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Applicability of the Stability Graph Method for Designing Large Caverns in Rock

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Abstract

Rock engineering classification systems have traditionally been widely used in the preliminary design of tunnels, mines and underground caverns excavated in rock. These systems constitute standardized empirical approaches based on field data and accumulated experience, enabling rapid and practical assessment of rock mass conditions. In particular, design charts derived from these classifications — such as the Q-system or the RMR—are commonly applied to estimate the maximum unsupported span and support requirements. In the case of civil engineering caverns, these aspects are especially critical due to the large dimensions of such openings. The stability graph method, introduced by Mathews in 1980, integrates the strengths of the Q classification with the introduction of the hydraulic radius as the design shape factor and the implicit consideration of the critical joint and failure modes. However, the original method was developed for mining stopes under non-entry conditions and short design life spans. This paper examines the applicability of the stability graph method to civil engineering caverns. Aspects such as shape, construction procedure, rock mass conditions or support demands are analysed, evaluating their consistency with the original assumptions and design principles of the method. The shortcomings of the classical mining method applied to civil caverns are exposed such as the requirement for long-term stability in civil caverns versus the short exposure of mining stopes, the different support system typologies, roof geometry, or variations in stress conditions — particularly in shallow and isolated caverns. Despite these limitations, the stability graph method has proven to be a valuable complementary tool for the preliminary design of large-span underground openings.

Keywords

Underground space, Tunnelling, Rock mechanics, Rock engineering classifications.

1 Introduction

Since ancient times the underground space has been used for multiple purposes: transport, good storage, defence, etc. This involves excavating different openings in both soil and rock masses such as tunnels, shafts, or caverns. Hard rock conditions have allowed the excavation of large-section openings. This is the case, for instance, of the powerhouses in hydroelectric projects, railway and metro stations, or the case of the 62 m-span Olympic Ice Hockey Cavern in Gjøvik, Norway (Barton et al. 1994). Nowadays, the green energy sector also calls for the use of underground space inthe form of caverns, for example, for hydrogen storage. The early and feasibility phases of these projects demand preliminary and quick calculations to estimate the geometry of the caverns. Rock engineering classification systems —such as the Q-system (Barton 1974)or the RMR (Bieniawski 1973)—have traditionally been widely used for that purpose. In these preliminary projects, the available geotechnical information is limited, so there are no geomechanical data available to perform more sophisticated calculations. Then, during detail design phase, once the geotechnical investigation has been completed, detailed kinematic analysis and both 2D and 3D numerical models are conducted to analyse the stability of the caverns and to define the different support systems and their implementation along the construction sequence. However, before this, the robustness of the calculation tools in early studies is crucial to make conclusive decisions on the feasibility of these large section projects. Also, during construction, rock engineering classifications are also commonly used to accommodate the predefined excavation and support systems to the real geotechnical conditions encountered as the cavern construction process progresses. Beyond the underground excavations typical of civil and industrial engineering projects, certain mining methods likewise involve the excavation of large-section underground openings, such as the sublevel stoping method, where the ore can be mined by means of non-entry production open stopes. Due to the shape and dimensional similarities between these open stopes and civil engineering caverns, the stability graph method (Mathews, 1980) has occasionally been applied to cavern stability analysis. In this paper the applicability of this method to the preliminary design of caverns is studied, analysing both compatibilities and limitations.

2 The stability graph method

The stability graph method (Mathews et al. 1980; Potvin 1988), developed in Canada to estimate stable spans in sublevel stoping mining, consists of a chart (Fig. 1) in which stable, potentially stable and caving zones are defined. In this chart, the hydraulic radius –defined as the ratio of the exposed surface area to its perimeter and used as shape factor - is determined by introducing the stability number N (Eq. 1).

$$N = Q' \, A \, B \, C \tag{1}$$

Where Q' modified rock mass quality index Q (Barton 1974)
A stress factor (Mathews et al. 1980; Potvin 1988)
B rock defect orientation factor (Mathews et al. 1980; Potvin 1988)
C design surface orientation or gravity factor (Mathews et al. 1980; Potvin 1988)

The parameter Q′ is obtained from the rock mass quality index, assuming both the stress reduction factor (SRF) and the joint water reduction factor (J_w) are equal to 1. Sublevel stops are large openings created in competent rock, comparable in size and shape to caverns in civil engineering projects. Due to the geometrical similarities between both types of openings, some studies have applied the "mining" stability graph method to the stability analysis of permanent caverns, specifically underground hydrocarbon storage caverns (Winn et al. 2018; Xingdong et al. 2020).

3 Applicability of the stability graph method

This section examines the applicability of the stability graph method to the pre-design of civil engineering caverns, emphasizing the method's compatibilities and limitations when applied to this type of permanent opening.

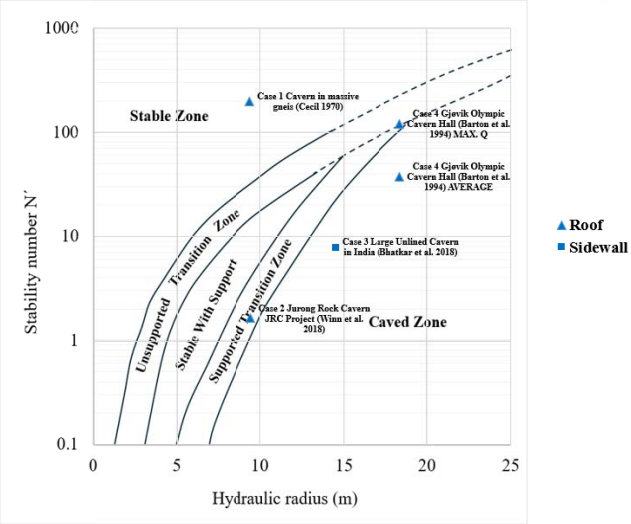


Fig. 1 Chart based on Nickson (1992). Case histories shown in chart are explained in section 3.3.

3.1 Compatibilities and advantages against tunnelling charts

3.1.1 Shape

Tunnel excavation exhibits an inherent three-dimensional stress–strain behaviour due to the tunnel face effect. However, in terms of geometry, due to tunnel width or span is often adopted as per operational criteria, the more relevant parameter to be defined depending on encountered ground conditions is the longitudinal maximum allowable unsupported span. Nevertheless, the caverns are larger section excavations, with significant height and limited length in comparison with a tunnel. Traditional tunnelling stability charts allow determining the maximum allowable cavern roof span or sidewall height. Although excavation and support installation are sequential processes, it is also important to analyse cavern stability as a whole, especially during preliminary design stages. In this context, the hydraulic radius accounts for the two dimensions of the cavern surfaces—roof, sidewalls, and face—in the same way open stopes are analysed when applying the stability graph method. Therefore, this method makes it possible to incorporate the 3D geometry of caverns into the stability analysis, in comparison with the classical geomechanical classifications traditionally used in tunnelling.

3.1.2 Stress environment

In the development of the stability graph method, the parameter SRF of the original rock mass quality index Q was replaced by the stress factor A, due to the SRF is based specifically on tunnelling case histories. This stress factor A, which ranges from 0.1 to 1, depends on the relation in between the induced compressive stress and the uniaxial compressive strength of the intact rock. Potvin highlights the differences between tunnelling and sublevel stoping, noting that in the case of this mining method, the rock mass may be pre-disturbed by adjacent stopes excavated earlier (Potvin 1988). This leads to stress concentrations in the intermediate pillars, in contrast to the virgin stresses generally assessed in tunnelling. However, in civil engineering caverns, it is common to excavate two or more caverns—two in the case of hydroelectric projects, or even more, as in oil storage cavern systems typical in Scandinavia. Additionally, the rock mass is also disturbed by access tunnels and galleries, mucking shafts, and other minor underground excavations around the cavern location. If factor A is assumed to be the inverse of the stress reduction factor (SRF) and corresponds to the inverse of the value ranges given by Barton (1974), it can be observed that for a strength-to-stress ratio greater than 5, the stability method approach aligns with the Q-system range (Fig.2). Conversely, for a strength-to-stress ratio lower than 5, the Q-system penalizes more the rock mass quality than the stability graph method, particularly in the case of the improved version by Potvin (Potvin 1988). The original graph (Mathews 1980) automatically considers failure when the strength-to-stress ratio is below 2. Potvin assumes a minimum A value of 0.1, based on highly stressed cases proven to be stable, although these were characterized by small dimensions. This assumption must be applied with caution in caverns, which are characterized by their large spans. Beyond the stress compatibility issues discussed in this section, limitations related to stress conditions may arise in isolated caverns under virgin stress states, in cases under lower strength-to-stress ratio or in shallow caverns located near the surface. The factor A has been analysed by Barton (Barton 2014), indicating that this factor could not account singular conditions such as shallow depths or faulting and brecciation. Also, despite the geometric similarities

between both openings, differences between caverns and mining stopes arise under singular stress environments. For example, this occurs when stope sidewall inclination is adapted to inclined ore body morphology, in outer stopes in which different rock mass strength conditions occur in between both sidewalls - ore versus host rock –and in secondary stopes which are flanked by previously filled primary stopes using paste backfill. Nevertheless, for most situations involving regular geometries and non-singular stress conditions, the rock stress factor A of the stability graph method can be reasonably applied to the cavern design scenario.

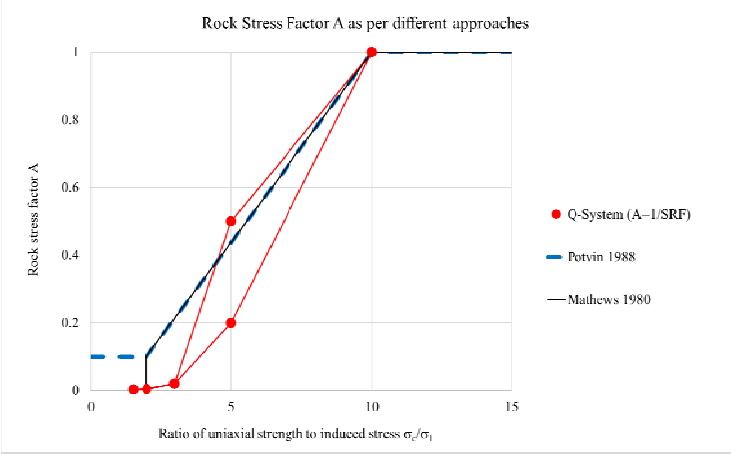


Fig. 2 Stability graph method factorA as per different approaches.

3.1.3 Anisotropy

The relative orientation between the cavern alignment and the joint systems is a critical aspect during the selection of the optimal position of the cavern. Inthe Ricobayo II project (Alonso and Jambrina 1999), the adopted criterium was to align the cavern with the bisector of the angle in between the two main joint system, ensuring that the cavern orientation is not parallel to the main joint directions. However, in tunnelling engineering classifications systems, rock mass anisotropy is not always explicitly implemented. Only the RMR system (Bieniawski 1973) introduces a correction factor that depends on the type of excavation and the relative orientation between the joint systems and the excavation. The stability graph method explicitly accounts for rock mass anisotropy in the design of underground openings by means of the B and the C factors (Potvin 1988). The B factor, which ranges from 0.2 to 1, depends on both the differences in dip and strike between the critical joint and the stope surface. Additionally, the C factor accounts the failure modes derived from the presence of joints and ranges from 2 to 8. Considering that these engineering classifications are widely used in feasibility studies and cost estimations, the stability graph method allows quantify the stability of a cavern more detailing that using the classical tunnelling systems.

3.2 Limitations

3.2.1 Groundwater

The parameter Jw is assumed equal to 1 due in stopes water inflow is negligible (Mathews et al. 1980; Potvin 1988). This could be explained because they are excavated in rock mass with very low primary permeability and the joints are closed at depth bellow 1000 m. However, in tunnelling, Jw may range from 0.1 to 1, depending on the water inflow rate and its evolution, as well as water pressure and associated phenomena such as joint filling outwash. In the particular case of caverns, desirable conditions are as much dry as possible. However, occasionally when excavating in fissured or weathered zones in competent rock masses, significant water inflows associated with higher permeabilities could occur (Geotechnical Engineering Office, 2018). Indeed, in the Honk Kong rock caverns registered up to 1989, Jw ranged from 0.7 to 1 was recorded (Barton 1989). The absence of Jw in the stability graph method has been highlighted (Barton 2014), indicating that the method could not be applied under conditions with Jw values lower than 1. As a conclusion, the fact that the stability graph method does not account the water effect in the stability number, the results in cases where significant water inflows could be expected would lead to optimistic results.

3.2.2 Roof shape

Generally, civil engineering cavern roofs are designed with an arched shape -the natural way to accommodate vertical stress redistribution - and to prevent rock blocks from falling from the

decompressed rock mass above the roof. The standard design usually adopts an arch height of 1/5 of the cavern span. Increasing arch height to improve stability and to reduce support requirements normally does not compensate the increase in excavation costs (Geotechnical Engineering Office, 2018). In open stoping, flat roofs are adopted to facilitate drilling and blasting operations and to prevent dilution, thereby reducing production costs. Moreover, the temporary nature of these openings does not require the stability standards demanded by a permanent cavern. In the case of roof shape, although there is a difference between mining stopes and caverns, the cavern roof surface may be assumed to be planar for the applicability of the stability graph method, resulting in a conservative estimate.

3.2.3 Support

When analysing a cavern using the stability graph method and the result falls within the "stability with support" zone, the support requirements should be evaluated according to the classical Q-system recommendations. This is because, in sublevel stoping mining, support is typically defined by the empirical cable bolt support design chart (Potvin and Milne, 1992), which—as its name suggests—only provides guidance on cable bolt density. Therefore, other support parameters such as bolt spacing and length, as well as shotcrete thickness, must be determined separately, if required.

3.2.4 Entry conditions, operative time and construction sequence

Differences between underground mining and tunnelling have been widely noted by various authors throughout history. The main difference lies in the supported exposure time – distinct from the unsupported exposure time defined the stand-up time concept (Lauffer 1958) - which is related to the distinct purposes of both types of excavations. The stability graph method has been calibrated based on data records on non-entry stopes opened during a relative short time, on the order of several months (Suorineni 2010), in comparison with the design life of civil engineering caverns (50 to 100 years and even >100 years in certain projects). While in stopes small size block falling is allowed, in caverns robust primary supports consisting of unreinforced or reinforced shotcrete and bolting are installed to prevent any size block or wedge falling. Also, is frequent to install a cast concrete secondary lining at the cavern roof. In the case of the Q-system, the parameter ESR - Excavation Support Ratio – accounts the minimum degree of safety and the importance level of an underground excavation allowing to adjust the required support demands and the maximum allowable span. However, this approach is generally regarded as too simplistic to adequately account for the differences that exist between mining applications and civil engineering tunnelling, as for example stated by Potvin 1988. Construction sequence also differs between caverns and stopes. Mining stopes are excavated by means of drilling and blasting from upper drifts, and the blasted ore is recovered from lower adits. In contrast, cavern excavation typically begins from a central gallery along the roof axis, which is then widened through additional galleries until the upper part is completed, while support is installed simultaneously. Afterwards, the cavern is completed vertically by means of successive benches, similar to open-pit blasting. Temporary mucking shafts may be opened to evacuate the muck from lower galleries. The main difference between both construction sequences is that, in the case of a cavern, excavation and support are performed sequentially. Consequently, the disturbance around the excavation—and therefore stress release—is lower than in the case of a stope.

Table 1. Case histories design parameters.

Case	Scenario	Surface	Span or height (m)	Length (m)	Hydraulic radius (m)	Q	Q´	A	B	C	N
1	Self-standing	Roof	20	300	9.4	100	250	0.4[(1)]	1	2	200
2	Supported	Roof	27	340	9.4	5	5	1	0.2	1.7	1.7
3	Collapse	Sidewall	30	840	14.5	10	20	1	0.2	4	8
4	Supported	Roof	62	90	18.4	1-30 (9.4)	1-30 (9.4)	1	1	4	38-120

(1) A value of A=1/SRF in which SRF=2.5 has been taken to account shallow conditions (18 m depth)

4 Example of application

In this section, four cases histories representing three different scenarios - stable without support, supported cavern and collapse - are depicted in the stability graph (Fig.1). Design parameters for each case are shown in Table 1. The grade of conservatism of the Q-system when applied to mining engineering was analysed by Barton (Barton 2014), plotting three self-supporting civil engineering

cases on the stability graph, showing that they were far from the unsupported transition zone, which demonstrates the higher level of conservatism adopted in civil engineering. However, as shown in Fig. 1, the stability method chart generally represents accurately the stability conditions for each case history, with the exception of the record span Gjøvik cavern, which falls within the zones delimited by dashed lines, intended to show uncertainty by its author (Nickson 1992).

5 Conclusions

Geometric similarities and the use the hydraulic radius provide a practical basis for overall stability assessment applying the stability graph method to caverns, offering advantages by explicitly considering rock mass anisotropy and the full geometry of the excavation. However, the approach has limitations, such as not accounting for groundwater effects, which can lead to optimistic results under permeable conditions. For cavern design, specific aspects must be addressed, including the common use of arched roofs for stress redistribution, reliance on the classical Q-system for support design, and careful consideration of the degree of conservatism. While the method is directly applicable to simple cases, more complex scenarios require additional considerations. Despite all these limitations, in cases of simple geometries, hard rock and high in-situ stress conditions, vertical sidewalls, systems of two or more caverns with intermediate pillars, and no water conditions, both types of openings are reasonably similar. Under these circumstances, the stability graph method can be applied to civil engineering caverns to obtain an overall approach to excavation stability conditions.

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