Problems of TBMs in Water Bearing Ground

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Abstract

Tunnelling in water bearing soft ground is always a challenge even for experienced crews and engineers. The stabilisation of the tunnel face and the water inflow into the excavated cavity can be mastered by application of mechanised tunnelling methodology. Even though risks can be reduced by TBM tunnelling, unexpected problems may still arise during the tunnelling process. Special methods need to be applied to overcome the problems and to guarantee a successful completion of the tunnelling project. The following four case studies, problematic TBM projects in water bearing soft grounds are presented to show how the problems were overcome.

1 Introduction

Water has a more or less significant impact on tunnelling conditions. The softer the ground, the more dramatic the influence. In hard rock-, the impact of water is restricted to fault zones with soft consistence.

However, in soft material the ground water determines the tunnelling methodology. If dewatering of the ground is not feasible, tunnelling in water bearing soft ground can only be performed if the inflow into the excavation area is prevented. To achieve this, the permeability of the ground can be reduced by injection or ground freezing, or the water inflow can be prevented by application of mechanized tunnelling methodology.

Modern Tunnel Boring Machines, with competent operation procedures, permit tunnelling in water bearing ground with limited risks. Nevertheless, due to the considerable spectrum of natural –ground conditions, even experienced tunnellers will continue to be surprised by unexpected events. An account of some of these events is given below.

2 Jammed by Compacted Soil in Surrounding Steering Gap

2.1 Pipe - Jacking Machu Picchu

In 1998 a major landslide occured along the Vilcanota River overflow for the Hydroelectric Power Project Machu Picchu in Peru at the feet of the world-famous Inka ruins. To re-establish the plant, a 150 m long twin-tunnel of 3,10 m outside diameter had to be driven through water bearing sedimentary soils in silt, clay and medium dense silty sands. The overburden was 43 to 58 m. A Slurry - TBM in front of a string of pipe sections each 2,5 m long had been jacked from a concrete lined start shaft.

Two intermediate jacking stations, each with a capacity of 20.000 kN, were installed, one behind the machine unit M1 and the other behind pipe section No°6.

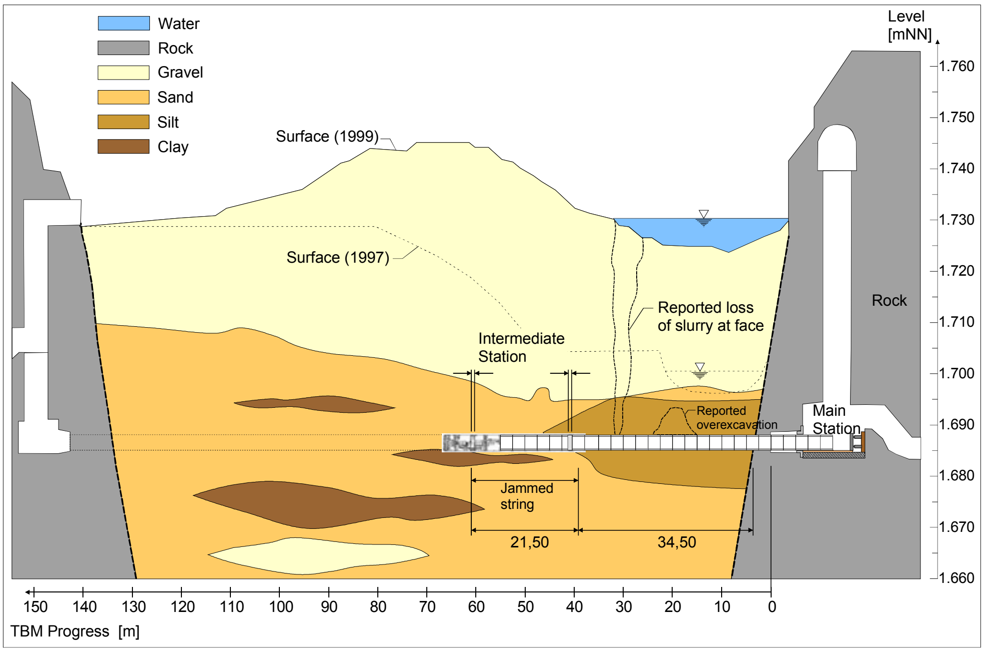

Figure 1: Project layout

After 66 m advance the drive came to a halt because of excessive friction around the perimeter of the forward string section. The 34,5 m long back part remains movable when pushed from the main jacking station in the start shaft to the intermediate station at section No°6. However, the 21,5 m long forward section between the intermediate station behind the machine unit M1 and the pipe section No°6 was jammed by soil compacted in the steering gap around the pipe sections.

The steering gap, usually 2 - 3 cm thick, is injected with Bentonite slurry to reduce the friction while jacking the pipe string through the ground.

In the blocked string section, the ground consisted of fine to medium graded medium dense sand, whereas cohesive soil had been encountered in the rest of the string. The permeability of the sand reached k - values of 10^{-4} m/s.

Because of the relative high permeability, the Bentonite slurry disappeared in the ground without creating the intended lubrication. Instead of the lubricant, fine sand filled the steering gap and blocked this section of the string. All endeavours to move the string failed. Attempts to flush out the sand by water injection had not been successful.

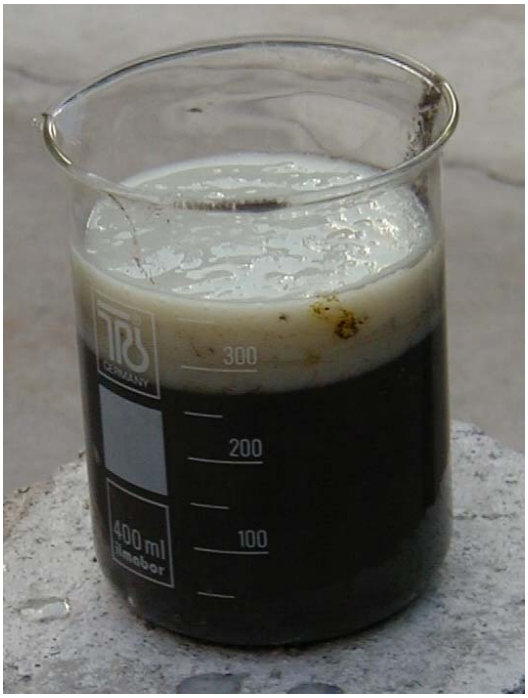

Figure 2: Special Bentonite mixture

Finally a special B~~B~~entonite suspension, containing polyanyonic cellulose, foaming agent and water soluble cutting oil was viscous and stable enough to keep the steering gap open. This suspension was injected in a controlled sequence under high pressure through a narrow pattern of outlets in the string.

Figure 3: Injection outlet pattern

In addition to the creation of -stable lubrication, the pore water pressure in the soil around the string was increased by the high injection pressure, thus reducing the shear strength in the sand to the stage of liquefaction.

After 2 months of interruption, the pipe jacking project could be successfully terminated.

2.2 Slurry - TBM under Albert - Channel in Belgium

For an utility transfer line, the Albert - Channel in Belgium had to be underpassed with 18 m cover to the channel bed by a Slurry - TBM with a boring diameter of 3.72 m. The tunnel was lined by grouted reinforced concrete segments.

In 1998 after passing through different water bearing geology, the TBM entered into a Calcaire formation. Here the thrust forces increased continuously to a level which stopped the TBM after 30 m, unfortunately exactly under the channel.

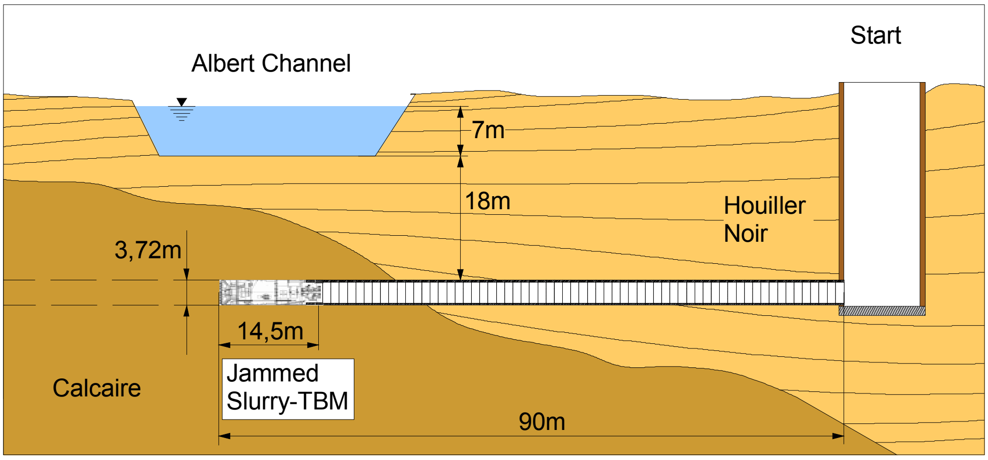

Figure 4: Project layout

The approx. 14.5 m long TBM was completely jammed by finely ground limestone particles which entered the steering gap around the shield of the TBM. This ground limestone passed through the gap between the cutter head and the soil. It was transported by the slurry due to a pressure difference between the support pressure at the face and the ground water pressure. Joints in the limestone facilitated the flow. The grinded limestone settled in the steering gap.

Also grinded limestone penetrated through the 3 - 5 cm wide gap in the cone crasher between cutter head and cutting edge of the shield.

On this TBM the so called back scrapers were missing. These are small scrapers attached to the back side of the cutter head rim to lift the finely grinded material from the bottom and to create local turbulence in the slurry. Otherwise the suction forces at the inlet of the transportation line are not strong enough for dislocation.

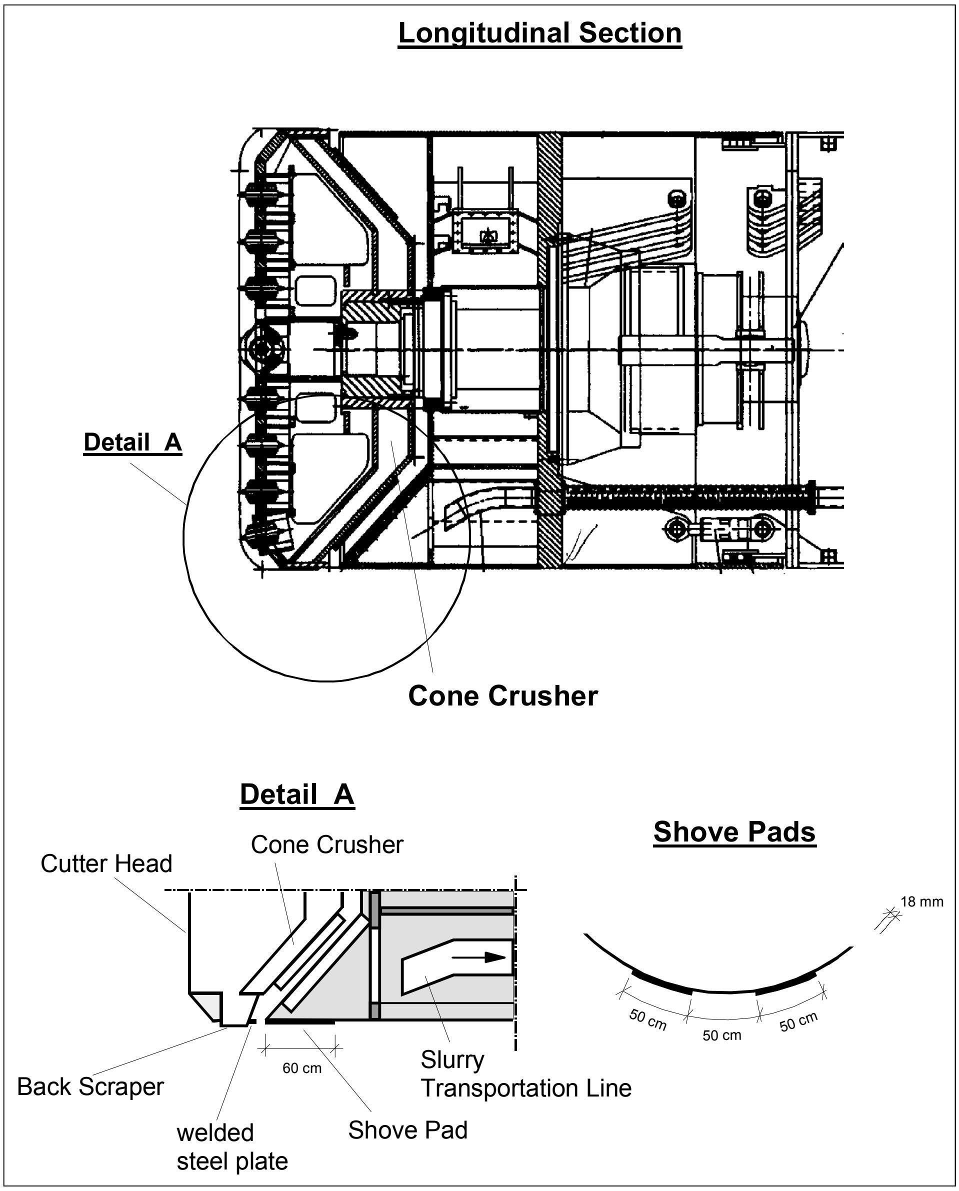

Figure 5: Cutter head

The grinded material finally jammed the TBM. It was concentrated at the invert area and was compacted under the shield.

This TBM was freed by systematic flushing with a rush of water through several additional outlets drilled through the skin of the shield and through the 7 injection outlets installed in the tail shield section.

The pressure of the injected water was 0.5 bar higher than the pressure in the working chamber at the front of the TBM. 200 m^3 water per hour were pumped continuously in circulation during several days to free the machine.

After adding back scrapers to the cutter head, and with a constant water flow from the tail shield area into the working chamber at the front, the drive continued without further problems.

Additionally, the width of the gap between cone crusher and edge of the shield was reduced by welded steel plates.

The constant water flow has been provided by injection through the 7 injection outlets at the tail shield. The pressure relative to the slurry pressure in the working chamber was 0.3 bar.

3 Fluctuating Support Pressure in EPB - TBMs

At a Metro project, 6,3 km tunnels will be excavated by EPB - TBMs with a boring diameter of 8,7 m.

The rock mass through which the tunnels have to be excavated comprises of Granite. The conditions vary from fresh to moderately weathered high strength granitic rock to completely weathered soil-like materials. It has to be realized that granite “core stones” of variable size are embedded in soil-like weathered material and that this results in mixed face conditions for the tunnel drive.

The permeability of the granitic mass is very heterogeneous and varies between $k = 10^{-4}$ to 10^{-6} m/s.

The geological and hydro-geological conditions lead to the decision to use an EPB-TBM.

Figure 6: Heterogene geology

Figure 7: Core samples of heterogene geology

At the end of 2000, on the beginning of the drive, the EPB - TBM was operated in closed mode and partly in a semi-closed mode. That is with a half filled working chamber and compressed air support applied to the upper part of the face.

During the first 400 m of the drive, 3 collapses happened, the last one caused destruction of an overlying house in which an occupant died.

This accident questioned the method of operation and it was stipulated that the EPB - TBM only be operated in the closed mode with strict control of the face support pressure.

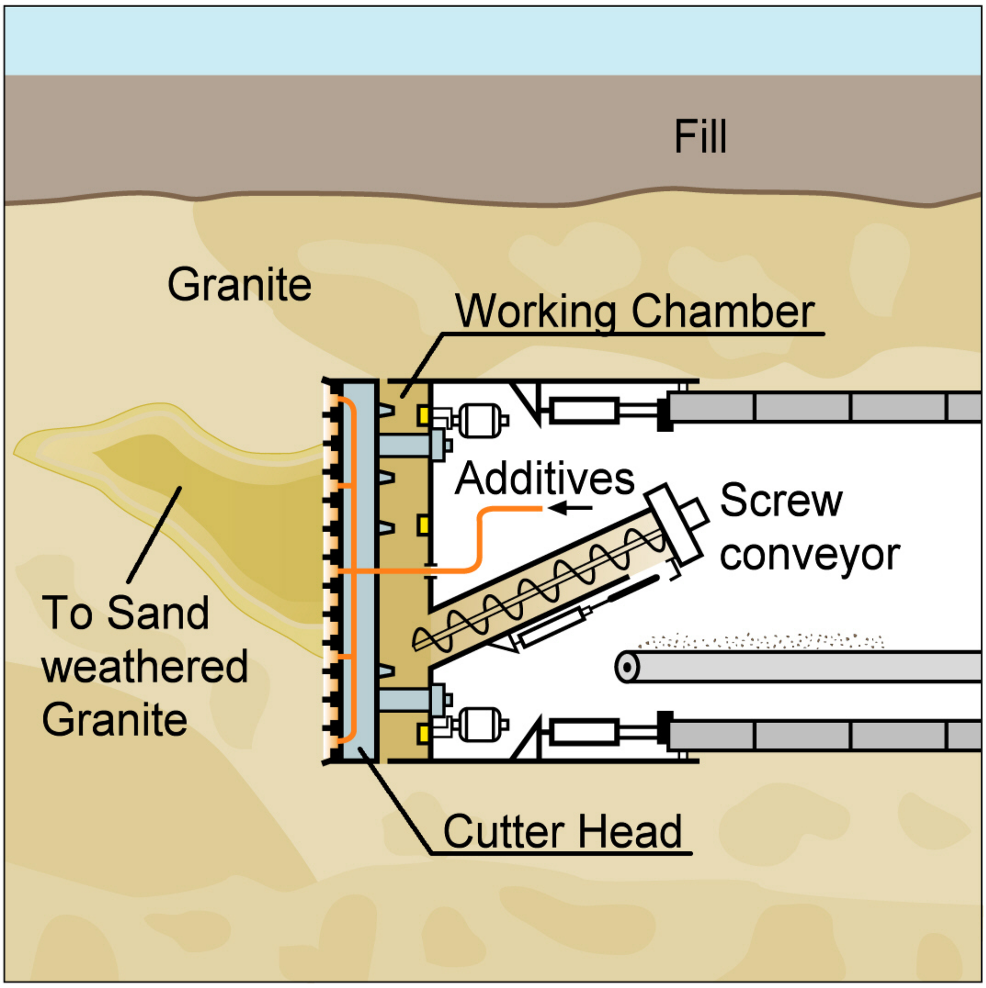

Figure 8: Earth Pressure Balanced - TBM

The face support pressure of EPB - TBMs is controlled by measuring the pressure at the bulkhead with pressure cells, approximately more than 1,5 m from the face.

In closed mode operation, the working chamber is completely filled with conditioned excavated material, the earth paste. The earth paste is pressurized by the advancing forces induced by the advance jacks via the bulkhead. The pressure level is controlled by the effectiveness of the excavating cutter head in relation to the discharging screw conveyor.

To verify a complete filling of the working chamber, the density of the earth paste in the working chamber will be controlled by pressure cells on the bulkhead at different levels. This method satisfies the demand of preventing a sudden instability of the face caused by a partially empty working chamber. But does it guaranty a reliable face support pressure?

Pressure measurement at the bulkhead, 1,5 m behind the face, provides only partial information about the support pressure at the face. The support medium, the earth paste created from excavated ground, conditioned by a suspension with different additives, must have the physical properties of a viscous liquid. However, the shear resistance in that viscous liquid reduces the support forces which can be transferred onto the face. The shear resistance of the earth paste depends on the excavated ground and the conditioning, which is a complex and sensitive procedure. Consequently, the shear resistance of the support medium often varies considerably.

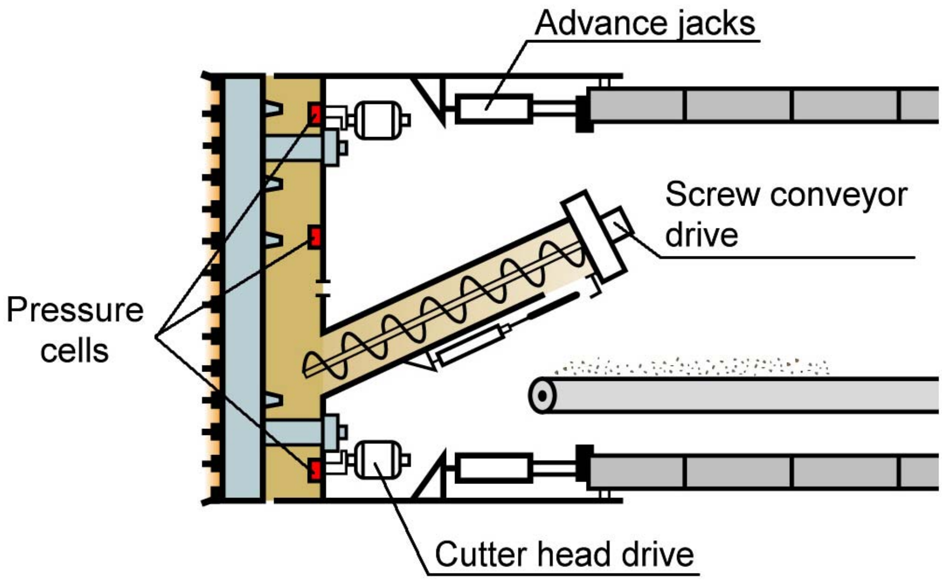

Figure 9: Measurement devices for face support pressure

Equipment for pressure measurement at the cutter head have been shown to be not reliable.

Therefore, the fluctuation of the face support pressure exceeds to more than 0.5 bar. This fluctuation might be acceptable in an homogeneous geology. However, in mixed ground, as found at the Metro project mentioned- above, the inconstant support pressure entails the danger of a creeping over-excavation.

An additional Active Support System can smooth down the frequency of face support pressure fluctuations.

This system positioned on the back-up train consists of a container filled with pressurised Bentonite slurry linked to a regulated compressed air reservoir. The Bentonite slurry container is connected with the crown area of the working chamber of a EPB - TBM.

If the support pressure in the working chamber drops down under a predetermined level the Active Support System automatically injects pressurised slurry as long as the pressure level loss in the working chamber is compensated. This Active Support System additionally installed to the EPB - Technology works in the same manner to that in a Slurry - TBM.

This automatic pressure control system reduces the range of fluctuations of the face support pressure down to 0.2 bar.

The automatism is especially required if the excavated ground is conditioned with foam, which consists mainly of air bubbles. The air bubbles diffuse after some time, reducing the volume of the support medium and consequently lowering the pressure level.

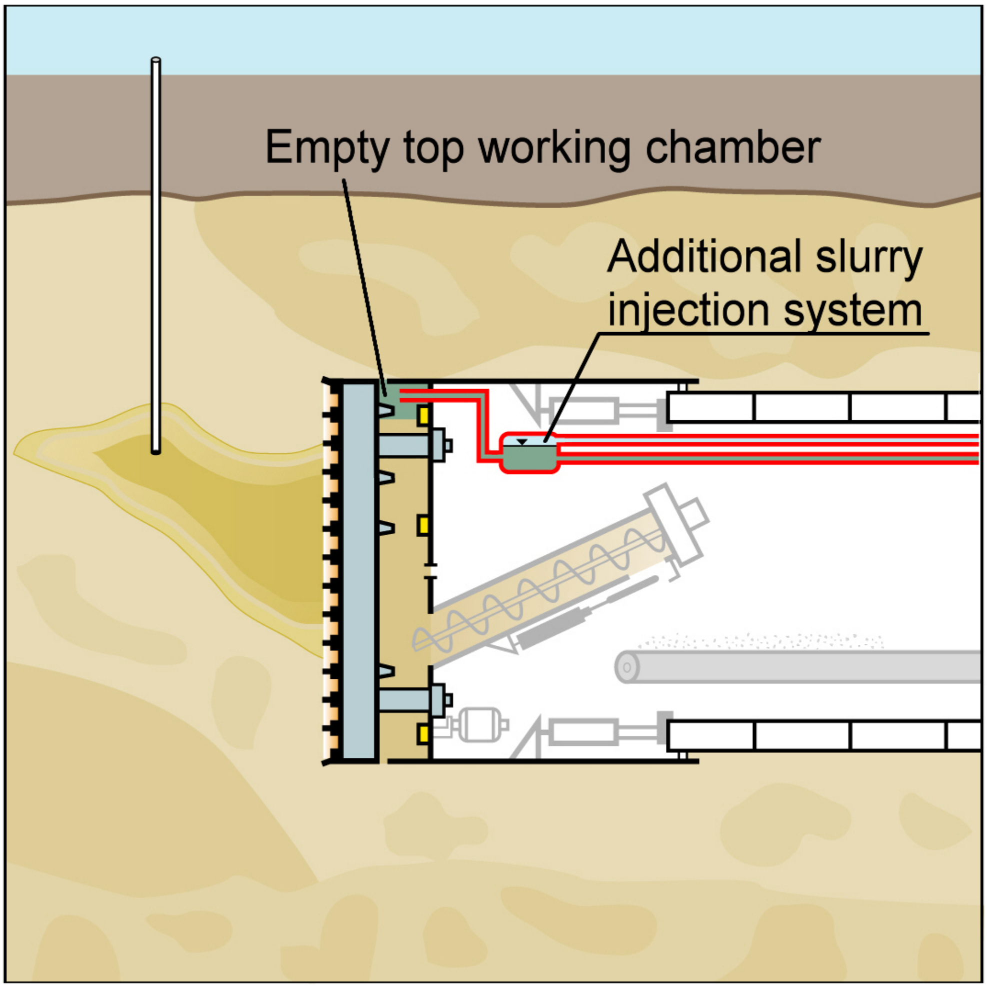

Figure 10: Active additional support system

The additional Active Support System was applied first time at the described project. It was the essential installation in the EPB - TBM drive of ∅ 8.7 m to underpass old houses with a cover of 3 m to the foundations, without any mitigating measures and with surface deformations of less than

5 mm. Simultaneously the Active Support System has been linked with the steering gap around the shield, filled with Bentonite slurry, providing a reliable filling of the gap under predetermined constant pressure.

4. Stones and Boulders a Hindrance to Pressurized TBM - Drives.

A tunnel drive in a glacial formed geology, as in Berlin, has to face stones and boulders embedded in a soft soil –matrix. These ground conditions represents a challenging task for pressurized TBM drives.

Figure 11: Glacial formed geology

At a 5,4 km sewer tunnel project in Berlin, 3 Slurry-TBMs have been used with a boring diameter of 3,8 m–. Whereas the Berlin ground in general favours the application of Slurry-TBMs, the frequently embedded stones and boulders often causes difficulties for the tunnel drive.

For example, a collapse of the face created a sinkhole to the surface. The overburden was 15 m. The TBM had been operated with a penetration rate of 45–60 mm per rotation in sand and gravel with embedded stones. The sinkhole– developed during attempts to free the cutter head which was apparently blocked by stones or boulders ripped off the face. The cutter head was freed by rotating in both directions without TBM advance and circulation of the slurry circuit.

An analysis of the machine and operation data shows that the TBM had been driven with a relatively high penetration rate of 45-60 mm per rotation. Encountered stones had been ripped off the face and crushed by the stone crusher. In this section where the cutter head was obviously blocked the number of stones had increased. The now larger number of stones banked up at the invert of the working chamber and blocked the cutter head.

Analysis of the objective data has demonstrated that the TBM had been operated in that section of the alignment with too high a rate of advance which had caused the event.

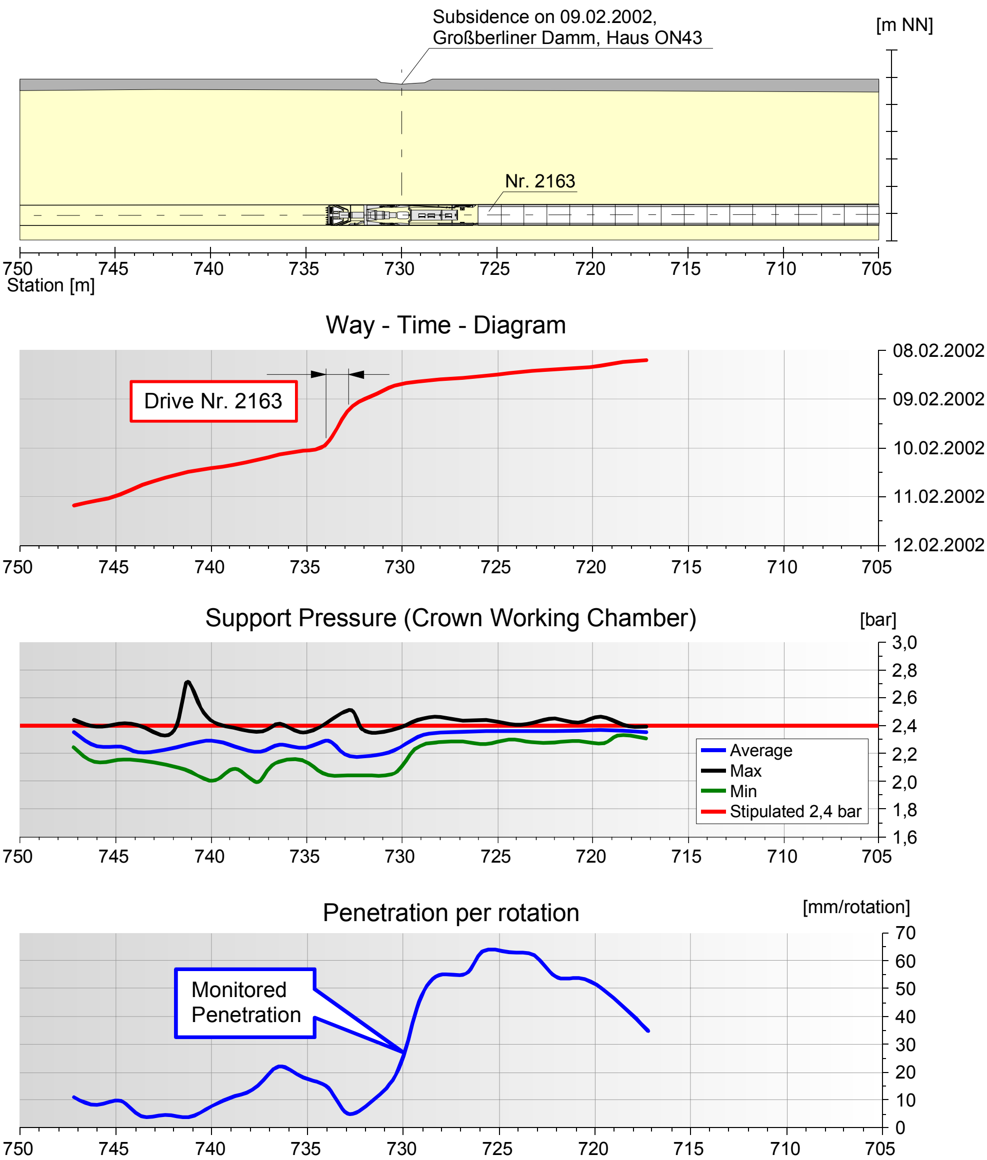

Figure 12: Data monitoring of TBM operation

The methodology to successfully excavate a tunnel in such geology with a Slurry-TBM has to follow some principles which can not been ignored.

During excavation by the rotating cutter head, the excavation tool passes easily through the soft ground until it abruptly hits a stone or boulder. If the cutter head is fitted with an adequate tool arrangement and if the operation procedure is prepared for these conditions (mainly regarding the appropriate penetration rate) the tunnel drive will be not adversely affected. Otherwise the tools will be destroyed or the stones will be ripped out off the soil matrix.

Figure 13: Prototype Slurry TBM 1974

At the beginning of the tunnel drive with Slurry-TBMs, the cutter heads had been equipped with simple steel bars as excavation tools. Smaller stones were ripped-off the face whereas boulders or blocks were shattered at the face by hand-operated hydraulic splitters from the working chamber under compressed air.

Stones and pieces of boulders which could not pass through the transport pipe lines because of their size were taken out of the empty working chamber by hand. Experienced crews did this during the period in which the segments were installed under the cover of the tail shield.

In 1986 e cutter head s were fitted for the first time with disc cutters to grind down stones and boulders in glacial geology with a pressurized TBM. Today-, cutter heads are fitted with a combination of disc cutters and scraper bits. The disc cutters are spaced up to 100 mm apart, and running 25-30 mm ahead of a series of scraper bits. The disc cutters should grind down the hard stones and boulders whereas the scraper bits should shave-off the weak materials such as sand/gravel, silt or clay.

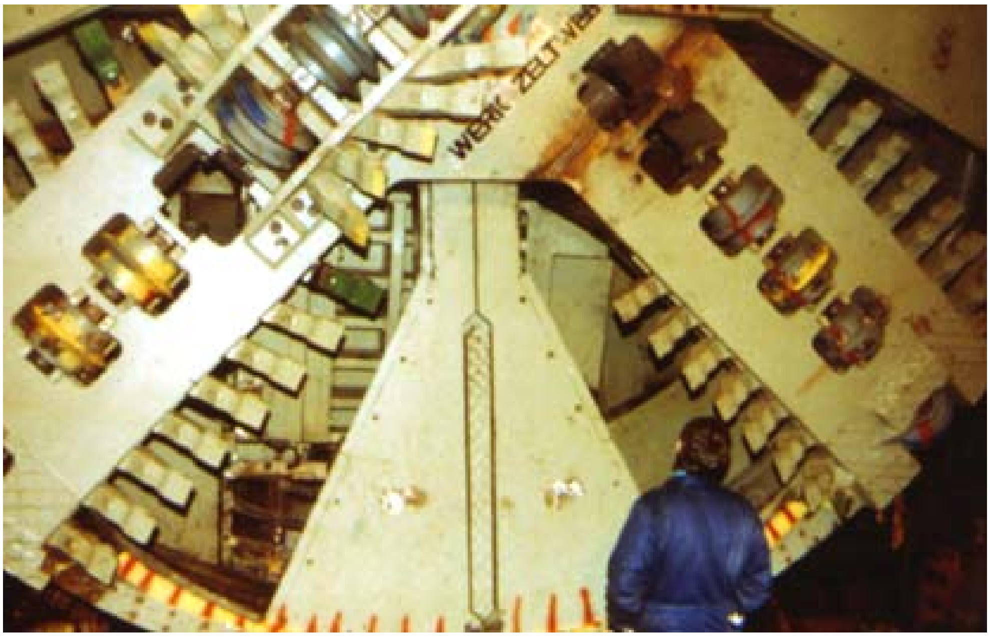

Figure 14: Tool combination – discs and scrapers

Because of the hardness of glacial boulders, the grinding procedure of the disc cutters has to follow the excavation principles of mechanized hard rock tunnelling. The load on a 17 ” disc should exceed 200 kN. The penetration rate per cutter head rotation is limited to 10 mm if granite boulders are encountered. The highly loaded cutting edge of the disc is only able to crush a 10 mm deep groove on a Granite boulder and splits-off chips at the flanks of the groove.

It must be realized that the prevailing component of the forces induced by the rotating disc cutter in the stone or boulder is directed perpendicular to the face and consequently press the stone or boulder into the ground. The tangential component which may rip-off stones out of the matrix is rather small on the assumptions that the penetration rate does not exceed above mentioned 10 mm and the disc cutter is not worn-out. This may happen easily when the disc passes through soft ground without rotating. To avoid stagnant disc cutters, the seals of the cutter bearings have to be de-stressed to the extent that the disc cutters can be rotated by hand.~~.~~

If the penetration rate is higher than 10 mm or the disc cutters are not maintained–, stones will be ripped-out of the matrix–, endangering the stability of the face and damaging cutter head and tools.

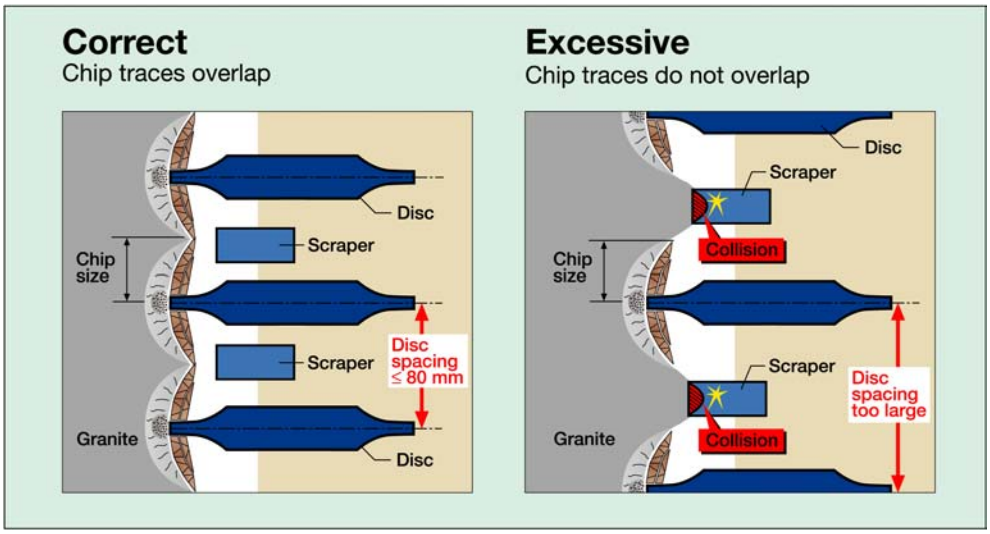

Figure 15: Disc spacing

There exist fundamentally different opinions on the removal of stones and boulders from the face on pressurized mechanized tunnel drive.

Grinding down these obstacles at the face does not endanger the stability of the face and is effective independent of the size of stones or boulders. The rubble of disintegrated boulders can easily be pumped through transportation pipe lines. An additional stone crasher is not required for this procedure on larger TBMs with a sufficient diameter of transportation pipe line. However the rate of advance is limited by the restricted penetration rate.

Ripping stones and boulders out of the matrix facilitates high rate of advance. Single stones, according to definition smaller than 200 mm, may be ripped-off without local collapse of the face. However boulders, in accordance to definition larger than 200 mm, can not pulled out without endangering the face stability.

Figure 16: Boulder ground down

Stones and boulders not ground down at the face fall down to the bottom of the working chamber and must be pushed through a stone crasher to the inlet of the transportation pipe line. The undefined forces for this transportation are generated by the inflow of excavated material and the suction effect of the circulation pump of the transportation pipe line.

However if the distance between the back the -cutter head and the pipe line inlet is too great, the ripped-off stones will be banked up and finally- block the cutter head. This effect is adversely influenced by increasing numbers of stones.

It is a frequently formulated opinion that a stone crasher installed in front of the inlet of the pipe line can solve the transportation problems of ripped off stones or boulders. There are stone crushers installed in some TBMs which may crush boulders with a diameter of 80 cm. But in ripping such boulders off the face, the cutter head will suffer enormous damage and the face will at least locally collapse. Additionally, the flow of excavated material is frequently interrupted during the closure sequence of the crasher. Also fine-meshed grill creates a hindrance to an unimpeded flow of loaded slurry and consequently a risk to a blockage of the cutter head.

Figure 17: Inlet of transportation pipe line with grill and crusher

The dimension of a stone crusher should be limited to a size which can crush boulders smaller than 30 cm. Larger boulders must be ground down at the face to that diameter.

It must be realized that a stone crusher can not be used in a EPB-TBM where the excavated material will be extracted from the working chamber by the protruding end of a screw conveyor. A stone crusher can not be installed at the inlet of the screw conveyor. Therefore the diameter of the screw conveyor limits the size of ripped off stones or boulders from EPB-TBMs.