Tunnelling in squeezing ground conditions

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Summary

Despite the development of new technologies, tunnelling through poor, jointed and faulted rock masses is a challenging task for the planners, designers, engineers and the geologists. The association of Central Mining Research Institute (CMRI), India with various hydroelectric project tunnels of the country has helped in collecting vital field data. This information has subsequently been used to develop new approaches and equations for predicting ground conditions, support pressure and closure in tunnels. The paper deals these approaches in addition to the effect of tunnel size on support pressure and ground reaction curve in squeezing conditions.

1. Introduction

Tunnelling through weak and jointed rock masses such as in Himalayas is a challenging task for the planners, designers, engineers and the geologists. It is difficult because of high overburden, poor rocks and highly varying geology with the presence of numerous small and big shear zones, faults, thrusts, etc. Due to these reasons, many tunnelling problems like squeezing, chimney formation, roof collapse, water in rush, etc. have been faced in the past and are still being met.

Squeezing phenomena has attracted the attention of International Society for Rock Mechanics (ISRM) which subsequently created a commission on 'Tunnelling in Squeezing Rocks'. While formulating the commission, it is intended to establish guidelines and recommendations for the design and construction of underground openings in squeezing conditions.

Prof. Giovanni Barla, President of the Commission has presented the work done so far in the form of a paper [Barla, 1995]. In the paper he has highlighted various definitions of squeezing, identification and quantification of squeezing, design and construction of tunnels in squeezing conditions, etc.

The association of Central Mining Research Institute (CMRI), India with various hydroelectric project tunnels including tunnels experiencing squeezing conditions has helped in generating information on rock mass characterisation, in situ measurements of support pressures and closures or deformations, etc. This information was then used to develop new equations and concepts for tunnel designs presented in the paper.

The approaches discussed here are mainly the empirical ones using a simplified rock mass index called the *rock mass number* (N).

2. Rock mass number

Rock mass number N is defined by the following equation.

$$N = [RQD/J_n]\,[J_r/J_a]\,[J_w] \qquad (1)$$

Equation 1 shows that N is Barton's rock mass quality Q with SRF as 1. Rock mass number N is used to avoid the problems and uncertainties in obtaining the correct rating of parameter SRF in Barton's Q [Kaiser *et al.*, 1986; Goel *et al.*, 1995a]. In the absence of SRF, stress - effect has been considered by incorporating overburden thickness or tunnel depth H in various equations discussed in the paper.

3. Prediction of ground conditions

Considering the tunnel depth (H), the tunnel span or diameter (B) and the rock mass number (N) from 99 tunnel sections, Goel *et al.* [1995b] have demarcated the zone of various ground conditions (Fig. 1). The equations of these demarcation lines are given in Tab. 1. These equations can be used to estimate the ground conditions and to fix the tunnel alignment through a better rock mass or reduced tunnel depth to avoid squeezing conditions and related tunnelling problems.

The squeezing condition is subdivided in Tab. I considering the following range of normalised tunnel closure u_a/a suggested by Singh *et al.* [1995]:

(i) Mild squeezing
  - normalised closure 1 - 3 percent of tunnel diameter

(ii) Moderate squeezing
  - normalised closure 3 - 5 percent of tunnel diameter

(iii) High squeezing
  - normalised closure > 5 per cent of tunnel diameter

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Tab. I – Prediction of ground conditions for tunnelling.
Tab. 1 – Previsione delle condizioni del terreno nello scavo di gallerie.

S. No.	Ground Conditions	Equations for Predicting Ground Conditions
1.	Self-supporting	$H < 23.4\,N^{0.88}.\,B^{-0.1}$ & $1000\,B^{-0.1}$ and $B < 2\,Q^{0.4}$ m (BARTON *et al.* 1974)
2.	Non-squeezing ($u_a/a < 1$ %)	$23.4\,N^{0.88}.B^{-0.1} < H < 275N^{0.33}.\,B^{-0.1}$
3.	Mild squeezing ($u_a/a = 1$ to 3%)	$275\,N^{0.33}.\,B^{-0.1} < H < 450N^{0.33}.\,B^{-0.1}$ $J_r/J_a < 0.5$
4.	Moderate squeezing ($u_a/a = 3$ to 5%)	$450\,N^{0.33}.\,B^{-0.1} < H < 630N^{0.33}.\,B^{-0.1}$ $J_r/J_a < 0.5$
5.	High squeezing ($u_a/a > 5$%)	$H > 630\,N^{0.33}.\,B^{-0.1}$ $J_r/J_a < 0.25$

Notations: Q = Barton's rock mass quality; u_a = tunnel closure/deformation; a = tunnel radius in metres; B = tunnel width in metres; H = tunnel depth in metres, u_a/a = normalised tunnel closure in percent; N = stress free Q, i.e., Q with SRF = 1, J_r = Barton's joint roughness number and J_a = Barton's joint alteration number.
Simbologia. *Q = indice di qualità di Barton; u_a = convergenza/deformazione, a = raggio della galleria in metri; B = luce della galleria in metri; H = profondità della galleria in metri; u_a/a = convergenza normalizzata in percento; N = indice Q per SRF = 1, J_r = numero di scabrezza di Barton, J_a = numero di alterazione di Barton.*

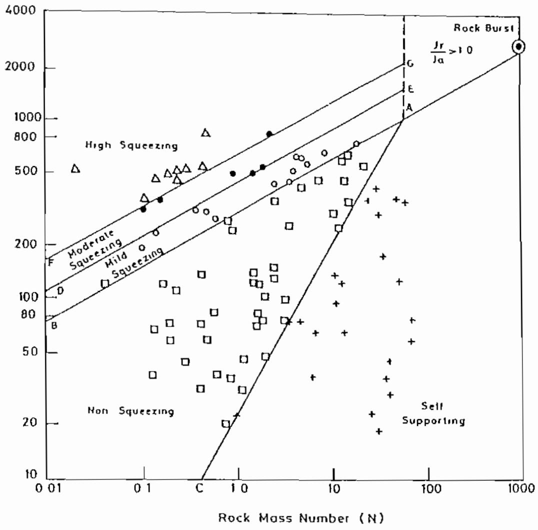

Fig. 1 – Criteria for predicting ground conditions for tunnelling using rock mass number N, tunnel depth and tunnel diameter.
Fig. 1 – Criteri di previsione del comportamento della galleria allo scavo mediante l'indice numerico dell'ammasso roccioso N, profondità e diametro della galleria.

Equations in Tab. I show that the ground condition is influenced by the tunnel size. This is probably because as the tunnel diameter increases, the rock mass confinement decreases and therefore the rock mass strength also decreases.

It may be added here that tangential strain ε_θ is equal to the ratio of tunnel closure and diameter. If it exceeds the failure strain ε_f of the rock mass, squeezing will occur. Moreover, mild squeezing may not begin even if closure is 1 % and less than ε_f in most cases [SINGH and GOEL, 1999].

4. Estimation of tunnel support pressure

Detailed field studies have been carried out for eight tunnelling projects located in the Himalayas and the peninsular India. The equations for estimating support pressure are based on measured support pressures and other related parameters of these Indian tunnels having steel rib supports.

Two sets of empirical equations for estimating support pressures for tunnels under non-squeezing and squeezing ground conditions have been developed as below [GOEL *et al.*, 1995c].

Non-squeezing Ground Condition

$$p_v\,(el) = \left[\frac{0.12\,H^{0.1}.\;a^{0.1}}{N^{0.33}}\right] - 0.038, \quad \text{MPa} \qquad (2)$$

Squeezing Ground Condition

$$p_v\,(sq) = \left[\frac{f(N)}{30}\right].10^{\left[\frac{H^{0.6}.\;a^{0.1}}{50\;N^{0.33}}\right]}, \quad \text{MPa} \qquad (3)$$

where,

$p_v(el)$ = short-term roof support pressure in non-squeezing ground condition in MPa,
$p_v(sq)$ = short-term roof support pressure in squeezing ground condition in MPa,
$f(N)$ = correction factor for tunnel closure obtained from Tab. II,
H & a = tunnel depth & tunnel radius respectively in metres and
N = rock mass number [Eq. 1].

Tab. II – Correction factor for tunnel closure in Eq. 3 [GOEL *et al.*, 1995c].
*Tab. II – Fattore di correzione per la stima della convergenza della galleria Eq. 3 [*GOEL *et* al., *1995c].*

S.No.	Degree of Squeezing	Normalized Tunnel Closure %	f (N)
1.	Very mild squeezing ($270 N^{0.33}. B^{-0.1} < H < 360 N^{0.33}. B^{-0.1}$)	1 - 2	1.5
2.	Mild squeezing ($360 N^{0.33}. B^{-0.1} < H < 450 N^{0.33}. B^{-0.1}$)	2 - 3	1.2
3.	Mild to moderate squeezing ($450 N^{0.33}. B^{-0.1} < H < 540 N^{0.33}. B^{-0.1}$)	3 - 4	1.0
4.	Moderate squeezing ($540 N^{0.33}. B^{-0.1} < H < 630 N^{0.33}. B^{-0.1}$)	4 - 5	0.8
5.	High squeezing ($630 N^{0.33}. B^{-0.1} < H < 800 N^{0.33}. B^{-0.1}$)	5 - 7	1.1
6.	Very high squeezing ($800 N^{0.33}. B^{-0.1} < H$)	>7	1.7

NOTE: Tunnel closure depends significantly on method of excavation. In highly squeezing ground condition, heading and benching method of excavation may lead to tunnel closure > 8%.
NOTA: La convergenza dipende in modo significativo dal metodo di scavo. In condizioni fortemente spingenti, il metodo di scavo a sezione parzializzata (calotta e ribasso) può portare a convergenze > 8%.

The above Eqs. 2 & 3 were evaluated using measured support pressures. It is found that the estimated support pressures are matching with the measured values even for larger tunnels (diameter or width more than 9m) in squeezing ground conditions.

5. Effect of tunnel size on support pressure

Various approaches for estimating support pressures have been developed in the recent past. Some researchers demonstrated that the support pressure is independent of tunnel size [DAEMEN, 1975; JETHWA, 1981; BARTON *et al.*, 1974; SINGH *et al.*, 1992], whereas other advocated that the support pressure depends upon the tunnel size [TERZAGHI, 1946; DEERE *et al.*, 1969; WICKHAM *et al.*, 1972; UNAL, 1983]. A brief review on the effect of tunnel size on support pressure with a concept proposed by GOEL [1994] is presented.

5.1. Review of Existing Approaches

Empirical approaches of estimating support pressure have been presented in Tab. III to study the effect of tunnel size on support pressure. A discussion is presented below.

5.1.1. INFLUENCE OF SHAPE OF THE OPENING

Some empirical approaches listed in Tab. III have been developed for flat roof and some for arched roof. In case of an underground opening with flat roof, the support pressure is generally found to vary with the width or size of the opening, whereas in arched roof the support pressure is found to be independent of tunnel size (Tab. III). RSR - system of WICKHAM *et al.* [1972] is an exception in this regard, probably because the system, being conservative, was not backed by actual field measurements for caverns. The mechanics suggests that the normal forces will be more in case of a rectangular opening with flat roof by virtue of the detached rock block in the tension zone which is free to fall.

5.1.2 INFLUENCE OF ROCK MASS TYPE

The support pressure is directly proportional to the size of the tunnel opening in the case of weak or poor rock masses, whereas in good rock masses the situation is reverse (Tab. III). Hence, it can be inferred that the applicability of an approach developed for weak or poor rock masses has a doubtful application in good rock masses.

GOEL *et al.* [1995a] have evaluated the approaches of BARTON *et al.* [1974] and SINGH et al. [1992] using the measured tunnel support pressures from 25 tunnel sections. They found that the approach of BARTON *et al.* may be unsafe for medium to larger tunnels (diameter more than 6m) in squeezing ground conditions. Moreover, the reliability of the approaches of SINGH *et al.* [1992] and BARTON *et al.* depend upon the rating of Barton's Stress Reduction Factor (SRF). It has also been found out that the approach of SINGH *et al.* is unsafe for larger tunnels (diameter more than 9m) in squeezing ground conditions.

5.1.3. EFFECT OF TUNNEL SIZE ON SUPPORT PRESSURE - NEW CONCEPT

Equations 2 and 3 have been used to study the effect of tunnel size on support pressure which is summarised in Tab. IV [GOEL *et al.*, 1996].

It is cautioned that the support pressure is likely to increase significantly with the tunnel size for tunnel sections excavated through the following situations:

(i) slickensided zone,
(ii) thick fault gouge,
(iii) weak clay and shales,
(iv) soft plastic clays,
(v) crushed brecciated and sheared rock masses,
(vi) clay filled joints, and
(vii) extremely delayed support in poor rock masses.

6. Estimation of tunnel closure

Behaviour of concrete, gravel and tunnel muck backfills, commonly used with steel arch supports, has been studied. Stiffness of these backfills has been estimated using measured support pressures and tunnel closures or deformations. These backfills stiffness values have been subsequently used to obtain effective support stiffness K of the combined support system of steel rib and backfill [GOEL, 1994].

On the basis of measured tunnel closures from 60 tunnel sections (35 non-squeezing and 25 squeezing), two separate correlations have been developed for predicting tunnel closures in non-squeezing and squeezing ground conditions as given below [GOEL, 1994].

Non-squeezing Ground Condition

$$\frac{u_a}{a} = \frac{H^{0.6}}{28.N^{0.4} \cdot K^{0.35}} \ \% \qquad (4)$$

Squeezing Ground Condition

$$\frac{u_a}{a} = \frac{H^{0.8}}{10.N^{0.3} \cdot K^{0.6}} \ \% \qquad (5)$$

Tab. III - Important empirical approaches and their recommendations [GOEL *et al.*, 1996].
Tab. III - Importanti approcci empirici e raccomandazioni [GOEL et al., *1996].*

Approach	Results Based on	Recommendations
TERZAGHI [1946]	a. experiments in sands b. rectangular openings with flat roof c. qualitative approach	support pressure increases with the opening size
DEERE *et al.* [1969]	a. based on Terzaghi's theory and classification on the basis of RQD	support pressure increases with the opening size
WICKHAM *et al.* [1972] RSR - system	a. arched roof b. hard rocks c. quantitative approach	support pressure increases with the opening size
BARTON *et al.* [1974] Q - system	a. hard rocks b. arched roof c. quantitative approach	support pressure is independent of the opening size
UNAL [1983] using Bieniawski's RMR	a. coal mines b. rectangular openings with flat roof c. quantitative approach	support pressure increases with the opening size
SINGH *et al.* [1992]	a. arched roof (tunnel /cavern) b. both hard and weak rocks c. quantitative approach	Support pressure is observed to be independent of the opening size (2 - 22m)

Tab. IV - Effect of tunnel size on support pressure [GOEL *et al.*, 1996].
Tab. IV - Influenza della dimensione della galleria sulla pressione sui sostegni [GOEL et al., *1996].*

S. No.	Type of Rock Mass	Increase in Support Pressure Due to Increase in Tunnel Span or Dia. from 3m to 12 m
	A. *Tunnels with arched roof*	
1.	Non-squeezing ground conditions	Up to 20 percent only
2.	Poor rock masses / squeezing ground conditions (N = 0.5 to 10)	20 - 60 percent
3.	Soft-plastic clays, running ground, flowing ground, clay-filled moist fault gouges, slickensided shear zones (N = 0.1 to 0.5)	100 percent
	B. *Tunnels with flat roof* (irrespective of ground conditions)	up to 100 percent

where,

u_a/a = normalised tunnel closure in percent,
K = effective support stiffness in MPa,
H & a = tunnel depth & tunnel radius (half of tunnel width) respectively in metres and
N = rock mass number [Eq. 1].

Equations 4 & 5 can also be used to obtain desirable effective support stiffness to contain the normalised tunnel closure within 4 to 5 percent.

7. Ground reaction curve (GRC)

Ground reaction curve is quite useful for designing the supports specially for tunnels through squeezing ground conditions. An easy to use empirical approach for obtaining the ground reaction curve has been developed using Eqs. 3 and 5 for tunnels in squeezing ground conditions [GOEL *et al.*, 1997]. The approach here has been explained with the help of an example.

For example, the tunnel depth H and the rock mass number N have been assumed as 500m and 1 respectively and the tunnel radius 'a' as 5m. The radial displacement of tunnel is u_a for a given support pressure $p_v(sq)$. These assumed values show squeezing ground conditions (Tab. I).

GRC Using Eq.3 : In equation 3, as described earlier, f(N) is the correction factor for tunnel closure (Tab. II). For different values of permitted normalised tunnel closure (u_a/a), different values of f(N) are proposed in Tab. II. Using Tab. II and Eq. 3, the support pressures [$p_v(sq)$] have been estimated for the assumed boundary conditions and for various values of u_a/a (column 1) as shown in Tab. V. Subsequently, using the p_v (column 3) and u_a/a (column 1) from Tab. V, GRC has been plotted for u_a/a up to 5 per cent (Fig. 2).

GRC Using Eq.5 : For obtaining GRC from Eq. 5, the following equation of support stiffness is also used.

$$K = [\, p_v / (u_a/a) \,] \qquad (6)$$

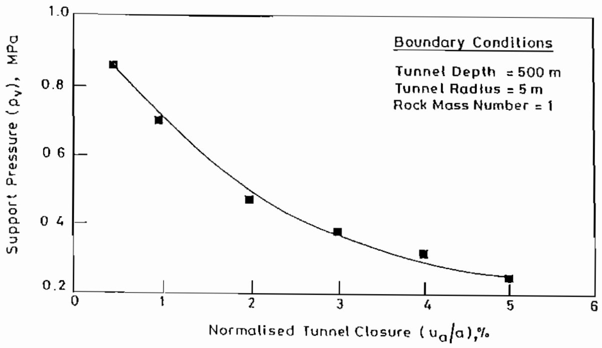

Fig. 2 – Ground reaction curve for squeezing ground condition obtained from Eq. 3.

Fig. 2 – Curva caratteristica della galleria in condizioni spingenti ottenuta con l'Eq. 3.

It is important to mention that u_a/a value for estimating K from Eq. 6 should be a dimensionless quantity and not in percent. It means that instead of 1 percent, the u_a/a value would be 0.01 in Eq. 6.

Using the values of u_a/a (dimensionless corresponding to percent value) and $p_v(sq)$ from columns 1 and 3 respectively of Tab. V in Eq. 6, K values (column 4, Tab. V) have been obtained. Using this K value in Eq. 5, normalised tunnel closure (u_a/a) is calculated for the given boundary conditions (H = 500m and N = 1) and tabulated in column 5, Tab. V. This value of normalised tunnel closure is then used to obtain support pressure from Eq. 5 (column 7, Tab. V) or from Eq. 6 (column 8, Tab. V).

Three sets of values of support pressures and normalised closures are available for plotting three ground reaction curves. One set of data is given in columns 1 and 3 (Fig. 2), second set is from columns 5 and 7, whereas the third set is represented by columns 5 and 8.

It is interesting to see that though the two equations (Eqs. 3 and 5) have been developed using different data and cases, the ground reaction curves obtained from these two equations are practically identical. This exercise has generated confidence on the utility of Eqs. 3 & 5 to obtain ground reaction curve.

Tab. V – Construction of ground reaction curve using Eqs. 3 and 5.

Tab. V – Costruzione della curva caratteristica della galleria mediante le Eqq. 3 e 5.

Assumed u_a/a (%)	Correction Factor (f)	$p_v(sq)$ from Eq. 3 (MPa)	K from Eq. 6 using cols. 1 & 3 (MPa)	u_a/a from Eq.5 for K at col. 3 (%)	f for u_a/a at Col. 5	$p_v(sq)$ from Eq. 3 (MPa)	p_v from Eq. 6 using cols. 4 & 5 (MPa)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0.5	2.7	0.86	172	0.59	2.6	0.82	1.03
1	2.2	0.7	70	1.04	2.2	0.69	0.73
2	1.5	0.475	23.75	2.05	1.4	0.44	0.48
3	1.2	0.38	12.66	3.02	1.15	0.36	0.38
4	1.0	0.317	7.9	4.02	1	0.31	0.32
5	0.8	0.25	5.06	5.37	0.85	0.27	0.27

8. Conclusions

The above equations and concepts would certainly help in solving some of the problems of tunnelling in squeezing ground conditions. The main conclusions are:

(i) The ground conditions for tunnelling can be predicted reliably using the Equations presented in Tab. I. It is also possible to predict the degree of squeezing.

(ii) The support pressure and the tunnel closure can be estimated using Eqs. 2 to 5. The ground reaction curve approach discussed in the paper may be used for designing the support system.

(iii) The support pressure increases with the tunnel size in case of poor rock masses and squeezing conditions (Tab. IV).

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Scavo di gallerie in condizioni spingenti

Sommario

Indipendentemente dallo sviluppo di nuove tecnologie, lo scavo di gallerie in ammassi rocciosi scadenti, giuntati o in zone di faglia rappresenta una sfida importante per pianificatori, progettisti, ingegneri e geologi. Il CMRI (Istituto Centrale di Ricerca Mineraria), India, ha raccolto un numero significativo di dati, durante lo scavo di gallerie idroelettriche. L'enfasi è posta sul problema di sviluppare nuovi approcci e relazioni per la previsione delle condizioni spingenti e della pressione sui sostegni, nonché della convergenza in galleria. La nota affronta tali problematiche insieme alla valutazione dell'influenza della dimensione della sezione di scavo sulla stessa pressione sui sostegni e sul calcolo dell'interazione sostegno-ammasso roccioso (curve caratteristiche, in condizioni spingenti).