Construction of Long Tunnels Using Mixshields in Slurry and Hard-Rock Mode - Finne Tunnel

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1. Summary

The twin-tube 6.8 km long Finne Tunnel is being driven on German railways' new Erfurt-Leipzig railway line using 2 TBMs and a single-pass segmental lining. After about 1,500 m, both of the mixshield-TBMs had to be converted from slurry mode to open mode. The TBMs were used consecutively to drive the slurry-shield section. Instead of constructing an underground conversion chamber, a safe conversion position in the area of a hard sandstone bed was chosen on the basis of a precise geotechnical prediction. Generally, alternating sequences of sandstone and mudstone of varying strengths were encountered in the area of the conversion position.

It was possible to carry out the conversion work to the cutting wheel from the rear under the protection of the shield so that working in the unsupported area in front of the cutting wheel was not necessary. In addition, all the slurry-mode components, such as locks, hydraulic power units and pumps, were dismantled to be used for the second TBM. Detailed workflow planning made it possible to limit the conversion periods to 28 days in the case of TBM 1 - including the launch of TBM 2 after 18 days - and 12 days in the case of TBM 2.

2. Overview

With a total length of 6.969 km, the Finne Tunnel is the longest tunnel on the German railways' new Erfurt-Halle railway line and the only tunnel on the whole line between Munich and Berlin where the two tunnel tubes are being driven using 2 TBMs in a staggered operation. In contrast, the other two tunnels on the Erfurt-Leipzig section are to be built with an inner lining using the NATM technique.

The tunnel consists of 2 parallel tubes with an outside diameter of 10.5 m, a 45 cm thick segmental lining and cross-passages that are built between the tubes at maximum intervals of 500 m. In all, there are 13 escape and rescue tunnels as well as 3 tunnels for technical facilities.

In December 2006, Deutsche Bahn AG, represented by DB Projektbau GmbH, Regionalbereich Südost (Regional Division South-East), awarded the contract to the Finne Tunnel Joint Venture, consisting of the companies Wayss & Freytag Ingenieurbau AG, Frankfurt, Germany; Max Bögl Bauunternehmung GmbH & Co. KG, Munich, Germany; Porr Technobau und Umwelt GmbH, Munich, Germany and Porr Tunnelbau GmbH, Vienna, Austria. The construction project is scheduled to be completed in late 2011.

Because of the prevailing geology, the tender documents stipulated that mixshields, convertible from slurry mode (chainage 0 to 1,550) to open mode (chainage 1,551 to 6,822) should be used,
and this type of shield was in fact chosen. The contract for the supply of the two TBMs was awarded to Herrenknecht AG in April 2007.

On the slurry-mode section, the two TBMs were used one after the other, which had the advantage, on the one hand, that is was not necessary to design the separation plant to be used on the first 1,500 m for two machines. On the other hand, it was possible to incorporate the findings gained during the first TBM drive into the concept of the second TBM drive. Optimisations during the slurry-mode drive of machine 1 were taken into account during the assembly of machine 2, and additional installations and modifications required were made. An example of this is the installation of a central spraying system to reduce clogging in TBM 2. The separation plant was also modified for the second drive by increasing the circulating volume from 2,000 m³/h to 2,400 m³/h and installing an additional centrifuge.

To tunnel underneath the Schnecktal valley (3 m minimal cover above the shield) it was necessary to make room in the upper and front area of the shield for the execution of the drilling and injection work. For this reason, almost all slurry-mode components (personnel lock, material lock, slurry and feed pumps, hydraulic power unit of the stone crusher, oxygen generation plant, Samson compressed-air regulating unit, telescopic pipelayer, etc.) had to be removed so that it was possible to use the components on both TBMs consecutively.

3. Geology and Hydrogeology

In the area of the Finne Tunnel the subsoil consists of Triassic sedimentary rock over the entire length of the tunnel. On their first 1,500 m, the tunnels were bored through Keuper, Muschelkalk (shellbearing limestone) and Buntsandstein (coloured sandstone) rock. In this area, the alternating sequences of clayey marlstone, limestone, siltstone, sandstone and clay were affected by the Finne fault, which according to the forecast, was to be expected in the form of two main faults and numerous secondary faults.

As the ground water table, which reached up to 50 m above the tunnel roof, could not be lowered by means of surface dewatering and constant changes between stable rock and heavily shattered ground and even soft ground were to be expected in the area of the faults, tunnelling in this area was carried out using the slurry mode. With increasing distance from the Finne fault, a considerably higher ground quality was expected and in fact encountered. In accordance with the officially approved plan, surface dewatering using drilled wells arranged in pairs was carried out from chainage 1,550 onwards. It was, and continues to be, carried out in advance of the tunnel drive, thus ensuring that the impact on the ground water conditions is minimal. Owing to the resolution made during the official plan approval procedure that dewatering should not be allowed on the first 1,550 m, the slurry mode had to be used to tunnel through largely stable ground on the last 300 m (chainage 1,250 - 1,550) after the fault zones had been cut through. The precise position for the conversion was then determined for each TBM on the basis of the ground conditions encountered in situ in the transition zone to the area where dewatering was used.

The strength of the sandstones encountered when the first TBM was approaching the planned conversion station varied considerably from bed to bed. Both brittle sandstones that could be crushed by hand and relatively hard sandstones with thicknesses ranging from a few centimetres to several meters were encountered. They were interbedded with claystones of varying strengths and thicknesses ranging from a few millimetres to several metres. The inflow of underground water varied between dripping water and 1 litre per second.

Although in all rock variants encountered at most small collapses in the heading occurred in the tunnel roof area during the execution of the normal tunnelling operations, there was no previous experience regarding longer standstills without face support in this type of geology. A hard sandstone bed, as compact as possible, was therefore favoured as the safest solution. Due to the fact that the bedding dips in the direction of the drive, the rock conditions lying ahead in the upper area of the cross-section and above the roof could not be determined just on the basis of the
geological documentation prepared during the tunnelling work. For this reason, an additional exploratory borehole was drilled at chainage 1,548. Within the mainly platy to thin-bedded brittle alternating sequences, an approx. 2.5 m thick compact, strong sandstone bed was encountered in the borehole at the height of the tunnel centre. A conspicuous, red mudstone layer, approx. 3.5 m thick, was encountered below the future tunnel floor during the drilling. It was possible to correlate this layer with the rock profile cut through until then. These findings allowed the subsoil conditions between the working face and the borehole to be determined very precisely. Accordingly, a 10 m long "corridor" was located, where the expected strong sandstone bed encountered in the roof area and at least another 1 m above the roof could act as the "roof" of the conversion place (Fig. 1 and Fig. 2).

![Diagram showing geological layers and borehole locations](image)

Fig. 1: Section with working face profiles and drilling logs between chainage 1,400 and 1,500 at the time when the location of the conversion station was determined. The conjectured arrangement of the layers between the individual logs is presented in pale shades (forecast).
The conversion position with the desired sandstone bed was reached at chainage 1,530, where the strength above the roof was checked on the basis of the drilling resistance encountered when a borehole was drilled in the excavation chamber by means of a simple hammer drill. Due to the favourable geotechnical conditions the conversion phase passed without difficulty. Whereas no changes occurred in the area of the sandstone roof (Fig. 3), the claystones within the narrow alternating sequences were softened relatively quickly and partially washed out by underground water (Fig. 3). Only towards the end of the standstill period did small collapses in the heading occur in the lower area of the working face due to sandstone plates breaking away (Fig. 3). In the roof area, these small collapses would probably have led to the work being disrupted and soil coming off at the roof.

Fig. 3: Photographs of the conversion area of TBM 1:
Left: Compact sandstone bed forming the "roof". Centre: Washout of the clay layers. Right: Small collapses in the heading in the lower working face area.
On the basis of the geological documentation prepared for the first tube and the continuous mapping of the second tube, it was possible to locate the comparable conversion position for the second TBM at chainage 1,528 at a relatively early stage. Although the same part of the strata column was encountered at the working face of the second conversion position, stability problems occurred here. Contrary to the first conversion position, the alternating sequence was penetrated by fissures running perpendicular to the bedding. The washout of softened claystone layers in conjunction with the fissures quickly resulted in small collapses in the heading and sandstone plates sliding from the working face in the lower area of the cross-section (Fig. 4). Since the blocks and plates that had loosened were wedged in front of the openings of the cutting wheel, no further collapses occurred in the heading. Due to the great thickness of the sandstone in the roof area, the upper part of the cross-section remained stable so that it was possible to continue the conversion work for 10 days. After two further small collapses with a maximum depth of approx. 1.50 m occurred in the heading, tunnelling was continued until 2 rings were built so that the remaining works could be performed subsequently.

4. Underground Conversion

4.1 Conversion programme

The whole conversion was divided into the following fields of work: conversion of the cutting wheel, conversion in the shield area and conversion in the area of the back-up system.

A detailed conversion programme (linked bar chart), which was exact to the day, was developed for this work in cooperation with the machine manufacturer. Every operation was listed in this programme, which made it possible to control the conversion work very precisely. The fast disassembly of the slurry-mode components, which were required as early as possible for the launch of TBM 2, was of special importance in the conversion of the TBM 1. 18 days after TBM 1 had reached its conversion position, TBM 2 was able to start tunnelling with the slurry-mode components that came from TBM 1. Following this, the conversion of TBM 1 to open-mode operation was completed, and it was possible to resume tunnelling after another 10 days.

During the conversion of the second TBM the slurry-mode components had also to be removed, but the experience gained during the first stage of the open-mode tunnelling of TBM 1 had shown that part of the welding work at the cutting wheel (grain size limiters, closing plates) was not necessary so that it was possible to reduce the conversion period to 12 days including the "intermediate tunnel advance" of 2 rings already mentioned.

Fig. 4: Photographs of the conversion area of TBM 2:
Left: Small collapses in the heading in the lower working face area. Centre: Sandstone plates wedged in front of the cutting wheel openings. Right: Stable compact sandstone bed despite fissures.
4.2 Conversion of Cutting Wheel

In the shield area, the focus was on the welding work required to close the openings used for the slurry-mode operation section by section, the installation of the grain size limiters, the adaptation of the muck conveying system in the rear of the cutting wheel as well as the start-up of the muck ring and the associated machine belt. Contrary to the slurry-mode muck removal, where the material flow took place via the lowest point of the shield, the excavated material has now to be conveyed to the muck ring at the centre of the shield (Fig. 5).

For the conversion of the cutting wheel, there were two options to choose from: On the one hand, excavation of an underground conversion chamber in front of the shield and, on the other hand, a conversion that was carried out completely from the rear of the cutting wheel.

Option 1: Underground Conversion Chamber

In cooperation with the TBM manufacturer, a concept was developed for the conversion that involved an underground chamber in the area of the tunnel crown (Fig. 6). The underground chamber allows the necessary welding work at the cutting wheel to be carried out easily. According to the concept, up to three welders can work at the 9, 12 and 3 o'clock positions. Since the welding work at the cutter head determines the duration of the conversion work, the number of welding workplaces is of decisive importance.

However, the construction of the underground chamber is problematic as the possibilities are very limited. The options drilling and section-by-section blasting, excavation by chiselling as well as the creation of single welding workplaces by manual excavation using pneumatic hammers were discussed. The excavated material can only be transported using a hydraulic transportation system so that this would have to be kept available for a longer period. Furthermore, the maximum grain size is predetermined by the stone crusher. Subsequent to these works a shotcrete support with or without reinforcement has to be installed. Since reinforcing steel meshes in the classical meaning cannot be placed in front of the cutter head, there is no other...
choice but to use steel fibres here. The works carried out until the completion of the underground chamber will largely be performed in the unsupported area of a 93 m² working face. The area below the centre axis will be unsupported during the entire conversion period so that stability will have to be provided by the underground conversion chamber and the step to the lower half of the working face thus created. Stability without support measures has to be ensured during the time required for the excavation and support of the underground conversion chamber, which was estimated to be 3-5 days. No other conversion work can be carried out at the machine during this period. On the other hand, if no underground chamber is built, this time will be available for the execution of the more difficult welding work.

Option 2: Conversion of the Cutting Wheel from the Rear

After weighing up the arguments the joint venture decided, in consultation with the Client and his experts as well as the machine manufacturer, to carry out the conversion and welding work at the cutting wheel exclusively from the rear without an underground chamber. The crucial factor in this decision was, above all, the fact that the number of personnel working in the unsupported area in front of the cutting wheel was minimized. A disadvantage were the harder conditions in which the welding work has to be carried out, which were due to difficult accessibility (welding overhead), on the one hand, and the more complex weld seams (Fig. 7), on the other hand. Part of these seams had to be produced as downhand welds under a protective gas shield. In addition, single vee groove welds were increasingly used instead of the usual fillet welds. Subsequently, all weld seams were subjected to the customary weld inspection.

To discharge the welding gases a separate ventilation system was required for the work in the cutting wheel area. A blowing ventilation system with several fans installed in the cutting wheel area was used.

4.3 Conversions in the Shield Area

In the shield area, the focus was on the dismantling of the slurry-mode components, such as the compressed air regulating unit and the two locks. To be able to continue further work the two locks have to be dismantled first. The locks were taken to the erector by means of a sliding track, fastened to the erector and rotated downwards (Fig. 8). The locks were transported to the end of
the backup-system via the segment feeder and transported outside by train. In the cleared area of
the locks the devices for the drilling equipment were assembled and the platforms for the tool
change installed. In addition, three circulation pumps had to be dismantled. For the removal of the
excavated material the muck ring and the machine belt were assembled in their final positions
and fine-tuning was carried out once the tunnel conveyor belt had been put into operation.

4.4 Conversions in the Backup Area and in the Tunnel

Primarily, the slurry pump, the hydraulic power unit of the stonecrusher, the medical oxygen
generation plant for the lock operation as well as various pipelines and the telescopic pipelaying
device had to be dismantled in the backup area. In addition, the dust removers were put into
operation and the tunnel ventilation ducting adjusted.

The conveyor belt system for the excavated material - with the exception of the belt itself - had
already been installed during the slurry mode operation so that only the belt had to be put in
during the conversion work. Part of the safety concept for the conversion was to put the conveyor
belt into operation as early as possible to ensure a temporary open-mode operation in case of
instability of the working face. This precautionary measure proved its worth when it was
necessary to build 2 tunnel rings during the conversion of the second TBM (see above).

Following the direct conversion, the slurry and feed pipelines as well as the two compressed air
pipelines were removed from tube 1 and re-used in the second tube.

In addition to the activities mentioned above, the TBM control and visualization system had to be
adapted and the belt conveyor system integrated into the TBM control system.

5. Conclusion/Recommendations

Thanks to the detailed work planning and the constructive collaboration of all parties involved in
the project, it was possible to carry out the underground conversion work very quickly without
constructing an underground conversion chamber. The decision to use the two TBMs
consecutively to drive the slurry-mode sections turned out to be right choice.

Based on the experience gained, two main recommendations can be given:

a. If two parallel tunnels are to be driven, it is helpful to keep one TBM well ahead of the other
   in order to optimize the second, should this prove necessary;

b. Conversion of TBMs, i.e. from slurry to open mode or vice versa, can be accomplished in a
   relatively short time if planned well and if competent personnel is available. Moreover, such
   conversions can be done without excavating a chamber in front of the TBM.