NUMERICAL MODELLING OF THE BRUSNICE TUNNEL

Matouš Hilar[1], Jakub Nosek[2]

[1]D2 Consult Prague and FCE CTU, Zelený pruh 95/97, Prague 4, 140 00, Czech Republic
[2] D2 Consult Prague, Zelený pruh 95/97, Prague 4, 140 00, Czech Republic

KEYWORDS
Numerical modelling, NATM, FEM.

1. INTRODUCTION

Basic information
Brusnice tunnel is a part of the Blanka tunnel complex, the significant construction of the northwestern section of the Prague City Circle Road. The constructed tunnel complex consists of two parallel one-way tunnel tubes with length over 6 km and constitutes an extension of existing ring road at Malovanka intersection, where the Strahovský tunnel results in. The tunnel alignment passing Hradčanská underground station proceeds to Letná area to divert beneath the Stromovka Park and go under the Vltava River. The trace is terminated by connection to existing road network at Pelc-Tyrolka intersection situated in the vicinity of Barikádníků Bridge.

The Blanka tunnel complex comprises mined tunnels (approx. 2,7 km) and cut-and-cover tunnels (approx. 3,3 km). The mined tunnels are constructed in two different sections. Excavation of Špejchar – Pelc Tyrolka tunnel with length 2,2 km was started as a first. The second section is characterized by Brusnice tunnel consisting of two triple-line tubes with length of about 550 m and connecting Myslbekova a Prašný most open pits.

The New Austrian Tunnelling Method (NATM) was used as an excavation technique for Brusnice tunnel tubes. Except the section of the northern tunnel tube (NTT) both tubes were mined downwards from the Myslbekova portal. NTT was excavated from the Prašný Most portal after the collapse of the overburden in a Ministry of Culture garden happened. Excavated profile area of each tube is approximately 170 m^2 and their overburden thickness is about 25 m along the majority of tunnel line. Separation distance between tubes is approx. 17 m.

The Blanka tunnel complex contractor is Metrostav a.s., designer Satra and investor Prague the capital.

Geological conditions
Results of engineering geological survey confirmed that geological and geotechnical conditions along the Brusnice tunnel line are very complex and highly variable.

The bedrock in area of interest consists of the Ordovician Letná formation structurally described as sandy schists with sandy concretions. Finely to coarsely micaceous schists are bedded in thick layers. Interlayers of fine-grained quartzite with thickness 6 – 20 cm are often to encounter. Depending on measure of tectonical failure the moderately to highly fissured rock predominate at construction lot. Individual degrees of weathering are designated from W5, weathered schist composed of cohesive soil with character of clay with variable content of schist fragments, to W1, hard non-weathered thickly bedded schist.

The Quaternary cover consists of anthropogenic (AN), eolic (EO), deluvial (DE) and fluvial (FL) sediments. The rock overburden thickness ranges along the tunnel alignment from 12 to 19 m. About 450 TM behind the Myslbekova portal the rock thickness falls to value of about 5 m.

Hard and slightly weathered schists (W1 to W2) have been encountered the most of the tunnel line. A layer of moderately weathered schists (W3 to W4) descended into the tunnel profile in the vicinity of Prašný Most portal. Excavation conditions in the NTT were getting worse in this area because of downcoming of weathered (decomposed) schists (W5) into the profile.

2. TUNNEL EXCAVATION (CONSTRUCTION PROCESS)

A vertical excavation sequence was originally designed for the excavation of both tunnel tubes. On the basis of lowering of a tunnel level and subsequent reaching of better geological conditions the horizontal sequence in detailed design was taken into account.

The excavation commenced with opening of the NTT top heading from Myslbekova portal in October 2009 using horizontal sequence. In January 2010 started the STT excavation in a same direction with prescribed vertical sequence (first 50 TM) including left and right side-drifts and completion of a central pillar. After finishing of these 50 TM the horizontal sequence in accordance with NTT was adopted.

Over a period of technical discussions about a continuation with horizontal sequence the NTT without complications reached a chainage 396 TM, where the excavation sequence on account of deterioration of geological conditions was changed to vertical subdivision. On 06/07/2010 the overburden between chainages 403 and 435 collapsed during a bottom completion and removal of internal side-drift walls. Excavation process was consequently stopped on both tunnel tubes (STT at chainage 374 TM). The NTT excavation was finished from Prašný Most portal with vertical sequence simultaneously with reconstruction works. The excavation operations were completed at STT using horizontal sequence with vertical subdivision of top heading.

3. NUMERICAL MODELS

Because of the fact that geological conditions from Myslbekova portal to Prašný Most portal were getting worse the excavation method for following meters were often taken into consideration. Set of numerical models of tunnel excavation carried out at D2 Consult Prague s.r.o. served as base for technical discussions.

All models were performed using software Plaxis V8. Finite element mesh composes of 15-noded triangle elements and the mechanical behavior of a ground was simulated using linear elastic ideally plastic Mohr – Coulomb constitutive model. Primary lining was modeled by linear elasticity using beam elements.

Analysis of chainage 220TM

In a distance of 220 m from Myslbekova portal a numerical model representing presupposed geological conditions and expected primary reinforcement was prepared (Fig. 1). The overburden thickness above the tunnel tubes reaches 25 m (NTT) and 26 m (STT). In simulated cross-section using the 3 NATM technological support category was expected with corresponding 30 cm thickness of primary lining. The tunnel profile is 16,5 m width and 12,7 m high with area of 169 m^2.

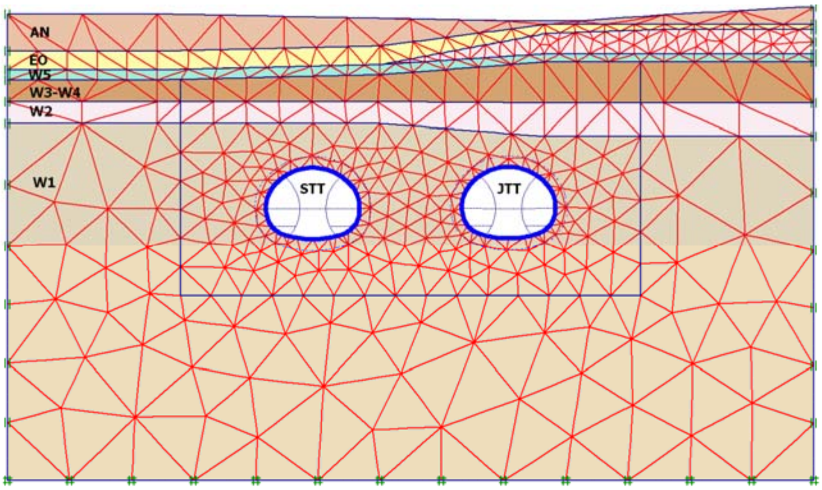

Fig. 1: Excavation model in chainage 220 TM

This model was prepared before commencement of excavation operations in period of valid final design with proposed vertical sequence for both tunnel tubes in their entire length. For that reason both considered profile subdivisions were modeled and compared.

In a simulation with horizontal sequence the NTT top heading excavation was modeled first followed by bench and invert simultaneously. The aim of this procedure was a fast closing of whole tunnel as supposed in final design. The STT excavation was simulated in the same way. Aforementioned phases were divided into phase of unreinforced profile loaded with 30 % of unbalanced forces and phase of lined profile with complete load applied.

In a simulation with vertical sequence, phases of the NTT excavation as stated below were modeled first, followed by same phases for STT.

1. Top Heading excavation of 1. Side-drift
2. Completion of 1. Side-drift
3. Top Heading excavation of 2. Side-drift
4. Completion of 2. Side-drift
5. Middle Top Heading excavation
6. Bottom and Invert excavation

Each of phases was divided again into two phases as in a case of the horizontal sequence. The tunnel excavation passed this cross-section using horizontal sequence and with regard to favourable monitoring results without requirements on fast profile closing. In addition to existing model with horizontal sequence one with separated phases of bottom and invert was prepared. This model is in result table stated as “realized horizontal sequence”. Geotechnical parameters of rock mass types employed in analyses are subject of Table 1.

Tab. 1: Geotechnical parameters in cross-section 220 TM

Layer	depth [m]	γ [kN/m3]	E [MPa]	c [kPa]	φ [°]	ν [-]	K_0 [-]
AN	0 - 4	20,0	11	10	19,6	0,399	0,66
EO	4 - 7	19,5	10	20	17,9	0,409	0,69
DE	4 - 7	19,5	20	8	23	0,379	0,61
W5	7 - 9	21,0	30	12	24,8	0,367	0,58
W4-W3	9 - 14	22,5	90	20	24,8	0,31	0,58
W2	14 - 18	24,5	220	40	26,6	0,25	0,55
W1b	18 - 80	26,3	500	140	32,9	0,23	0,46

Predictions of surface settlements and tunnel deformations obtained with horizontal sequence with fast closing and vertical excavation sequence produce small differences between individual methods (order of millimeters). Additional model with “realized horizontal sequence” confirmed reliability of simulations in this cross-section. Predicted and measured values differ minimally (see Tab. 2).

Tab. 2: Comparison of predictions and monitoring data

	Vertical sequence	Horizontal sequence	Realized horizontal sequence	Monitoring data	
Max. vertical deformation	24	27	38	39	[mm]
Max. horizontal deformation	7	4	6	-	[mm]
Max. bending moment	87	55	68	-	[kNm]
Max. axial force	2270	1280	1420	-	[kN]
Max. surface settlement	13	15	26	33	[mm]

Analysis of chainage 361 TM

Further analysis was realized in cross-section of chainage 361 TM. The simulation was performed in May 2010 after the NTT top heading and bench passed the simulated cross-section and stopped at chainage 394 TM. 220 meters were excavated in STT top heading at the same time. The goal of presented simulations was provide so exact predictions of rock mass behavior within the STT pass and NTT invert finishing as possible. Both variants horizontal and vertical excavation sequence were considered again.

From Myslbekova portal in distance of 361 m the model representing presupposed geological conditions and primary tunnel reinforcement was set up. The overburden thickness is 24 m. Since ground surface and geological strata are in-situ only slightly inclined the model could be simplified to horizontal. In simulated section using the 5a NATM technological support category was expected with corresponding 40 cm thickness of primary lining. The profile is 16,5 m width and 12,7 m high with area of 174 m^2.

Initial simulation of NTT excavation was carried out with geotechnical parameters of individual layers based on characteristic values (see Tab. 3).

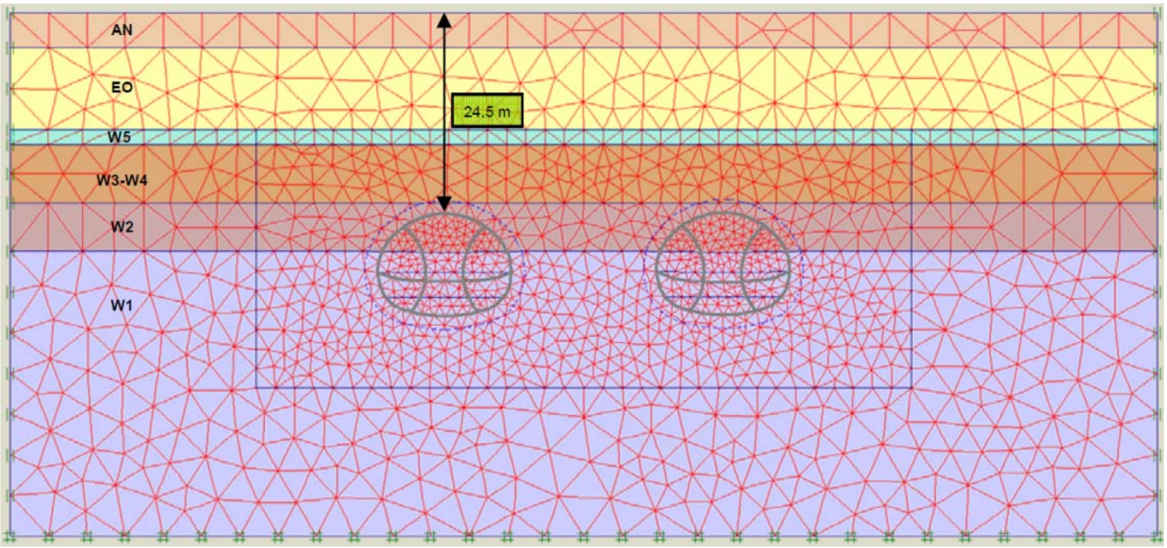

Fig. 2: Excavation model at chainage 361 TM

Tab. 3: Geotechnical parameters for cross-section at chainage 361 TM

Layer	Depth [m]	γ [kN/m^3]	E [MPa]	c [kPa]	φ [°]	ν [-]	K_0 [-]
AN	0-5	20.0	11.0	13	24	0.372	0,59
EO	5-14	41048,0	10.0	25	22	0.385	0,63
W5	14-16	21.0	30	15	30	0.333	0,50
W3-W4	16-23	41051,0	90	25	30	0.31	0,50
W2	23-29	41053,0	220	50	32	0.25	0,47
W1a	29-65	25.75	300	125	37	0.25	0,40

Initial analysis was performed in five phases (in parenthesis the appropriate loading stated):

1. NTT Top Heading excavation (30%)
2. Lining installation of NTT Top Heading (50%)
3. Lining installation of Invert of NTT Top Heading (100%)
4. NTT Bench excavation (20%)
5. Lining installation of NTT Bench (100%)

After completion of aforementioned phases for NTT, excavation and lining installation of top heading and bench, monitoring data were analyzed. From surface settlement trough points measured by leveling, points at lining and measurements of an extensometer located above the crown, was determined maximal surface settlement of 17 mm and max. crown deformation of 43 mm.

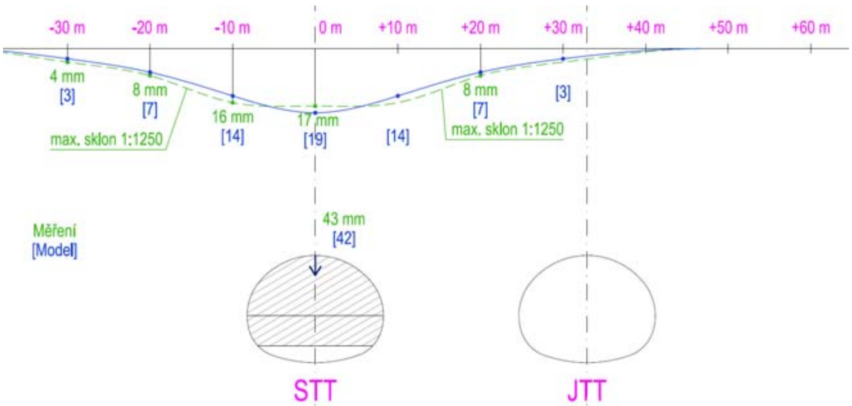

Fig. 3: Comparison of measured surface settlement with tuned model predictions

Surface settlements predicted with original parameter set were overpredicted on 140 % and 170 % of measured values. Based on these results the model was tuned and a good agreement with monitoring data was achieved by Young modulus increasing to 160 % of original value for each layer (Fig. 3).

The tuned model was used for simulation of the NTT invert excavation and subsequently the STT vertical or horizontal excavation sequence. In case of horizontal sequence the phases of simulation were as follow:

6. NTT Invert excavation and lining installation (100%)
7. STT Top Heading excavation (30%)
8. Lining installation of STT Top Heading (50%)
9. Lining installation of Invert of STT Top Heading (100%)
10. STT Bench excavation (20%)
11. Lining installation of STT Bench (100%)
12. STT Invert excavation and Lining installation (100%)

In case of vertical sequence model the calculation continued with phase 6 “NTT Invert excavation and lining installation” and further followed the STT vertical subdivision used for chainage 220 TM (see above).

In-situ the typical horizontal excavation sequence corresponding to modeled phases was applied. Simulation results are concluded with monitoring data in Tab. 4 together.

Tab. 4: Comparison of predictions and monitoring data

Settlement in STT axis	Horizontal sequence	Vertical sequence	Monitoring data	
Tunnel	42	31	49	[mm]
Surface	21	15	22	[mm]

The assumption, that horizontal subdivision in simulated tunnel section is applicable, was confirmed based on obtained analysis results. Horizontal sequence leads only to slight increase of surface settlement of 5 mm when compared with vertical model. Since the increase of surface settlement did not represent any risk for surrounding buildings the horizontal sequence was applied with regard to time and economical profitability.

4. CONCLUSION

Numerical analyses quantified the effect of face subdivision on deformations of rock mass caused by tunnel excavation. Horizontal sequence has proved to be convenient solution in modeled tunnel sections and predicted deformations were in conformity with measured data. Brusnice tunnel excavation, including also the dealing with collapse, has been successfully completed.

ACKNOWLEDGEMENTS

Financial support by the research grants TACR TA01011816 and GACR P105/12/1705 is gratefully acknowledged.

REFERENCES

Hilar, M. - Pruška, J. (2008), Statistical Analysis of Input Parameters on the Modelling of Underground Structures. Acta Polytechnica 48/5, pp. 3-8.

Barták, J. - Hilar, M. - Pruška, J. (2002): Numerical Modelling of the Underground Structures. Acta Polytechnica. 42/1, pp. 53-58.