PAPER 16

Latest achievements in microtunnelling:

Progress by experience and innovation

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ABSTRACT

Trenchless technology is in a constant process of gaining importance due to rising ecological and economical awareness and restricted conditions on the surface. Growing cities and industrial zones need innovative sewerage and drainage systems, including deep tunnels and shaft structures. In order to build-up sustainable underground infrastructure with minimal disruption on the surface, trenchless methods have been further developed and improved during more than 30 years of Microtunnelling worldwide. Limitations of trenchless applications are continuously shifted to open-up new opportunities. Technical innovations and contractor´s expertise set new milestones on an international scale. Long-distance drives of up to more than 2km, tight curve drives and the ability to handle high groundwater pressures provide more flexibility in the design stage of microtunnel alignments. Early consideration of technological possibilities can even reduce overall costs of microtunnelling projects.

Within the construction of deep sewer systems for example, mechanized shaft sinking with VSM presents an economical alternative with rising depth and groundwater level. Since 2006, a total of 83 shafts in up to 115m depth have been sunk using the Vertical Shaft Sinking Machine (VSM).

This paper highlights the latest innovations and microtunnelling achievements in international projects and presents recent case studies for special applications, e.g. Pipe Arch and Cross passage construction.

INTRODUCTION

With a growing world population and increasing urbanization, the need to lay services underground is on the rise, especially in large cities. Today, water shortages are widespread and cities around the world are meeting the fresh water needs by building desalination plants, dams and large transfer schemes. At the same time, the volumes of sewage are increasing, particularly in growing urban areas, which requires larger capacities in sewage transport and treatment. The systems built decades ago need to be modernized extended or replaced to ensure healthy and sustainable water and wastewater management. To build such infrastructure, we need tunnels of all diameters.

1. ADVANCED MICROTUNNELLING

Trenchless Technology is the collective term for all kinds of trenchless construction methods to install utility tunnels underground for services, such as sewage, water, cables, oil and gas. In Microtunnelling a remote-controlled tunnelling machine is used to construct a tunnel.

Generally, trenchless technology is used whenever conditions on the surface are restricted or when ecological and economic reasons require an environmentally friendly installation method. Often, trenchless technology is utilized in urban areas or in places where barriers have to be overcome. For passing obstacles like railway tracks, roads and waterways, it is often the only choice. The different machine types available provide trenchless solutions for all ground conditions, and even below groundwater tables.

The advantages of trenchless technology are manifold. Municipalities realise direct cost savings by leaving existing roads undamaged and reducing excavation and back-filling. Furthermore, tunnelling avoids lowering the ground water table and delays due to geological conditions.

It is also more reliable in terms of schedule and budget. Indirect cost savings include: no interruption on surface (maintain traffic and opening of stores), reduced maintenance due to high quality tunnel, and reduced emission and noise (Figure 1).

Furthermore, using trenchless leads to a reduced risk of settlement of roads and buildings. By avoiding backfilling, a pipe that has been laid using trenchless technology has no punctual loads, even after multiple years past installation. This not only reduces settlements on the surface but also has a positive effect on the longevity of the pipe itself. Still, today many project owners opt to use conventional open-trench methods when tendering a project. At a first glance, trusted open-trench solutions often seem cheaper than investing in tunnelling equipment. However, with a rising number of projects executed with trenchless technology, clients and consultants become more and more aware of trenchless possibilities and their huge benefits considering lifetime costs and impacts.

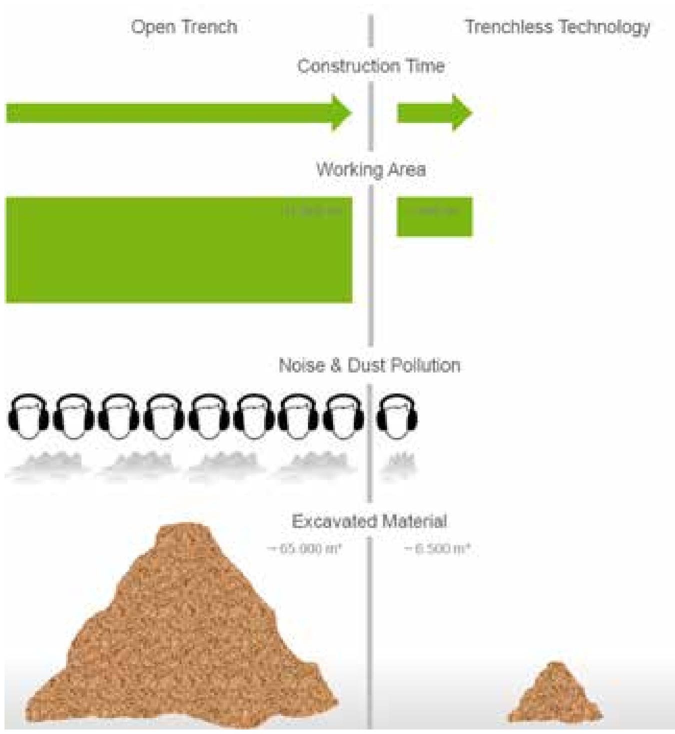

FIGURE 1: Advantages of Trenchless Technology. Comparison of 1.000m of DN 2 000 pipe installation at a depth of 12m

FIGURE 2: General pipe jacking jobsite layout with AVN machine

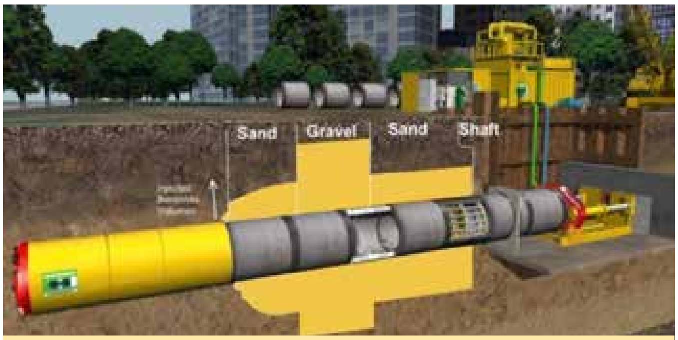

FIGURE 3: Volume-controlled bentonite lubrication for different geological sections along the tunnel route

Innovative concepts in process and machinery and continuous further development enable a very flexible planning in microtunnel alignments enabling longer drives, tighter curve radii, higher groundwater pressures and more difficult geological requirements.

1.1. Long-distance pipe jacking

In pipe jacked microtunnelling powerful hydraulic jacks are used to push the jacking pipes through the ground. At the same time, excavation at the tunnel face is taking place within a steerable shield. The remote-controlled microtunnelling machines are operated from a control panel in a container which is located on surface next to the launch shaft. This is an advantage regarding safety regulations, because no staff has to work in the tunnel during construction. The position of the remote-controlled machine is supervised by a guidance system. A typical Pipe Jacking jobsite overview can be seen in Figure 2.

The typical maximum drive lengths ten years ago with larger microtunnelling machines (> DN 1 500) was in a range of 600 to 800m. Today, the developed tunnelling technique enables the realization of long distance advances, also in difficult ground conditions. It is meanwhile usual to discuss pipe jacking projects of max. drives of 1.200 to 1.400m and even longer. Of course, the availability of appropriate lubrication technology is a key factor for a successful execution of long drives and is absolutely essential in this context. Furthermore, to include the right interjacking equipment into the plannings is mandatory to minimize potential risks. The following tunnelling equipment and features reduce friction and jacking forces.

Automatic Bentonite Lubrication

During the pipe jacking process the whole pipeline is pushed through the ground. Rising friction forces between the surrounding ground and the pipe string lead to increasing jacking forces. However the maximum jacking force is strictly limited by the maximum permissible pipe load. To reduce friction, the pipeline should be lubricated continuously. Bentonite suspensions act as lubricants during the pipe jacking process. They are mixed in bentonite plants at the job site and are pumped into the tunnel via hoses or pipes. Through injection nozzles within the jacking pipes, the lubricant is squeezed into the annular gap between the pipeline and the surrounding ground. Thus, the jacking forces can be reduced considerably. Reduced jacking forces optimize the performance of the pipe jacking process in terms of lower pipe loads and thus longer jacking distances.

A new generation of Herrenknecht's bentonite lubrication system enables the optimal adjusted automatic distribution of bentonite suspensions along the alignment by controlling the injected bentonite volumes along each pipe at the same time. It allows to select and to adjust the desired bentonite volume of each meter along the tunnel route, also considering changes in geology (see Figure 3). Monitoring, control and recording of

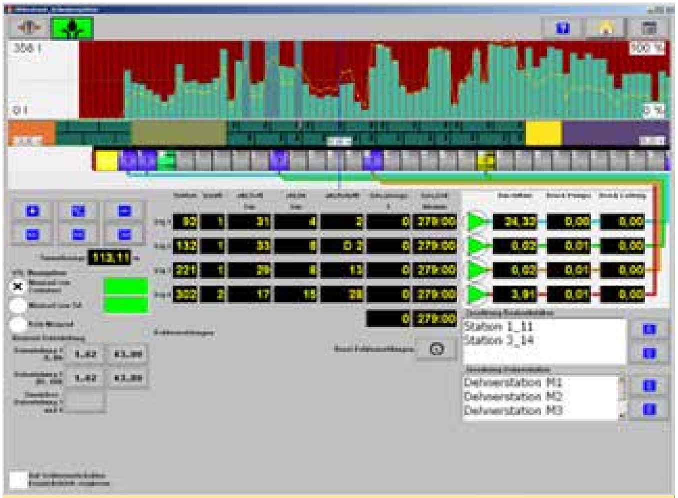

FIGURE 4: Monitoring display in control container

relevant data, such as bentonite volumes, pressures and friction forces, is done in the control container where the machine operator supervises the pipe jacking process (see Figure 4).

Intermediate Jacking Station

Another, mostly additional possibility to handle jacking forces in difficult ground or long drive lengths, is the use of intermediate jacking stations. The interjacking stations are installed in steel pipes (see Figure 5) used in determined distances in the pipeline and serve to separately advance the pipeline in sections. In general, it is not foreseen to operate the intermediate jacking stations continuously, but in case the pipeline has not been moved for a while (e.g. due to maintenance reasons) it is much more safer to re-start pushing by single sections than jacking the complete pipeline from the launch shaft. This allows to avoid extremely high jacking forces at the rear pipes. Also, sudden heavy raise of push forces indicates the risk of a blockage along the pipeline. In order to locate the critical area and to take measures it is recommendable to push the pipeline in sections by use of the intermediate jacking stations. An interjacking station in operation is shown in Figure 6.

In order to achieve long drive lengths, all process factors have to be carefully analyzed and adapted. The equipment has to fulfill the project requirements which mainly includes the cutterhead design according to the project geology. In addition, the quality of the bentonite and a smart lubrication along the tunnel route are decisive factors to reduce friction forces. The worldwide pipe jacking distance record was set in 1994 on the Europipe project in Germany where a tunnel length of 2.5km has been achieved (OD 3 800). In a smaller diameter of OD 3 200 a new record was

FIGURE 5: Interjacking station installed in pipe

FIGURE 6: Interjacking station in operation.

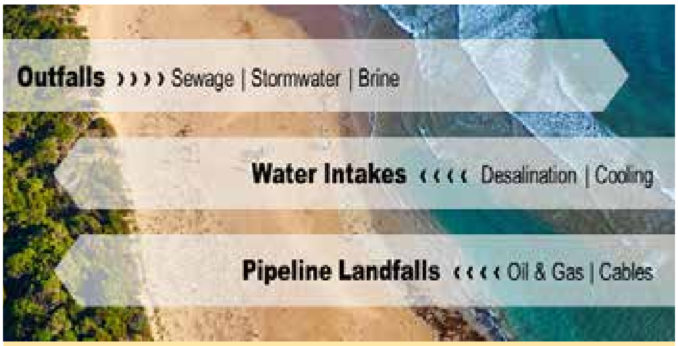

FIGURE 7: Application fields of sea outfalls, intakes and landfalls

FIGURE 8: Function principle of Pipe Jacking marine outfall technology

set in 2018 in Mexico, where a 2,246m long pipeline casing outfall tunnel has been installed using the pipe jacking technology.

1.2. Sea Outfalls, Intakes and Landfalls

In the construction of utility infrastructures in coastal areas or in river regions, trenchless Outfalls, Intakes and Landfalls are an effective and sustainable method. With the help of sea outfalls wastewater can be transported away from the coastline and discharged at locations where diffusion, dispersion and decomposition are enhanced. The municipal wastewater may be fully treated, pre-treated or untreated. Sea Water intakes are required to supply fresh water for desalination or cooling water to power plants. If no beach or sandy floor exists near the plant location, or if the site conditions are inadequate for infiltration, a tunnelled offshore intake system is the ideal choice. The worldwide growing demand for oil and gas makes the construction of pipelines on and offshore necessary. Pipeline landfalls, the section to connect offshore and onshore installations, is one of the key elements of large-scale pipeline projects. With the growing amount of offshore windparks cable shore approaches in tunnels or steel pipe casings are also gaining importance.

When a Sea Outfall tunnel is built using Pipe jacking technology, the machine is installed in a launch shaft on the landside and is then pushed through the ground to a target point on the seabed.

Machine Recovery

Tunnelling machines to be used for Sea Outfalls are equipped with an additional recovery module, consisting of a steel can with bulkhead to close the machine and hydraulic cylinders to separate tunnel and machine. The supply of hydraulic oil for these cylinders is done by divers and connected from the outside skin of the recovery module. After complete installation of the tunnel, the seaside end of the pipeline is mostly closed with a bulkhead equipped with a valve.

In most cases the tunneling equipment has to be recovered and lifted up to the surface. Therefore, the jacking machine is equipped with lifting eyes on its upper side. There are two ways to lift the tunnelling machine:

1. A barge with a crane is moored at the position from which the jacking machine shall be recovered. To be more independent from the sea, a jack-up platform with crane can be installed which is able to lift higher weights than a floating barge. The crane is connected to the lifting eyes of the jacking machine by means of a spreader beam. The connection has to be carried out with the help of divers. The jacking machine is lifted to surface by the crane.
2. Another possibility to lift the machine from seabed to water surface is the application of airbags. These are fixed by divers to the lifting eyes of the machine. A compressor installed on a ship or barge on the surface inflates the number of airbags needed to lift the weight of the machine. Water level fluctuations caused by ebb and flood may be considered to reduce the lifting height. The barge or a ship transports the jacking machine to the next harbour, where it can be taken out of the water by a high-capacity crane.

1.3. Retractable machine concepts

Retractable tunneling machines generally operate according to the pipe jacking method where the pipe jacking machine cannot be recovered in the reception shaft or by subsea recovery, but instead is pulled back to the launch shaft. This pullback is not reversible, meaning that once the

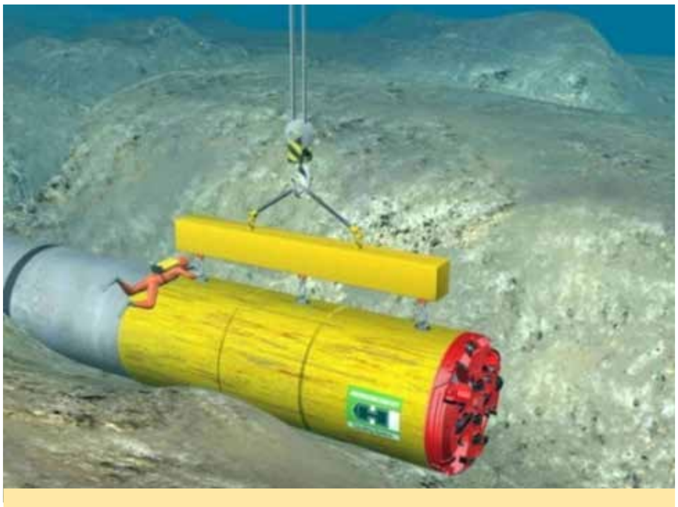

FIGURE 9: Machine is uncovered by special suction system or excavator

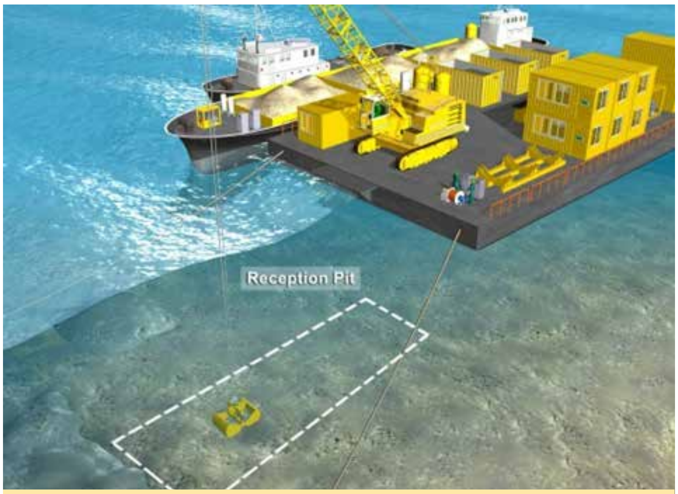

FIGURE 10: Divers fix the crane to lifting eyes

FIGURE 11: Recovery of tunnelling machine via airbags, lifting by crane in harbor

machine is retracted, it cannot be brought back to its initial position. For pulling the machine through the pipeline back to the launch shaft, the TBM shield is designed with a double skin, where the inner shield is connected to the outer one by means of couplings. The cutter head can either be folded up or it consists of an outer cutting ring and an inner cutting ring. In the last case, the outer cutting ring stays in the ground together with the outer skin of the machine shield.

Prior to pulling back the machine, the supply lines will have to be disconnected from the machine and pulled back separately through the tunnel. During a second stage the cutter head will either be folded up or separated from its outer ring. The inner shield of the machine will be disconnected from the outer shield and the machine will be pulled back by the adapted jacking frame. Figure 12 shows the pullback of a retractable AVN800 and its foldable cutterhead (Figure 13).

1.4. Curved and inclined alignments

The technical standard of modern microtunnelling machines enables curved and inclined tunnel alignments. Curved alignments can help to optimize planning for example to avoid existing lines underground, foundations or buildings or for river crossings. Furthermore, the number of shafts can be reduced. Regarding the respective curve radius, the length of the machine sections and pipes is a decisive factor. The smaller the radius, the shorter the machine sections and pipes. In addition, a stable geology helps to maintain a precise steering of the machine by the operator and the navigation system. A precise steering is also mandatory where a constant gradient of gravity lines, for example sewage tunnels, is required.

In the past, various pipe jacking projects have also been realized successfully going uphill with high slope. Here, some adaptations are required to maintain a functioning supply of the machine components, such as the hydraulic fluids. Furthermore, higher pump capacities are needed to overcome the height difference between the launch point and the machine position in a higher position.

1.5 Cross passages technology

The general approach to connect two underground structures by a cross passage is not new. The technical approach is very similar to standard pipe jacking, where two shafts serve as launch and reception structures for the tunnelling equipment. The following figure gives an overview about different cross passage concepts.

Shaft to tunnel

Currently, the most common application field for cross passages is the link of a shaft and a tunnel. When emergency exits have to be installed to existing traffic tunnels, this can be realized by a conventional or a mechanized approach. The shaft, at the same time, can serve as a final structure for safety or ventilation. For a mechanized approach pipe jacking can be considered as the preferred technology, also assuring construction safety and installing the final lining. In this case, a tunnel boring machine starts

FIGURE 12: Retraction of AVN800 in testing in workshops Schwanau, Germany

FIGURE 13: Foldable cutterhead of retractable AVN800

excavation in the shaft and then breaks through in the tunnel, where it is dismantled and transported back to surface.

In Spain, a total of nine shafts have been built by a mechanized shaft sinking equipment (VSM) to add the required emergency exits and ventilation to the express train route from Montcada to Trinitat. The shafts are up to 57m deep and have been linked to the tunnel using conventional excavation methods.

Tunnel to tunnel

The application more in the focus for cross passage concepts is the link between two tunnels for rescue purposes. In general, twin traffic tunnels have to be connected to fulfill the necessary safety standards. The concept and design of the mechanized approach depends on whether one or both tunnels are still under construction, in operation or already finished and fully accessible.

Shaft towards tunnel – Blind hole

In some cases, the tunnel has to remain unaffected by the construction of the cross passage for as much as possible. Here exists a mechanized solution using a retractable machine concept that allows the construction of the cross passage without interruption of the traffic in the tunnel or without affecting logistics when the tunnel is still under construction.

The tunnelling machine excavates the cross passage until the predetermined end position close to the tunnel. Then, it can be retracted to the launch shaft or dismantled, according to the machine concept and the project conditions. In the last step, the connection between cross passage and tunnel can be made, mostly by means of a grout block, at a time when disruption to the tunnel can be minimised.

For mechanized cross passage construction different machine concepts and lining methods can be considered according to the geology and groundwater conditions. In unstable ground with groundwater pipe jacking will be the chosen lining process. Only in dry and stable conditions conventional lining can be considered as a real alternative. Figure 16 shows the pipe jacking cross passage installation concept with AVN3000 linking two traffic tunnels in Hongkong, where a total of 46 cross passages of approximately 14 meters have been installed simultaneously to the main tunnel construction.

FIGURE 14: View in tunnel (ID 2 000) with curve radius of 110 m constructed in France

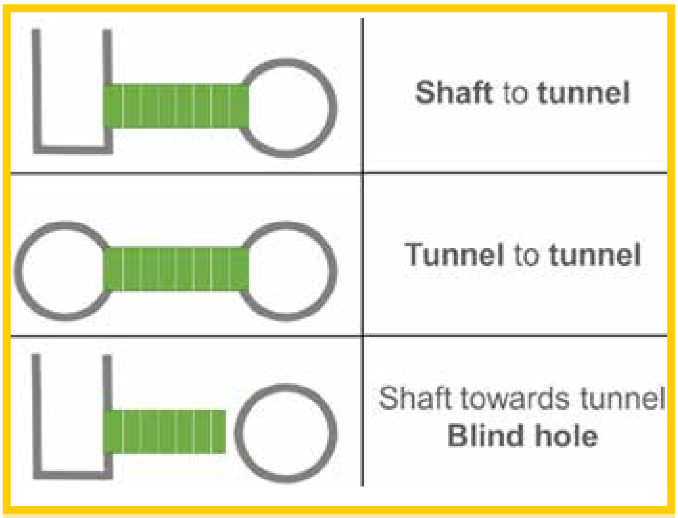

FIGURE 15: Different cross passage concepts

2. MECHANIZED SHAFT SINKING - VSM

Almost all tunnelling projects require shafts, either as start and reception shafts for the tunnelling process or for inspection, ventilation and rescue purposes (see Figure 17). Also, a current trend towards infrastructure installations in growing depths can be observed. It is driven, among other things, by deep sewer construction projects that aim to avoid pumping stations as well as the need to build new installations below existing infrastructure.

The Vertical Shaft Sinking Machine (VSM) was originally developed by Herrenknecht for the mechanized construction of deep launch and

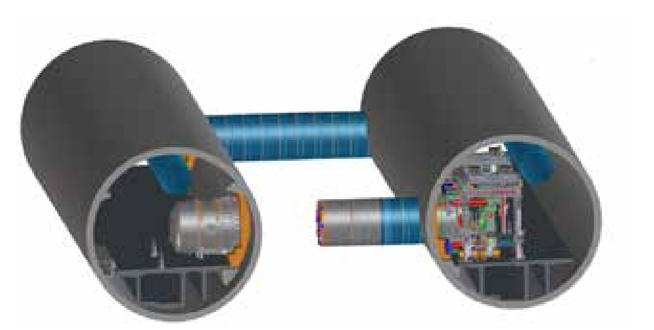

FIGURE 16: Cross passage installation simultaneous to tunnel construction

reception shafts for microtunnelling. After starting design and testing in early 2004, the first Herrenknecht VSM equipment went into operation in Kuwait and Saudi Arabia in 2006. The machine concept, fully remote-controlled from the surface, as well as its implementation on site proved to be an efficient solution right from the start for the safe and fast realization of shafts especially in difficult, inner-city environments without lowering the groundwater table.

To date, approx. 83 shafts have been successfully installed worldwide with the Herrenknecht VSM technology, reaching depths of up to 115m. They serve today, for example, as ventilation shafts for metro systems, maintenance or collector shafts for sewage, or as temporary microtunnelling shafts (Figure 17).

VSM machine components

The VSM consists of two main components (Figure 18): the excavation unit and the lowering unit. The excavation unit systematically cuts and excavates the soil and consists of a cutting drum attached to a telescopic boom that allows excavation of a determined overcut. The lowering unit on the surface stabilizes the entire shaft construction against uncontrolled sinking by holding the total shaft weight with steel strands and hydraulic jacks. When one excavation cycle is completed, the complete lining can be lowered uniformly and precisely.

A slurry discharge system removes the excavated soil and a submerged slurry pump is located directly on the cutting drum casing. It transports the water and soil mixture through a slurry line to a separation plant on the surface. The whole operation takes place from the surface and is controlled by the operator from the control container on the surface. All machine functions are remote-controlled without the necessity to view the shaft bottom or the machine. Power supply for the submerged VSM is secured by the energy chain. After reaching its final depth, the VSM is lifted out of the shaft by the recovery winches and the jobsite crane.

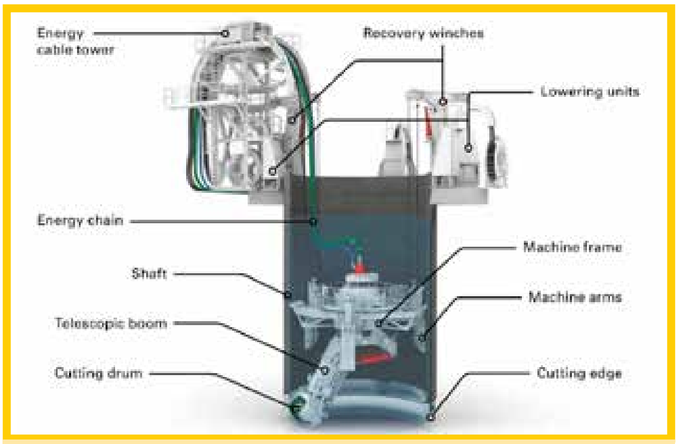

FIGURE 18: VSM machinery installation and components

3. CONCLUSION

Over the last years, boundaries of microtunnelling have continuously been shifted. Further development of existing technologies as well as the development of new methods and technical features opened up new possibilities in terms of project feasibility and planning approach. Public interest is increasing due to environmental and quality of life issues, where trenchless technologies prove out their benefits. Nevertheless, acceptance and level of utilization of trenchless solutions strongly depend on the region or country under consideration. In some North African Countries like Egypt, Algeria or Morocco, trenchless technology is already quite common whereas other regions of Africa still have to be informed and trained to get the technologies and its wide range of application into the minds of planners and consultants.

Milestone projects like the "Kpone Independent Power Project" in Tema, Ghana, where an AVND 2000 tunnelling machine installed a total of 4 drives with lengths of up to 1,100 meters in difficult rock conditions make the public aware of what can be achieved with trenchless technology. For this reason, the presentation will show the state-of-the-art microtunnelling technology with some relevant milestone projects.

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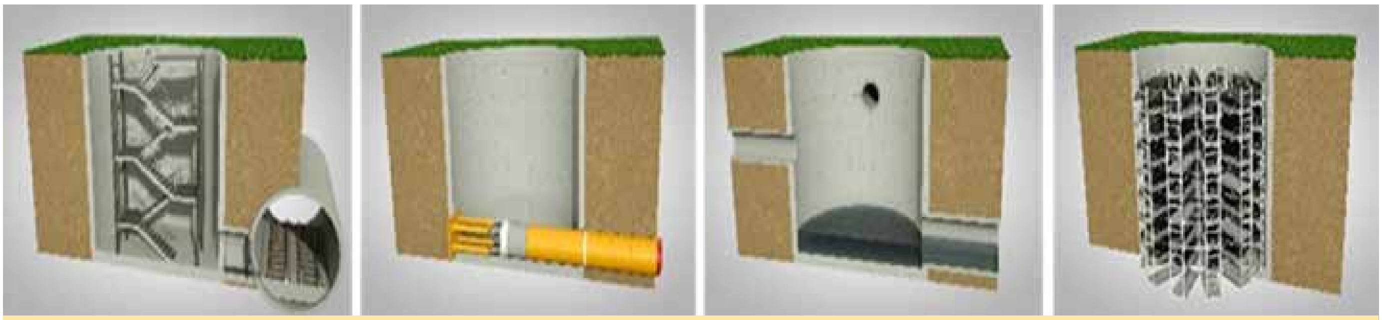

FIGURE 17: Overview of VSM applications, from left to right: ventilation / emergency shaft, microtunnelling shaft, sewage collector shaft, U-Park® shaft