MYSLBEKOVA STREET – PRASNY BRIDGE (MYPRA) SECTION OF THE CITY CIRCLE ROAD PRIMARY AND SECONDARY TUNNEL LINING DESIGN METHODOLOGY

VACLAV KRCH, RADKO RIEGER

Introduction

North of the grounds of Prague Castle, the route of the City Circle Road leaves the space of Patočkova and Milady Horákové Streets (where the circle road runs through cut-and-cover tunnels) and enters the space between Jelení and Milady Horákové Streets. A mined tunnel is designed for this section. The reason for the selection of this route and construction system is the requirement for the traffic on Milady Horákové Street to be maintained uninterrupted, above all for the purposes of the residential traffic in Petřiny and protection of the sensitive, heritage designated area of Hradčany. The area which the mined tunnel passes through is relatively sparsely developed. However, a part of the Baroque fortification of Hradčany (bastions No. XI – č. XIX) is found directly above the tunnel; the building of a former municipal orphanage (currently used by the Ministry of Culture) is in the close vicinity of the tunnel route, as well as historic buildings in Jelení Street.

Design assumptions and methodology

Basic geometrical features of the mined tunnel:
The length of the northern tunnel tube (NTT) is 536.50m.
The length of the southern tunnel tube (STT) is 551.80m.
Excavated cross-sectional area is about 180 m2.
Maximum longitudinal gradient is 3.60 % .

The New Austrian Tunnelling Method (NATM), which uses the advantage of the composite action of the ground mass and its self-supporting capacity, was selected as the optimum method of the tunnel excavation through the given variable geological environment.
Four NATM excavation support classes are proposed for the tunnelling, i.e. classes III, IV, Va,Vb, which differ from each other in the advance round length, the number and length of anchors, thickness of the temporary lining and the reinforcement. The assessment of the designed horizontal alignment and vertical alignment, which was carried out in relation to the results of a detailed geological survey, led to the determination of three locations of typical cross sections (the cross-sections 1-1, 2-2 and 3-3).

The structural analysis of these cross sections was carried out for the NTT and STT using a 2D mathematical model. The portal sections (the cross-sections 1-1 and 3-3) were selected for the calculations, where the height of the overburden is reduced and geological conditions are worsened. The third cross-section, which is characteristic of the remaining route, was selected approximately in the middle of the mined section (the cross-section 2-2). With respect to the nearness of its route to existing buildings and the dimensions of the cross section, the ventilation duct was also assessed using a mathematical model.

The following results were provided by the mathematical modelling:

1. The determination of the deformational state and stress state of the rock mass during the tunnel excavation.
2. The prognosis of the possible plastic deformation of the rock mass and changes in the state of stress in the rock mass.
3. The anticipated development of deformations of the rock mass and the lining in the individual excavation phases.
4. The prognosis of the overall deformational effects on the ground surface.

The structural analysis of the temporary lining is carried out using a numerical model of the sequential excavation, by the Finite Element Method using the GEO4 FEM tunnel program. It is a two-dimensional model and the elements used are isoparametric. The rock mass is dealt with in the state of plane deformation and is defined as Mohr-Coulomb elasto-plastic material. The final lining is then assessed using the outputs obtained from the mathematical model solved using calculation programs developed for concrete.

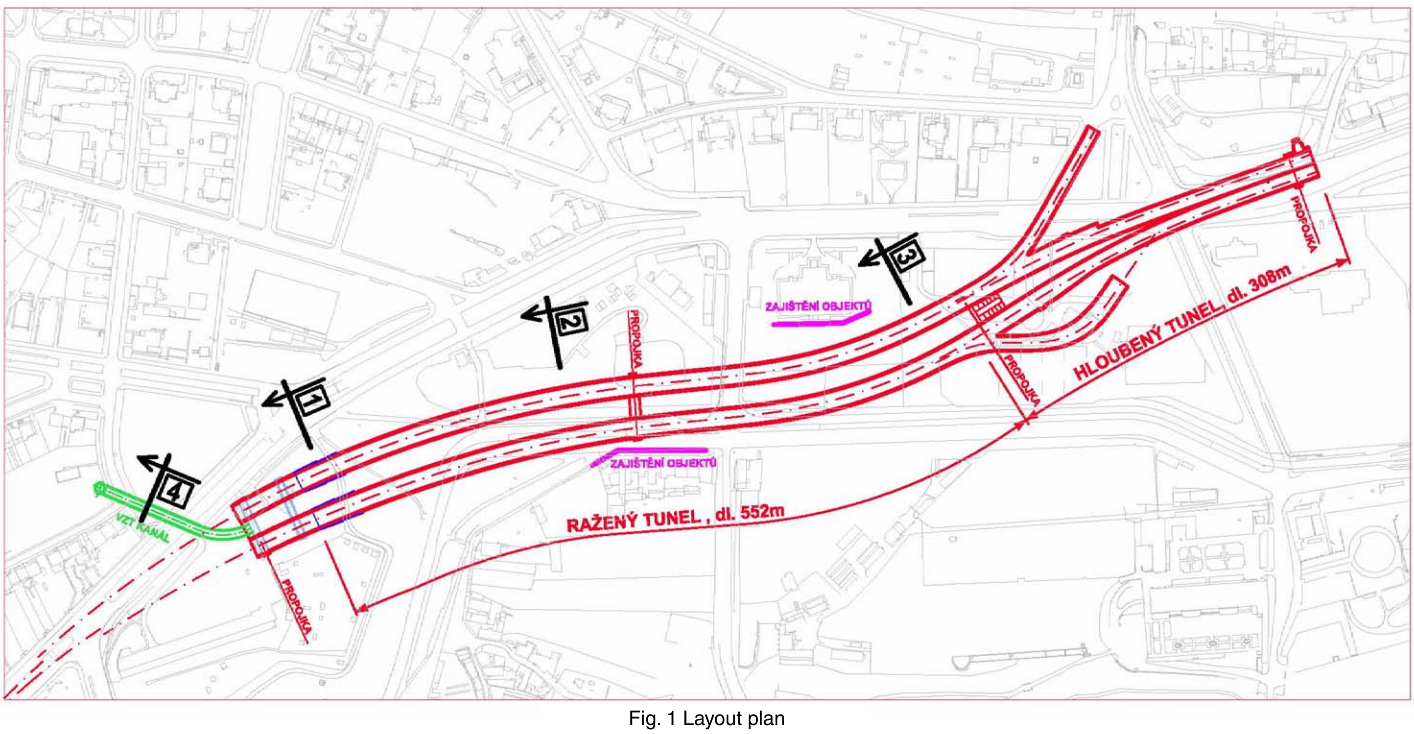

Fig. 1 Layout plan

Mechanical properties of the rock mass; incorporation of the properties into the model

It follows from the geotechnical survey that the geological conditions along the route are complex and very variable. The bedrock in the area of operations is formed by the co-called “monotonous-evolution” type of the Letná Member. In terms of the structure, it can be characterised as sandy greywacke shale. In terms of the degree of tectonic faulting, medium to significantly fractured rock prevails. The Letná Member rock which originated through the monotonous evolution is less weathering resistant; the thickness of the mantle of waste reaches 3-5m. The results of the detailed geological survey which was carried out for the project were decisive for the determination of the geotechnical parameters of the rock mass and the superficial deposits which were used for the calculation. In the mathematical model, the rock mass is defined as an elastic-plastic environment. The Mohr-Coulomb model applied to the calculation, with an assumption that irreversible deformations will develop, which means that plastic areas will develop. The model describes the state of stress at fracture which is found in the state of planar deformation.

Mechanical properties of temporary lining; introduction of the properties into the model

The primary lining is, in general, designed to be from SB 25-grade sprayed concrete reinforced with mesh and lattice girders. The thickness of the lining of the side-wall drifts, top heading and invert was designed specifically for each support class. When introducing mechanical properties of the SB 25 concrete into the model, we start from the assumption that the full loading develops approximately at a distance of 3m behind the excavation face. The process of concrete ageing is introduced into the model by applying a different modulus of elasticity. The increases in the modulus of elasticity Et and strength of the sprayed concrete were determined using experimental measurements and recommendations “Shotcrete application rules” (the ITA/AITES Czech Tunnelling Committee) by means of the modulus of elasticity corresponding to that of three-day old concrete, i.e. “green concrete” and 18-day old concrete, i.e. “old concrete”.

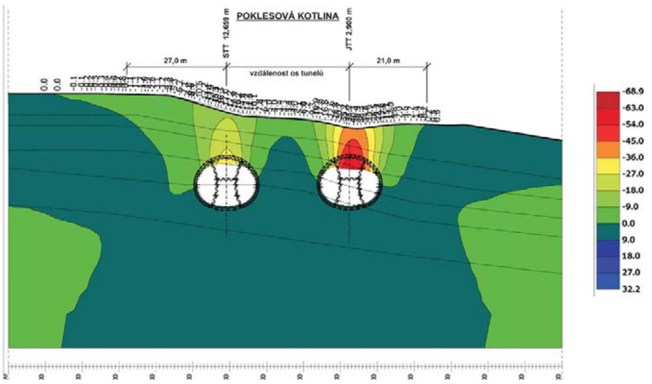

Fig. 2 Cross section 1 – 1

Anchors and jet grouting; their introduction into the model

The modelling of the action of radial anchors in the excavation support system is based on the assumption that one of the main functions of the anchors is to improve the shear parameters of the rock mass in the area where they are installed. In our case, the additional values of the cohesion c and angle of internal friction in the cross sections 2-2 and 1-1 were so low that they were not introduced into the calculation. Thus the calculation result is on the safe side. Regarding the cross section 3-3, where the jet grouting is used to create 600mm-diameter columns around the cross-section perimeter, the grouting modelled as an area in which the cohesion value c is increased to 100 kPa.

Excavation sequence; introduction of the sequence into the model

The NATM with the vertical excavation sequence (with sidewall drifts) is designed for the NTT and STT excavation. The NATM will also be used for the excavation of the ventilation duct, but a vertical sequence will be applied (top heading and bench). The structural analysis models the excavation of 1linear metre of the tunnel in several calculation steps – phases according to the progress of the works. The principle based on the ground response to the stress relief resulting from the excavation was used when the model for the cross sections 1-1 and 2-2 was being developed. It allowed us to express the influence of the location of the excavation face on the development of deformations in the overburden in percents. The immediate installation of the lining was modelled in the case of the cross section 3-3.

Individual calculation phases

The individual phases of the calculation were carried out in the following steps:

1. The introduction of the values of geotechnical parameters of the individual layers and girder elements respecting the vertical excavation sequence. The geotechnical values assigned to individual layers of the model respect the conclusions of the geological survey.
2. Generation of a finite element mesh with the densification of the mesh in the vicinity of the profile, in an annulus around the excavation.
3. Introduction of the state of primary stress in the rock mass.
4. Excavation of the left sidewall drift - the NTT (phases 1a and 1b – see Fig. 5).
5. Activation of the temporary lining.
6. Excavation of the right sidewall drift - the NTT (phases 2a and 2b – see Fig. 5).
7. Activation of the temporary lining.
8. Excavation of the top heading – the NTT (phase 3 – see Fig. 5).
9. Activation of the top heading temporary lining.
10. Excavation of the core and invert concurrently with the removing of lattice girders (phases 4 and 5 – see Fig. 5).
11. Activation of the lining at the bottom of the profile.

The STT excavation is subsequently introduced into the calculation using similar steps.

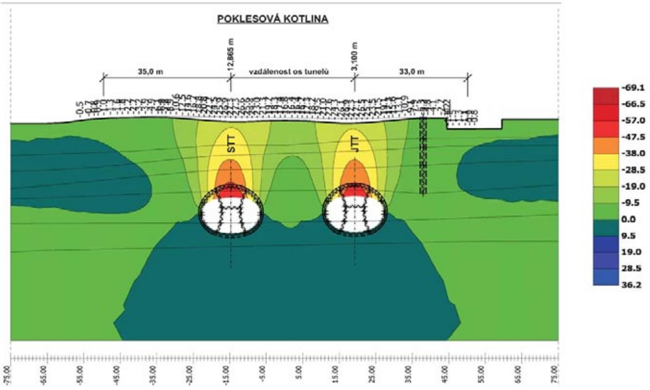

Fig. 3 Cross section 2 – 2

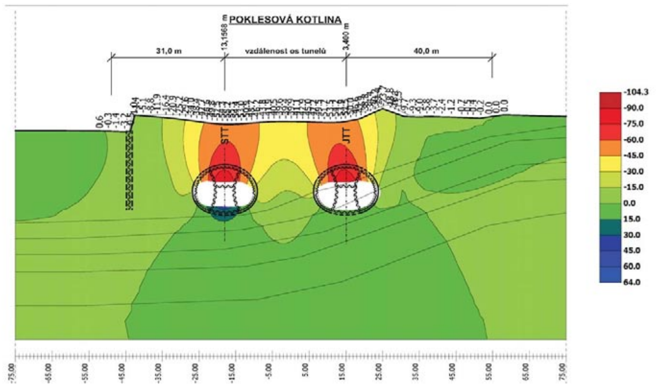

Fig. 4 Cross section 3 – 3

Zone of influence, prognosis of development of the magnitude of settlement and the impact on existing surface buildings and utility networks in the overburden

The prognosis of the terrain settlement and the width of the settlement trough was carried out by means of an FEM analysis. The analysis was performed for both tunnel tubes, at the three above-mentioned cross sections. The calculation for the portal section determined the maximum settlement of the surface at the cross section 1-1 which is to be encountered during the excavation of the NTT on the centre line of the tunnel to amount to approximately 20mm, at the width of the settlement trough of about 43m. The aggregate settlement curve determines that the settlement after the excavation of both tunnel tubes will be about 40mm (see Fig. 2).

The results of the calculation for the cross section 2-2, which is found in the Letná Member environment, suggest that the maximum settlement of the surface which is to be encountered during the excavation on the centre line of the northern tunnel tube will be about 30mm, at the width of the settlement trough of about 70m. The aggregate settlement curve shows the settlement after the excavation of both tunnel tubes at about 30mm (see Fig. 3).

The calculation for the portal section, the cross-section 3-3, determined the maximum settlement of the surface on the centre line of the NTT due to the excavation at about 55mm, at the width of the settlement trough of approximately 63m. The aggregate settlement curve shows the settlement after the excavation of both tunnel tubes at about 60mm (see Fig. 4).

The settlement values and the extent of the settlement trough depend on many factors, first of al on the excavation advance rate, excavation procedure and execution of the temporary tunnel lining. With respect to this dependence, the theoretical calculations must be considered to be only a prognosis.

The eastern portal is located in the close vicinity of a rampart, where an aggregate settlement of 60mm is theoretically predicted by the prognosis. The consequences of the excavation will be probably alleviated by means of the jet grouted excavation support which will be installed ahead of the excavation face. This support, however, cannot be unambiguously introduced into the model. The development of the settlement and the width of the settlement trough will be followed in the framework of the geotechnical monitoring. When the initial experience of the excavation is obtained and, above all, the geological situation at the portal sections is refined and verified (within the framework of the excavation of the trenches in front of the portals), the results of theoretical calculations will be confronted with the reality and, if necessary, verified by means of another mathematical model, so-called back analysis. It is possible to state on the basis of the completed calculations that the maximum settlement values should not exceed 60mm and the settlement trough will affect the ground surface up to a maximum distance of 40m from the tunnel centre line.

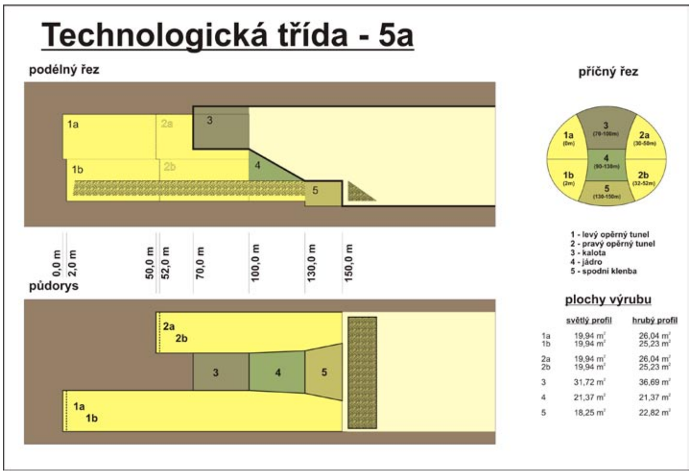

Fig. 5 Diagram of the excavation categorised as support classes 5a

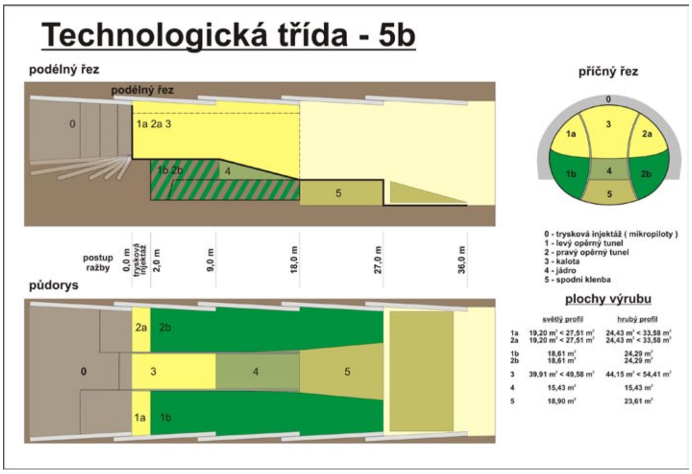

Fig. 6 Diagram of the excavation categorised as support classes 5b

The impact on surface buildings and utility networks in the overburden

The tunnels in the section between Myslbekova Street and the Prašný Bridge run under a sparsely developed area and no residential/administration building is found directly above the tunnel. However, the tunnels lead under a listed monument, a rampart, which is a brick lined stone masonry structure. This structure must be paid maximum attention during the tunnel excavation and the impact of the excavation on it must be minimised. The excavation under the historic rampart is designed to be protected by jet grouting carried out ahead of the excavation face, which will significantly reduce the impact of the excavation on the surface. The "Orphanage" building, which is today used by the Ministry of Culture, and historic buildings lining the northern side of Jelení Street are found in the vicinity of the tunnel route, at the edge of the settlement trough. The design protects those buildings by means of "curtains", which will be installed prior to the excavation. The curtains will significantly reduce the impact of the excavation on the structures; this fact has been verified by calculations. The curtains will have the form of piled retaining walls, which will be keyed into the bedrock. However, the developing settlement trough will affect the utility networks crossing or running parallel to the tunnel. The main focus of the protection will be on the networks which will have to be unconditionally operable throughout the tunnel excavation, such as sewerage and high-pressure gas lines. It follows with absolute certainty from the results of the model that the settlement will exert a load on the networks. Additional structural and technological measures will have to be implemented to reduce the settlement.

Conclusion

The viability of the mined tunnel construction by the NATM technique was verified by the mathematical model and its results. The outputs were further used for the final reinforced concrete design. The substantial output of the completed calculation is, above all, the effect of rigid pile walls located in the vicinity of existing surface buildings, which will significantly positively affect the development of the settlement trough. The objective of this solution is to avoid temporary support structures to be installed in the affected buildings, which would cause either undesired restriction of the operation or unwanted structural impacts on historic buildings. The structure of the Baroque rampart will be most of all affected at the eastern portal (the Prašný Bridge area); horizontal jet grouting ahead of the mined tunnel excavation face is added to the means of excavation in this area.

Ing. Václav Krch
PUDIS, a. s.
Nad Vodovodem 2/3258
100 31
Praha 10

tel.: 274 775 253
e-mail: vaclav.krch@pudis.cz

Ing. Radko Rieger
KO-KA, s. r. o.
Thákurova 7
166 29
Praha 6

tel.: 233 321 234
e-mail: r.rieger@ko-ka.cz