PAPER 3

Deep Tunnel Sewerage Systems: Singapore's Success Story

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ABSTRACT

With a growing world population and increasing urbanization, volumes of sewage are rising especially in large cities which require larger capacities in sewage transport and treatment. The systems built decades ago need to be modernized, extended or replaced to ensure efficient and sustainable wastewater management.

A Deep Tunnel Sewerage System is – especially from an operation cost point of view – a very cost-efficient solution to meet long-term needs for wastewater collection, treatment and disposal. Deep sewer systems involve large diameter main tunnels that convey wastewater by gravity to centralized treatment plants, mostly located outside the cities. Smaller diameter, often pipe jacked, link sewer networks and deep shafts are further parts of these schemes.

Due to the length and the required slope towards the treatment plant, tunnels and access shafts are installed in increasing depths, which represents a challenge for tunnelling and shaft sinking, especially if high ground water tables are present. In addition, cities demand the construction of such large-scale schemes to be quick and safe, with minimal impact on population and environment. One of the benefits of deep tunnelling is the activity takes place well below other existing and future municipal services.

The first large-scale Deep Tunnel Sewerage System (DTSS Phase 1) has been completed in Singapore. Due to a high population density and a continually developing economy, Singapore faces a lack of land space for development and is therefore a leading innovator in sustainable planning and managing its underground space. Singapore has already moved other municipal infrastructure and utilities below ground, including metro lines, retail, parking and pedestrian walkways. The next major milestone is the construction of the DTSS Phase 2. Fourty kilometers of deep tunnels – average depth 30m - (ID 3m to 6m) and sixty kilometers of link sewers (ID up to 3m) are currently under construction for the new wastewater infrastructure system.

The deep tunnels will connect with the existing used water infrastructure to create one seamless and integrated system; the link sewers will create an interconnected network to channel used water from the existing sewerage pipelines to the deep tunnels. Numerous tunnelling and mechanized shaft sinking machines are deployed to ensure a reliable and cost-effective construction of the high-quality structure.

INTRODUCTION

Challenges for urban wastewater systems

Metropolises around the world are all facing the same challenges when it comes to sewage: The systems that were built decades ago are just not effective enough for the future. Capacity constraints outdated existing infrastructure and space constraints in cities demand new solutions.

According to the UN, 9.8 billion people will be living on the planet by 2050 with growth particularly coming from Africa and Asia (Figure 1). A total of 70% of that population will be urban, a 1.7-fold increase compared to 2015. Cities will have to invest massively in sewage capacity to serve this growing population. In addition, climate change will further stress capacity. Extreme weather is confronting cities with high amounts of rainwater to be collected, discharged and -at least partly- treated within a short period. Diminishing surfaces for infiltration add to the problem by leaving fewer opportunities for rainwater to drain naturally.

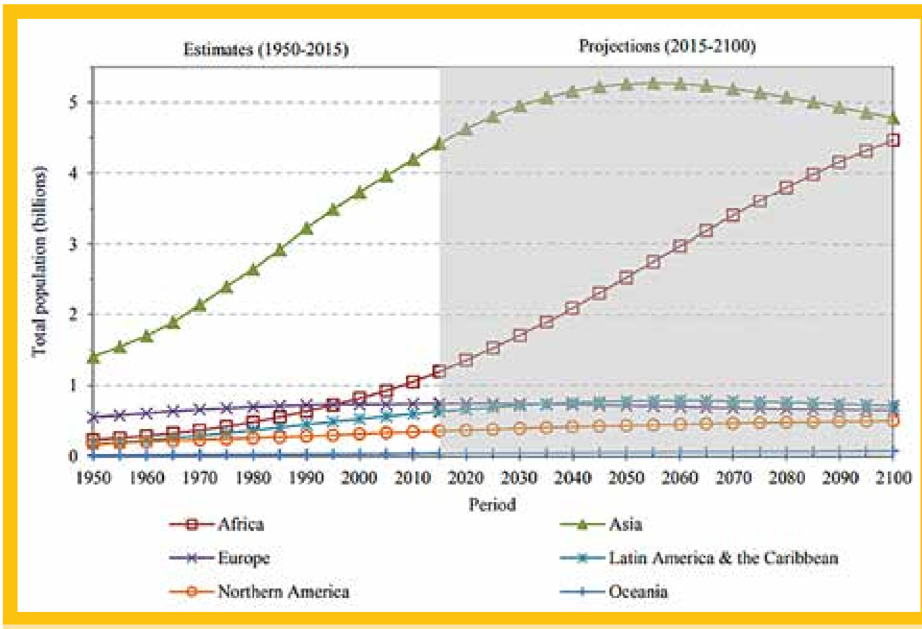

FIGURE 1: World Population predictions.
(Source: United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Revision. New York: United Nations)

This paper will present the concept of the Deep Tunnel Sewerage Systems and Singapore´s pioneering role as an example of what could be replicated by South African cities. Furthermore, it will discuss the application of mechanized tunnelling and shaft sinking technologies to realize deep sewer projects to the benefit of all parties involved.

The body of the paper will be structured as per the following headings:

1) The City of Singapore in a nutshell.
2) Description of Singapore's deep tunnel sewerage system.
3) The equipment used to execute the project:

FIGURE 2: The City of Singapore

3.1) Mixshield TBM

3.2) Verticle Shaftsinking Machine (VSM)

4) The Taus Wastewater Recycling Plant.

1. THE CITY OF SINGAPORE IN A NUTSHELL

The Republic of Singapore is a sovereign island city-state, has an area of 730 square km and a population of 5,7 million people. Despite having the second highest population density in the world this country boasts of the second highest GDP per capita in the world and Singaporians enjoy one of the world's longest life expectencies.

One of the challenges facing Singapore is to ensure the security of its water supply which is derived from three sources:

- **Imported Water**

  40% of Singapore's water is imported from the Johor catchment in Malaysia via a 1km causeway. Singapore has an obligation to supply 2% of this water back to Malaysia once treated and the agreement with expires in 2061.
- **Reclaimed Water**

  30% of Singapore's supply is presently obtained from 5 state-of-the art treatment works. This ultra-clean water known as "NEWater" is used for both domestic and industrial consumption.
- **Desalinated Water**

  30% of its need is obtained from Singapore's 4 desalination plants. Each uses the energy intensive reverse osmosis process.

2. DESCRIPTION OF SINGAPORE'S DEEP TUNNEL SEWERAGE SYSTEM (DTSS)

The first sewage systems date back to the early Mesopotamian Empire in Iraq, around 5 000 years ago. While these systems focused on efficient collection and conveyance, treatment and discharge only gained importance in the 19th century due to the cholera outbreak in Europe (de Feo; et. al 2014). Although the basic logic of collection, conveyance, treatment and discharge has remained the same ever since, today, sewage systems are put under scrutiny once again: Rapid population growth, increasing urbanization as well as climate change demand for larger sewage capacities and a thorough treatment of the disposal, often located outside the city. In addition, cities want to re-use sewage instead of discharging it into nearby waters.

Expanding capacity however is not enough. Ageing infrastructure needs replacing and health and environmental requirements have changed. Booze Allen Hamilton estimated in 2007 that some US$41 trillion would have to be spent on this replacement by 2030. Of this US$22 trillion would be for water and sanitation services.

In the past years, more and more cities utilized mechanized tunnelling technology to build large-scale sewage systems. Doing so does not only ensure fast and reliable construction times with minimum surface disruption but also -more importantly- overcomes constraints in terms of tunnelling distance and depths. So-called Deep Sewer Systems involve large diameter main tunnels that convey wastewater by gravity over large distances to centralized treatment plants, where the sewage is pumped to the surface and treated. In addition, smaller diameter, often pipe jacked, link sewer networks and deep shafts are parts of these schemes. The following paper will explore the need and concept of deep sewers, give an overview of the technologies available and finish with Singapore´s deep sewer project, one of the most famous examples for sustainable wastewater management.

Singapore's National Water Agency, known as PUB, has coined this project as "Singapore's Sanitary Superhighway". Consisting of two phases once complete it will convey wastewater to three centralized treatment plants. The DSTT will finally consist of 200km of new sewers at depths of up to 60m.

Phase 1 is already complete and the body of this paper will focus mainly on Phase 2 which is presently underway.

FIGURE 3: Underground view of the deep sewer system

DTSS Phase 1

Refer to Figure 4. This phase was completed in 2008. Built in the Eastern part of Singapore this phase effluent conveyance system consists of deep tunnels and link sewers which conveys effluent to the Changi water reclaimation plant and sea outfall situated on the south east of the island.

DTSS Phase 2

Refer to Figure 4. This deep tunnel system extends to the South Western part of the island and will feed effluent to the new Taus water reclaimation plant. It will consist of 40 km of deep tunnels, 60 km of link sewers and a specialised industrial sewer network. The main South Tunnel will vary in depths ranging from 35m to 55m.

FIGURE 4: Plan showing the extent of Phase 1 and Phase 2

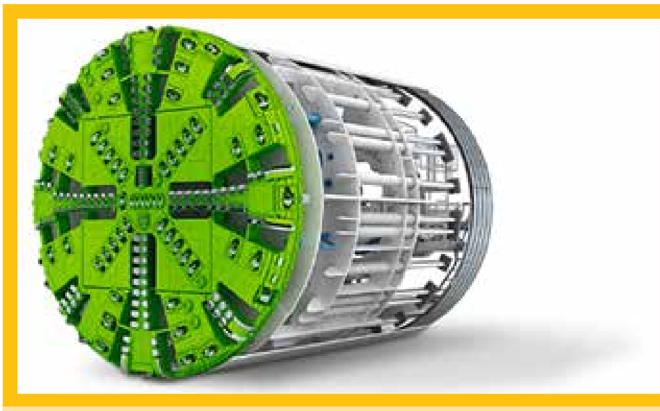

FIGURE 6: Front view of a Mixshield TBM machine

The client chose to break Phase 2 into 5 tunnelling contracts as described below:

- **Contract T-07**
  Four Mixedshield TBMs constructing 12 km of tunnels and odour control shafts. (Diameters 7,56m and 4,86m).

- **Contract T-08**
  Four Mixedshield TBMs constructing 10 km of tunnels serving the industrial area and two undersea tunnels. (Diameters 7,46m and 4,35m).

- **Contract T-09**
  Three Mixedshield TBMs constructing 8 km of tunnels (Diameter 7,51m).

- **Contract T-10**
  Two Mixedshield TBM and one EPBM Shield machine constructing 8km of tunnels.

- **Contract T-11**
  Five AVN Machines and specialised Veertical Shaft Sinking (VSM) equipment.

Many benefits are to be gained by using an entirely gravity fed deep sewer system. The need for constructing new intermediate pump stations is eliminated and a number of old existing pump stations will be removed thus releasing valuable land for housing development and reducing energy costs. Obstacles at shallower depths are easily avoided – e.g. the South Tunnel passes well below busy freeways, large buildings, a section of sea-bed and many existing services.

FIGURE 5: TBM with cutter head removed

The tunnels will be concrete segment lined with a secondary inner HDPE lining which will eliminate the threat of corrosion. Tunnel conditional monitoring will be undertaken via a system of fibre optics within the tunnel lining and the need for human entry for inspection will be drastically reduced.

Odour control will be achieved by using forced ventilation shafts.

3. THE EQUIPMENT USED TO EXECUTE THIS PROJECT

3.1 Mixshield TBM

Two of the many issues that must be considered when deciding on the best machine to use for a particular job are the geological conditions and the ground water conditions. It is vital that the soil properties (i.e, grain size, compactness and consistency) and the rock properties (i.e., compressive strength, tensile strength and R.Q.D. index) are accurately determined and catered for.

Complex geological conditions were encountered for this project. The tunnels pass through the Jurong Formation which is made up of a mix of limestone, sandstone and argillite which is a sedimentary rock with a high clay and silt content.

The Mixshield machine was chosen as the best option due to its ability to handle heterogeneous ground conditions and its ability to withstand very high water pressures (up to 15 bar). Figure 6 shows a typical Mixshield TBM and Figure 7 shows an internal view thereof. Safe working conditions are achieved using a hydraulic support system of slurry suspension together with a controlled air cushion system.

Excavated material is removed through a closed slurry circuit and hydraulic thrust cylinders within the shield area push the machine forward. The cutting wheel is made up of both knives and disc cutters and boulders and stones are crushed and screened to a manageable grain size for conveying to the surface.

3.2 Vertical shaft Sinking Machine. (VSM)

This is the first time that VSM technology has been used in Asia. This equipment has made it possible to sink 5 shafts with an ID of 10,0m (depths up to 60m) and 2 shafts with an ID of 12,0m (depth of 52m).

Challenges which had to be overcome include fines with clogging potential, areas of highly abrasive rock, varying geology and ground water which was, at times, 2m from the surface and the lowering of the water table was not permissible. Two of the shafts were situated less than 2m apart.

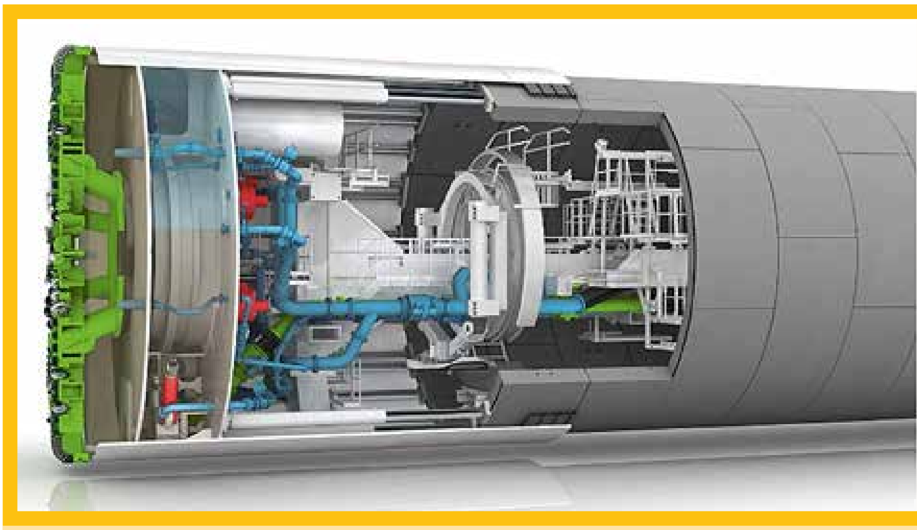

FIGURE 7: Internal view of a Mixshield TBM machine

the new plant. Once fully operational its output will increase the amount of reclaimed water use in Singapore from 30% to 55% of its total. The plant's output will be 800 ML per day. This purified water will be sold as potable NEWater and to industry. Any excess treated water will be discharged into sea outfalls. Thanks to this project the older Jurong and Ulu Panda recycling plants will eventually be phased out.

State-of-the-art design ensures higher energy efficiencies and features such as the use of membrane reactors (which replace the need for primary sedimentary tanks, bioreactors and secondary sedimentation tanks) and this will result in a smaller footprint of the plant. Reverse Osmosis and UV Disinfection will form part of the treatment process. Biogas will be used to reduce energy dependency.

Some of the benefits derived from VSM technology include safe working conditions, a continual construction process with sinking rates of up to 2,4 m per day.

Shafts for odor control, air jumpers and drop shafts which lead to the main tunnels are required.

A hydraulically powered cutting drum equipped with excavation tools controlled by a telescopic boom loosens the soil on the shaft bottom. The excavated material is removed to the surface using a submersible pump. Typical advance rates of up to 5m per shift can be achieved in soft and stable soils and excavation can be undertaken below the water table. The operation is controlled from the surface.

The completed shafts are protected by pre-cast concrete segments. The shaft lining is installed at the surface and is in most cases made up with precast concrete segments. Alternatively, in-situ concrete casting of the shaft walls can also be implemented. In this case, the slower progress of shaft construction works is compensated to some extent by having a "continuous" structure without joints and by the possibility of integrating entire entry and exit structures for Microtunnelling activities in the walls of the shaft.

4. THE TUAS WATER RECLAMATION PLANT

The layout of the Tuas Wastewater Reclamation Plant is shown in figure 10. Effluent will be fed via the Southern Tunnel and then treated at

CONCLUSION

Around the world, there is an increasing demand for sophisticated water and wastewater management. That holds true especially for cities where population is growing but space is restricted. The paper shows that deep sewers offer an effective solution for cities to collect and centrally treat their wastewaters thus adding capacity to their systems and at the same time freeing up valuable space for development.

Tunnel boring machines and vertical shaft sinking machines help to execute such projects quickly, safely and with a minimum impact on the population and environment. They offer solutions for the prevailing geological and hydrogeological conditions and can excavate at the extreme depths required in a deep sewer system. Especially, shaft-sinking machines offer an alternative state-of-the-art solution to excavate deep shafts in difficult ground conditions without lowering the ground water table and risk for involved personnel and settlements.

RECOMMENDATIONS

In South Africa, and Africa as a whole, client Government and Local Authorities and Consultants should explore and consider the benefits of employing deep tunnelling solutions for projects with similar demands and conditions as those encountered in Singapore.

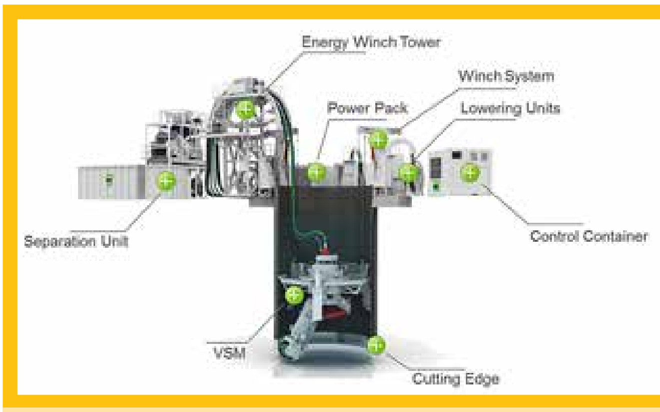

FIGURE 8: Vertical Shaft Sinking Machine (VSM). DTSS11

FIGURE 9: Aerial view of shaft sinking site

FIGURE 10: Tuas Water Reclamation Plant

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