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Implications of Micro-Tunnelling on Wastewater Pipeline Constructions

(A case study from Muscat Wastewater System: Al Khuwair Project)

Kokila Ranasinghe

Abstract: Al Khuwair is a sub city located in Muscat in the Sultanate of Oman. It is presently growing rapidly with illustrious highways, modern housing complexes, commercial centres, hospitals, schools etc., being built. Even though the local population represents around 60% of the total population, developing infrastructure is an essential need in order to cater to the needs of both the local and foreign migrant population and also the tourists. The present trend of development of the city indicates that Al Khuwair would provide a considerable proportion of the Muscat's wealth. The yellow tankers roaming around the city are not uncommon in AlKhuwair even though it might surprise the visitors at their first glance. They enter every house and restaurant at least once a month in order to empty the septic tanks of those properties. It is also not uncommon to see overflowing septic tanks emitting in tolerable odours when tankers fail to arrive promptly to empty the overflowing septic tanks. The aim of the paper is to present the actual experience from Muscat Waste water Project that has been implemented in order to overcome the above mentioned most critical issue. It highlights the problems which surfaced with regard to pipe deviations, deflections and pipe cracking that occurred during the micro tunnelling of 1000mm diameter polycrete wastewater pipes. The attempts made to provide technical solutions for the deficiencies and possible alternatives to overcome the defective situations are comprehensively discussed in the paper.

Keywords: micro-tunnelling, pipe alignment, polycrete pipes, deviation, deflection

1. Introduction

Horizontal Directional Drilling (HDD) and micro tunneling are two available "trenchless" construction methods used to install new pipelines and other facilities. HDD refers to a steerable system for the installation of pipes, conduits, and cables in a shallow arc using a drillrig at ground surface. Micro tunneling is a procedure that uses a remotely-controlled, tunnel boring machine with a relatively moderate diameter. One major advantage of trenchless pipeline construction is the freedom it provides to follow the most direct route between any two points provided the right-of way is available. Open-cut trench construction normally has to follow existing pipe utility easements, roadways or other unobstructed surface structures.

Because HDD and micro tunneling are applied underground, these methods allow flexibility to go straight between any two points, even when this route traverses directly beneath utilities, structures, or other surface features. Recent technological advances in HDD and micro tunneling equipment allow longer drives with greater accuracy, resulting in a reduction in both project costs and completion times. Equipment guidance systems that use gyros for steering can be used for curved drives to tunnel between inaccessible obstructions. The applicability of HDD or micro tunneling for pipeline construction is primarily a function of the required pipe size and material, alignment tolerances, ground conditions and available staging areas. The selection of an appropriate method depends on the site conditions and project priorities.

Trenchless methods can improve worker safety because the workers do not have to work in trenches as they do in the conventional cut-and-cover projects. Environmentally sensitive areas such as wetlands and streams can be bypassed underground with trenchless methods. In areas affected by soil or groundwater contamination, a low degree of excavation resulting from the use of trenchless methods as compared to cut-and cover trenching methods, also reduces public and worker exposure to potential contaminants. In addition, in congested urban areas, trenchless construction methods can save time compared to traditional cut-and-cover construction methods, and they can also

Late Eng. Kokila Ranasinghe, C. Eng., MIE(Sri Lanka), Prov. M. Eng. (APEGBC – Canada),M. Eng. , P.G. Dip – IT (Moratuwa), P.G. Dip – App. Sociology (Colombo).
The author was last attached to Engineering Consultants (Pvt) Ltd and was the Resident Engineer for Boursure 03 project under Associated Consulting Engineers (Intl.), Muscat, Sultanate of Oman. He also performed as the Municipal Water Project Manager, Kerr Wood Leidal Associates, Burnaby, BC, Canada and was at one time an Assistant General Manager of the NWSDB, Sri Lanka

facilitate construction in areas where cut-and-cover trenching may not be practical. All of these advantages can combine together to reduce project costs and risks.

2. Micro Tunnelling in Al Khuwair

A 1000mm diameter polycrete pipeline had to be constructed using micro tunnelling in Al Khuwair under the Muscat Wastewater Project. The Authorities implemented Borsure 03 Project component of the Muscat Wastewater Project to connect all premises of the sub city of Al Khuwair to a new sewer network from which the collected sewage was to be carried through a 1000mm diameter polycrete trunk main to the wastewater treatment plant at AlAnsab where it was to be treated under gravitational forces.

The design of the 1000mm diameter polycrete pipe was challenging due to lack of experience on the behavior of the pipe material and the remedies that could be implemented to repair the pipes in case of a failure during infiltration and exfiltration tests and if cracks appear in pipes while they are being driven. Even though polycrete pipes have been used in the wastewater industry during last 15 years, there is not much information available on record to indicate its performance during micro tunneling. The polycrete material is made of polymer concrete. The advantages of polymer concrete include its high compressive strength which allows for a high jacking force and ensures maximum safety, a GRP joint collar for maximum safety during jacking, a smooth outer pipe surface which reduces friction resulting in lower jacking forces, parallel pipe ends providing uniform distribution of jacking forces, highly accurate dimensions avoiding ovality or tight joints and providing perfect matching, elasticity, reduced point loading and risk of rupture, low weight which allows ease of installation, adaptable dimensions making it suitable for all micro-tunneling and jacking equipment, smooth and even inner surface allowing a high flow rate, high corrosion resistance providing reliability throughout the long service life; and the availability of complete systems for jacking pipes, open cut pipes and manholes.

3. Sewer design considerations for micro-tunnelling

In a sewer network, it is usual to lay trunk mains deep in the ground because of the gravitational hydraulic flows of the branch sewer network. The micro tunnelling section of the 1000mm diameter polycrete trunk sewer in Al Khuwair had to be laid in a low lying valley at a depth of 9m to 20m. The top of the ground water table was at a depth of 12m from the identified ground level.

The design considerations for micro tunnelling are given below:

- **Geotechnical Investigations**: This is required to identify the type/nature of sub soil strata across which the pipes have to be driven using micro-tunnelling and to estimate the overburden soil pressure
- **Ground Water Table:** This is required to identify, from what depth the dewatering has to be introduced.
- **Location of the Entry and exit points :** This is to ensure that adequate provision/space is available to erect entry/exist shafts, or construct a pit with sheet piling to position the micro-tunnelling or pipe jacking machine facilitating tunnelling or jacking
- **Clearance from existing utility service providers:** This needs to be obtained before the design is finalized to ensure smooth operation. The pipe to be driven should be kept away from the specified distances from the existing underground utilities or should be provided encasements as required.
- **Assessment on the type of Micro tunnelling (MT)/Pipe jacking (PJ) machines to be used:** The capacities of the MT and PJ machines are estimated based on the sub soil characteristics, diameter of the pipe to be driven and the type of pipe to be tunnelled or jacked.
- **Pipe material**: The type of the pipe to be tunnelled is selected based on sub soil properties, length of drive, compressive strength of pipe material, and tendency to deform.

Considering the above, concrete shafts were introduced in Al Khuwair for pipe entry and exist. Figure 1 shows how micro tunnelling machine reaches the exit shaft of the Al Khuwair 1000mm diameter main trunk sewer.

Figure 1 - Micro tunnelling machine emerging from the exit shaft

3.1 Hydraulic design criteria:

According to the standard design manual, tunnelling for wastewater pipes is governed by the design criteria given in Table 1.

Table 01 - Design criteria for micro tunnelling / Pipe Jacking

Design Criteria	Limits
Normal depth of micro tunnelling and pipe jacking	6m to 30m, considering building foundations and other services
Minimum cleansing velocity at peak flow excluding storage	1.0 m/sec
Maximum flow velocity in the pipe at peak flow	3.0 m/sec
Depth of flow at peak flow	Flowing full
Normal range of micro tunnelling / pipe jacking Diameter	Outer dia. (O.D) = 500mm to 2700mm Int. Dia. (I.D) = 300m – 2400mm
Minimum tunnel gradient	To provide 1.0 m/sec flowing full at peak flow
Acceptable pipe material for micro tunnelling / Pipe jacking	200mm – 800mm dia. Extra Strength verified clay pipe Polymer Concrete pipe (800mm – 1800mm dia.) GRP lined Concrete pipes PVC lined Concrete pipes HDPE lined concrete pipes
Minimum vertical clearance for utility crossing	300mm
Minimum distance between shafts for micro tunnelling / pipe Jacking	100m
Variation from line and grade Micro tunnelling / Pipe jacking (Entire alignment at entrance and exit shafts)	+/- 300mm
Vertical tolerances (Micro tunnelling pipe jacking)	+/- 25mm

3.2 Selection of the pipe size and material for micro tunnelling in Al Khuwair:

Several options were available for Design Engineers to decide on the pipe diameter and the material based on the above mentioned design considerations and criteria. There was a long time period available to complete the design and the upsizing of the pipes from time to time had to be minimised and due consideration had to be given to the potential increase in the loading.

Estimation of pipe size:

The pipe size was estimated based on loading calculations and peak flow assessment for the specified design requirements of the project. To be in accordance with the design manual, the estimation of the flow rates was based on both the population and average rate of flow per capita, or for new developments by multiplying the number of dwellings by the anticipated occupancy rate. The Wastewater Design Engineers usually worry on the septicity that could develop in the sewers especially in hot climates that prevail in the gulf region. It is observed that because of the hot climate, sewage lacking in re-aeration has the potential to turn septic fast.

The estimation of peak flows for determining average system hydraulic capacity needs to consider the degree of development of the design area.

The Design Manual recommends to consider three scenarios in finalizing the design flow and the size of the pipes as highlighted below:

- For fully developed areas, peak maximum flow shall include both sewage and infiltrations/inflows
- In undeveloped areas, where infiltration and inflow can be controlled, Merrimack formula could be used to determine the peak flow
- For small catchments with less than 5-100 properties the peaking factor shall be taken as 4-5

The Merrimack Formula is expressed as:

$\mathbf{Q_{pdf} = 2.65 \times Q_{adf}^{0.087}}$

Where Q_{pdf} = Peak Daily Flow - ML/Day

Q_{adf}= Average Daily Flow - ML/Day

To determine the sizes of the sewerage network pipes and their slopes, two more equations are recommended in the design code of practice. i.e Colebrook – White and Manning's equations.

Colebrook – White Equation is expressed as:

$$V = 2(2gDS)^{1/2}\log [K_s/3.7D+2.51v / D(2gDS)^{1/2}]$$

Manning's equation is expressed as :

$$V = (1/n)\, R^{2/3} S^{1/2}$$

Where, V = Velocity in m/Sec
D = Diameter of pipe (mm)
S = Hydraulic Gradient (m/m)
K_s= Equivalent roughness
v = Kinematic viscosity m^2/s
g = Acceleration of gravity(m/s/s)
n = Manning' friction coefficient
R = Hydraulic Radius (m)

In accordance with the Design Manual, the minimum sewer diameter is taken as 200mm and the governing slopes depending on the diameters and flow conditions will vary as indicated below:

Table 02 -Slopes of sewers depend on pipe diameters and flow conditions(50% and 65% full)

Pipe Dia. mm	Slope	$V_{0.5}$	$V_{0.65}$
200	5.00 mm/m		0.79
250	3.70 mm/m		0.79
300	2.90 mm/m		0.79
350	2.40 mm/m		0.79
400	2.05 mm/m	0.75	
500	1.54 mm/m	0.75	
600	1.20 mm/m	0.75	
800	0.82 mm/m	0.75	

The Wastewater Manual also states that for sewers greater than 1000mm in diameter, the flow velocity at peak flow should be 1 m/s.

Al Khuwair is reasonably developed having a number of urban features. The system had to provide provisions for large scale future development of mostly non-residential and commercial entities where wastewater generation would be relatively high. Giving due consideration to the potential development related projects in the future and the design flow calculations and complying with all the above mentioned requirements, the diameter of the main trunk sewer was selected as1000mm.

Selection of pipe material:

There were several options available for the Design Engineers to select the micro tunnelling pipe material. The main concern was the strength and the durability of the pipe and its compressive strength against the jacking force and torque generated by the micro tunnelling machines in driving pipes. The Design Manual specifies following pipe types for micro tunnelling:

- Reinforced concrete pipes with GRP lining. The jacking pipe concrete has to comply with BS EN 206-1: 2000/BS 8500 and the GRP internal liner shall have a design life of 100 years when used for gravity flow applications.
- The sheet steel pipes welded in sections of 03-06 meter lengths and with corrosion protection lining
- Polymer concrete pipes (Polycrete pipes) and fittings. The standard specification for Polymer Concrete pipe is ASTM D 6783-02

From among the above mentioned options, polycrete pipes of 1000mm diameter were selected for micro tunnelling work of the Project based on the following:

- Being able to be driven straight in to and across the ground as a carrier pipe without requiring any sleeve pipes
- High compressive strength
- Being able to pass through natural hard soil formations
- Absence of ovality at pipe end
- Ease of handling because of the moderate weight.

- Highly corrosion resistant smooth inner surface that allows high flow rates
- Reduced point loading and reduced risk of rupture
- Adoptable detentions and availability of large diameter pipes

4. Site Investigations

Five bore holes were drilled in order to determine sub soil characteristics, top of the ground water table and soil bearing pressures at the depths where polycrete pipeline was to be laid. It was revealed that ground water table appeared at an average depth of 10m and the gravity trunk pipe therefore had to be laid at a depth of 9-13m along the pipe route. This required continuous dewatering from the entry shaft throughout the duration of micro tunnelling.

According to soil investigation results, the sand layers appeared at ground level in general with a layer of hard laterite soil underneath. There was evidence of boulders beneath the hard laterite soil layer. As there was hard soils at all of the proposed elevations of the pipeline soil conditions were found favourable for micro tunnelling. However, arrangements had to be made for continuous dewatering, for a pipe system that would remove crushing material when pipes were being driven, and the injection of sealant material to the annular space between the pipe and the ground during micro tunnelling. To make the operation easier and faster in the presence of hard soil and boulders, lubricant material had to be applied. The pipe arrangement for the exercise is illustrated in Figure 2.

Figure 2- Typical pipe arrangement at the driving end/shaft of micro tunnelling

5. Problems encountered when micro tunnelling 1000mm diameter Polycrete pipes

In micro tunnelling there are several important factors as indicated below to be focused on while maintaining accurate records:

- Pipe alignment through the laser beam
- Pipe elevation (using instrument height and plumb line)
- Pipe driving speed (length of drive over time)
- Control room pipe driving
- Smooth operation and continuity of driving

Irrespective of what precautions and monitoring mechanisms are in place, micro tunnelling is an exercise that cannot be inspected directly and which has to be supervised through mechanical means and remote control devices. Therefore deviations, deflections and pipe cracking could happen while driving the pipes. Pipe cracking is not allowed under code recommendations but limiting values have been specified for pipe deviations and deflections. The recommended limits are indicated in Table 1. According to this Table , the variation from line and grade Micro tunnelling / Pipe jacking (entire alignment at entrance and exit shafts) allows only +/- 300mm and allowable vertical tolerance (micro tunnelling pipe jacking) is only +/- 25mm.

5.1 Pipe deviation of Al Khuwair 1000mm gravity trunk main

In the Al Khuwair gravity main, the pipeline was observed to have deviated at two places exceeding the 300mm limit. The following Figure shows the deviation.

Figure 3 - Deviation of pipeline at AlKhuwair

As per the Contract, the pipeline was not allowed to deviate for more than 300mm horizontally between any two manholes. Even though the pipeline could not be accepted according to the Contract, the drive was done under continuous supervision. It was very clear that the pipeline had deviated at the tail end of the pipe section especially along the last 10m length out of a total micro tunnelling length of 88 m. Although the deviation was noticed in the control room the operating technician was confident that he could complete the drive not exceeding the tolerance specified for deviation. The Consultants to the Project who were responsible for the quality control of the construction did not accept the micro tunnelled pipe section. Technical investigation was carried out on the pipe deviation and the following conclusions were arrived at:

- The Contractor should have stopped the pipe driving soon after the deviation was observed without continuing any further, as it was not certain whether the drive could be completed complying with the allowable limit for deviation
- To introduce a new manhole at the point where deviation started and a new pipe length to be driven from that location.
- To reject the deviated length and to recommend no payments to the Contractor in respect of the deviated pipeline which was about 10m long.
- To accept the entire pipeline based on the requirement of the Client as there was no significant impact on system hydraulics and flow patterns and no possibility for increased infiltration as the joints were properly sealed.

It was also revealed from investigations that the above mentioned favourable conclusion in respect of the deviated section of the pipeline was possible because of the relatively large diameter and the fact that the deviated length was only 10m.

The Contractor was also requested to find out the reasons for the pipe deviation and his investigations had revealed the following:

- As a limited number of boreholes was done along the pipe route, data available was not sufficient to precisely decide on sub soil properties. It was reported that pipe deviation commenced in a region where soil properties have changed from boulders to soft soil
- The soil overburden pressure could have changed due to the presence of compacted soil layers on top of the existing utilities placed at lower elevations. It was noticed at the point of deviation of the 1000mm diameter trunk sewer, that there was a 33,000 KVA electrical cable surrounded with concrete at a lower level.
- The possible impact on deviation due to machine performance and pipe material discrepancies were ruled out by the Contractor as rest of the pipeline was micro tunnelled smoothly and it was believed that the problem was due to the specific conditions at the location.

5.2 Pipe cracking

Cracking of polycrete pipes was noticed at two locations during micro tunnelling. This was again a concern that required detailed investigations. It puzzled the Engineers as they had no previous experience of using polycrete pipes in micro tunnelling . Micro tunnelling of the Project was carried out using 2.0m polycrete pipe lengths. As the micro tunnelling machine proceeded towards the soil strata, 2.0m long polycrete pipes followed one after the other with rubber rings at the joints. A collar was introduced at the pipe joint to withstand the jacking force. The annular space created between the pipe's outer surface and the ground was grouted through a jetting arrangement so that as indicated in Figure 3 the laying of the pipe line could be completed in accordance with the designed elevation and alignment. The cracks that appeared in the micro tunnelled polycrete pipe section are shown in Figure 4 below.

Figure 4 - Cracking of polycrete pipes

This pipe cracking was found at a 13m distance from the ground level. The pipes were driven in accordance with the specified alignment maintaining accurate elevations for a 123m length, although pipes began to crack while being driven through one particular location. The soil condition at the location was found to be aggressive. Although nine of the pipes that cracked could be taken away from the receiving end four pipes still remained inside as shown in Figure 4. The cracked pipes that were removed were sent to the manufacture's laboratory to check their compressive strength and the pipe material was found to be defective. The pipes that were removed were replaced as much as possible although nothing could be done for the damaged pipes that remained underground. Studies were made to find out the causes for the pipe cracking and to find out a mechanism to repair the four damaged pipes that were stuck in the pipeline.

The Contractor's investigations revealed the following as factors that caused the pipes to crack:

- Point load caused by the uneven jacking force applied to the sewer by a defective hydraulic power pack. The specialized Subcontractor who tested the jacks confirmed that they were working properly at the time of their operation. The higher forces of the jacking station were not applied at the front of the tunnel. If it was the case, it would have been the pipes near the jacking rig that would have cracked.
- It was confirmed that during the drive there were issues with the speed control of the hydraulic system. These have been corrected after the completion of the drive. Even though jacking pressures in excess of 600 tons would have been exerted during the process, pipes were not damaged, as they were able to withstand pressures up to 800 tons.
- Stoppage due to cracked pipes and safety measures adopted making the soil on the top of the sewer to lock and thereby increasing the loadxfriction causing back pressure. The Subcontractor kept on injecting 12 tons of bentonite during to page of work although 2 to 3 tons were the norm for a 100 meter drive.
- Deviation in pipeline had caused the jacking force to increase continuously resulting in a point load. There had been deviations in the driven pipe line immediately after the cracking. This might have been caused by soil conditions or by pipe cracking. Being a single wallpipe it might not have allowed there distribution of the forces and would have given a lower steering tolerance to the machine.
- Polycrete pipe collar width might have been insufficient for the allowance on the tunnelling work in a situation where deviations have occurred. This might have caused a reduced face load contact generating a pressure exceeding the limit allowed.

- **The pipes had cracked under moderate pressure (300 tons) at a position where there had not been any cracks earlier. This had happened after the tunnel was completed and during the initial replacement of the nine of the cracked pipes. The soil condition and pressure at the location led to the belief that cracked pipes could have had hairline cracks before they were put to use.**

The rectification of the remaining damaged pipes of the trunk sewer was the major concern to make the trunk sewer acceptable.

5.3 Rectification of damaged pipes

Since the polycrete is a composite material with resin as a binder, repair of the defects either at the site or at the factory was possible.

Repairing procedure was as follows:

1. The location of the crack on the pipe was marked.
2. The surface of the marked area was grinded to a width of 150 mm.
3. Any dirt present in the grinded area was wiped off.
4. In a mixing bowl a sufficient amount of resin mix catalyzed with an appropriate curing agent was prepared and one coat of the paste was applied to the prepared area using a round profile brush.
5. The coat was allowed to seep through the crack until it started to gelfy. One more layer of resin mix was applied to make the coat approximately 20 micron thick and make it gelfy.
6. Polycrete motor was applied evenly on the crack using a putty pallet.
7. At least 20 minutes were allowed for the applied polycrete to cure.

The experience gained in AlKhuwair, clearly indicates the important areas that need to be focused on in the micro tunneling projects with special attention paid towards laying of wastewater pipelines. The construction difficulties faced in Al Khuwair highlight issues as indicated below that could be shared among wastewater design/construction engineers handling micro tunneling of sewers.:

- Soil Investigations: the Al Khuwair example clearly indicates that the main reason for pipe deviation was the lack of understanding on sub soil properties. It was realized that changes in sub soil properties from hard to soft had an impact on the pipe alignment during micro tunnelling. If the change in sub soil properties was known, then the driving torque that had to be provided could have been changed accordingly to suit soft soil conditions.
- Existing Utilities: When existing utilities were present at low elevations, disturbed soils and compacted soils on top had an impact on the micro tunnelling which had to be executed below those utility services.
- Impact of point loads:
  When point loads were generated on the pipe to be micro tunnelled, there was a tendency for the pipes to get damaged. Therefore the driving force had to be applied throughout the pipe circumference.

6. Basic Design Considerations for Polycrete pipes

Polycrete pipes for jacking are designed to resist all loads and damage from construction processes, including crushing of the material due to load transfer at the joint. The design shall be carried out using a design procedure commonly used in Europe and around the world, such as ATV rules and standards A 161: static calculation of driven pipes, DVGW Specification GW 312: Static computation of driving pipes etc., and using wherever applicable published codes and standards.

The thickness of the jacking pipe wall usually determined by the pipe manufacturer is a function of the following:

- Maximum Jacking force
- Length of the drive
- Dead and live loads and hydrostatic pressure.
- Designed jacking forces at the maximum angular deflection
- Pipe stiffness requirements
- Handling and positioning of the pipe

7. Conclusion

The Al Khuwair component of the Muscat Wastewater Project reveals a number of important factors related to micro tunnelling of waste water pipes. The problems surfaced from the case study can be summarised as follows for the benefit of new micro tunnelling practitioners.

- Selecting the appropriate pipe material for micro tunnelling is a major factor as pipe deviations and deflections need to be avoided while driving the pipes. Once the pipe material is selected, driving has to be done to minimize point loads on the pipe and considering sub soil properties.
- More precise soil investigations to be carried out along the pipe route in order to apply the driving torque applicable to the available sub soil strata.
- Detailed investigations need to be done on existing underground utilities in the area to identify disturbed soils and compacted soils that would have emerged during the laying of those utility services at lower elevations as these could have had an impact on the micro tunnelling pipes placed deep in the ground as these can cause pipe cracking pipe deviations and excessive settlement of the pipe line
- It is recommended to stop pipe driving and fix an additional manhole when pipe deviation is noticed through the laser beam at the control room as controlling deviations would not be possible in some cases. The Contractors should not take risks in micro tunnelling as the rejection of the work done by them, additional costs incurred to redo the work or cost cuttings by Consultants/Clients for the deviated pipe sections may not be bearable.

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