Rational design for tunnel ground support with membranes based on the geomechanically classification of Q by Barton

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ABSTRACT: The parameters to consider for an optimal solution for the design of underground rock support are the lifetime of the tunnels, the use of the tunnels, the safety level, and the cost. One of these design systems was developed by Barton. Nevertheless, the system has some limitations when it comes to dynamic ground conditions or higher static loads. With new ground support high-tensile steel membranes, the focus shifts from the bolt only, to an underground rock retention system where the membrane plays a significant role. An optimal load transfer from rock mass to the support system, be it dynamic or static, can be reached by high tensile steel meshes, that allow a wider bolt spacing. The proposed extension of the Q System considers the severe conditions the mining industry faces to get the ore from increasingly deep stops.

Keywords: Q System, rock support, ground conditions, ground support membranes, tunnel safety, high tensile steel membrane.

1 INTRODUCTION

Support in the underground works must allow control and stability of the excavations for the safety of the personnel throughout the useful life of the works. The deformation of the supported structure must be compatible with this time constraint, and it must be operationally and economically efficient. The behaviour of the rock mass in front of natural and induced actions determines the stability conditions and, therefore, the support measures to apply. If the rock is competent, no problems will appear during the excavations. On the contrary, if the massif is incompetent with low resistance and the discontinuities are unfavourable, it will present difficulties. Based on the behaviour of the terrain, the support is designed (Fig. 1).

Figure 1. Ground support of a mining gallery with electro-welded steel mesh and high-resistance steel mesh in rolls, both fixed with bolts.

The calculation of the support of underground works can be done through analytical, observational, empirical and numerical methods. As a good practice, it is convenient to compare the models, and it is not advisable to take a single method as a reference. The *Q* Geomechanical classification system was developed at the Norwegian Geotechnical Institute (NGI) between 1971 and 1974 (Barton et al. 1974). The empirical index comes from the retrospective analysis of many underground excavations around the world. It is a method applicable to underground works, and since its implementation, there has been considerable breakthroughs in ground support and excavation technology. The classification also can be used to characterize the massif and provide estimates of support needs. The *Q* system has its best results in the case of falling blocks. For other types of terrain behaviour, the *Q* system has limitations, like other empirical methods. In this case, equivalence is used between the quality of the rock mass *Q* and the necessary support required by the excavation to dimension an anchored solution with a high tensile flexible facing.

2 ROCK MASS QUALITY INDEX *Q*

The Geomechanical classification system (Barton et al, 1980), expresses the quality of the rock mass in the so-called *Q* value, on which the design and support recommendations for underground excavations are based. This index is determined from the expression (1):

$$Q = \frac{RQD}{Jn} \cdot \frac{Jr}{Ja} \cdot \frac{Jw}{SRF} \quad (1)$$

RQD: rock quality designation (core)
Jn: number of joint families
Jr: joint roughness
Ja: weathering of joints
Jw: water in the joints
SRF: stress reduction factor

The first term, *RQD* (rock quality index) divided by J_n (joint set number), represents the structure of the rock mass and considers the size of the intact rock blocks in the massif (100/0.5-10 /20). The second term, J_r (joint roughness) divided by J_a (joint alteration), represents the roughness and resistant characteristics of the joint walls and the filling materials in them, considering the shear resistance along the discontinuity (4/0.75-0.5/20), and the third term, J_w (water reduction factor) divided by *SRF* (stress reduction factor), takes into account the effective stress, which is the stress in intact rock blocks and discontinuities around the underground excavation (1/0.5-0.05/20). The *Q* result can range from 0.001 for an exceptionally poor rock mass to 1000 for an exceptionally good rock mass. The use of the *Q* method is conceptually extraordinary, since on occasions this evaluation process is visually conducted. Due to this, the experience and good judgment of the geomechanics determining the parameters and verification tasks are essential.

3 TRADITIONAL SUPPORT SOLUTION CONSIDERING THE EQUIVALENT DIMENSION OF EXCAVATION

The following chart (Fig. 2) shows the support solutions according to the *Q* index criterion (Grimstad and Barton, 1993), resulting from practical experience. In this abacus its defined, from *Q* and *De*, a set of up to nine standard solutions, for which it established the use of shotcrete, the addition of reinforcing fibres or trusses and the spacing between bolts, as well as their length (considering 20mm bolts standard steel quality). The proposed support solutions described are based on experiences in multiple tunnels at a global level, so they are only referential and should be complementary to more detailed models.

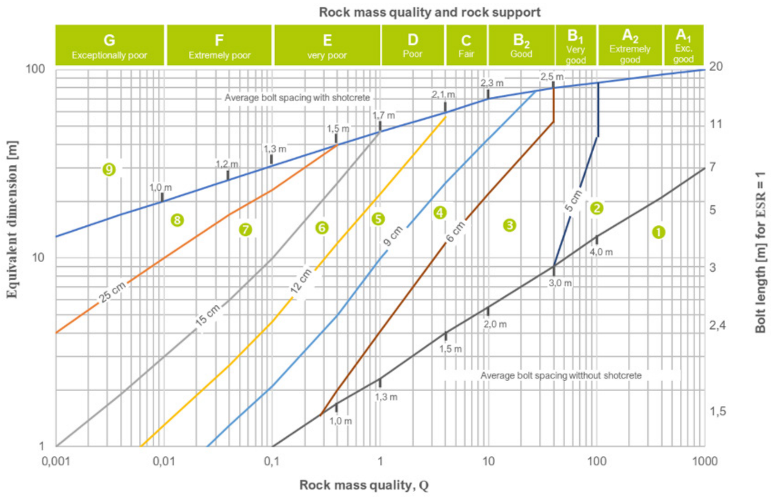


Figure 2. Estimated support categories according to the *Q* index.

4 REQUIRED PRESSURE BEARING ON THE ROOF AND GABLES

Over the last 50 years in mining multiple ground support solutions were installed using shotcrete as a base, as well as steel trusses covered with shotcrete supported by a set of bolts. Unfortunately, in some cases, the solutions have been based on experience without evaluating the necessary support pressure that the system must provide.

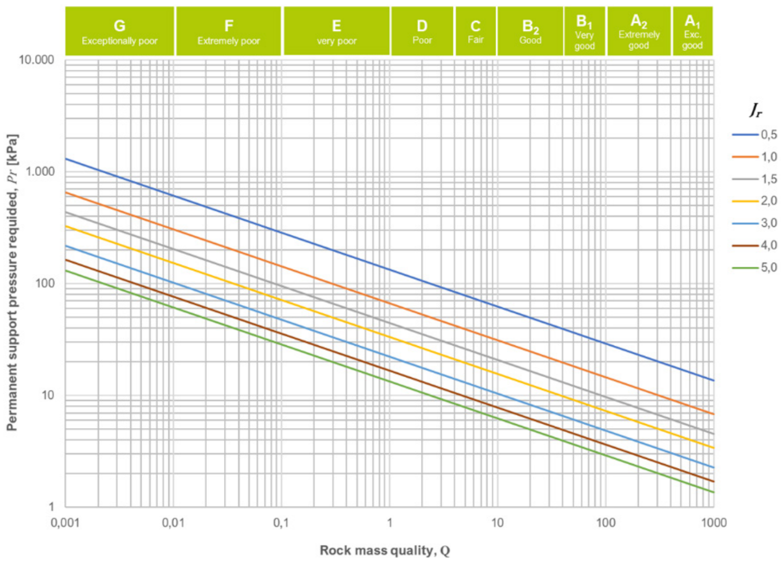


Figure 3. Support pressure related to the Q and J_r index for values of $J_n = 1$.

This behaviour causes the use of excess solutions, which means a problem from the point of view of the overuse of resources or even situations that compromise the safety of the operation. Figure 3 shows a graphic relationship between the Q index and the sustaining pressure or permanent support on the roof P_r known as the value of J_r based on the case studies of Barton et al. 1974. The graph considers a value $J_n = 1$, so to obtain the support values, the resulting value must be corrected by multiplying by the square root of J_n.

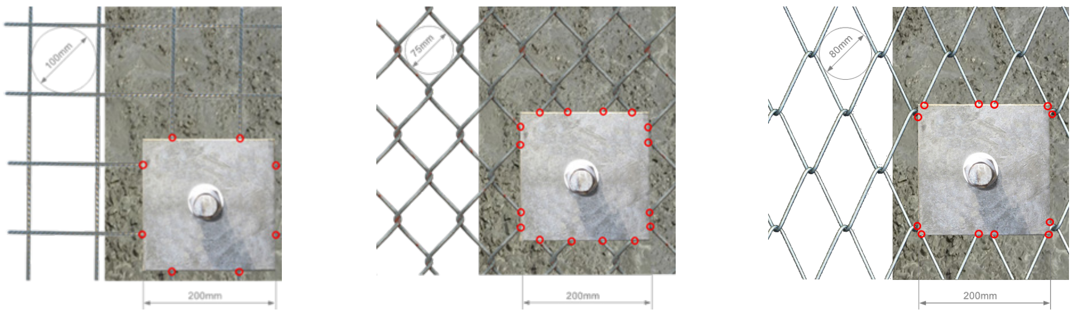
5 SUPPORT CAPACITY OF THE FLEXIBLE FACING

The support capacity that the flexible support system can provide is subject to the puncturing resistance of the membranes. This property is associated with the ability of the assembly to support a load concentrated at a point around the anchor head. For similar membrane geometries, what matters most is the diameter and above all the type of steel f_{yk}. The capacity of the system [kPa], its calculated by the quotient of this value and the area between bolts (Luis-Fonseca and Roduner, 2022). The membrane puncturing resistance value (2) is determined from the shear resistance of the system at the anchor head (Luis-Fonseca, 2010).

$$D_{R\,calc} = N_{wire} \cdot T_{wire} \cdot \frac{\sqrt{3}}{3} \quad (2)$$

D_{Rcalc}: puncturing resistance of the membranes, [kN]
N_{wire}: number of contact points on the border of the distribution plate
T_{wire}: tensile strength of a wire, [kN]

For example, below are steel membranes of different geometry and steel composition, for which the puncturing resistance value is determined (Fig. 4).



Electro-welded mesh, 100x100 steel f_{yk} 350MPa wire diameters 3.2-5.9mm

Chain-linked mesh, 75x75 steel f_{yk} 900MPa wire diameters 3.2-3.8mm

Diamond-linked mesh, G80 steel f_{yk} 1770MPa wire diameter 3.0-5.0 mm

Figure 4. Number of perimeter contact points, due to the geometry of the mesh and the distribution plate (commonly used 200x200mm).

The dimensioning process of a flexible system will start by selecting the mesh whose resistance allows for optimizing the anchorage pattern. Figure 5 relates the support pressure requested [kPa] with the anchor pattern [m^2].

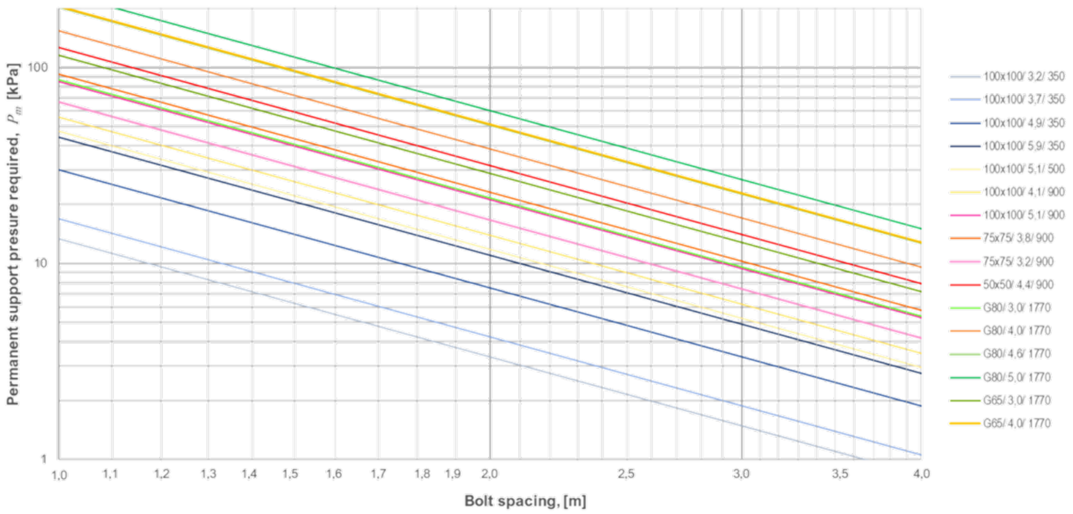


Figure 5. Selection of type of mesh to solve the requested support (bolt spacing between 1.0 and 5.0 m).

For example, a required ceiling support value of P = 20kPa is achieved with the weakest mesh (electro-welded 100x100/3.2/350) in a 0.8x0.8m pattern. Meanwhile, with the most potent mesh, G80/ 5.0/ 1770, the spacing between bolts can be up to 3.5x3.5m. It is important to conduct a deformation control, it may also be necessary to conduct a specific analysis of wedges, which allows to notice stresses in the area between bolts. The key is to streamline using a regular bolt pattern, together with a strong membrane, which ensures the redistribution of stresses between anchors.

6 REVIEW OF TYPE AND DIMENSIONS OF ANCHOR BOLTS

One of the most important limitations in the use of design charts (Fig. 2) is the assumption that anchor bolts or bolts are always 20mm in diameter. Fortunately, following the properties of high-strength membranes, diverse types of anchors can be used. Figure 6 shows a design chart for mortar-injected self-tapping rock bolts (GEWI) made of f_{yk} 500MPa steel, as an example.

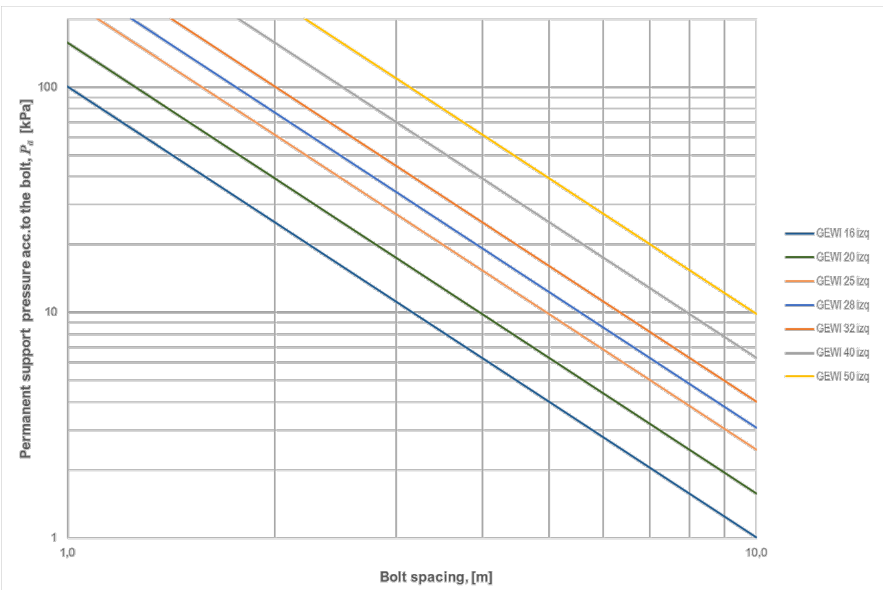


Figure 6. Example chart for review of solid steel bar anchors type GEWI.

For the same example above for a required support value on the roof of P = 20kPa, a pattern of 2.2x2.2m is achieved with GEWI 16mm. Meanwhile, with a 40mm bar, the spacing could be 5.5x5.5m. For corrosive environments, it is highly recommended to consider rusting-away thickness. All system components must have a similar safety factor. In cases, it is advisable to conduct an additional shear stress review.

7 CONCLUSIONS

- The *Q* system that relates to the recommended measures of reinforcement and permanent single-layer support has proven its value during its 50 years of existence. In some countries, it was widely adopted, both as one of the standard empirical characterization tools and as a method to aid tunnel design.
- The widespread use in civil engineering and mining in the main mining countries (USA, Canada, Brazil, Peru, Chile, Australia, and South Africa) allows recommendations for the use of *Q* for the calculation of support and reinforcement. Although the system indeed has limitations, it has proven to be valid.
- The appearance of flexible high-resistance steel membranes has changed the way of thinking and the way of solving support problems, both for static and dynamic loads. Its use has allowed to both minimize the use of concrete, and optimize the bolting pattern, thus achieving economic, safe solutions, and a significant reduction in the generation of greenhouse gases.
- The combination of the *Q* geomechanical classification methods, together with the method of design and review of high-resistance flexible membrane systems, is a robust and efficient proposal, which is committed to increasing the safety of exploitation.

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