Vertical shaft machines. State of the art and vision

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Vertikálne a tunelovacie mechanizmy. Prítomnosť a budúcnosť.

This paper illustrates five different projects that are partly already completed or still in the planning phase. These projects demonstrate potential applications in the mechanical shaft construction and highlight different requirements that have to be met by the tate-of-the-art machine technology.

Key words: *Shaft sinking machine, Microtunnelling, piling technology*

Introduction

While the process technology of tunnel boring machines deployed in mechanical tunnelling and their auxiliary equipment have advanced rapidly, the methods used in today's shaft construction are still comparatively conventional.

The main reason for the low degree of mechanization is the required flexibility regarding:

- diameter or cross section,
- depth,
- geology,
- presence of groundwater and
- construction lining / blind - enlargement

The pipe jacking method, in particular, has shown that tunnel sections can generally be driven in conformity with the project plan, i.e. within the scheduled time frame and calculated financial limits. Whereas the construction of the shafts required for these works often considerably exceeds deadlines and cost limits. In this context, the Herrenknecht AG based in Schwanau, Germany, decided to develop a relevant machine technology to meet these requirements.

Shaft sinking machine VSM 8000

Since 2003 a particularly large Microtunnelling project has been under construction in Kuwait. By order of the "Ministry of Public Works" a total of almost 100 km of sewerage lines will be installed with diameters ranging between DN 200 and DN 2250, 38 km of this system will be laid using the pipe jacking method.

The geology in this region of Kuwait mainly consists of sand, cemented sand, loam and limestone. Due to the proximity to the Persian Gulf, the groundwater level is in many places only 3 m below the surface. In the field of pipe installations below a groundwater level, the Microtunnelling technology can specially show its full advantages over open-type construction methods: The groundwater level does not have to be lowered and the ecosystem remains intact. The pipe jacking works could be carried out safely and efficiently at depths of up to 28 m (with a maximum 2.5 bar water pressure).

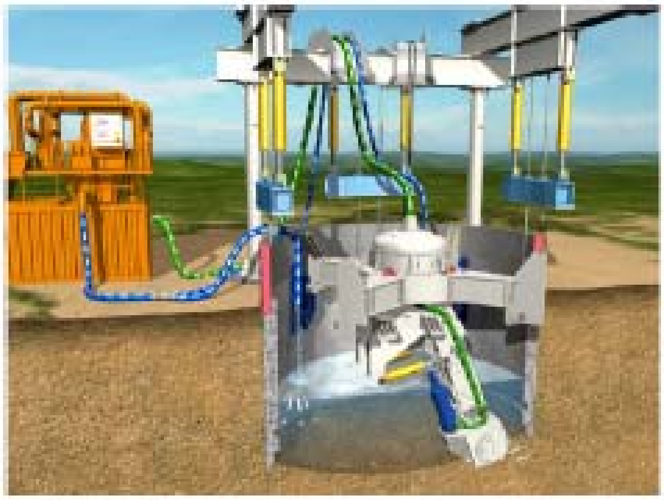

Fig. 1. Structure of the shaft sinking equipment with the shaft sinking and boring unit.

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In the course of this giant sewerage project, various launch and target shafts were constructed for the drives with larger nominal widths (DN 1800 to DN 2250). These shafts were between 8 and 28 m deep and had inside diameters in the range of 6 to 8 m.

In addition to the conventional shaft sinking with the sheet piling technology, five shafts were constructed with the most state-of-the-art machine technology using the segment construction method. In co-operation between the machinery manufacturer and the contractor, a new shaft sinking unit was developed for this project aiming to make the shaft construction, particularly, in difficult geological conditions, safer and more efficient.

The designed shaft sinking equipment (fig. 1 and 2) consists of two main components: the shaft sinking and the shaft boring unit. The sinking unit is firmly anchored to the foundation on the shaft surface. A continuous shaft construction is carried out with concrete segments. Above ground, the segment ring is formed with the help of a crane. Thrust cylinders mounted on the sinking unit push the connected segments vertically in the direction of advance at a defined stroke length.

The shaft boring unit is installed in the first shaft section, cast in concrete, equipped with integrated adapter plates for a precision-positioning and connection of the shaft boring unit (fig. 3). A launch section is connected to the segments which form the shaft. The connection between the shaft sinking and boring unit or the launch section, is provided through rods that are gradually extended relative to the excavation depth.

Fig. 2. On-site shaft sinking equipment.

To counteract the groundwater pressure and to avoid settlements, groundwater intrusions in the shaft under construction are not avoided and the excavation of the ground is instead carried out under water (fig. 4). A functional principle of the excavation is similar to that of a partial-face machine. The installed cutting boom rotates at 190° in both directions starting from its basic position. The rotating cutter drum equipped with special tools is mounted on the boom and excavates the ground on the "horizontal" tunnel face.

Fig. 3. Shaft boring unit gripped in the launch section.

Fig. 4. Vertical drilling below the groundwater.

Similar to the mucking principle of a slurry Microtunnelling machine, the excavated material is directly pumped out to a separation plant on the shaft surface, where the separation of the mucked slurry is carried out. The overall control of the material excavation and transportation is carried out from the control panel in the control container that is located on the surface.

During the deployment of the shaft sinking equipment in Kuwait, a total of five 15 to 27 m deep shafts with 8 m diameters was constructed. The jobsite team familiarized themselves quickly with the new technology. On the first construction day, 2 m of shaft could already be built. The ground excavation and the material transportation operations were carried out without problems. The construction of the second 25 m deep shaft with the same diameter could be completed in only one week. In addition to the machinery, concrete segments and statics were also included in the scope of delivery. This allows the machine manufacturer to meet the ever-increasing requirement to work as a system supplier (P. Schmäh, 2004).

The project in Kuwait set standards with regard to the deployment of shaft sinking equipment, which can be used wherever a quick and safe shaft construction in difficult geological conditions below a groundwater level becomes necessary. A new and innovative method has been created for the construction of launch and target shafts, shaft constructions in inner-city metro stations and offshore or high-rise structure foundations.

Shaft sinking machine VSM 2500

In co-operation with the University of Karlsruhe (Technical College) and the Federal Ministry of Education and Research (BMBF), the Herrenknecht AG was a part of a research project carried out on the south coast of the Indonesian island of Java. The population suffered from a shortage of water although huge underground water supplies existed in more than 1,000 caves. To keep the precipitation in the faulted karst stone (with rock strengths of up to 85 mpa) from flowing unhindered and unused through the underground river system into the ocean and to store the water, a 100 m deep shaft was constructed until early December 2004, leading vertically to an underground cave (fig. 5).

The Herrenknecht shaft sinking equipment VSM 2500, which was developed in view of the know-how and specific conditions required in Indonesia (appropriate technology) and started tunnelling in early July 2004, will be explained in detail below.

This shaft sinking unit designed for a 2.5 m drilling diameter loosens the ground with a cutter drum that is controlled by an operator located in the machine underground.

The vertical mucking system with a hydraulic cable excavator, chosen for the project in Indonesia, offers many advantages in terms of energy consumption, maintenance, repair and functional safety during the operation of the shaft sinking equipment. The cutter drum directs the excavated material towards the cable excavator at the lower return point in the shaft invert; where the cable excavator bucket (which is controlled by a second operator), falls into the excavated material due to its dead weight to také up the material. From here, the bucket is transported to the surface through a shaft.

Below the upper return point a gate opens, the bucket is opened and the excavated material falls into a muck skip via a slide. This cycle is continuously repeated, while the rock is being excavated with the cutter drum. After a bucket is filled it is pulled out of the shaft by a crane, dumped above the ground and lowered back into the shaft.

To secure the shaft, eight steel segments are installed in the shaft and bolted together to form a ring. After the completion of approx. 0.7 m to 1 m, the segments are lowered in the shaft, where they are mounted in the ring form protected by the steel jacket, hydraulically lifted, bolted to the last steel ring and fastened in the rock with special anchors. The annular gap, that is generated due to the overcut between the rock and steel segments, is grouted with a mortar.

The steel frame (fig. 6), with rods to connect the frame with the machine, is located on the surface. The four rods are led through hollow piston cylinders, which sink the machine uniformly after each drive section. The cylinders for lifting and sinking can be operated independently and allow for an exact vertical position of the equipment. If the end of the 3 m long rods is reached, the rods are extended upwards in pairs. One pair of rods is compensated by the second pair which supports the machine weight. Through this sinking systém, the machine is suspended freely in the drilled shaft.

During the drilling process, a hydraulic gripper system stabilizes the shield in the rock. Due to the gripper extension, the machine can be maintained in its position and controlled.

After completion of the shaft, the machine is recovered. Since the diameter of the steel-segment lined shaft is smaller than the machine diameter, the equipment consists of an inner part and an outer jacket to recover the equipment in two steps.

In a first step the jacket is braced against the rock and the inner part is detached from the jacket. With the cylinders and rods, which permanently connect the equipment with the steel frame above the ground, the equipment can gradually be pulled to the top. After the inner part has been recovered, the shield jacket is divided in four segments and lifted through the lined shaft.

This system does not require a second lifting system such as the second heavy duty rane with a 100 m rope length. But in Indonesia a winch system was deployed for safety reasons to secure the equipment additionally.

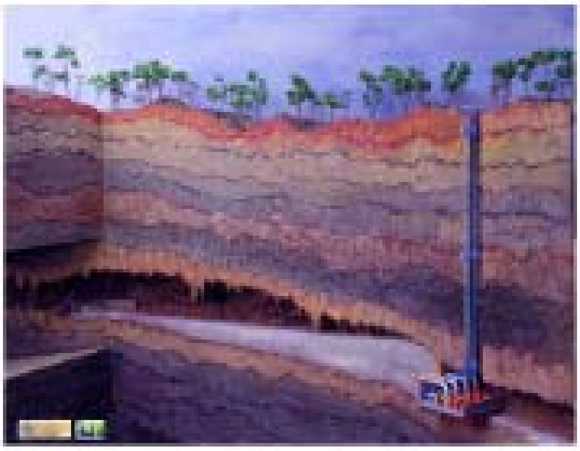

Fig. 5. Cross section of the cave system with a small hydropower plant.

Fig. 6. Shaft sinking equipment VSM 2500 for a 100m deep shaft.

The VSM 2500 offers advantages such as the recovery of the drilling equipment as two-piece construction and the easy assembly and disassembly. In addition, the equipment has a low energy consumption. The units that are used on the construction sites are standardized, which also facilitates the handling and logistics. The shaft sinking equipment is also designed to allow for a faster and more economical transportation in standard containers.

Shaft sinking equipment VSM 7700/5500

A shaft sinking equipment similar to the VSM 8000 was designed and manufactured for a deployment in St. Petersburg, Russia. As a part of a large-scale project the VSM 7700/5500 will construct shafts with drilling diameters ranging between 5.5 m and 7.7 m at depths of up to 85 m. After the completion, these shafts will be used as access shafts, connecting constructions and basins for the existing sewerage system.

The underground in the "Venice of the North" consists of sand and loam. While the upper layer is groundwater bearing up to a depth of approx. 60m, the lower layer consists of hard but dry loam. In the transition area of both formations, boulders of up to 2.5 m length are expected (fig. 7).

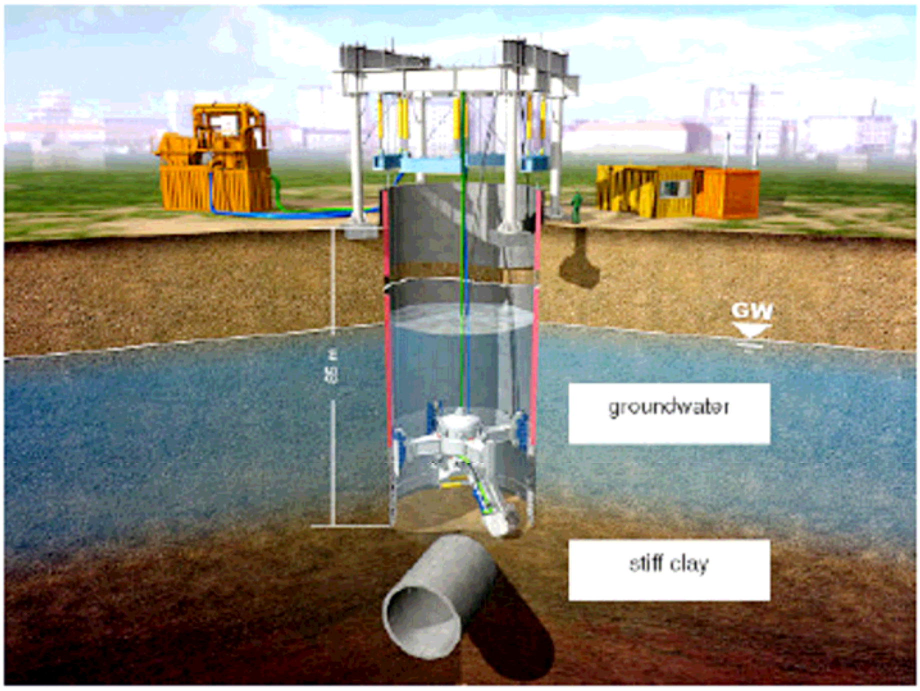

Fig. 7. Illustration of a shaft construction project in St. Petersburg.

High standards have to be met in terms of shaft construction, since there is no additional lining planned. The tightness of the completed shafts has to be certified. A vertical precision of 1 % must also be provided during the sinking process. The machine technology is planned to guarantee safe and controlled shaft sinking works.

The sinking unit (fig. 8), which is connected to a stable concrete-ring foundation on the shaft surface, is the second complex system component beside the actual shaft boring unit (fig. 9). A controlled and safe sinking process of the shaft up to the enormous depth required can be carried out only if the shaft is lowered as one piece – with the boring unit being gripped against the first shaft section. Eight threaded rods generate the gripping force and provide the connection to the sinking unit between the launch section and the shaft boring unit. The shaft (2,400 t at the shaft depths of 85 m and a 8.4 m diameter) is held by the sinking unit, with a special cylinder arrangement (support and pressure cylinders) providing the required gripping force for the shaft sinking. Depending on the geological conditions, this means that the shaft can be "dug" into the ground with the pressure cylinders to counteract settlements or similar problems or the vertical shaft can be lowered by excavating the tunnel face.

To compensate the gripping forces and to stabilize the adjacent ground, 25 m long piles are placed in the ground around the shaft.

The hydraulic and control container, two mobile units on the shaft surface, serve as an external supply and control center for the entire equipment. The hydraulic container provides the boring unit, sinking unit, crane and the survey system with a required energy; the control system of the equipment developed by Herrenknecht AG is operated from the control container. The boring unit is remote-controlled due to the deployment below the groundwater level. All information with regard to the drilling process is collected and monitored in the control container.

The operator can regulate technical parameters of the shaft sinking equipment during the vertical drilling to adapt and optimally adjust the equipment to local conditions.

A combined control surveying of the equipment and the shaft position allow to define the current vertical position of the shaft at all times and to adjust the shaft position via the boring or the sinking unit.

Fig. 8. Shaft sinking equipment in Schwanau - Assembly in St. Petersburg.

Fig. 9. Sinking unit in St. Petersburg.

Fig. 10. Scheme of the bentonite lubrication.

Shaft lining is carried out on the shaft surface parallel to the excavation. Four 1 m high segments, designed for pressures of 8.5 bar, are installed as a "suspended" ring segment, held by a crane on the shaft sinking unit, and positioned on the previously installed ring segment. To reduce the friction during the vertical advance, the annular space is lubricated through a bentonite lubrication system similar to the pipe jacking method in Microtunnelling. The production rate is in average 5 meters per shift.

The shaft boring unit is supplied with a hydraulic and electric power, lubricants and fresh water via an energy chain system between the hydraulic container on the shaft surface and the shaft boring unit. With the crane, which is positioned diagonally on the sinking unit, the boring unit can be pulled to the shaft surface for refurbishment or repair works or after the vertical drilling has been completed.

The first shaft has been successfully sunken at a deviation of +29 mm / - 19 mm at a depth of 60 m.

Shaft sinking equipment VSM 6500

In the Middle East, another shaft construction project is currently being conducted, with several 25 and 45 m deep target or launch shafts being under construction as a part of different Microtunnelling projects. In a first step, the shaft with an inside diameter of 6.5 m and an outside diameter of 7.3 m have now been sunken successfully in 2006. After this, the equipment will be modified to sink vertical shafts with up to 10 m inside and 11 m outside diameters.

The ground consists of sand, sandy clay, hard coral, and limestone. Due to the enormous porosity of this limestone and coral,shaft construction works are impacted by large groundwater intrusions. Since the drainage is problematic, or even impossible due to a particularly large water volume, a shaft sinking equipment similar to the above mentioned VSM 8000 is deployed (fig. 11). The excavated material is mucked out through the groundwater-flooded shaft. In addition, a slurry system is used for the spoil transport.

Due to local regulations, it is not allowed to use pre-fabricated segments during this project. The shafts are done by an Insitu casting instead. Two to four meters lifts are část every two days by a quick handling form work and reinforcement system. The production rate is one to two meters a day in average.

Fig. 11. Deployment of a shaft sinking unit in Jeddah Saudi Arabia.

The functional principle of this sinking unit is also different from the methods described above. Due to the experience gained during the construction of conventional sinking shafts, this sinking unit only provides a holding and sinking function. The connection of the shaft lining with the sinking unit is provided by wire cords arranged in four sections. This allows a controlled sinking and synchronous holding process of the entire shaft and the boring unit.

Shaft extension equipment

Another shaft construction project is currently being carried out in stable rock formations with rock strengths of an average of 100 MPa. Temporary, up to 200 Mpa could be managed with the equipment. Shafts with inside diameters of 7 m to 9 m at depths of more than 150 m are planned to be constructed. The shaft construction will be carried out in non-groundwater bearing soils. The transportation of the excavated ground is being carried out downwards through a pilot-drilled hole. The equipment, which is braced against the outside shaft by three grippers, is equipped with different platforms, similar to a Gripper TBM divided into different working areas. The control panel is located in an air-conditioned cabin on the machine frame. The working platform required for the shaft lining is mounted above. On the top of the working platform, another platform is installed equipped with the auxiliary equipment required for the operation of the shaft sinking unit (electrical equipments such as transformers, compressors and shotcrete pumps).

The sinking equipment, which is connected to the grippers through a cord system, holds the equipment during the gripper displacement, providing a controlled and safe sinking of the equipment and working platforms (Fig. 12,13).

Fig. 12. Workshop acceptance of the Herrenknecht V-004.

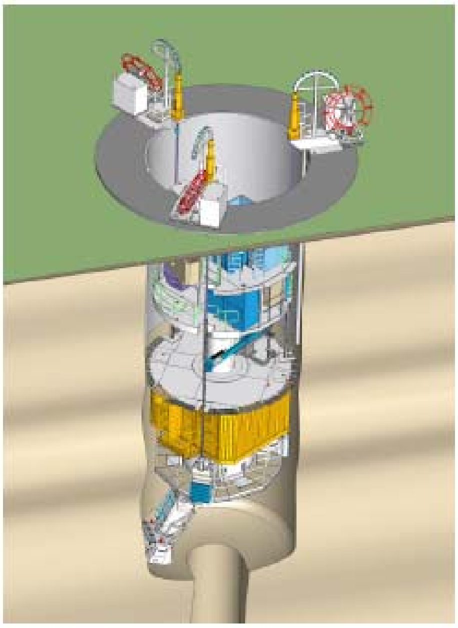

Fig. 13. Illustration of the shaft enlargement equipment. Shaft diameter 8 m

During the excavation process, the rock anchoring can be done parallely. Due to logistic issues, the spry concrete process is done as a separate process each 2 m of excavation with the help of a automatic manipulator. During the first shaft, performances of 4m per day could be achieved.

Large diameter shafts

Shaft sinking machines with cutting diameters of up to 12 m have been realised until now. For larger shafts, several concepts have been worked out. The basic principle remains the same. Mainly, the size and the amount of the cutting units will be modified. Following a concept for a 30 m shaft, which has been worked out of a study for a metro station.

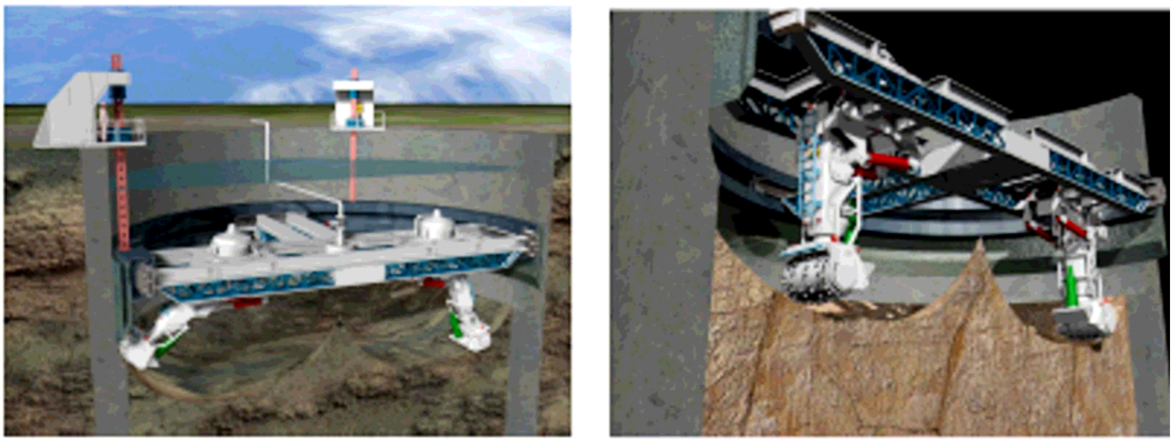

Fig. 14. Illustrations for the construction of large diameter shafts.

Future business and further applications

The initial idea for the development of the described shaft sinking equipment was to present an economic solution for the construction of start and reception shafts for micro machines. Recently, several other concepts have been worked out or other applications have already been realised.

One interesting application is the shaft construction for foundations. For example large bore piles to realise ridged foundations in difficult ground conditions. These can be executed on shore as well as off shore. For the off shore applications, the building of foundations for wind turbines is a possible further spin off of this equipment.

A further innovative and promising application is the excavation of large holes for the erection of sub terrestrial parking garages. Especially for big cities with a lot of traffic, limited space and no further available areas, this technology will effectuate a lot of sustainable advantages.

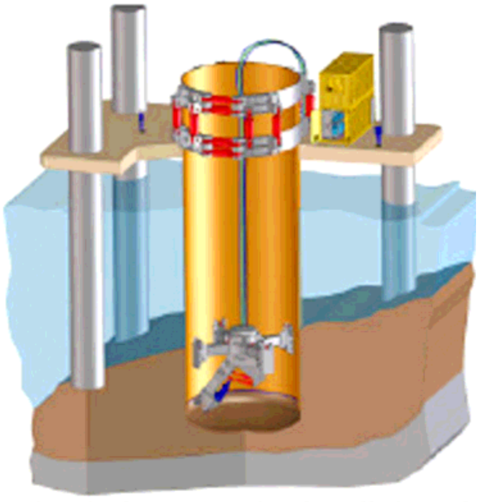

Fig. 15. Illustration for the shaft construction for off shore foundations.

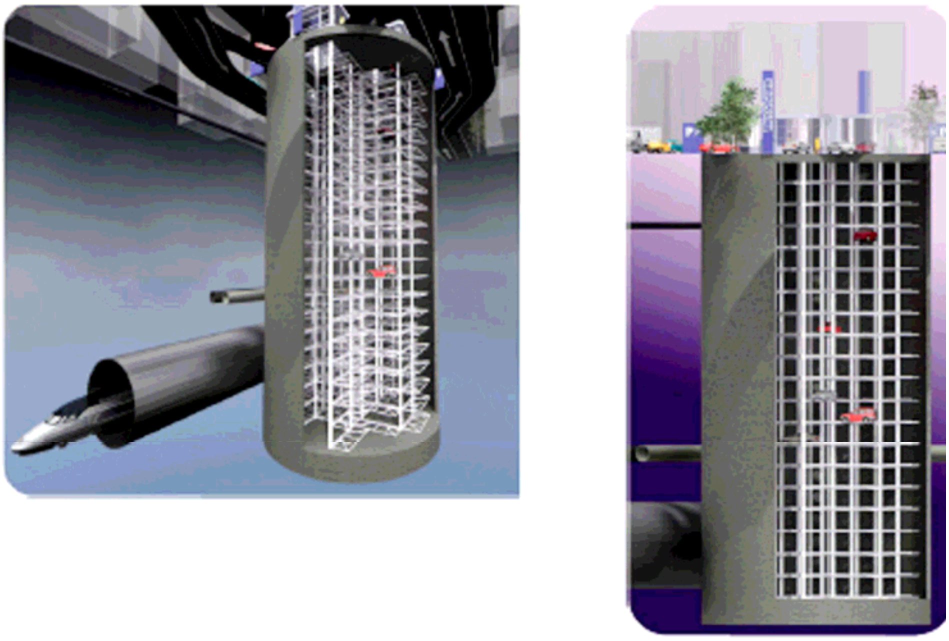

Fig. 16. Illustrations for the construction of large diameter shafts for sub terrestrial parking garages.

Conclusion and outlook

The illustrated projects and the experiences gained show that the mechanical construction of shafts offers an enormous potential for the development and that present mechanical solutions meet with a general approval.

Shaft diameters of up to 11 m at a depth of over 60 m have already been realised with this equipment. Concepts and studies for diameters of up to 30 m and a depth under groundwater of 100 m and even more have been worked out. Different applications ranging from start shafts for microtunneling systems to sub terrestrial parking systems as well as shafts for mining purposes have been developed and realised with different shaft construction technologies.

With regard to geological and hydrological conditions, solutions can already be provided for any non-groundwater bearing and groundwater bearing soils. The partial-face design allows to excavate soft to medium hard rock; and for a limited period sections with rock strengths of 200 MPa and more also be driven.

Economically, a shaft must have a minimum depth to make this machine technology more attractive compared with conventional methods. This minimum depth ranges between 15 m and 25 m and is determined by, geological conditions and the shaft number. It is already concluded that a calculation for the installation of shaft is more precise due to less risks.

During this development process, the aim is to further optimize the process and the machine technology illustrated above and to develop new innovative processes in the field of mechanical shaft construction.

References

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