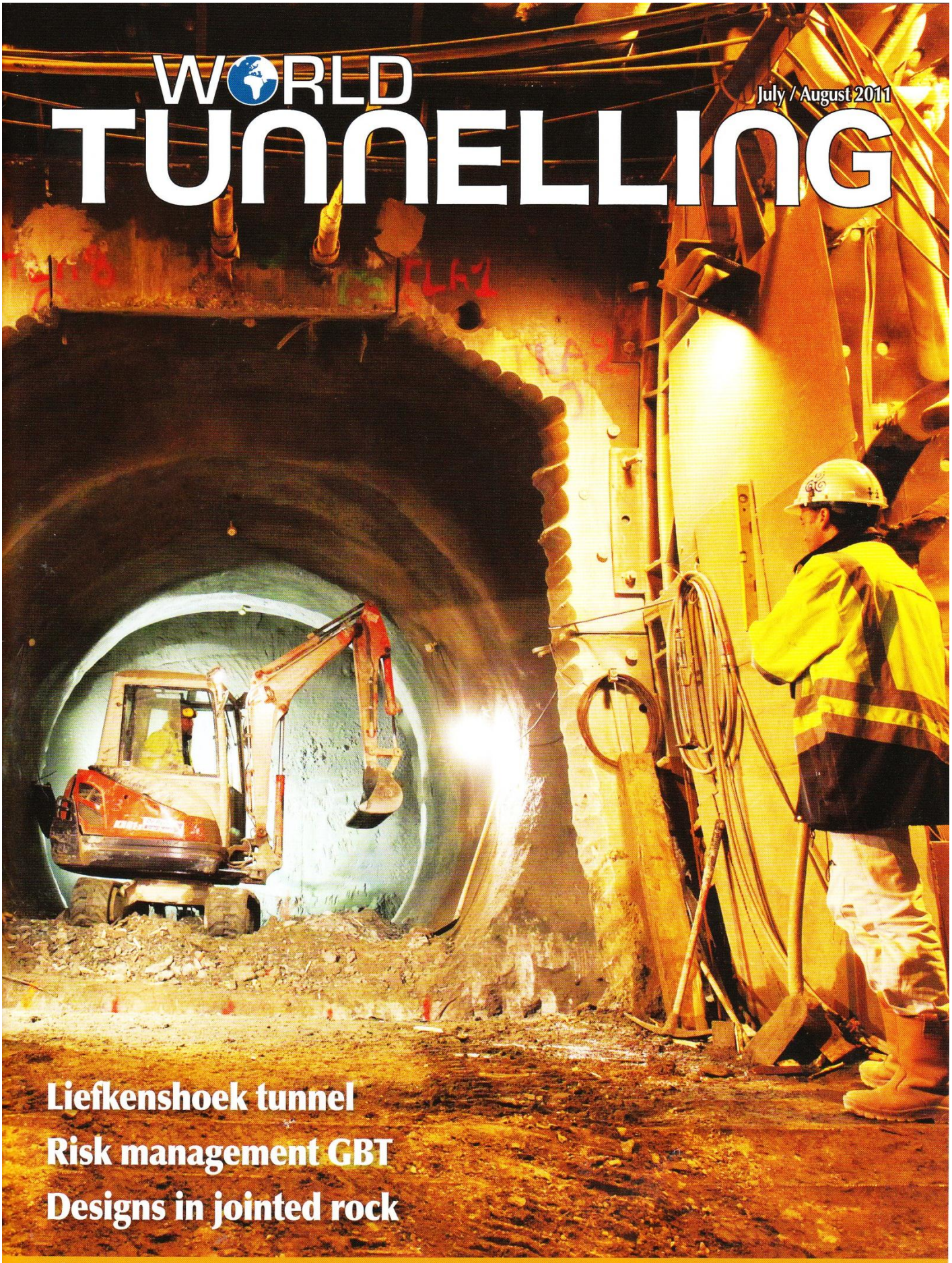
WORLD TUNNELLING

July / August 2011



Liefkenshoek tunnel

Risk management GBT

Designs in jointed rock

www.world-tunnelling.com

Designs in jointed rock

Dr Walter Wittke and Dr René Sommer compare rock mechanical models and classification systems, and ask whether their application involves any risk

TWO frequently applied design methods for tunnels in jointed rock are the rock mechanical models and corresponding analysis, and the plan based on classification systems.

The first method is mainly based on the results of comprehensive geotechnical investigation and stability analysis, as well as on monitoring during construction. It is applied predominantly in German-speaking countries, and has proven to be successful for the safe and economic design of tunnels in jointed rock. Confidence in the method has also been gained by numerous post-analyses of completed tunnels.

A characteristic feature of classification systems is that rock-mass properties and other factors influencing the stability of a tunnel, such as in-situ stress and groundwater conditions, are condensed into a single numerical value, referred to as the 'rock mass rating index'.

According to Mr ZT Bieniawski, the developer of the RMR classification system, "a classification system is not intended to replace analytical modeling, site investigations and monitoring, but should be used in conjunction with these tools of rock engineering design".

In contrast, classification systems in the recent past have been used increasingly as design methods in their own right, without any kind of analysis.

This paper will review critically two design methods for tunnels in jointed rock and compare them using examples.

DESIGN: ROCK MECHANICAL MODELS

This design method's basic procedure is outlined in figure 1. A rock mechanical model is established, based on the results of geotechnical investigations, and engineering and geological judgement. This includes models describing the structure and texture of the intact rock and discontinuities. In addition, the rock mechanical model includes parameters that describe the stress/strain behaviour and permeability of the rock mass for all of the units through which the proposed tunnel will pass.

The in-situ stress state must be considered. The orientation of the discontinuity system with respect to the tunnel considerably influences the type and amount of support measures, and thus is an important aspect of every model (figure 1).

As an example, figure 2a represents schistose rock (clay slate) and the corresponding rock mechanical model. The clay slate is separated mainly by three sets of discontinuities, denoted with D1, D2 and Sch. Their orientations are found to be approximately vertical (D1 and Sch) and horizontal (D2). The intact rock has a planar grain structure caused by the schistosity Sch, which, in this particular case, has the same orientation as the bedding. The structural model of this rock mass and the most important rock mechanical parameters leading to the corresponding rock mechanical model are represented in figure 2b.

On the basis of such rock mechanical models, stability analyses and serviceability proofs are carried out, taking into consideration parameter

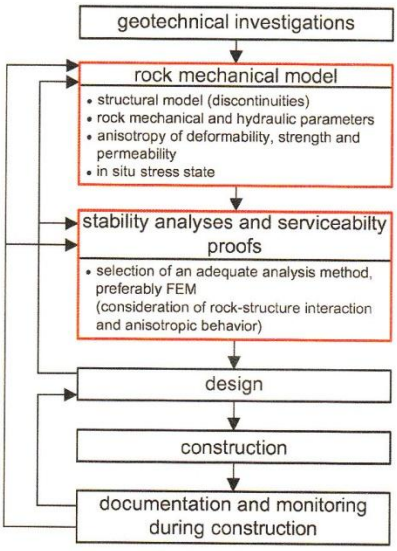
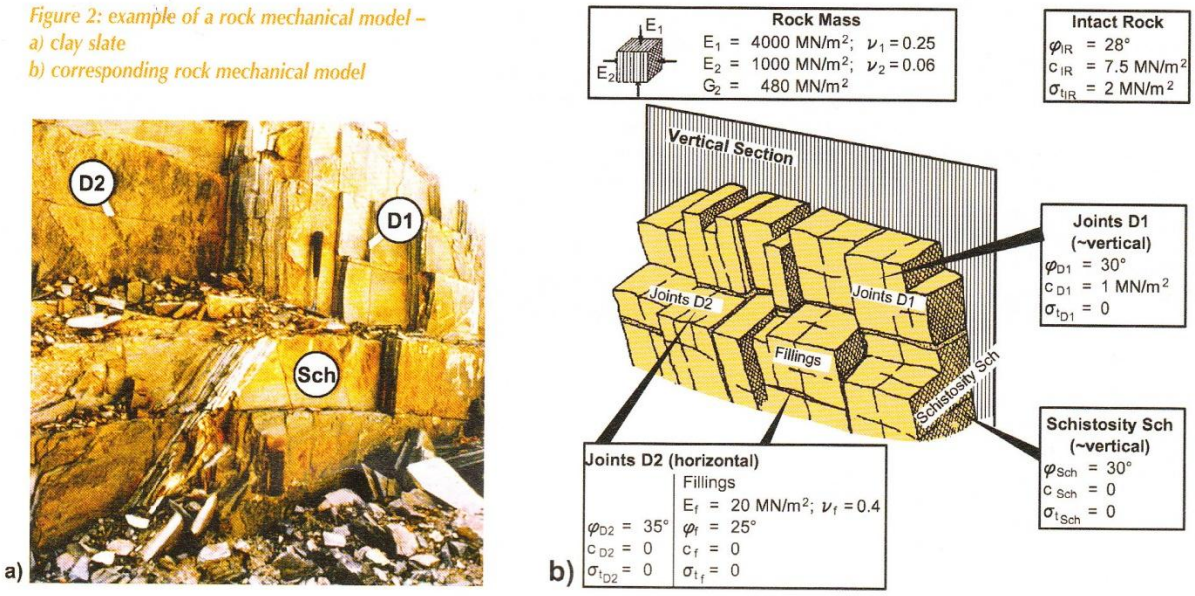


Figure 1: design based on rock mechanical models

Figure 2: example of a rock mechanical model – a) clay slate b) corresponding rock mechanical model



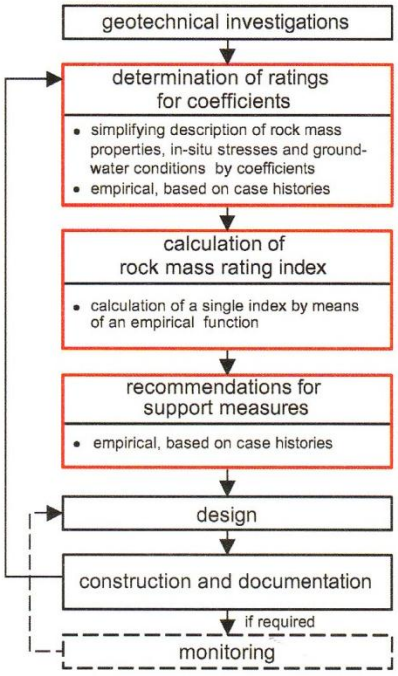


Figure 3: design based on classification systems

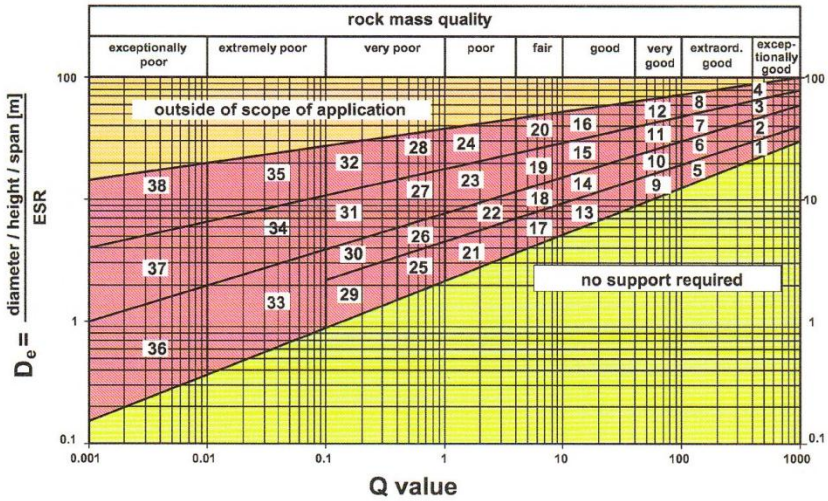


Figure 4: Q-System, evaluation of support classes

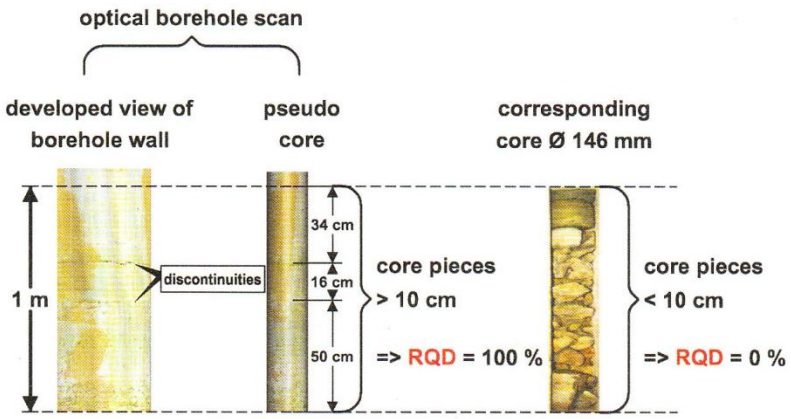


Figure 5: comparison of an optical borehole scan with a corresponding core

variations. Rock structure interaction and anisotropic rock-mass behaviour are accounted for using a suitable analysis method, such as the finite element method (FEM). Supplementary analysis with regard to the stability of rock wedges adjacent to excavation surfaces may also become necessary. On the basis of the analysis results, the final design is carried out, followed by construction of the tunnel (figure 1).

During construction, documentation of the different construction phases and a monitoring programme are carried out (figure 1). In addition to monitoring displacements and, eventually, anchor loads and stresses in the shotcrete and reinforced concrete lining, geotechnical mapping of the temporary face is carried out.

By these means, design assumptions can be reviewed by comparing the results of monitoring and analysis. Post-analysis may be required if the result of monitoring does not agree with the prediction. Thus, if necessary, support measures can be adapted or modified during construction. Reduced level monitoring can be continued after construction, if required.

A characteristic aspect of this design method is the iterative procedure in which individual steps may be repeated several times, if necessary.

This design method was recommended by the tunnelling study group of the German Geotechnical Society, as well as the European Regional Technical Committee No 9 for Tunneling and Underground Construction (ERTC 9) of the International Society for Soil Mechanics and Foundation Engineering (ISSMFE); it has been applied successfully by the WBI and other consulting engineers for several decades.

DESIGN: CLASSIFICATION SYSTEMS

GENERAL PROCEDURE

In principle, all classification systems are based on coefficients – a means of trying to account for rock mechanical parameters, in-situ stresses and groundwater conditions. Tables, formulas, diagrams and combinations are used to obtain ratings for these coefficients. By means of the empirical functions of the coefficients, the so-called 'rock mass rating index' is calculated. Based on such a single index design, recommendations are made for support measures, denoted as 'support classes'.

During construction, the different building phases are documented and the rock mass rating index is reviewed on the basis of the encountered rock mass conditions; eg at the temporary face. If no agreement is obtained, the rock mass rating index needs to be re-evaluated, which may lead to a modification of the support class. A monitoring programme is not always necessary.

The basis of each classification system is empirical. This means that the selection of influencing variables, their rating and the recommended support classes are based on the experience of the developer, gained from practical cases. As a consequence, classification systems generally have a subjective aspect.

In the following, the 'rock quality designation index', which serves as an input parameter for different classification systems, as well as the Q-system developed by Barton, are briefly described. Another widely used classification method is the RMR system, developed in 1974 by Bieniawski, and updated in 1989. The RMI system was developed more recently by Palmström.

ROCK QUALITY DESIGNATION INDEX

The RQD had been introduced already by Deere et al in the late 1960s. It can be evaluated by the mapping of cores from drillings and is defined as follows:

$$RQD = \frac{\text{length of rock pieces} > 10\text{cm}}{\text{total length of core}} \times 100\ [\%] \qquad (1)$$

By means of the RQD, the rock mass is subdivided into five classes, ranging from 'very poor' to 'excellent'.

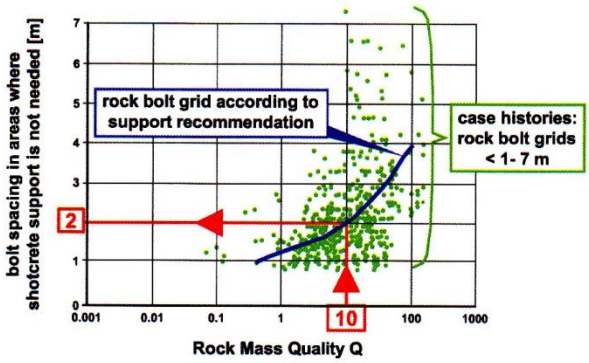


Figure 6: Q-System support recommendations on the basis of case histories

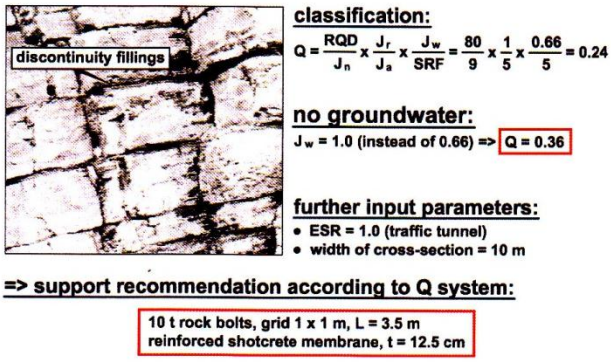


Figure 7: classification of a limestone according to the Q-System

Q-SYSTEM

The Q-System was developed originally for conventional tunneling and then later extended to other applications in rock mechanics. The rock mass rating index of the Q-System denoted as 'rock quality index' (Q) for conventional tunnelling is defined as the product of three factors:

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF} \quad (2)$$

The first factor comprising RQD and joint set number Jn considers the influence of the discontinuity system. The second factor characterises the discontinuity properties by the joint roughness number Jr and the joint alteration number Ja. The third factor accounts for the effects from groundwater, weak zones and in-situ stresses, which are described by the joint water reduction factor Jw and the stress reduction factor SRF. Q can range from 0.001 to 1,000; ie from 'exceptionally poor' to 'exceptionally good' (figure 4).

The support classes in the Q-System are evaluated with the aid of the Q-value and the so-called 'equivalent dimension' De, which is the ratio of the diameter, height or span of the cross-sectional area of the excavation and the 'excavation support ratio' (ESR).

The ESR is dependent on the purpose of the underground structure. Unlike permanent support, the temporary support designed for smaller safety margins is achieved by replacing Q and ESR by 5 x Q and 1.5 x ESR, respectively.

A total of 38 support classes are defined, from which support class 1 requires almost no support, whereas for support class 38 the largest amount of support is necessary (figure 4). For each class, the amount of support can be taken from corresponding tables.

ASSESSMENT OF RQD

The RQD is dependent on a number of influencing factors, such as the orientation of the corresponding borehole with respect to the discontinuity system, the drilling method, the core quality and core diameter.

In figure 5, the result of an optical scan of a 1m-long wall of a borehole is compared to the photo of a corresponding core obtained from the same depth. The borehole scan reveals two discontinuities, with spacing of more than 100mm resulting in a RQD value of 100%.

"By means of the RQD, the rock mass is subdivided into five classes, ranging from 'very poor' to 'excellent'"

In contrast, the corresponding core from the drilling process is separated into pieces less than 100m, corresponding to an RQD value of 0.

This example shows that the RQD evaluated for a rock mass can be completely different, depending on the exploration method. Furthermore, the RQD value depends on the orientation of the borehole with regard to the discontinuity system. Thus the value of RQD with regard to the rock mass quality is very limited.

CLASSIFICATION SYSTEM FLAWS

In the following, some striking deficiencies of classification systems that can lead to unsafe design or over-design are demonstrated by means of the Q-System.

The diagram in figure 6 relates Q-value to rockbolt spacing. The green points indicate the spacings that have been carried out in the considered case histories on which the Q-System is based. These case histories refer to areas where shotcrete support was not needed. As can be seen from the large scatter in figure 6, no clear correlation between spacing and Q-value exists.

Nevertheless, a correlation between bolt spacing and Q-value has been evaluated. This is represented by the blue line in figure 6, and is meant to serve as a basis for support recommendations according to the Q-System. An example is also given. Therefore a support recommendation based on this correlation cannot be considered reliable.

The significant influence of discontinuity set orientation on the required tunnel support that

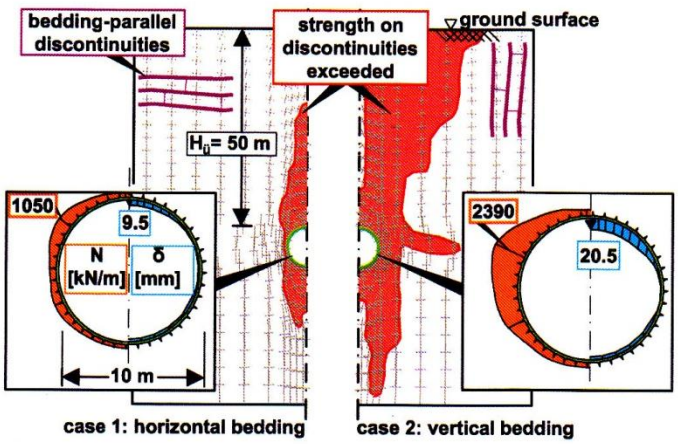


Figure 8: influence of orientation of discontinuities on the stability of a tunnel

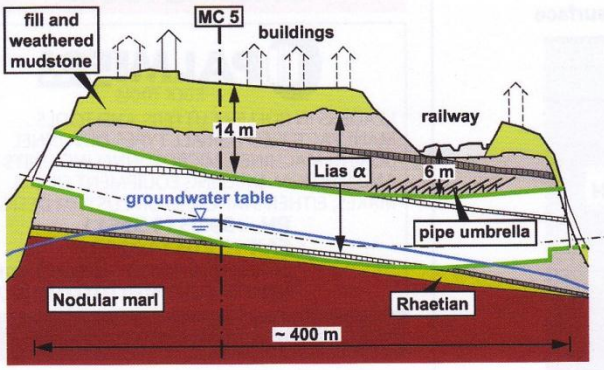


Figure 9: Österfeld Tunnel, longitudinal section

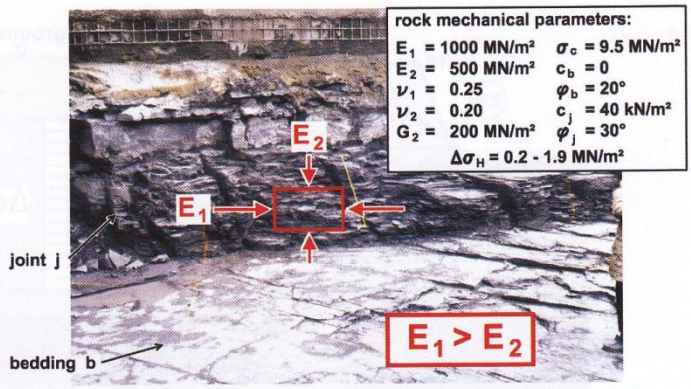


Figure 10: Liasα rock mechanical parameters and anisotropic deformability

cannot be adequately accounted for by means of classification systems shall be demonstrated by means of a traffic tunnel located in limestone.

The limestone reveals three orthogonal discontinuity sets, consisting of a bedding-parallel discontinuity set and two joint sets (figure 7).

The bedding-parallel discontinuities are filled by layers of unconsolidated volcanic ash, resulting in a very low friction angle of 11°. This rock mass was rated by Barton et al to a value of Q = 0.24. If no groundwater is considered, Q = 0.36 is obtained (figure 7).

According to the Q-System, for a 10m-diameter traffic tunnel with a circular cross-section in such rock mass conditions, the recommended support consists of 3.5m-long rockbolts spaced at 1m apart and a 125mm-thick reinforced shotcrete membrane. It should be noted that this support recommendation is independent of the tunnel overburden and the orientation of the discontinuities.

In order to check this support recommendation, 2-D stability analysis, according to the FEM using program system FEST03, were carried out in which the overburden of the tunnel was assumed to be 50m. Two cases were investigated.

In case 1, horizontal bedding-parallel discontinuities are assumed. In case 2, the bedding-parallel discontinuities are assumed to dip vertically and strike parallel to the tunnel axis (figure 8). A full-face excavation and the above-mentioned support measures – which are required according to the Q system and are independent of the orientation of the discontinuities – were simulated.

In figure 8, the characteristic results of these analyses are represented. In case 2, the zones in which the shear strength along the bedding-parallel discontinuities is exceeded are much larger, compared with case 1, and reach to the ground surface. As a consequence, the stress resultants of the shotcrete membrane are also considerably larger in case 2 than in case 1.

The maximum normal thrusts and displacements at the contour of the tunnel differ more than a factor of two. In case 1, minimum reinforcement of the shotcrete membrane is sufficient, which is in agreement with the support recommendations of the Q-System.

In case 2, however, an increase of the thickness of the shotcrete membrane and a much stronger reinforcement become necessary. Thus, in this case, the required support evaluated on the basis of the Q-System is insufficient.

CASE HISTORY: ÖSTERFELD TUNNEL

Around 400m long, the Österfeld tunnel is part of the eastern bypass around Vaihingen, a suburb of Stuttgart (figure 9).

The tunnel is almost completely located in mudstone layers of the Lower Jurassic (Liasα). Figure 10 shows a photo of the Liasα, including the most important rock mechanical parameters, indicating a marked anisotropy of deformability ($E_1 > E_2$). In-situ stress measurements, according to the overcoring technique carried out before construction, showed that horizontal stresses of $\Delta\sigma_H$ = 0.2-1.9MPa exist in the ground, in addition to those stresses resulting from self-weight due to horizontal constraint.

A mouth-shaped cross-section was carried out with an internal width of 11.2m and a height of 9.7m (figure 11a). Due to the large excavated cross-section of some 100m², as well as for construction reasons, the cross-section was subdivided into vault, bench and invert. For the same reasons, and in order to minimise surface subsidence, the vault was designed with a temporary invert of reinforced shotcrete.

The temporary support of the tunnel consists of a reinforced shotcrete layer of 200-300mm thickness, steel sets and systematic rockbolting around the vault and bench (figure 11a).

Stability analyses for the construction stages were carried out according to the FEM. Figure 11b shows analysed normal thrusts in the shotcrete layer for the final excavation stage, assuming →

"Striking deficiencies of classification systems that can lead to unsafe design or over-design are demonstrated by means of the Q-System"

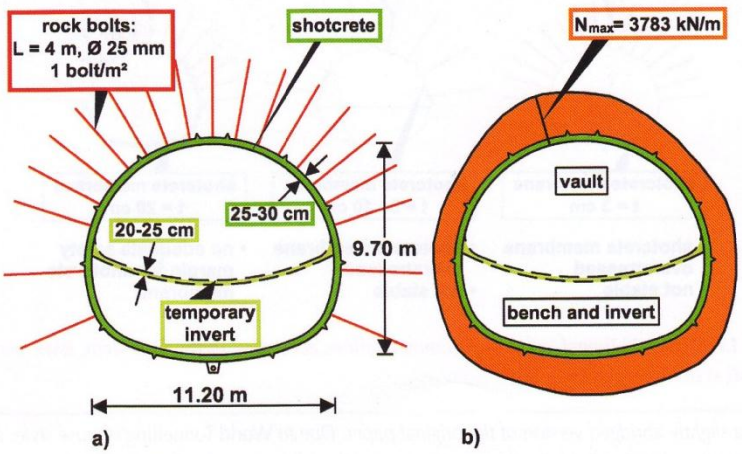


Figure 11: Österfeld Tunnel: a) cross-section and temporary support; b) normal thrusts of the shotcrete membrane

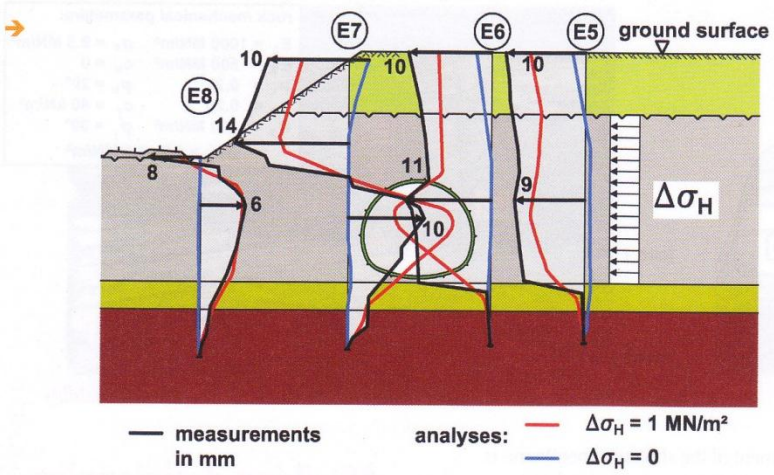


Figure 12: Österfeld Tunnel, measured and calculated horizontal displacements (MC 5)

$\Delta\sigma_H$ = 1MPa. The resultant bending moments were very small and are not shown in figure 11.

During excavation of the tunnel heading, an extensive monitoring programme was carried out, the results of which were evaluated and compared with predictions. Figure 12 shows the comparison of measured horizontal displacement and analysis results at measuring cross-section MC 5 (figure 9). Accordingly, for $\Delta\sigma_H$ = 1MPa, a good correspondence was found.

The support required for this tunnel, according to the Q-System, RMR-System and RMi-System, was evaluated, assuming $\Delta\sigma_H$ = 1MPa.

As a result, each classification system leads to a different support recommendation (figure 13). In addition, the results of stability analyses, according to the FEM, indicate that the tunnel would not have been designed safely with any of the three classification systems (figure 13).

CONCLUSIONS

The design method based on rock mechanical models and adequate analysis procedures has proven to lead to safe, economic design. When applying this procedure, no rock mass classification system is needed.

The review of classification systems has shown that the correlation between rock mass rating index and required support is not unambiguous; ie the same rock mass conditions may lead to distinctly different rating indices and vice-versa.

In addition, rock mass rating indices do not adequately cover all influencing parameters, such as the orientation of discontinuity sets, deformability and potential anisotropies.

As a consequence, classification systems can lead to unsafe and uneconomic design, as this paper shows.

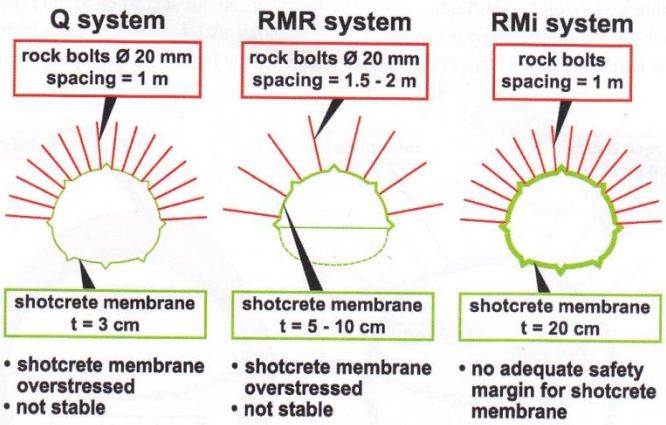


Figure 13: Österfeld Tunnel, support recommendations according to the Q-System, RMR system and RMi system

This is a slightly abridged version of the original paper. Due to World Tunnelling*'s house style, all references have been omitted. Readers wanting to read the full paper with references should contact Prof Walter Wittke, managing director, or Dr René Sommer, project manager, at WBI Consulting Engineers.* ***wbi@wbionline.de***

SUPPLIES & SERVICES

DRILLING TOOLS

PALMIERI ROCK TOOLS
LEADERS IN ROLLER CUTTERS AND TOOLS MANUFACTURED FOR ALL TYPES OF TUNNEL BORING MACHINES, MICROTUNNELING UNITS AND VERTICAL DRILLING EQUIPMENT OF ALL MAKES, EITHER STANDARD OR CUSTOM DESIGNS
PH. +39 0534 32511
FAX +39 0534 32501
sales@palmierirocktools.com
www.palmierigroup.com
Agents wanted in selected countries
Please apply to: a.tasselli@palmierirocktools.com

ENGINEERING

Clayton
World Leading Locomotives & Haulage Solutions ...
...for Mining, Tunnelling & Surface Transport

Clayton Equipment Ltd
www.clayton-equipment.co.uk
Tel +44 (0) 870 112 9191

SHAFTS & TUNNELS

Sp SPECIALIST PLANT
• Shaft jacking systems
• Grout mixer/pumps - 200 L to 2000 L
• Vent fans 500 ø to 1500 ø
• Locos - battery and diesel
• Track and pipework
• 610 gauge rolling stock
• CIFA tunnel shutters
Specialist Plant Associates
Tel: +44 (0) 1234 781882 Fax: +44 (0) 1234 781992
Email: info@specialistplant.co.uk

WORLD TUNNELLING
Why wait?
Go to www.world-tunnelling.com to subscribe and receive your own copy

pass on the message...