Risk of a high hydrostatic pressure on the tunnel Prague - Beroun

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SUMMARY: The construction of the Prague – Beroun high-speed railway tunnel is currently in the planning stage. This tunnelling project has no equivalent in the Czech Republic, the tunnel will be the longest Czech transport with the highest overburden exceeding 170 m above tunnel axis. Majority of tunnel is expected to be excavated by tunnel boring machines (TBMs). Risk analysis evaluating tunnel excavation and operations has been completed, possible high hydrostatic pressure was identified as one of major risks, thus its impact had to be evaluated.

In current design phase the segmental tunnel lining is expected to be impermeable with full hydrostatic pressure. Exact position of underground water table (WT) is currently not clear, in the worst case the water table can be close to surface with the full hydrostatic pressure acting on the tunnel lining. Impact of various values hydrostatic pressure on required tunnel lining was investigated; tunnel lining was evaluated for various water table levels between 10 m and 177.5 m above the tunnel axis. Also study of mechanized tunnels with high hydrostatic pressure has been realised.

1. PROJECT HISTORY

The planning study for the Prague Smíchov – Plzeň Main Station section was carried out in 2002, within the framework of the planning for the optimisation of the lines of the 3rd rail transit corridor. This document proposed, in compliance with the specification, that the optimised line follow the existing route, with local improvements to the parameters of the horizontal alignment. The work on the design for the land allocation process started subsequently. It was confirmed during the work that the operating rail line between Prague and Beroun, which follows the course of the Berounka River, did not allow any principal increase in the traffic speed because the existing line is in direct contact with the nature reserve of Bohemian Karst, which meant that no substantial modifications of the horizontal alignment were possible. This is why the decision was made that a new system of the high-speed railway connection between Prague and Plzeň running through long tunnels had to be examined.

Several variants of the new connection line, which comprised both underground and surface sections, were submitted. The assessment of the variants resulted in a conclusion that they were unrealistic, with respect to the fact that the area south of Prague is built up. For that reason, other solutions were sought, with exceptionally long tunnels covering the major part of the route. The planning study which was carried out in 2005 assumed that the new rail line would lead through the 19km long Barrandov tunnel, beginning at Hlubočepy in Prague and ending in the valley of the Loděnice River, near the village of Svatý Jan Pod Skalou. The new line was to cross the valley on a 700m long viaduct, which would be followed by the 4km long Svatý Jan tunnel, ending in the valley of the Berounka River. In the spring of 2006, an attending study was issued, which elaborated the planning study and further solved variants of the tunnel mouth in Prague (at Hlubočepy and Malá Chuchle) and the technique of the crossing of the Loděnice River in Svatý Ján Pod Skalou (either a bridge or an underpass). An extended geological information search, which gathered all knowledge about the geological structure of the area of operations, was also carried out in the spring of 2006. The information search was followed by an initial risk analysis, which provided the evaluation of construction and operating risks.

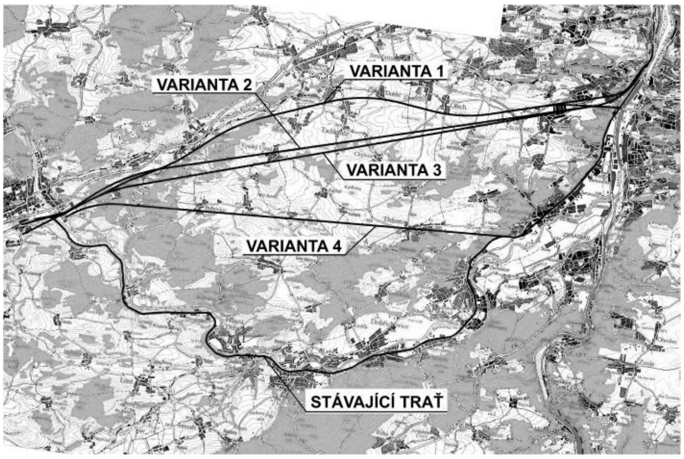

Figure 1. Variants of the Prague – Beroun tunnel alignment.

Of the possible route variants, the winning variant was the 24.7km long tunnel which partially bypasses the karst area between Prague and Beroun by means of a north-running curve (see Fig. 1). The preliminary geotechnical survey for the selected route was finished in May 2007. The design documentation for issuance of zoning and planning decision for the new railway connection between Prague and Beroun was submitted in June 2007; responses to the comments were incorporated into the documentation before the end of 2007. Danger of high hydrostatic pressure was evaluated by realised risk analysis as one of of the major project risks which should be evaluated.

Shorter variants of the Prague – Beroun tunnel (Variant 4 on Fig.1) are currently evaluated due to a very high cost of the original project.

2. TBM PROJECTS UNDER A HIGH HYDROSTATIC PRESSURE

2.1. Basic overview

A basic overview of tunnels excavated by tunnel boring machines (TBMs) under a high hydrostatic pressure is presented on Fig.2. The maximal hydrostatic pressure was measured on the water tunnel Arrowhead in the USA, measured pressure was 2000 kPa which correspond to the water table location 200 m above the tunnel.

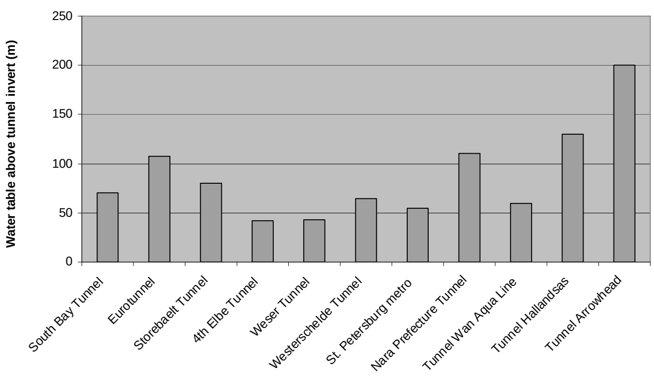

Figure 2. Overview of tunnels with a high hydrostatic pressure

Design of the Hallandsas tunnel in Sweden considered maximal hydrostatic pressure 1300 kPa, segmental lining with thickness 540 mm was designed for the hydrostatic pressure 1500 kPa. Completed tunnels with a high hydrostatic pressure are South Bay Ocean Outfall tunnel (700 kPa), railway Eurotunnel under La Manche (1000 – 1100 kPa), railway tunnel Storebaelt (800 kPa), road 4th Elbe tunnel (420 kPa), Wesertunnel (430 kPa), Westerschelde tunnel (640 kPa), red line of the metro in St. Petersburg (550 kPa), the Nara Prefecture Water Conveyance Tunnel (1100 kPa) or road tunnel Wan Aqua Line under Tokio Bay (600 kPa).

2.2. Existing experience

Parameters of mentioned TBM projects are compared in tab.1. Some of the projects, such as the Storebaelt tunnel and the Channel tunnel the encountered groundwater head was much less than anticipated due to dewatering or ground of very low permeability. During excavation, the applied face support pressure was generally maintained slightly above the groundwater pressure on all selected projects in order to provide face stability.

During interventions, there was a wide range of applied pressures. On some projects the applied compressed air pressure was much lower than the groundwater head and interventions were executed only in stable, low permeable ground such as on the South Bay Ocean Outfall project and on the Nara Prefecture tunnel. On all other projects the applied compressed air pressure was in the same order as the ground water pressure.

There are only two projects where mixed gases were used: the Westerschelde tunnel and the Red Line in St. Petersburg. There is only one project so far, where saturation diving was used (Westerschelde). On all other projects compressed air support was used for cutterhead inspections or free air face access was performed in single cases of very strong, low permeability ground conditions that did not require face support.

Following key points can be summarized based on existing experience (Holzhäuser at al. 2007):

High groundwater pressure (above 4 bar) makes tunneling much more difficult and requires special knowledge of cutting edge technologies during design and construction.

TBM, tunnel equipment and tunneling procedures should be designed to enable reliable application of adequate support pressures at all times during excavation and hyperbaric interventions to counterbalance the acting groundwater head.

Table 1. Parameters of tunnels with a high hydrostatic pressure

Name	Location	TBM	Number of TBMs	TBM Manufacturer	TBM Diameter(m)	Tunnel Length (km)	Geology	Overburden (m)	HPV above tunnel invert (m)	Measured hydrostatic pressure (bars)	Design TBM pressure (bars)	Applied TBM pressure (bars)	Design pressure for lining (bars)	Number of segments (bars)	Internal tunnel diameter (m)	Lining thickness (mm)	Length of segments (m)	Material of lining	Construction
South Bay Tunnel	USA	EPB	1	Mitsubishi	3,98	5,795	clay and sand	58	70	7	8,5	7,3	7	5 + 1	3,35	300	3,81	RC	1995 - 1999
Eurotunnel	France	EPB	3	Robbins	5,72 a 8,72	15,6; 20 and 18,9	chalk	90	107	3,5	11	3,5	10	5 + 1	7,6	400	1,6	RC	1988 - 1991
Storebaelt Tunnel	Denmark	EPB	4	Wirth	8,75	2 x 7,412	marble, glacial sediments	45	80	6,3	8	3	8	5 + 1	7,7	400	1,65	RC	1990 - 1994
4th Elbe Tunnel	Germany	Slurry	1	Herrenknecht	14,2	2,561	glacial sediments	35	42	4,2	6	5	5,5	6 + 1	12,35	700	2	RC	1995 - 2000
Weser Tunnel	Germany	Slurry	1	Herrenknecht	11,71	2 x 1,645	clay and sand with boulders	20	43	4,3	6	5,3	6	8 + 1	10,3	500	1,5	RC	1998 - 2002
Westerschelde Tunnel	Netherlands	Slurry	2	Herrenknecht	11,33	2 x 6,6	clay and sand	35	64	6,4	8	7,4	7	6 + 1	9,2	450	2	RC	1998 - 2001
St. Petersburg metro	Russia	Slurry	1	Voest Alpine	7,4	2 x 0,8	glacial sediments	55	55	5,5	8	6,4	6	7 + 1		350	1,4	RC	2002 - 2004
Nara Prefecture Tunnel	Japan	EPB	1	Kawasaki	3,95	1,151	clay and sand	135	110	11	11	11	11	5 + 1	2,4		1	Steel	1984 - 1988
Tunnel Wan Aqua Line	Japan	Slurry	8	Kawasaki	14,14	2 x 4,5	clay and sand	20	60	6	9	6,5	6	11 + 1	11,9	650	1,5	RC	1994 - 1997
Tunnel Hallandsas	Sweden	EPB	1	Herrenknecht	10,6	2 x 5,5 (TBM)	gneiss, tectonic faults	150	130		13	11	15	7 + 1	10,12	540	2,2	RC	2004 - 2015
Tunnel Arrowhead	USA	EPB	2	Herrenknecht	5,8	13,8	gneiss	630	200	20	10		27,5	5 + 1	3,65	330	1,524	RC	2002 - 2010

If adequate primary components and backup systems are not installed on the TBM, major problems including cost overruns and time delays can occur, as happened on the Storebaelt tunnel.

Tunnel excavation in strong, fine grained cohesive soils and rock under high groundwater pressure is generally not problematic for Slurry- and EPB-TBMs, as typically the face is stable and the amount of inflowing water is low due to low permeability of the ground.

In coarse-grained soil or unstable rock, tunnel excavation requires a reliable active face support to provide face stability and prevent excessive lost ground during tunneling and interventions.

Suitable active face support is easier to achieve with Slurry-TBMs. On EPB-TBMs, adjustments to the muck conditioning needed for pressure control takes time and EPB-TBMs are often not responsive enough to abrupt ground condition changes to be effective at controlling water inflow and ground loss such as happened on the San Diego, Storebaelt and Nara Prefecture tunnels.

Depending on the level of the groundwater pressure, abrasiveness of the ground and the length of the corresponding tunnel sections, the TBM should include provisions for hyperbaric interventions using regular compressed air, mixed gases or saturation diving, depending on pressure level and duration of intervention time expected.

Only in very strong, low permeability soils or in competent rock are risks of attempting cutterhead interventions under free air reasonable (if not otherwise restricted), but there should always be provisions available to apply adequate compressed air support or ground treatment if needed.

Maximal hydrostatic pressure on single-track railway tunnels was recorded on the Hallandsas tunnel, where water table was located 130m above the tunnel and pressure between 900 and 1100 kPa was applied by TBM on the tunnel face. On Hallandsas tunnel an impermeable lining with thickness 540mm was used to prevent water table lowering. Hallandsas tunnel excavation was significantly expensive due to special procedures during excavation (rock mass grouting, special procedure of annulus grouting, etc.).

3. STATIC CALCULATIONS

Static calculations were realised in cross-section km 25,600 (about 2 km from Beroun portal). This cross-section was chosen due to maximum overburden which is 177.5 m above a tunnel axis.

Geotechnical parameters of rock mass were determined from the preliminary site investigation report. Basalts, calcareous and silty shales are in calculated tunnel cross-section, higher above tunnel was encountered limestone, ash rock and tufaceous shales.

Average values of geotechnical parameters of calcareous and silty shales were used for calculations which are lower in comparison with parameters of basalts. Rock mass was considered as homogeneous.

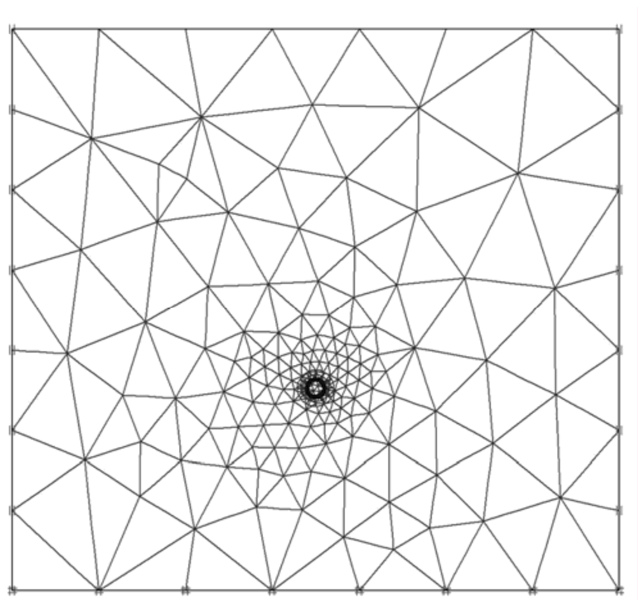

Figure 3.Numerical model geometry

Several assumptions were considered for provided calculations. The calculation assumes mechanised excavation with TBM (shield) with a pressure on the face (EPB or slurry TBM) which means no change of hydrostatic pressure (ie. no water ingress to the tunnel). The calculation assumes ground relaxation, value of relaxation was assumed as 1% of voluime loss.

Parametric study was realised for various hydrostatic pressures, locations of water table was assumed from 10m to 177.5m above the tunnel axis.

Table 2. Results of the parametric study evaluating impact of water table location on internal forces and deformations

WT above tunnel axis (m)	N (kN)	M (kNm)	d (mm)
177.5	7830	62	31
140	6220	63	30
100	4500	59	29
50	2310	61	28
10	583	63	27

The tunnel lining was evaluated for the load caused by an effective and a hydrostatic pressure. Also load caused by TBM (thrust and torque). TBM parameters were based on Hallandsas project, where tunnel parameters are similar (railway tunnel, TBM profile 10.6m, maximum overburden 150m, maximum water table 130m above the tunnel). Parameters of lining required for an acting load are summarised in the Table 3.

Table 3. Results of a parametric study (impact of water table location on tunnel lining parameters)

WT above tunnel axis (m)	Lining thickness (mm)	Reinforcement (cross)	Reinforcement (long.)	Bolts (mm)
177.5	680	28 x Ø12	22 x Ø12	Ø40
140	580	24 x Ø12	18 x Ø12	Ø35
100	460	18 x Ø12	20 x Ø10	Ø30
50	320	18 x Ø10	14 x Ø10	Ø26
10	200	12 x Ø10	10 x Ø10	Ø26

Realised calculations give a basic idea about a required tunnel lining thickness and reinforcement for various water table levels.

Some assumptions have a significant impact on the results. A full hydrostatic pressure acting on the tunnel lining is assumed, the lining is assumed to be completely impermeable (ie. no pore pressure dissipation around the tunnel).

Calculations were realised for the cross-section km 25.600, where a favourable ground parameters are expected. Therefore considered effective load was quite low. Worse ground parameters would mean higher effective load which would require a higher tunnel lining thickness.

4. CONCLUSION

Realised evaluation gives a better idea about measures which would require a higher hydrostatic pressure on the railway tunnel Prague – Beroun. Detailed site investigation should give a better idea about expected hydrogeological conditions (water table level, rock mass permeability, etc.). Consequently an adequate measures should be adopted (especially in case of detail excavation and tunnel lining design).

Realised calculations showed that originally proposed tunnel lining thickness 400mm would be sufficient up to water table level 80m above tunnel axis. Higher water table level would require either higher lining thickness. Another option would be re-evaluation of an original concept of fully watertight tunnel lining.

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