Installation of Grouted Jacket to Protect Existing Major Water Pipes for Trenchless Construction in Hong Kong

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ABSTRACT

To sustain development of our first new town, Tsuen Wan, drainage improvement works were carried out in Tsuen Wan and its adjacent district Kwai Chung in order to alleviate flooding impact to them. One of the major works of the drainage improvement was to lay a large diameter stormwater pipe across heavily trafficked Texaco Road which is a strategic road and houses numerous underground utilities such as gas pipes, storm and foul drains, power cables and pressurized water mains including a freshwater trunk main and an asbestos cement saltwater main. To carry out the drainage improvement works under the above site constraints while to ensure a safe and healthy working environment as well as to minimize disturbance to the residents in the neighborhood, we devised an innovative grouted jacket as a major protection measure to existing water mains for laying of stormwater pipe by trenchless construction. The grouted jacket could overcome the inadequacy of soil arching strength due to shallow soil cover, eliminate the risk of flooding the workers inside the pipe bore in case of bursting of water main, and confine the pipe jacking activities within the grouted jacket. To construct the grouted jacket, ODEX drilling method was adopted with a revised Tube-A-Manchette (TAM) grouting method. Successful completion of the grouted jacket and pipe jacking for the drainage improvement works were achieved.

Keywords : Grouted Jacket, Water Mains, Trenchless Construction, Safety.

1. INTRODUCTION

The application of pipe jacking techniques is becoming more and more common in the urban areas of Hong Kong to circumvent the traffic problems brought by road openings. Unlike open-trench construction, the underground utilities cannot be exposed and diverted by trenchless method during construction. Alignments of the underground utilities have to be accurately ascertained before commencement of pipe jacking in order to avoid them from the first beginning as there will be no chance for the jacking pipe to twist and dodge around them once pipe jacking is started.

There are cases when the upstream and downstream invert levels are fixed by existing drainage system while the overburden soil strata is not adequately thick enough to enable full soil arching effect to be mobilized above the jacking pipe, or the underground utilities are in direct conflict with or in very close proximity to the proposed jacking pipe. The latter means that diversions of these underground utilities are extremely difficult if not impossible, as the utility undertakings would have to face the same traffic problem when they are trying to carry out the road openings, expose and divert the utilities.

Such situation was faced by the project team for urban drainage improvement project in Tsuen Wan and Kwai Chung of Hong Kong during the construction of a 1800mm diameter stormwater pipe across Texaco Road near Tsuen Wing Street, Tsuen Wan. The Employer of the project was Drainage Services Department (DSD) of the Government of Hong Kong SAR, the Engineer of the project was Maurice Lee & Associates Ltd. and the Contractor was Shanghai Urban Construction (Group) Corporation. The overburden soil of the stormwater pipe was around 2.6m which was less than two times of the pipe diameter (1800mm) necessary to utilize the soil arching effect according to normal practice. Further, among other underground utilities, there were a 750mm diameter mild steel (MS) freshwater trunk main and a 450mm diameter asbestos cement (AC) saltwater main. The latter was laid in 1970s particularly attracted concerns because it was brittle. It was found only 890mm above the external circumference of the proposed jacking pipe. See Figure 1.

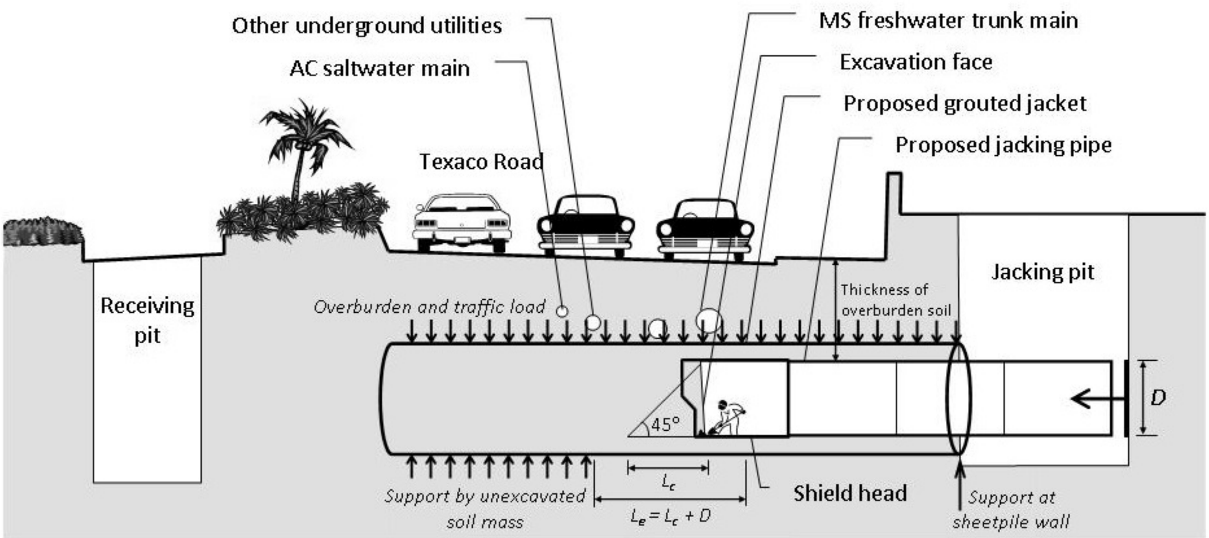

Figure 1 Longitudinal profile of Texaco Road and effective span of the grouted jacket

Texaco Road is a district distributor which connects Tsuen Kam Interchange in the north and Tsuen Tsing Interchange in the south. The upstream stage of pipe jacking would cover three lanes of Texaco Road, including the southbound slow lane, southbound fast lane, and a northbound lane to Tai Wo Hau Road, and finally reached the planter in the middle of the road under the Texaco Road Flyover.

The proposed 1800mm diameter pipe jacking works across Texaco Road have to be laid by two stages. The downstream stage of 36.7m long was completed first as it was more straightforward relatively. The upstream stage of 23.2m long, which would be completed thereafter, would be in close proximity to the water mains.

Both the water mains were critical supply mains to Tsing Yi and Kwai Chung South districts. Among them, the AC water main was more critical. It was durable in withstanding internal water pressure, but relatively brittle and weaker than the MS water main in withstanding excessive external load or pressure. Although use of AC pipe for both new works and maintenance works has been discontinued for many years, but still there are plenty of such pipes in the existing water supply system in Hong Kong **[10]**. Its normal operation pressure was around 10 bars. Since AC material has a tendency to burst abruptly when damaged instead of gradual breaking when compared with other pipe materials, risk assessment indicated that if the subject AC water main bursts, water could burst out from the pipe at a speed of around $1m^3/s$ resulting considerable ground subsidence and imposing immediate danger to the workers working under the jacking shield head as well as to the motorists and pedestrians.

This paper discusses how this difficult situation was overcome with the satisfaction of the stakeholders including maintenance authority of the watermains, i.e. Water Supplies Department (WSD) of the Government of Hong Kong SAR.

2. SITE CONDITIONS

2.1 Exposure of underground utilities

When designing the pipe jacking works, the depth and alignment of the utilities under Texaco Road had been reviewed by record drawings from utility undertakings, Ground Penetrating Radar (GPR) detection and trial pit excavations as well as in the utilities co-ordination meetings.

The locations of the water mains were ascertained by few trial pit excavations. The freshwater main was found to be around 2.1m below the southbound slow lane of Texaco Road while the AC water main was around 1.8m below the southbound fast lane. In the longitudinal section, they were at around 7.5m and 12m respectively from the upstream end of the 23.2m long jacking pipe.

2.2 Geological formation under Texaco Road

From previous ground investigations, the geological formation under Texaco Road was underlain by a 4.5m to 8.4m thick Fill layer. Beneath the Fill was a 1.5m to 4.8m thick Completely to Highly Decomposed Granodiorite over bedrock. The proposed pipe jacking works, around 4m below ground, would be completely within the Fill layer.

A horizontal borehole was drilled in May 2008 along the centerline of the upstream pipe jacking alignment. The total 18.9m of drilling was entirely within the Fill stratum which was described as "slightly sandy SILT / silty SAND with gravel / sandy GRAVEL / COBBLE with gravel". No groundwater was encountered during the whole drilling process despite it was in the rainy season.

Aerial photograph interpretation showed that the areas around Texaco Road was within the original coastal boundary of Tsuen Wan and was not reclaimed from sea. The Fill material was most possibly deposited to form the required level for development.

Characteristics of Fill such as colour, compactness, consistency and grain size can vary over a very wide range, dependent mainly on the origin of the material, and the methods of placement and compaction **[4].** The water content of the Fill excavated upstream and downstream of the Texaco Road pipe jacking works varied from 9% to 23%, and therefore the porosity (n) might be assumed to be ranged from 35% to 42%.

3. DESIGN CONCEPT

3.1 The adopted pipe jacking method

The open shield method was adopted for the pipe jacking works after consideration of its short length and large diameter. Unlike the publicly known tunnel boring machine (TBM) method, there would be no boring machine. Instead, manual workers were used to excavate the soil. A shield head which was a tubular steel structure with a diameter (slightly larger than the spigot of the proposed jacking pipe) would be used as an excavation chamber for the workers and a leading pipe for the jacking pipes to plug in and follow into the subsoil like a train.

For such a large diameter pipe, the space of the shield head was adequate to accommodate 3 workers concurrently working inside. After excavating about 100mm deep into the soil, the hydraulic jacks in the jacking pit would push the jacking pipes and the shield head into the recently formed space to prevent the soil from collapsing.

Given the large pipe diameter, the bare soil exposed inside the shield head would be around 2m high which was susceptible to collapse, particularly after heavy rainstorms and where groundwater level was high. From previous ground investigation, the groundwater level at Texaco Road was measured at around 0.7m to 2.4m below ground, or 2.9m to 4.6m above the jacking pipe. The actual water level was at around 1m above the jacking pipe. The major threat was the bursting of the AC water main before the shield head went pass it (after passing it, the shield head and jacking pipes would protect the work face from direct impact of the water flushing out). The water flushed out would likely liquefy the soil in front of the shield head causing a mud avalanche towards the pipe bore which would be extremely dangerous.

On the other hand, the shield head was not jacked into the soil but was pushed into the space just excavated by the workers; this would make it easier to control the alignment and reduce the pressure acting on the jacking pipe. The space was a bit larger than the external diameter of the shield head and the jacking pipe. Therefore, there would be slightly over-breaking around the circumference of the jacking pipe, allowing a space for re-structuring of the overburden soil and settlement.

3.2 Prediction of settlement of the pipe jacking works

Pipe jacking in soft ground inevitably would cause ground movements. The smaller the over-breaking, the lesser the magnitude of settlement would be. A straight as-built alignment of the jacking pipe could help reducing over-breaking.

Prediction of settlement was carried out in the design stage by following the relationship recommended by Mair et al. **[6]**. They demonstrated that the settlement profile would be in the form of a trough (Gaussian distribution curve) along the centerline of the pipe jacking alignment.

Normal pipe jacking operation relies on the arch effect of the soil strata above the excavated soil. In order to allow the arch to be completely and securely formed, the depth of soil cover normally has to exceed 2 times the diameter of the jacking pipe (*D*). 3 times the *D* is preferred. In the case of pipe jacking crossing Texaco Road, the depth of overburden soil was only 2.6m or 1.4*D*, less than 2*D*. It would not enjoy the benefit of the arch effect and would be subject to almost full overburden pressure, probably wide trench condition, which would increase the friction between overburden soil and top of pipe, increase the risk of collapse of the excavation face in front of the shield head, and increase the deflection magnitude of the overburden soil during pipe jacking.

Further, the congested utilities, including the water mains, in the overburden soil were stretching across the "arch zone" in a direction perpendicular to the pipe alignment, which also prevented a full development of the arch effect. The utilities on the other hand would share part of the overburden load, though in a very small scale with respect to their small diameters.

Using a settlement model without arch effect, the prediction showed that the maximum settlement was 16mm along the centerline of the jacking pipe and would gradually reduce to 0mm at around 4m from the centerline. This prediction was considered as within the normal acceptable range of open shield pipe jacking. However, considering the nature of the AC water main, WSD was concerned by their experience that any movement would cause it suddenly burst without warning. According to current standard of Highways Department **[5],** any trenchless works should not cause road settlement greater than 12mm over every 10m, but this tolerance might be reduced subject to existence of any vulnerable structures nearby. By this ratio, the upper limit for this 23.2m long upstream pipe jacking works was 28mm.

While it was impractical for the pipe jacking works to target for zero settlement, it was also impractical to assume any settlement tolerance that the AC water main could sustain as it would be subject to the degree of deterioration of the AC material, ground conditions, moisture content, and previous movement / settlement.

In order to protect the water main from disturbance by soil movement, and thereby protect it from bursting and endangering the safety of the labourers working inside the shield head, the project team came up with a schematic proposal to construct a roofing between the AC water main and the jacking pipe. It was aimed to confine the soil movement induced by the pipe jacking operation below the roofing and therefore virtually allow the AC water main undisturbed.

3.3 *Behavior of the grouted jacket*

After further studies, the roofing concept was intensified to a tubular hollow section which could entirely wrap up the jacking pipe. It was named as the "grouted jacket". In addition to the above advantages, the jacket could also reduce seepage of groundwater into the pipe bore during pipe jacking works and further reduce the magnitude of settlement.

The grouted jacket was assumed to behave globally as a hollow tubular section supporting the overburden with minimum settlement like a beam, and at the same time the supports on both sides would behave as a rigid hollow tube that would prevent the collapse of the tubular section along the excavated portion during pipe jacking.

When considering the hollow tubular section as a beam, the composite action of the grouted jacket would be spanning between supports on two sides, with effective span (L_e) supporting the design loading, see Figure 1.

The upstream support was the unexcavated portion of the grouted jacket which was assumed to be naturally supported while the installed pipeline was assumed to provide rigid support to the excavated but unsupported section. Borrowing the idea of reinforced concrete beam design, the effective span L_e = clear span L_c + effective depth D **[7]**.

The obvious critical modes of failure would be bending and shear. Bending failure was assumed to be resisted by composite action of the steel tubular section and the grouted soil, see Figure 2.

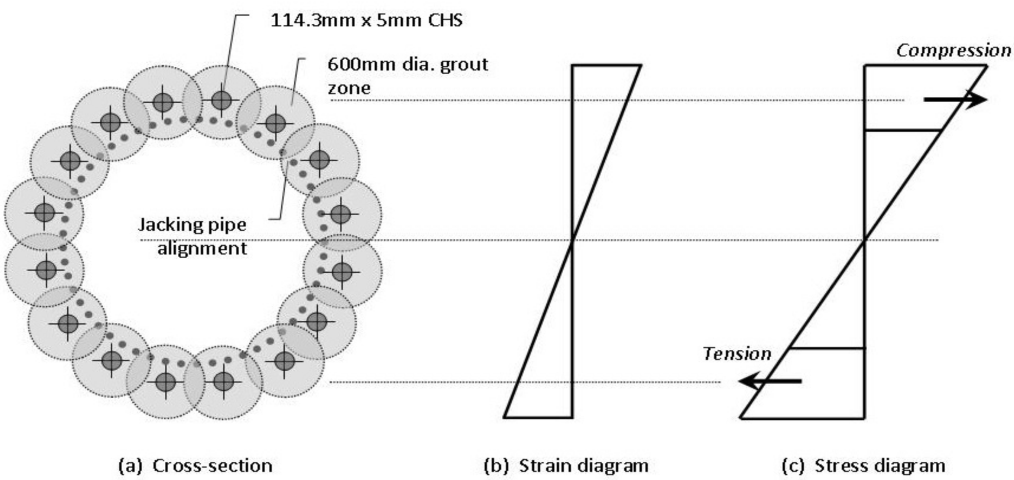

Figure 2 Structural arrangement and effective span

It was assumed that the grouted soil would provide adequate bonding to the sleeve grout pipe so that composite action would take place, further test was recommended to justify the design parameters.

When considering the support at the rigid hollow tube section, the rigid hollow section would behave as a circular ring, subject to external pressure, there would be circumferential compression and some circumferential bending.

The unfactored design loads consisted of overburden pressure, live load and traffic load, which gave a total factored force of 255kN/m acting on the hollow section. The grouted jacket was assumed to act as a reinforced cement-soil tubular hollow section resisting the load in three modes as follow:

(i) circumferential compression as a cement-soil pipe,
(ii) longitudinal load as a hollow tubular structure, supported between the frame at jacking pit and soil under the other end,
(iii) local flexural failure of the reinforcing CHS, supported between the shield head and unexcavated grouted soil mass.

From the design, the grouted jacket consisted of a densely grouted cement-soil ring of minimum 600mm thick surrounding the jacking pipe with 16 nos. 114.3mm × 5mm thick circular hollow sections (CHS) as reinforcement evenly distributed along the circumference of a 2765mm diameter circle. The length of grouted jacket should be at least 4m beyond the position of the AC water main in order to strengthen the soil strata and enhance the arch effect during pipe jacking, thus reduce the risk of settlement and failure of the AC water main.

Though the grouted jacket was assumed to behave as a hollow tubular structure, the effectiveness of the grouted cement-soil pipe structure depends on:

(i) behavior of grouted soil,
(ii) quality control and testing data of grouted cement-soil is available,
(iii) tolerance of grout tube, thus the alignment of the grouted jacket and its reinforcing CHS.

A complete grouting of the pipe bore inside the grouted jacket (commonly called advance grouting in pipe jacking works) was proposed as a redundancy to safeguard collapse of the road section.

3.4 *Cement grout mix*

Grouting has been frequently used as a means of improving the ground for constructional purposes, either temporarily or permanently. By injection into the ground, it improves the soil properties in terms of strength and permeability while bringing minimum disturbance to the insitu soil, adjacent structures and inconvenience to the public.

Xanthakos et al. **[11]** identified four typical categories of soil grouting: hydrofracture, compaction, permeation and jet. The first three are illustrated in Figure 3. Jet grouting is not shown as it is not applicable to this case.

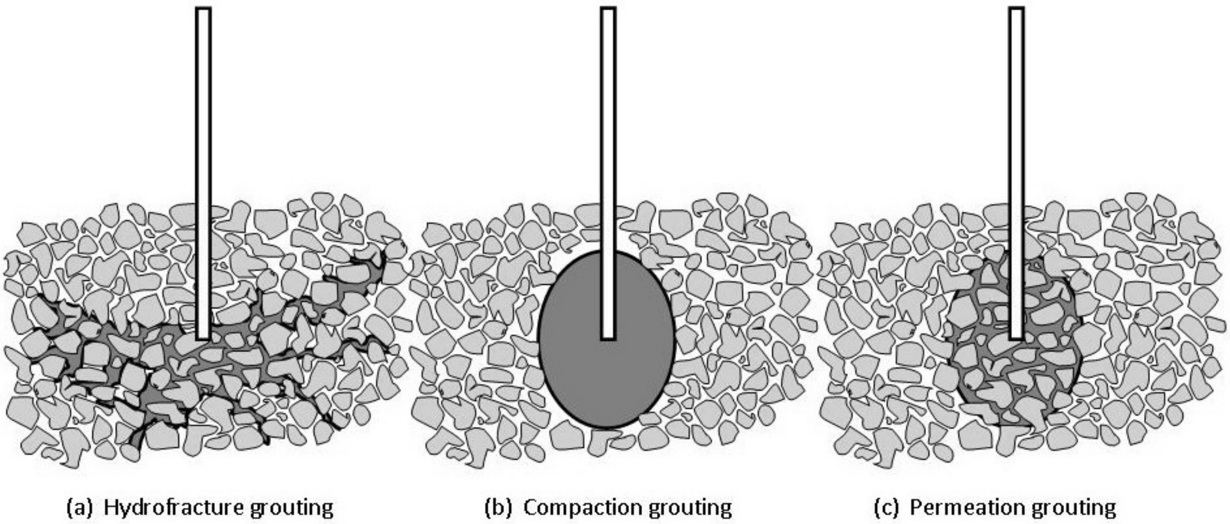

Figure 3 Typical categories of soil grouting **[12]**

In permeable grouting, grout is introduced into the soil pores under a low pressure (say 1 to 2 bars) without any essential change in the original soil volume and structure. It is therefore adopted for the grouted jacket.

The ingredients of the grout or the grout mix had to be designed such that it could form the cement-soil ring of the grouted jacket inside the soil of Texaco Road according to the proposed distribution. It is the normal practice for the specialist sub-contractor to propose in order to suit their plant, equipment and operation. The Engineer will provide a performance specification for the grouting according to the design.

Cement grouts are formed basically from ordinary Portland cement (OPC) and water, with or without additives. Raffle et al. **[9]** developed an expression which relates the characteristics of grouts with their capacity to permeate soil. From the design, a grout mix with water/cement ratio equaled to 0.5 was proposed to be injected into the soil through a 1.71m to 1.82m equilateral spacing of holes. This was achieved by 16 nos. of holes along a 2765mm diameter circle wrapping the jacking pipe, giving a spacing of 543mm.

Additives may be added to improve the characteristic of a grout. Grout with sodium silicate (commonly known as LW grout) has the characteristics of better penetration under low pressure and controllable gel time. The LW grout would quite easily hydro-fracture the loose fill material to form a seam of hard grout and at the same time consolidate the adjacent soil by compression **[8].** It is comparatively impermeable, but its mechanical strength was not as high as the traditional cement grout. Thus it might be used for grouting the pipe bore inside the grouted jacket (advance grouting) since the soil inside the pipe bore would soon be excavated so as to ease the worker's task.

3.5 Method of permeation grouting

The most economical means of grout injection for shallow depth is through the driven lance, inserted into the ground by hammer or pneumatic hammer and extracted by jacking **[3].** However, penetration of the driven lance becomes increasingly difficult beyond 10m to 12m, depending on the soil conditions, and at these depths the tendency of the lance to wander off course will increase.

Since the grouted jacket would be 18m long, the sleeve grout tube (Tube-A-Manchette, TAM) method was more preferred than the driven lance. The TAM method features the use of a grout tube with groups of grout holes drilled at regular intervals along its length, protected by rubber sleeves (i.e. the Manchette). The casing will be retrieved and sleeve grout (a weak clay-rich grout mix) will be injected to temporarily support the hole before the perforated grout tube is inserted for grouting **[2].**

In order to minimize disturbance to the soil mass and avoid the risk of hole collapse during construction of the grouted jacket, the Engineer decided that withdrawal of the casing was not preferred. The CHS was therefore modified to act as a permanent casing and a structural framework of the grouted jacket as well as a grout tube. The rubber sleeves were still installed to prevent soil from blocking the grout holes during installation.
With pressure, the grout would force the rubber sleeves open and exit into the surrounding ground directly with no sleeve grout to pass through. Upon cessation of grouting, the sleeve would re-close and prevent ingress of injected grout.

3.6 Method of drilling to bring in the grout tube

In order to bring in the CHS into the soil under Texaco Road, the overburden drilling with eccentric bit (ODEX) method was specified by the Engineer. This method was characterized by its eccentric reamer which could swing out and ream the pilot-hole wide enough for the casing to slide in the hole. See Figure 4. In step 1, when drilling starts, the ODEX reamer swings out and reams the pilot hole wide enough for the CHS grout pipe to slide deep behind the drill bit assembly. In step 2, when the required depth is reached, rotation is reversed carefully, whereupon the reamer swings in, allowing the drill bit assembly to be pulled out through the CHS grout pipe. In step 3, the CHS grout pipe which will be left in the drill hole is then used for grouting its circumferential soils.

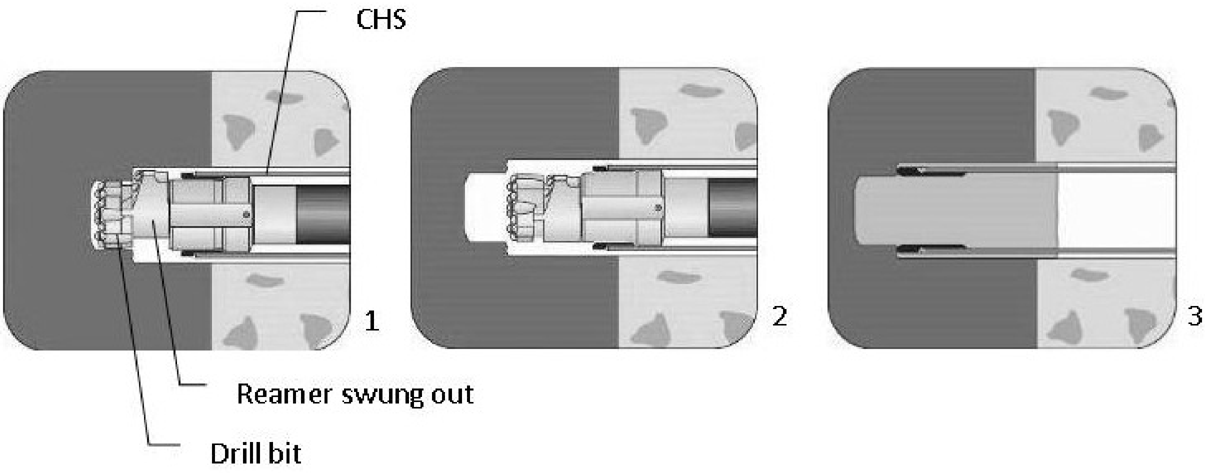

Figure 4 Drilling sequence of ODEX method **[1]**

The ODEX method provided an advantage of carrying the CHS to position as a permanent casing because it could completely retrieve the drill bit. In traditional rotary drilling, the drill head could not be swung into a size small enough to be pulled out through the casing or large enough to drill a path for the casing. As such, a circular bit had to be installed in the front end of the casing such that it could drill a circumferential path for itself. The circular bit was pretty expensive if it was to be retained and sacrificed with a permanent casing. By using permanent casings, there was no chance of hole collapse. The size of the ODEX hammer was manufactured according to the commercially available steel tubes used for the casing. It would fit into the proposed CHS size.

4. OTHER PROTECTIVE MEASURES OF THE WATER MAINS

In addition to the grouted jacket, following supplementary precautionary measures were also proposed:

1. set up check points to monitor ground movement;
2. lower the jacking pipe away from the AC water main without lowering the invert levels;
3. reduce the flow in the AC water main and monitor its condition regularly;
4. close attention to monitor the underground utilities by relevant utility undertakings;
5. provide contingency plans for WSD, Police Force and Transport Department (TD); and
6. complete grouting of the pipe bore inside the grouted jacket (advance grouting) by using LW grout before pipe jacking.

4.1 Movement monitoring

The most ideal and effective way to monitor the settlement was to install monitoring check points in a small interval along the centerline of the pipe jacking alignment where the settlement would be maximum (Gaussian distribution). However, the traffic lane of Texaco Road was covered by bituminous material and heavily used by traffic. Any monitoring device installed on bituminous material would be moved by the bitumen which was subject to measurable plastic deformation caused by traffic. It would make the measurement of the device irrelevant. Further, monitoring and surveying in the middle of the heavy traffic lane would impose potential danger both to the Surveyor and traffic. In view of this, the settlement check points were installed on the pedestrian walkway and the planter, and around the jacking and receiving pits, which were equipped with a 100mm × 100mm pad rested on bare soil. A steel rod was intruded from the center of the pad to the ground surface for measurement. This could ensure that the ground soil movement instead of the road surfacing movement was measured.

4.2 Increasing the clearance between the AC water main and jacking pipe

Lowering the invert level of the proposed jacking pipe was restricted by the upstream and downstream conditions of the existing system. Simply lowering the invert level of this section of pipeline would mean storage of stagnant water in the pipe during the dry seasons. Since the stormwater drainage system was not a close system, and had openings in the gullies and manhole covers, mosquitoes were able to assess the water and breed.

In order to lower the soffit level without lowering the invert level and sacrificing the hydraulic capacity of the pipe or the flow area, the jacking pipe had to be expanded laterally to form a horse-shoe shape which was not readily available in the market.

A large 1950mm diameter pipe was proposed to replace the original 1800mm diameter pipe. The 1950mm diameter pipe would be jacked in a level 480mm lower than the original invert level. This would increase the clearance between the AC water main and the jacking pipe from 890mm to 1370mm. After filling the lower 480mm portion of the 1950mm diameter jacking pipe with concrete, the invert level would be flushed with its upstream and downstream pipes, and the upper portion would be the oval shape required to maintain the hydraulic capacity. While the height of the flow area was reduced from 1800mm to 1520mm, the width was increased from 1800mm to 2000mm which provided a slightly larger sectional area. The wetted perimeter was reduced in the process which together gave an overall better hydraulic performance.

4.3 Reducing the flow and monitoring of the AC water main

Inter-department liaison meetings were frequently held among DSD, the Engineer, the Contractor and WSD in order to come up with a practical and effective protection plan for the water main. After understanding the importance of the water main to the water supply system and its detrimental consequence in case of damage, all parties agreed that temporary reduction of the water flow inside the AC water main was necessary and preferable during the critical stage of pipe jacking. WSD would also monitor leakage in the AC water main by low frequency signal. Detectors were installed in the valve pits of the AC water main which would transmit the signal. The time taken for the leak sound to reach respective sensors was measured. Knowing the velocity of sound and distance between sensors, the leak position could be determined. The detectors would record the signal which could be transmitted to a receiver installed in a running vehicle for later analysis.

4.4 Contingency plans

The Contractor was required to prepare contingency Temporary Traffic Management Schemes (TTMS) for road closure in Texaco Road in case of pipe bursting. Three different scenarios including closure of a section of the southbound slow lane, entire closure of the southbound slow lane, and entire closure of both the southbound fast lane and slow lane were prepared. Temporary diversion of traffic and their impacts were illustrated on the drawings for discussion with the Police Force and TD. In case of emergency, the police would first arrive at the scene to manually divert the traffic according to the TTMS while WSD's term contractor would later set up the required traffic signals and directions for the temporary traffic diversion before replacing the damaged water main. TD would notify the public immediately about the temporary closes and alternative traffic routings.

5. CONSTRUCTION

5.1 Construction of the grouted jacket

The grouted jacket construction commenced on 20 August 2008 and completed on 4 October 2008. A total of 16 holes were drilled and grouted. The left hand side of the bottom two pairs of holes was numbered as DH-1, while the other holes were numbered from DH-2 to DH-16 in a clockwise sequence. See Figure 5.

Each hole would be grouted before another hole was drilled. The sequence of drilling was so arranged such that drilling would not be carried out in the vicinity of a recently grouted hole to allow adequate curing time for the grout before disturbance. Further, the grout has a tendency to go upwards after leaving the grout tube due to dispersion towards space with less overburden pressure. The drilling sequence was also arranged such that the bottom holes were drilled and grouted before the top holes. This bottom-to-top sequence could also provide a better support to the holes above as the lower holes which had a larger overburden thickness were grouted and strengthened.

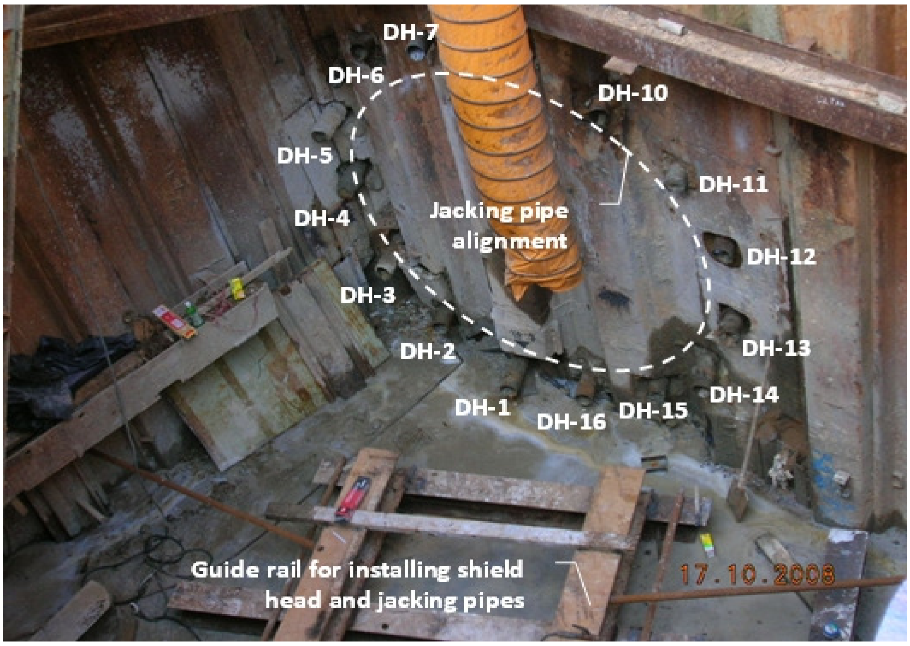

Figure 5 Completion of the grouted jacket (DH-8 and DH-9 were behind the vent pipe)

Joining of the CHS was carried out on site by butt welding. The level and alignment of the connecting casing was surveyed before and after welding to ensure that it was in line with its precedent casing. Whether the precedent CHS would be drilled correctly was largely controlled by the Fill mass under Texaco Road. Gravels and cobbles were extracted from previous ground investigating borehole in the Fill. They might deviate the drilling alignment extensively. Although the Engineer's specification allowed a tolerance of ±2° to ensure no penetration into the AC water main would occur, fortunately no deviation was recorded after completion of the 16 holes.

The grout mix was designed on site by the specialist sub-contractor according to the soil properties. It was an empirical art based on the specialist's experience. The Engineer specified that the grout mix had to produce a crushing strength of 25MPa at 28 days. After several trial mixes, the adopted grout mix included 180kg cement with 90kg of water and no admixture. The water cement ratio was 0.5.

Since the grouting application for the grouted jacket would be carried out at a minimum depth of around 2m below ground, close monitoring and execution of the grouted pressure was required by following the criteria below:

1. cease grouting if grout pressure was greater than the overburden pressure;
2. cease grouting if grout volume exceeded 200 litres per liner metre, or significant vertical deformation was observed.

The overburden pressure of each hole varied due to their different depth underground. To achieve permeation grouting, the grout pressure had to be large enough to inject the grout into the voids of the soil mass far enough to achieve the 600mm diameter cement-soil zone, but could not mobilize or deform the soil mass as well as the underground utilities inside and the carriageway on top. The applied grout pressure ranged from 0.2 bar in hole no. DH-8 and DH-9 to 1 bar in hole no. DH1 and DH-16.

Since the porosity of the Fill material under Texaco Road was from 35% to 42%, this gave an air content of 7% to 19%. The expected grout volume was from 350 litres to 980 litres, which matched with the actual grout volume ranged from 304 litres to 760 litres.

Average construction period for each hole including construction of working platform, installation of drilling machine on the platform, drilling, grouting and removal of drilling machine and working platform took an average of around 2.1 days per hole.

5.2 *Pipe jacking operation*

After removal of the working platform and ODEX drilling rig used in the construction of the grouted jacket, the Contractor installed the jacking apparatus including the guide rails, jacks, etc., and commenced the jacking operation on 22 October 2008 by carrying out the 1st stage of advance grouting.

After temporarily strengthening the soil by LW grout to prevent it from sudden collapse, the shield head was laid onto the guide rail in the jacking pit, and jacked to touch the opening. Labours entered the shield head and began the excavation process.

The pipe would be jacked 6m before another stage of grouting was carried out to ensure that all excavations were within the grouted soil. Therefore, for a 23.2m long pipe jacking works, a total of 4 stages of advance grouting were carried out. The rate of pipe jacking was shown in Figure 6 below. Due to the accurate installation of the CHS of the grouted jacket, the shield head never ran into any CHS.

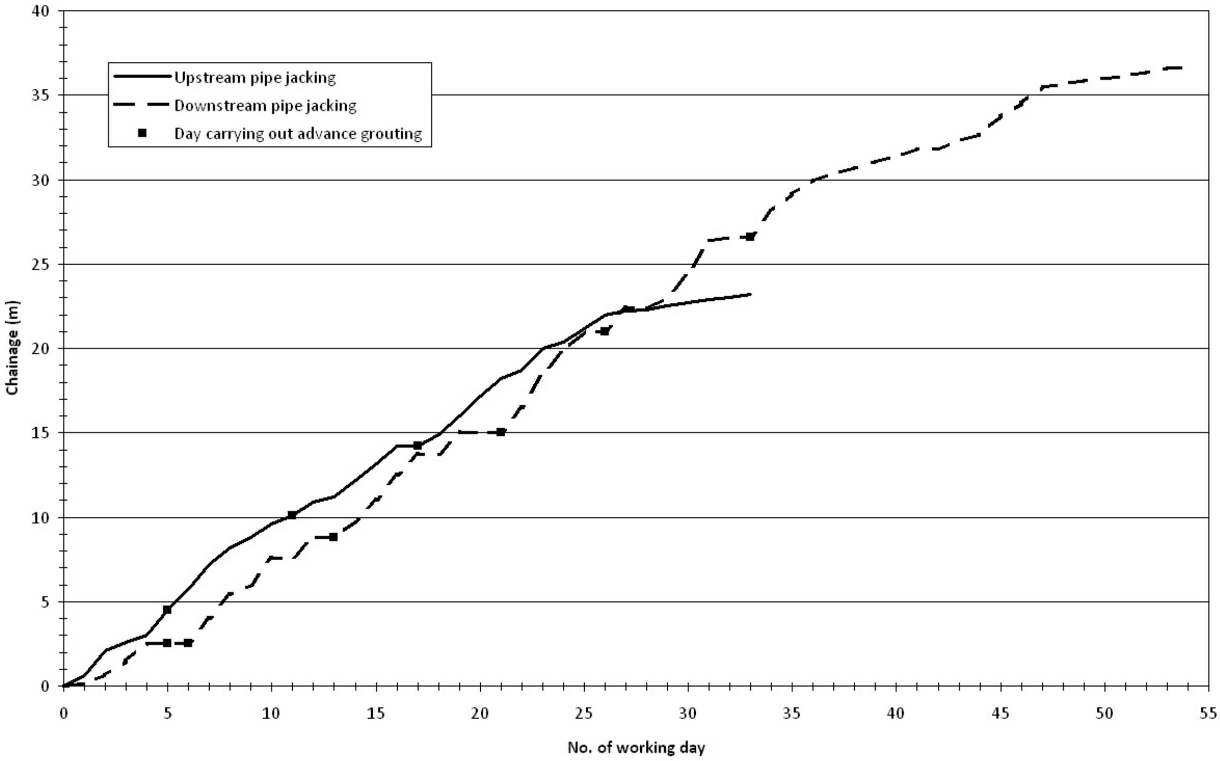

Figure 6 Rate of pipe jacking

After the shield head was completely removed, and the precast jacking pipes reached the downstream manhole, grout was injected into the over-break ring around the jacking pipe through the two grout holes precast on each of the jacking pipes. Assuming that there was no leakage of grout as adjacent soil had been fully grouted during the grouted jacket and advance grouting, the over-break circle was only 17mm thick by back calculation, comparing with the 29mm in the downstream pipe jacking works across Texaco Road.

6. MONITORING AND PERFORMANCE

The 15mm settlement tolerance of the grouted jacket construction and the subsequent pipe jacking operation was prepared by making reference to the predicted settlement in the design stage.

The grouted jacket construction was commenced on 20 August 2008. A settlement check point SM3A on the footpath near the jacking pit soon recorded substantial settlement, which eventually reached 13mm when the grouted jacket was completely constructed on 4 October 2008. Another check point SM2A adjacent to SM3A also recorded maximum 8mm settlement. The other markers recorded negligible settlements. See Figure 7.

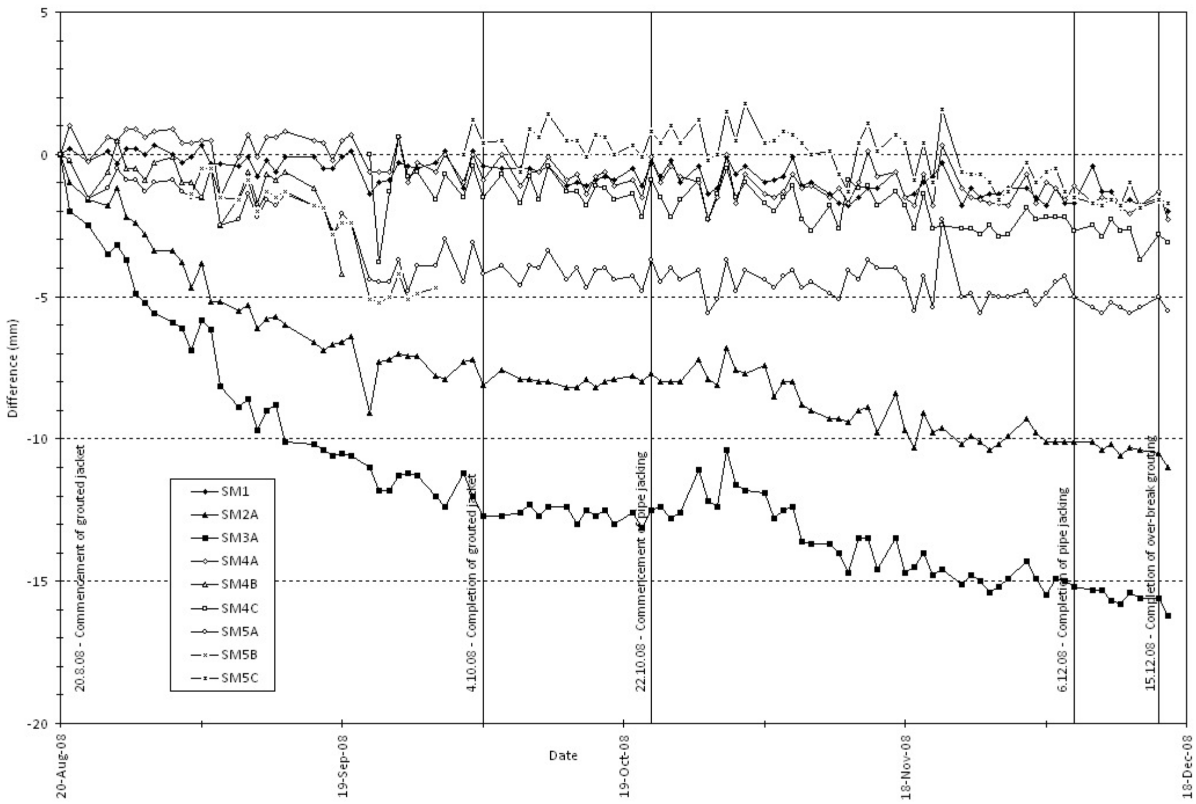

Figure 7 Settlement due to construction of the grouted jacket and pipe jacking operation

The noticeable settlement was investigated before commencement of the pipe jacking works. Since no settlement was visually observed on the concrete kerb line and bituminous road surfacing, it was deduced with confidence that the settlement recorded was a local one restricted near the jacking pit and had not extended to the carriageway nor the AC water main.

The footpath where the check points SM2A and SM3A were located was covered by light duty bricks. A crater-like settlement of the bricks around the check points and a slight tilting parallel to the face of the adjacent 2m high concrete partition wall were observed. It was suspected that there was localized loss of underground soil near the jacking pit, probably brought into the jacking pit by groundwater through the local gaps in the sheet pile wall. This was later confirmed when the jacking pit was backfilled and the sheet pile wall removed. A cavity of around $1m^3$ was found under the concrete cover behind the top end of the sheet pile wall.

The pipe jacking operation commenced on 22 October 2008 and was completed on 6 December 2008, following by the completion of over-break grouting on 15 December 2008. Not more than 4mm settlement was recorded in all settlement check points during the whole process. WSD also reported that no leakage was observed by their regular monitoring using low frequency signal. The flow of the AC water main was turned back to normal operation volume in March 2009.

Due to adopted grouted jacket and advance grouting, groundwater was blocked outside the grouted jacket and the open end of the shield head. The amount of water seeping into the pipe bore was negligible.

7. DISCUSSIONS

As the overburden soil strata above the pipe jacket was occupied by congested utilities, the concept of arch effect over the jacking pipe would be less dominant, while the overburden loading would be acting on the utility lying perpendicular to the jacking pipe alignment or the grouted jacket which was parallel to the pipe alignment. Comparing the stiffness of individual utilities and that of the grouted jacket, which was much higher, it was likely that the vertical loads were resisted by the grouted jacket as a hollow tubular section. The insignificant settlement favored this theory.

The project in overall was a success with the jacking pipe substantially completed on time without any damage to the adjacent underground utilities.

Considering that the downstream pipe jacking works was also within the same Fill strata of Texaco Road, it may be used as a control for the assessment on the effect and performance of the grouted jacket. The rate of the upstream pipe jacking works which was 0.70m / working day was slightly faster than the downstream pipe jacking works which was 0.67m / working day due to lack of groundwater ingress.

The volume of over-break grouting in the upstream pipe jacking works was also substantially less than the downstream pipe jacking works, proving that over-breaking (one of the causes of settlement) was reduced due to the soil was strengthened and compacted.

The predicted settlement for both upstream and downstream pipe jacking works was 16mm, which was less than the 28mm and 44mm allowable by the current standard of Highways Department. The actual maximum settlement was only 6mm (2mm by grouted jacket plus 4mm by pipe jacking operation) for the upstream pipe jacking works and 10mm for the downstream one.

The grouted jacket is used by DSD for the first time in the drainage improvement works to overcome the congested underground problem, it is opined that the technique can be further refined and improved in future project.

8. CONCLUSIONS

To facilitate the smooth delivery of trenchless construction for drainage improvement works in proximity of underground watermains, installation of grouted jacket in advance of the man-entry pipe jacking operation can be adopted in order to reduce the risk impact to the watermains and enhance the site safety.

Protection of adjacent delicate utilities can be done by minimizing the settlement induced by the pipe jacking operation. The conventional ways, such as preventing work face collapse by advance grouting and minimizing over-breaking, can in fact be supplemented by construction of a grouted jacket around the proposed pipe jacking alignment.

The grouted jacket has the merits of confining the ground movement induced by the pipe jacking operation within its circular body and therefore virtually isolates the utilities from the pipe jacking operation. It can also strengthen the surrounding soil and protect the workers working inside the pipe bore in case of water main bursting, as well as reducing groundwater seepage into the pipe bore.

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