BÁTAAPÁTI DETAILED DESIGN AND DESIGN SUPPORT DURING CONSTRUCTION

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Multidisciplinary design, rock support design, sprayed concrete lining, numerical modelling, design support on site.

INTRODUCTION

Upon completion, the Bátaapáti underground repository complex will provide safe storage for approximately 40000 m^3 of low and medium-level radioactive waste from the Nuclear Power Generating Station of Paks. The complex includes two approximately 1.7 km long inclined access tunnels, cross-passages at every 250 m, transformer chambers and the ancillary tunnels from where the emplacement cavern access tunnels open. The area in between the ancillary tunnels gives place to the sumps and pump chambers to serve the operation of the emplacement caverns. In total 5.5 km of tunnel was constructed and ca. 188000 m^3 rock excavated.

Detailed design of the facility had been ongoing between May 2008 and August 2011. Design support on site during construction of two chambers went on continuously from April till October 2011 when tunnelling was finished. This paper will describe the design of the excavation support of the above mentioned tunnels, chambers and the emplacement caverns themselves and the experiences learnt during design support on site.

DESIGN PARAMETERS

The first step of detailed design is the definition of design parameters. It is important to define the majority of the parameters directly from measurements, although it is inevitable to have some of the parameters calculated from the existing parameters or based on empirical methods. In some situations we have measured data but not in sufficient number for the precise and direct determination of parameters. In these cases the parameters have to be defined or refined with empirical methods, but the results have to be checked with the measured data.

Before the commencement of the emplacement cavern designing a thorough programme of laboratory and in-situ measurement was completed to ensure the amount of measured data for the direct derivation of design parameters. The measured data was statistically processed to filter the extreme results and to identify the results that most realistically describe the examined rock. The plate jacking test can be an example for the insufficient number of measurement as there were only six measurements which does not allow the designer to derive the exact Young modulus of the rock mass from it. In the end the parameter had to be calculated from the Young's modulus of the intact rock which could be checked with the measured data. The calculated parameters proved to give a realistic estimate as it showed a close match with the measured results.

The derivation of each design parameters is detailed in the Geotechnical Interpretive Report. For better understanding the parameters of the intact rock and the most common rock class, class III are presented in Table 1 and 2. As the exploration programme progresses in Bátaapáti we have more and more information on the design parameters. It should be noted therefore, that these parameters were defined based on the data available in the time of detailed design of chambers.

Table 1: Rock mechanical parameters of intact rock

Property	**Value**	
Uniaxial compressive strength (σ_c, average)	101.92	MPa
Poisson's ratio	0.17	
Density	2710	kg/m^3
Porosity	3	vol.%
Ratio of horizontal and vertical in-situ stresses ($K=\sigma_h/\sigma_v$)	1.0	
Hoek-Brown parameter (m_i)	15.9	
Young's modulus (E)	45.87	GPa
Permeability	10^{-9}	m/s

Table 2: Hoek-Brown parameters for class III intact rock and disturbed rock zone

Rock class	**D (-)**	**E_m (GPa)**	**m_b (-)**	**s (-)**	**a (-)**
III.	0.0	6.385	1.741	0.001019	0.513
	0.5	3.121	0.832	0.000257	0.513

GEOTECHNICAL CRITERIA

The design of a nuclear waste repository comes with harsh criteria, which become stricter as we come to the design of the actual emplacement caverns. When designing the rock support the geotechnical criteria are the most important to be understood and kept, but a thorough and careful design can promote the compliance of the hydrogeological criteria also.

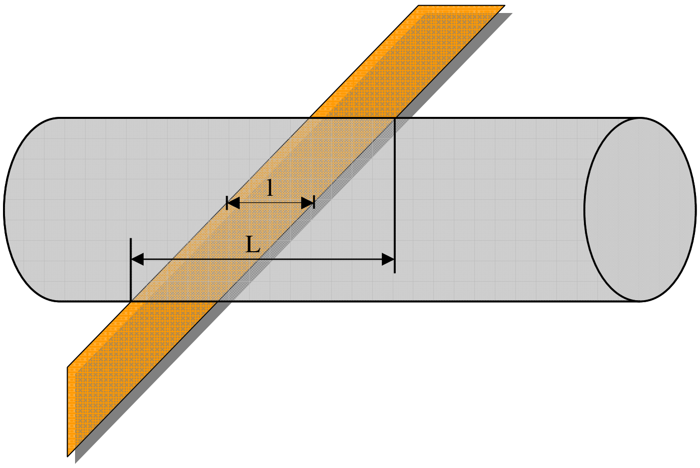


Figure 1: Interpretation of the 1st geotechnical criterion (Forgó & Kandi, 2009)

The 1st geotechnical criterion was defined as follows:

The emplacement caverns cannot cross a zone more than 40 metres wide of a rock qualified less than 0.025 with Barton's Q value (class V rock). The emplacement caverns cannot cross a zone more than 60 metres wide of a rock qualified less than 0.1 with Barton's Q value (classes IV and V quality rock). The interpretation of the 1st criterion is shown in the figure on the right (Forgó & Kandi, 2009).

Definition of the 2nd geotechnical criterion:

The final headwall of the emplacement cavern cannot be constructed in a rock formation with a quality of less than 0.025 defined by Barton's Q value (rock class V). (Forgó & Kandi, 2009).

The construction of the emplacement cavern can only cross a zone of rock which has a lower Q value than 0.025 in 5 metres length (marked with 'l' in Figure 1). The cavern can only cross a zone of rock which has a Q value lower than 0.1 in 20 metres length (marked with 'L' in Figure 1).

In highly weathered rock the effect of arching can only be considered if the distance between better rock can be spanned over for example by spiling. If a longer zone of rock is classified as rock class V the tunnel might become unstable. The same principle applies for the better quality rock zones which remain stable even for longer zones under the same circumstances.

To achieve the above mentioned criteria, a restriction had to be applied in the design of the emplacement chambers. One of these restrictions states that it is not recommended to excavate junctions in zones where rock quality based on Q is less than 0.1 (rock class IV and V).

On the basis of the second geotechnical criterion final headwall was designed in a way to simplify construction. Rock support was defined for two cases. In the first case the headwall is constructed in rock class I-III and sprayed concrete and rockbolts have to be applied according to the requirements for rock class III. When the headwall is excavated in rock class IV, a more robust rock support system determined for rock class IV has to be applied.

To refine and verify geotechnical criteria several 2D and 3D numerical models were made. These models were based on the most up-to-date geotechnical criteria in the location of the caverns.

DESIGN OF ROCK SUPPORT

The detailed design of the emplacement caverns is an iteration process and is based on a combination of empirical and analytical design methods and state-of-the-art numerical modelling (Váró et al., 2009). The design approach is shown in Figure 2.

The initial step in the design is the classification of the rock mass using the Q-system (Barton et al., 1974), (Grimstad & Barton, 1993). The method incorporates geological, geometric and design parameters to determine the Tunnelling Quality Index (Q). The host rock mass in Bátaapáti is classified into 6 different rock classes ranging from hard to extremely weak rock. A summary of the defined rock classes is given in Table 3. Recommended support measures are derived from a design chart on the basis of the Q-value, the geometry of the section and the intended use of the facility. In the case of each class recommended support measures are determined considering the lowest Q-value relevant to the class.

Table 3: Rock classes

Rock class	Q-value	Rock description
I	$Q > 10.0$	Massive, continuous, large blocks, fresh
II-A	$10.0 \geq Q > 4.0$	Large blocks (size: 0.6-2.0 m), fresh
II-B	$4.0 \geq Q > 1.0$	Blocky (size: 0.2-0.6 m), slightly weathered
III	$1.0 \geq Q > 0.1$	Small blocks (size < 0.2 m), moderately weathered
IV	$0.1 \geq Q > 0.02$	Highly weathered and altered granite
V	$0.02 \geq Q$	Highly crushed, sheared and fragmented granite

Initial empirical recommendations in terms of support measures are refined by limit-equilibrium calculations. The stability of the excavation is governed by different mechanisms depending on the discontinuousness of the rock mass. In the case of blocky rock the most probable failure mechanism is the sliding or falling of large blocks along the periphery of the excavation (Goodman & Shi, 1985). Support requirements for potentially loose wedges are provided by stability analysis software UnWedge. The software can automatically find the most unfavourable fracture geometry and calculate the factor of safety accordingly. Input parameters for the 3D analysis include the geometry and orientation of the structure, dip and dip direction of rock joints, rockbolt pattern and lining thickness. Rock support is considered adequate if the calculated factor of safety exceeds the required level of 1.5 for each unstable wedge.

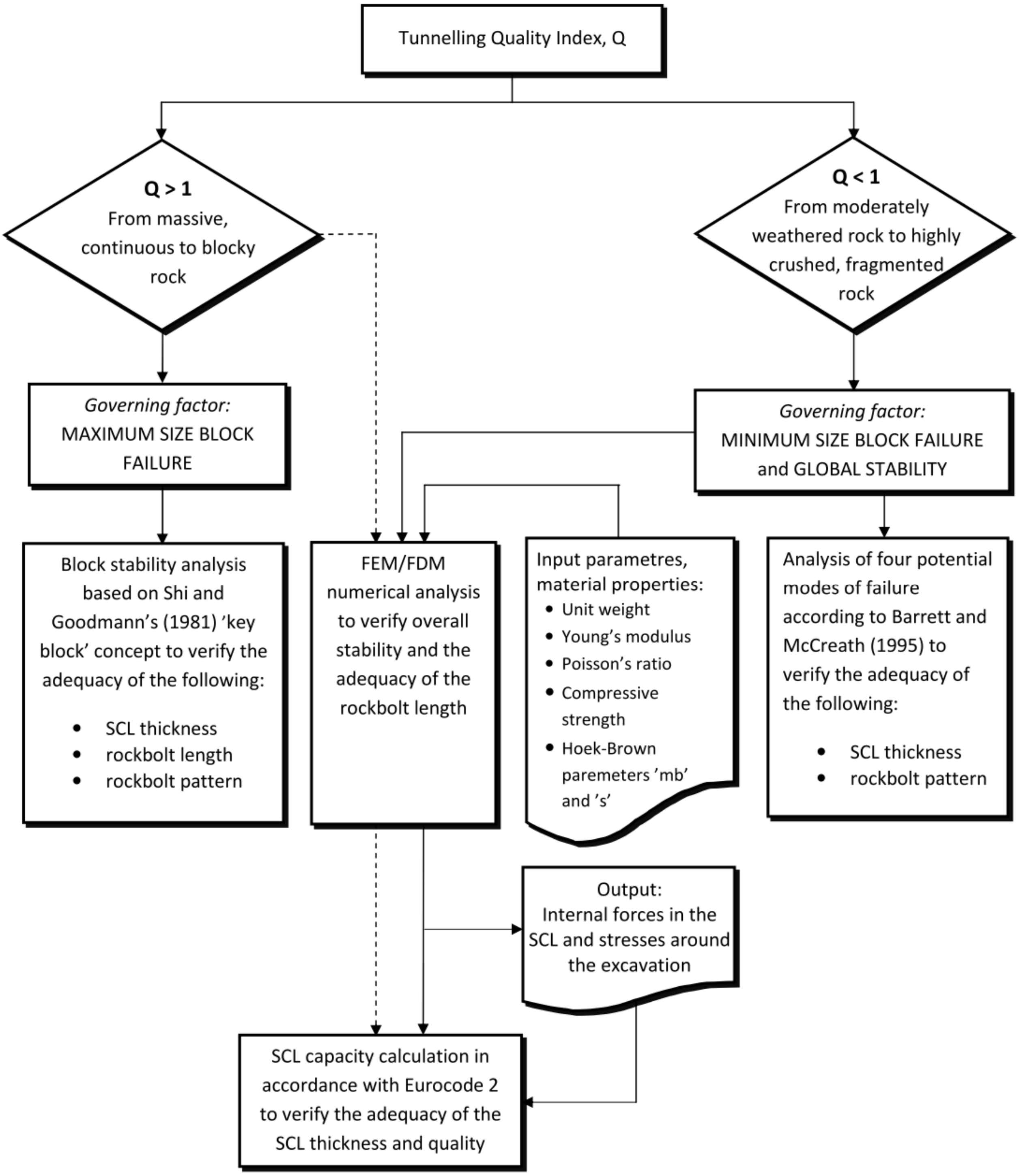


Figure 2: Design flow chart (Váró et al., 2009)

In the case of poor quality rock masses, where the presence of large blocks is unlikely, the stability of the excavation is governed by the behaviour of the sprayed concrete lining. In such cases the sprayed concrete lining (SCL) is designed to prevent the rock mass from revelling and loosening by supporting the smaller key blocks that remain unsupported by bolts. A deterministic approach have been introduced by Barrett and McCreath (Barrett & McCreath, 1995) to check the capacity of the SCL that is governed by one of four mechanisms, namely the adhesion loss, the direct shear, the flexure or the punching shear. Tests indicated that, if adhesion to the rock is maintained, the failure of the SCL will be controlled by direct shear failure. If adhesion is lost, then and only then does the flexural and punching shear failure become kinematically possible. The most likely methods of sprayed concrete failure are illustrated in Figure 3.

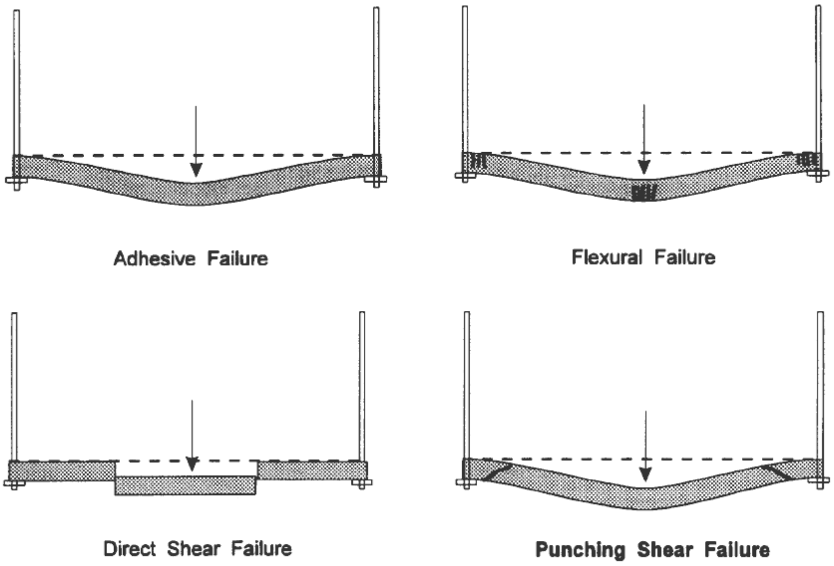
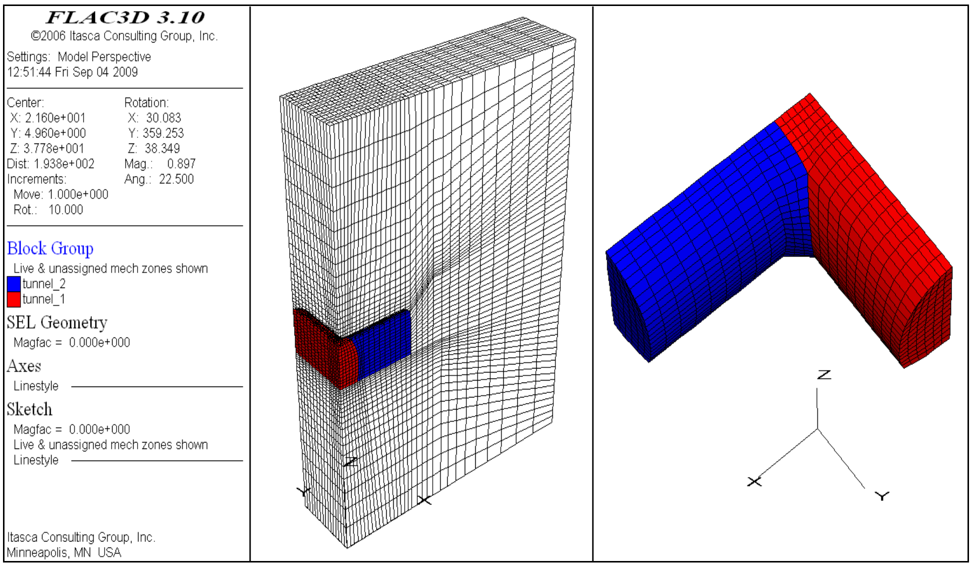


Figure 3: The most likely modes of shotcrete failure in blocky ground (Barrett & McCreath, 1995)

NUMERICAL MODELLING

Having proved the adequacy of the rock support by analytical methods, the following step in the design process is the numerical modelling of critical cross-sections and junctions to verify the overall stability of the excavation and to investigate the interaction of adjacent structures. In the design of rock support for the underground structures of the National Radioactive Waste Repository various numerical methods were used. Analyses were carried out using the finite element code Phase^2, finite difference code FLAC was applied for both 2D and 3D analyses (see Figure 4), and discrete element code UDEC was used for calibration modelling purposes. Software employing the finite element or finite difference method treat the rock mass as a continuous domain. In such cases the effects of discontinuities are taken into consideration by assigning equivalent continuum properties that are determined based on the geometry of the contained fracture systems and the physical properties of the intact rock and the fractures.



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FLAC3D 3.10
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Settings:  Model Perspective
12:51:44 Fri Sep 04 2009

Center:                  Rotation:
 X: 2.160e+001            X:  30.083
 Y: 4.960e+000            Y: 359.253
 Z: 3.778e+001            Z:  38.349
Dist: 1.938e+002         Mag.:    0.897
Increments:              Ang.:  22.500
  Move: 1.000e+000
  Rot.:   10.000

Block Group
  Live & unassigned mech zones shown
🟦tunnel_2
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SEL Geometry
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Figure 4: A FLAC3D model of a junction

2D numerical analysis is sufficient for the design of running tunnels and to study the interaction of adjacent tunnels running parallel to each other as in such cases the stress distribution around the excavation is considered uniform along the axis of the tunnel. In 2D analyses relaxation steps are implemented to account for the longitudinal distribution of stresses. The strength and stiffness of sprayed concrete changes considerably during its early age. Therefore in each relaxation step the material properties of the SCL are updated according to the age of the concrete. Actual properties are estimated using equations provided by Chang and Stille (Chang & Stille, 1993).

In the case of tunnel junctions and adjacent tunnels that do not run parallel to each other it is crucial to study the 3D redistribution of stresses that is only feasible with the application of 3D numerical modelling. Numerical modelling offers the ability to optimize the excavation sequence. In the instance of the modelling of the emplacement chambers several variations of excavation stages were considered in the models.

DEVELOPMENT OF DETAILS

On the basis of the calculations the design of rock support and excavation sequences can be carried out. Table 4 summarizes support for the most frequent rock class (rock class III).

Table 4: Rock support requirements in rock class III.

Rock class	**Sprayed concrete lining**		**Rockbolt**	**Lattice girder**	**Additional support (only if necessary)**	**Spiling**	**Advance length**
	type	thickness (mm)	length (m) / spacing (m)	spacing (m)		length (m) / spacing (m)	(m)
III.	SFRS	200	4.0 / 1.0×1.0	-	Headwall support with SFRS	-	1.0-1.5

Two types of permanent support are installed depending on the rock class. In good or blocky rock steel fibre reinforced sprayed concrete lining (SFRC) is applied while in highly weathered rock SCL is reinforced by steel mesh. Because of the large excavation profile steel mesh is required in rock class IV and V.

Smooth blasting and excavation sequence

The design of rock support includes the determination of appropriate excavation sequences when the effect of blasting on the surrounding rock has to be considered. Smooth blasting has to be applied with great attention in some particular places. This is the case for the excavation of the neck of the caverns which is important to block water ingress. To satisfy the special requirements, the advance length of the neck and the enlargement (the transition zone between the neck and the full sized emplacement cavern) for all rock classes is 1 m in favour of enabling smooth blasting. To reduce water leakage fully grouted IBO bolts have to be installed in the critical places and grouting is applied to prevent water seepage into the tunnels from drilled holes.

Grouting requirements to satisfy water ingress limits

The aim of the grouting is to guarantee long-term radiological safety by isolating the underground facilities from rapid flow paths leading to the surface, ensuring economical and safe tunnel conditions, minimizing the impact of tunnelling on the surrounding rock mass. The Client's (RHK Kft) requirement for inflow is 5 l/min/100 m for tunnels and 5 l/min for the full length of an emplacement cavern.

Regarding the requirements of long-term radiological security the technology of pre-grouting was developed in a way that the installed rock support does not reduce the efficiency of pre-grouting. Grouted zones are determined with sufficient overlap and they cannot be punched through by rockbolts either. In Figure 5 a possible solution for grouting is represented. Profile of the cavern is shown in blue in the 3D drawing, while the green surface is offset by the length of the bolts plus one meter. The length of the grouted zones should always exceed the perimeter of the green zone to ensure that rock support does not damage the grouting.

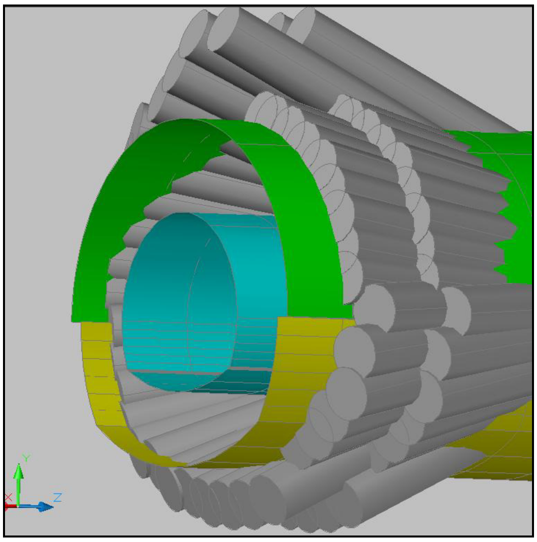

Figure 5: Grouting of the emplacement chambers in multiple steps

The position of rockbolts in the headwall has to be considered when the grouting holes in the headwall are designed. Because of the requirements of long-term radiological safety grouting can be only performed by materials which have a proved long-term chemical stability, or do not contain organic material, do not form colloids and gases.

Sprayed concrete specification

Apart from the above mentioned requirements the immediate participation in load bearing, adaptability to all tunnel shapes and durability have to be considered as well. Sprayed concrete with adequate materials used can meet all these requirements. For the inclined access tunnels polyester fibre reinforced sprayed concrete was specified but for the base tunnels, transport tunnels and emplacement caverns steel fibre reinforced sprayed concrete is designed. Requirements for sprayed concrete are reviewed in Table 5.

Table 5: Requirements for sprayed concrete

Concrete grade	C32/40
Quality of cement	Minimum CEM I 42.5
Quantity of cement	Minimum 400 kg/m^3
Aggregate	Graded and washed, crushed and natural quarzose aggregate
Grain size	Maximum nominal size: $d_{max} = 8$ mm
v/c	< 0.45
Steel fibre content for steel fibre reinforced concrete (SFRS)	Minimum 40 kg/m^3
Consistency	F5 (56-62 cm)
Temperature of sprayed concrete when sprayed	15-30°
Required compressive strength – J2 curve according to MSZ EN 14487	
1 hour	> 0.5 MPa
3 hours	> 1.0 MPa
6 hours	> 1.7 MPa
12 hours	> 2.5 MPa

Monitoring and observation values

The design of rock support also includes the site survey of the tunnels, maintenance and monitoring plan during construction and for long-term purposes. The results of monitoring were critical in case of the emplacement caverns for both construction and long-term stages. The specified measurements provide information for further design as for the stability of the examined tunnels during the excavation process also. To ensure this trigger values were specified during the design phase for critical measurements.

ADVANCEMENT OF CONSTRUCTION

The twin inclined access tunnels with 6 cross passage at a distance of approximately 250m from each other were finished in May 2008 with a total length of approximately 3650m.

The 1st phase of chamber area construction ("Small loop") was completed between September 2008 and April 2009. The following tunnels were completed in this phase: Eastern Ancillary Tunnel, Western Ancillary Tunnel, Cross passage 7, Cross passage 8 and the launch section of the transport tunnels.

The length of tunnels excavated in 1st phase is approximately 650m.

The following tunnels were excavated in the 1st stage of 2nd phase: Transport tunnel, Emplacement cavern transport tunnel, Emplacement cavern access tunnel, Compressor chamber and Pump chamber (sections where no plan modification was required).

Approximately 620m of tunnels were excavated in the 1st stage of the 2nd phase. The transport tunnels were completed by the breakthrough of the Cavern access Tunnel on 6 May 2010.

The 2nd stage of the 2nd phase included the excavation of sumps and pump chambers. The length of the tunnels is approximately 210m. The water treatment facilities of the 2nd stage were completed in March 2010.

The two emplacement chambers were constructed with a total length of 190m between January and October 2012.

The total length of tunnels, sumps, adits and chambers now reaches 5500m.

DESIGN SUPPORT DURING CONSTRUCTION

The design support during construction had two phases. From 4th April 2011 to 14th August 2011 continuous design support was present on site. Between 15th August 2011 to 21st October design support was provided on site weekly.

Design support during construction means that representative engineers of the Designer (Mott MacDonald Magyarország Kft) were present on site to answer the questions of Contractor (Mecsekérc Zrt) and the Construction Supervisor and to carry out smaller changes in design that promoted construction.

Continuous design support on site is for solving any upcoming technical problems, for working out special engineering/designer solutions and for providing special geotechnical consulting if required (Váró & Kandi, 2011).

In Bátaapáti the following tasks were included in design support:

- Attendance on daily cooperation meetings,
- Attendance on weekly coordination meetings with the Client or his representative,
- Daily review of monitoring results, compiling weekly monitoring reports (both for the Client and for the Contractor),
- Review of face mapping and record results of review in construction diary. Ensuring designer approval.
- Proposal or designer recommendation for definition of custom rock support.
- Review of over- and underexcavation. Working out action plan for exceeding limits.
- Survey of final tunnel support.

- Answering all questions and queries related to design during construction in design statements or in construction diary. Carrying out changes in design. Approval of construction technology specifications and their changes for the Client.

During construction of emplacement chambers the designers on site could experience the behaviour of rock more deeply by following with attention the in situ measurements, their results and geotechnical documentation and the construction sequences. These observations were summarized in a report to aid further works of the Designer and the Contractor.

The most important experiences are presented in the following subsections.

Rockbolting

Considering efficient corrosion protection and better interaction between rockbolts and sprayed concrete lining rockbolts are to be fully covered by sprayed concrete. Hang out end of rockbolts and anchor plates shall be considered when designing lining thickness. In case these are not covered by sprayed concrete during construction, they are to be covered subsequently (Váró & Kandi, 2011).

Optimisation of rock support in class IV

Top heading of the chambers were to be carried out in two sequences according to the original design. To enhance tunnelling efficiency the design has been reviewed and a new rock class (class IV/A) has been introduced when geological face mapping showed at least 34% of the face better than class IV rock. Tunnel support in class IV/A was the same as in class IV, but the top heading was excavated full-face.

The design amendment detailed the excavation sequence, tunnel support, monitoring system and trigger levels, the terms of using 1 m advance length, control plan and the decision hierarchy of face mapping evaluation (Váró & Kandi, 2011).

Development of class IV/A was an excellent example of Designer-Contractor cooperation.

Site experiences also confirmed that the rules of rock classification should be reviewed and therefore overconservative approaches can be filtered out. Considering site experiences in design can lead to avoid changes tunnel support from e.g class III to class IV when prognoses show rock quality reducing to class IV (but close to class III limit) in a short (2-3 m long) section. The opposite case (changing to class III support on short distance from class IV support) leads to the same problem, because different neighbouring support systems can cause not just difficulties in construction but even breaking off of sprayed concrete lining. Using less conservative classification system or dividing rock class IV into two classes can help very likely to avoid big changes in the support system, but refinement of other parts of classification system also needed (Váró & Kandi, 2011).

Experiences of two-step excavation of top heading in rock class IV

In emplacement chamber I-K1 between chainage 31.6 m and 48.5 m top heading was divided into two construction sequence. In accordance with the design support additional support elements were built in the right side of top heading left part to support ongoing excavation (Váró & Kandi, 2011).

The figure on the right shows the first advance of divided top heading in chamber I-K1 with the relevant rock support.

Figure 6: Required rockbolting on face and starting steel support arch in case of divided top heading in rock class IV (Váró & Kandi, 2011)

Experiences from invert excavation
During construction of tunnel invert the mapped rock might seem better or worse as it was defined during top heading construction. If the rock is weaker in the invert than it was in the top heading then additional support is required. Design support on site can help the Contractor to determine these additional support measures instantly thus improving construction efficiency.

Monitoring
As part of design support during construction the design engineers on site cared about the schedule and installation of monitoring elements. All available monitoring data were reviewed daily by the design engineers on site and even measurements were observed when it was possible (Váró & Kandi, 2011).

The following short term and long term monitoring elements have been used in Bátaapáti according to the detailed design (Váró & Kandi, 2011):

- survey and sounding of sprayed concrete lining (short term),
- optical convergence measurements (short term),
- mechanical convergence measurements (long term),
- extensometer measurements (long term),
- load cells tests for rockbolts (short term),
- load washer tests (short term),
- load cells tests for sprayed concrete lining (short term),
- hydraulic potential tests (long term),
- deformation measurements using “deformation measuring triangles” (long term).

CONCLUSION

The design of a tunnel or tunnel complex starts with the definition of the design parameters and the careful understanding of the design criteria. The design of rock support have many calculation steps and iterations through empirical methods on one hand, such as the world wide used Barton’s Q system, analytical methods on the second hand, such as Barrett’s calculations for sprayed concrete thickness and rockbolt pattern checking, but the final step is the state-of-the-art numerical modelling, which takes into account all the above mentioned factors and analysis global stability and interaction of adjacent or connecting tunnels.

Throughout the whole design process, the development of the details gives the final precision to the design package. Such details ensure the completion of requirements and criteria. When designing tunnels in fractured rock such details can be about grouting against water ingress with the consideration of the applied rock support, determination of the method of excavation for each rock class and fulfilling the material requirements of the rock support materials.

Going through all the design steps, developing the details the detailed rock support and excavation plan of many tunnels and the first two chambers have been finished for the Bátaapáti project. After excavation works were finished at the emplacement caverns at the moment 5500 m of tunnels are already constructed.

Mott MacDonald Magyarország Kft has provided design support during construction of the emplacement chambers from April to October 2011. All in all the design support during construction was successful. All problems were solved quickly that made construction works more fluent, successful cooperation has been carried out with the Contractor, Subcontractors and the Construction Supervisors.

During construction of emplacement chambers the Contractor offered variances from the detailed design in many cases. To assist the construction efficiency and make the construction more economical the Designer on site amended or revised the detailed design instantly while formalities were still kept.

Specified monitoring elements were successfully installed and short term monitoring was carried out. All monitoring data show that no trigger values have been reached in any case. Long term monitoring still goes on without interruption in the constructed emplacement chambers.

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