Squeezing rock in tunnelling: identification and important factors

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Summary

Squeezing rock conditions in tunnels are defined to occur due to shearing of the ground with an associated inward movement of the tunnel perimeter. The factors influencing squeezing conditions are complex. The initial state of stress is important, which is usually difficult to determine in poor quality rock. Ground strength and deformability are other important factors. They can practically only be estimated from correlation to a ground property index, of which the most suited is the Geological Strength Index (GSI). Orientations of the rock structure and groundwater conditions are also important factors. Squeezing conditions are best identified by an estimate of the ground properties and an analytical estimate of convergence is the best estimate of boundary conditions. Construction and lining procedures influence squeezing potential as well. Simple empirical rules are no substitute for analysing the complexity involved in squeezing rock conditions.

1. Introduction

Squeezing rock conditions are an important phenomenon in tunnelling through rock or rather ground, usually at great depth. When such conditions are not anticipated or identified prior to construction of the tunnel, construction delays and increased costs may result. One major effect of squeezing behaviour is the large rock pressure exerted on the lining, which may lead to collapse of the support and lining systems. Although most tunnelling is through rock, the material in these zones that exert squeezing conditions is often soil-like, crushed rock or the surfaces of the rock discontinuities are covered by clay reducing the shear strength. The conditions are not only a rock mechanics problem, but rather one of soil mechanics, but where a substantially higher stress level becomes important. Much has been learned from case histories where important factors could be identified. The limitations of analysis methods and the difficulties of predicting boundary conditions for analysis will be shown.

2. Identification of squeezing conditions

2.1. Definition

The definition of squeezing rock has been developed by the ISRM Commission on Squeezing Rock [Barla, 1995] and has been summarised by Einstein [1996] as:

"Time-dependent shearing of the ground, leading to inward movement of the tunnel perimeter".

In contrast, swelling behaviour is defined as:

"Time dependent volume increase of the ground, leading to inward movement of the tunnel perimeter".

The two definitions are rather similar. Squeezing and swelling may occur simultaneously, or one may lead to the other. The scope of this paper is to deal with squeezing behaviour, i.e. shearing of the ground.

2.2. Rock vs. Soil Mechanics

In soil mechanics, in particular for the stability of the tunnel perimeter and the face in clays, laws based on undrained shear strength [Broms and Bennermark, 1967] have been applied. Since undrained shear strength S_u and unconfined compressive strength σ_c are related in a first approximation ($\sigma_c = 2\ S_u$). In rock the unconfined compressive strength may, with a "correction factor" be used for the prediction of failure around a tunnel in competent rock. On both ends of the possible scale, a definition based on mechanics is possible. For intermediate material, this is more difficult. The main issue is the determination or definition of ground strength parameters.

3. Classification methods

Many methods exist for the classification of squeezing rock conditions. Terzaghi [Proctor and White, 1946] presented a behavioural description of the ground by assigning a pressure related to loading of the initial support, earlier often made from timber. The load was estimated from the inferred loads on the timbering [Steiner, 1980]. From their experience with rock tunnels in Japan, Aydan *et al.* [1993]

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propose to relate the strength of the intact rock to the overburden. This procedure implies that the uniaxial compressive strength of the intact rock and of the rock mass is the same. Earlier JETHWA *et al.* [1984] presented a criterion based on rock mass uniaxial compressive strength in relation to overburden. These relations and limits of behaviour are similar to the criteria used in soft clay soil mechanics. However, the main issue is the estimate of the rock or ground mass strength, which is a particularly problematic issue in crushed and strongly fractured rock.

SINGH *et al.* [1992] correlated the overburden with Q; in particular, when the overburden exceeds $350Q^{1/3}$, squeezing conditions are to be expected. However, the determination of Q requires the evaluation of SRF, the "Stress Reduction Factor". Squeezing conditions are considered as input and should be the results of a classification. A classification system should positively identify ground conditions and it appears that overburden is considered twice. This shortcoming of the NGI classification for including Stress State in the classification system of ground has been recognised for hard rock by HOEK *et al.* [1995]. They propose that Q', which does not consider the strength and water parameters (SRF and J_w) in describing the rock mass, depends only the spacing (RQD and J_n) and the rock strength parameters, joint rock strength number (J_r) and joint alteration number (J_a).

The Geologic Strength Index, GSI, proposed by HOEK [1995] and HOEK *et al.* [1998], assigns deformability parameters and strength to a rock structure and discontinuity pattern. The rock mass properties, both strength and deformation are then estimated, and used in analyses, closed-form solutions or numerical analyses.

Research has been carried out on the classification of fault gauge at the Laboratory for Geology of the Federal Institute of Technology, Lausanne, Switzerland [BURGI and PARRIAUX, 1999; BURGI *et al.*, 1999; and BURGI, 1999]. The cataclastic rocks are characterised by rock fabric (clasts and discontinuities) using thin section analysis, and semiautomatic image analysis. The texture coefficient, TC, is used to describe the clast characteristics and the matrix coefficient, MC, to describe density, orientation and roughness of discontinuity traces. Cataclastic rocks can be classified based on TC, MC and the mineralogy. Further research is necessary to obtain correlation with rock properties. Mineralogy is an important factor for distinguishing between squeezing and swelling rocks.

Different classification systems cover parts of the issues involved in squeezing rock conditions. The limits of application of some of the classification systems are not well understood. This conclusion is synonimous with findings of RIEDMULLER and SCHUBERT [1999].

4. Factors influencing ground behaviour

For a better understanding of squeezing conditions, an attempt is made to combine analytical procedures and empirical evidence. This should lead to a comprehensive picture of the most important factors leading to squeezing conditions. Squeezing conditions are influenced by internal factors in the ground and by external factors (Fig. 1), like the position and orientation of the underground structure relative to the ground's geological structure and the construction procedure chosen. Since we assume that a mechanical model for squeezing conditions can be created, the factors influencing these models are discussed.

4.1. Internal factors

From theoretical considerations of the stress state, vertical stress, expressed as overburden, and horizontal stresses in the ground play a major role. The water pressure in the ground and the rock type with its mechanical properties (strength and deformation characteristics) are of major importance, together with the extent of the "homogeneous zones".

4.2. External factors

Squeezing conditions are mainly observed in traffic and hydro-power tunnels where it is not possible to avoid difficult ground conditions. Squeezing conditions may also be observed in shallow tunnels, in particular in older tunnels where a closed invert was not used. Another external factor is the construction procedure chosen.

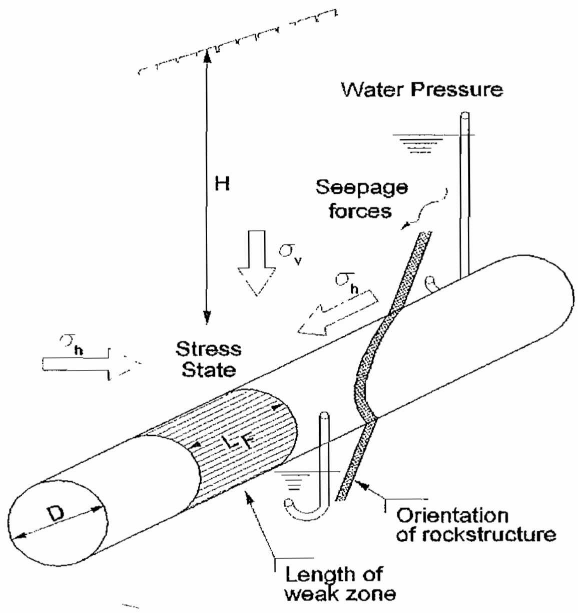

Fig. 1 – Factors influencing ground behaviour.
Fig. 1 – Fattori influenzanti il comportamento del terreno.

4.2.1. CHOICE OF POSITION OF UNDERGROUND OPENING

Empirical evidence from field observations suggests that the orientation of the underground opening relative to the rock structure is important. Such observations were made in several tunnels where cuts were constructed perpendicular to the main tunnel. Substantially smaller convergence occurred, often an order of magnitude less, where a tunnel crossed perpendicular to the rock structure than parallel to the rock structure. For traffic or hydropower tunnels the alignment is often dictated by topographic and alignment constraints such that problems cannot be avoided. In contrast, caverns are usually located in favourable rock and in the best possible position. The rock structure may be determined by foliation, schistosity or faults. Observations on the influence of orientation of the structure were made in the Arlberg and Tauern tunnel in Austria [STEINER, 1980; 1996] and the Frejus tunnel between France and Italy [PANET, 1996]. The effect of rock structure on stability has been presented by BARLA and BARLA [1998].

4.2.2. SELECTION OF CONSTRUCTION PROCEDURES AND SUPPORT SYSTEMS

In squeezing rock deformations due to the ground forces acting on the support are such that the support often cannot sustain these without damage. Support is often applied in a way such that deformation can be taken. Examples of support procedure have been given by Terzaghi [PROCTOR and WHITE, 1946]. The use of sliding joints in u-shaped steel sets used in mining is another example. EGGER [1989] gives examples of the influence of construction procedures.

In the shotcrete lining of the Tauern tunnel, longitudinal slots were used for the first time to avoid over-stressing and crushing of the lining. In several tunnels [SCHUBERT, 1996] in Austria steel elements that allow controlled yielding have been successfully applied. The slots in the shotcrete are bridged over by strength controlled elements, that allow deformation at a controlled stress level. Comparisons in the field and by analysis have shown that these force transfer elements help substantially to reduce convergence [SCHUBERT *et al.*, 1997].

Excavation often has to be sequential because sufficient time must be available to place support. Observations also exist that a timely placement of support is essential in reducing convergence.

In the tunnelling literature at the beginning of 20^{th} century, there were substantial disputes as to which method was most suited for crossing squeezing conditions. The so-called Italian method, in which the invert first was installed [BARLA, 1995] followed later by the crown arch, was considered particularly suitable for squeezing conditions.

5. Prediction and analysis of squeezing conditions

For the analysis of squeezing ground conditions the analytical solution for a circular hole in an externally pre-loaded plate with elastic-plastic material properties is mostly used [SCHWARTZ *et al.*, 1980; PANET, 1995]. These methods have some inherent simplifications. The far-field stress field is axial symmetric, i.e. the horizontal and vertical stresses are equal. The solution depends only on the radius and is one-dimensional. In elastic solutions different overburden and horizontal stresses are considered [EINSTEIN and SCHWARTZ, 1977] and interaction analyses are possible [SCHWARTZ and EINSTEIN, 1980]. This limitation stems also from the fact that for non-symmetric conditions no simple elastic-plastic solutions can be found. The effect of support is usually modelled as support pressure. The application of numerical methods has been discussed by GIODA and CIVIDINI [1996].

5.1. Theoretical Considerations

5.1.1. STRENGTH OF GROUND

The ground is modelled as elastic-plastic material with or without strain softening [PANET, 1995; AYDAN, 1993]. The peak strength expressed as Mohr-Coulomb material, is described by a cohesion intercept or by an unconfined compressive strength and a friction angle. Curved failure envelopes have been studied by BROWN *et al.* [1983]. For homogeneous conditions like in over-consolidated clays, good agreement of computations to behaviour was found as mentioned by Habib in the foreword to PANET [1995].

5.1.2. INITIAL STATE OF STRESS

The initial state of stress is usually set to the estimated overburden stress. Squeezing ground is usually of such poor quality that stress measurements are not feasible.

5.1.3. GROUND DEFORMABILITY

Ground deformability has to be estimated. It is usually an unloading modulus and often assumed to be the same in the plastic and elastic region of the problem.

5.1.4. EFFECT OF PLASTICITY (FLOW RULE)

In the plastic region additional plastic strains may occur. The initial theories assumed either a perfectly plastic dilatant behaviour, with plastic strain according to the Drucker-Prager rule with an angle of dilatancy equal to the friction angle, or non dilatant with angle of dilatancy equal to zero.

5.1.5. LENGTH OF ZONE OF SQUEEZING ROCK

The effect of the length of the zone with poor quality rock has been studied by KOVARI and ANAGNOSTOU [1995]. They show that the length of the tunnel in relation to the overburden may lead to a significant reduction (an order of magnitude) in the convergence. For a zone of limited length, the poor quality rock may transfer a substantial amount of the stresses by shear to better quality rock adjacent to the poor zone.

5.2. Example computations

Squeezing conditions may encompass a wide range of conditions. For a better understanding some example computations have been carried out that illustrate the effect of overburden, varying ground strength and the effect of water pressures. The results are shown in Figs. 2 to 4.

5.2.1. EFFECT OF OVERBURDEN

The relation of initial stress to possible support pressures is also important. For shallow tunnels, with less than 100 m overburden, the support pressure exerted by a concrete lining is such that no or a small plastic region develops. Predicted convergence including three-dimensional effects can be sustained by a concrete liner. However, for larger overburden the convergence cannot be carried by a stiff lining like concrete. The structural capacity of a liner with large overburden, say 500 metres or more, is not sufficient to limit the convergence. For similar ground conditions, the liner must be able to yield in a controlled way. The non-linear effect on convergence of the stress-state is further illustrated by the computed convergence for 2000 meters overburden. If such a condition should exist in nature one might conclude that the tunnel is not feasible to be constructed.

5.2.2. GROUND STRENGTH

The effect of ground strength for an overburden of 500 meters and otherwise constant conditions is shown in Fig. 3. Ground strength has a significant effect on predicted convergence together with dilatancy in the ground. In reality dilatancy may not be constant with plastic strain, rather it may increase with strains from an initial non-dilatant behaviour. One may conclude that variable dilatancy may best represent reality.

5.2.3. INFLUENCE OF WATER PRESSURE

The substantial effect of groundwater pressure introduced as a reduction of effective stresses is

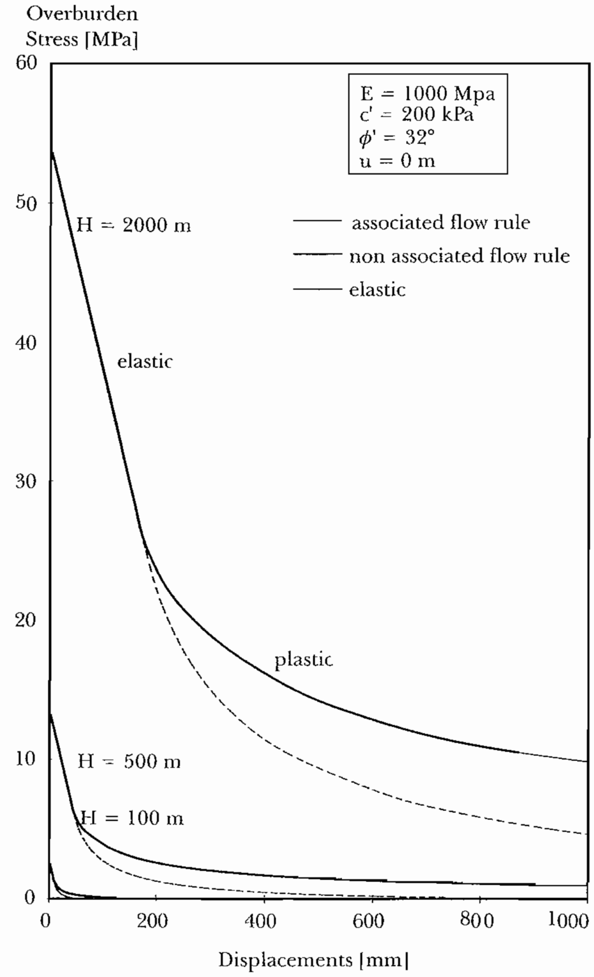

Fig. 2 – Example calculations: effect of overburden.
Fig. 2 – Esempio di calcolo: influenza della copertura.

shown in Fig. 4. Empirical evidence [STEINER, 1996] has shown that the influence of water pressures on ground behaviour, as well as the effect of gas pressure, can be important [ADACHI *et al.*, 1995].

5.3. Estimate of ground properties

For tunnels in homogeneous conditions where representative samples can be taken, predictions of squeezing potential and convergence are feasible. This was the case in the clays of Belgium [Foreword by HABIB in PANET, 1995] and many of the Japanese cases [AYDAN *et al.* 1993 and 1996]. However, in many other cases the determination of ground properties is more difficult. They have to be estimated with correlation to spacing patterns. The most recent advances have been made by applying the "Geologic Strength Index", GSI, developed by Hoek and co-workers [HOEK, 1994; HOEK *et al.*, 1995; HOEK and BROWN, 1997; HOEK *et al.* 1998]. The GSI is estimated based on the discontinuity pattern and the strength of the discontinuities. Deformation properties (in-situ modulus of deformation)

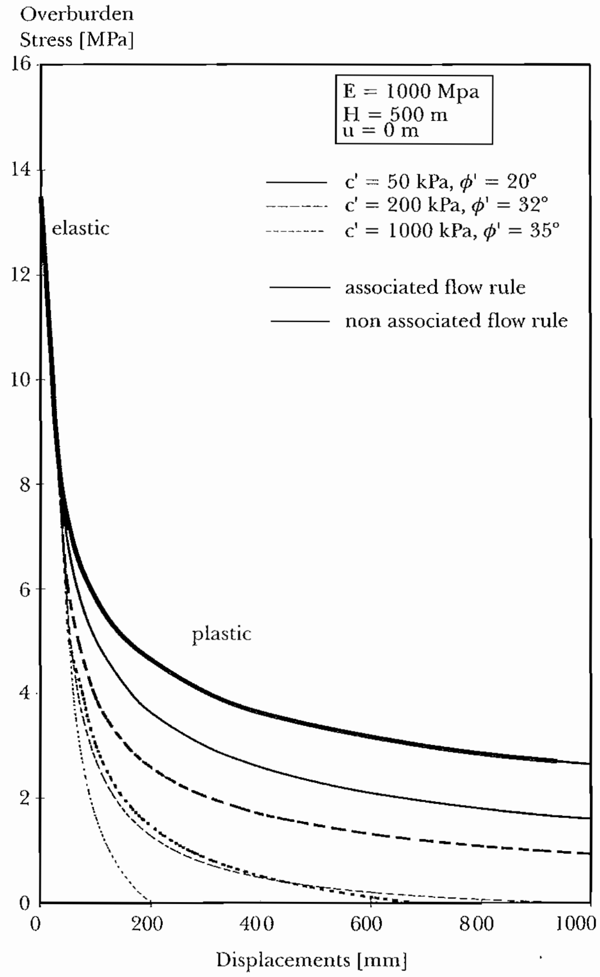

Fig. 3 – Example calculations: effect of ground strength.
Fig. 3 - Esempio di calcolo: influenza della resistenza del terreno.

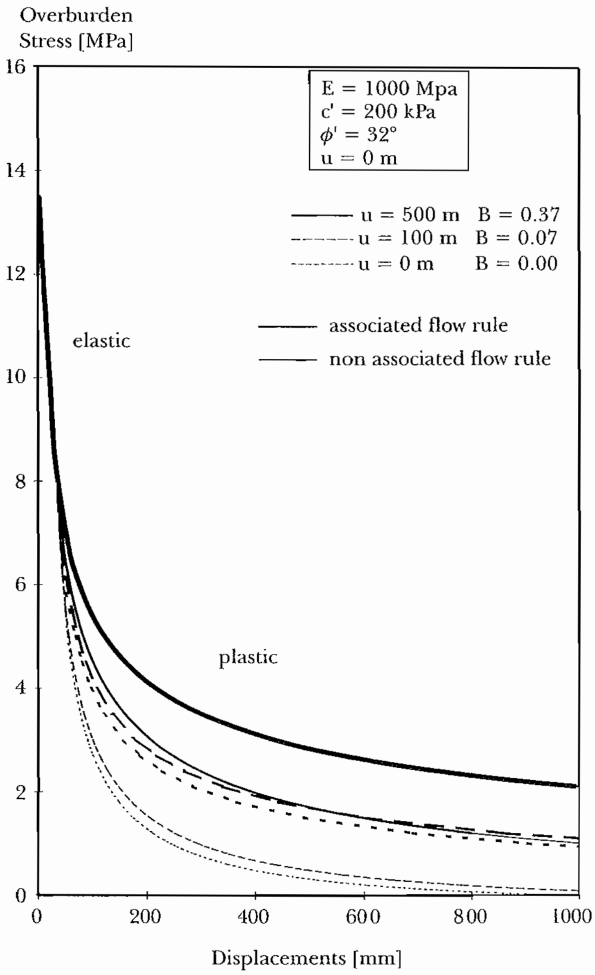

Fig 4 – Example calculations: effect of Porewater pressure.
Fig. 4 - Esempio di calcolo: influenza della pressione interstiziale.

and Mohr-Coulomb strength properties are estimated from intact rock strength σ_{ci}, the material constant m_i and the GSI. The properties are thus an extrapolation of intact rock strength. The method of GSI applies only to rocks with fracturing essentially giving an isotropic rock mass. Rock masses with pronounced anisotropy cannot be treated directly.

5.3.1. Transition from soil to rock-like behaviour

Completely crushed rock has the character of a soil and the strength and deformation parameters may be determined from laboratory triaxial tests of the soil mechanics type. HABIMANA *et al.* [1998] carried out an investigation on cataclastic rock and developed a sampling tool that can be used in tunnels for the rapid sampling of cores. They carried out tests on different types of rock from tunnels in Switzerland and Italy. The result is a relationship (Figs. 5 to 7) of the ground parameters with a transition from soil to rock-like behaviour related to GSI. This is an interpolation of the properties and not an extrapolation as made earlier.

5.3.2. Criteria for judging squeezing potential

Observed strain, defined as convergence divides by radius may serve as criteria for judging squeezing potential. Below one percent ground conditions are considered as non-squeezing [SCHUBERT, 1996]. Extreme squeezing conditions are for strains exceeding 10 %.

6. Conclusions

Squeezing rock conditions are governed by many internal and external factors. Boundary conditions (geologic, stress-state and hydrogeology) have to be identified to be able to analyse the system and to classify the conditions. One of the most difficult tasks is the estimate of ground properties, which are best based on the Geologic Strength Index, GSI. More sophisticated analyses may be necessary to analyse complex, oriented structures. An empirical classification system cannot be applied to identify the complex non-linear relationships between the ground conditions involved in squeez-

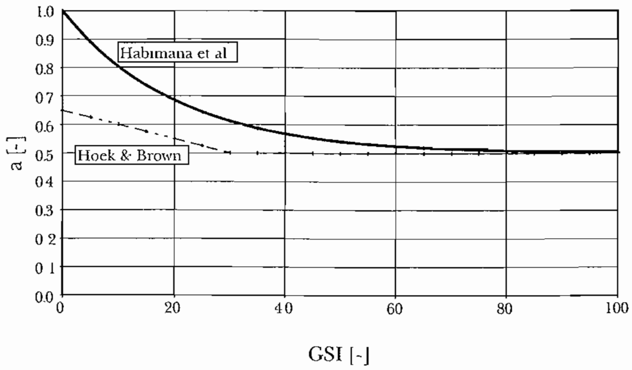

Fig. 5 – Relation between GSI and factor m_b [HABIMANA *et al.*, 1999; HOEK *et al.*, 1998].
Fig. 5 – Relazione tra GSI e m_b [HABIMANA et al., *1999; HOEK* et al., *1998].*

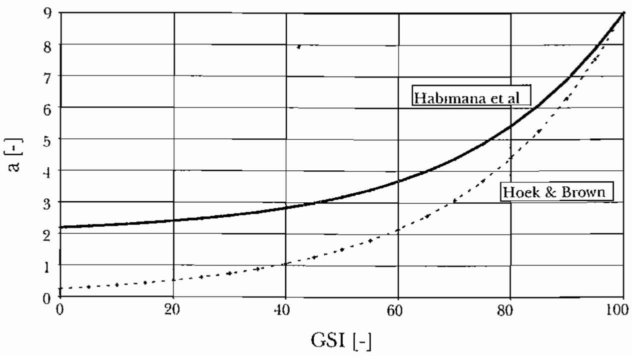

Fig. 6 – Relation between GSI and factor a [HABIMANA *et al.*, 1999; HOEK *et al.* 1998].
Fig. 6 – Relazione tra GSI e a [HABIMANA et al., *1999; HOEK* et al., *1998].*

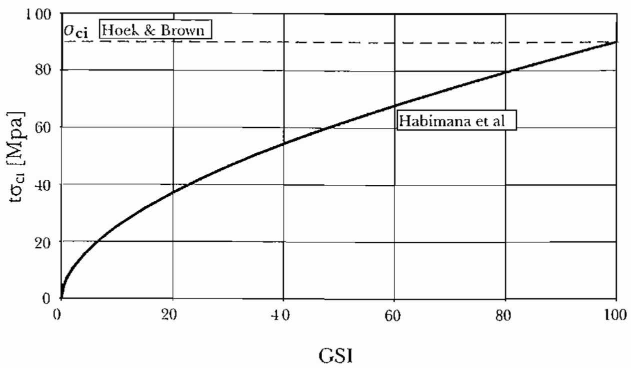

Fig. 7 – Change of intact rock strength as function of GSI (HABIMANA et al., 1999; HOEK et al. 1998).
Fig. 7 – Variazione della resistenza della roccia intatta in funzione di GSI [HABIMANA et al., *1999; HOEK* et al., *1998].*

ing rock conditions. The complexity has to be analysed and cannot be substituted by a simplified empirical classification. The limitations of the analysis methods must be known. Squeezing conditions in tunnels can be classified based on predicted strains.

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Roccia spingente durante lo scavo di gallerie: identificazione e fattori importanti

Sommario

Le condizioni di comportamento spingente dell'ammasso roccioso durante lo scavo di gallerie sono associate al superamento delle caratteristiche di resistenza al taglio della roccia e si manifestano con convergenze del perimetro di scavo dipendenti dal tempo. I fattori che influenzano tali condizioni sono complessi. Lo stato tensionale in situ è un fattore rilevante, ma è usualmente di difficile determinazione in rocce scadenti. I parametri di resistenza e deformabilità sono fattori altrettanto importanti. Essi possono essere stimati in pratica soltanto mediante correlazione con indici rappresentativi dell'ammasso roccioso, di cui il Geological Strength Index (GSI) è da ritenersi come il più idoneo. Anche l'orientazione delle caratteristiche strutturali dello stesso ammasso roccioso e la distribuzione delle pressioni interstiziali sono da considerare come fattori di rilevante interesse. Le condizioni spingenti sono individuate al meglio mediante una stima delle caratteristiche geotecniche del mezzo in cui avviene lo scavo e la valutazione analitica dell'entità delle convergenze indotte dallo scavo rappresenta il metodo più idoneo per poter apprezzare le condizioni di contorno. Allo stesso modo il comportamento spingente risulta influenzato dal metodo di scavo adottato e dai sostegni/rivestimenti messi in opera. Relazioni empiriche semplici non sono necessariamente idonee per l'analisi delle complessità associate al comportamento di tipo spingente.