Horizontal Directional Drilling (HDD) Technique for Undersea Microtunnelling

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ABSTRACT

The Harbour Area Treatment Scheme (HATS) Stage 2A project is currently under construction to collect the sewage generated from the northern and south-western parts of Hong Kong Island and to convey the sewage to Stonecutters Island Sewage Treatment Works for treatment before discharging into the Victoria Harbour. The works involve the construction of a deep sewage conveyance system with a total length of over 20 km. This paper focuses on a 1.4 km section of the system connecting Ap Lei Chau and Aberdeen, which is being constructed using the Horizontal Directional Drilling (HDD) technique.

The construction works of this section involve the installation of twin 600mm internal diameter High Density Polyethylene (HDPE) pipes of 1.4 km length at a depth reaching at maximum approximately 100m below sea level along the East Lamma Channel using HDD, which is a surface-launched drilling technique. This paper reviews the design considerations and technical challenges of the HDD works; the steering control for pilot hole drilling; the selection of cutting tools; the reaming for hole enlargement; and the HDPE pipe pullback, jointing and testing processes.

1. PROEJCT BACKGROUND

To further improve the water quality of the Victoria Harbour, the Drainage Services Department is now implementing the Harbour Area Treatment Scheme (HATS) Stage 2A Project to collect sewage generated from the northern and south-western parts of Hong Kong Island and to convey the sewage to Stonecutters Island Sewage Treatment Works for centralized treatment before discharging into the harbour. The entire HATS Stage 2A Project is anticipated to be commissioned at the end of 2014. Works under HATS Stage 2A include the construction of over 20km of deep sewers along the coastline of the Hong Kong Island and across the Victoria Harbour.

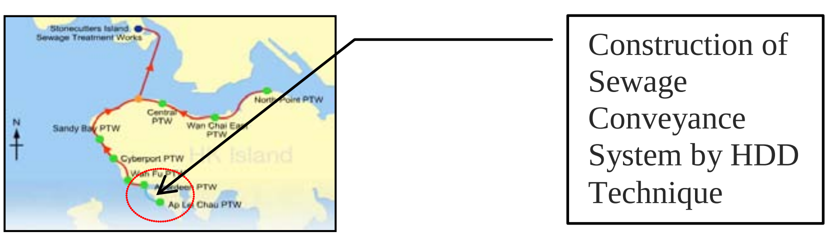

Fig.1: HATS2A-Tunnel Route

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As part of the HATS Stage 2A Project, two sewage tunnels, namely Q1 and Q2, of 600mm internal diameter, 1.4km long and reaching approximately 100m below sea level between Aberdeen and Ap Lei Chau along the East Lamma Channel, are to be constructed using the HDD method.

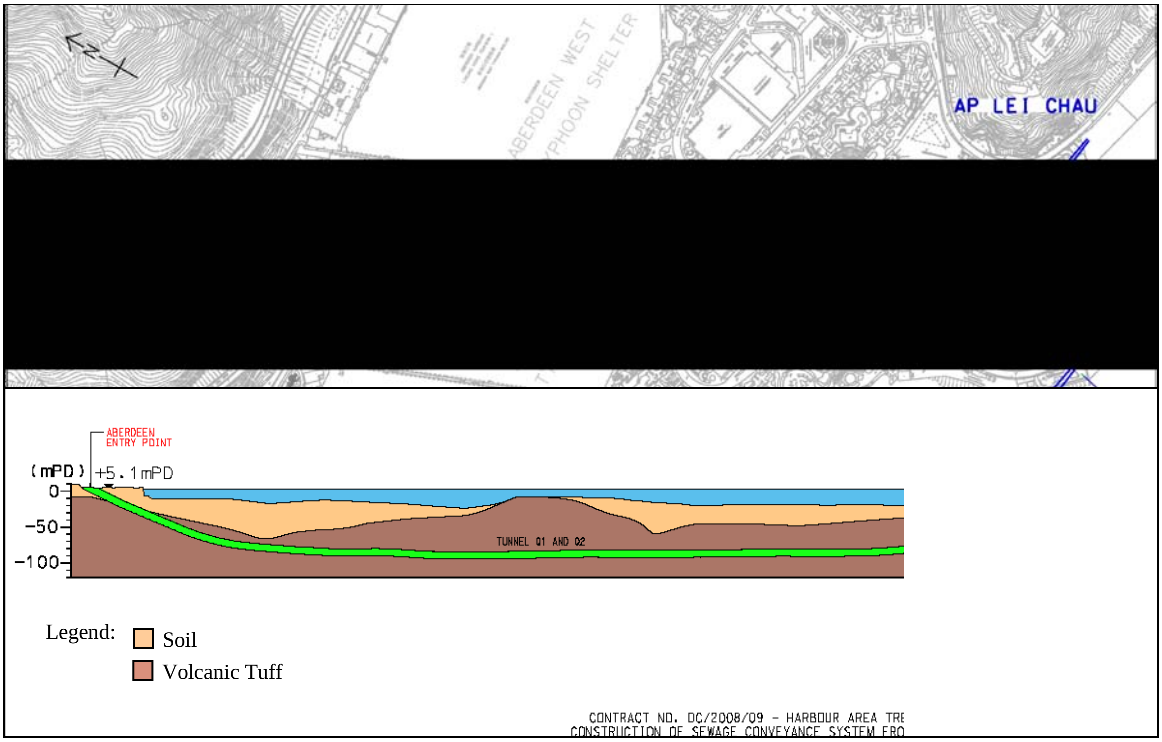

Fig.2: Horizontal and Vertical Profiles of Tunnels Q1 and Q2

2. DESIGN CONSIDERATIONS

2.1 Design Tunnel Alignment

The tunnel alignment has to be designed to accommodate the acquired easements, to minimize impact on the potentially hazardous installations (PHI) such as the Town Gas Holder and the Shell LPG depot located near to the tunnel entry and exit points, and to avoid undersea obstructions such as submarine cables. In addition, the combined curvature of the alignment needs to be gradual and smooth to limit the bending stress in the HDPE pipeline. To meet these demands, a detailed ground investigation has been carried out and a tunnel alignment incorporating both horizontal and vertical curvatures have been formulated with the majority of the tunnel alignment passing through the volcanic tuff bedrock, as shown in **Figure 2**.

2.2 HDD Technique

HDD is a surface-launched, remotely controlled drilling technique using bentonite slurry to support the excavated tunnel, to transmit torque during pilot hole drilling and to transport the rock cuttings through a mud circulation system.

Basically, the HDD process involves 3 main stages. The first stage involves the drilling of pilot hole of 12-1/4" (311mm) diameter along the proposed alignment of the tunnel from Aberdeen to Ap Lei Chau. In the second stage, the pilot hole will be enlarged in steps to the final size of 36" (914mm) diameter. Lastly, the High Density Polyethylene (HDPE) pipes will be jointed and pulled back into the enlarged hole forming the sewage tunnels.

2.3 HDPE Pipeline

High Density Polyethylene (HDPE) pipe is used in this project mainly because it is relatively flexible and can accommodate the curvature of the tunnel alignment. It also has good scratch resistance and the fused jointing system gives it a zero-leak-rate joint with design tensile capacity equal to that of the pipe proper. Unlike steel pipe, it is not subject to corrosion. The HDPE pipe chosen for the twin sewage tunnels has an outside diameter of 740mm and an internal diameter of 600mm, with a standard dimensional ratio (SDR) of 11 and a pressure rating of 16 bars. It is designed to be maintenance free as there is no need for man-entry maintenance. The HDPE pipeline is designed to resist the pullback loads during installation, including tensile pull forces, external hydrostatic pressure, bending stresses and other loads such as groundwater and surcharge loads occurring over the life span of the pipeline.

Fig.3: Surfaced Based HDD Rig-PB320

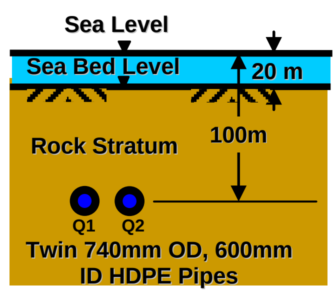

Fig.4: Twin HDPE Pipeline Cross-section

3. TECHNICAL CHALLENGES

There are several technical challenges to be overcome in this HDD project. They are described in the following sub-paragraphs.

3.1 Geological Fault Zones

The alignment of Tunnel Q will pass through a number of faults, such as the Aberdeen Fault Zone with the associated monzonite intrusions, and zones with low rock cover. These geological features will pose construction risks to tunnelling work by tunnel boring machine (TBM) or the drill and blast method. To minimize such risks, and after consideration of various factors including the tunnelling size and length involved, HDD technique was selected to avoid such risks by eliminating the need for man entry as most of the plant and equipment are set up at surface level with the drilling and reaming work remotely controlled. It is noted that weathered zones and highly fractured bedrock may cause problems in keeping the bore open during HDD drilling, reaming and pipe installation and in steering control during the pilot hole drilling operation. By controlling the viscosity and density of the bentonite slurry, the tunnel in the fractured zones is stabilized by the pressure exerted on the bare excavated surface to support the bore and to guard against ingress of groundwater. By using HDD, the risks of groundwater drawdown as well as ground settlement are minimized. The bentonite slurry support is provided continuously throughout the process of pilot hole drilling, reaming and pipe pulling operation.

3.2 Ground Condition at Tunnel Entry & Exit Points

The tunnel entry and exit points are situated on reclaimed land formed with fill materials and pell mell rubble of the existing seawall. These highly permeable materials can cause loss of bentonite slurry in circulation, thus can induce ground settlement and jeopardize the HDD works. To overcome this problem, 48” diameter protective steel casings have been installed through the soft ground section beneath Tin Wan Praya Road before Tunnels Q1 and Q2 enter into the bedrock. The steel casings have been installed by pipe ramming technique with some special tools fabricated on site to facilitate the removal of hard spoils by coring and augering. The pipe ramming technique is useful in avoiding open excavation on Tin Wan Praya Road which is the only vehicular access to the neighbouring community. To overcome hard and big boulders encountered, the HDD subcontractor, Mersing, used core casing to cut through the big boulders and successfully installed the open ended steel casing into the Grade II/III bedrock interface.

Fig. 5 Pipe Ramming of 48” Steel Casing

Fig. 6 Special Tools for Augering

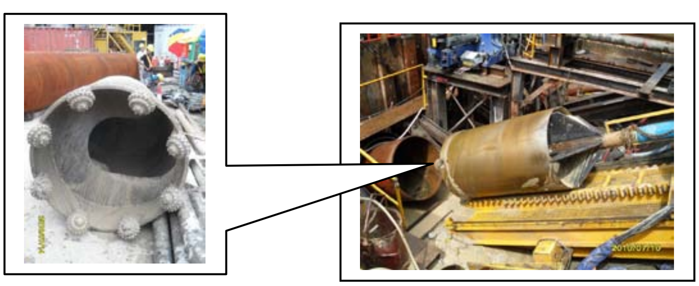

Fig.7: Special Tools of Core Casing

3.3 Site Layout

The works area provided for the HDD set up is quite limited and the site layout for the HDD set-up has to be carefully planned to accommodate all the heavy plants and equipment, such as the crane, mud pumps, power pack, mixing tank, recycling tank and the storage of drill rods at both the tunnel entry and exit areas to facilitate smooth and safe construction operations. A photo of the set up at the entry area is shown in **Figure 8**.

Fig. 8: HDD Plant & Equipment Set Up at Aberdeen Entry Point

3.4 Environmental and Safety Control

As most of the plants and equipment are located on surface, it is necessary to monitor and control the impact to the environment. In order to minimize the noise generated during the HDD works, noise barriers and noise enclosures have been erected to contain noisy equipment, such as the power pack and the mud pumps. The barriers erected can also minimize the visual impact to the nearby residential areas.

The HDD tunnel entry and exit sites are also close to two potentially hazardous installations (PHIs), i.e. a town gas holder tank and an LPG depot. To minimize the risk of accidental damage to the PHIs and their associated pipelines during construction, a monitoring plan has been implemented. Settlement markers, piezometers, vibration control points and gas detectors have been installed and are closely monitored. In addition, risk assessments have been carried out regularly during the construction stage to identify the potential hazards and to review the mitigation measures.

3.5 Steering Control and Tracking for the Deep Offshore Alignment

The steering control and detection of drill path for this offshore tunnel alignment are one of the major challenges of the HDD works. Also, the presence of two groups of high tension submarine electric cables on the seabed along the drill path poses additional challenge to the steering of the drill head. The steering control and detection system during pilot hole drilling of Tunnels Q1 and Q2 are described in the following sub-paragraphs.

3.5.1 Steering Control

Steering control has been achieved by the application of an 8”OD high torque, medium speed positive displacement motor or mud motor with an adjustable tilt angle. A near-bit stabilizer is installed on the motor together with various under-sized string stabilizers to enhance the 3-point geometry of the bottom hole assembly (BHA) when drilling in rock. The rest of the drill string consists of oversize 6-5/8” drill rods, which provides better rigidity and deviation control.

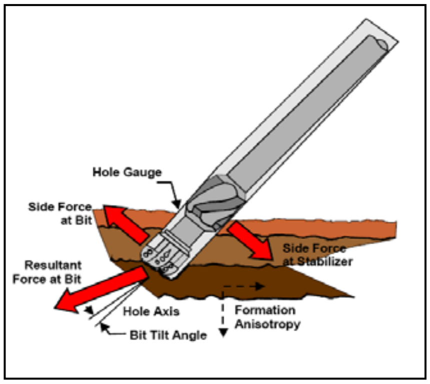

Fig.11: Deviation and Side Forces

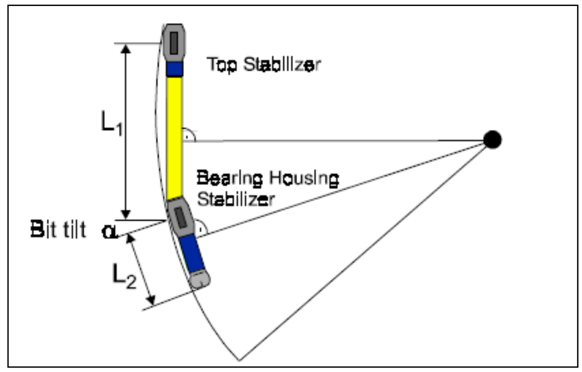

Fig.12: The 3-Point Geometry

When drilling the pilot hole with a mud motor assembly, directional changes can be achieved mainly through the action of the outer cutters of the bit directed by pushing action of the mud motor. The result of this action cannot be seen immediately as the survey sensor is about 16m away from the bit. Therefore, the directional driller would have to use his intuition to constantly project ahead based on his gained skills and past experience in previous HDD projects. He should also be cognizant that any wear on the outer cutters would affect the drilling curvature, the effect of which cannot be seen immediately. In addition, any wear on the stabilizers can alter the 3-point geometry of the drilling assembly and change the drilling radius. The directional driller has to constantly update and anticipate the true action at the bit during pilot hole drilling.

3.5.2 Tracking System

The checking of the drilled alignment was generally conducted by the downhole survey system of ParaTrack. In view of the long drill path, the Beacon Tracker System was used to provide an additional remote reference signal for tracking the drilled alignment. Gyro surveys have also been conducted to validate the magnetic surveys as any stray magnetic fields such as those induced by the high tension submarine cables may introduce an additional magnetic field which could mislead the interpretation of measurements.

Both the ParaTrack and Beacon Tracker System consist of a magnetic field generator powered by AC current through coils and a magnetic field detection probe for steering housed inside a non-magnetic drill pipe behind the drill head and mud motor. The steering probe consists of solid state electronics that measure magnetic fields and the acceleration due to gravity in three planes at right angle to one another. The steering probe transmits detected data to the surface via a mono conductor electric wireline, which verifies the magnetic heading of the drill path and provided information of the magnetic azimuth, inclination and orientation of the mud motor. Low frequency AC current instead of DC current was preferred and used in this project as it provides a better distinction from the Earth's field and the stray magnetism induced by electrical appliances and massive metallic structures. To avoid the interferences from the magnetic fields of the drill string, the probe has been placed inside an 8"OD non-magnetic drill collar (NMDC).

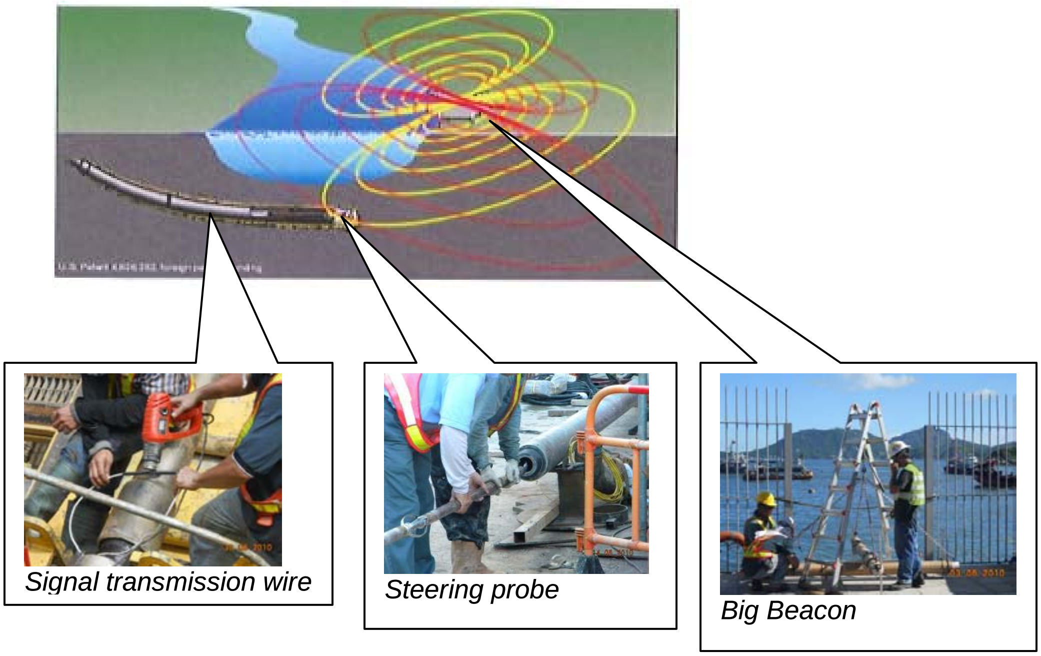

Fig. 13: ParaTrack & Beacon Tracker System

Beacon Tracker System basically consists of 2 solenoids placed horizontally at right angle to provide a remote reference magnetic field for tracking the alignment.

Practically, interference and noise generated from the natural environment could affect the precision of any surveys. Any stray magnetism or steel structures in the vicinity such as the drill string, power cable and container tankers can affect the azimuth survey. Therefore, non-magnetic downhole (along bottom of the hole) gyroscopic surveys have been conducted for counter-checking. However, the contemporary gyroscopes are very delicate and need continuous power supply which makes their operation time consuming. Both downhole magnetic and gyroscopic surveys consist of a series of projection using incremental reading of inclination and azimuth over a measured length. Therefore, errors associated with each reading will accumulate. The downhole surveyor must exercise extra care to constantly cross check the predicted values against the measured values.

After the completion of the first pilot hole for Tunnel Q1, a wireline was drawn through the drill string still remaining in the tunnel bore. Both ends of the wireline were then grounded to the ParaTrack system and earthed to provide a reference magnetic field for the survey of the 2nd pilot hole drilling in Tunnel Q2. Under this tracking system, the pilot holes of Tunnels Q1 and Q2 punched out successfully at the target exit point.

4. HDD EQUIPMENTS AND CUTTING TOOLS

4.1 HDD Drilling Rig

The two HDD rigs used in this project belong to the maxi rig class, which are capable of either pushing or pulling up to 3,800kN and generating 122kN-m rotary torque. The push/pull action is achieved via a rack and pinion assembly powered by two 460hp diesel engines. It is complemented by two specially designed and tailor-made small footprint F600 triplex mud pumps and a mud recycling system consisting of a series of shakers and desilters.

4.2 Tri-cone Rock Bit

Both pilot holes Q1 and Q2 have been drilled with 12-¼" tri-cone rock bits. Bit selection is crucial to the success of the operation. Oilfield industry type bits with IADC code 6-4-7 or harder have been selected. These bits have been reinforced with high quality gage and back ream protection. Bit bearing is also important and only high grade sealed or metal-to-metal seal types are used. When pilot hole drilling starts, the bentonite slurry is pressurized by a mud pump and is pumped through the drill rods to the mud motor. The pressure head of the bentonite slurry is converted into power to turn the tri-cone bits at the end of the mud motor. The tri-cone bit is pushed to punch into the rock face causing continuous failures at the rock surface.

4.3 Reamers

After the completion of pilot hole drilling, reamers or hole openers are used to enlarge the tunnel bore to facilitate installation of the HDPE pipe. There exists several reamer types and proper selection is based on soil or rock conditions, hole size and mud pump capacity. The final hole size should be sufficiently large to allow for an annular void for the return of bentonite slurry and cuttings, and to reduce frictional pullback forces during pipe installation. In this project, 20"(508mm), 26"(660mm) and 36"(914mm) hole openers using rolling cutters with tungsten carbide inserts arrayed on top have been used for reaming the tunnel bore in rock formation.

Fig.14: Tri-cone Bit for Pilot Hole Drilling

Fig.15: Photo of a 36" Diameter Hole Opener

5. REAMING FOR HOLE ENLARGEMENT

To enlarge the pilot hole, a reamer or hole opener is attached to the drill pipe and the drill pipe is pressurized to ensure the jets are open. The reamer is then rotated and pulled or pushed through the pilot hole to enlarge the hole in one or more reaming passes. This can be done by either backward reaming from the tunnel exit point or forwarding reaming from the tunnel entry point. The rock cutting mechanism of the reamer is achieved by exerting a cutting thrust on the rock surface using tungsten carbide inserts that are arrayed on the rolling cutters of the reamer. The number of reaming passes to be carried out mainly depends on the diameter of the pipes to be installed and the ground conditions. In this project, three reaming passes are used to enlarge the pilot hole of 311mm diameter to a final bore size of 36” (914mm) diameter. **Figure 16** illustrates the mud circulation system for concurrent reaming of Tunnels Q1 and Q2. The setting up of forward reaming for Q1 and backward reaming for Q2 is necessary due to limited site areas at both the entry and exit points such that a mud circulation system has to be installed separately at both the entry and exit points.

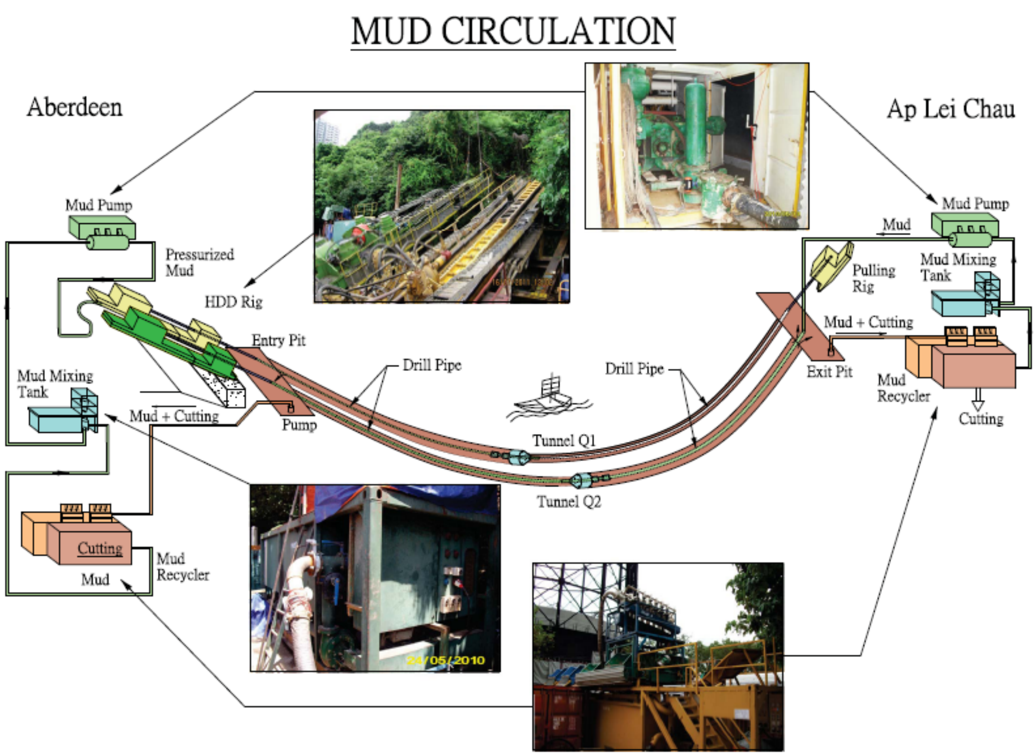

Fig.16: Mud Circulation System for Concurrent Forward Reaming of Q1 and Backward Reaming of Q2

6. HDPE PIPE PULLBACK, JOINTING AND TESTING PROCESSES

After hydrostatic pre-installation pressure testing to 15bar and testing to 10bar under a pulling force equal to 1.2 times of the maximum designed pulling load, 50.3ton have been completed, the HDPE pipe will be installed in the tunnel bore by the pullback process. A barrel reamer is designed to lead a pulling head of the HDPE pipe. A swivel is installed between the reamer and the pulling head to prevent the rotation of the pipe during pipe pulling. The pipe should be properly positioned and supported before entering the bore. In this project, the HDPE pipe segments are designed to be butt-fusion jointed to form the complete pipeline. Butt fusion is a method of jointing by thermoplastic resin. The ends of the jointing pipe segments are heated to the semi-molten state and then rapidly pressed together to form a fusion joint. The pipeline will be supported on rollers during pulling into the tunnel bore to prevent damage to the pipe surface. The pullback process should be carried out continuously in order to reduce the risk of getting stuck in the tunnel. Finally, hydrostatic pressure test with a test pressure of 15 bars will be conducted to the installed HDPE pipeline to test for any leakage.

7. CONCLUSION

Both the pilot holes for tunnels Q1 and Q2 have been successfully drilled and punched out at very precise exit points and in the right orientation. Reaming of the pilot holes is currently being carried out. There are many difficult challenges since the commencement of the works, but with the perseverance and close cooperation among the client, consultant engineer, contractor, HDD specialists and the crew, it is expected that the whole HDD works could be successfully completed soon by mid 2012.

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9. ACKNOWLEDGEMENTS

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