The trajectory control could be achieved, although the tolerance was expected to be relative larger than that in rock condition. Risks in soft ground as mentioned above might exist, however, the HDC works were considered workable by careful planning and drilling operation, and implementation of preventive and remedial measures.

Due to other difficulties encountered during construction as discussed in Section 5, the final trajectory is not as same as the planned trajectory.

5. CONSTRUCTION OF THE SUBSEA HDC

5.1 Working Platform at Sea

5.1.1 Design of Working Platform

A temporary steel working platform with dimension of 15m x 20m was designed to place the HDC drilling rig, casings and ancillary equipment for marine operation. The platform was constructed using sheetpile decking and was supported by four numbers of 1.2m diameter (16mm thick) circular hollow steel piles. The piles were drilled through a few meters of marine deposit and founded into alluvium layer. Dead load, live load, wave load and vessel impact load were considered in the platform design. The maximum design vertical load for each pile was 1440kN. An inclined steel sleeve was installed from the platform to the sea bed to protect the drilling rod of the HDC from damage by marine vessel. The general layout, cross section and details of the working platform are illustrated in Figure 6.

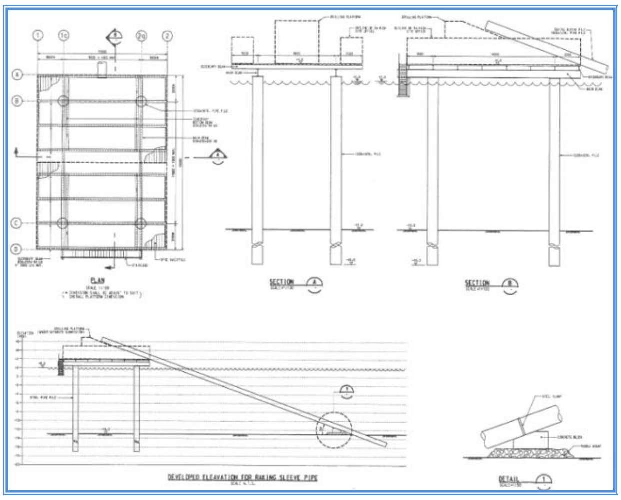

Figure 6 Layout and details of the working platform at sea

5.1.2 Construction of Working Platform

The piles were lifted up by crawler crane located on the flattop barge and were pitched into the sea bed with their self-weight until harder layer was encountered. Low frequency vibration hammer was then used to drive the piles to the design level. The sheetpile decking was prefabricated on land in two pieces. Each piece of the decking was delivered to site by barge and connected together by welding. The construction process of the working platform was illustrated on Photos 1 to 3. The duration of construction and that of demolition of the working platform were 1 month and 2 weeks respectively.

Photo 1 Erection of steel beams on top of piles

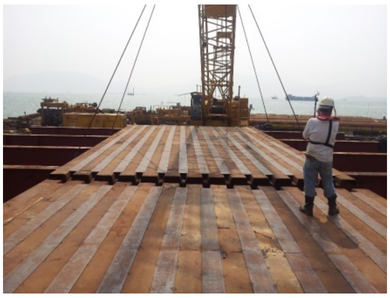

Photo 2 Erection of steel decking

Photo 3 Completed temporary working platform

5.1.3 Construction Safety

Vessel impact was one of the major construction risks to the working platform because it was located very close the container terminal. Precautionary measures such as buoys, lanterns and warning flags were installed around the working platform to alert the other vessels as shown on Figure 7. The risk of typhoon was also considered during construction stage and it was concluded that no works would be carried out during the typhoon season from July to September (2012?).

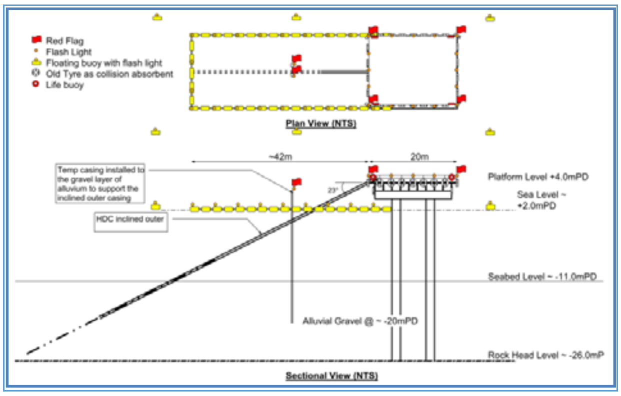

Figure 7 Precautionary measures installed around the working platform

5.2 Drilling of HDC Works

5.2.1 Equipment

HDC works were carried out by using a steerable core barrel as shown on Photo 4. The major components of the barrel included the Dogleg, eccentric housing and packer assembly. The packer assembly controlled the drilling direction and the eccentric housing adjusted the curvature of the trajectory. The maximum bending angle of the core barrel was 9 degree per 30m (R=180m). The maximum core-run for deviated section and straight section was 3m and 6m respectively. The diameter of rock core samples obtained from deviated section and straight section were 31.5mm and 47mm respectively.

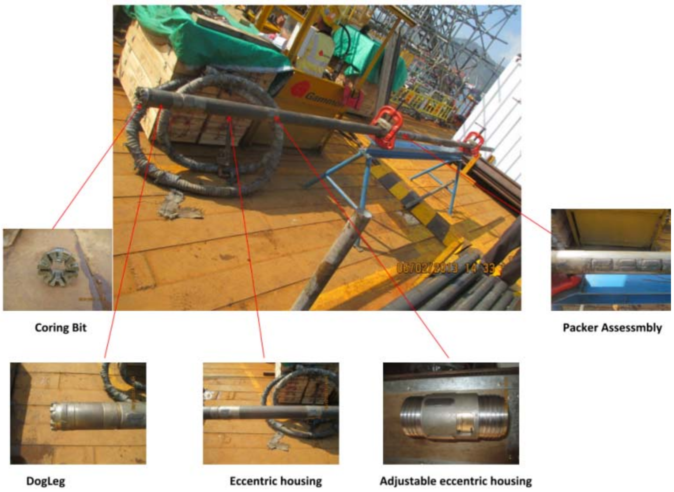

Photo 4 HDC steerable barrel

A non-magnetic electronic multishot surveying equipment (Photo 5) was used to measure the co-ordinates and level of the trajectory. The equipment was connected with a wireline system which run inside the casing and stopped at any specified interval for carrying out survey works. In the case of TM-CLKL, survey was carried out at 25m intervals for the straight section and at 6m intervals for the curved section. The surveying data was transmitted to the computer through a USB modem.

Other equipments such as drilling rig, generator and steel casing were also used during HDC works.

Photo 5 The non-magnetic electronic multishot surveying equipment.

5.2.2 Drilling Process

The drilling rig, generator and casings were mobilized to the temporary working platform by crawler crane installed on flat top barge. The drilling rig was fixed on the working platform to prevent movement when carrying out the drilling works. The drilling rig was set at an inclination angle of 23 degrees downward to the horizontal according to the planned trajectory.

Conventional drilling method was used for the straight section from chainage 0m to 145m, and HDC drilling was adopted for the curved section beyond chainage 145m. Down-the-hole survey using the multishot survey equipment was carried out throughout the drilling process at specified intervals to ensure the HDC run was in accordance with the planned trajectory, and to correct any deviation noted. The rock cores recovered from the drillhole were stored in the core boxes and some of the samples were selected for laboratory testing. The HDC works was eventually carried out in three branches with a total length of 708m, which was slightly different from the planned trajectory as a result of deviated ground conditions and difficulties encountered. The duration of the drilling works consequently took 5 months to complete which was within the original plan. Figure 8 shows the as-built HDC trajectory. The HDC hole was subsequently backfilled by a cement/bentonite grout.

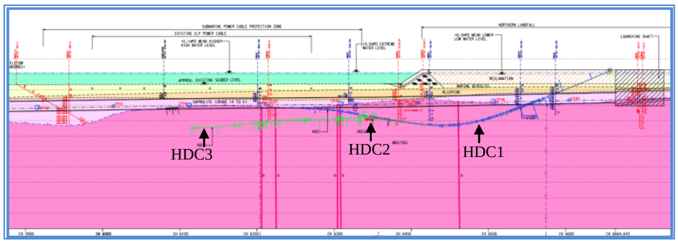

Figure 8 As-built trajectory of HDC

5.3 Difficulties and Corresponding Solutions

5.3.1 Site Location and Constraints

The HDC temporary working platform was constructed in marine condition with heavy marine traffic flow for a long duration (i.e. 8 months including erection of platform and drilling works). The Marine Department (MD) was very concerned about the potential risk of vessel collision with the working platform. Apart from installation of buoys, lanterns and warning flags around the platform (Figure 7), a guard boat working 24 hours a day was also provided to direct the marine traffic under the requirement of MD. Simplified Temporary Land Allocation (STLA) was normally not required for marine ground investigation works when using jack-up barge or flat top barge as working platform. However, MD required the HDC works to be carried out under a STLA in view that the working platform was supported by piles for more than half a year.

5.3.2 Liaisons

Utility detection was carried out before commencement of the HDC works. The latest utility plan indicated there were high voltage CLPP submarine cables within the works area. The results of the geophysical survey also indicated the cables were located on top of the proposed trajectory. After several liaison meetings, the proposed HDC works was subsequently approved by CLPP. In addition, approval of the MD by way of Marine Department Notice should also be obtained by providing details of the proposed works, location and extent of the works area, safety measures such as buoys and lanterns provision, risk assessments etc., prior to commencement of the works.

5.3.3 Jammed Drill Barrel

During HDC drilling, weak zones with low and even no core recovery were encountered in several locations. Every time when the entire length of barrel was required to be retrieved for maintenance, such as to replace the drilling bits, there was a chance that the weak zone would collapse hence jamming the drilling rods and bits. Although pressure grouting were carried out in the weak zones, unexpected broking and jamming of drill bits and drill barrel were occurred in several locations. Destructive drilling of broken NQ barrel in the HDC drillhole was carried out but unfortunately the destructive drill bit was also jammed for once. Any obstruction especially metal must not be left in-situ and not induce risk for future TBM operation. The only method to retrieve those stuck drill bit/ barrel was to form a larger diameter hole. HQ size was reamed from the bottom of NX casing to retrieve the jammed bullnose bit (Photo 6) and NQ barrel.

Photo 6 The Jammed bullnose bit and casing were retrieved from drillhole.

5.3.4 Geology and Unfavourable Ground Conditions

The principle of the HDC steerable core barrel operation depends on the packer assembly operated in a differential pressure on the rock face to control the drilling direction. However, unforeseen soft ground condition was encountered at chainage 435m so that the core barrel was not able to change the direction. Further drilling would result in hole alignment being out of the allowed drilling envelop and entering the proposed tunnel alignment. After reviewing the available ground investigation information, it was decided to form a branch hole at chainage 287m and continue the HDC works with a new alignment. However, soft ground was encountered again after drilling for short distance in the new alignment. The third branch was therefore formed to suit the actual ground condition and the HDC works was subsequently completed at chainage 535m. The as-built trajectories of the three branches namely HDC1, HDC2 and HDC3 are illustrated in Figure 8.

In addition, there were other unforeseen ground conditions encountered. The lower than anticipated rockhead forced the steerable HDC operation to be started at a deeper location, sharper drilling curvature had to be carried out to adjust the trajectory to meet the control points. The existence of weak zones with no core recovery caused the drilling route of HDC deviated from the planned trajectory and impossible steerable drilling, pressure grouting had to be implemented to avoid hole collapse and to provide strong enough media for steerable drilling reaction. The changing and unfavourable geological conditions and the HDC drilling operations were reacted. The drilling operation might have to be revised in accordance with the planned backup scheme and remedial measures, when encountering different ground conditions.

6. CONCLUSION

Despite the HDC technique has been employed in several other tunnelling projects in Hong Kong, it is the first time that HDC has been carried out in marine condition drilling through mixed ground under the TM-CLKL project.

As a ground investigation method, the subsea HDC works aim to investigate the ground conditions underneath the submarine cable protection zone, and has successfully achieved its objective, obtaining important geological data for the TBM design and risk control.

The technique proves to be an effective means to explore ground conditions and obtain rock samples from locations where conventional vertical or inclined drilling cannot be achieved.

7. ACKNOWLEDGEMENTS

The paper is published with the permission of the Highways Department, the Government of the Hong Kong Special Administrative Region for which the authors would like to gratefully acknowledge.

8. REFERENCES

Cunningham, B. & Tam, J.K.W., 2012. Ground Investigation Guidelines – 04.9 – Horizontal Directional Coring. Association of Geotechnical & Geoenvironmental Specialists (AGS), Hong Kong.

Cunningham, B., Tam, J.K.W., Tattersall, J.W., Nip, G.C.Y. & Seit, R.K.F., 2012a. "Planning of Horizontal Directional Coring for Deep Subsea Tunnel", Proceeding of the HKIE Civil Division International Conference 2012 – innovation and Creativity of infrastructure Development for Quality Cities. HKIE (Civil Division).

Cunningham, B., Tam, J.K.W., Tattersall, J.W. & Seit R.K F., 2012b. "Horizontal Directional Coring (HDC) and Groundwater Inflow Testing for Deep Subsea Tunnels", Proceeding of the HKIE Geotechnical Division 32 Annual Seminar – Geotechnical Aspects of Tunnelling for Infrastructure. HKIE (Geotechnical Division).

Lam, Y.C., Tam, K.W. and Lo, Y.C. 2008. "Ground Investigation for Tunnel Works", Proceeding of 28th Annual Seminar, Hong Kong Institution of Engineers, Geotechnical Division. Hong Kong, 2008

Lindhjem, Rune and Tai, Chris (2008), "Directional Core Drilling in Tunnel Construction", Proceeding of World Tunnel congress 2008 – Underground Facilities for Better Environment and Safety, India, P1183 - 1191

Lo, J.Y.C., Chau, S.F. and Cheuk, J.C.Y. (2010). "Water Inflow During Ground Investigation and Construction at Po Shan Drainage Tunnels". The HKIE Transactions, Volume 17 Number 2, June 2010. The Hong Kong Institution of Engineers, Hong Kong, 2010

Lo, J.Y.C. and Cheuk, J.C.Y. (2006). "Water Inflow Characteristics in Rock Tunnels". Proceeding of 26th Annual Seminar, The Hong Kong Institution of Engineers, Geotechnical Division, Hong Kong, 2006