Pipe Jacking: Case Study on Overcoming Ground Difficulties in Hong Kong SAR Harbour Area Treatment Scheme

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Abstract: The Harbour Area Treatment Scheme (formerly known as Strategic Sewage Disposal Scheme) is an environmental improvement project aimed at cleaning up the waters in the Victoria Harbour. The first stage of this project, which commenced at the beginning of 1994, consists of the construction of transfer tunnels linking the preliminary treatment works located at the southern part of Kowloon and eastern part of Hong Kong island to a centrally positioned enhanced treatment works at Stonecutter's Island. As part of this project an adit tunnel between two shafts was constructed under a recent reclamation area using the pipe jacking method.

This case study is based on the construction of a 1.8m diameter pipe jacked tunnel between two shafts at 22m below ground using an EPB Slurry Shield Machine. This 31m long adit tunnel suffered excessive inflow and ground loss when the tunnel eye was being formed in the diaphragm wall prior to the launch. The launch was made possible by freezing the soil around the eye. Later on the TBM was trapped in the marine sand and could not be propelled forward even with the maximum thrust. This problem was overcome by the injection of a polymer instead of bentonite to improve lubrication.

INTRODUCTION

In 1995, a 31m long tunnel between two shafts was constructed in the marine sand at Kwun Tong site by pipe jacking. During the construction of this tunnel several ground difficulties were encountered. This paper describes the nature of the problems and the solutions that were adopted to achieve a successful outcome. Artificial ground freezing method was used as a means of stabilising the ground and making it temporarily impermeable. It is believed to be the first ever use of this method in such ground conditions in Hong Kong. The paper describes the pipe jacking process, the process of ground freezing using liquid nitrogen, associated safety precautions and the details of the methods adopted to suit the local ground

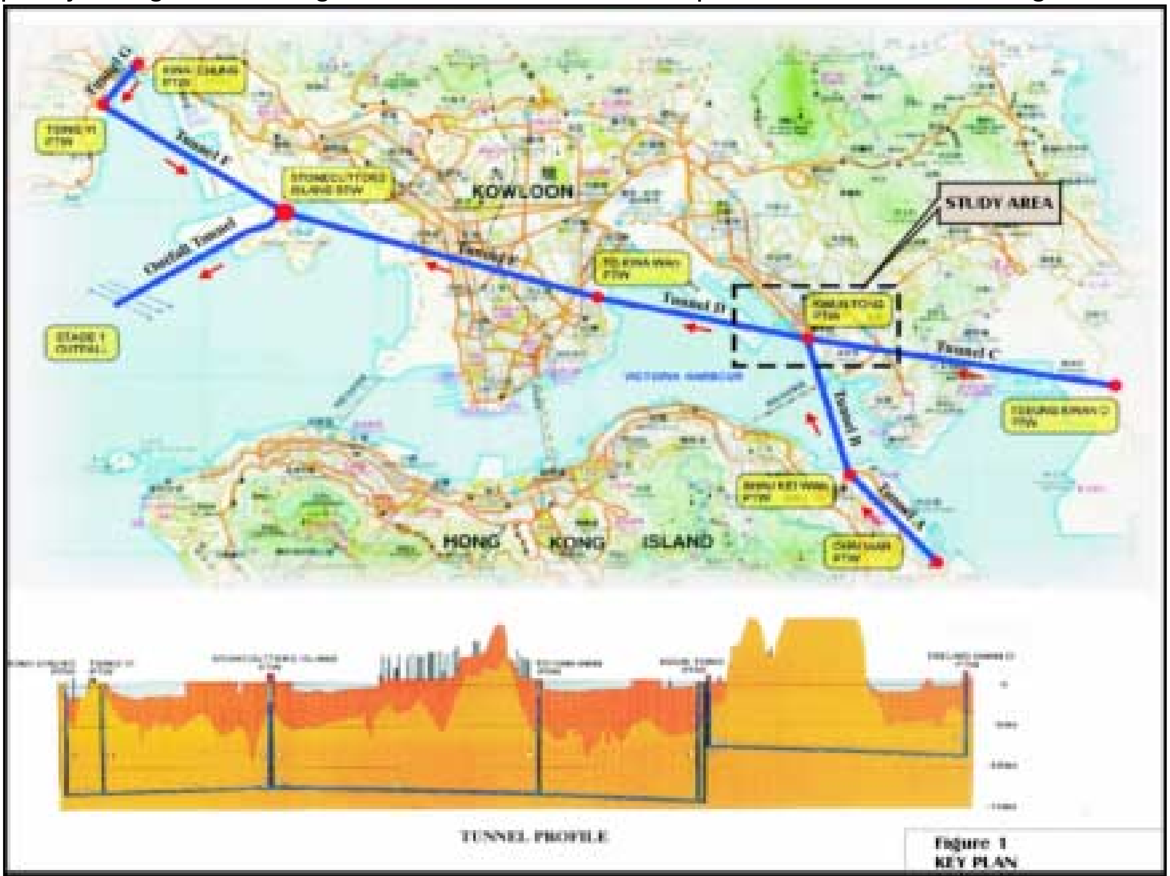

Figure 1
KEY PLAN

1 *The job story is provided by Dr Alan Kwong (Hong Kong Universiy of Hong Kong)*

conditions.

BACKGROUND

The Hong Kong SAR Government is undertaking the Harbour Area Treatment Scheme (formerly known as the Strategic Sewage Disposal Scheme) to reduce the water pollution in Victoria Harbour. The Stage 1 of the scheme has been completed and is now in operation. Sewage is collected from the eastern end of Hong Kong Island, Tseung Kwan O in the eastern Kowloon and urban Kowloon to a central enhanced sewage treatment facility at the Stonecutter's Island via a network of deep tunnels and shafts (Figure 1). Sewage is also collected from Kwai Chung and Tsing Yi in the west to the treatment facility at the Stonecutter's Island.

Sewage from Tseung Kwan O is pumped to Kwun Tong. Sewage from Chai Wan and Shau Kei Wan treatment works flows by gravity through a deep tunnel (Tunnel B) to Kwun Tong and a pumping station was built at Kwun Tong to raise the flows from Tunnel B to the surface (Figure 2).

PURPOSE OF ADIT TUNNEL

Due to the head losses over the nearly 5km distance between Chai Wan and Kwun Tong, a Pumping Station is required at Kwun Tong to lift the sewage prior to diverting it to a drop shaft. For operational reasons it was decided to construct the pumping station shaft some distance away from the riser shaft as shown in Figure 2. This necessitated the construction of a connection adit tunnel between the two shafts.

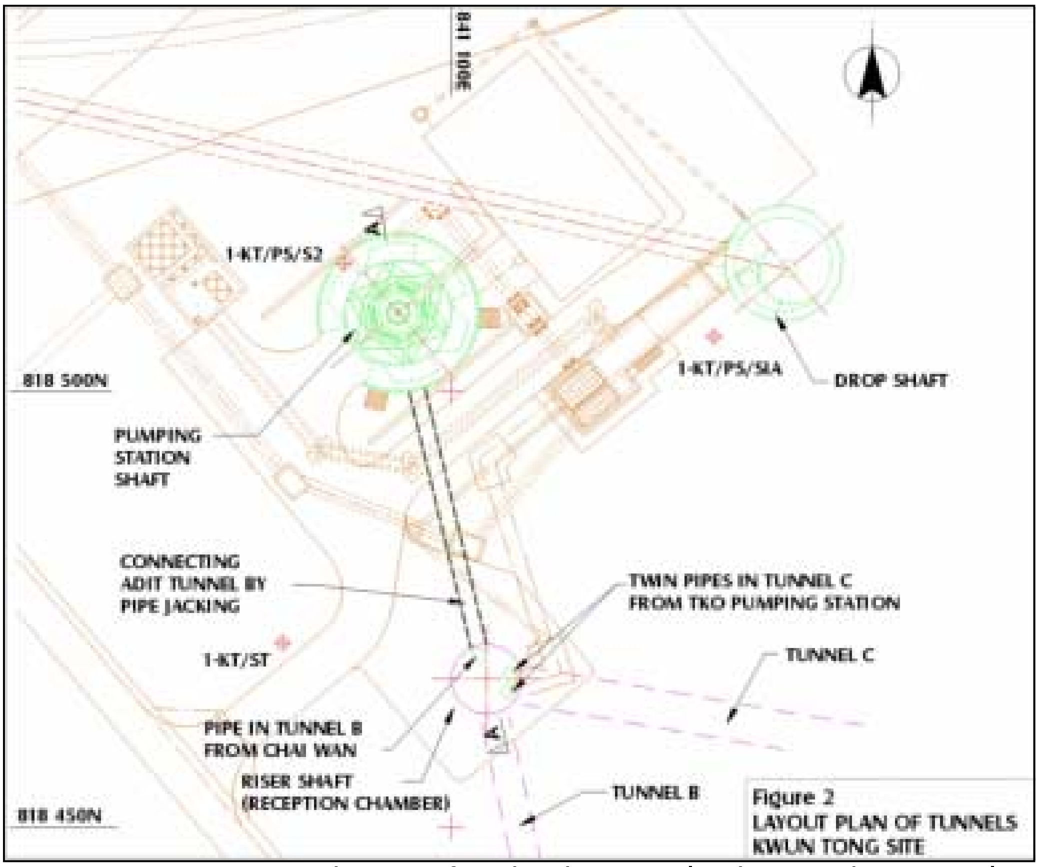

Figure 2
LAYOUT PLAN OF TUNNELS
KWUN TONG SITE

The transfer pipe in Tunnel B is 1.4m in external diameter and therefore the connecting adit tunnel

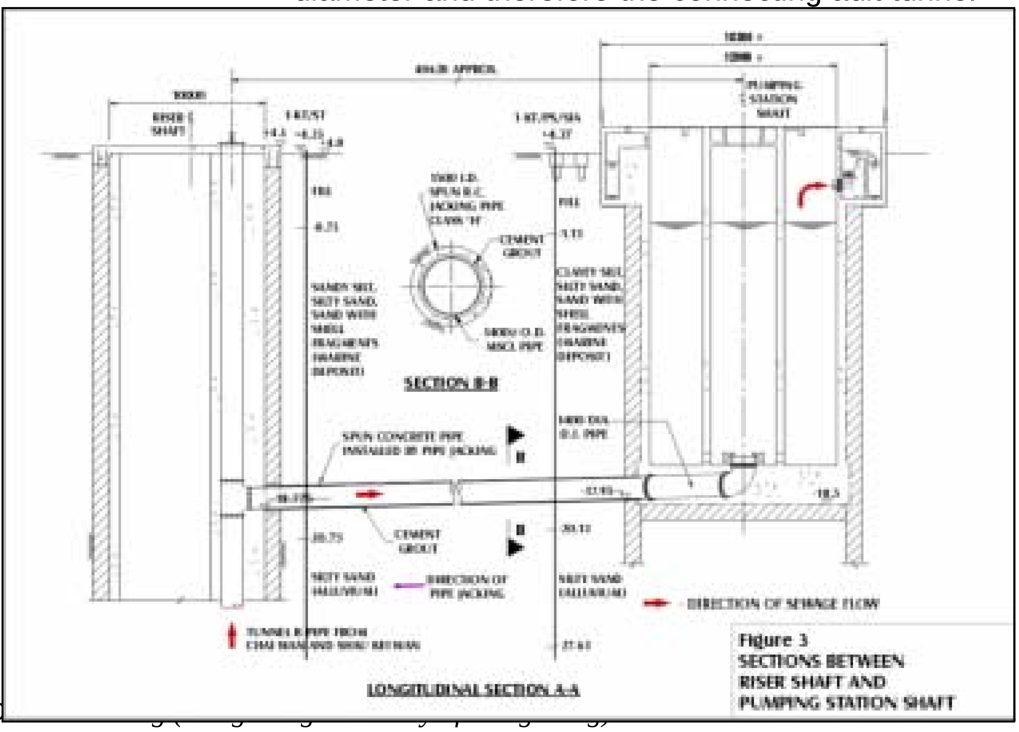

Figure 3
SECTIONS BETWEEN
RISER SHAFT AND
PUMPING STATION SHAFT

between the riser shaft and the pumping station was designed to have the same diameter and in a straight line with a rising gradient toward the pumping station (Figure 3).

GROUND AND GROUNDWATER

The Kwun Tong site is located on reclaimed land built before 1964. A summary of the typical subsurface geology according to a number of boreholes in this area is as follows:

Subsurface Material	Approximate Thickness	Indicative SPT
Fill	5m	< 10
Marine Deposits	20m	6 to 14
Alluvium	10m	20 to 30
CDG	< 10m	> 50
Bedrock (Granite)		

Information from these boreholes revealed that the marine deposits were not removed during the reclamation process. The adit tunnel was located at a depth of 22m and marine deposits were encountered during the excavation. The marine deposit at the adit tunnel horizon can be described as loose to medium dense, dark grey, silty SAND with some shell fragments. The SPT value was about 10 at the tunnel excavation level.

PIPE JACKING MACHINE

A 1.8m diameter ISEKI M.E.P.C.B. tunnel boring machine (TBM) appropriate for the soft soil conditions was selected for the construction of the adit. This machine was capable of balancing the earth pressure at the tunnel face in order to minimise ground subsidence and heave.

The TBM was jacked against the thrust block at the pumping station shaft using a combination of spacers and thrust ring and the maximum travel distance of the jacks at each stroke was 1m.

Spoil removed from the cutter head was mixed with bentonite mud which was pumped to the tunnel face and circulated back to the ground surface where it was discharged into a slurry tank. The pressure applied to the tunnel face was monitored using sensors mounted on the cutterhead and controlled by a valve in the pit by-pass unit placed in the jacking shaft (Figure 4).

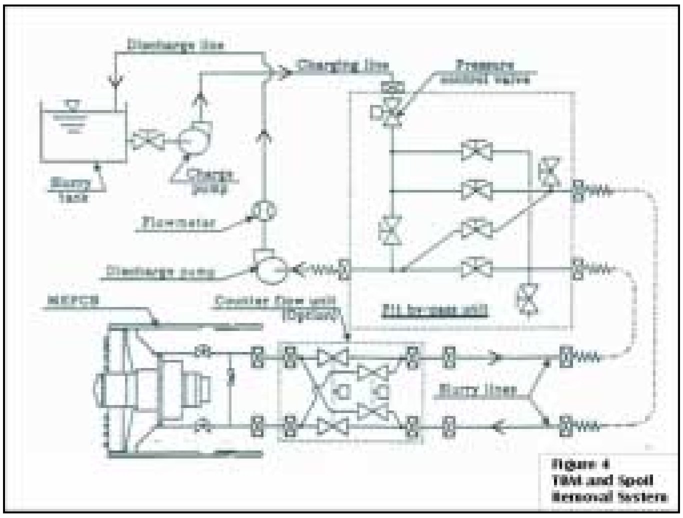

Figure 4
TBM and Spoil Removal System

As the TBM advanced, 3.0m long 1.5m internal diameter spun reinforced concrete class 'H' pipes 140mm thick were installed. These were joined together with tee shaped mild steel collars and compressible rubber gaskets were installed at both ends making the joint watertight. Each pipe consisted of 2 x 3 nos. of 20mm grout holes equally spaced around the circumference and at 750mm from either end of the pipe. A total of eleven pipe lengths were required to complete the adit tunnel.

SETTING UP FOR PIPE JACKING

The launching shaft was 13.2m in diameter and was constructed by diaphragm walling technique. A 1m thick reinforced concrete base slab was constructed at –20.0mPD and a 1m thick and 1.5m wide reinforced concrete thrust wall was built cantilevering from this slab.

The marine deposits (mainly loose silty sand) at the tunnel horizon could become unstable and collapse if they were not supported when forming the 1.8m diameter tunnel eye opening in the diaphragm wall. Therefore it was decided to strengthen the silty sand with a block size of approximately 3.5m wide x 6m high x 1.5m thick by grouting using the tube-a-manchettes technique (TAM). A total of seven grout holes were drilled vertically from the surface and 40mm internal diameter PVC TAM pipes were installed as shown in Figure 5. These holes were grouted in two stages. At the first stage bentonite-cement-water grout mix with a ratio of 1:20:33 (1m^3 of grout = 25kg Bentonite, 500kg OPC cement, 825kg water) was used. At the second stage chemical grout with a set time of 5 minutes was used at a silicate-water mix ratio of 1:1.77

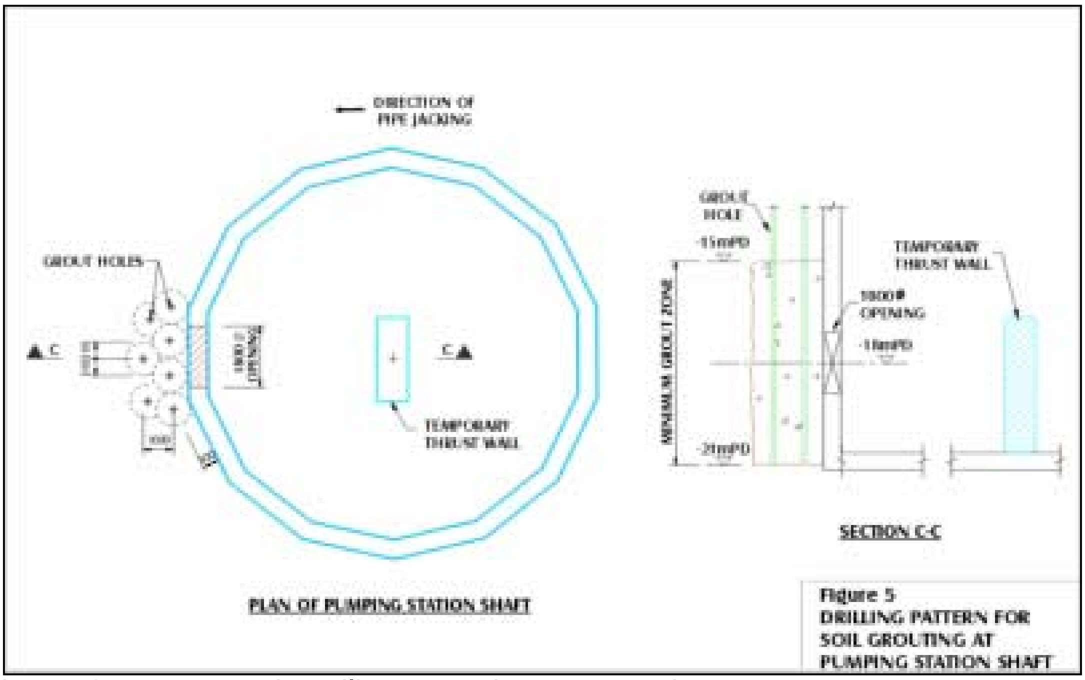

Figure 5
DRILLING PATTERN FOR SOIL GROUTING AT PUMPING STATION SHAFT

(1m^3 of grout = 400kg Silicate, 708kg water and 45 litres of reagent).

Grouting was carried out using a double packer in a bottom up sequence starting first from alternate holes. The stage length was set at 0.33m. The grouting was stopped if the grout pressure exceeded the overburden pressure by more than 20 kPa or if the grout intake reached 375 litres/metre. This intake volume limit was set on the assumption that the soil porosity was 0.4, the effective radius of grout travel was 0.75m and that 50% of voids were to be filled with cement/bentonite grout and the remaining 50% filled with the chemical grout.

The riser shaft, which was to become the reception chamber for the TBM to break through into, was very deep. Rock excavation was in progress in this shaft when preparations for pipe jacking were underway. A block of soil immediately outside the tunnel eye of the riser shaft was also grouted using the TAM technique in a manner identical to the pumping station shaft. In addition a steelwork platform was erected cantilevering from the shaft wall in order to form the tunnel eye opening and to receive the TBM during the break through.

FLOODING INCIDENT

After completion of the TAM grouting from the surface, an exploratory hole was drilled from the centre of the tunnel eye to verify the effectiveness of the grouted zone outside the launch shaft. Following the completion of this exploratory hole, drilling of closely spaced core holes to form a concrete disc at the tunnel eye began. A lifting plate was fitted to the centre of the concrete disc and during an attempt to lift it out, a sudden in rush of sand and water occurred. The lifting works ceased immediately and a steel beam was installed as a prop to prevent the disc from falling out and causing a catastrophic loss of ground. The shaft was evacuated and the water level in the shaft continued to rise.

OPTIONS CONSIDERED FOR DEALING WITH THE FLOODING

The pipe jacking works were on the critical path of the programme when the flooding incident occurred. The Contractor therefore was faced with choosing a method that was quick, certain of achieving the objectives, safe and cost effective. Three options were considered. These were: 1) undertaking further soil grouting, 2) open trench excavation and 3) ground freezing.

Option 1) was not considered further since further grouting in marine deposits, which predominantly contain sand and small amount of silt, could be very time consuming and the chances of complete sealing were not high. Option 2) required the construction of diaphragm walls which would take fifteen to twenty weeks and involved substantial expenditure. Option 3) generally satisfied all the criteria but there were concerns about the safe use of ground freezing, as there was no precedent case documented in Hong Kong. The main contractor and the ground freezing specialist sub-contractor were however had the view that ground freezing was the most suitable method. They considered that it could be done safely through adequate designs, independent checking and a comprehensive working and monitoring procedure.

CONCEPT OF GROUND FREEZING

The principle behind ground freezing is to reduce the temperature of the ground in the vicinity of the proposed excavation so that groundwater is frozen into ice. Soils exhibit much higher shear strength when they are frozen and the frozen zone could also provide an impermeable barrier through which water will be unable to enter the excavation.

In order to be successful in ground freezing it is necessary to design and drill holes at some optimal spacing and patterns. Pipe is then installed and the refrigerating medium, either a chilled brine or liquid nitrogen is introduced. Brine requires continuous circulation whereas liquid nitrogen is not recoverable. Where ground freezing may be required over a long duration, it is economical to use refrigerated brine. Liquid nitrogen has a much lower initial temperature (-196°c) and offers a viable alternative when it is required to achieve rapid freezing in a relatively short duration. A typical arrangement for ground freezing using liquid nitrogen is shown in Figure 6.

In this case, it was more preferable to use liquid nitrogen as the cooling agent as it takes only 2 to 7 days to create a suitable ice wall when compared to the brine cooling system which could take 3 to 12 weeks.

GROUND FREEZING METHOD

The aim was to freeze a block of soil of approximately 1m thick around the tunnel eye in the diaphragm wall so that the concrete disc can be removed safely and the TBM can be launched.

Boreholes were drilled from the ground surface by the ODEX method with 195mm diameter casings down to approximately 24m deep (Figure 7). The casings were replaced by 140mm O.D., 5.4mm thick heavy duty mild steel pipes. The pipes were in 6m length and were joined together on site by butt welding.

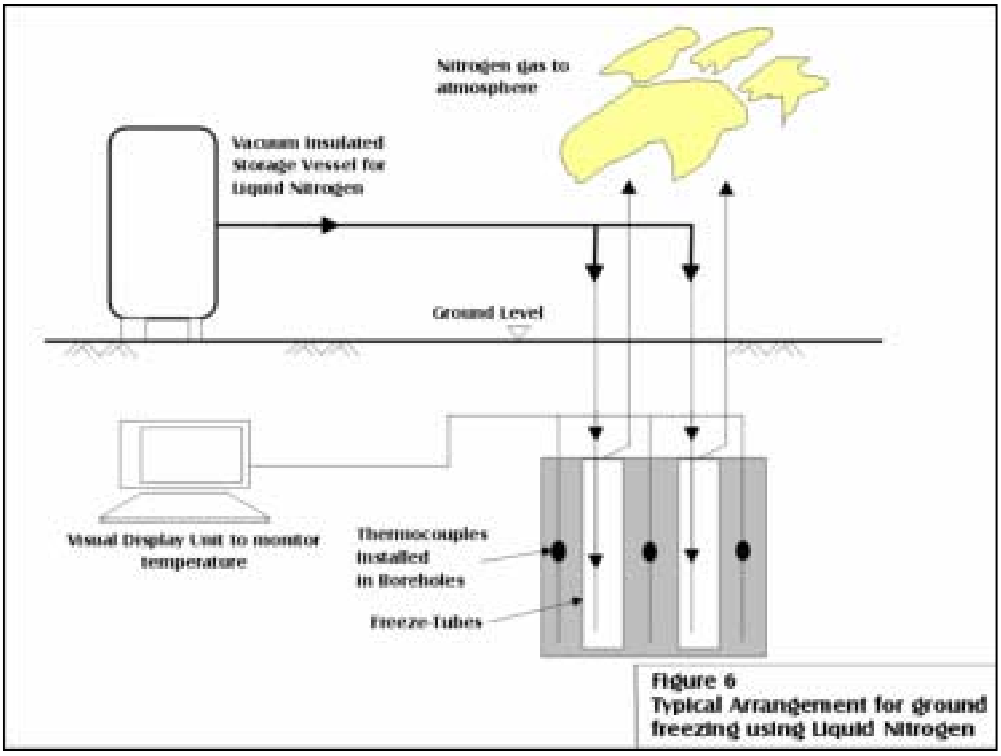

Figure 6
Typical Arrangement for ground freezing using Liquid Nitrogen

Aluminum freezing pipes 102mm O.D., 3mm thick were installed inside the casing pipe in the lower section requiring freezing. The upper section was made up of 76mm O.D., 3mm thick pipes. The upper section of the aluminum freezing pipes was insulated with a polystyrene type material. Thermocouples and wiring were attached to the freezing pipes before lowering (Figure 8).

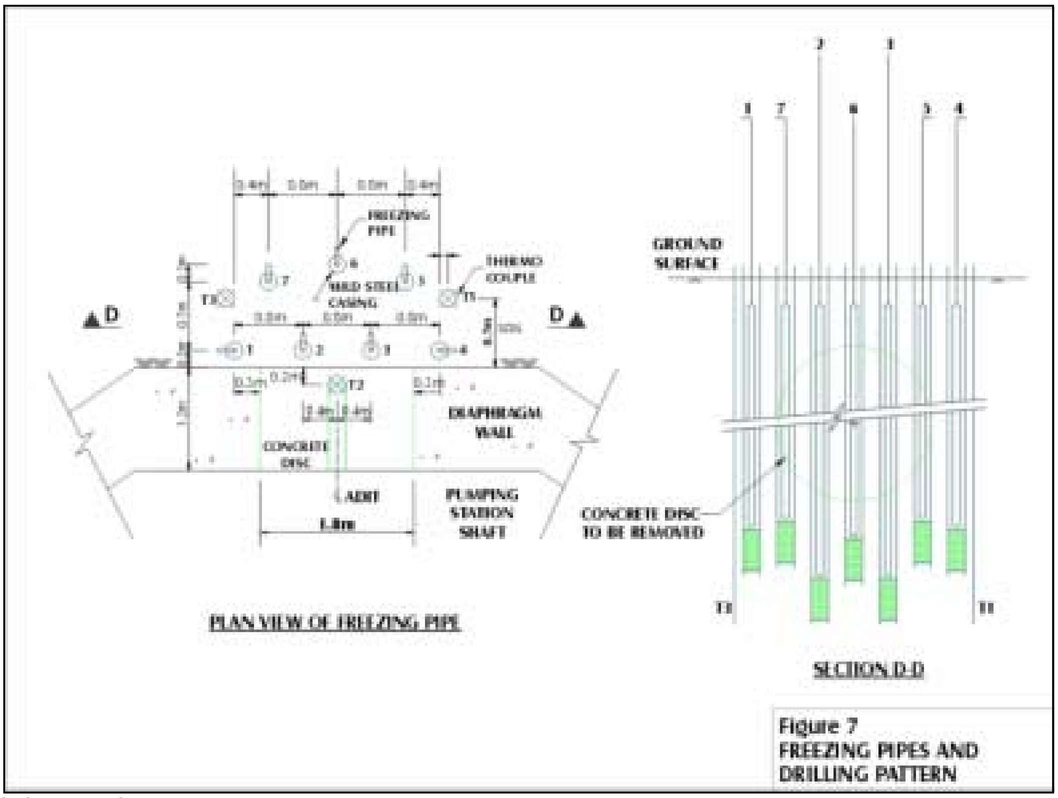

Figure 7
FREEZING PIPES AND DRILLING PATTERN

On the inside of the aluminum freezing pipe a 10mm O.D., 1.5mm thick annealed copper pipe were installed. The copper pipe was connected to a cryogenic valve and the exposed sections of the pipe were insulated with 20mm thick polystyrene.

Two additional boreholes were drilled on either side of the freeze pipes to install thermocouples for the purpose of monitoring the rate of temperature reduction during freezing. One more thermocouple was placed in a hole drilled in the concrete disc near the centre of the tunnel eye.

SAFETY PRECAUTIONS

The provisions in the Dangerous Goods (General) Regulations, Chapter 295 stipulates the statutory requirements on the safety precautions in relation to the conveyance of liquefied gases and the requirement for a license to store the gases in bulk. Not withstanding the other relevant provisions, Regulation 73 stipulates that:

- No container containing liquid nitrogen shall be stored otherwise than in a place approved by the Authority (Director of Fire Services) and marked to the satisfaction of the Authority by one or more notice in English and Chinese indicating the storage of liquid nitrogen.
- No container containing liquid nitrogen shall be stored otherwise than under the care of a person having reasonable experience in the handling of liquid nitrogen.

Liquid nitrogen was supplied by Hong Kong Oxygen and Acetylene Company Limited (HKO) in tankers designed to comply with the Hong Kong regulations. On site, two bulk storage tanks for liquid nitrogen were installed by HKO. These were namely 23,000 litre vacuum insulated tank and 10,000 litre iso tank giving a total capacity of 25 tonnes. However the maximum capacity stored on site was limited to 20 tonnes. The liquid nitrogen supply lines were fitted with cryogenic globe valves and a pressure relief valve.

The Contractor had given notice to the Director of Fire Services that he was carrying out operations utilising liquid nitrogen. All plant and pipe work used in the freezing operation were carefully selected to ensure that it was safe and complied with the regulations. The liquid nitrogen containers and the working area were cordoned off to permit access to authorised persons only.

The ground freezing system was designed by a specialist company with proven experience and was independently certified by another consultant.

The representatives of the ground freezing specialists were on site to supervise the fabrication and installation of the freezing system and to carry out the subsequent freezing activities.

PROGRESS OF GROUND FREEZING

The drilling of boreholes for ground freezing started on 27 April 1995 and was completed on 01 May 1995. At the same time temporary foundation slab for the liquid nitrogen storage containers was installed and the freezing pipes were fabricated on site. The independent checking engineer's certificate was signed off on 15 May 1995 and agreement to the proposals by the Engineer was given on 17 May. The ground freezing operations commenced at 9 pm on 17 May 1995.

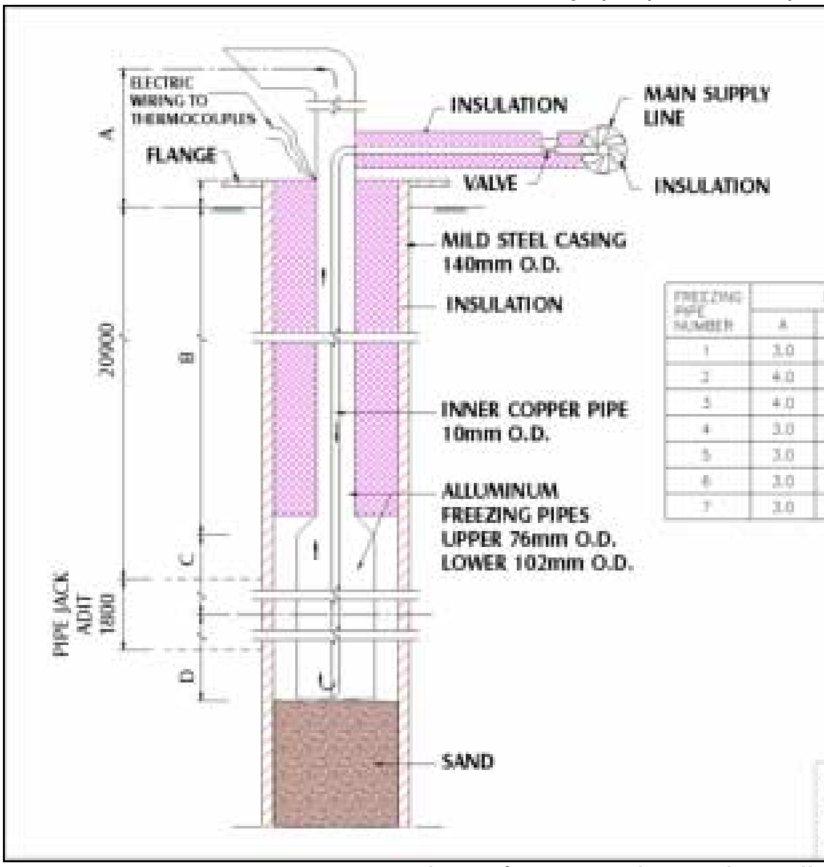

Figure 8 DETAILS OF FREEZING PIPE

The freezing was continued for four days when the designed temperature of below -10°c was achieved in the thermocouples T1, T2 and T3 confirming a satisfactory block of frozen ground has formed behind the tunnel eye.

Following the completion of freezing, the water collected in the pumping station shaft was pumped out and the sand and mud that got washed in were removed. The guide rails for the TBM and pipes were installed in preparation for launching the TBM.

The concrete disc at the tunnel eye was removed and a stiff rubber sealing ring was bolted around the eye. The purpose of this ring was to provide a seal around the TBM/jacking pipes to prevent water leakage. After the tunnel eye and the support frame for the sealing ring were shotcreted in, the TBM was lowered and moved into position.

Immediately after the tunnel face was supported by the TBM, the removal of freezing pipes and mild steel casing was carried out. The Contractor initially proposed to pull these pipes approximately 3.0m above the adit tunnel crown and leave it in the ground. This proposal was not accepted since other surface structures were to be constructed in this area and the pipes were fully removed.

The central copper pipe and aluminum freezing pipes were removed after being loosened by blowing steam. Although it was envisaged to thaw the ice block by circulating hot brine it did not become necessary due to a delay in starting the pipe jacking as a result of further grouting work under taken near the riser shaft.

As the frozen ground melted, some minor leaks were observed between the rubber seal and the TBM but these was not very significant.

ADDITIONAL GROUND TREATMENT AT RECEPTION SHAFT

In view of the unsatisfactory performance of the ground grouting treatment at the launch chamber, it was decided to drill several exploratory holes through the tunnel eye of the reception shaft diaphragm wall. These holes confirmed the presence of loose soils in the treated block of ground. This required undertaking further ground treatment from the surface using the TAM technique. Slight modifications were made to the grout mix from that used previously. This time it was decided to thicken up the grout progressively until the upper limit of the grout volume or pressure was reached, as shown on Table 1.

Water:Cement :Bentonite	**Grout Intake (litres/metre)**	**Maximum Grout Pressure (bar)**
500:100:5	150	5 or refusal
400:100:5	150	5 or refusal
300:100:5	150	5 or refusal
200:100:5	no restrictions	refusal

Table 1 Grout Intake and Pressure

In total, fifteen number holes were drilled and grouted as shown on Figure 9. Before commencement of grouting, packer tests were carried out to determine the permeability of the ground. In the holes where water inflow was less than 5 lugeons (1 lugeon = 1 litre/min per metre @ 10 bar head), microcement was used.

UNUSUAL GROUND RESISTANCE DURING JACKING

After completion of additional ground treatment at the reception shaft, pipe jacking commenced. When the thrust jacks were retracted to install spacers, noticeable sliding back (reversal) of the TBM was observed because of the ground pressure at the face. Soon after the first pipe was pushed through the tunnel eye, a frame was bolted to the shaft wall and a strap with a hydraulic jack to prevent sliding back of the pipe was installed. At an early stage the ground frictional resistance was minimal and no lubricant was used. This situation changed very suddenly after installing Pipe No. 9 when it became impossible to push the TBM forward even at very high thrust force. Cracking at the base of the concrete thrust wall was also observed. As additional thrust pressure was applied more damage to the wall foundation occurred instead of the TBM moving forward. The pumping of bentonite to lubricate the pipes in quantities far exceeding the theoretical void space appeared to be of little value.

Several explanations for this situation were postulated:

- The depth of the adit at 22m was beyond the limit for pipe jacking, due to high overburden pressure.
- During a weekend stoppage, the sandy soil has consolidated around the pipe, due to dissipation of excess pore pressure generated by grouting.
- The bentonite lubricant could not travel in an even manner around the pipe perimeter.
- Pipe collars were acting as shear keys.

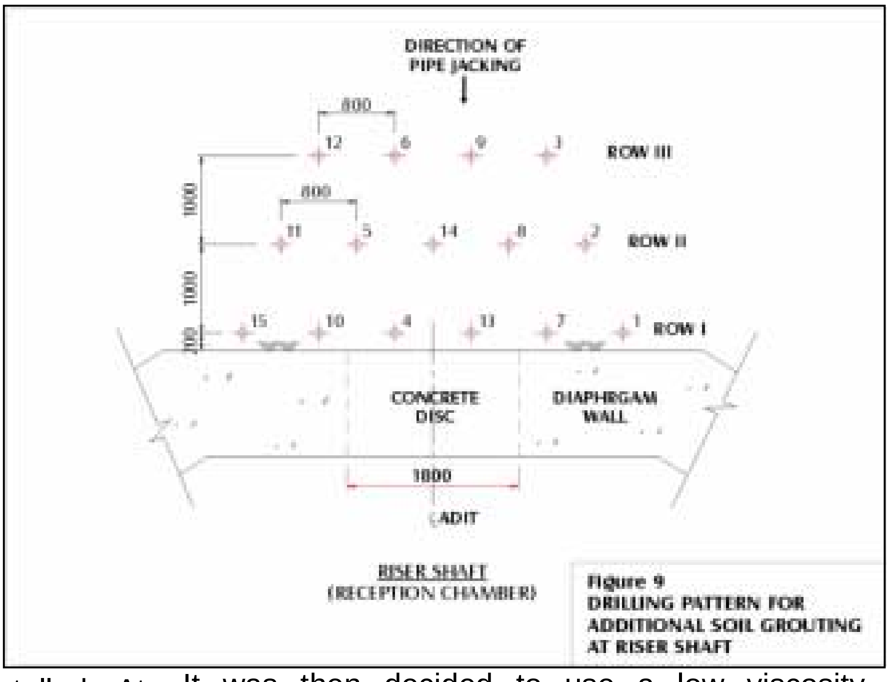

Figure 9
DRILLING PATTERN FOR
ADDITIONAL SOIL GROUTING
AT RISER SHAFT

It was then decided to use a low viscosity polymer as lubricant instead of bentonite. This substitution achieved the desired results and the pipe jacking was completed on 26 July 1995.

BREAKTHROUGH

At the time of break through, another run-in of sand and water occurred, this time in the reception shaft. The quantity of material washed in was not as much as that at the launch shaft and the wash out reduced when the TBM body was pushed into the diaphragm wall opening. Timber wedges were driven in to reduce the large inflows. After the TBM has passed through the tunnel eye and the final pipe was pushed into place, the leaks around tunnel eye were diverted using pipes and sealed with water plug.

The ends of the jacking pipes forming the junction with the shaft walls were shotcreted and the temporary water diversion pipes were grouted.

The flooding incident together with the other difficulties mentioned contributed to a total programme overrun of approximately 14 weeks to complete the pumping station shaft works.

GROUND SETTLEMENT

The ground settlement measured at the surface was less than 25 mm at both launch chamber and reception chamber ends. No settlement was recorded in the remaining mid section of the tunnel as a result of the pipe jacking.

LESSONS LEARNT

From the pipe jacking works carried out at the Kwun Tong Pumping station, the following lessons were learnt:

- Particular attention is needed to forming tunnel eyes when constructing diaphragm wall shafts (as well as other types of shafts).

- Grouting in sand may not be relied upon to give a sufficiently long stand up time to form tunnel eyes.

- Ground freezing is a suitable alternative to strengthen the soil and to make it impermeable.

- The use of liquid nitrogen in ground freezing was successfully carried out in Hong Kong satisfying the safety regulations.

CONCLUSIONS

This paper sets out the problems encountered during the construction of a relatively short length of pipe jack tunnel together with a description of the solutions adopted. These were namely:

- Loss of ground and excessive inflow of groundwater was encountered during preparations to launch the TBM.

- Use of liquid nitrogen in ground freezing was successfully carried out in strengthening the ground and providing an impermeable barrier.

- Unusual ground friction was encountered during pipe jacking and it was overcome by using low viscosity polymer.

REFERENCE

Harris, J.S. and Wills, A.J. 1993. Introduction to artificial ground freezing, Technical Memorandum TM 1.