3D numerical simulation of a mine using cohesion-softening, friction-softening and hardening behavior

PK Rajmeny and PK Jain
Hindustan Zinc Ltd.
Rampura Agucha mines, India
Pramod.rajmeny@vedanta.co.in

Abouzar Vakili
Mining One Consultants Pty Ltd.
Melbourne, Australia
avakili@miningone.com

***Abstract*—Numerical modeling is a potent tool to evaluate stability and to assist in long term planning of a mine along with predictive modeling of planned mining situations. However, selection of proper input properties regarding the rock mass still intrigues the Rock Mechanics community. A well-documented case study of a hard rock mine situated in moderately high stress regime practicing sublevel open stoping has been simulated using 3D finite difference method (FLAC3D). The mine was modeled using three types of constitutive material model – Mohr-Coulomb with strain-softening post peak, bi-linear Mohr-Coulomb with strain-softening post peak, Mohr-Coulomb with cohesion softening/friction hardening (CSFH) post peak. Outcome of all approaches have been compared with actual ground conditions. The comparison revealed that the numerical models using the bi-linear Mohr-Coulomb with strain-softening post peak provides most realistic match to the observations in the mine including instability of the crown pillars.**

Keywords*— *cohesion softening; friction softening; strain softening; spalling; breakouts;

I. Introduction

Numerical modeling is a potent tool available to rock mechanics engineers to evaluate stability of underground openings through a mining cycle. Long-term mine planning decisions are increasingly taken based on predictive numerical simulations. It is important to note however that numerical outcomes are highly dependent on selection of material model, rock mass parameters and boundary conditions. Normally, intact rock properties are determined in laboratory and are extrapolated to rock mass properties through rock mass characterization indices like GSI, etc. using, Hoek-Brown criterion (and commercially available software like RocLab/RocData) [1]. Barton and Pandey [2, 3] also proposed an alternative approach, using the Q system, to determine these input for the numerical modelling.

There are many failure criteria and associated material behavior models like Hoek-Brown, Mohr Coulomb strain softening/ hardening, ubiquitous joint, etc., available to represent yielding rock mass response. In the current context, three commonly applied constitutive material behavior in the mine have been chosen for detailed investigation. These include- Mohr-Coulomb with strain-softening post peak, bi-linear Mohr-Coulomb with strain-softening post peak and Mohr-Coulomb with cohesion softening/friction hardening (CSFH) post peak. This paper applies above mentioned three different material models to a back analysis of a well-documented case study of sublevel open stoping practicing Balaria mine in India. Simulation results are compared with actual rock mass response. The outcome of the instant experimentation will provide robust guidelines to Rock Mechanics practicing engineers for selection of rock mass parameters, specially the constitutive material properties.

II. Balaria Mine - Case Study

Zawar group, belonging to Hindustan Zinc Ltd., is the locus of the oldest lead zinc underground mining operations in India. The Group, situated 43km south of Udaipur (Rajasthan), comprises of Mochia, Balaria, Zawarmala and Baroi mine. Mochia and Balaria mines are situated in a similar limb of a geological fold (Sisa Magra anticline, Fig.1). Both mines are inter connected at various levels and are served by separate shafts and Adits. A 90m wide vertical pillar left (Fig. 2 & 3) at western extremity of Balaria to protect Tiri River (and Udaipur Ahmedabad railway line) provides global stability to these mining sections as the main regional pillar.

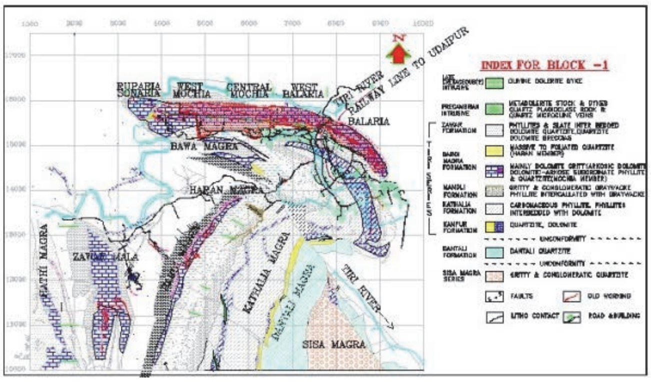


Fig. 1. Regional geology of the area showing location of Balaria and Mochia mines of Zawar

Extensive open stoping in Balaria has culminated in form of a network of open stopes surrounded by crown and rib pillars (Fig. 2 and 3).

A. Geology and Geotechnical Conditions

The rocks of the Zawar area form part of the Aravalli system of middle Pre-Cambrian age and overlie Banded gneissic complex. The main rocks in the area are phyllite, slate, conglomerate, greywacke, dolomite, quartzite, etc. The lead-zinc mineralization occurs in dolomite horizons. The area witnessed two major tectonic cycles and each of the cycles resulted in a system of folding and faulting. Two major folds, i.e. Sisa Magra anticline and Zawarmala anticline, are present in this area along with some other folds. As described, western stopes of Balaria mine truncate across the Railway pillar (Fig. 2&3). The area is characterized by dominant horizontal stresses acting perpendicular to the strike of ore body in Balaria Mochia region. Based on in-situ stress measurement carried using hydraulic fracturing at various depths [4] the following stress relation-ships were derived.

$\sigma H = 0.048\ H + 4.4$ MPa N-S (perpendicular to strike)

$\sigma h = 0.024H + 2.2$ MPa E-W (parallel to strike)

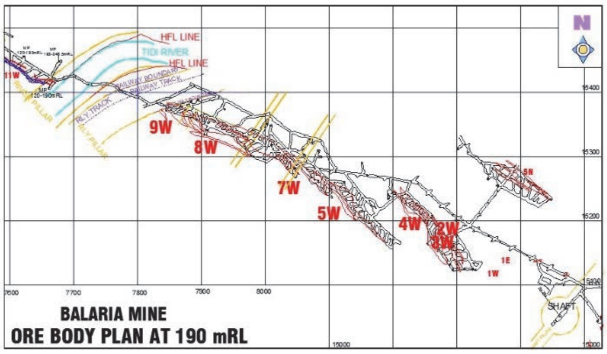


Fig. 2. Level Plan at 190 m RL of Balaria showing various stopes

TABLE I. DETAILS OF HYDRAULIC FRACTURING TESTS CARRIED OUT

Mine	Area	Total depth	S_H (MPa)	Direction of S_H	S_h (MPa)
Balaria	378 mRL	96 m	8.2	N110-120	5.6
Zawarmala	355 mRL	235 m	17.7	N156-167	9.6
Balaria	105 mRL	315 m	20.4	N 110-120	11.8
Mochia	39 mRL	500 m	28.6	N-S	

Tri-axial laboratory tests on the dolomite determined its uniaxial compressive strength as 120 MPa while the young's modulus 40 GPa. The dolomite is massive in nature with only a few joints. The Rock Mass Rating [5] of the dolomite varies from 60-70 with m_i around 16.7 (Table II). The rock mass strength of the host dolomite is around 38-43MPa [6].

TABLE II. VARIOUS PARAMETERS OF ROCK MASS RATING (RMR)

S.N	Parameter	Description	Rating
1	RQD	60-70%	10
2	Intact rock strength	120 MPa	11
3	Joint spacing	2 joint sets, spacing 10cm and 20cm	11
4	Joint condition	Wavy, unidirectional, smooth and no alteration	25
5	Water condition	wet	10
		Total	67

B. Background information

As described earlier, mineralization at Balaria consist of a series of lenses dis-positioned on en-echelon pattern and normally each lens is extracted separately (Fig.2 &3). The entry to Balaria mine is through service shaft which is accessed through the Adit at valley level of 378 mRL (Fig. 2&3). The lenses strike almost east-west. The shaft is located approximately at the middle of the mineralization. The western stopes (under current investigation (Fig. 2&3) consists of 5W, 7W, 8W and 9W-10W and they occur in en-echelon pattern, with insignificant overlap and therefore they were modeled in a continuous manner as a single opening (Fig. 5). Width of these lenses varies in range from 3m to 30m and dip from 60° to 75° and plunge westerly at 55°. The 4W stope is about 100m away from these western stopes and thus has not been included in the combined geometry of the 5W to 9W stopes. Extraction of these western stopes is terminated against regional vertical pillar of Tiri River & Railway pillar (Fig. 3&4).

III. NUMERICAL MODELLING

Simulation of stress build up in various pillars in Mochia and Balaria mines was extensively carried using conventional strain softening material behavior [7,8]. More recently, western part of Mochia was numerically modeled using the – a novel approach suggested by Barton along with CSFH material behaviour [2]. In this approach, strain softening-strain mobilization approach using Q-system is used. Q_c formulation i.e. cohesion component (cc) and frictional component (fc) are extracted directly from Q-logging of the underground mine and knowledge of the UCS. The Q-based approach also uses a depth dependent modulus. The Q_c formulation can be determined as:

Cohesion component (cc) = $(RQD/J_n) * (1/SRF) * (\sigma_c/100)$

Frictional component (fc) = $\tan^{-1}[(J_r/J_a)\ J_w]$

Barton and Pandey [2] used Q- values logged in Mochia and have utilized the Qc formulation as potential sources for peak cohesive and frictional strength. These values, are respectively, softened or mobilized to peak frictional strength reduced towards residual.

Balaria mine, situated in same ground condition as Mochia (being situated in same limb of Sisa Magra anticline) (Table III). Under instant experimentation, Balaria was simulated with three different material constitutive properties on FLAC-3D:

- Linear Mohr Coulomb with Cohesion softening and friction softening – (Lin-CSFS) constitutive material behavior. Hoek's RocLab software was used to derive rock mass input parameters like cohesion (c_{rm}) friction angle ϕ_{rm} , modulus (E_{rm}) and tensile strength (σ_{trm}) from the tri-axial test data and GSI.

- Bi-linear Mohr-Coulomb cohesion softening and friction softening constitutive material behavior (Bi-CSFS) with differential values of cohesion and friction angle at different confinement level. Also, modulus (E_{rm}) was modified based on experience of previous modeling. and

- Mohr-Coulomb cohesion softening and friction hardening (CSFH) constitutive material behavior. While same inputs were used as derived by Barton and Pandey [2] at Mochia mine based on the Q and the Q_{max}. The output of these models was compared with the documented behavior of Balaria.

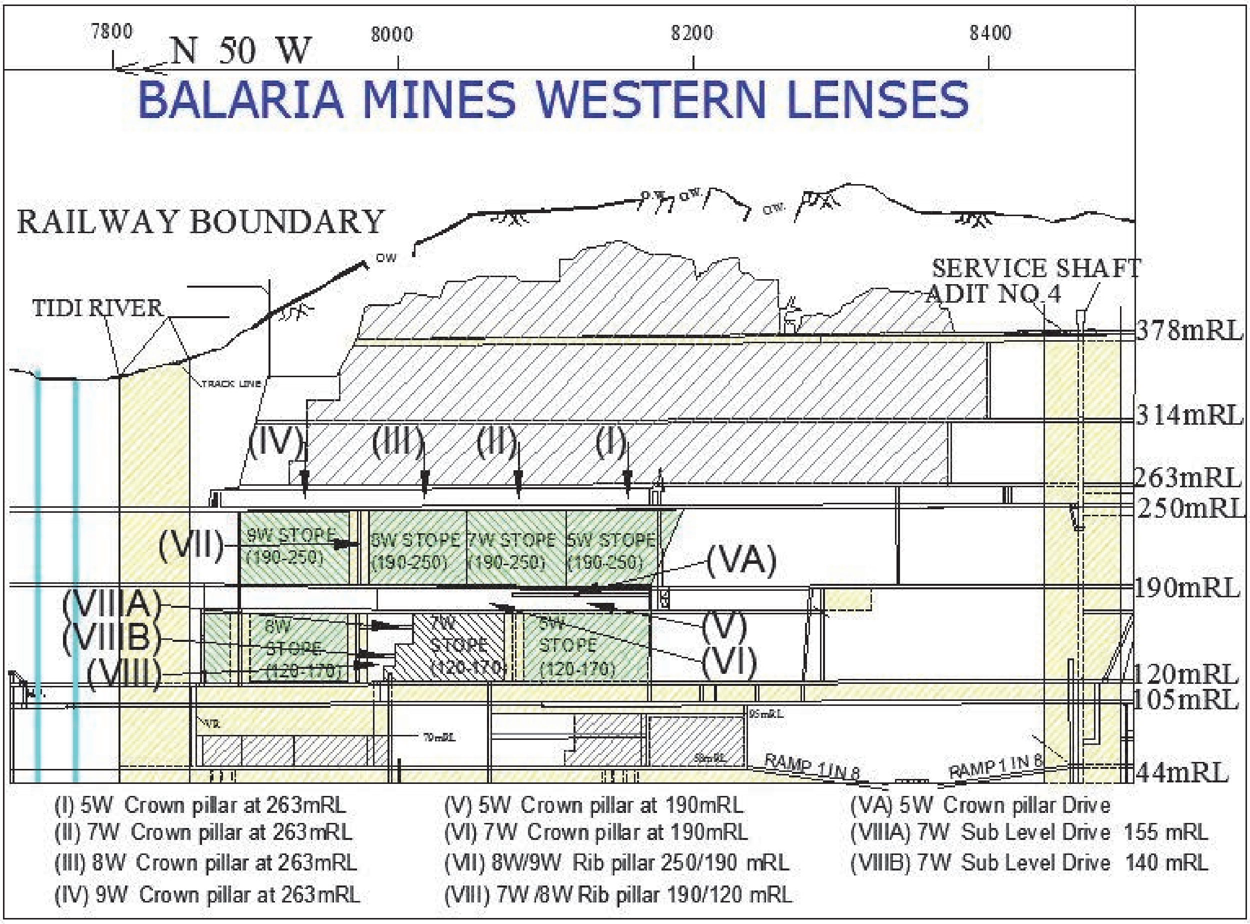


Fig. 3. Long vertical section of western stopes of Balaria

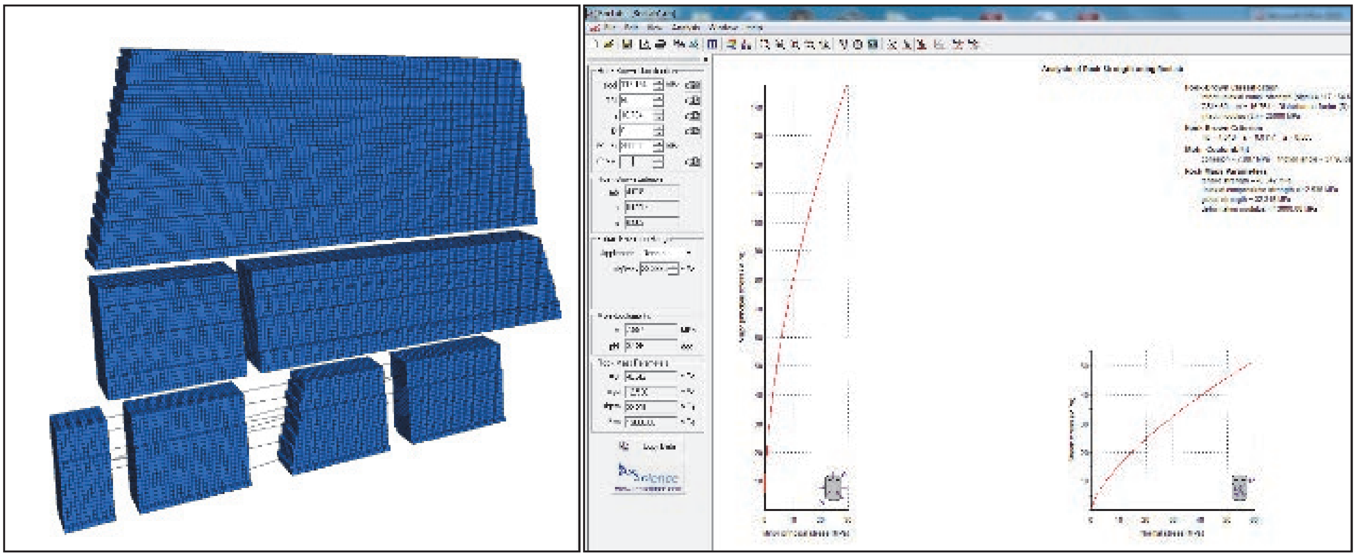
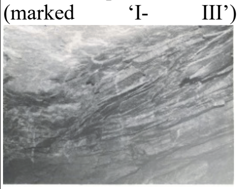
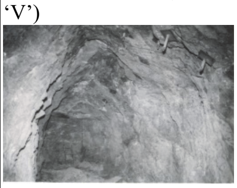
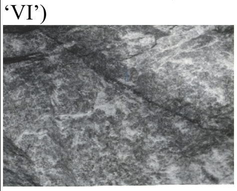


Fig. 4. The model geometry as built on FLAC-3D & RocLab output

A. *Linear Mohr Coulomb Cohesion Softening & Friction Softening (Lin-CSFS) Material Model*

The classical Mohr-Coulomb peak strength criterion and associated constitutive material models received wide acceptance and application in the field of geotechnical engineering. Despite its wide application, several research works and studies questioned its usefulness and accuracy for many rock mechanics problems. This is particularly more pounced when linear Mohr-Coulomb is used in an unsuitable modeling software code or when other fundamental failure processes like strain-softening, dilation, confinement dependency, anisotropy, etc. are ignored. According to Brown, the linear Mohr-Coulomb consisting of two)

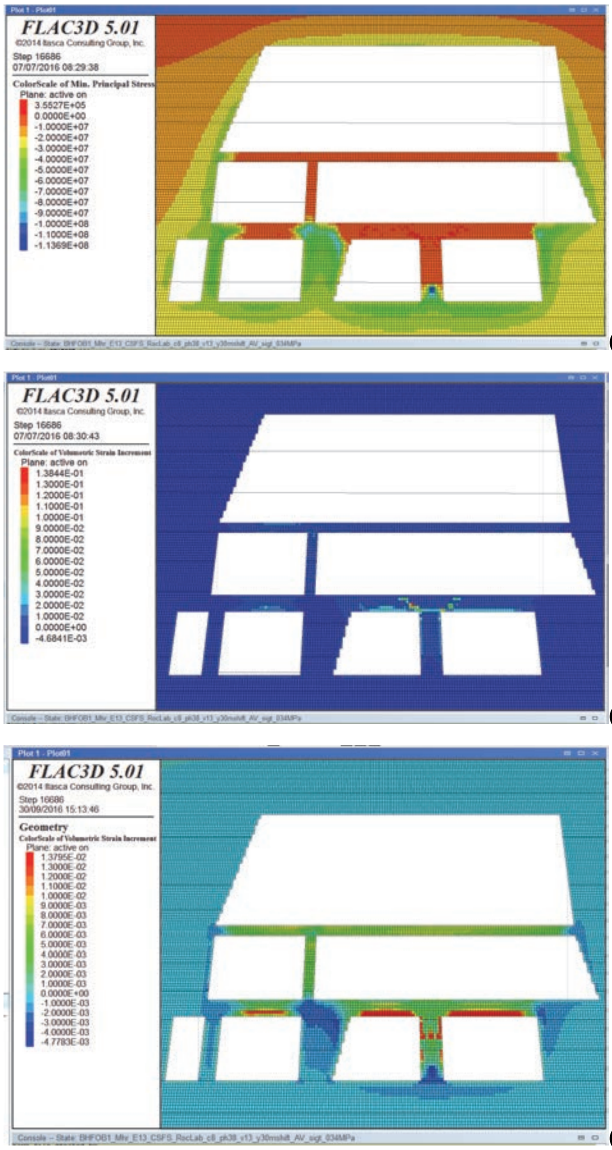
TABLE III. GROUND CONDITIONS AT BALARIA

Mine structure	Ground Condition
8W crown pillar 263mRL (marked 'I-III') 	It spalled very severely, accompanied by strong micro-seismic activities in its mid-span & got holed through within 48 hours. The phenomenon thereafter extended towards either ends when extraction in 8W stope (263-190mRL) was completed in 1993.
9W 263 Crown (marked 'IV')	The 9W crown, likewise, destabilized in 1994 progressively and gradually.
5W 190 Crown (marked 'V') 	The stope back spalled very severely and its lower periphery arched by 10m thickness (165-175mRL, marked VA) during extraction of 5W stope between 190-120mRL. Roof of the drive at 180mRL present in the pillar spalled very severely. It was characterized by formation of micro slabs in beginning and then followed by macro-slabbing [8,12].
7W 190 Crown (marked 'VI') 	Similar to 5W crown, its lower periphery also arched by 10m (165-175mRL) during the 7W stope extraction (190-120mRL).
Rib 8W-9W 263-190 (marked 'VII') 	The rib pillar severely spalled. The man-pass raise present in it experienced dog-erring along E-W direction (general mine strike) and had to be abandoned for regular services when the extraction of 8W between 190-120mRL reached final stage.
7W-8W rib 190-120 (marked 'VIII') 	Very severe spalling observed on 7W stope side. Pillar drives on 7W 155 (marked VIIIA) and 139mRL (marked VIIIB) spalled very severely 1-1.5m high along with borehole breakouts. The extraction in 7W western part had to be abandoned and about 25% ore locked in thicker rib had to be abandoned.

Using 33 sets of tri-axial data, GSI as 60, disturbance independent cohesive and frictional components does not provide a realistic representation of the progressive failure and disintegration of rock under stress. Some recent studies such as [2, 3 and 9] regarding application to predict damage in the rock material also highlighted the limitation of this model and factor as zero for rock mass. The RocLab formulation (Fig.4) determined following parameters for the rock mass (Table IV

TABLE. IV. MODEL INPUT PARAMETERS USED IN LIN-CSFS MODEL

Bulk Modulus	Shear modulus	Cohesion	Friction angle	Tensile strength	Res. Cohesion	Res. Fric angle
GPa	GPa	MPa	(°)	MPa	MPa	(°)
8.66	5.2	8	38	0.34	0	33



(a)

(b)

(c)

Fig. 5. Output of Li-CSFS model (a) major principal stress (b) minor principal stress (c) volumetric strain

The mine geometry (Fig.4) using these input was run on the Finite Difference code FLAC-3D. Various output of the model with different parameters like major and minor principal stresses, volumetric strain for main mine structures are shown in Fig. 5 with a general trend:

- The major principal stress in main mine pillars was in range of 1-5MPa
- the volumetric strain up to 2.5%.

In stress space, against instability of 8W & 9W 263 mRL crown pillars (marked I to IV, Fig. 3, breakout in 8W/9W rib pillar between 263-190 mRL (marked VII, Fig.3) the model is showing very low stress of 1-5MPa. Likewise, 5W and 7W crown pillars at 190mRL (marked V and VI, Fig. 3) and 7W/8W rib pillar between 190/120mRL (marked VIII, Fig.3) were experiencing very severe spalling at their peripheries, while major principal stress is again predicted by the model is very low. The volumetric strain in these pillars show substantial dilation of pillars by about 2.5% . On the whole, it appears that the properties used in the model are softer and predicting stability condition of various pillars worse than the actual.

B. Bi-linear Mohr-Coulomb Cohesion Softening & Friction Softening (Bi CSFS) Material Model

To overcome the limitations of the linear Mohr-Coulomb failure criterion, some practitioners apply an improved peak failure criterion which incorporates a bi-linear curve fitting procedure to obtain a better match to the Hoek-Brown failure criterion [1]. Sainsbury [10] demonstrated that a bi-linear fit can provide a more accurate strength estimate over the range of expected stresses. Vakili et al. [11] showed that a multi-linear Mohr-Coulomb peak failure criterion was sufficient to reproduce the observed excavation damage in vertical shaft.

Using Hoek Brown failure criterion, following input were used Table-V along with enhancing young's modulus to 24GPa based on our previous experience in the area (RMR/100* E_{Lab}) [7].

TABLE V. MODEL INPUT PARAMETERS USED IN BI-LINEAR-CSFS MODEL

Bulk Mod	Shear mod	Cohesion		Friction angle		Tensile strength	Res. Cohesion	Res. Fric angle
GPa	GPa	MPa		(°)		MPa	MPa	(°)
		Segment 1	Segment 2	Segment 1	Segment 2			
16	9.6	6	8	44	38	0.34	0	33

Using these parameters judiciously, following input were used in FLAC3D.The output of the model with various parameters- like major and minor principal stresses, etc. produced in Fig. 6. The model shows that the major principal stress in the crown pillar of 8W at 263mRL (marked III, Fig.3) has risen to a level comparable with peak rock mass strength (38-43MPa) and then fell down to 1-5MPa in the central part of the crown pillar while that of 9W 263mRL (marked IV, Fig.3) is loaded to 22-27MPa. The periphery of 9W, 8W, 7W and 5W stopes 190-120mRL (marked V & VI, Fig.3) experienced the minimum principal stress of order of 0-5MPa (-ve).

The 8W 263 mRL crown (marked III, Fig. 3 & 6) has dilated 0.3-0.7% strain, 8W/9W rib pillar 263-190mRL (marked VII, Fig.3 & 6) dilated 0.15% are in line with actual ground conditions.

C. Mohr Coulomb with Cohesion Softening and Friction Hardening (CSFH) Material Model

Hajiabdolmajid [12], adopted a "cohesion weakening and friction strengthening" (CWFS) criterion to predict the extent and depth of brittle failure of rocks. Similarly, Martin et al. [13] used a model with cohesion weakening and friction-hardening as a function of plastic strain implemented in FLAC code to numerically model the shape and extent of brittle failure for AECL's Mine-by test tunnel constructed in Lac du Bonnet granite.

In this case, the input derived for Mochia mine by Barton and Pandey [2] were used from Q-system proposed by (Table VI) along with cohesion degradation and friction strengthening material model (Fig. 7).

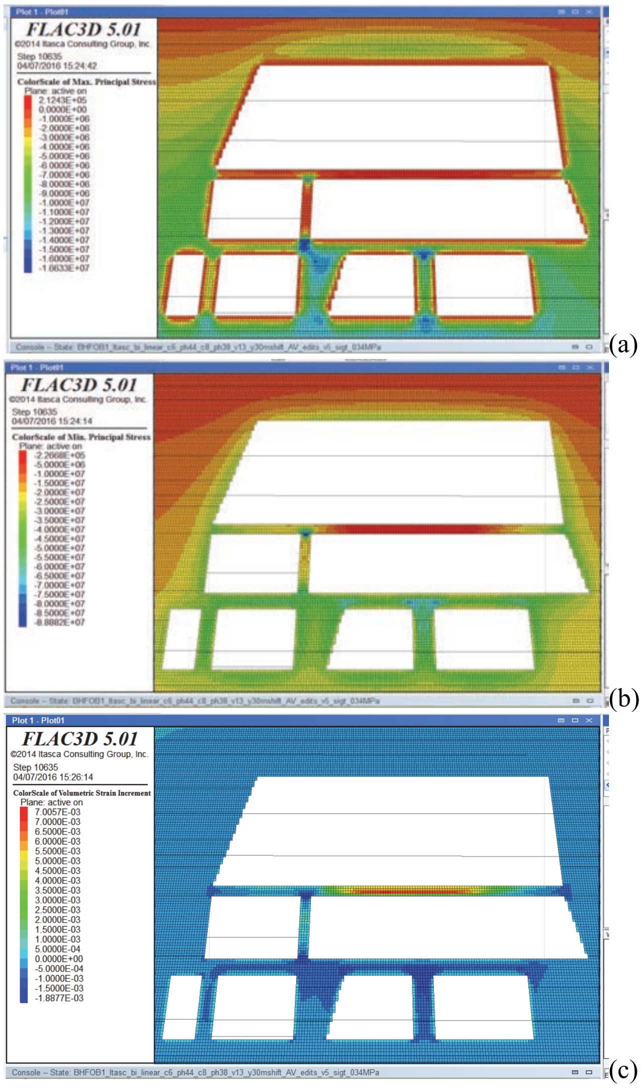


Fig. 6. Major and minor principal stress & volumetric strain distribution in Bi-linear CSFS model

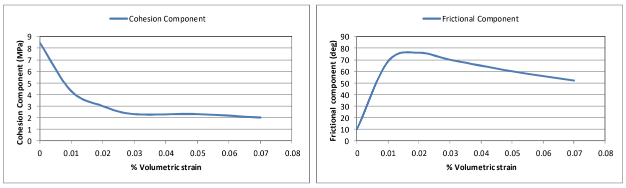


Fig. 7. Cohesion softening and friction hardening material model used by Barton & Pandey [2]

TABLE VI. MODEL INPUT USED IN BARTON PANDEY CSFH

Bulk Modulus	Shear modulus	Cohesion	Friction angle	Tensile strength	Res. Cohesion	Res Fric angle
GPa	GPa	MPa	(°)	MPa	MPa	(°)
27.2	16.3	17	76	4.3	4	54

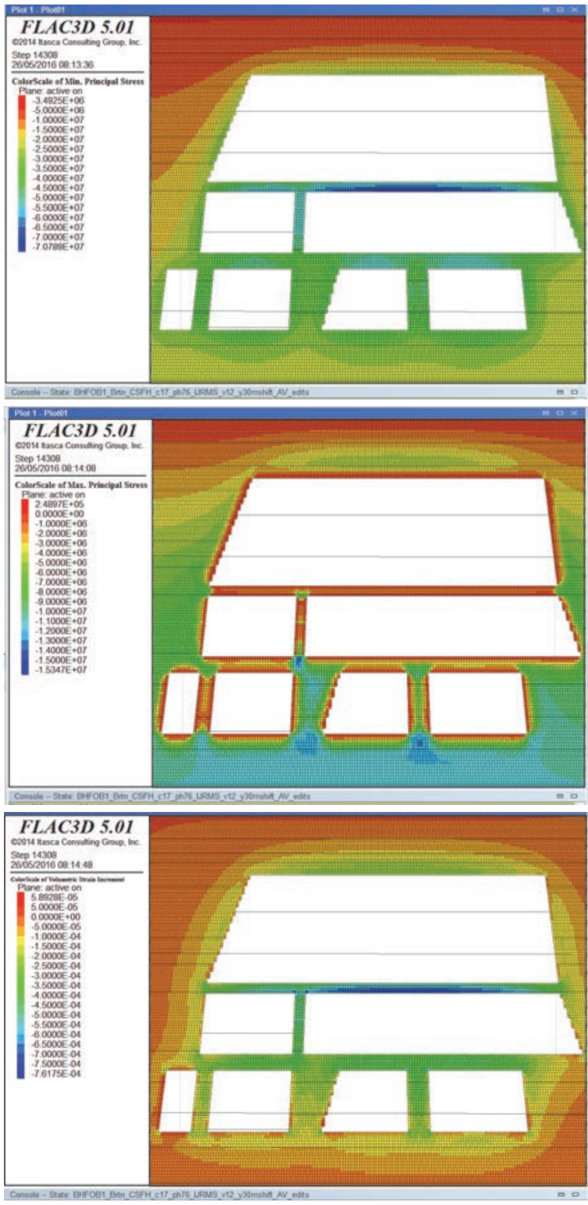
The CSFH WB model predicted rising trend of major stress in the mine pillars of 8W 263mRL (marked III, Fig.3) in range of 52-71MPa (Fig.8) with no falling off signs unlike a normal rock behaviour. Similar is the trend in 5W, 7W 190mRL crown (marked V & VI, Fig.3) with stress in 49-54MPa (Fig.8). Likewise, the 8W/9W (263-190) rib pillar (marked VII, Fig.3) is loaded to 54-55MPa (Fig.8) while the 7W/8W 190/120 rib (marked VIII, Fig.3) to 31-38MPa (Fig.8). The immediate periphery of 9W, 8W, 7W and 5W 190-120mRL (marked V & VI, Fig.3) stopes are experiencing minimum stresses almost uniformly or evenly within the stress arch and are in range of 0-4MPa (Fig.8) (not absolutely negative or tensile in nature).

Holistically, periphery of all the stopes, represents dominant major stress higher than the rock mass strength and low confining stress of the order of 0-3 MPa. Looking at the volumetric strain, all these pillars are subjected to various level of volumetric strain ranging from 0.012- 0.07% but in negative space i.e. compressive. Hence none of the pillars are dilating thus showing their intactness and are in line with predictions in the stress space too.

IV. ANALYSIS

Results of the numerical simulation of Balaria mine using three types of constitutive material model – Mohr-Coulomb with strain-softening post peak, bi-linear Mohr-Coulomb with strain-softening post peak, Mohr-Coulomb with cohesion softening/friction hardening (CSFH) post peak are produced in previous section. Now this outcome would be compared with the ground conditions of the mine pillars in detail:

- using major and minor principal stresses to assess the condition of the mine structure whether in pre-peak or post peak region of strength,
- the volumetric strain is used to understand the mechanism of their failure. In a mine
- pillar consisting of competent rock such as at Balaria, it is expected to undergo sizeable shearing (developing shear strain) and then dilate. FLAC determine positive volumetric strain as dilation while negative as still under compression analogous to stress regime.



(a) (b) (c)

Fig. 8. Major and minor principal stress and volumetric strain distribution in CSFH modelLinear Mohr-Coulomb Cohesion Softening & Friction Softening (Li- CSFS)Material Model

During this work, Mohr-Coulomb parameters were estimated using RocLab formulation. On comparing salient features- major and minor principal stress and volumetric strain with the benchmarks (Table V), the model predicted:

- The 8W crown pillar of 263mRL (marked III, Fig.3) is subjected to a very low magnitude of major principal stress -1-2MPa and almost 1MPa (Fig. 5) tensile stress indicating complete loss of strength or de-stressing. It is further supported by the prediction of built-up of high dilation of 0.8%. Against these parameters, the prediction of complete loss of strength is matching with brittle failure of the pillar. Whereas with similar predictions in 9W 263mRL crown (marked IV, Fig.3 & Fig.5), it does not match with progressive destabilization as it started towards the 8W side and gradually spread on to western side in longer span of time.

- Near similar stress regime (1-4MPa major stress level and almost equal minor stress, Fig.5) 5W & 7W 190mRL crown pillars (marked V & VI in Fig.3) indicative of complete loss of strength and high degree of the dilation up to 0.8%. It is not matching with their actual behavior where in the drive present in 5W crown pillar at 180mRL (marked VA, Fig.3) witnessed very severe roof arching. Similar is the case with 7W crown pillar at 190mRL (marked VI, Fig.3). Hence the model predictions do not match with actual ground conditions of 5W and 7W crown pillars at 190mRL.
- Near similar stress and strain regime in the 8W rib 263/190 pillar (marked as VII Fig.3) as above mentioned pillars against the rib pillar experiencing post peak symptoms - breakout witnessed in the man pass situated at its core and very severe spalling of its outer edges facing adjacent stopes. Hence the model predictions do not match with the actual ground conditions.
- The 7W/ 8W rib 190-120mRL (marked VIII, Fig.3) is subjected to 31-42MPa (Fig.5) stress in outer peripheries facing 5W on eastern and 7W stope on western peripheries. The pillar is very wide (about 40m at mid height as some of the ore was left un-blasted because of experiencing high stress induced failures in 7W stope pillar drives at 175 and 155mRL, marked as VIIIA & B, Fig.3). The outer edges of the pillar are dilating with volumetric strain in range of 0.016% and thus in post peak region while its core is still under compression. Thus the model predictions are matching with ground conditions.

A. Bi-Linear Mohr Coulomb Cohesion Softeing & Friction Softening (Bi- CSFS)Material Model

Analysis of results of Mohr-Coulomb strain softening criterion indicated a complete loss of strength and very high degree of dilation of the mine pillars indicates lower modulus of the mine. Likewise while prevalence of low confinement stress suggests to use confinement specific failure criterion i.e. bi-linear. Accordingly, the modulus of the intact rock 40GPa was reduced by about 60% (equal to RMR/100 of the mine) [7] and used in this modeling exercise.

The model predicted major principal stress in main mine crown and rib pillars rising to a level comparable with Rock mass strength of 38-43MPa [6] and then falling down to post peak region (i.e., strain softening). While the periphery of stopes were subjected to low confinement level 1-5MPa. The pillars or part of their experiencing dilation are in post peak while in contraction are still taking load.

The comparison of numerical modeling outcome with actual ground conditions:

- The crown pillars of 8W & 9W 263mRL (marked III & IV, Fig.3) are subjected to major principal stress of 1 to 5MPa and 22 to 27MPa (Fig.6) respectively. These pillars are also experiencing dilation 0.02 to 0.05% volumetric strain after getting sheared. Under these conditions, the 8W pillar is fully distressed and complete loss of strength and thus supposed to destabilize which is matching with the brittle and failure within 48 hours. However, in case of 9W 263mRL crown (marked as IV, Fig.3), the instability initiated towards its eastern side (i.e. towards 8W stope) and gradually spread west ward. The 9W crown pillar at 22-27MPa post peak region (Fig.6) indicates that the pillar has crossed peak strength and getting instable progressively.
- Likewise, the lower periphery of 5W and 7W crowns at 190mRL (marked V &VI in Fig.3) are in post peak at 23MPa and 24-35MPa (Fig.6) respectively. The outer periphery is under dilation with volumetric strain of 0.02-0.03%. The drive present in 5W crown pillar at 180mRL drive (marked VA in Fig.3), sublevel drives of 7W 171, 7W 155mRL (marked VIII A & B, Fig.3) witnessed severe roof arching with micro-slabs, degree increases to very severe spalling indicate brittle failure in predominant major compressive principal stress and with low confinement. It is congruous with brittle failure analysed by Golchinfar [14]. Thus the numerical modeling results are matching with actual ground conditions of these pillars.
- The 8W rib 263/190 pillar (marked VII, Fig.3) is subjected to 20MPa (Fig.6) and in dilation mode with volumetric strain of 0.05%. Thus the rib pillar is in post peak corroborating with breakout witnessed in the man pass situated at its core and very severe spalling of its outer periphery facing adjacent stopes along with extensile fractures and its abandonment later on.
- The 7W/ 8W rib 190-120mRL (marked VIII Fig.3) is subjected to 30-35 MPa (Fig.6) stress in outer peripheries facing 5W on eastern and 7W stope on western peripheries. The pillar is very wide (about 40m at mid height as some of the ore was left un-blasted because of experiencing high stress induced failures in 7W stope pillar drives at 175 and 155mRL, marked VIIIA, VIIIB, Fig.3). The outer peripheries of the pillar are dilating with volumetric strain in range of 0.03% and thus in post peak region while its core is still under compression. Hence the model prediction matches with the actual ground response.

Thus, Balaria bi-linear Mohr Coulomb strain softening model predictions are closely matching with the actual field conditions.

Comparison of results with Mohr-Coulomb and Mohr-Coulomb Bi-linear models:

- The bi-linear strain softening model predicted major stresses comparable with rock mass strength of Balaria rock mass 38-43MPa which happens to represent the actual behavior of the various mine pillars. Whereas the Mohr-Coulomb strain softening model predicted major principal stress to extremely low magnitude of 1-5MPa and complete strength loss which does not match with mine response.

- Likewise, on dilation front the former predicted 0.02-0.05% for progressively destabilizing pillars to 0.7% for fully destabilized pillar of 8W crown 263mRL contrary to 0.15 to 3.8% for progressively destabilizing pillars to 0.88% for fully destabilized crown pillar of 8W 263mRL. Hence, for progressively destabilizing pillars, the dilation predicted by the bi-linear model is about 1/10th of the Mohr-Coulomb value.
- The bi-linear strain softening model predicted z-displacement in range of 0.2 to 2.8cm against 0.29 to 19cm in the Mohr-Coulomb strain softening model.

B. Mohr Coulomb with cohesion softening friction hardening (CSFH) material model

The west Balaria **CSFH** model predicted the main crown and rib pillars to experience major principal stresses rising more than the rock mass strength Rock mass strength of 38-43MPa [6] and not falling down (i.e., strain hardening). The sigma_3 is low and is in range of 1-3MPa. Holistically, immediate stope periphery rocks are subjected to major compressive stresses higher than rock mass strength and a very low confining stress of the order of 1-3MPa.

On comparing the model predictions with actual ground conditions:

- 8W and 9W crowns at 263mRL (marked III & IV, Fig.3) which were subjected to 52-71MPa and 41-57MPa respectively (Fig.8) against Rock mass strength of 38-43MPa [6]. Additionally, these pillars are experiencing contraction in range of 0.03-0.05% of volumetric strain. Thus, at this stage, these pillars have not destabilized and instead attracted compression. Thus, the model outcome showed their strain hardening behaviour while these failed in brittle mode and failed to capture the basic mechanism of pillar destabilization.
- Similar is the case of crowns of 5W and 7W stopes at 190mRL (marked as V & VI, Fig.3) are subjected to major principal stress in range of 49-52MPa (Fig.8) and are in contraction mode with volumetric strain in range of 0.012 to 0.046 %. Thus the model's prediction of these pillars subjecting to stress higher than rock mass strength shows that they are in strain hardening mode against - the drive present in 5W crown pillar at 180mRL drive (marked VA, Fig.3), witnessed severe roof arching with micro-slabs, gradually the degree increases to very severe spalling, are indication of brittle failure in predominant major compressive principal stress and with low confinement. Hence the model outcome is not matching with actual ground conditions in these pillars nor could it capture the actual destabilization mechanism.
- The model predicted the rib pillars of 8W/9W 263 to 190mRL (marked as VII, Fig.3) and 7W/8W rib 190-120mRL (marked as VIII, Fig.3) are subjected to 54-55MPa and 31-38MPa major principal stress (Fig.8). Their outer peripheries facing adjoining stopes are experiencing 0.042% and 0.08% volumetric strain and in contraction against their severe spalling at outer edges and breakout of the raise. Likewise, the sublevel drives of 7W 171, 7W 155mRL present in the rib pillar (marked VIIIA & B, Fig.3) witnessed severe roof arching with micro-slabs, degree of spalling increases to very severe indicated brittle damage in predominant major compressive principal stress and with low confinement.

Hard rock like dolomite is known to fail by brittle failure as characterized by spalling, slabbing, development of extension fractures, etc. The strain hardening behavior predicted by the model is not representative of rock behavior. Diederichs [15] studied breakout of Mine-by tunnel using Hoek-Brown general failure criterion on PHASES^{2D} and demonstrated that rock material reaches to peak (yield) stress and the stress drops instantaneously to the post-peak ultimate strength envelope which is much lower than the peak strength. When post-peak strength is higher than peak (yield) strength, the material exhibits a **strain hardening** behavior. This type of hardening behaviour may be seen in materials such as steel but is certainly not a behavior for rocks. A ductile behavior in which the post-peak strength is equal to the peak strength is the closest behaviour that can be expected from a rock at very high confinement. While in instant case, with very low the confinement level of 1-3MPa of these crown and rib pillars elastic brittle behaviour is expected.

The outcome of the CSFH West Balaria model, thus, is not representing behavior of the rock at WB.

Comparison of bi-linear CSFS and CSFH models:

- the CSFH model predicted 41 to 71MPa as major principal stress of almost all mine pillars much higher than the rock mass strength of 38-43MPa and are about 1.8 to 3 times that of the bi-linear CSFS model predictions. The former is much higher than rock mass strength observed in the mine.
- On volumetric strain front, the CSFH predicted compression of about 0.03% which is about 1 to 2 times the dilation predicted by the bi-linear CSFS model.

V. CONCLUSIONS

Rock response of Balaria mine situated in competent dolomite horizons and subjected to intermediate to high stress environment was simulated with using three types of constitutive material model – Mohr-Coulomb with strain-softening post peak, bi-linear Mohr-Coulomb with strain-softening post peak, and Mohr-Coulomb with cohesion softening/friction hardening (CSFH) post peak. Outcome of all approaches have been compared with actual ground conditions. The comparison revealed that the numerical models using the bi-linear Mohr-Coulomb with strain-softening post peak provide most realistic match to the observations in the mine including failure of the crown pillars.

- Using Linear Mohr Coulomb constitutive material model with Linear- CSFS strain softening criterion in combination with rock mass input parameters like cohesion, friction angle, young's modulus and tensile strength derived from RocLab software based on Hoek formulation, predicted very low value of major principal stress indicating complete loss of strength of various mine pillars. Also the model predicted high degree of volumetric strains. The model's prediction did not match with actual ground conditions.

- Using Bi-linear Mohr Coulomb constitutive material model (Bi-CSFS) with strain softening post peak material properties in combination with modulus of rock mass enhanced to RMR/100 of its intact rock value. Likewise, The other input parameters cohesion and friction angle for rock mass derived from RocLab were slightly modified: the cohesion and friction angle for rock mass in low and high confinement regions were estimated from Hoek-Brown failure criterion fitted on tri-axial tests [1]. The predictions of the model very much matched with the actual ground conditions:

  - The numerical modeling (Bi-CSFS) predicted major stress in the stope pillars rising to a value comparable with rock mass strength of 38-43MPa and then falling to post peak to a value of 20-35MPa i.e. strain softening of the mine pillars.

  - The complete stress regime around stopes i.e. in crown and rib pillars consists of predominantly uniaxial compressive stress i.e. magnitude close to Rock mass strength (of 38-43MPa) and a very low confinement having magnitude of 1-3MPa. Under such stress regime, the nature of destabilization observed in crown pillars and roof spalling in drives located in the crown pillars and stope fronts in Balaria are in line with brittle failure suggested by Golchinfar [14].

  - The (Bi-CSFS) modeling has captured appropriate failure mechanism in hard rock and matched with the actual ground conditions at Balaria- the pillars undergoing shearing and then dilation with the major principal stress is in post peak region. These pillars witnessed strain softening. While the core of the progressively failing pillars like 7W/8W rib pillar (190-120mRL) is under contraction (rather than dilation) and the stress is in pre-peak strength region.

- The Mohr Coulomb model with cohesion weakening and friction hardening (CSFH) using input derived by Q and Q_{max} predicted stress rising much beyond a value corresponding to rock mass strength of 38-43MPa and then not falling down i.e. strain hardening of the mine pillars. The strain hardening behaviour of mine pillars produced by the CSFH model is unrealistic for rock substance [16]. Outcome of the CSFH modeling of the mine also did not conform with actual ground conditions.

Hence on every front, the bi-linear strain softening model captured appropriate mine response than the Mohr-Coulomb strain softening and cohesion softening/friction hardening models. It is in line with finding of Hoek and Brown [17] demonstrating that unlike the traditional Mohr-Coulomb criterion, the peak failure envelope at different confinement levels follows a non-linear relationship in major and minor principal stress space.

It is recommended that for realistic replication of rock mass response of a hard rock mine situated in moderately high stress mine:

- using tri-axial test results and GSI, determine the rock mass parameters using Hoek Formulation through RocLab software,
- Modify the modulus of the mine as RMR/100 times the Laboratory value rather than using RocLab determined value,
- Using Hoek-Brown failure criterion on tri-axial tests, determine value of cohesion and friction angle for rock mass in two regions- low and high confinement ranges by curve fitting,
- Use bi-linear Mohr Coulomb strain softening criterion

REFERENCES

[1] E. Hoek and E.T. Brown ET, The Hoek–Brown failure criterion—a 1988 update, In: Curran J (ed) Proceedings of the 15th Canadian Rock Mechanics Symposium. University of Toronto, Toronto, pp 31–38, 1988

[2] N. Barton, S.K. Pandey, S.K, "Numerical modeling of two stoping methods in two Indian mines using degradation of c and mobilization of phi based on Q-parameters," International Journal of Rock Mechanics and Mining Sciences, Volume 48, Issue 7, pp 1095-1112, 2011

[3] N. Barton, Shear strength cirteria for rock, rock joints, rockfill and rock masses: Problems and some solutions," Journal of Rock Mechanics and Getoechnical Engineering, 5(4), pp.249-261. 2013.

[4] F. Rummels , "Rock Mechanics with Emphasis on Stress", Balkema Publishers, pp 37-42, 2005.

[5] Z.T. Bieniawski, "Engineering rock mass classification," John Willey & Sons, New York, 251 p, 1989.

[6] P.K. Rajmeny, U.K.Singh and B.K.P. Sinha, "A new model to estimate rock mass strength accounting for the scale effect", in International Journal of Rock Mechanics and Mining Science, Vol. 41, No. 6, Aug. 2004, pp 1013-1021, 2004.

[7] P.K. Rajmeny and A. Joshi, "Numerical Simulation of a Major Depillaring Operation and Predicting its Ground Response using DFM Model at Mochia mine", ISRM International Symposium 2010 and 6th Asian Rock Mechanics Symposium, New Delhi, India, pp 1-8, 2010.

[8] P.K. Rajmeny, U.K.Singh and S.S. Rathore, "Predicting failure of boreholes and drives adjacent to open stopes in Indian mines with high stress", in International Journal of Rock Mechanics and Mining Science, June 2002 Vol. 39, No. 2, pp 151-164. 2002

[9] V. Hajiabdolmajid, P.K. Kaiser and C.D. Martin, "Modelling brittle failure of rock," Int. J. Rock Mech. Min. Sci. Vol. 39. pp. 731-741, 2002

[10] B.A. Sainsbury, 2012. "A model for cave propagation and subsidence assessment in jointed rock masses," Doctoral dissertation, The Univeristy of New South Wales, 2012.

[11] A. Vakili, M. Sandy and J. Alhrecht, "Interpretation of non-linear numerical models ingetomechaics – a cae study in the application of numerical mdeolling for raise broed shaft design in hihgly stressed and folatiated rock mass," In Mass Min 2012: Proceedings of the 6th International Conference and Exhibition on Mass Mining, 2012.

[12] V. Hajiabdolmajid, "Mobilization of strength in brittle failure of rock," Ph.D. thesis, Dept. Of Mining Engineering, Queen's University, Kingston, Ont. 268 pp, 2001

[13] C.D. Martin and W.G. Maybee, "The strength of hard-rock pillars" International Journal of Rock Mechanics and Mining Sciences, 37(8), pp1239-1246, 2000.

[14] N. Golchinfar, - "Numerical modeling of brittle rock failure around underground openings under static and dynamic stress loadings," Masters thesis submitted to University of Laurentian, Sudbury, Ontario, 2013.

[15] M.S. Diederichs MS, "Mechanistic interpretation and practical application of damage and spalling prediction criteria for deep tunnelling," Can Geotech J 44(9):1082–1116, 2007.

[16] M.S. Diederichs, J.L. Carvalho and T.G. Carter, "A Modified Approach for the Prediction of Strength and Post Yield Behaviour for high GSI rockmasses in Strong Brittle Ground," In Proc. of 1st Canada-US Rock Mechanics Symposium, Vancouver, Canada, pp 249-257, May 2007.

[17] E. Hoek and E.T. Brown, "Underground Excavations in Rock," Institution of Mining and Metallurgy, London. 1980