

Sewer Installation by Pipejacking in the Urban Areas of Hong Kong

Part I – Planning, Design, Construction and Challenges

This paper highlights the planning, design and construction of 4 km of 600 mm-, 1200 mm- and 1800 mm-diameter trunk sewers, using slurry operated tunnel boring machines, in highly variable ground conditions in two busy urban areas. This was the first time that curved alignment tunnels have been constructed in Hong Kong, with one segment having an S-curve alignment (404 m long). The project also included tunnelling through, and being received in, already constructed permanent shafts, also a first for such a construction technique in Hong Kong. The problems encountered and the solutions provided were also discussed. The paper should be read in conjunction with Part II: Performance of Works, Lessons Learned and Improvements Proposed.

Keywords: Pipejacking, Slurry Operated Tunnelling Boring Machines, Curved Alignment, Shaft Temporary Works, Jacking Force, Intermediate Jacking Station, Lubricant, Line and Level of Pipeline

Wilson W S MOK

Black & Veatch Hong Kong Limited

Maxwell K W MAK

Drainage Services Department

Felix H T POON

Black & Veatch Hong Kong Limited

Introduction

Pipejacking is the technique of installing pipelines by hydraulic jacking of a pipe string, including a tunnelling shield in front (either operated mechanically or manually for excavation), from a jacking shaft to a receiving shaft. Jacking pipes are added one after another to the end of the pipe string as the preceding pipe/shield advances. The excavated materials are then transported to the ground surface through the slurry discharging pipe (for slurry shield), or the screw conveyor to the jacking shaft by a trolley system (for earth pressure balance (EPB) shield and hand excavation), and then lifted up to the ground surface. This procedure is repeated until the pipe string reaches the receiving shaft [1].

Microtunnelling is the term for pipejacking small-sized pipelines, using steerable remote-controlled mechanical tunneling shields. The size of the shield generally ranges from 600 to 900 mm and is not suitable for safe man-entry working [1].

The history of using the pipejacking technique in Hong Kong has been short to-date. The first Government contract to use this technique with track record was the Fanling Trunk Sewer project for the Territory Development Department (TDD), in mid 1989, with the construction of 370 m of 1350 mm diameter sewer, located 6 - 14 m below ground, passing beneath new roads, footpaths, a cycle track, a pedestrian subway and the embankment of the Fanling Bypass, using a Iseki's Unclemole Earth Pressure Balance TBM [2].

Since 1991, more than 16 km long pipelines, using different pipejacking techniques, have been completed by the Drainage Services Department (DSD), under different ground conditions, in a number of contracts of different scales [3].

Before 1996, the length of most of the sewers constructed in a contract was generally less than 1 km and one even had a length of only 50 m for crossing a road junction. These sewers generally had a depth range of 3 to 10 m, with an average of 5 m, and a length range of 60 - 100 m.

Between 1991 and 1996, Earth Pressure Balance TBMs were widely adopted. These TBMs generally performed satisfactorily in homogeneous, plastic ground (made of sand and clay) but had a problem to cut through big boulders, resulting in the necessity of a rescue shaft in some cases.

Starting from 1996 onwards, more and more DSD contracts used pipejacking, with different types of TBMs and in different modes, to account for the ground conditions likely to be encountered, for sewer construction on a large scale, with the length of pipeline increased to

a few kilometres. It was also at such time that hand tunnelling was first used for constructing pipelines crossing old seawalls and artificial obstructions.

DSD Contract No DC/2000/11

– Wan Chai East and North Point Sewerage – Trunk Sewers

Scope of Works

Contract No DC/2000/11 was one of the five contracts, implemented by DSD, to improve the wastewater infrastructure and capacity in the Wan Chai East and North Point areas so as to meet current and anticipated development needs. Black & Veatch (B&V) has been responsible for the design and supervision of construction of all of the contracts under this Project. This HK\$427 million Trunk Sewer Contract – the main focus of this paper, started in May 2002 and was completed in December 2005. The Contractor was the Leighton – Kumagai Joint Venture.

The works comprised the construction of two lengths of trunk sewers; one 1.1 km long along Yee Wo Street, Hennessy Road, Percival Street and Gloucester Road in Causeway Bay and the other 2.9 km long along Electric Road and Java Road in North Point. There were 27 nos temporary shafts in between the trunk sewers, which were used as either a jacking shaft or a receiving shaft, to enable the tunnelling works. These shafts were also used for the construction of permanent shafts for future maintenance, after the completion of the sewers.

The locations of shafts and the alignments of sewers in between are shown in Fig 1.

Planning

For other similar completed contracts, the locations of most of the jacking and receiving shafts were designed to be located at heavily trafficked junctions with the alignment of the pipeline in between confined to a short straight section. However, in the absence of a full-scale investigation and trials, before the commencement of the contract to investigate the presence of underground utilities and services, the traffic conditions and the underground obstructions and conditions, some of the shafts had to be relocated during the construction stage, resulting in changes to the tunnel alignment. This would of course induce risks to the contractors due to uncertainty as no knowledge of sub-soil conditions and the potential obstruction of utilities and services at the new shaft locations

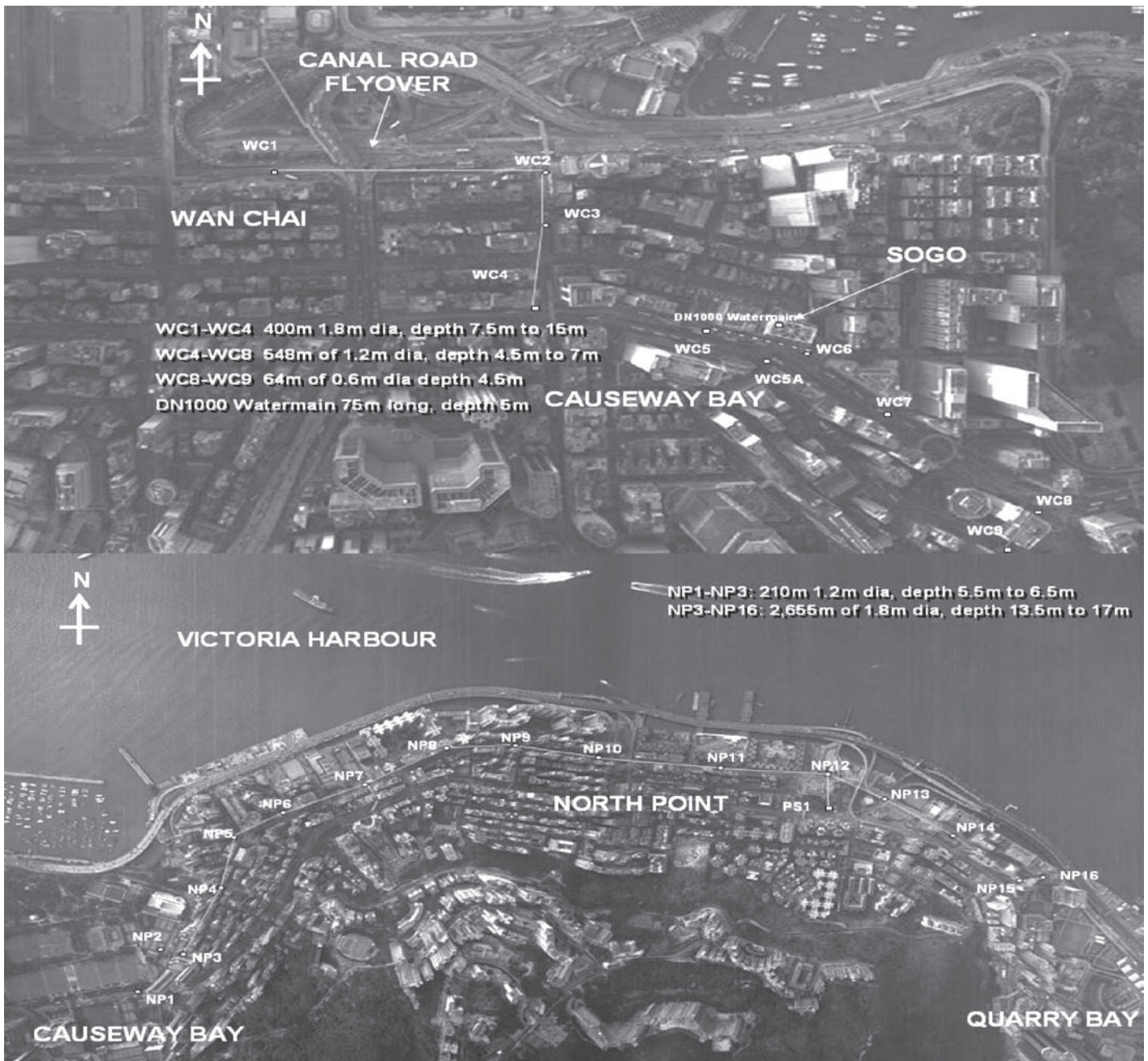


Figure 1 – Layout Plan of Trunk Sewers

was available. As a consequence, the works were often delayed and claims were received, incurring additional expenditure.

After absorbing the above experience, B&V and DSD determined to carry out an advance contract (Contract No DC/99/11 – Advance Works) to carry out further investigation on various aspects such as traffic condition, utility constraints and underground obstructions, and the results would be available for the tenderers to review during the tendering period. The aim of this arrangement was to provide relevant information as much as possible to the tenderers such that more reasonable tender prices would be formulated and the construction risks and the associated claims and disputes could be substantially reduced.

In the Advance Works Contract, full-scale trial runs were conducted for the tentatively selected shaft locations, to ensure that their implementation would not adversely affect the traffic. At certain locations, the shafts had to be shifted towards the side street, thus necessitating some of the sewer alignments being on a curve. Trial trenches were then dug to expose the existing utilities and advance co-ordination and planning for utilities diversions were executed. Upon finalising the optimum locations

of the shafts, boreholes were sunk to determine the ground and groundwater conditions, with soil samples obtained for laboratory testing.

Baseline noise monitoring was also included in the Advance Works Contract. This was to provide the tenderers the information of the background noise level when assessing the need for noise mitigation measures, induced by the plant and machinery for different stages of works.

Geological Conditions

The trunk sewers in Wan Chai have depths in the range of 5.8 to 7.6 m. The ground conditions generally consist of Fill, with SPT'N' values ranging from 3 to 17, overlying thin layer(s) of marine deposits and/or alluvium.

The construction of temporary shafts and the tunnels in between was therefore mainly in soft ground. However, due to poor control of filling materials in old reclamation (in stages since 1841), hard materials such

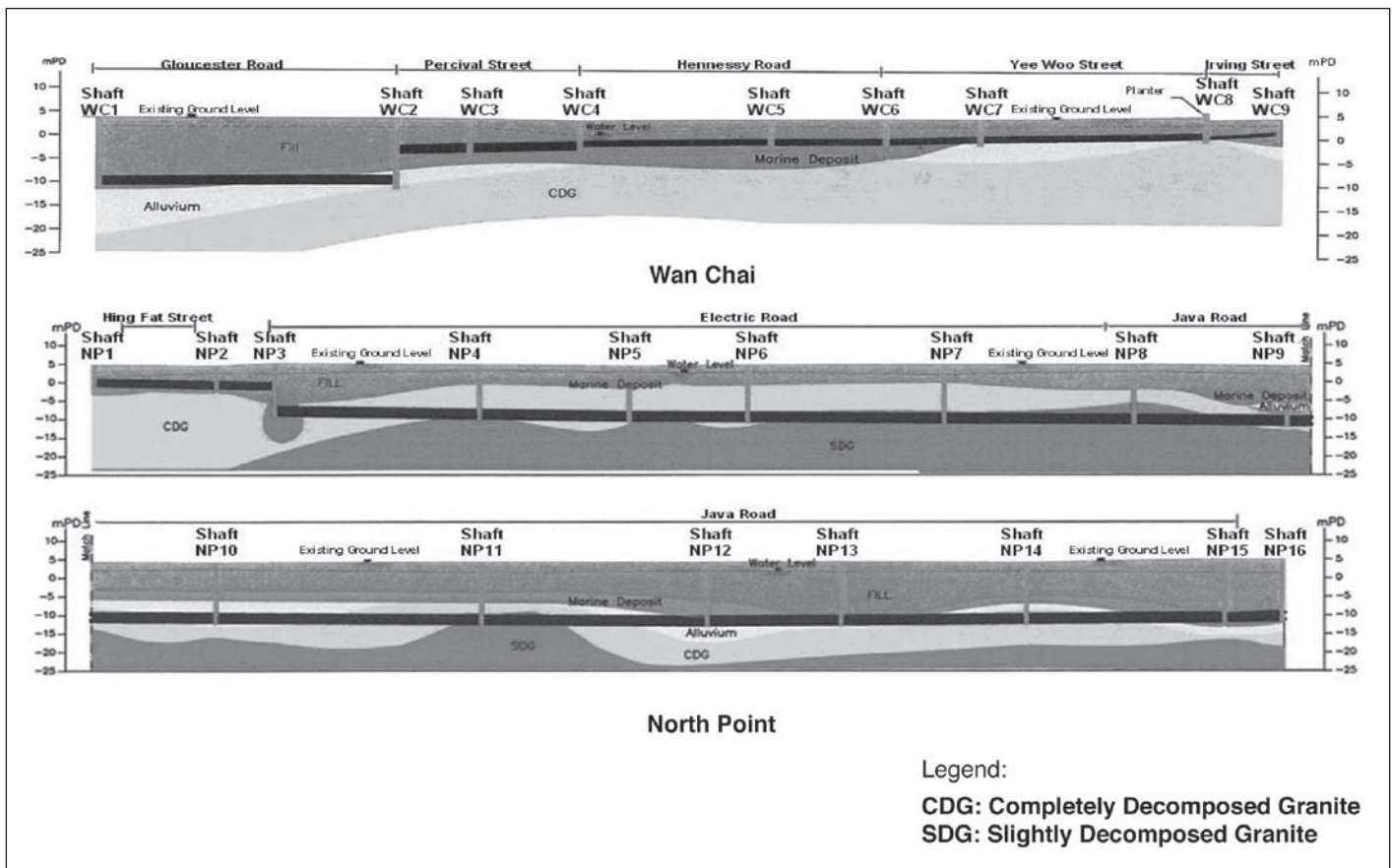


Figure 2 – Inferred Geological Profile along Trunk Sewers

as boulders and brickworks were also found at different locations in this layer.

Deep sewers, with depths between 10 to 18 m, are mostly located in the North Point area. The top layer is mainly Fill (5 – 14 m thick), with SPT'N' values ranging from 3 to 20 and boulders of different content, and is underlain by marine deposits, alluvium, completely decomposed granite (CDG), and at depth moderately to slightly decomposed granitic (M/SDG) bedrock.

The ground conditions along most of the tunnel alignments are highly variable, and some bedrock exists only 5 m below ground level while others are over 20 m deep. Some CDG strata are very dense, with SPT'N' values greater than 100, and have occasional corestones.

The groundwater table for the two Trunk Sewers was about 2 - 3 m below ground level. The inferred geological conditions along the two trunk sewers are shown in Fig 2.

Shaft Temporary Works

Design Considerations

Based on the results of the Advance Works Contract, most of the shafts were located in the carriageway adjacent to the kerbside, with a few partly shifting towards side streets to avoid causing a traffic bottleneck at the junction. These shafts were generally circular such that the member sizes could be reduced. However, some of them were changed to rectangular to account for constraints of existing utilities and services. A jacking shaft, with a size of about 8 m x 8 m or 8 m in diameter, was designed to accommodate the 1800 mm diameter TBM, the thrust wall at the rear, the launching eye at the front and other auxiliary equipment. A receiving shaft, which was for the retrieval of the TBM, had sizes of about 7 m x 7 m or 7 m in diameter. For smaller TBMs, the size of jacking and receiving shafts was reduced correspondingly. A treated soil block, about 3.5 m x 3.5 m and 3 m thick (for the 1800 mm diameter TBM) and created by either vertical or horizontal grouting, was

designed at the locations of launching and receiving eyes to provide a rigid support for TBM launching and reception, and prevent excessive ingress of water and soil during the breakthrough as a result of sudden change of groundwater pressure.

In general, the temporary shafts at alternate locations served as jacking shafts for the pipejacking works in two directions. On two occasions, the shaft was used to jack the pipelines in three directions.

Construction Considerations

The sheetpiling method (Fig 3) was commonly used for homogeneous, sandy ground, due to its fast operation and cheaper cost, whereas at locations where boulder obstructions were present or rockhead was high, the pipepiling method (Fig 4), with the aid of a down-the-hole hammer, which has the ability to penetrate with high efficiency to the required depth, was adopted. Vibration monitoring was carried out at sensitive utilities and structures throughout the course of pile driving.



Figure 3 – Sheetpiling Works in Progress



Figure 4 – Pipejacking Works in Progress

toe grouting to avoid excessive vibration and noise nuisance as a result of hard driving, and to maintain piping stability. Difficult driving was experienced in bouldery ground although preboring was carried out in advance, affecting the vertical alignment and in the worst case, resulting in the broken toe and the necessity of extracting sheetpiles and using pipepiles instead.

With the aid of the computer software FREW and SEEP/W, the settlement caused by driving of piles, deformation of the material used to form the temporary works and dewatering in the temporary

shaft was estimated. The total estimated ground settlement varied from 20 mm to 100 mm, depending on the depth of the temporary shaft and geological condition. Its effects on the adjacent carriageways, footways, utilities, services and structures were assessed before the commencement of the temporary works construction.

As the pipejacking works were carried out in urban areas, it was extremely difficult, if not impossible, to have a shaft site completely free of existing utilities and services. As such, numbers of utilities and services ran across the shaft locations. Although the utility undertakers are generally obliged to divert their installations to give way for Government properties, such diversions are usually time-consuming from planning and investigation, to execution. In order to do so, sufficient unobstructed space must be available at an adjacent location. In areas with congested and layered utilities and services, this was always a complicated exercise. Therefore, an assessment had to be made of which utilities actually obstructed the pipejacking operations such as lowering of the TBM and jacking pipes and construction of ventilation, access and desilting openings for the permanent manhole later on.

For those utilities and services which were not required to be diverted/slewed away from the shaft locations, they were temporarily supported across the shaft. This required the sheetpiles or pipepiles to stop at both sides and the windows below the supported utilities had to be protected by steel lagging plates. A grout curtain had to be formed at the window locations using vertical and raking grout pipes, to prevent ingress of water, before excavation. For large windows, the grout curtain had often been found ineffective as the grout injected by the raking grout pipes



Figure 5 – Construction of 5.5 m Diameter Concrete Ring Wall

might not have fully and effectively penetrated into the soil. Similar situations also existed in clayey ground. Therefore, concrete ring walls had to be constructed as a waling system to prevent ingress of water (Fig 5). This arrangement was also adopted for the temporary shafts formed by pipepiles where existing watermain were in close proximity. This was because their bursting could cause migration of the surrounding soils into the shaft through the gap in the piles, causing road collapse, despite the fact that a grout curtain had been formed outside the shaft in advance, by injection of grout from the slots of the piles.

At locations where trunk utilities and services were present, a combination of sheetpiles and pipepiles was used to overcome the problem. Raking piles were also used at critical locations to increase the space in the lower portion of the shaft for pipejacking works (Fig 6).

Settlement monitoring markers, including the sub-surface type for concrete pavement, were installed and monitoring was carried out on a daily basis.

There had been some occasions that the shaft had to be constructed in stages, with the piling work completed in one traffic lane such that it could be decked-over and released to traffic, before the work was moved to the adjacent lane.

Since most of the shafts were located in land reclaimed after World War II, the Contractor was required under the Contract to carry out bomb detection, by means of a bomb-detector, at every metre of excavation at each shaft to protect the working personnel.

During the whole course of pile driving and rock excavation, noise levels were measured at the nearby Noise Sensitive Receivers. If the levels

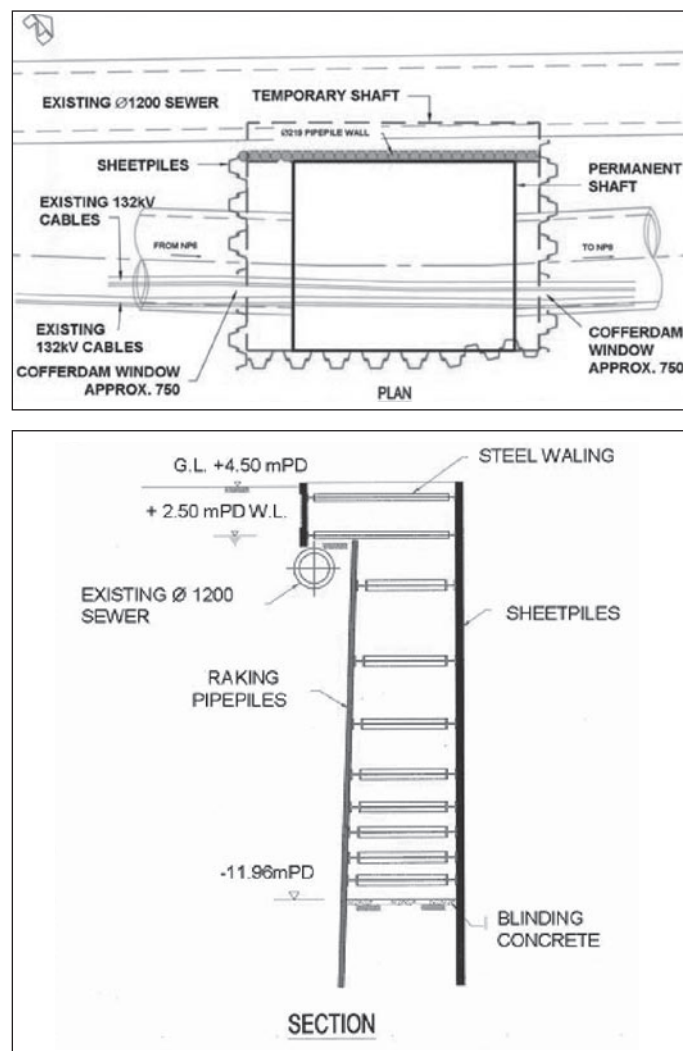


Figure 6 – Temporary Works Formed by a Combination of Sheetpiles and Pipepiles

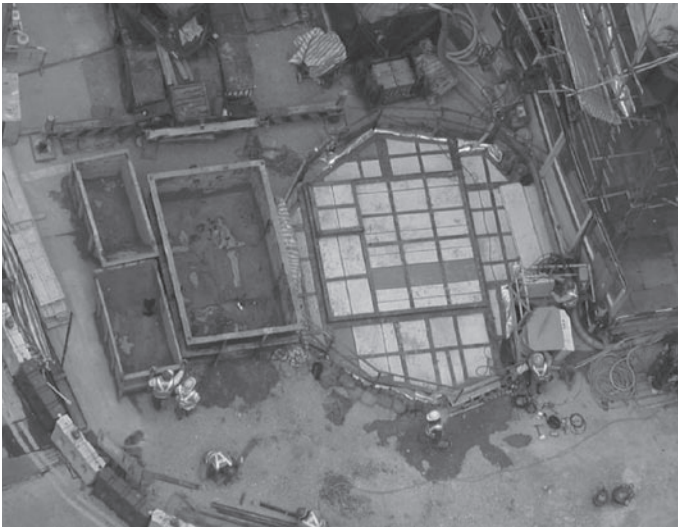


Figure 7 – Acoustic Panel for Rock Excavation in Temporary Shaft

exceeded the maximum allowable value (usually 65 - 75 dB depending on locations and time), noise reduction skirts or acoustic reduction panels, as appropriate, were provided for the respective activities (Fig 7). This could usually reduce the noise level by 2 - 3 dB.

Depending on the size and depth of the shaft, and the ground conditions encountered, each shallow shaft generally required 6 to 8 weeks for completion from piling to excavation. The construction time for the deep shafts, however, ranged significantly from 12 to 18 weeks due to the high variation in ground conditions, particularly the rock content.

In order to avoid causing disturbance to the surrounding ground during extraction, affecting the utilities and services and causing instability to the permanent shaft and the connected pipelines, all the piles were left-in-place, with the top 2 m cut-off.

Tunnel Design

Alignment

Straight sewers were adopted for the sections where no obstructions were present in the alignment between the jacking and receiving shafts. For those sections with site constraints such as lot boundaries of buildings, traffic, highways structures and major utilities/services etc, curved alignments were required. Due to operation and maintenance requirements, the curved alignment was not considered suitable for sewers with a diameter less than 1200 mm. After consulting with TBM manufacturers, the alignments of the curved sewers were fixed, with a curvature range of 340 m to 1965 m, so as to ensure proper alignment control by the TBM, smooth loading transfer between pipes and watertightness at pipe joints.

Besides simple straight or curved sewers, some sections consist of a combination of straight and single curve or double curves (S-shape). Detailed discussions on the first S-shape sewer in Hong Kong are included under the Section 'The Challenges'.

Jacking Pipe

3.0 m long standard and 1.5 m long short concrete jacking pipes, manufactured by Doran, were adopted. With a strength of 50 MPa, these pipes were checked to ensure that they had sufficient capacity to withstand the overburden pressure and surcharge loads applied, and the required jacking force for both straight and curved pipelines. This also included the ovalisation check of the pipes. The pipe barrels were designed using simple compression theory [4], with only nominal longitudinal reinforcement, in the form of a steel cage, required. Hoop reinforcement was also provided to resist bending due to ground pressures, and to protect the pipe ends which are subject to complex three dimensional stress conditions.

The allowable axial strength of the 1200 mm diameter and 1800 mm diameter pipes was 5200 kN and 10800 kN respectively for straight pipelines. For pipes with 0.5° allowable angular deflection (which was specified as the maximum allowable tolerance for curved sewers in the Contract), loading transferred at the joints is in the form of a triangular distribution [4] and this will result in much higher loadings acting on one side of the pipes, thus reducing their capacity by about 33%. In order to allow a more uniform loading distribution and have higher axial loading capacities, an 18 mm thick soft wood cushion ring was provided at the pipe joints for better dispersion of the eccentric loading, for pipelines with a minimum radius greater than 1000 m. For other pipelines, a 9 mm thick cushion ring was used. A steel collar was cast in the rear end of each pipe acting as a guide and preventing the concrete from damage during the jacking operation.

Watertightness at pipe joints with the respective allowable angular deflection was tested in the pipe factory under a simulated water pressure for the deepest pipeline.

To prevent the concrete pipes from the attack of hydrogen sulphide (H_2S) emitted from sewage, their inner surface are protected by a PVC lining. The PVC lining only covers 359° of the pipe with a gap left at the invert to allow infiltration from the pipe joints, and thermal expansion/contraction, and to prevent spalling out due to deformation of the pipes under overburden loading.

Pipeline

The tunnel face stability, tunnel bore stability, elastic ground closure, local yield of ground, ground settlement, pipe friction and pipe joint loading, etc for each pipeline was checked, based on the procedure laid down in [4].

Ground Settlement

The ground settlement for shallow and deep drives was estimated to be in the range of 10 to 18 mm, using the empirical formulae recommended by O'Reilly and New (1982) [5]. The effects of these settlements on the utility installations and structures at and in the vicinity of the alignment of the pipeline were assessed based on the material used (allowable flexibility in the joints), and the type of foundation, respectively. Acceptable values for such were agreed with the respective owners.

Pipe Layout

A pipe layout had to be prepared to specify the locations of long pipes, short pipes and intermediate jacking stations, for each pipeline between two or more permanent shafts. During the course of pipejacking works, pipes and intermediate jacking stations were jacked according to the sequence indicated in the pipe layout. The numbers and positions of the intermediate jacking stations were based on the pipeline design and were subject to review and revision when the actual jacking force deviated significantly from the predicted values.

The 2 nos short pipes at each side of the permanent shaft, as highlighted in the General Specification [6], were measured from the outer edge of the sheet/pile piles forming the temporary shaft, to account for the rigidity of its base slab and the left-in section of piles below the completed pipeline.

Tunnel Construction

Tunnelling Method and TBMs

As indicated by the site investigation, the jacked pipelines in the Wanchai area would pass through a layer of filling materials with boulders at different locations, whereas those in the North Point area would tunnel through an alternating, highly variable ground made of marine deposits, alluvium, CDG and M/SDG bedrock, with non-homogeneous materials.

Based on the above, the records of underground artificial features such as old seawalls, disused piles, left-in sheetpiles, and the lengths and sizes of the pipelines, the earth pressure balance method was not considered

TBM	Herrenknecht AVN 1800T	Lovat 2000 mts	Herrenknecht AVN 1200TC	Herrenknecht AVN 600
Length	14 m	9 m	6 m	5 m
Outer Diameter	2150 mm	2170 mm	1450 mm	780 mm
Sizes of Pipeline to be Jacked	1800 mm	1800 mm	1200 mm	600 mm
Ground Conditions Likely to be Encountered	Hard rock and highly variable grounds	Soft grounds with occasional boulders	Filling areas with boulders	Filling areas with boulders
Allowable Jacking Load	8548 kN	10000 kN	5088 kN	2600 kN
No of Steering Jacks	4	3	3	3
Cutting Wheel	Dome type with 11 nos 305 mm diameter single and double disc cutters	Semi-dome type with 11 nos 305 mm diameter single and double disc cutters	Dome type with 9 nos 280 mm diameter single and double disc cutters	Dome type with 6 nos 250 mm diameter single and double disc cutters
Allowable Water Head	3 bar	3 bar	1.5 bar	1.5 bar

Table 1 – Details of TBM

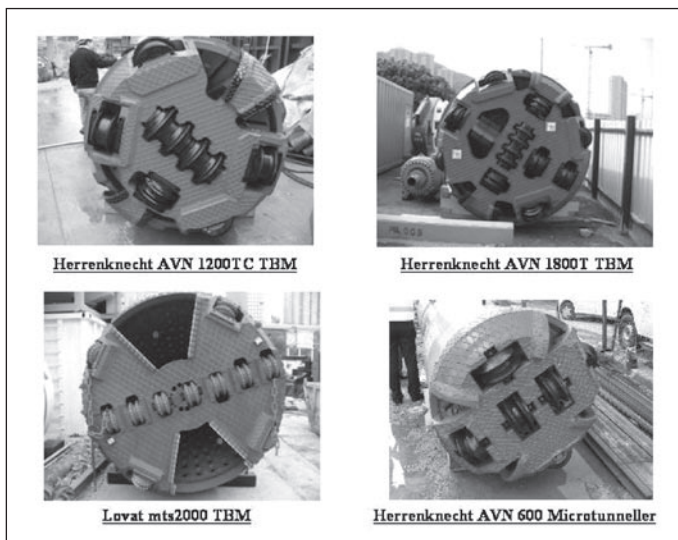


Figure 8 – Appearance of TBMs Adopted

suitable. The slurry pressure balance method, with the deployment of 4 nos full-face slurry TBMs equipped with disc cutters for rock excavation (Fig 8), was selected to construct the two trunk sewers. Key information is summarised in Table 1.

Operations

Both the Herrenknecht AVN1800T and Lovat 2000 mts TBMs were equipped with an air-lock chamber, to enable inspection of the condition of disc cutters and facilitating their necessary replacement. The Herrenknecht AVN1800T TBM had a telescopic section at the rear to provide sufficient capacity for smooth excavation in hard ground. The typical configuration of this TBM is shown in Fig 9. For the Herrenknecht AVN600 TBM, due to the limited size, there is no access to the rear of the cutting wheel for replacing damaged disc cutters.

Before the commencement of pipejacking a drive, sub-surface settlement markers, in the form of a mild steel rod, were installed at 5 m intervals along the centre line of the pipeline by coring through the concrete slab. Protected by a PVC sleeve pipe, the steel rod was 25 mm in diameter and 600 mm long. It was welded to a circular base plate and placed in

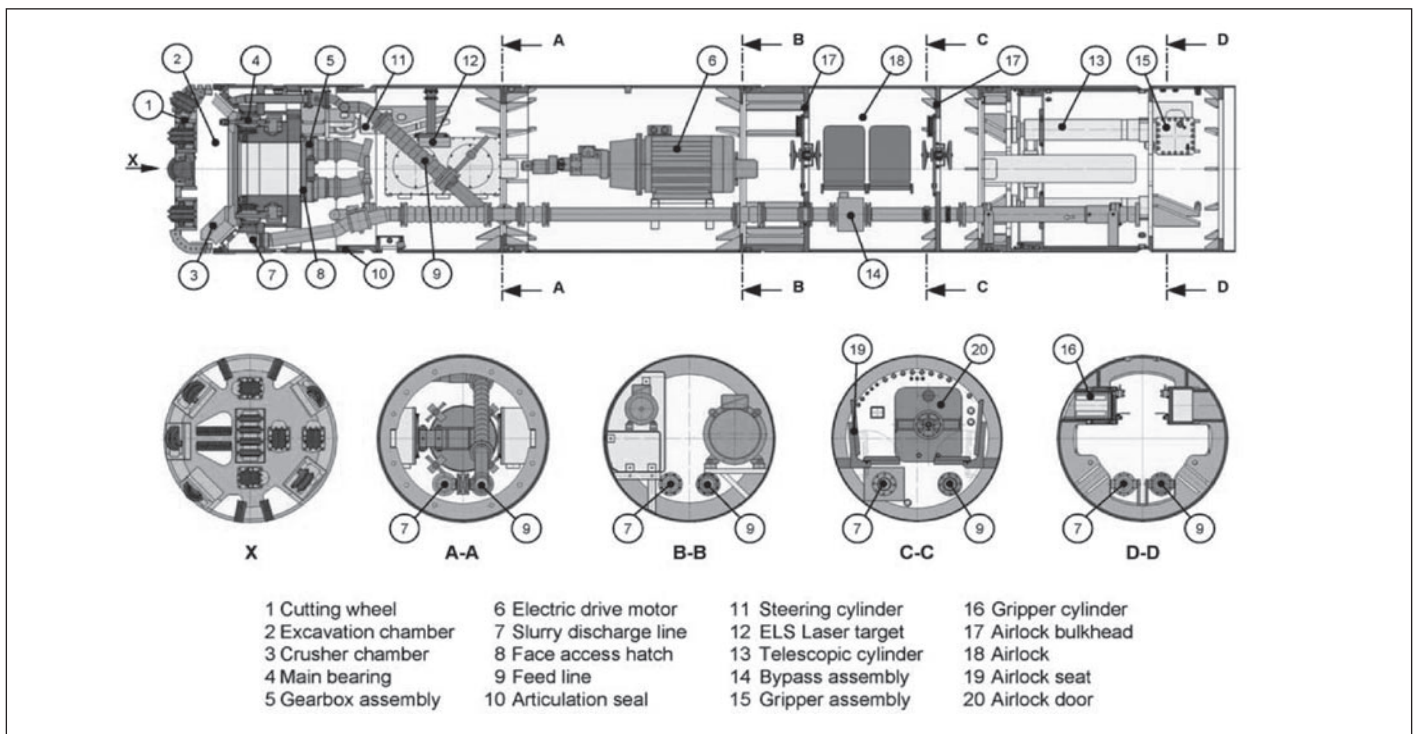


Figure 9 – Typical Configuration of TBM (Courtesy of Herrenknecht AG)

contact with the soil beneath the slab. Another 2 rows of markers at 5 m offset were also installed at the two sides. In addition, nail markers were installed in structures sitting on shallow foundation, for monitoring of settlement and tilting. Settlement monitoring was carried out 4 times a day during the course of works. The works were stopped when the measured ground settlement suddenly increased or exceeded the predicted value, and an investigation would be carried out on its cause, with remedial works executed as necessary, prior to resuming the works. As a double assurance, visual inspections were also conducted regularly, with particular attention paid to whether the joints of concrete slab had dislocated, and whether cracks existed in the flexible pavement and structures nearby. The frequency of monitoring was reduced to daily after the completion of the pipejacking works. This frequency was further reduced to weekly for a duration of 4 weeks when the settlement became stabilised. If no further settlement was detected, the monitoring would continue at a monthly frequency for a further 3 months.

A works area, about 8 m x 60 m, was provided at each jacking shaft site for setting up the plant required for the pipejacking works (Fig 10). At some locations, a satellite works area was required due to insufficient space.

For all TBMs, bentonite based slurry, with a viscosity of 40 - 50 Marsh sec. for sandy ground (equivalent to about 4% of bentonite by weight), was constantly pumped into the excavation chamber, through a slurry

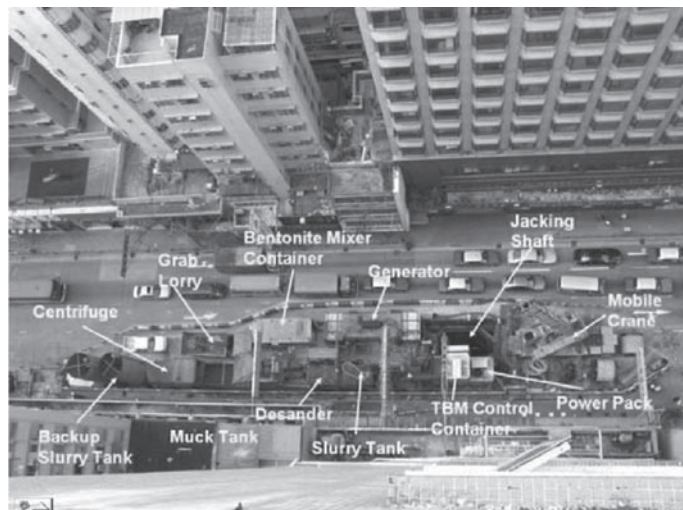


Figure 10 – Temporary Traffic Management Scheme for Pipejacking Works

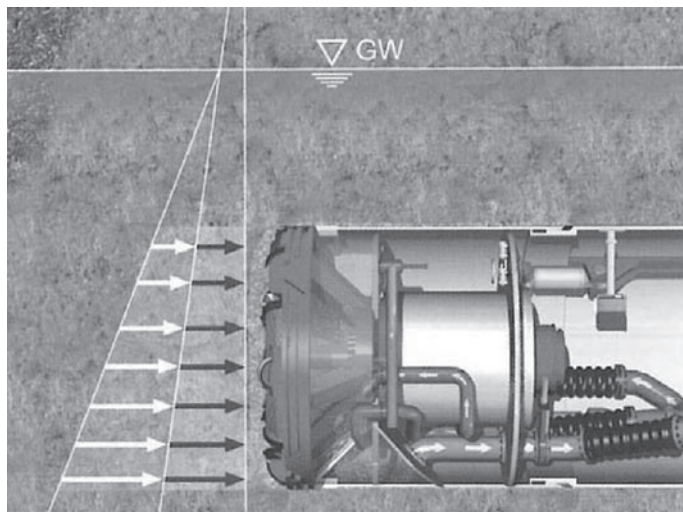


Figure 11 – Mechanism of Slurry Pressure Balance (Courtesy of Herrenknecht AG)

charge pipe. This forms a cake over the excavation surface, to stabilise the face and prevent the ingress of groundwater (Fig 11). The materials were agitated by the cutting wheel and fell into a conical crusher behind, after mixing with the slurry, for further reduction in size (to 40 mm or smaller), before entering into the spoil removal chamber at the invert of the TBM, for transportation to the surface, via a slurry discharge pipe. These materials were then separated by a desander, with the slurry being for recycling use and the spoil disposed off site. The mix of slurry had to be adjusted from time to time to suit the ground conditions encountered. Occasionally, polymer needed to be added to improve the performance. For clayey ground, no slurry was used and water under pressure was injected for such purposes. The slurry and water pressure, which was usually 1.1 to 1.2 times greater than the total horizontal stress in the excavation face, was constantly monitored and adjusted to avoid blowing out the ground.

For rock excavation, a thrust was exerted by the disc cutters onto the rock face, forming vertical and radial cracks in circular kerfs at distances of 60 - 100 mm. By repeated rotations of the cutting wheel and disc cutters, these cracks were enlarged and eventually caused the rock mass in between to be broken into small fragments. The mechanism of rock cutting and the kerfs formed in the rock face are given in Fig 12 and 13 respectively.

The volume of slurry injected and spoil removed was shown on the monitor in the control room such that any excessive over-excavation could be known immediately.

The over-excavation was minimised by maintaining a torque pressure of at least 90 - 100 bar in the cutting wheel against the excavation face.

Lubricant, in the form of bentonite (with thinner mix) or polymer (under adverse ground condition), was injected to the overcut along the pipeline, formed by the TBM, in every fifth pipe, through the 2 nos lifting holes at the crown of the jacking pipe and the holes in its axis, by an automatic

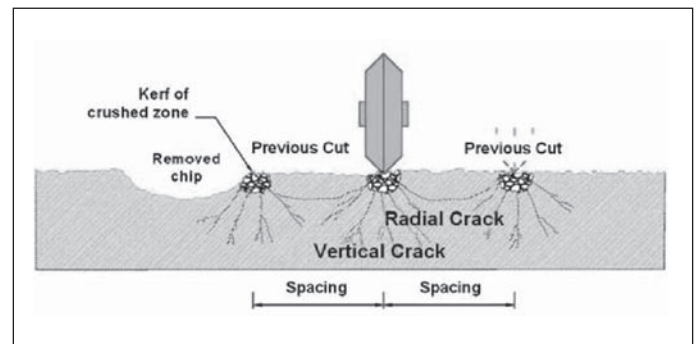


Figure 12 – Rock Cutting with Disc Cutters

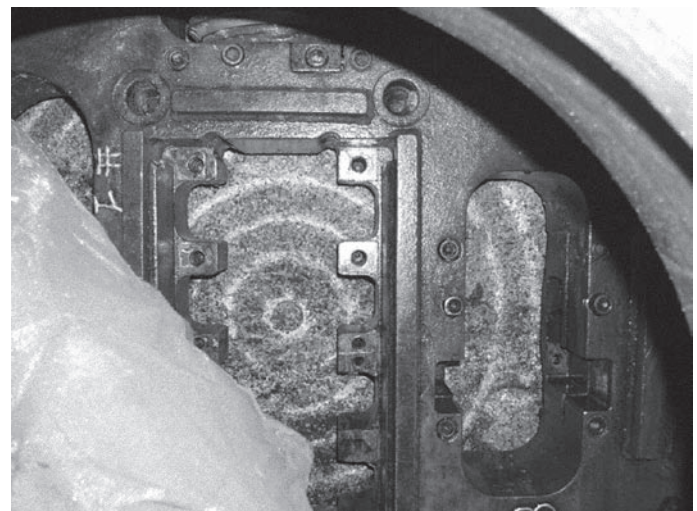


Figure 13 – Circular Kerfs in Rock Face Formed by Disc Cutters

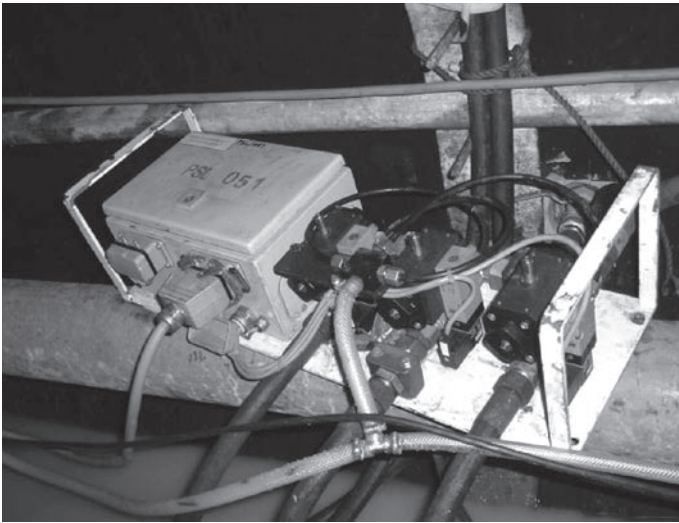


Figure 14 – Automatic Lubrication System in Jacked Pipeline

system with pre-set timer and volume of flow (Fig 14). This was done to increase the shear strength of the surrounding soils, thus maintaining the stability of the overcut from closing-up, and to reduce the frictional force along the pipeline during the jacking operation. In sandy ground with gravel and cobbles, a viscosity of as high as 60 - 120 Marsh sec. had to be used, whereas in clayey ground, neither bentonite nor polymer was required.

The volume of lubricant used for each pipejacking drive depended very much on the length of driving, its curvature and the ground conditions encountered. It generally ranged from 14,000 to 55,000 litres for the drives through homogeneous silty to sandy materials, and from 200,000 to 300,000 litres for the drives through highly variable ground conditions. A consumption of 800,000 litres and 1,800,000 litres of lubricant had been recorded for the two longest curved alignments with lengths of 404 m and 370 m respectively.

Intermediate jacking stations (Fig 15), each with 8 to 12 nos 80T hydraulic jacks, were installed at pre-determined locations of the pipeline, usually every 80 - 100 m, to avoid excessive loading in the main jacking station. These stations were operated one by one, with the jacks in a station extended 500 mm each time. Some of the stations were not used due to consistently low jacking forces after the application of bentonite/polymer, and this also sped up the jacking operation. For long stoppages during the course of a drive such as the change of disc cutters and malfunction of the TBM, the stations had to be operated as friction resistance on the pipeline would develop rapidly, resulting from movement/collapse of the surrounding soils onto the pipeline.

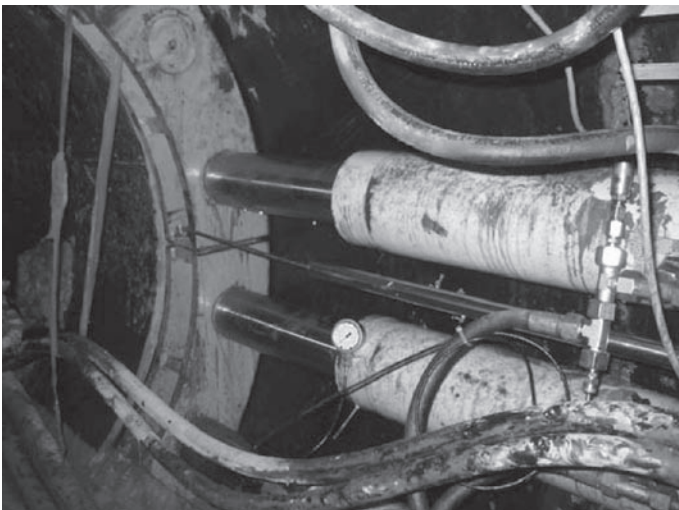


Figure 15 – Intermediate Jacking Station in Operation

Water leakage was found in some of the stations during the driving of the curved sewers (Fig 16). It was later found that the rubber gasket provided at the rear part of the station was torn out after the repeated extension and retraction of the hydraulic jacks. The situation was rectified by reinforcing the steel rims at its two sides from the original 300 mm spacing single-face-spot-weld to 100 mm spacing double-spot-weld.

High water pressure was present in some of the deep drives, pushing the TBM and the first few jacking pipes back when they were launched into the ground. This resulted in the necessity for a steel bracket temporarily fixed in the TBM/pipe and rigidly connected to the surrounding temporary works as support during the pipe connection (Fig 17).

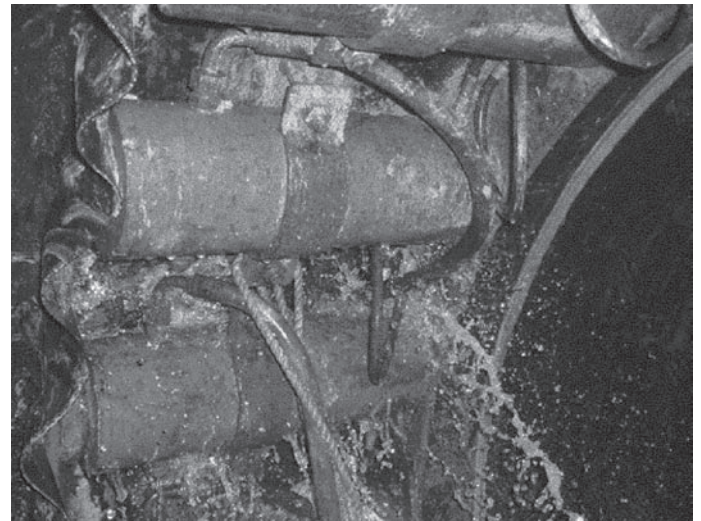


Figure 16 – Water Leakage in Intermediate Jacking Station

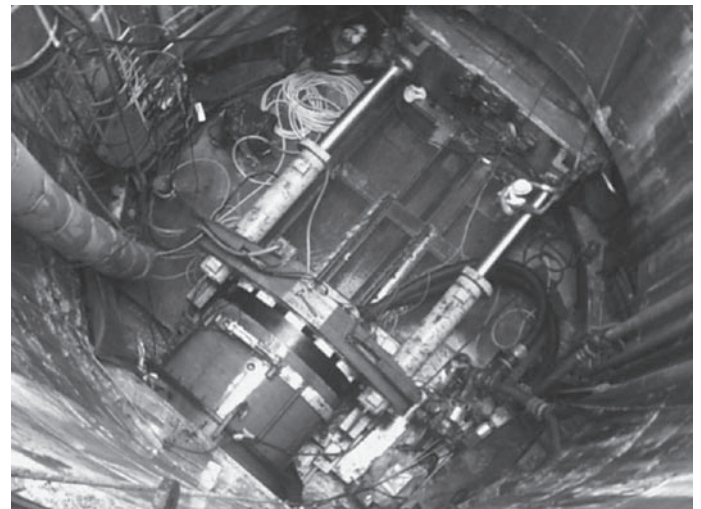


Figure 17 – Provision of Steel Bracket for Fixing Jacking Pipe to Launching Eye During Pipe Connection

On some occasions, the TBM was found to roll during the course of jacking. The situation was compensated for by excavating with the cutting wheel operating in the opposite direction. This could also be achieved by extending the rotation compensation wing, in the case of the Lovat TBM (Fig 18).

Failure of the grout block was experienced at two receiving shafts, causing significant ingress of water and migration of soil, through the receiving eye (Fig 19). After this incident, the jacking and receiving eyes for the remaining drives were modified to be formed from a single concrete structure to a complete ring wall cast against the sheet/pipe piles, with double layers of rubber seal provided.

Tunnelling through clayey ground often caused slow transportation rates in the slurry discharge pipe due to the plastic material accumulated in

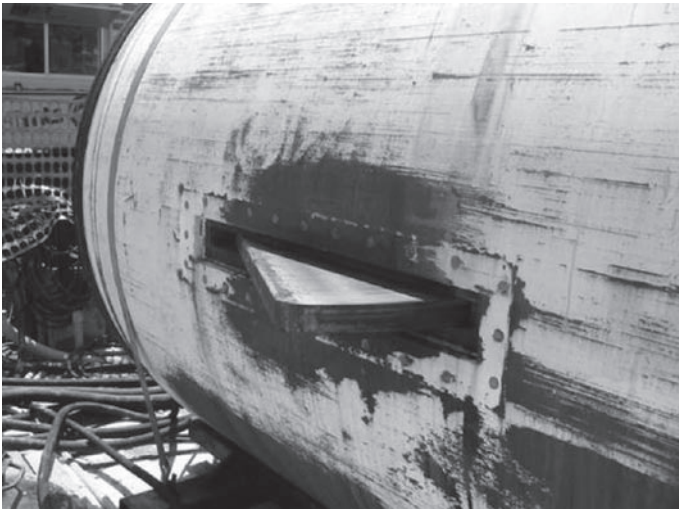


Figure 18 – Rotation Compensation Ring in TBM



Figure 19 – Grout Plug Failure during TBM Breakthrough

the inlet of the spoil disposal chamber. High pressure water had to be used to disperse such material through the nozzles provided nearby. Pipe blockage was also found when obstructions such as timber, steel bars, etc, were encountered, resulting in the long time to dismantle the respective sections of the pipe for clearance.

Typical operations in a jacking shaft and the condition of a jacked pipeline are shown in Figs 20 and 21 respectively.

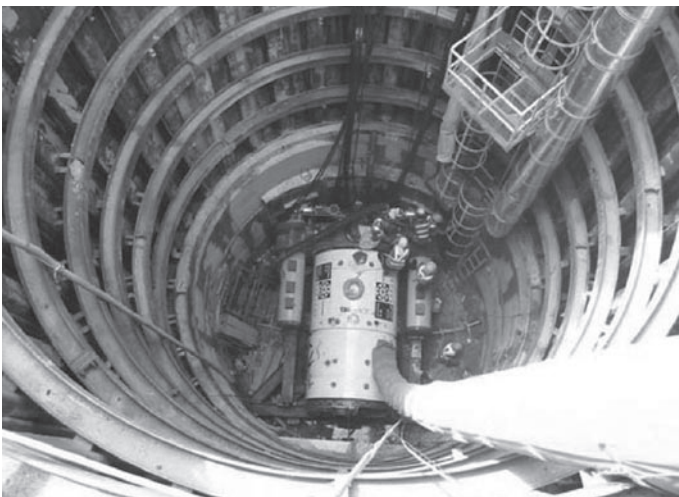


Figure 20 – Launching of TBM in Jacking Shaft



Figure 21 – Typical Condition of a Jacked Pipeline

Control of Line and Level of Pipeline

A laser guidance system, which consisted of a laser device installed at the rear of the temporary shaft and a target plate in the machine can of the TBM, was used for checking the line and level of a pipejacking drive. The relative position of the laser beam on the target plate was automatically transmitted to the control room for reference. For curved drives, a SLS-RV laser guidance system was used to control their alignment. Traditional survey check was carried out for every 30 m of driving, using Gyro theodolite.

Through the above system, the position of the TBM was displayed on the computer monitor in the control room during the course of pipejacking works. Correction of the line and level of a pipeline, if necessary, was made, by gradually adjusting different combinations of extension and retraction in the steering jacks (with a maximum 100 mm stroke), to avoid damaging the jacking pipes.

Inspection of Cutting Wheel and Disc Cutters

For sandy ground, activation of the TBM air-lock was required for the inspection of the disc cutters and making replacements if necessary when little or no advancement was achieved by progressive pushing under consistent high torque pressure and jacking force, and/or metallic pieces were found in the desander. Under the compressed air working environment, PU grout, a jelly form of chemical grout which swells rapidly with groundwater, was applied to the excavation face and the periphery of the rear of the TBM, to prevent ingress of water, before the access opening in the front bulkhead of the TBM was opened for such purposes. When disc cutters were replaced in rock pockets or clayey ground, activation of the air-lock was not required due to the low permeability of the materials in the excavation face.

Replacing disc cutters during the course of pipejacking works was time-consuming as for each replacement, the dismantling of the complete bearing system of the disc was required, and at times the rock mass in front of the cutting wheel had to be trimmed locally by hand tool to give sufficient room for the installation (Fig 22). On average, each replacement took 3 hours for completion.

The conditions of some of the worn-out and damaged disc cutters are shown in Fig 23.

On one occasion, the TBM could not advance further under high jacking force after driving speedily over a certain length in soft ground. After inspection from the access opening, it was found that almost all of the disc cutters were either seriously damaged or worn out. However, they could not be replaced due to the damage/distortion of their connections to the TBM, necessitating a rescue shaft for the replacement of a new cutting wheel with a different configuration of disc cutters before the resumption of works.

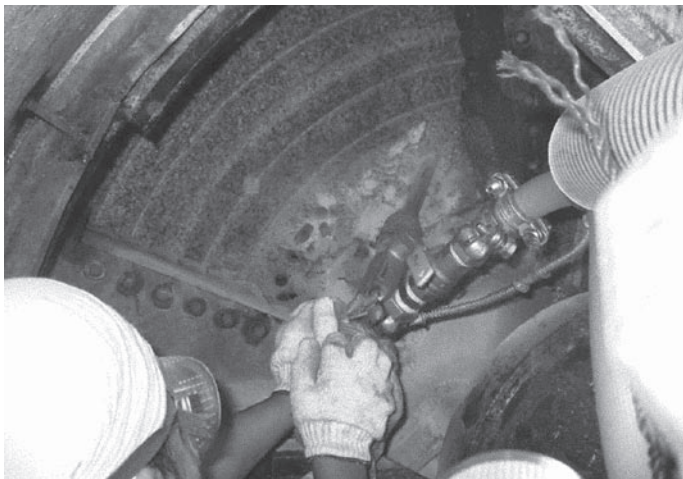


Figure 22 – Breaking of Rock Face for Installation of New Disc



Figure 23 – Conditions of Damaged Disc Cutters

The performance of works for the pipejacking drives, using different TBMs and under different ground conditions, is discussed in Part II of the Paper.

Other Special Considerations

In addition to the technical compatibility of the works, safety was given top priority on the Contract and full consideration was given to the safety of the general public and all of the operatives engaged on its construction. Detailed risk assessments were carried out before any activity could proceed and a Safety Plan, drawn up by the Contractor, under the Contract, in full compliance with Hong Kong Regulations and the particular requirements of the Drainage Services Department, and rigorously applied by B&V Resident Site Staff.

Public relations also received paramount importance. Information pamphlets, newsletters, and Public Consultation and Liaison Meetings had been used to keep the District Councils and the public well informed of the progress of the work. A 24-hour Telephone Hotline, was in place, to enable the public to pose questions, lodge complaints and make general enquiries on all and any aspects of the contract that might affect them. All enquires and complaints were dealt with within 24 hours, with improvement works carried out as far as practicable.

Suitable safety measures were provided during the course of the works. This included implementation of a permit-to-work system, detection of gas before entering a confined space, provision of sufficient ventilation, provision of fire extinguishers, clean-up of spill material, sand bucket, fire blankets, and breathing apparatus, as appropriate, at different locations of the shaft and the jacked pipeline. Safety nets were also placed on top of the shafts when no work was carried out.

The work sites were generally surrounded with corrugated sheeted hoarding/fences. However, in order to improve the aesthetics of these hoardings and to lessen the visual impact and intrusion on the site environment, the vast majority of these hoardings were constructed with transparent panels (with three options to suit the need of the residents and shops, namely, fully transparent panels (Fig 24), alternate half transparent panels, and half transparent panels) to improve lighting, sightlines, and security. They also helped to keep the public abreast of the progress of the works, as the works were always in the public view.

Allied to the importance placed on safety, was that placed on maintaining the cleanliness and tidiness of the sites. This included proper stacking of materials, provision of a chemical store, provision of a rubbish bin and skip, sweeping of the site, cleaning of signs, water-filled barriers, steel fence barriers and hoardings. A CCTV camera was also provided at each works site to monitor site tidiness, with the master station located in the Resident Site Staff's Office. The Resident Site Staff also carried out daily inspection, with a site tidiness checklist to ensure that there was no non-conformity. A patrol unit was also assigned to check all work sites during night time and public holidays for such purposes.

The above measures were greatly appreciated by the public, leading to the receipt of commendations from local residents and the District Councils, and various awards from the Considerate Contractors Site Award Scheme (for 3 consecutive years), the Construction Site Housekeeping Award Scheme 2005, and the Civil Service Outstanding Service Award Scheme 2005 – Front Line/Counter Service.



Figure 24 – Fully Transparent Hoarding in a Work Site

The Challenges

Pipelines Passing through a Narrow Gap with MTRC Pedestrian Tunnel at Bottom and Trunk Water Main and Sewer on Top

Two 1200 mm diameter pipelines, the first one being a straight section and the second one being a curve with a minimum radius of 340 m, were to be constructed outside Sogo in Hennessy Road (Figs 25 and 26).

The line and level of these two pipelines was carefully assessed and determined to avoid conflicting with the Mass Transit Railway Corporation (MTRC) pedestrian tunnel below and an existing 1200 mm diameter sewer and a newly installed 1000 mm diameter fresh watermain on top. Due to such constraints, the corresponding clearance was 600 mm and 1000 mm respectively.

To minimise the ground movements when the TBM was passing through the gap between the tunnel structure and the utility installations, cement stabilised soil was used to backfill the excavated trench for the watermain.

When the TBM was 5 m from the tunnel, the works were stopped and a joint survey with MTRC was carried out to ensure that the line and level

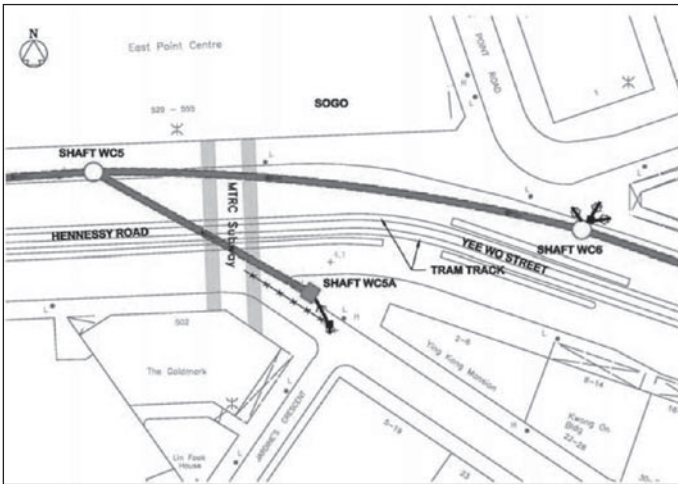


Figure 25 – Plan Showing Alignments of the Two Jacked Pipelines

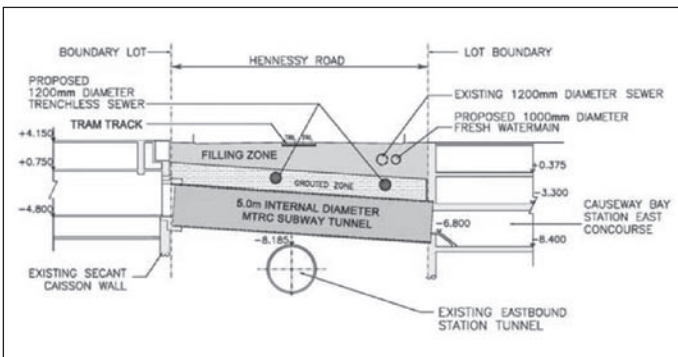


Figure 26 – Cross-section Showing the Two Jacked Pipelines and Site Constraints

of the TBM was correct. When the TBM arrived at the edge of the tunnel, the same survey was also conducted before moving further.

Strain gauges were installed inside the tunnel at locations agreed with MTRC and monitored every 2 hours when the TBM was passing through above. Continuous vibration monitoring was also carried out inside the tunnel and at the watermain at the same time.

The jacking speed was limited to between 50 mm and 100 mm/min under low jacking force. The line and level of the two pipelines was controlled within ± 10 mm and no damage was found in either the pedestrian tunnel and utility installations.

Pipeline Passing through Raking Piles Supporting the Canal Road Vehicular Flyover

A 1800 mm diameter pipeline, with a minimum radius of 1500 m, was proposed to be constructed along Gloucester Road and pass between the raking piles of the elevated Canal Road Flyover (Fig 27). Although the as-built records of the raking piles indicate no obstruction to the proposed jacked pipeline, the construction tolerance may introduce an alignment conflict.

In view of the above, a geophysical survey was carried out under the Advance Works Contract with the aim to determining the true as-built geometries of the piles such that the jacked pipeline design could be reviewed and revised, as necessary.

The radar method was firstly employed to define the piles. Based on the field trials, the effective penetration of the radar signal was only 0.85 m at the pipe depth. It was considered not practicable, in view of the traffic constraints and high concentration of underground utilities, to have pairs of holes for every single pile, with separation of only 0.85 m.

The vector magnetic method, which depends upon the magnetic polarization of the steel reinforcements in the piles, was finally adopted.

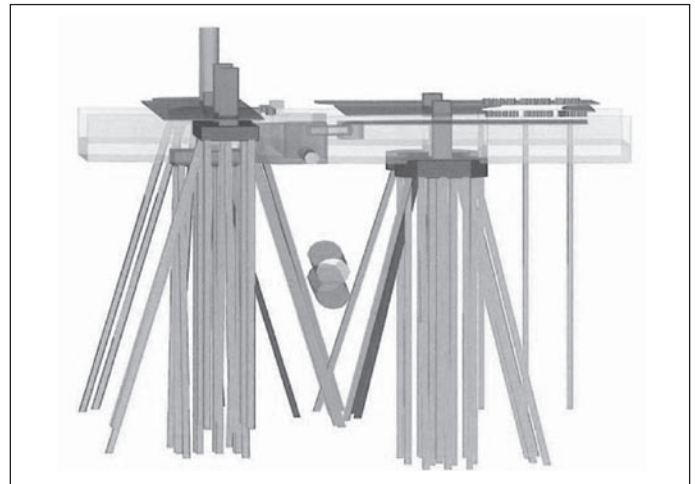


Figure 27 – Alignment of Jacked Pipeline between Raking Piles

This method successfully located the piles from single drill holes within 2 m in radius. 15 nos drill holes were sunk at the selected locations to define the piles.

The survey indicated that these piles mainly deviated toward the jacked pipeline and, based on such results, the designed pipeline was elevated for 2 m to avoid the potential conflict (with a clearance of 450 mm) [7].

Following the revised design alignment, the pipeline was successfully completed.

Construction of a 404 m Long S-shape Pipeline

Shaft NP4, located at the junction of Electric Road and Wing Hing Street, was originally designed as a jacking shaft for 2-direction driving. Since the implementation of the temporary traffic management scheme, a significant number of complaints, mainly related to inconvenience, traffic congestion, loss of business and environmental issues, were received. In view of the public's concern about these works, DSD requested B&V and the Contractor to review the construction programme and working methods to determine whether there was any way to expedite the works and relieve the disturbance to the public.

After several discussions between DSD, B&V, ER and the Contractor, it was established that the drives NP4-NP3 and NP4-NP5 could be combined into one single drive (404 m long on a S-shape alignment), from NP5 directly to NP3 (through NP4), such that Shaft NP4 would not be used as either a jacking or receiving shaft. It was also proposed to construct the complete permanent shaft of NP4 (intermediate shaft), except the benching, and the base slab and shaft wall of NP3 (receiving shaft), before the commencement of this long pipejacking drive NP5-NP3 (Fig 28).

The benefits of such proposal included eliminating the need for setting up the pipejacking equipment at Shaft NP4, thus reducing the disturbance to the public. It also allowed a much earlier completion of the shaft, as

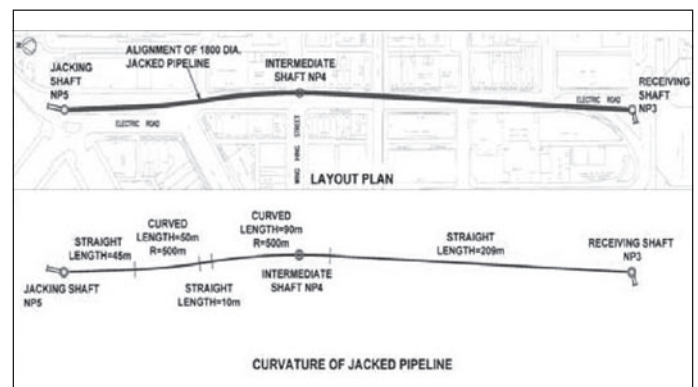


Figure 28 – Plan Showing the S-shape Pipeline

it would be constructed and reinstated before the commencement of the pipejacking drive.

As the S-shape alignment using pipejacking methods and the completion of permanent shaft construction before the commencement of the respective pipejacking works were new concepts in Hong Kong, the technical feasibility of the proposal had to be assessed and reviewed carefully, in particular the design of S-curve alignment, whether the clearance to nearby buildings as a result of the revised alignment would pose any problem, whether the load could be properly transferred between the two curves, the methods and details on how the TBM could tunnel through a 'completed' manhole structure without causing any damage (Figs 29 to 31), and the effect of vibration of TBM breakthrough on that permanent structure.

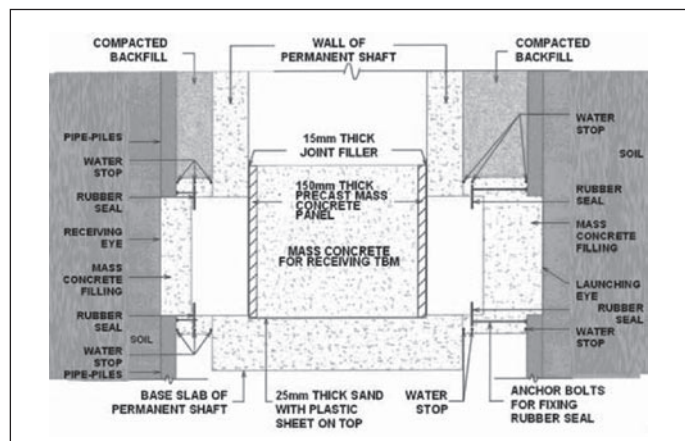


Figure 29 – Details of Intermediate Permanent Shaft before Reception of TBM

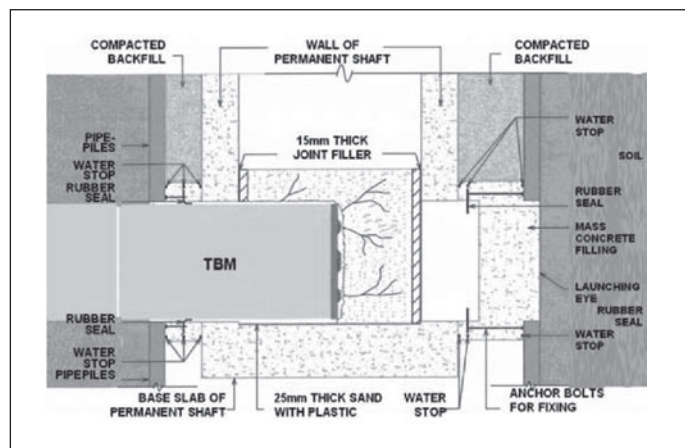


Figure 30 – TBM Launching into Intermediate Permanent

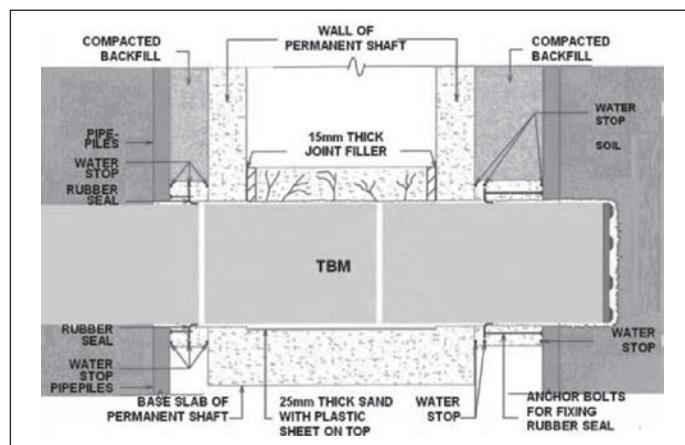


Figure 31 – TBM Passing through Intermediate Permanent Shaft



Figure 32 – TBM Breakthrough in Receiving Permanent Shaft



Figure 33 – Lifting-up of the Longest Machine Can of TBM from Receiving Shaft

The clearance between the shaft wall of NP3 and the longest section of the TBM, at the narrowest point, was only 100 mm. This had to be checked carefully and repeatedly, so as to ensure that the TBM could be lifted up upon completion of the drive.

The shaft site NP4 was completed and reinstated about 10 months earlier than the originally programmed completion date and the 404 m long, S-shape pipejacking drive NP5-NP3 was satisfactorily completed in June 2005.

The TBM breakthrough at NP3 and the condition of the TBM when lifting up are shown in Figs 32 and 33 respectively.

Typical arrangements in the intermediate and receiving permanent shafts and the procedure of tunneling through these shafts are given under the heading 'Options of TBM Driving' in Part II of the paper.

Conclusions

Certain observations and conclusions may be drawn from the experiences gained on this Contract.

- 1) The works carried out under the Advance Works Contract have proved to be extremely useful to the success of the Trunk Sewer Contract, in that the shaft locations basically remained unchanged, except for a few shafts which needed to be slightly shifted to suit existing utilities, and that less time was used for liaising with utility undertakers for the diversion works. It is suggested that other large

scale pipejacking contracts should carry out similar works in the design stage.

- 2) Although site investigations had been carried out at the shaft locations in the design stage, the ground conditions varied significantly along the tunnel alignment in some of the deep sewers. This affected the line and level, and on one occasion, resulted in the stoppage of the TBM. It is considered that further site investigation should be carried out as much as possible at suitable locations between any two shafts, when traffic permits. This could be carried out either during the design stage or as a contract requirement, in the construction stage, such that appropriate tunnelling method and TBM can be selected and the advance planning of the TBM operator made, to minimise such risks. This could also enable the accurate prediction of ground settlement.
- 3) The successful completion of this Contract gives engineers in Hong Kong confidence in constructing curved alignment tunnels by the pipejacking method. This greatly enhances the feasibility of installing pipelines in busy urban areas where site constraints such as congestion of utilities, heavy traffic and presence of highways structures, etc are always a major problem for the open trench method. Such technique also allows the manholes of trunk drains/sewers located away from the main street of traffic junctions, thus enabling easier maintenance.
- 4) For small size TBMs (less than 900 mm in diameter), there is no access to the rear of the cutting wheel for replacing damaged disc cutters. It is therefore of paramount importance to determine the ground conditions and whether obstructions exist along the alignment of pipeline, and to remove such, if necessary, by horizontal drilling from shafts, before launching the TBM into ground.
- 5) The intermediate jacking stations in some of the drives were not used. However, they did provide a measure of insurance when poor ground conditions were encountered or the TBM was stationary in the ground for some time due to malfunction or replacement of disc cutters. This was because the overlying soil could collapse onto part of the pipeline, as the lubricant may not be able to effectively travel and condition the ground between the grout injection holes in the pipeline under such a no-motion situation.
- 6) The 404 m long S-curve alignment had travelled into the 2 nos already constructed permanent shafts (intermediate shaft and receiving shaft), through the prefixed opening, in a correct position, without causing any damage or instability to the structure, by the Herrenknecht AVN1800T TBM. The special construction joint details ensured that the grouting of the pipeline annulus did not result in any grout influx to the permanent shaft, and the watertightness of the permanent shaft. The mass concrete filling inside the intermediate shaft can however be modified to prevent the leakage of water and slurry when the TBM is cutting through. The success of this drive and other curved drives gives more flexibility and confidence to clients and contractors in programming of the works, particularly in the event of delays.
- 7) Excessive increase in jacking forces due to increase in frictional forces between TBM/pipeline and soil can be minimised through lubrication and/or conditioning of the ground by the slurry/polymer, as well as by the application of intermediate jacking stations, or a combination of both, as evidenced by both the straight and curved drives.
- 8) The sub-surface settlement markers are an effective tool for monitoring surface ground movement in concrete carriageways during the pipejacking works. However, their locations should be aligned in such manner that they are distant from the road joints to avoid causing traffic problem during installation and monitoring, and, more importantly, the requirement of full panel reinstatement which would oppose the spirit of using the trenchless techniques.
- 9) The skill, response and knowledge of the TBM operator plays an important role in the success of the works. Sometimes, problems arise as a result of human errors. These could be minimised by employment

of well-experienced operator who is familiar with the operation of the TBM and the ground conditions likely to be encountered. It is vital to react quickly and stop the TBM immediately when obstructions are encountered, as chain reactions might occur and disc cutters or even part of the cutterhead could be damaged.

Acknowledgements

The authors wish to express their gratitude to the Drainage Services Department of the Government of Hong Kong SAR, for permission to extract the materials from the respective project, to publish this paper. The assistance provided by Mr Derek Arnold, Director of Black & Veatch Hong Kong Limited, and Mr K C Leung and Mr Ivan S W Wong of the Resident Site Staff in analysing the field data, are also appreciated. Special acknowledge is given to Herrenknecht AG for his permission to extract the photographs from technical brochures in making Figs 9 and 11.

References

1. Thomson, J., Pipejacking and Microtunnelling, pp. 3-6, Black A&P, UK., (1993).
2. McFeat-Smith, I., Tunnelling in Hong Kong in the 1990s, Tunnelling in Hong Kong Seminar, Hong Kong (1993).
3. Research and Development Section, Trenchless Pipe Installation and Renovation Techniques, Review of Pipe Jacking/Microtunnelling Techniques for Construction of Drainage Pipelines, Research & Development Report No. RD 1005/2, Drainage Services Department, Government of the Hong Kong SAR, Hong Kong (2002).
4. Pipe Jacking Association, Guide to Best Practice for the Installation of Pipe Jacks and Microtunnels, pp. 24, 44 - 56, U.K., (1995).
5. O'Reilly, M.P. and New, B.M., Settlement above Tunnels in the United Kingdom – Their Magnitude and Prediction, *Proceedings Tunnelling '82 Symposium*, Institute of Mining and Metallurgy, U.K (1982).
6. General Specification for Civil Engineering Works, Volume 1, pp. 131 -132, Civil Engineering Department, Government of the Hong Kong SAR, Hong Kong (1992).
7. Final Report on Geophysical Investigations of Raked Piles, Canal Road, Wan Chai, Cosine Ltd. (2001).

About the Authors



Wilson W S MOK BASc BA CEng RPE(Civil & Geotechnical) CPEng CSci MICE MIMMM MIEAust MHKIE

Email: wilsonwsmok@netvigator.com

Ir Wilson Mok graduated from the University of Windsor in Canada and has over 28 years practical working experience in a wide variety of geotechnical and civil engineering projects in both design office and site. He is particularly experienced in dealing with design and construction associated with geotechnical investigations and instrumentation, deep excavations, tunnels, ground improvements, settlement analysis, reclamation, site formation, slope preventive measures, foundations and sewerage works. He has been involved in the design, supervision and administration of more than 16 km of trunk sewers construction in the urban areas of Hong Kong, using different types of trenchless techniques from relining, TBMs to hand tunnelling, and has carried out extensive research on such. He is currently employed by Black & Veatch Hong Kong Limited as Senior Resident Engineer on a DSD contract.



Maxwell K W MAK BSc Dip HE Delft PCLL MA
Arb CEng MIEAust MICE MHKIE MIHT

Email: kwmak@dsd.gov.hk

Ir K W Mak is currently Chief Engineer in Drainage Services Department. In the past few years, he has participated in numerous large-scale and prestigious drainage and sewerage projects, including the Wan Chai East and North Point sewerage project, the first tertiary sewage treatment plant at Ngong Ping, Lantau Island, as well as the 6 km long rainwater-intercepting tunnel in Tsuen Wan. Previously, he spent six years in the then Works Bureau dealing with slope and water

policies. During his earlier years with the Drainage Services Department, Ir Mak received post-graduate training in river engineering in the Netherlands, and had then worked in the Shenzhen River Regulation Project. He obtained a Master of Arts in the area of dispute resolution and arbitration. On top of his engineering engagements, Ir Mak acquires legal qualification and is a non-practising Barrister-at-law of the High Court of the HKSAR.



Felix H T POON BEng MSc CEng MICE MHKIE

Email: poonfelix@gmail.com

Ir Felix Poon graduated from the University of Hong Kong with First Class Honours and joined Black & Veatch Hong Kong Limited in 2000. Since then, he has participated in various projects including design and construction of pipe-jacked sewage tunnels, deep shafts, water transfer tunnel, box and large diameter pipe culverts, river channels and other drainage and sewerage features. He had been actively involved in DSD Contract No DC/2000/11: Wan Chai East and North Point Sewerage – Trunk Sewers, during the stages from

design, tendering to construction, in that he was posted as an assistant resident engineer responsible for supervision of the respective construction by trenchless technique, and the analysis of the field data obtained from the works. He is currently an engineer in the design office working on a drainage improvement project in Northern New Territories and a water transfer tunnel project on Lantau Island.