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A Decade of Experience in Micro-Tunnelling in Switzerland

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ABSTRACT: Micro-tunnelling and pipe-jacking are methods that are used to construct crossings beneath existing traffic arteries (railways, motorways) and rivers or other man-made or natural obstacles. Each case is unique and poses different smaller or larger challenges. Over more than one decade of experience has been accumulated for different sizes of micro-tunnelling in vastly different ground conditions. Based on this experience it is possible to identify the factors depending on ground conditions and machine size and draw more general conclusions than from single cases. Subsoil conditions dictate the choice of the methodology. Below the groundwater table essentially only closed-face machines can be used. Above the groundwater table open-face pipe-jacking may be possible. In clean sands and gravel incidental measures like grouting may be necessary to prevent instability of the face with a cave-in to the ground surface. Boulders in glacial soils may pose a larger hindrance to smaller diameter micro-tunnelling machines than to larger ones.

1 INTRODUCTION

Micro-tunnelling and pipe-jacking are used to construct crossings for services and infrastructure (electric cable lines, communication cables, gas, water and wastewater lines) beneath rivers and existing roads or railways. The required diameter of the placed pipes depends, on one hand, on the size and number of the cables and pipes to be placed and also, on the other hand, on the possibilities and capabilities of the machines used. Groundwater conditions determine whether an open-face shield with pipe-jacking can be used or a closed face system must be used. For very small diameters and a single pipe or cable, directional drilling may be used which is not within the scope of this paper. General requirements for pipe-jacking and micro-tunnelling will be given first, followed by the experiences of several case histories.

1.1 Pipe-jacking above the groundwater table

Pipe-jacking requires a minimum internal diameter of 1.25 meters such that men can work inside the pipe and excavate the soil at the face. Theoretically, an internal diameter of 1 meter can be excavated by a small person, which is used only when external constraints do not permit the use of a larger diameter. These small diameter pipes are used only if the pipe is not to be entered after installation of the cable or the product pipe or if it is to be employed as a wastewater line. For cable ducts with main cables it may be necessary to enter the pipe afterwards, this requires a minimum internal diameter of 2.0 meters. The thickness of the pipe wall (lining) is about 10 percent of the diameter. For a 2 meter diameter pipe this means 200 mm or for a 1.5 meter diameter pipe the thickness of the lining is 150 mm. Each case has to be individually designed, taking into consideration the jacking forces for the entire pipe string including intermediate jacking stations.

In case the pipe-jacking crosses through water-bearing ground dewatering is necessary or compressed air may be applied. In running ground without groundwater pre-treatment by grouting may be necessary.

1.2 Micro-tunnelling above and below groundwater

Micro-tunnelling allows use of substantially smaller diameters that can no longer be entered by persons, either during driving or in service, than pipe-jacking. Manufacturers sell machines as small as 150 mm diameter. In the geological conditions of Switzerland with mostly quaternary glacial soils, the minimum external diameter used is 860 mm for a pipe that is not to be entered. For pipes that are to be entered an internal diameter of 1.2 meters is usually used, giving an external diameter of 1.6 meters. The next practical size up is a diameter which can be walked through, with an internal diameter of 2.0 meters. The linear dimensions from each type of machine to the next larger one increase by a factor of two, the cross-section of the machine with a factor of four and the volume and mass by a factor of 8, nearly one magnitude. Even though all these machines are characterized as micro-tunnelling machines there are substantial differences in size, power and mechanical equipment. The operation of micro-tunnelling equipment and handling of the ground in general, particularly with boulders, differs with the size of equipment.

2 PIPE-JACKING

Pipe-jacking is primarily used above the ground water table or in cases where the water table can be lowered from the surface. The two following examples indicate the use of pipe-jacking above groundwater and the importance of the content of fines on face stability.

2.1 Natural gas pipeline beneath a motorway

A natural gas main pipeline of 24" (625 mm) diameter had to cross beneath a major motorway in central Switzerland (Figure 1). Now, some years later, a new high-speed railway is being built parallel to it. The exploration on both sides of the motorway indicated the presence of clean gravel without fines. The groundwater table is about five meters below the surface. It was thus possible to select a gradient above the water table. Based on the results of the exploration on both sides of the motorway, the potential of face instability was judged to be high. Incidental measures were planned, like grouting ahead of the face.

However, the contractor learnt from his senior staff that, during construction of the motorway some three decades ago, the gravel underneath the motorway had been excavated down to groundwater level and was substituted by glacial till. The gravel was used for the construction of the motorway (base course) itself. This information could be verified during construction of the gas pipeline. The ground beneath the motorway consisted of exchanged fill, mostly clayey and silty gravel to gravelly clay. The excavation beneath the motorway could thus proceed without danger to the motorway from face instability. In this case the main lesson derived was that good quality ground for road construction was substituted with poorer quality ground which is, however, much better ground for pipe-jacking. A similar project constructed later in clean gravel required much more attention from the construction personnel during excavation and very careful backfilling of the voids along the pipe string.

2.2 Electric cable duct beneath two railways

A cable duct from a substation had to be constructed below two major railway lines in the city of Berne, one being the main east-west line in Switzerland, linking Zurich via Bern to Geneva. The second line is a major suburban line that passes beneath the main line. In the area between the two lines lies the depot for the suburban railway, which was to be enlarged and required the replacement of an existing cable. The new cable duct required an internal diameter of 2 meters in order for it to be entered by personnel to maintain or replace cables. The ground conditions, the tracks above the pipe and the other structures are shown in Figure 2.

The ground had been formed by retreating glaciers and had experienced some man-made interventions. Beneath the main railway and the switching freight tracks on the south side, the original gravel had been left in place. Samples taken from borings on both sides of the main railway indicated gravel with a fines content (d =0.06mm) less than 10 percent. The gravel extended beneath the area of the depot. However, to the north, gravel had been removed above glacial clay and fill placed. The fill consisted of clayey gravel and some building debris (bricks). Ground conditions were judged with the empirical criteria presented by Deere et. al. (1969). Driving beneath railway tracks poses a danger due to settlements and face instabilities. Underneath the local railway the pipe had 2 meters of overburden. The fill had some cohesion but was not groutable. The only measures taken was monitoring of the track position, which was particularly delicate in the curve of 177 meters radius. The position of the track was corrected by tamping during pipe-jacking.

The main railway authorities requested the placement of temporary auxiliary bridges in case face collapse could not be positively avoided. With an overburden of 6 meters in gravel the possible width of a crater was estimated to be around 12 meters. Thus temporary bridges with a span of about 18 meters would be required. The cost of these bridges and the disruption would be substantial. An alternative was selected which consisted of grouting the soil close to the pipe, about one meter all around. With these measures the bridges were no longer necessary.

For grouting, three fans of borings were drilled from outside the track area (Figure 2). The fans were spaced at 1.5 meters perpendicular to the pipe. The centre fan was located in the axis, the lateral fans with their pipes were located immediately outside the pipe. The borings were equipped with sleeve packer pipes (tubes-à-manchettes) spaced every 0.33 meters. The grouted material had to have a minimal unconfined strength of $\sigma_c > 1$MPa but not exceed $\sigma_c < 4$MPa in order to be excavated without too much effort in the pipe jacking. The grouting started first with two outer rows, finalizing with the centre row for each stage of grouting. A limiting quantity, corresponding to filling the voids 1.5 meters around the pipes, was specified per opening. A second criteria was a limiting pressure of 10 bars after opening the packers. Grout for the first stage was made from a mixture of bentonite, cement and water. For the second stage silicate grout was used. The centre row was grouted last. The phased grouting was used to verify the success of grouting. The least amount of grout was used in the ports of the centre rows, thus indicating that the ground around the pipes was successfully treated.

Pipe-jacking started from the northern shaft and proceeded without difficulty underneath the local railway. The position of the tracks was rectified once the measurements indicated the necessity. No incident occurred until the second last pipe was jacked, when suddenly heave occurred which shifted the position of the rails sufficiently, such that the overhead current collector "derailed" and damaged the catenary of the local railway. Heave was most likely caused by a brick that was shoved by a joint in the pipe string.

In the fill excavation proceeded without much difficulty. However, once the shield of the pipe-jacking entered the short zone of gravel, the face was at limit equilibrium and face stability could only be guaranteed with an intermediate platform that kept back the running gravel. The shield became difficult to steer, although no face collapse occurred. Once the shield entered the grouted zone these problems vanished. Thus the proof of the necessity of pre-grouting could be made in-situ.

The main tracks were levelled prior to grouting and during pipe-jacking no measurable heave or settlement was recorded, thus indicating a successful tunnelling operation.

3 MICRO-TUNNELLING

In case the planned pipeline lies below the groundwater table micro- tunnelling is applied. Experience with an external diameter of 864 mm corresponding to 600 mm internal diameter was gained as well as with 1200 mm internal diameter and 1550 external diameter pipes. In all these cases boulders were to be expected, thus the cutter head was equipped with disc cutters to cope with boulders or rock. The machines incorporated a stone crusher made from the cutter head and a conical piece of the body.

3.1 Small diameter micro-tunnelling (D =864 mm)

Small diameter micro-tunnelling is used for wastewater pipelines or the placement of small diameter gas pipes. Three cases, each about 80 meters long, with different ground conditions are described.

3.1.1 Pipe for gas pipeline beneath road junction

A gas pipeline of 250 mm diameter had to be replaced during a complex widening project of a road junction. A pipe with an internal diameter of 600 mm was sufficient. The existing gas pipeline had been placed in the old underpass of the motorway access which was to be doubled in width. At the same time the roads and a railway crossing over the motorway and pipeline had to be widened. A longitudinal section is shown in Figure 3.

The soil consists of post-glacial clay on the northern side and glacial clays to the south, both underlain by glacial sands. The bridges were founded on driven piles. An 864 mm external diameter micro-tunnelling machine was used from the south. The starting and retrieval pits were constructed with sheet piles. The departure and entry openings for the machine were stabilised by dewatering with well-points.

Driving was mostly in glacial clay with a tendency to some stickiness. This was overcome by using a strong flushing of the liquid circuit.

3.1.2 Drainage pipe beneath four railway tracks

This pipe was similar in length to the previous one and forms the drainage at the western portal of the Grauholz tunnel (Steiner, 1988). The gradient had to be maintained accurately. The pipe is located in clay and terminal moraine. The clay caused stickiness problems which were overcome by strong flushing as in the case described above. Another section contained many boulders with diameters of 300 to 500 mm. With increasing driving distance the torque and the jacking thrust increased substantially, however, the whole length was driven successfully. Once the machine arrived in the dewatered open retrieval pit, the reason for this increase in resistance could be identified. Several boulders with 300 to 500 mm diameter had accumulated ahead of the machine and were shoved ahead and turned around. The boulders were torn from the dense silty gravel and once loose could no longer be cut by the disc cutters. This does not mean that the disc cutters and stone crusher were ineffective and unnecessary, it instead illustrates their limited effectiveness.

3.1.3 Wastewater pipeline in a rock slope

A wastewater pipeline at the base of a steep slope had to cross a rock ridge over 90 meters in distance. At first an open trench with a depth of up to 6 meters was considered. This would have caused problems of safety and environmental impact due to blasting or hydraulic excavation, not to mention the considerable costs. Instead, an 864 mm micro-tunnelling machine with a rock cutting head equipped with disc cutters was selected. The major problem that developed during driving was the production of sand, which was not all carried into the cutter head and transported away by the transportation circuit. The sand remaining outside accumulated in the gap between stable rock and the outside of the machine and pipe. This void might thus become filled with sand and the pipe string together with the machine might become stuck in the ground. In order to remove most of the sand, stronger flushing was applied which proved successful. Also some bentonite was added to the liquid. In addition, the void between the pipes and rock was filled with bentonite slurry to lubricate the advance.

The three case histories presented are all located within a 10 kilometre radius to one another, they illustrate the importance of the local ground conditions that have to be taken in consideration.

3.2 Medium diameter micro-tunnelling (1.55 m)

Medium diameter micro-tunnelling was applied for the placement of the major gas pipeline beneath a motorway above water saturated silts and sands. A longitudinal section with geometry and underground conditions is shown in Figure 4. The silt and sand with the groundwater table close to the natural surface can only be successfully dewatered with closely spaced well-points, which was obviously not feasible in this case without causing substantial disruption of traffic. Thus micro-tunnelling with a closed face was used. The starting pit with a depth of 4 meters was excavated within sheet piles and well-points were applied for stabilizing the departure face. The machine was equipped with disc cutters and a stone crusher. The tunnel drive did not encounter any particular obstacles and arrived without problems in the retrieval pit.

3.3 Micro-tunnelling in gravel beneath a river

The same gas pipeline as above had to cross beneath a major river. Two parallel micro-tunnels had to be driven for the new and existing pipeline which before had crossed over the river (Figure 5), actually a canal, built during the 19th century. The subsoil is glacial gravel which was deposited by the retreating Rhone glacier. The gravel is rounded with the majority of the grain size smaller than 100 mm. Larger sized stones and boulders can, however, still be found in this ground. The pipes also had to have a minimum cover of 2 meters under the river bed. Groundwater was high, close to the ground surface. After a comparison of various alternatives it was decided to place the starting and retrieval pits inside the lateral dams in the upper flooding zones. These zones had not been flooded during the last 25 years. Thus the small risk was taken that the pits could be flooded. An extreme flood actually occurred when the starting and retrieval pits were excavated, flooding both pits, but luckily the micro-tunnelling equipment had not yet been installed.

For access of the micro-tunnelling machines two deep shafts were built on both sides of the river (Figure 5). The excavation depth was 11 meters and the maximum cover of the pipe was 9 meters. The starting pit was 8 meters long and 6 meters wide, whereas the retrieval pit was 6 meters long and 6 meters wide. The sheet piles were 17 meters long and after excavation a concrete slab was placed at the bottom of each shaft. For the departing and entering of the micro-tunnelling machine a hole had to be cut into the sheet piles of the shafts. These zones had to be stabilized by grouting with cement-bentonite and silicates.

During the driving of the first pipe string the machine experienced very high resistance about every 8 to 10 meters but tunnelled successfully through the entire 72 meter drive. However, with the second drive the machine was completely blocked after 56 meters (Figure 5). When the machine was reversed it was possible to rotate the cutter head again, however, when advancing, the cutter head became completely blocked again. The reason for this blockage was difficult too identify and therefore difficult to find a remedy.

At first when the river bed was inspected by divers, they located a crater in vicinity of the blockage but could not identify any obstacle in the river bed. In a second phase material was excavated and exchanged from a pile drilling rig on a pontoon. Five overlapping drill holes of 1.3 meters diameter were carried out in front of the tunnelling machine. The two drilling closest to the machine indicated stones of up to 150 mm in diameter. In the drill holes further away the maximum diameter stone found was only 60 mm. No other obstacle, such as a pile or sheet pile was found.

Despite the exchange of soil it was still not possible to advance the machine. Therefore, a retrieval plan was started. A second tunnelling machine with the same diameter was started from the retrieval pit and driven towards the blocked machine. This drive of 16 meters was safely carried out. Once this second machine had reached the first one, the first tunnelling machine was driven again so that the second machine with its pipe string was being pushed back into the retrieval pit. The second pipe string could thus be completed and both machines recovered.

Once the first machine was recovered a very hard rounded boulder of quartzite with a diameter of 300 mm was found inside the stone crusher. Quartzite has a very high compressive strength ($\sigma_c > 300$ MPa) as well as an extremely high tensile and point load strength. This boulder may have been the reason for the blockage. The necessary strength for splitting such a boulder can be assessed from the relation of the size correction for point load tests and a splitting force exceeding 1000 kN was estimated. This force is sufficient to pull the cutter-head out of the machine body and to block up the machine completely. This was considered to be the most likely reason for the blockage.

Since the pipe-crossing is located close to the training area for building emergency bridges, piles were first suspected in the area, although the pipes were located outside the recorded area of bridge exercises. Also the driving of wooden piles had to be stopped after about one meter of pile driving, as the piles no longer penetrated and the pile shaft was being damaged. Thus the presence of an artificial obstacle must be considered to be rather remote. The piece of metal found in the muck of the machine was most likely shaved off by the much harder quartzite rock from the body or cutting wheel. Financial matters have been resolved and the pipelines are in operation.

4 LESSONS LEARNT AND CONCLUSIONS

The experience from various micro-tunnelling and pipe-jacking projects allows one to draw some general conclusions, not possible from single case histories alone. With micro-tunnelling underground crossings that would otherwise be impossible have become feasible.

4.1 Boulders

Boulders may present a major obstacle to micro-tunnelling. Small sized micro-tunnelling machines have openings in the cutter head of about 100 to 150 mm diameter, which mean boulders that are larger cannot enter the cutting head and stone crusher. In case they are torn out of the soil matrix they will be dislodged and rotated around ahead of the cutter head.

Boulders are mostly made from the strongest available rock within the reaches of the glacier. The largest boulders often have the highest strength. The medium sized micro-tunnelling machines have larger openings in the cutter head, thus larger sized boulders may enter the stone crusher. The size and strength of boulders may exceed the capacity of the stone crusher, leading to a blockage. It is not possible to enter the working chamber of small (less than 1 meter diameter) and medium (1.5 meter diameter) sized micro-tunnelling machines. An opening for entry from the compressed air chamber into the working chamber may be possible for machines with a larger diameter (> 2.5 meters). In large properly equipped slurry shield machines boulders present a minor problem (Steiner & Becker, 1991; Scheidegger et al. 1993).

Boulders are present in glacial deposits or close to mountain ranges in the different mountain ranges of the world and must be dealt with during planning and tendering.

4.2 Sticky soil

Sticky soils (clays) may present an obstacle so that the liquid circuit and the cutting chamber become clogged. In order to reduce the risk of clogging the circuit has to be operated at a sufficiently high rate of flushing.

4.3 Face stability

Face stability and loss of ground may become a problem in very pervious ground and similar measures as in large diameter slurry shields (Jancsecz et. al., 1994) have to be taken.

4.4 Complexity of projects

Micro-tunnelling projects are usually complex. The starting and retrieval shafts are often major works of their own that have to be built to withstand high water pressures. The zones of ground where the micro-tunnelling machine leaves the shafts has to be designed accordingly. Ground has to be stabilized with appropriate means, like grouting if feasible, jet-grouting, freezing or localized dewatering, similar to larger tunnels (Steiner, 1997).

4.5 Misleading subsoil information

It is possible that subsoil investigations made at the side of the obstacle to be under-crossed may deviate from the conditions beneath it. Soil may have been removed and substituted by fill which has different characteristics. In one case described the poorer soil for road construction was good material for pipe-jacking.

In gravel the fines content may be overestimated since the fines did not occur naturally, but as powder, a bi-product of drilling.

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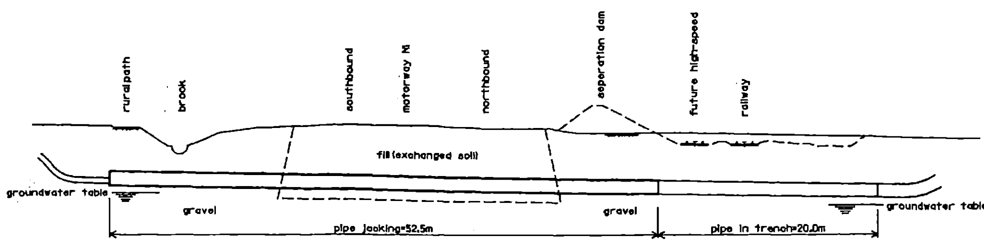

Figure 1. Pipe-jacking below motorway through previously exchanged soil

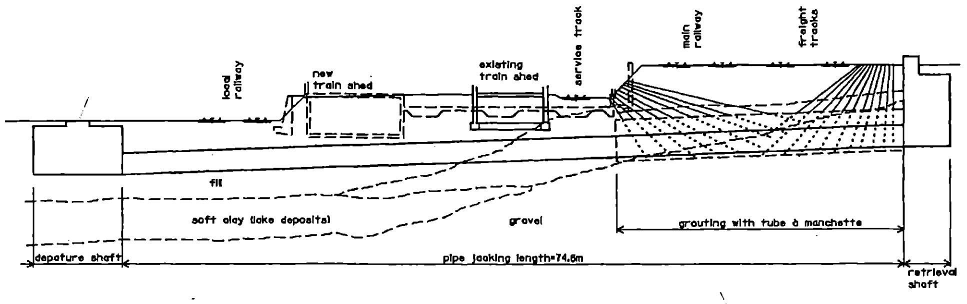

Figure 2. Section along cable duct beneath railways

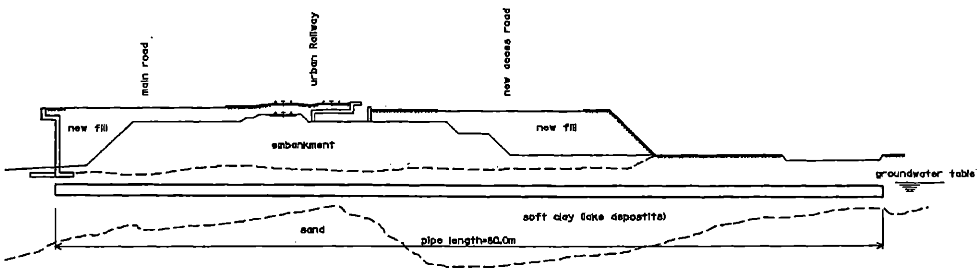

Figure 3. Micro-tunnelling at road intersection through sand and clay below the groundwater table

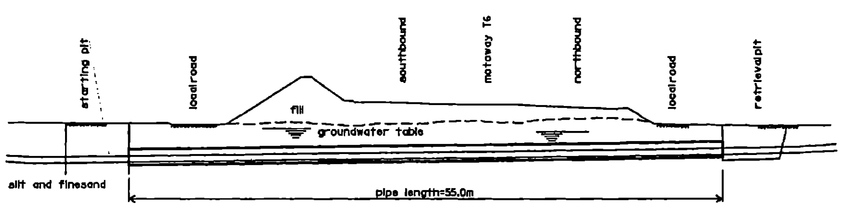

Figure 4. Micro-tunnelling ($D_e = 1.6$ m) beneath motorway through saturated silt and sand

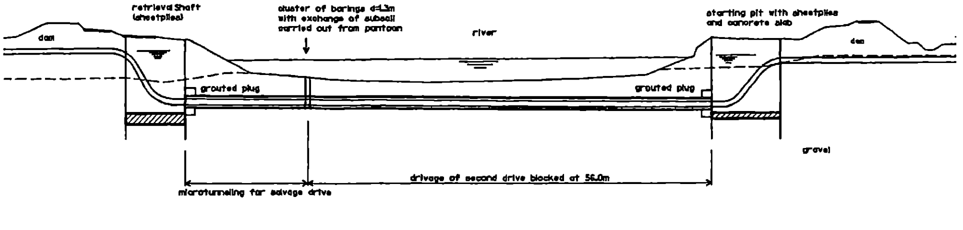

Figure 5. Micro-tunnelling, two parallel drives beneath a major river through gravel; Location of incident during second drive and recovery effort with soil exchange and counter advance