PLANNING OF HORIZONTAL DIRECTION CORING FOR DEEP SUBSEA TUNNEL
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ABSTRACT

For tunnelling at great depth beneath a submarine environment, it is important that the rock mass quality and groundwater inflow prognosis is as close to the actual as possible. This is for the benefit of the development of construction programme and cost estimation. Six Horizontal Directional Cored holes (HDC) were drilled for the deep subsea sewage tunnel (up to 160 m below ground) of Harbour Area Treatment Scheme Stage 2A (HATS 2A). The HDCs were carried out along the proposed tunnel alignment primarily where major faulting was suspected and in areas with difficult marine access for conventional drilling. The primary aim was to reduce geological and hydrogeological uncertainty to a level that would not be achievable with a conventional investigation programme using isolated vertical or inclined drillholes.

HATS 2A is the first Hong Kong project where HDC has been used to investigate subsea tunnels. This paper mainly discusses the typical considerations when planning the HDC for tunnel works.

1. INTRODUCTION

A comprehensive ground investigation (GI) plan is important to identify problematic ground and the groundwater conditions along the proposed tunnel alignment. Continuous geological and engineering information is difficult to get on land, but even more so in the marine environment.

HDC can provide a continuous core sample along the tunnel alignment. Hence, the risk of unforeseen tunnelling conditions can be minimized compared to using only conventional vertical and inclined boreholes. The HDC launching point can be positioned on land for core sampling seawards and under water.

This paper discusses the typical considerations when planning the HDC for tunnel works, particularly referring to the HATS 2A project. It also provides the fundamental principles of the directional coring method and introduces three typical field tests that can be carried out in a HDC for tunnel project.

2. HDC IN HATS 2A

The HATS 2A project in Hong Kong includes the construction of a deep sewage conveyance system (SCS) with thirteen vertical shafts. The total tunnel length amounts to 20 km at a depth of between 70 m and 160 m below sea level. The GI contract of HATS 2A was spread over a period of two years and was completed in 2009, before the construction of SCS tunnels and shafts commenced in July 2009.
During the detailed design stage, six HDCs were drilled along the proposed tunnel alignment where major faulting was suspected (Figure 1). The HDCs provided continuous core (reaching 160 m below sea level) with the longest drillhole extending 1,250 m below Victoria Harbour (HD01). Another ‘first’ was the use of groundwater inflow tests carried out over 50 m to 120 m long segments to supplement conventional packer test data to give greater insight into the transmissivity of the rock mass at the scale of the tunnel.

![Figure 1 Layout plan showing the proposed HATS 2A tunnel, the completed HDC, and the inferred major geological features](image)

3. BACKGROUND OF DIRECTION CORING METHOD

The system of directional coring was developed in Norway in the 80’s, and the wireline version was subsequently launched in 2001. The key specialist service provider is a Norwegian registered company that has more than 20 years of worldwide experience in directional coring.

The directional coring method has been used in petroleum and mineral explorations, as well as tunnel projects. One of the typical uses of directional coring is “Side-tracking” drilling for investigating the extent of the target ore body (Figure 2). The concept is to create multiple branches of drillholes extending out from a single primary hole drilled from one position. Directional coring is also commonly used in “Steerable” drilling along a planned trajectory, such as the HDC along a proposed tunnel alignment as shown in Figure 3.
4. **FUNDAMENTAL PRINCIPLES OF DIRECTIONAL CORING**

The working principles of directional coring include three key components: planning, steerable drilling and coring orientation surveying as summarized below:

- **Planning**
  - Windows software package that has been developed by the drilling specialist is used for the planning and plotting of the borehole trajectory. The designer should provide the coring trajectory with control points (i.e. coordinates and elevation of the proposed coring) and tolerance envelope of drilling. Then the drilling specialist will plan the drilling route with preset bending and roll angles.

- **Steerable Drilling**
  - Steerable drilling is carried out using a steerable core barrel with wireline operating system. The drilling trajectory is navigated by the “toolface angle” (i.e. roll angle) that controls the drilling direction and the “dogleg angle” (i.e. bending angle) that controls the curvature of the trajectory. The straight section of the coring will be drilled by conventional wireline system, and the deviated section will be drilling by the steerable wireline system. Figure 4 illustrates the key components of the steerable core barrel.

- **Coring Orientation Surveying**
  - Core surveying is carried out using a miniature electronic multishot (EMS) instrument with timing interval specified by the drilling specialist. The EMS records the azimuth and inclination of borehole for the specific point at different depths. The as-built borehole trajectory will be compared with the proposed trajectory after each coring survey, in order to ensure the coring is advancing within the tolerance envelope of the proposed trajectory.

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**Figure 2** Side-tracking drilling  
**Figure 3** Steerable drilling along proposed tunnel alignment

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**Figure 4** Illustration diagram of the directional core barrel
5. CONSIDERATIONS FOR HDC PLANNING

The designer needs to understand the drilling method and the capabilities and limitations of the steerable coring system in order to assess the suitability of the technique and develop an appropriate ground investigation plan that yields optimal results.

5.1. Specifications of steerable coring system

Coring with the steerable barrel can provide deviated rock core when drilling in a controlled direction at a controlled rate in relatively competent rock.

- Maximum bending angle: 9 degree/30 m (Bending radius = approximately 180 m).
- Maximum core-run: 3 m in deviated section; 3 or 6 m in straight section.
- Core diameter: 31.5 mm in deviated section using steerable system; 47 mm in straight section using conventional wireline system.
- Hole diameter: Typically in N-size (76 mm). B-size (60 mm) can be drilled, but not common practice.

The relatively small diameter of the core places some constraints on laboratory tests such as UCS, Poisson’s ratio and Young modulus. Special equipment and data corrections are required to provide equivalency to tests carried out on more typical larger diameter core.

5.2. Navigation of steerable coring system in mixed ground or weak zone

The primary steerable coring system cannot control the drilling direction in soil or soft ground. It was originally designed for directional coring in competent rock, and a supplementary soil coring barrel will be required when coring in mixed ground. The navigation of drilling significantly depends on the response of coring system to the surrounding ground.

When coring in a mixed ground, the drilling specialist will carry out coring surveys more frequently and adjust the drilling trajectory in any sections of competent rock that are encountered. Where no competent rock is encountered for a long section of drilling, a steerable drill head for drilling in soil might be used to control the drilling direction. However, no soil sample can be recovered with this type of drill head.

When coring through a weak zone such as a fault zone, the conventional wireline system is used for coring straight section instead of the steerable wireline system. Some sections of weak ground might require grouting for coring stability reasons. Pressure grouting with cement grout can be carried out through a smaller non-cored hole. When the grout is set properly, the grouted section can be re-cored with the larger diameter directional coring barrel.

5.3. Working area

For HATS 2A, a typical works area of 25 m long and 20 m wide was required for the operation of a HDC hole approximately 1,200 m in length. For HDC holes approximately 600 m long, a typical works area of 15 m long and 10 m wide was required. Appropriate head room should also
be provided for the inclined HDC launching ramp. Figures 5 and 6 show the works areas of 
HDC that were drilling for different lengths.

![Figure 5 HDC04 at Stonecutters Island (coring length 1085 m)](image1)  
![Figure 6 HDC02 at Central (coring length 610 m)](image2)

5.4. Proposed HDC trajectory

Referring to the past projects in Hong Kong, different options of HDC trajectory had been 
planned and driven for different investigations. For example, HDC had been driven sub- 
horizontally into the hillslope from tunnel portals, or initially at inclined angle into the ground 
and then turned to sub-horizontal at the tunnel level. Subject to the site condition and 
investigation purpose, HDC trajectories have been designed and steered within proposed tunnels, 
in between two tunnels or above the tunnel crown. The drill rig should be positioned and drilling 
gle should be set to provide a smooth launching of cored hole into the proposed trajectory.

The designer should specify the dimension of the tolerance envelope and the control points at 
intervals along the HDC, so that the drilling specialists have adequate information to develop 
their drilling strategy. Continuous survey of the coring profile should be carried out to ensure 
that the drillhole is following the specified alignment. A plan and section with 3-D coordinates is 
produced in order to compare the as-drilled trajectory with the specified tolerance envelope.

For the HATS 2A project, the six HDC drillholes were planned at approximately 8 m above the 
proposed tunnel crown and a tolerance envelope of 5 m radius was adopted. The applied bending 
gle angle for the HDC was generally 0.2’ to 0.3’ per 1 m, with maximum angles occasionally up to 0.5’ 
to 0.6’ per 1 m. Figure 7 shows the as-built coring trajectory and tolerance envelope for the 1250 
m long HD01 which was drilled from Sai Ying Pun towards Stonecutter’s Island beneath Victoria 
Harbour.
5.5. Typical drilling duration

The drilling time is influenced by the ground conditions, drilling length, field test quantity and dimension of tolerance envelope. The drilling rate of steerable drilling is 9 m to 15 m per day in a single shift (9 hours). When drilling in straight section using wireline system, the rate is about 25 m to 35 m per day in a single shift (9 hours). Drilling progress reduces in proportion to the length of the hole and the number of tests. An average progress rate of 5.6 m per day was experienced for the 1250 m long HD01.

The six horizontal directional coreholes driven for the HATS 2A project have a combined total length of over 5 km. Table 1 summarizes the duration of the drilling and the field tests carried out in each borehole.

<table>
<thead>
<tr>
<th>HDC</th>
<th>Duration</th>
<th>Length</th>
<th>Level of Horizontal section</th>
<th>Nos. of Inflow Test</th>
<th>Nos. of Packer Test</th>
<th>Nos. of IP Test</th>
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<td>HD01</td>
<td>10 months</td>
<td>1250 m</td>
<td>~140 mPD</td>
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<td>13</td>
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<td>~145 mPD</td>
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<td>655 m</td>
<td>~145 mPD</td>
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<td>~150 mPD</td>
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<td>~135 mPD</td>
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<td>9</td>
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</tr>
</tbody>
</table>

Table 1 Summary of drilling duration and field tests for the HDC of HATS 2A

6. FIELD TESTS IN HDC OF HATS 2A

6.1. Groundwater inflow test

Groundwater inflow tests were carried out using the “Pump Down Packer System” to measure the sectional inflow continuously along the proposed tunnel alignment. The typical length of testing section was 100 m and ranged from 50 m to 120 m. Groundwater inflow measurements
under atmospheric condition give the natural inflow rate into the cored hole by pumping out water and measuring the resulting range of drop in pressure and also the rate at which the system regains equilibrium. The testing method more closely simulates the effect of tunnel construction than packer tests which rely on forcing water into the surrounding rock mass which can induce dilation of the rock joints. The inflow measurements can be used to gain better insight into the hydrogeological regime and the potential effects of tunnel construction.

6.2. Water absorption test

Water absorption test was performed to determine the equivalent rock mass permeability over relatively short lengths (3 m) in a horizontal direction. The water absorption test is a conventional injection method to measure the water acceptance by the rock mass under elevated pressures. The measurement represents the volume of water that can escape from an uncased section of coring, in a given time and under a given pressure above ambient groundwater pressure. The water absorption test provides an approximate equivalent permeability for the insitu rock mass. However, the results are very sensitive to the specific jointing conditions within the test length (which are difficult to quantify) and may dilate the rock joints as mentioned above which may overestimate the actual transmissivity of the rock mass.

6.3. Discontinuity survey

Discontinuity surveys were carried out using impression packers and electronic multishot survey instrumentation over testing lengths of 2 m. The discontinuity data can be used for assessing the potential for rock wedges within the tunnel and can be useful to identify any preferred orientation of relatively open joints which might affect the intensity of grouting required.

7. CONCLUSIONS

HDC is generally much more expensive than the drilling of conventional vertical and inclined boreholes. Therefore, in order to warrant the investment in HDC, it should be used when the approximate alignment has been fixed and when a good geological model has been developed to identify and target potential areas of concern. The advantages of HDC for tunnel works include:

- Areas of concern can be investigated from a remote drilling point where access from directly above the alignment is severely restricted by buildings, infrastructure or the marine environment.
- More realistic groundwater inflow measurements can be carried out to help define the hydrogeological regime, potential groundwater inflows and provide a better basis for estimating grouting requirements.
- Continuous core sampling along the tunnel alignment can greatly reduce the risk of unforeseen ground conditions when compared to a conventional investigation of isolated vertical and inclined boreholes where the conditions between each drillhole need to be inferred. In general, it can reduce the often high geotechnical risk associated with tunnelling.