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Prediction of Squeezing Condition of Tunnel: A Case Study of Tamakoshi V Hydroelectric Project, Nepal

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Abstract
This paper is focused in the assessment of squeezing potential of 8.1Km headrace tunnel (HRT) of Tamakoshi V Hydroelectric Project (TKV). The tunnel length was divided into 41 section at the interval of 200m each and subsequently squeezing assessment was done. Probability of squeezing was checked with the Empirical Methods: Singh et al. (1992), Goel approach (1994), Jimenez and Recio (2011), Farhadian et al (2020); Semi-analytical Method: Jethwa et all (1984), Barla (1995), Hoek and Marinos (2000); Analytical Method: Convergence Confinement Method (Carranza-Torres and Fairhurst, 2000) and Numerical Method (NM): $Phase^2$. Since rock mass characterization is approximation, to get vivid understanding of the rock squeezing behavior three possible cases was evaluated with minimum value of RMR and Q as case I, with computed average value of RMR and Q as Case II and Maximum value of RMR and Q as case III from the available range of values for particular section. Rock mass parameters those not available were estimated from the empirical equations proposed by different scholar. After analysis approximate length of tunnel that may face squeezing were estimated. Without support installation about 50% to 55%, 10% to 20% and 0% to 5% of the tunnel section were estimated to have probability of different degree of squeezing for case I, case II and case III respectively.

Keywords
Rock Squeezing, HRT Tunnel, Squeezing prediction , $Phase^2$

1. Introduction

Nepal is gaining quantum momentum in terms of infrastructure development. Especially expansion of road networks, railway projects, hydropower projects etc. are the major mega projects that are expected to boom in the coming years. These infrastructures are certainly be using tunnel as a sustainable development & cost effective option. Previously, the tunnel was being extensively used in the hydropower projects only but now Nepal braces the need of tunnel in the other infrastructural construction as well and thus it is popularly said these days that Nepal has entered in the tunnel era.

Since almost 83 percent of Nepal is mountainous and has young, fragile geological formation, it is challenging to complete tunnel construction within the allotted time frame and budget. Nepal is a Himalayan country. Poor rock condition, faults, shear zones, ground water in rock mass, fracturing and disintegration, severe overburden, and tectonic stresses are major obstacles to tunnel construction and stability. Rock squeezing, bursting, raveling, and spalling are just a few of the risks and uncertainties that may be encountered as the tunnel progresses linearly through variable rock cover. Rock mass in fault region and rock mass schist, phyllite, and schistose gneiss, which are weak and pliable forms of rock, cannot resist high ranges of tangential stress that results in the squeezing of a tunnel section [1]. As a result, tunnel squeezing is a serious issue, especially when it comes to the fragile rock masses of the Nepal Himalaya, which are not able to bear high pressure [1]. This particular issue that the majority of Nepal's hydropower projects, including Chameliya [2, 3], Kaligandaki A [4], and Khimti-1 [5] confronted throughout construction. The research intend to concentrate on the evaluation of tunnel under squeezing condition in reference to TKV HRT.

Since it's clear that squeezing is a sabotage in tunneling and hence it needs to be dealt with appropriate counter measure with intense analysis of the rock behavior. The most essential consideration of the rock mass to deter the probability of rock squeezing is to estimate the amount of rock squeezing prior to the excavation and apply the economical and safest support system based on the numerical and empirical approaches [6].

2. Geological setting of the study area

The research area is the Tamakoshi V Hydroelectric Project, which is situated in the Dolakha destrict of Bagmati Province along the Tamakoshi River. The geological subdivision of the area is shown in Figure 1 and geological section of HRT is shown in Figure 2. The project consists of an 8.1Km long head race tunnel (HRT). In the upper reaches of the Tamakoshi River, the Main Central Thrust's hanging wall is made up of medium- to high-grade metamorphic rocks and Miocene granites from the Higher Himalaya, while the footwall is made up of Lesser Himalayan meta-sediments.

The chlorite schist rock type is expected to be encountered along a portion of the HRT that is about 2860mlong. Another area of augen gneiss can be observed further north. This rock sequence is expected to be present for around 253m of the tunnel span. Quartzite, meta-sandstone, and chlorite schist follow the rock up-section. At the top of the final series, a succession of medium- to thin-banded pale grey to white, extremely fine quartzite may be found. It is projected that this rock sequence in the tunnel section will be around 901m long.

Black graphitic schist alternates with the meta-carbonate band. As the graphitic schist moves farther north, two more meta-carbonate bands are added to the meta-sandstone bands. The rock eventually transforms from chlorite schist to biotite schist and finally to garnet schist as the grade of metamorphism rises. This tunnel stretch's rock sequences are expected to be around 3026m long.

Along the MCT, the Higher Himalayan succession's kyanite schist and gneiss supersedes the Lesser Himalayan succession. It is estimated that this rock sequence in the tunnel stretch will be 1215m long.

3. Failure Behavior in Tunnel

Discontinuities in the rock mass is not only the sole reason for tunnel failure but rather it's the combined interaction of stress component distribution and weak zone in the rock mass. In the absence of weak zone also tunnel may fail due to the exceeded stress in the periphery of the excavated tunnel than that of rock mass strength capacity. Redistribution of stress cause to stress concentration along the periphery of excavated tunnel that results various nature of failure. Rock squeezing is commonly faced stress controlled failure in tunnel.

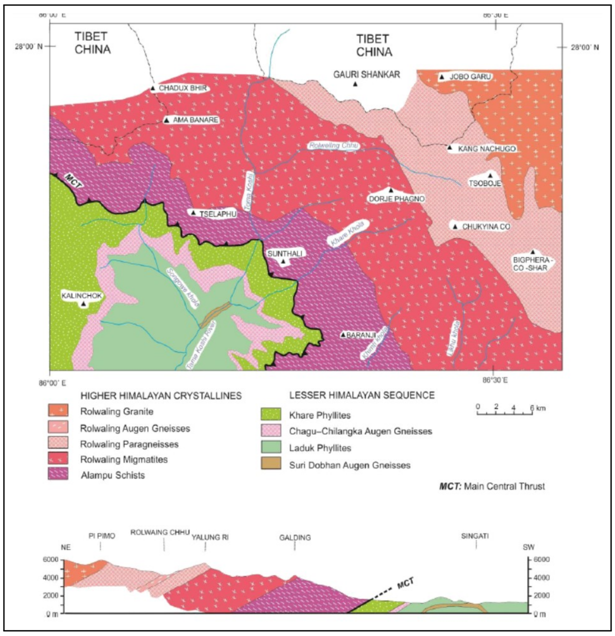

Figure 1: Geological Subdivisions of the Tamakoshi Area (Source: Part F3 - Geological, Geotechnical and Construction Material Investigation Report- TKV

3.1 Rock squeezing

According to Barla [7] "Squeezing of rock is the time dependent large deformation which occurs around the tunnel and is essentially associated with creep caused by exceeding a limiting shear stress. Deformation may terminate during construction or continue over a long time period". The squeezing nature of any tunnel can be elucidated by the amount of the radial convergences along the periphery of the tunnel, rate at which the tunnel converges and the degree of yield zone from the face of excavation. The rock mass properties, state of in-situ stresses, rock mass strength, geological and geotechnical conditions, ground water condition and pore water pressure, method of excavation and the support system used influences the squeezing behavior of tunnel. In particular, strength anisotropy, flakiness, slaking, and weathering qualities are assessed using the mineralogical analysis to determine the mechanical

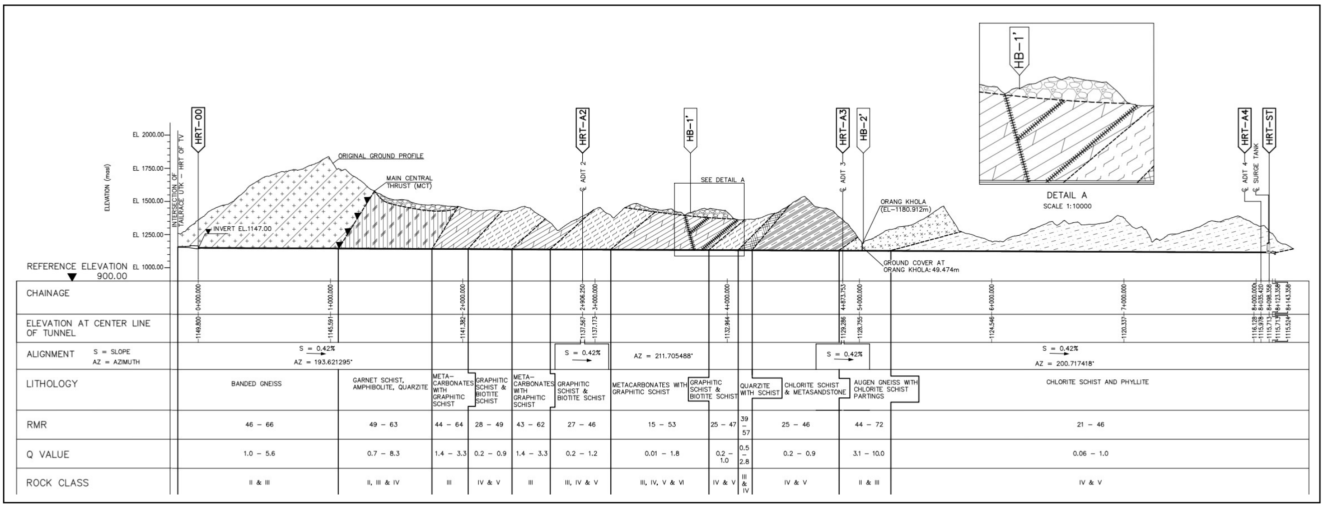

Figure 2: Geological Section along the HRT Alignment of the TKV HEP (Source: Part F3 - Geological, Geotechnical and Construction Material Investigation Report- TKV) .)

character of the rock mass. Detailed petrographical studies and XRD analyses of the rocks were not done so mineralogical composition and its impact on the squeezing phenomena has not been conducted in this research. Rock's permeability and moisture variation may significantly influence how quickly rock pressure and deformation occur however its impact has been also ignored in the study.

In reality, the squeezing prediction is not always accurate. It is possible to see much more ground deformation around the tunnel support system's perimeter than was previously anticipated [8].

3.2 Criteria for squeezing ground condition

3.2.1 Empirical approach

The empirical methods primarily rely on classification systems, which are based on experience and comparison. Singh et al. [9] developed a equation 1 to separate squeezing rock types in terms of overburden depth H and rock mass quality Q.

$$H = 350Q^{1/3} \tag{1}$$

Goel [10] approach come up with equation 2 for squeezing assessment which is primarily based on the rock mass number N, which is for simplification is defined as stress-free Q as N= (Q)SRF= 1.

$$H = 275N^{0.33}B^{-0.1} \tag{2}$$

Degree of squeezing as per Goel [10] calculation and based on Goel et al. [11, 12] classification of squeezing is as presented in Table 1

Table 1: Tunnel convergence, Goel et al. [11, 12]

Equations	DS
$270N^{0.33}B^{-0.1} < H < 360N^{0.33}B^{-0.1}$	VMS
$360N^{0.33}B^{-0.1} < H < 450N^{0.33}B^{-0.1}$	MS
$450N^{0.33}B^{-0.1} < H < 540N^{0.33}B^{-0.1}$	MMS
$540N^{0.33}B^{-0.1} < H < 630N^{0.33}B^{-0.1}$	MS

DS= Degree of Squeezing, VMS= Very Mild Squeezing, MS= Mild Squeezing, MMS= Mild to Moderate Squeezing, MS= Moderate Squeezing

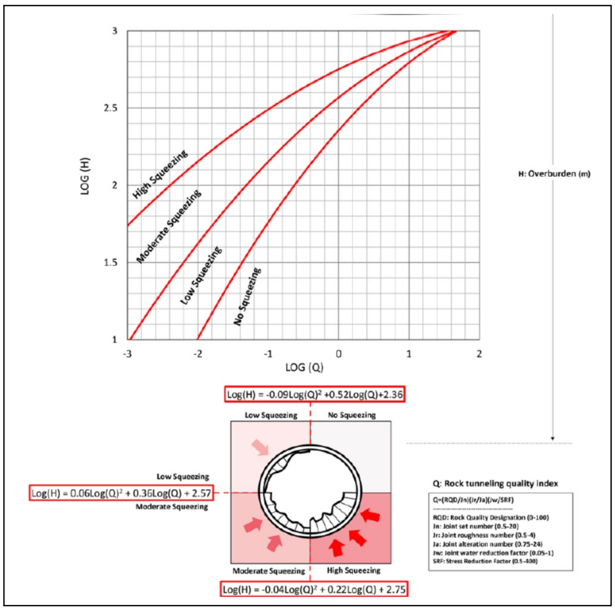

Figure 3: Tunnel squeezing classification chart Farhadian et al. [13]

Jimenez and Recio [14] approach is based on the application of the theory of linear classifiers to an extensive database of 62 case histories (from tunnels in the Himalayas and Himalayan foothills that has been compiled from the literature). The class-separation line is given by equation 3:

$$H = 424.4Q^{0.332} \tag{3}$$

Farhadian et al. [13] used data from 225 case histories from various countries, including Andorra, India, Iran, Japan, Nepal, Spain, Turkey, and Venezuela, to develop a new classification tool for tunnel squeezing that predicts the condition based on two parameters: Q, the tunneling quality index, and H, the depth of the tunnel. Degree of squeezing by this approach is evaluated based on figure 3.

3.2.2 Semi-analytical approach

The semi-analytical approaches can be used not only to predict squeezing behavior of rock mass but also can be used to estimate the deformation quantitatively and/or support pressure required to sustain the radial pressure exerted by rock mass.

On the basis of the rock mass's uniaxial compressive strength and the tunnel's depth below the earth's surface, Jethwa et al. [8] defined Equation 4 to calculate the degree of squeezing.

$$N_c = \frac{\sigma_{cm}}{\gamma H} \tag{4}$$

Table 2: Squeezing condition Jethwa et al. [8]

N_c	Squeezing condition
< 0.4	Highly squeezing
0.4 - 0.8	Moderately squeezing
0.8 - 2.0	Mildly squeezing
> 2.0	Non squeezing

The classifications of squeezing potential as per Jethwa et al. [8] is as described in Table 2.

Barla [7], proposed as shown in Table 3 to classify the squeezing behavior of tunnel after study of tunnel from Venezuela, Taiwan and India.

Table 3: Squeezing behavior Barla [7]

$\frac{q_c^{mass}}{\gamma H}$	Squeezing condition
> 1.0	No squeezing
0.4-1.0	Mild squeezing
0.2-0.4	Moderate squeezing
< 0.2	High squeezing

Hoek & Marinos [15] proposed following equations 5 to determine deformation of a tunnel in squeezing ground.

$$\frac{\delta_i}{d_o} = (0.002 - 0.025\frac{P_i}{P_o})\frac{\sigma_c^m}{P_o}^{\frac{2.4P_i}{P_o}-2} \tag{5}$$

The different classes or degree of squeezing as proposed by Hoek & Marinos (HM) [15] which is based on the strain around the tunnel ε_t is as listed in Table 4.

Table 4: Squeezing behavior HM [15]

ε_t	Squeezing condition
≤ 1.0	Few support problem
1-2.5	Minor squeezing
2.5-5	Severe squeezing
5-10	Very severe squeezing
< 10	Extreme squeezing

3.2.3 Analytical approach

The Convergence-confinement method (CCM) is an analytical tool for estimating support pressure and displacements in a tunnel. Using axisymmetry assumption the problem is solved as a two or one dimensional and thus it makes vivid understanding of the interaction between ground and support at working face of tunnel. The basic components of the CCM are the ground reaction curve (GRC), the longitudinal displacement profile (LDP) of the tunnel walls, and the support reaction curve (SRC) . Elasto-plastic behavior of rock mass is taken in to account by this method. CCM was also used to estimate radial deformation in this paper.

3.2.4 Numerical method

For underground or surface excavations in rock or soil, *Phase*^{2} is a powerful 2D elasto-plastic finite element stress analysis program. For the Khimti-1 and Melamchi hydropower tunnels in Nepal, Shrestha [16] performed numerical modeling. Shrestha then advocated using numerical modeling in addition to analytical calculations to identify critical stress situations and deformation magnitude for large and non-circular tunnels.

4. Methodology

4.1 Collection of Data

The Tamakoshi V Hydroelectric Project's report was used to collected required information. The report "Part F3: The Geological and Construction Material Investigation Report" included general information on unit weight, elastic modulus, Poisson's ratio, uniaxial compressive strength, rock type, rock mass classification, and other rock mass attributes. While precise information, such as tunnel dimensions, plans, and ground profiles of the orientation of the tunnel, were collected from drawings. Based on the many pieces of existing literature, the required information have been hypothesized.

4.2 Estimation of rock mass properties

Estimation of rock mass properties includes parameters such as in-situ deformation modulus and uniaxial compressive strength. Since these parameters are difficult and expensive to determine in the field, it was determined using empirical relations and average value obtained were used.

4.3 Assessment of squeezing potential

The 8.1 Km long tunnel was divided in to 41 section at the interval of 200m each and overburden for each of the sections were determined from the longitudinal profile of the project. Likewise, Q and RMR value were taken from the report "Part F3 - Geological and Construction Material Investigation Report". The geological profile figure 2 had anticipated range of Q and RMR value for particular section of the tunnel so, the squeezing assessment was done based on these given range. The impact of anticipated minimum and maximum value for the section was tried to visualize by creating three cases of studies. The squeezing assessment based on the minimum value of Q and RMR from the given range was considered as case I where as for maximum value for the same was considered as case III. Another case was also studied considering the computed arithmetic mean value of the RMR and Q for the given range in the particular section of chainage. Analysis was done considering the two types of rock i.e. Schist and Gneiss. Similarly value for Poisson's ratio, uniaxial compressive strength (σ_{ci}), rock density, deformation modulus (E_i) were adopted from the project report.

The analysis of squeezing phenomenon was done using the empirical methods, semi-analytical methods, analytical method and numerical method. In this paper Case I is presented in detail.

Table 5: Properties of material taken for analysis

Rock Type	$\sigma_i(MPa)$	E_i (MPa)	m_i
Schist	47.12	20060	9
Gneiss	37.25	32590	23

5. Result and discussion

5.1 Empirical approach

The outcome of Singh et al. [9]'s analysis is shown in Table 6. According to which, 66 percent of the tunnel's length is more likely to be squeezed. This method has no any provision to access the degree of squeezing. Since the prediction entirely depends on the Q value and the overburden for the section the reliability solely depends upon the estimation of true representative Q value for the section.

According to the findings of Goel et al.[11, 12] (Table 6), around 76 percent of the tunnel's entire length has a chance of being squeezed; however along the squeezing section, about 12 percent of the length has a degree of very high squeezing, and around just 2 percent has a degree of high squeezing.

According to Jimenez and Recio [14]'s assessment of squeezing behavior, there is a likelihood of squeezing along around 61 percent of the tunnel's whole length. However this approach doesn't classify the degree of squeezing.

Similarly, Table 6 also displays the findings from Farhadian et al.[13] approach, which indicates that there is a chance of 90 percent tunnel section under squeezing, with only 24 percent experiencing degree of strong squeezing and 41 percent possibly experiencing degree of moderate squeezing. Likewiswe 24 percent is likely to face low squeezing.

Empirical methods can only help for early overview of probable squeezing but however they can not be completely relied. Squeezing behavior as obtained from Singh et al. [9], Goel et al. [11, 12] and Jimenez and Recio [14] approach are highly consistent with each other whereas Farhadian et al [13] result showed higher squeezing percentage of tunnel length (90 percent) however the chainage having squeezing potential is more or less similar as other empirical approaches.

After empirical analysis of the tunnel section for the case I, the probability of the section getting prominent squeezing problem lies at the section with chainage 1+000m, 3+200m, 3+400m, 3+600m, 3+800m, 4+600m and 5+600m.

5.2 Semi-analytical approach

Jethwa et al. [8] showed the probability of squeezing is in almost part of the tunnel i.e. 98 percent. Highly squeezing section includes about 20 percent whereas moderately squeezing and mildly squeezing includes 49 and 29 percent respectively of the total length. The result of the analysis is in Table 6.

Result from Barla [7] approach are presented in Table 6 and it shows about 20 percent of the tunnel section is non-squeezing. The rest of the tunnel faces mild (60%) to moderate (20%) squeezing. Chainage that has possibility of experiencing major squeezing problem as estimated by this method are 3+200m to 3+800m, 4+600m, 5+600m, 7+000 and 7+800m.

Hoek and Marinos (HM) [15] approach estimates the 49 percent of tunnel length will have few support problem whereas rest of the length have some sort of squeezing problem ranging from minor squeezing (27%) to very severe squeezing (2%). 2 percent of the section will have severe squeezing whereas there is no section that can face extreme squeezing. The details of squeezing behavior based on this approach is as listed in Table 6 and presented in Figure 4 and Figure 5.

Results obtained from Jethwa et al. [8] were predicting very high percentage of squeezing tunnel. Barla and HM methods were consistent in predicting the chainage with possible higher degree of squeezing

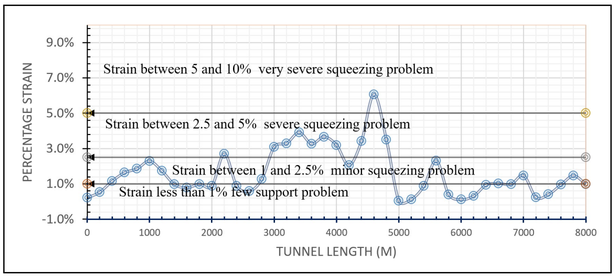

Figure 4: Percentage strain with tunnel length by Hoek and Marinos [15], Case-I

of the tunnel and these result were also more or less consistent with the result obtained from empirical methods. Since, HM method is based in numbers of parameter it is considered as reliable estimate. Semi analytical approach suggest that the tunnel at chainage 2+200m, 3+000m to 4+000m and 4+600m has greater possibility of facing higher degree of squeezing.

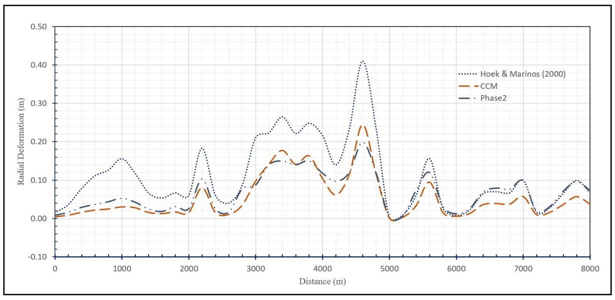

Figure 5: Comperative radial deformation, Case-I

5.3 CCM approach

CCM method was used to determine the radial deformation of each section. GRC and LDP were drawn as depicted in Figure 6 to vividly visualize the ground response. CCM analysis results showed maximum deformation of 0.18m and 0.24m at chainage 3+400m and 4+600m respectively.

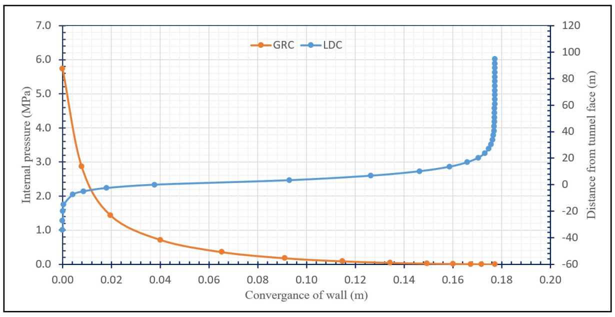

Figure 6: GRC and LDP at chainage 3+400m, Case-I

5.4 Numerical modeling

Numerical model were prepared for 41 section. The default boundary conditions were assumed to be fixed for external boundary. Constant field stress was applied to the model. Full face excavation was considered. As stated previous, 41 section at the spacing of 200m was selected and model for each section was prepared and out put as Figure 8 was used to estimate the radial deformation. For each section maximum strain was calculated and the strain was used to classify the degree of squeezing based on HM method. From Figure 5 it can be seen that the result from *phase*^{2} and CCM are consistent to each other with few exception. *phase*^{2} is more reliable due to greater flexibility of modeling the exact ground condition provided the rock parameter and in situ stress are in confirmation to actual ground condition.

Table 6: Evaluation of Squeezing behavior Case-I

Ch(m)	[9]	[11, 12]	[13]	[8]	[7]	[15]
0	No	NS	NS	MS	NS	FSP
200	No	VMS	LS	MS	MS	FSP
400	Yes	MS	MoS	MoS	MS	MiS
600	Yes	MMS	HS	MoS	MS	MiS
800	Yes	MMS	HS	MoS	MS	MiS
1000	Yes	MoS	HS	MoS	MS	MiS
1200	Yes	MMS	HS	MoS	MS	MiS
1400	Yes	MS	MoS	MS	MS	FSP
1600	Yes	VMS	MoS	MS	NS	FSP
1800	No	NS	LS	MS	MS	FSP
2000	No	NS	LS	MS	NS	FSP
2200	Yes	MS	MoS	MoS	MS	SS
2400	No	NS	LS	MS	NS	FSP
2600	No	NS	NS	MS	NS	FSP
2800	No	VMS	LS	MoS	MS	MiS
3000	Yes	MMS	MoS	MoS	MS	SS
3200	Yes	VHS	HS	HS	MoS	SS
3400	Yes	VHS	HS	HS	MoS	SS
3600	Yes	VHS	HS	HS	MoS	SS
3800	Yes	VHS	HS	HS	MoS	SS
4000	Yes	MMS	MoS	MoS	MS	SS
4200	Yes	MMS	MoS	MoS	MS	MiS
4400	Yes	MoS	MoS	MoS	MS	SS
4600	Yes	VHS	HS	HS	MoS	VSS
4800	Yes	MoS	MoS	MoS	MS	SS
5000	No	NS	NS	NS	NS	FSP
5200	No	NS	NS	MS	NS	FSP
5400	Yes	MS	MoS	MoS	MS	FSP
5600	Yes	HS	HS	HS	MoS	MiS
5800	No	VMS	LS	MoS	MS	FSP
6000	No	NS	LS	MS	NS	FSP
6200	No	NS	LS	MS	MS	FSP
6400	Yes	MMS	MoS	MoS	MS	FSP
6600	Yes	MMS	MoS	MoS	MS	MiS
6800	Yes	MMS	MoS	MoS	MS	FSP
7000	Yes	MoS	MoS	HS	MoS	MiS
7200	No	NS	LS	MS	MS	FSP
7400	No	VMS	LS	MoS	MS	FSP
7600	Yes	MMS	MoS	MoS	MS	FSP
7800	Yes	MoS	MoS	HS	MoS	MiS
8000	Yes	MMS	MoS	MoS	MS	FSP

Very High Squeezing =VHS; High squeezing =HS; Moderate Squeezing =MoS; Mild to Moderate Squeezing =MMS; Mild Squeezing =MS; Very Mild Squeezing =VMS; No Squeezing =NS; Low Squeezing =LS; Extreme squeezing =ES; Very Severe Squeezing =VSS; Severe Squeezing =SS; Minor Squeezing =MiS; Few Support Problem =FSP

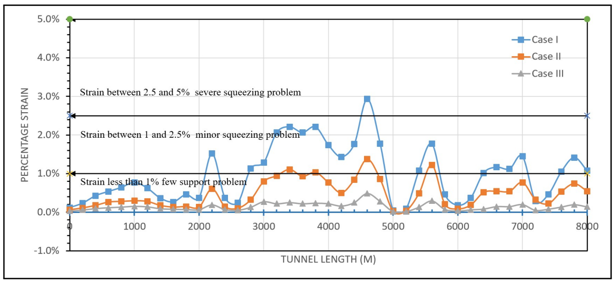

Figure 7: Squeezing behavior of tunnel based on *Phase*^{2} outputs classified based on HM for different cases I, II and III of study

The squeezing behavior of the tunnel based on *Phase*^{2} output and classified based on HM approach for case I, case II and case III can be visualized from Figure 7. From the figure it is clear that for case III there is no problem of squeezing along the length. There is only few support problems throughout the length. Likewise for case II probable minor squeezing problem can be encountered at chainage 3+400m, 3+800m, 4+600m and 5+600m that accounts for 10 percent of the tunnel length.

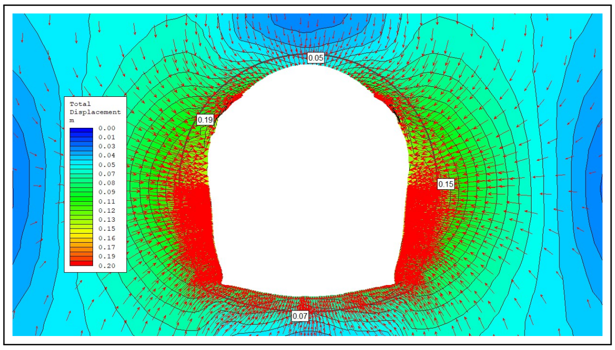

Figure 8: Deformation result obtained after plastic analysis for Ch 4+600m Case-I

6. Conclusion

Empirical methods are based on experience from different existing projects and requires less inputs for analysis. Goel et al. was more efficient than others as various level of squeezing intensity can be predicted and indeterminacy in SRF estimation is also eliminated. It was found Goel et al. and Farhadian et al. are enough and suitable empirical tools for first identification of probable squeezing zone. HM was found to be more reliable compared to empirical methods as it uses wide range of rock parameters but however it does not take account of time dependent deformation. CCM method can quantify the deformation (non time dependent) and GRC, LDP can be drawn to visualize the ground behavior. Likewise, NM can also truly reflect tunnel behavior taking in account of tunnel shape and real field conditions.

HM and CCM result were validated since *phase*^{2} output were comparable and agreed with the result obtained. Since, *phase*^{2} is more reliable due to greater flexibility of modeling the exact ground condition and all the real field parameters can be incorporated in the model, classifying squeezing based on HM approach for *phase*^{2} outputs can clearly indicate the risk possibility.

Based on HM and *phase*^{2} analysis it is estimated that without support installation about 50 to 55 percent, 10 to 20 percent and about 0 to 5 percent of the tunnel section may have probability to face squeezing problem for case I, case II and case III respectively. From the overall analysis the chainage 1+000m, 2+200m, 3+000m to 4+000m, 4+600m, 5+600m, 7+000m and 7+800m are the probable section that may face squeezing issues during construction for case I. Similarly Chainage 1+000m, 3+000m to 4+000m, 4+600m, 5+600m, 7+000m and 7+800m may face minor squeezing problem for case II whereas for case III no squeezing problem is seen except at chainage 4+600m where there is possibility of slight squeezing problem only.

It is very challenging task to get reliable prediction of squeezing phenomena. As uncertainties exist in all the method of estimation of in situ stress and rock mass parameters, the results acquired can be documented and compared with the real data obtained from instrumentation and monitoring during construction phase so that final validity of squeezing risk prediction can be checked for different assumed cases.

Acknowledgments

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