A Novel Framework for Analysis of Tunneling Projects in Lower Himalaya

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Abstract. In the Himalayan region, geology of rock mass is highly complex and fragile and hence excavation of large size underground structures in such a material is a very difficult job. Excavation of large size tunnels and caverns becomes safe if the condition of the ground is known a-priori. Knowledge of the ground condition will not only help in proper design of support system but will also help in keeping contingency plans ready before any untoward eventuality. It is therefore necessary to develop a simple framework that will predict the ground condition. In this paper, a unique multiple-graph based framework has been proposed for the preliminary estimation of ground conditions during tunneling through rock masses. This method has been established based on the estimation of three quantities in a logical sequence, viz., rock mass strength, competence factor and finally the ground condition. A new empirical ground condition classification has also been suggested in this paper for both soft and hard rock masses. The proposed framework is validated by applying it to five tunnel sections from Sawra-Kuddu Hydroelectric Project in Himachal Pradesh, India. The proposed framework is an efficient tool for quick prediction of ground condition in the preliminary stages of design as well as during the excavation of tunnels.

Keywords: Multiple Graph Method, Ground Condition Prediction, Self-Supporting Ground, Squeezing and Non-Squeezing Ground.

1 Introduction

As a part of development of infrastructure in the country as a whole, many railway and roadway tunnels in hill regions, tunnels and caverns for hydroelectric projects, large size caverns for underground storage of petroleum products as well as other infrastructure projects are in the stage of either planning or construction in India. Majority of these projects involving deep excavations are situated in the Himalayan region. In this region, geology is highly fragile and complex due to presence of major discontinuities like joints, faults, folds, shear zones, fault zones and thrust zones and due to fracturing and weathering of rock masses. Hence, excavation of large size underground cavities in such a material is problematic due to unfavorable and adverse topography, geology and climatic conditions. All of these factors directly disturb the strength of rock mass and control the ground conditions, which in turn define the construction methodology, sequence of construction and the nature of support systems. It is therefore necessary to develop a framework that will predict ground condition before the actual excavation starts so that engineers can take adequate measures at critical sections.

Depending on in-situ stresses and strength of rock mass, ground condition could be categorized as stable (self-supporting), non-squeezing or squeezing ground conditions [1]. In case of stable and elastic ground, in-situ stresses in rock mass remain below the yield stress limit. This condition is further sub-divided into two categories, namely self-supporting (tunnel closure < 0.1%) and non-squeezing (0.1% < tunnel closure < 1.0%). The former condition does not require any supports, however, the later one sometimes needs light supports for stability. On the other hand, a weak over-stressed rock mass shows squeezing behavior while a hard and massive over stressed rock mass may experience rock bursting. A squeezing ground (tunnel closure ≥ 1.0%) is further sub-divided into: very mild, mild, moderate, high and very high squeezing ground conditions based on the percent tunnel closure [2]. In this paper, the threshold value of normalized tunnel closure (critical strain) defining the boundary between squeezing and non-squeezing ground has been taken as 1.0%. Some investigators argue that this critical strain may be different from 1.0% in some cases [3].

To evaluate the stress induced instability problems in underground constructions, Aydan et al. [4] referred the concept of Competence Factor $\left(F_C\right)$ defined as the ratio of uniaxial compressive strength $\left(\sigma_{cm}\right)$ of rock mass to overburden pressure [5]. Based on these studies, Russo [6, 7] focused on probable ground conditions and potential hazards during tunnel excavation from Geological Strength Index (GSI), σ_{cm}, F_C and self-supporting capacity (RMR). However, the influence of few factors, such as shape of opening, excavation methods etc., was neglected. Further, in poor quality rock masses (GSI<25), where squeezing condition is found very often, performance of this method is not satisfactory. Actually, Russo's method [7] either overestimates or underestimates the ground conditions in Lower Himalaya [8, 9]. Therefore, a need was realized for an appropriate multi-graph method for the Himalayan geology.

In order to address the above issues, a novel multiple-graph based framework has been proposed in this paper for preliminary estimation of rock mass ground condition. This technique is proposed based on the estimation of few quantities in a logical sequence, namely σ_{cm}, F_C and RMR, and finally from these parameters, the ground condition is obtained. Additionally, an empirical ground condition classification has also been proposed based on 25 case histories from literature.

2 Multiple-Graph Based Framework for Prediction of Ground Condition

The multiple-graph method was developed for preliminary estimation of ground conditions in the lower Himalayan region. It involves four sub-graphs, as shown in Fig. 1, where each of these graphs leads to calculation of a parameter related to this prediction procedure. The process starts from the bottom graph (I), then proceeds to top middle graph (II), and finally ends in either top left graph (III.a) for soft rocks or top right graph (III.b) for hard rocks.

2.1 Graph-I: Computation of rock mass strength

At the beginning of multi-graph method, rock mass compressive strength is obtained using Eq. (1). Herein, normalized rock mass quality (Q_C) is coupled with rock mass density (γ) giving some additional sensitivity to the reduced or increased porosity [10]. In Eq. (1), normalized rock mass quality (Q_C) is defined by Eq. (2).

$$\sigma_{cm} = 5\gamma\left(Q_C\right)^{1/3} \quad (1)$$

$$Q_C = Q\left(\sigma_{ci}/100\right) \quad (2)$$

where σ_{cm} and σ_{ci} are in MPa and γ is in t/m^3. In Eq. (2), Q is the rock mass quality estimated along the tunneling direction [10]. Here, uniaxial compressive strength (σ_{ci}) of intact rock contributes towards the quality of rock mass. Contribution of deformation modulus, porosity and density of rock mass is also reflected through σ_{ci} value. In Graph-I, a set of curves is plotted between σ_{cm} and Q on a semi-log scale for different values of σ_{ci} using Eq. (1), and these curves are named as Iso-intact strength curves. If one has the values of Q and σ_{ci} for any rock mass, then σ_{cm} can be found from this Graph-I (Fig. 1).

2.2 Graph-II: Computation of rock mass competence factor

The second step in this framework is determination of rock mass competence factor (F_C). It is defined as the ratio of rock mass strength (σ_{cm}) to the tangential stress (σ_θ) on the excavation periphery [6, 7], and is given by Eq. (3),

$$F_C = \sigma_{cm}/\left(2\gamma H\right) \quad (3)$$

where H and γ denote depth of overburden above tunnel and average unit weight of rock mass respectively. σ_{cm} is obtained from Graph-I in Fig. 1. F_C is dependent on three variables. However, due to the inherent limitation of 2-D graphical representation, two variables are varied in a complementary manner while γ is kept constant at its average value ($\gamma = 25.30$ MN/m^3). In this study, in-situ stress is computed by assuming k (i.e. ratio of horizontal to vertical in-situ stresses) as equal to 1, i.e. a hydro-static state of stress.

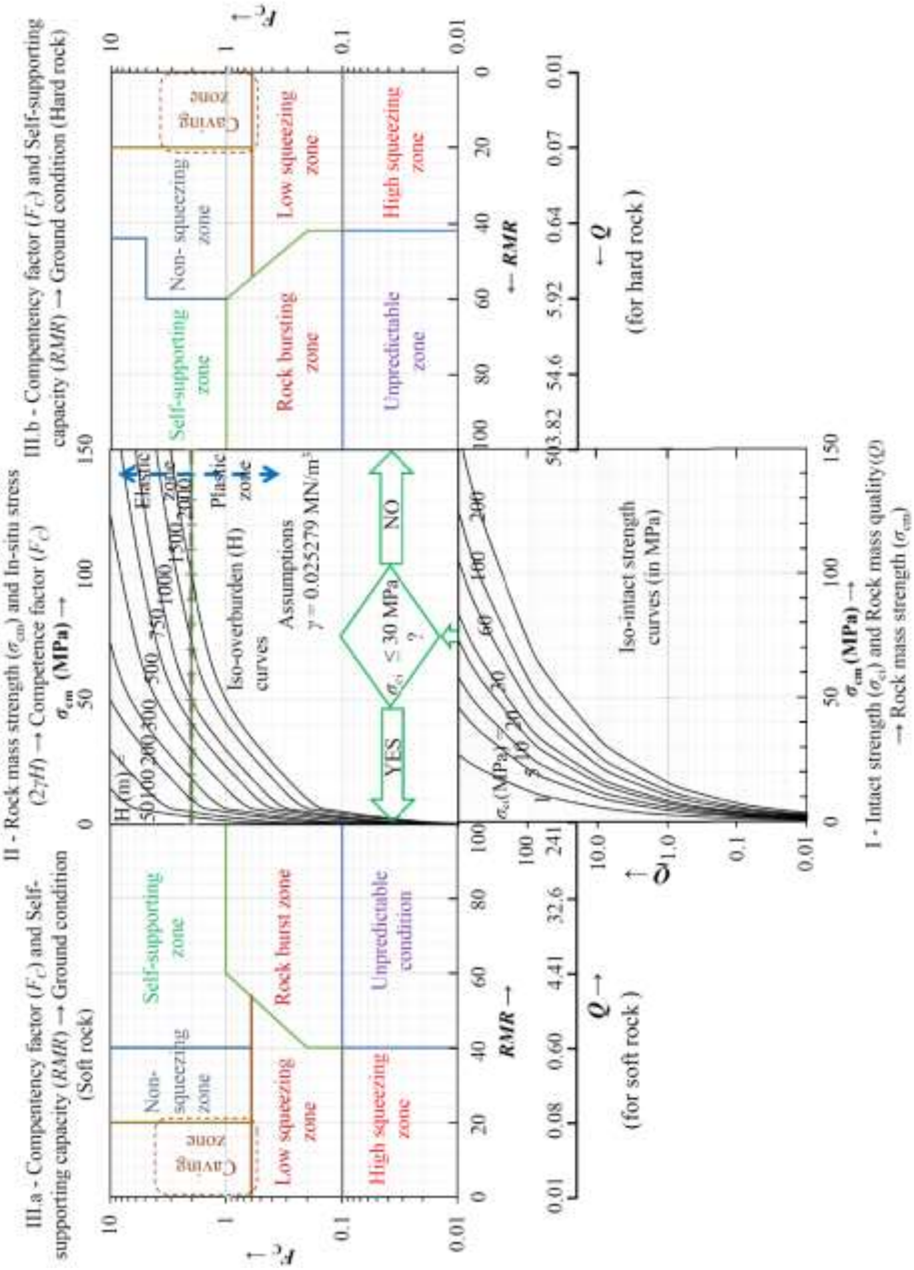

Fig. 1 Multiple-graph method proposed for primary estimation of ground condition [8, 9]

However, in case of circular tunnels, when $k \neq 1$, the maximum tangential stress can be approximated by Eq. (4). Then, dividing $\sigma_{\theta\max}$ by $2.\gamma$ (stress concentration factor for hydrostatic situation = 2), an imaginary value of H can be obtained which will produce an equivalent σ_θ value corresponding to $k = 1$ [7].

$$\sigma_{\theta\max} = 3\sigma_1 - \sigma_3 \tag{4}$$

For non-circular tunnels and for non-hydrostatic in-situ stresses, σ_θ may be taken based on solutions available in Obert and Duvall [11]. A set of curves are plotted between σ_{cm} and F_C for different values of H on a semi-log scale in Graph-II (Fig. 1) using Eq. (3). Once H of any section is known, F_C can be easily determined from this graph. When F_C is less than 1, ground is in an overstressed state. Therefore, an elasto-plastic boundary line has been marked in Fig. 1 (green dotted line in Graph–II) corresponding to $F_C = 1.0$, so as to separate the rock mass state as elastic and plastic.

2.3 Graph-III: Prediction of ground condition

In the third step, ground condition is predicted depending upon the rock mass competence factor (F_C) obtained from Graph–II and the self-supporting capacity of rock mass, *i.e.* RMR [6, 7]. RMR should be obtained preferably from field data. However, if RMR data is not available from the field, RMR may be calculated from Q-value of rock mass by using either Eq. (5) for soft rock [12] or Eq. (6) for hard rock [13] as -

$$RMR = 10\ \ln(Q_m) + 36 \qquad \text{for soft jointed rocks} \tag{5}$$

$$RMR = 9\ \ln(Q) + 44 \qquad \text{for hard jointed rocks} \tag{6}$$

where Q_m defines rock mass quality, Q at SRF = 1.0. The classification of rock material between soft rocks $(\sigma_{ci} \leq 30\ \text{MPa})$ and hard rocks $(\sigma_{ci} > 30\ \text{MPa})$ is as per ISRM [14]. Moreover, scales have been provided in Graph-III.a and Graph-III.b below horizontal axis to compute the RMR from Q value directly using Eq. (5) and Eq. (6) respectively.

A conceptual relationship among different ground conditions in terms of geo-structural quality and stress to strength ratio [15, 16], as shown in Fig. 2. Following this concept, a new ground classification has been proposed in this paper based on the field data of 348 tunnel sections from 25 case studies. All data points are plotted in two semi-log plots as RMR versus F_C (Fig. 3.a and Fig. 3.b). From the observation of these plotted data points corresponding to different ground conditions and the conceptual relationship of Fig. 2, a new ground condition classification has been proposed for both soft and hard jointed rocks as shown in Figs. 3.a and 3.b.

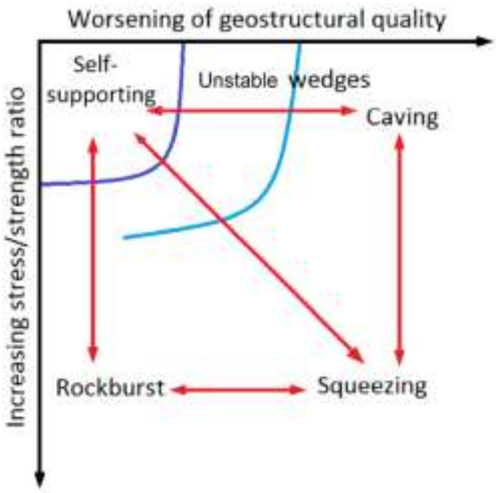

Figure 2 Conceptual scheme for classification of ground conditions upon excavation [17]

In Figs. 3a,b, a zone is marked as stable or self-supporting when $F_c > 1.0$ and RMR is fairly high. Rock masses falling in this region are stable on their own upon excavation. Therefore, no support system is required at all. Another zone in Fig. 3, with RMR within the range of either 20–40 in case of soft rocks (Fig. 3.a) or 20–60 in case of hard rocks (Fig. 3.b) and competency factor, i.e. $F_c > 0.5$, has been identified as non-squeezing zone. This is basically a transition zone between self-supporting and caving or self-supporting and squeezing/rock bursting where the normalized tunnel closure < 1.0 % along the tunnel periphery. However, some local stability problems may be encountered due to unstable wedges of rock mass on cavity roof /wall.

The ground condition is classified as 'caving', when rock mass shows very poor self-supporting capacity $(RMR \leq 20)$ associated with low in-situ stress condition $(F_c > 0.6)$ as shown in Fig 3. In case of caving, highly fractured rock mass of tunnel wall or cavity initially deforms elastically and then experiences sudden failure before reaching its yield point due to gravitational collapse of fractured rock blocks [18]. It may be noted that no data points corresponding to caving-in of rock mass were available in literature. Hence, the caving zone has been decided based on studies of various researchers [6, 7, 18, 19] , and the authors' field experience.

Poor quality rock masses (for soft rock, $\mathrm{RMR} < 40$ and for hard rock, $\mathrm{RMR} < 44$ as shown in Figs. 3.a,b respectively) having very low competence factor $(F_C < 0.6)$, are generally found to experience squeezing ground conditions. The squeezing phenomenon can be defined as large elasto-plastic deformation of tunnel cavity due to over-stressing (σ_θ exceeding its σ_{ci}) of incompetent rock mass [20].

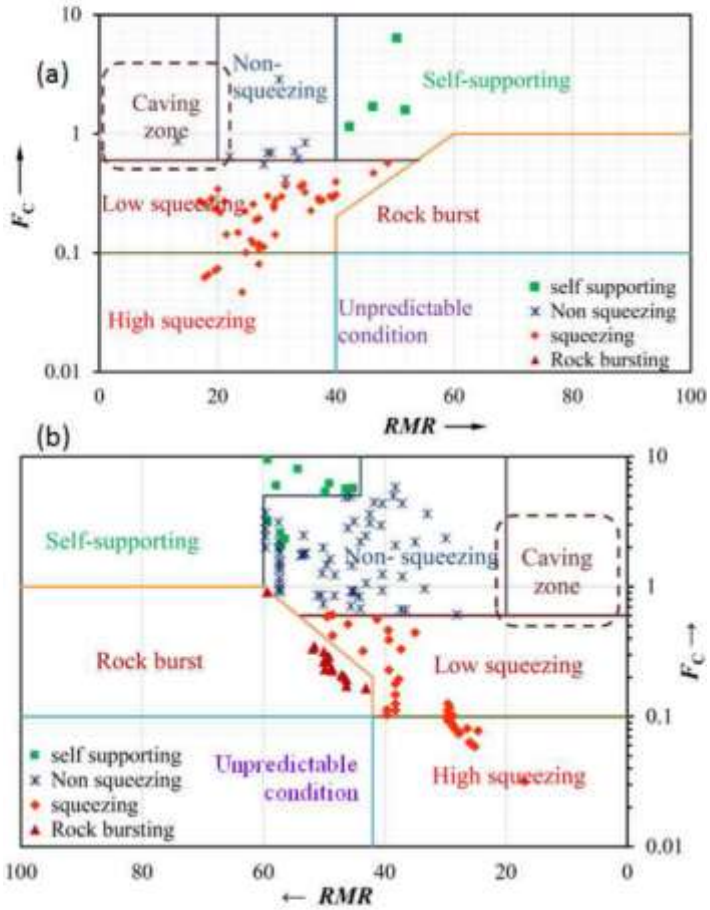

Figure 3 Data from different case studies for developing ground condition classification scheme: (a) soft rock material and (b) hard rock material.

Based on the degree of competency, squeezing category in Fig. 3 has been divided into two zones, namely, low squeezing zone $(F_c > 0.1)$ and high squeezing zone $(F_c \leq 0.1)$. The rock burst phenomenon in underground excavations can be defined as spontaneous and violent fracture of rock mass. When brittle and massive rock mass (for soft rock, $\mathrm{RMR} > 40$ and for hard rock, $\mathrm{RMR} > 44$ as shown in Fig. 3.a, b respectively) is subjected to high in-situ stress, it may literally cause the rock mass to explode as it attempts to re-establish equilibrium along the opening periphery after excavation.

The proposed ground condition classification systems (as shown in Fig. 3) have been joined with the two earlier graphs (Graph-I and Graph-II) as Graph – III.a and Graph – III.b and a novel ground condition prediction framework has been suggested in Fig. 1. However, a look at Fig. 3 shows that no data point exists in "caving" zone (RMR in the range of 0-20 and $F_C > 0.5$), "rock bursting" zone in soft rock. The corresponding demarcating lines are therefore only tentative. Hence, as more and more data points become available, the authors would certainly like to update the proposed multiple–graph technique further. This technique has been validated by applying it to 32 tunnel sections from lower Himalayan region [8, 9].

3 Sawra-Kuddu Hydroelectric Project

3.1 Salient Features

The Sawra-Kuddu hydroelectric project (SKHEP) is located on the Pabbar river, in Himachal Pradesh state, India. It was planned to utilize average head of water i.e.182.48m for generation of 111 MW power. From the barrage, located near Hatkoti village, water is carried through a water conductor system involving 11.364 km long, 5 m diameter (finished), D-shaped Head Race Tunnel (HRT) to power house cavern located on left bank of the Pabbar river near Snail village. The layout plan of this project is shown in Fig. 4.

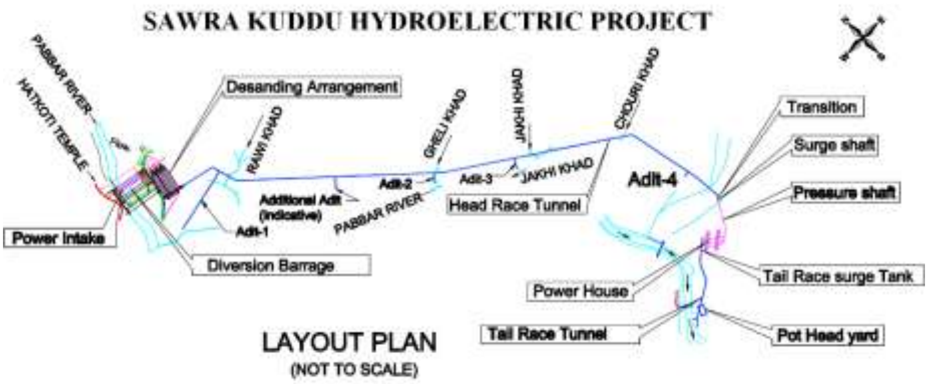

Fig. 4 Layout plan of Sawra-Kuddu hydro-electric project in Himachal Pradesh, India [21]

3.2 Geology along Head Race Tunnel

In SKHEP, as shown in Fig 4, there were four alignment changes along the path of HRT. It has an overall slope of 1 in 350 m. The tunnel cavity was constructed mainly through drill and blast method. However, at some reaches where quality of rock mass is very poor, the heading and benching method was also employed. Initially, four D-shaped, 5 m diameter adits were planned for excavation of the tunnel, namely Adit-1, Adit-2, Adit-3 and Adit-4. However, in the later stage, a 430.996m long additional adit was excavated at reduced distance (RD) 1461.457 m to expedite the construction procedure. Various geological characteristics, encountered during excavation of HRT through different adits and the support systems provided at these geological conditions are provided in Table 1 [22].

3.3 Estimation of ground condition

In Table 1, section-2 and 5 were reported as non-squeezing sections whereas in section-1 high squeezing ground condition was observed. An image of tunnel closure due to squeezing ground at RD 585 m and the provided support systems are shown in Fig. 5.

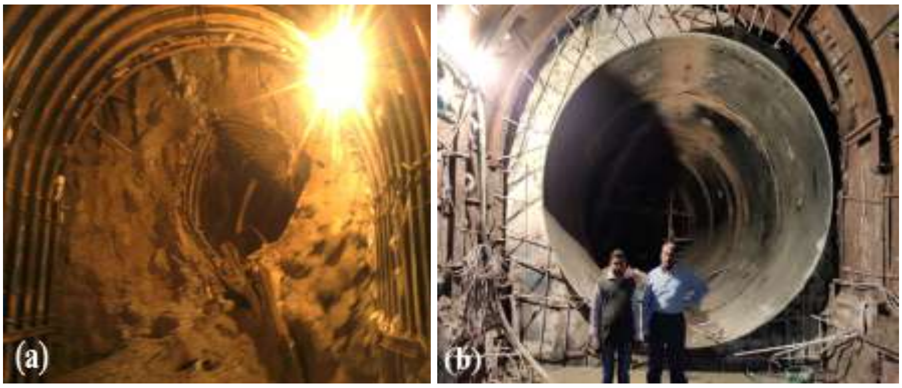

Fig. 5 Images taken at adit 1, F1 at RD 585 m. (a) Displacements of tunnel periphery due to squeezing ground (b) Support systems provided, Sawra-Kuddu HEP.

In the present study, authors' have made an exercise to apply most of the recently developed ground condition prediction approaches including the proposed framework discussed in section 2, to these five tunnel sections and re-estimate the ground conditions along the HRT. The predicted ground conditions at these tunnel sections are also presented in Table 1. One may notice in this table that most of the predicted results are consistent with the observed ground conditions.

By observing carefully, section-1 in Table 1 can be declared as the tunnel section with poorest ground condition as, all the methods in Table 1 have identified this tunnel section with various degrees of squeezing; from low squeezing to mild squeezing. Therefore, the designers can select the first section of Table 1 for detail numerical analysis using appropriate numerical tool [23].

4 Conclusions

A novel multiple graph based framework has been suggested for the preliminary estimation of ground conditions and associated probable hazards during/after excavation

Table 1. Rock mass properties and predicted ground conditions

Section No.	**1**	**2**	**3**	**4**	**5**
Reduced Distance (m)	587-600	764-767	1494-1496.7	2583-2593	4383-4405
Q value	0.02	0.555	0.055	0.125	2.95
Height of Overburden (m)	180	225	300	450	117
In-situ Stress (MPa)	4.41	5.74	7.65	11.04	2.98
σ_{ci} **(MPa)**	58.4	72.3	72.3	58.4	95
Support System	SFRS, S.RIBS	SFRS + Rock bolts	S.RIBS	S.RIBS	Rock bolting
Rock Type	Chlorotic mica schist	Quartz mica schist	Quartz mica schist	Micaceous schist	Quartzite
Prediction of Ground Conditions					
Singh, 1992 [20]	Squeezing	No squeezing	Squeezing	Squeezing	No squeezing
Verman, 1993 [12]	Squeezing	No squeezing	Squeezing	Squeezing	No squeezing
Goel, 1995 [24]	Mild Squeezing	No squeezing	Mild Squeezing	Mild Squeezing	No squeezing
Dwivedi, 2014 [25]	Squeezing	No squeezing	Squeezing	Squeezing	Self-supporting
Russo, 2008, 2014 [6, 7]	Caving/ Flowing ground	Wedge instability/ rock fall	Caving/ Flowing ground	Caving/ Flowing ground	Improbable condition
Proposed Framework	*Low squeezing*	*No squeezing*	*Low squeezing*	*Low squeezing*	*Self-supporting*
Field Observation	*High squeezing*	*No squeezing*	*Squeezing*	*Squeezing*	*No squeezing*

Note: SFRS – steel fiber reinforced shotcrete; S.RIBS – steel ribs

of tunnel cavity in the Lower Himalaya. The framework has been developed on the basis of sequential quantification of - rock mass strength, competence factor, and then ground condition of rock mass. The method has been presented in a graphical form (Fig. 1) where four sets of graphs are included together in a sequential manner, i.e. from bottom to top and then either to left (for soft jointed rocks) or to right (for hard jointed rocks). In addition, a new ground condition classification system is also presented in this paper for both soft rock and hard rock. The applicability of this framework is illustrated by using five HRT sections from Sawra-Kuddu Hydroelectric Project in India.

It is recommended here that a number of sections should be considered along tunnel alignment to get clear picture of ground conditions and then perform detailed numerical analysis at these critical sections for predicting tunnel closure (convergence), support pressure, and design of adequate support system. Finally, as more and more data becomes available and is reported from different project sites (from within India or abroad), the proposed method will be updated further.

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References

1. Bieniawski ZT (1984) Rock Mechanics Design in Mining and Tunneling. Balkema, Rotterdam
2. Goel RK, Jethwa JL, Paithankar AG (1995) Indian experiences with Q and RMR systems. Tunn Undergr Sp Technol 10:97–109. doi: 10.1016/0886-7798(94)00069-W
3. Singh M, Singh B, Choudhari J (2007) Critical strain and squeezing of rock mass in tunnels. Tunn Undergr Sp Technol 22:343–350. doi: 10.1016/j.tust.2006.06.005
4. Aydan O, Akagi T, Kawamoto T (1993) The squeezing potential of rocks around tunnels; Theory and prediction. Rock Mech Rock Eng 26:137–163. doi: 10.1007/BF01023620
5. Wood AMM (1972) Tunnel for roads and motorways. J Eng Geol 5:117–126.
6. Russo G (2008) A simplified rational approach for the preliminary assment of the excavation behaviour in rock tunnelling. Tunnels Ouvrages Souterr. 207:
7. Russo G (2014) An update of the “multiple graph” approach for the preliminary assessment of the excavation behaviour in rock tunnelling. Tunn Undergr Sp Technol 41:74–81. doi: 10.1016/j.tust.2013.11.006
8. Majumder D, Viladkar MN, Singh M (2017) A multiple-graph technique for preliminary assessment of ground conditions for tunneling. Int J Rock Mech Min Sci. doi: 10.1016/j.ijrmms.2017.10.010
9. Majumder D, Viladkar MN, Singh M (2018) Corrigendum to “A multiple-graph

technique for preliminary assessment of ground conditions for tunneling" published in [Int. J. Rock Mech. Min. Sci. 100 (2017), 278–286]. Int J Rock Mech Min Sci 112:398–400. doi: 10.1016/j.ijrmms.2018.08.013

10. Barton N (2002) Some new Q-value correlations to assist in site characterisation and tunnel design. Int J Rock Mech Min Sci 39:185–216. doi: 10.1016/S1365-1609(02)00011-4
11. Obert L, Duvall WI (1967) Rock Mechanics and The Design of Structures in Rocks. John Wiley & Sons Inc.
12. Verman MK (1993) Rock mass - tunnel support interaction analysis. PhD Thesis. University of Roorkee, India
13. Bieniawski ZT (1976) Rock mass classification in rock engineering. In: Bieniawski ZT (ed) Proc. symp. Cape Town, Balkema, pp 97–106
14. ISRM (1981) Basic technical description of rock masses. Int J Rock Mech Min Sci Geomech Abstr 18:85–110.
15. Russo G (2007) Improving the Reliability of Gsi Estimation: the Integrated Gsi-Rmi System. In: I.S.R.M. Work. "undergr. Work. under Spec. Cond. Madrid, pp 123–130
16. Grasso P, Xu S, Pescara M, et al (2006) A Methodology for the Geotechnical Design of Long High-Speed Rail Tunnels Under the Conditions of Uncertainty. In: China Int. Symp. HighSpeed Railw. Tunnels Exhib. Beijing, China, pp 1–27
17. Majumder D, Viladkar MN, Singh M (2018) A Multi-Graph Technique for Initial Prediction of Ground Condition for Tunnelling. In: Int. Conf. Adv. Constr. Mater. Struct. IIT Roorkee, Roorkee, p 144
18. Singh B, Goel RK (1999) Rock mass classification: A prectical approach in civil engineering. Elsevier
19. Russo G, Grasso P (2007) On The Classification of The Rock Mass Excavation Behaviour In Tunnelling. In: Proc. 11th Congr. Int. Soc. Rock Mech. Lisbon, pp 979–982
20. Singh B, Jethwa J., Dube A., Singh B (1992) Correlation between observed support pressure and rock mass quality. Tunn Undergr Sp Technol 7:59–74. doi: 10.1016/0886-7798(92)90114-W
21. HPPCL (2018) Himachal Pradesh Power Corporation Limited. www.hppcl.in/. Accessed 1 Jul 2017
22. HPPCL (2019) Geological Report on Sawra-Kuddu Hydroelectric Project. Hadkoti
23. Majumder D, Viladkar MN, Singh M (2018) Modelling of response of tunnels excavated in squeezing ground condition. In: Indian Geotech. Conf. Bengaluru, pp 1–9
24. Goel RK, Jethwa JL, Paithankar a. G (1995) An empirical approach for predicting ground condition for runnelling and its practical benefits. In: University of Nevada (ed) 35th U.S. Symp. Rock Mech. (USRMS), 5-7 June,. Reno, Nevada, pp 431–35
25. Dwivedi RD (2014) Behaviour of underground excavations in squeezing ground conditions. IIT Roorkee