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Analysis of strata behaviour during final extractions in underground coal mining under difficult caving characteristic of roof condition

During bord and pillar depillaring with caving in underground coal mining, strata pressure in the goaf roof keeps on mounting with increasing span of goaf. The strata pressure may propagate into the workings in the form of dynamic loading effects carrying potency of premature collapses. The loading effect can be revealed at goaf edges and influenced zone of workings by strata control instrumentation monitoring for convergence, load, local induced stress etc. Such strata pressure reaches to a peak and is termed as ultimate induced stress, before main fall occurs in the goaf. When overlying rock formations are strong enough, it may lead to caving constraints and propagation of strata movement into workings may occur in a larger way, requiring proper control measures. Principal control measures include, adequate support provisioning in the vulnerable places including at goaf edges, proper methodology of extraction, artificial induced failure of goaf roof etc., which are possible, only when the peak strata movement is predicted in advance of roof fall. The objective of the study is to analyse the strata behaviour during peak loading hours and prediction of ultimate strata movement during extraction under strong roof conditions, using the already developed model of the author, 'Roof Fall Warning Index'.

Keywords: *Underground coal mining, strata pressure, dynamic loading effect and strata movement.*

1. Introduction

Bord and pillar depillaring in underground coal mining is associated with hazards relating to strata movement in active mining zone. Strata pressure in the goaf roof keeps on mounting with continuous increase in size of goaf. Extraction is safe when the strata pressure/mining induced stress are limited to goaf area only, which seldom happens. The strata pressure may propagate into the workings in the form of dynamic loading effects having potency of release of stress in the vulnerable working geometries, causing subsequent premature collapses [1]. As per accessibility, the dynamic loading effect is experienced usually maximum near goaf edges and gradually reduces inside the working, subsequently requiring higher support resistance at goaf edges and proportionately less support resistance in the loading zone inside the workings [2]. When overlying rock formations are strong enough, it may lead to caving constraints and propagation of dynamic loading effect into workings may occur in a larger zone and intensity. This may lead to a situation of high hazard on strata movement front, requiring proper control measures. Principal control measures include, adequate support provisioning in the vulnerable places including at goaf edges, proper methodology of extraction, artificial induced failure of goaf roof etc., which are possible, only when the peak strata movement is predicted/apprehended in advance of roof fall.

2. Background

The study is pertinent to analysis of the vulnerable parameters responsible for loading effect and subsequent prediction/apprehension of the peak strata movement during extraction under strong roof conditions, using the already developed model of the author, 'Roof Fall Warning Index (RFWI)'. The model is a mathematical expression of interaction between ultimate induced stress before main fall and different parameters including geo-mining information, physico-mechanical properties of formations and the strata control instrumentation results during depillaring.

Exploring the study further, a detailed literature review is done. As an outcome, it is observed that very few models are there relating to apprehension of dynamic loads and related stresses during bord and pillar extractions. Models [3-11] are based upon computation of induced stress and are related to this kind of study, but with limitations of physical monitoring of stress, which may vary during actual operations. Models Poulsen [7] and Singh, A. K. et al. [10] are directly synonymous with the research study. Prime consideration behind Model Poulsen [7] is the extraction ratio, which may be acceptable for research work analysing load characteristic

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in the workings with easy to moderate caving characteristic. For roof mass with higher tensile formations and caving constraints, the model Singh, A. K. et al. [10] works well because of 'Caving Index' is one of the input parameters for determination of optimum induced stress during extractions. But, the model has limitations for extraction at higher depth of cover.

From the literature review it is also observed that, none of the models involve strata control instrumentation-information directly for apprehension of strata movement during dynamic loading situations of bord and pillar extraction. This requires continuing the research further, to develop a model for apprehension of strata movement in different geo-mining situations with inclusion of strata control monitoring outcomes as one of the input parameters. Subsequently, a model, "Roof Fall Warning Index (RFWI)" is developed by the principal author for the purpose, which is detailed further.

3. Study area

The study area is concerned to two different bord and pillar extraction panels with caving, 38LE and 22X panels of Churcha underground coal mine of South Eastern Coalfields Limited (SECL), Coal India Limited. Characteristic of roof formations in the whole mine, including the study panels is of difficult on caving and with high value of cavability index. Depillaring in the mine is associated with constrains/ difficulties, such as higher depth of cover and presence of hard and massive roof formations almost throughout in the cover with average RMR of about 70. Basic information of the study panels are gathered in Table 1.

Information on strata movement during two of the main/ major falls from each study panel is taken into considerations. Strata control instrumentation monitoring is being done in both the depillaring panels with stress cells, convergence recorders and load cells, installed at strategic locations. Working plans with main fall details for both the panels, 22 X cut and 38 LE are shown as Figs.1 and 2 respectively.

Table 2 shows the fall details taken into considerations for the study and can also be referred to from the working plans given in Figs.1 and 2.

4. Assessment of induced stresses

Influence of strata pressure and dynamic loads due to increasing size of goaf become optimum before main fall while the strata pressure/induced stress reaches to a peak value, termed as ultimate induced stress. Control measures are possible, only when the peak strata pressure, the ultimate induced stress (UIS) is assessed and the strata movement is predicted/apprehended in advance of roof fall.

In this research study, resultant mining induced stress near goaf edges, which is generally predominant with vertical component, the gravity loading has been taken into assessment in following ways.

TABLE 1: DATA TABLE (BASIC INFORMATION OF THE STUDY PANELS)

Panel / Parameters		22Xcut	38LE
Geomining information	H (m)	303	236
	h (m)	3.1	2.9
	Pillar (m)	45 × 45	50 × 35
	Gallery (m)	4.2	4.5
	A (m^2) Fall 1,2…	7179, 7266	23088, 7949
	e	0.7	0.7
	Mechanisation	LHD	SDL/LHD
Physico-mechanical parameters	σc (MPa)	44.63	44.63
	σt (MPa)	4.46	4.46
	σtc (MPa)	2	2
	ρ (kg/m^3)	2240	2240
	v	0.25	0.25
	vc	0.2	0.2
	Ec (Gpa)	2	2
	E (Gpa)	8.26	8.26
	Cr (MPa)	0.989	0.989
	Cc (MPa)	0.8	0.8
	Φr (degree)	35	35
	Φc (degree)	38	38
	I	9168	9168
Strata control instrumentation (maximum cumulative value)	Str (kg/cm^2) Fall 1,2…	16.639	18.08
	Cv (mm) Fall 1,2…	129, 106	124, 187
	Cl (Te) Fall 1,2…	-	12.61

H = depth of cover, h = thickness of working, A = area of fall, e = extraction ratio, σc = uniaxial compressive strength of roof rock, σt = tensile strength of roof rock, σtc = tensile strength of coal, ρ = density, v = Poisson's ratio (rock), vc = Poisson's ratio (coal), Ec = elastic modulus of coal, E = elastic modulus of roof rock, Cr = cohesion of roof rock, Cc = cohesion of coal, Φr = angle of friction of roof rock, Φc = angle of friction of coal, I = cavability index, Str = cumulative stress, Cv = cumulative roof convergence

TABLE 2: MAIN FALL DETAILS

Panel	Main fall	Date	Area of fall (m^2)
22 X cut	Fall-1	29.05.2015	7179
22 X cut	Fall-2	22.07.2015	7266
38 LE	Fall-1	28.09.2013	23088
38 LE	Fall-2	02.04.2014	7949

1. Mathematical assessment, using existing models, Poulsen [7] and Singh, A. K. et al. [10].
2. Numerical simulations/modelling.
3. Physical monitoring with stress cells installed to rib side in the workings.

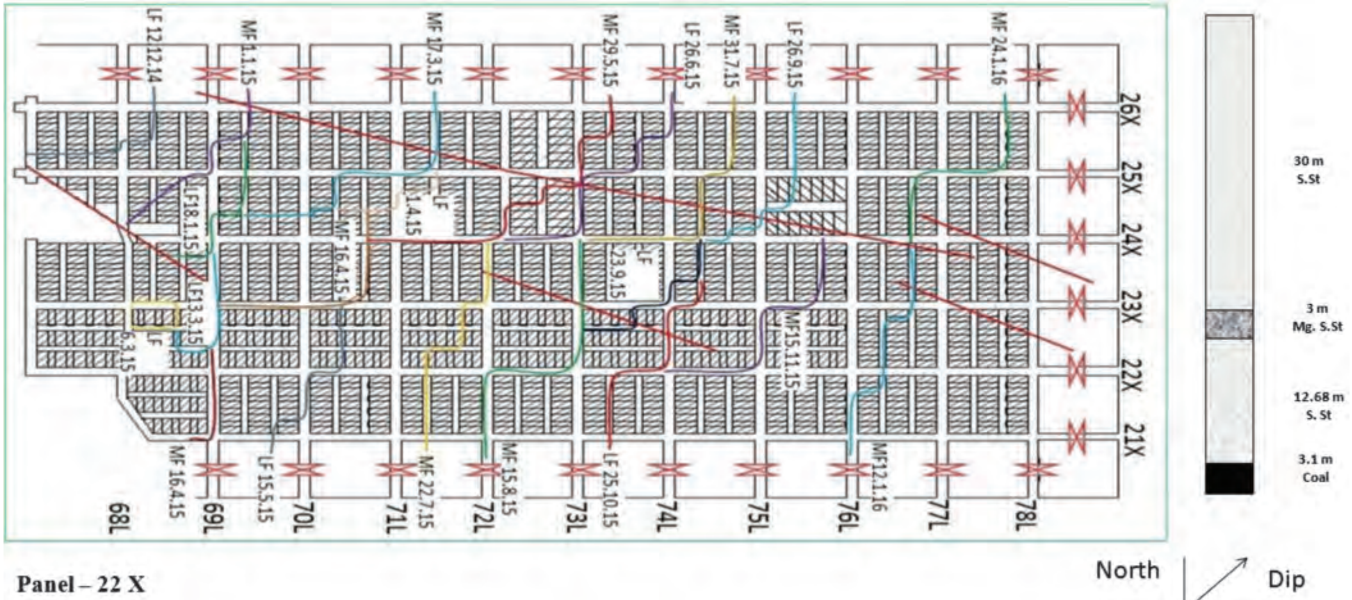
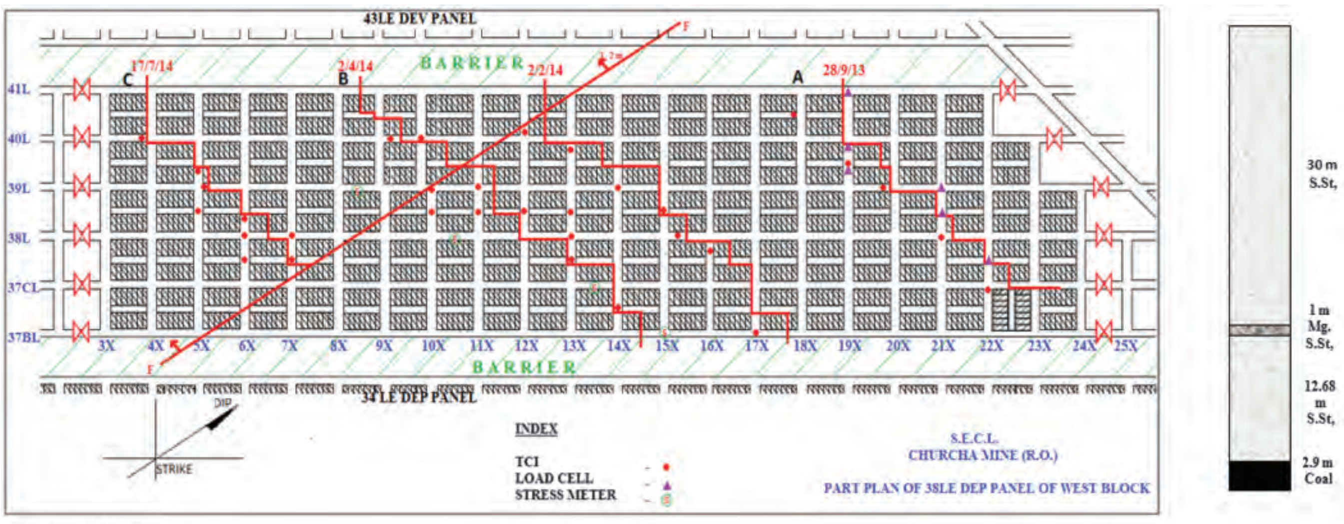


Fig.1 Working plan of 22X panel, Churcha UG with fall details cross section of roof formations including coal seam



Panel – 38LE

Fig.2 Working plan of 38LE panel, Churcha UG with fall details cross section of roof formations including coal seam

4.1 MATHEMATICAL MODELS

4.1.1 As per model, Singh, A. K. et al. [10]

As per this model, ultimate induced stress (Su) is assessed as an expression of cavability index and depth of cover and is explained as Eq. (1).

$$Su = 0.0033I + 0.059H - 9.85 \text{ MPa} \quad ... \quad (1)$$

where,

I = cavability index

H = depth of cover in m

$I = (\sigma^{ln} t^{0.5})/5$

σ = uniaxial compressive strength, kg/cm^2

l = average length of core in cm

t = Thickness of strong bed in m

n = 1.2 (in case of uniform massive rock with weighted RQD of 80% or above)

n = 1 (in other case)

Range of influence (R), ahead of depillaring face may be estimated by the expression as Eq. (2):

$$R = 0.106I + 0.1H - 12.45\text{m} \quad ... \quad (2)$$

Singh et al. model (for depth of cover less than 200m), as Eq. (3), follows:

$$Su = 0.025H + 8.646*10^{-4}HI^{0.5} \text{ MPa} \quad ... \quad (3)$$

where,

I = cavability index

H = depth of cover in m

Range of influence, as Eq. (4):

$R = 0.16H + 9.63*10^{-3}Im$ ... (4)

m = elastic modulus of cover rock

4.1.2 As per model, Poulsen [7]

As per the model, ultimate mining induced stress is the peak pillar stress, assessed principally based upon extraction ratio during final extractions given as Eq. (5).

Pillar stress = $\rho gH/(1- e)$ ... (5)

where,

H = depth of cover (m)

ρ = sp. gravity

e = extraction ratio, between, zero for no extraction and one for 100% extraction

Peak/ultimate induced stress is assessed for the main falls, for each study panel, using both the models and are tabulated in Table 3.

TABLE 3: ULTIMATE INDUCED STRESS AS PER MATHEMATICAL MODELS

Panel	Ultimate induced stress (MPa)	
	Model: Singh A. K. et al [10]	Model: Poulsen [7]
22 X cut	38.28	21.76
38 LE	34.33	16.95

4.2 AS PER NUMERICAL SIMULATIONS/MODELLING

Also the peak/ultimate induced stress is simulated with numerical models using FLAC-3D software involving numbers of input parameters including geo-mining inputs and physico-mechanical properties of formations. For the simulation, coal is considered to be a strain-softening material. Failure criterion for immediate roof is considered to be of Mohr Coulomb principle, while main roof and floor are considered to be elastic in nature. Goaf is considered as linearly elastic as suggested by Jaiswal and Shrivastva (2015), with the following mathematical relationship as Eq. (6).

$E = 1970\exp^{-7.4I/10000}$ ... (6)

where

E = Young's modulus

I = cavability index

Boundary conditions

As far as boundary condition is concerned, the bottom of the model is restricted in downward direction whereas sides are restricted in normal direction.

Stress initialization

Vertical stress has been initialized in the model as formula given as Eq. (7):

$\sigma_v = 0.025H$ ... (7)

Horizontal stresses have been estimated by using Sheorey formula (Sheorey et al.12) as Eq. (8):

$\sigma_h = \sigma_v[v/(1-v)] + [\beta EG/(1-v)]*[H+1000]$ ... (8)

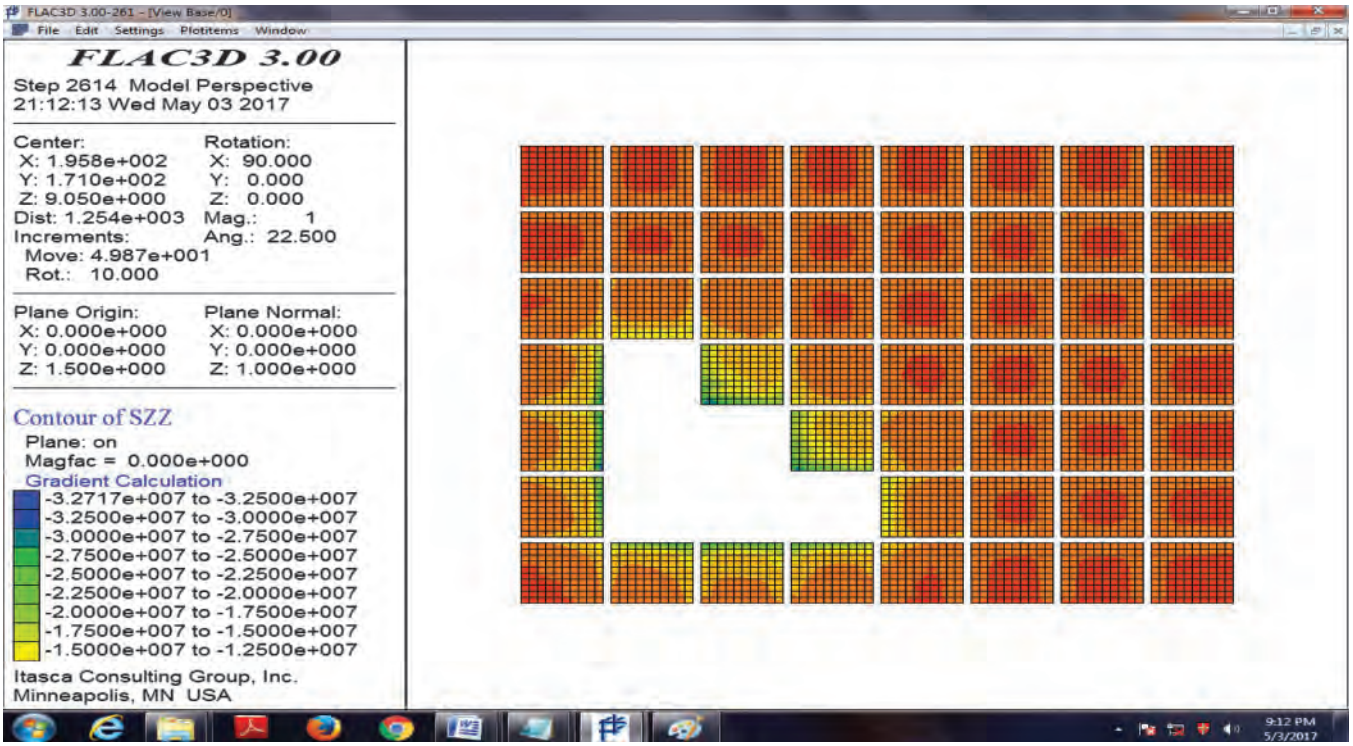


Fig.3 Churcha-22x-fall-1 (ultimate induced stress)

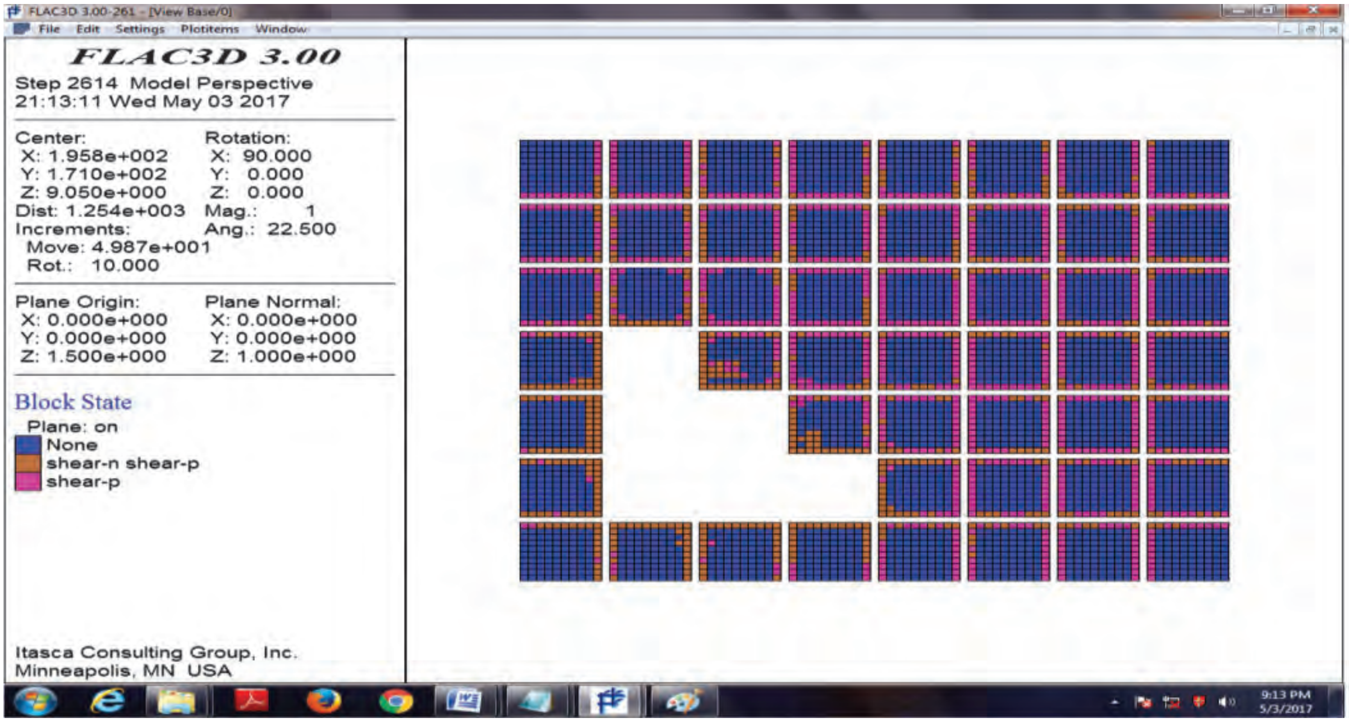


Fig.4 Churcha-22X-fall-1 (yield profile)

where, σ_v is vertical stress, σ_h is the horizontal stress and H is the depth of cover.

Feeding the values of parameters in the above equation, i.e., v = 0.25, $\beta = 3 \times 10^{-5}$/ºC, E = 2000 MPa, G = 0.03ºC/m, the generalized horizontal stress formula can be represented as Eq. (9):

$$\sigma_h = 2.4 + 0.01H \text{ MPa} \quad \ldots \quad (9)$$

Modelling is done for the main falls, two from each depillaring panels of the study area using the input parameters given on Table 1 and excluding the strata control parameters and the outcomes are as follows.

4.2.1 Panel no. 22 X cut

Fig.3 and Fig.5 show the numerical simulation during extraction before first and second main falls with the peak induced stress of 32.72 MPa and 37.99 MPa respectively and the Fig.4 and Fig.6 represent the subsequent failure/yield profiles in the working geometry, discreteising the shear failure zone of about 2 m and 3 m thickness of either side of the pillars from the corners along the diagonal line of extraction, facing the goaf line, just before the main falls.

4.2.2 Panel no. 38LE

Fig.7 and Fig.9 exhibit the numerical simulation during extraction before first and second main falls with the peak induced stress of 30.79 MPa and 24.82 MPa respectively and the Fig.8 and Fig.10 represent the subsequent failure/yield profiles in the working geometry, discreteising the shear failure zone of about 1 to 2 m thickness of either side of the pillars from the corners along the diagonal line of extraction, facing the goaf line, just before the main falls.

4.3 As per monitoring by stress cells

Local induced stress is monitored physically by installing stress cells near goaf edges during the main falls, in the study panels and the outcome are already given in Table 1.

Table 4 shows a comparision of values of induced stress assessed as per different models and also physical monitoring by installing stress cells.

Referring the information and values given in Table 4, following observations are ascertained.

The values of monitored stress are too less with respect to the values obtained from mathematical models and numerical modelling. It is ascertained that stress cells are strategically installed in the underground workings and their monitoring values become location specific and very less in comparision to the holistic stress value of the entire goaf. Rather, such monitored stress value is indicative in nature for increase or decrease in strata pressure and subsequent effect of dynamic loading. So, the values of strata control instrumentation, including monitored stress are found suitable to be considered as input parameters for analysis of strata behaviour for subsequent prediction/apprehension of peak strata movement.

The values of ultimate induced stress as per Singh, A. K. et al. [10] in both the panels are 38.28 MPa and 34.33 MPa respectively. These values are very nearer to the values as per numerical models (average values), i.e., 35.35 MPa and 27.80 MPa respectively. Whereas these values as per Poulsen model [7], i.e., 21.76 MPa and 16.95 MPa, which are farther from that of values of numerical modelling. This implies that the assessment as per Singh, A. K. et al. [10] models holds good for both the study panels having strong roof conditions where cavability index is too high.

5. Prediction/apprehension of strata movement

Induced stress during extraction reaches to an optimum height and becomes ultimate before the roof breaks for main fall. The ultimate induced stress is also directly proportional to other geo-technical parameters as follows.

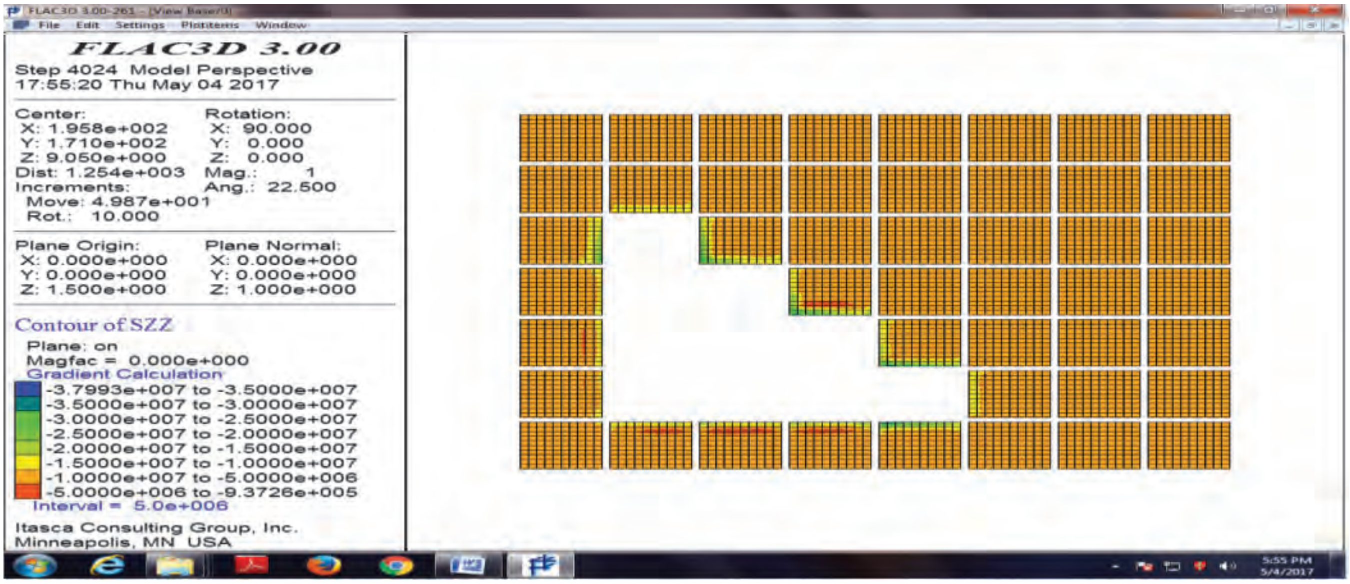


Fig. 5 Churcha-22x-fall-2 (ultimate induced stress)

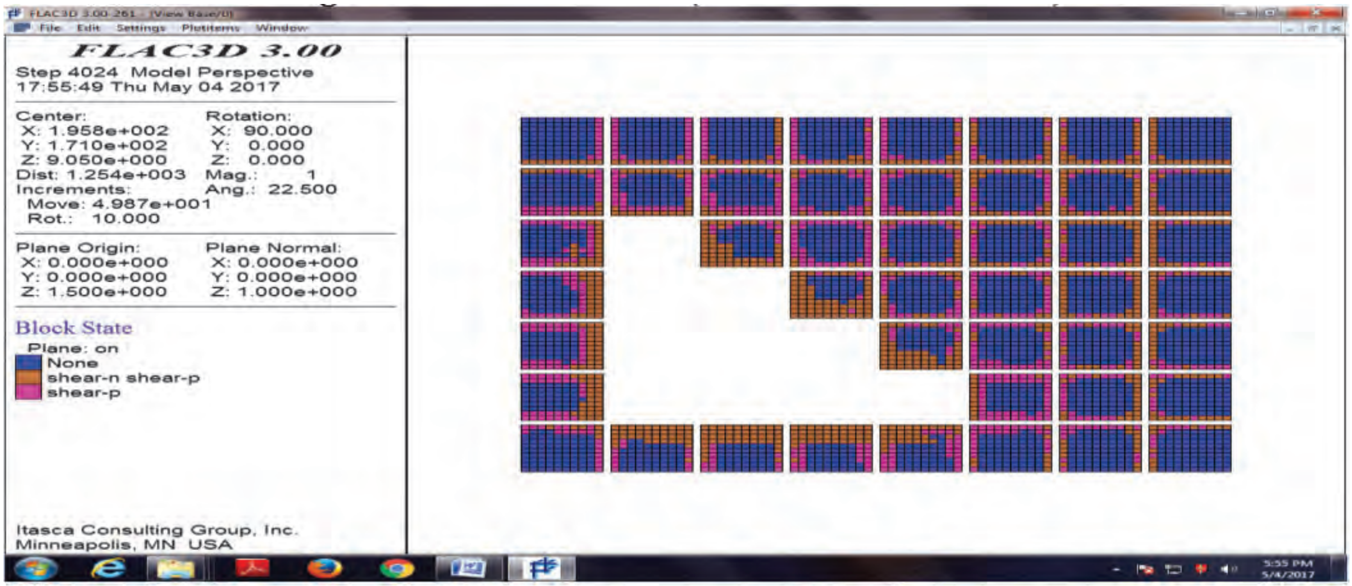


Fig.6 Churcha-22X-fall-2 (yield profile)

TABLE 4: COMPARISION OF VALUES OF ULTIMATE INDUCED STRESS

Panel	Main fall	Cavability index (I)	(Su) Ultimate induced stress (MPa)				Monitored stress (kg/cm^2)
			Singh A. K. et al. [10]	Poulsen [7]	Nu. modelling	Nu. modelling (average)	
22 X	Fall-1	9168	38.28	21.76	32.72	35.35	16.639
22 X	Fall-2	9168	38.28	21.76	37.99	35.35	-
38 LE	Fall-1	9168	34.33	16.95	30.79	27.80	-
38 LE	Fall-2	9168	34.33	16.95	24.82	27.80	18.08

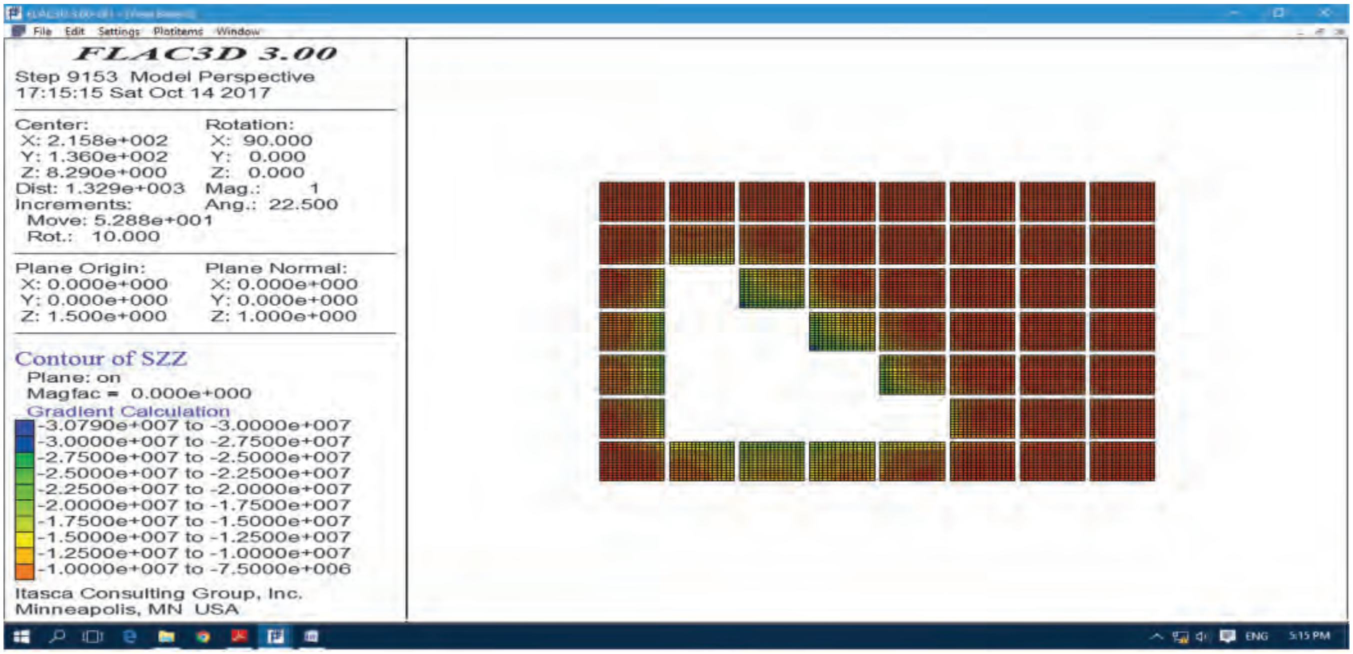


Fig.7 Churcha-38LE-fall-1 (ultimate induced stress)

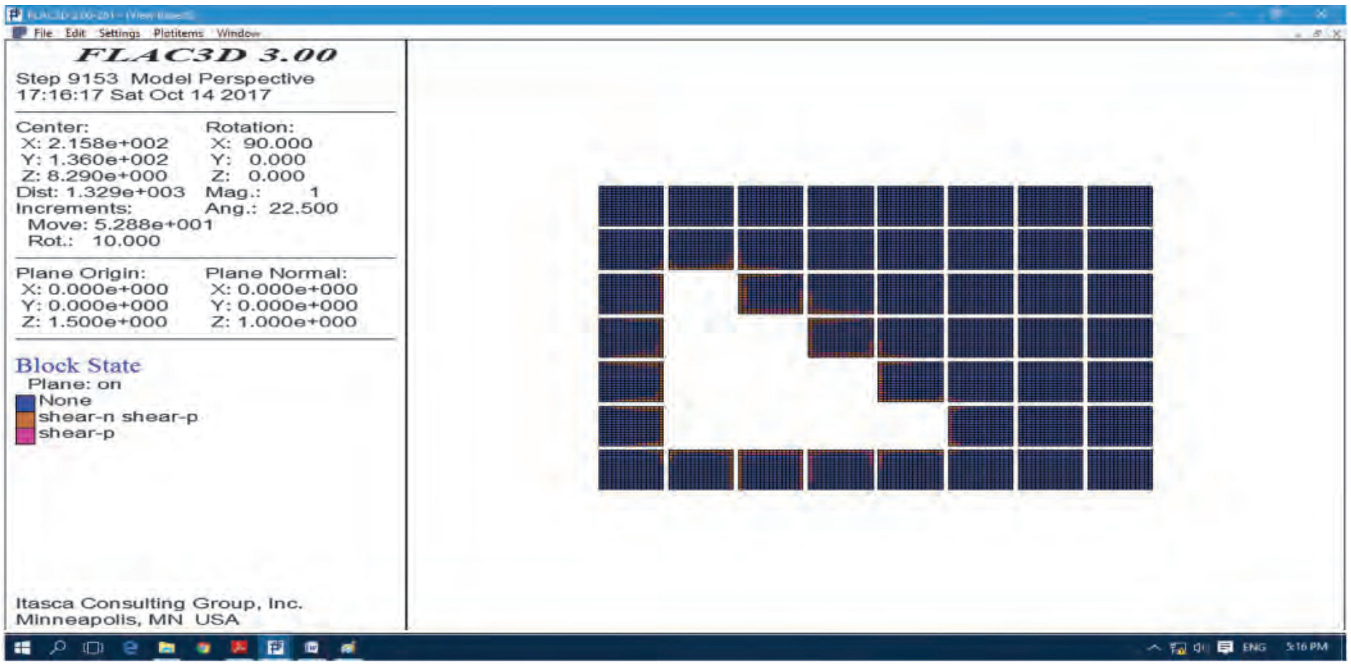


Fig.8 Churcha-38LE-fall-1 (yield profile)

Su α H

Su α A (where 'H' is the depth of cover and 'A' is the area of hanging goaf/fall)

Su α tensile strength of roof formation

Su α cohesion of roof formation

Su α angle of internal friction

Su α monitored strata control parameters, such as convergence, load and stress.

These geo-technical parameters are identified as the critical parameters for the study influencing ultimate induced stress and subsequent strata movement. The identified critical parameters, can be brought into mathematical relationship with ultimate induced stress (Su) are as under.

K1 = Su/A

K2 = Su/H

K3 = Su/tensile strength of roof rock (σt)

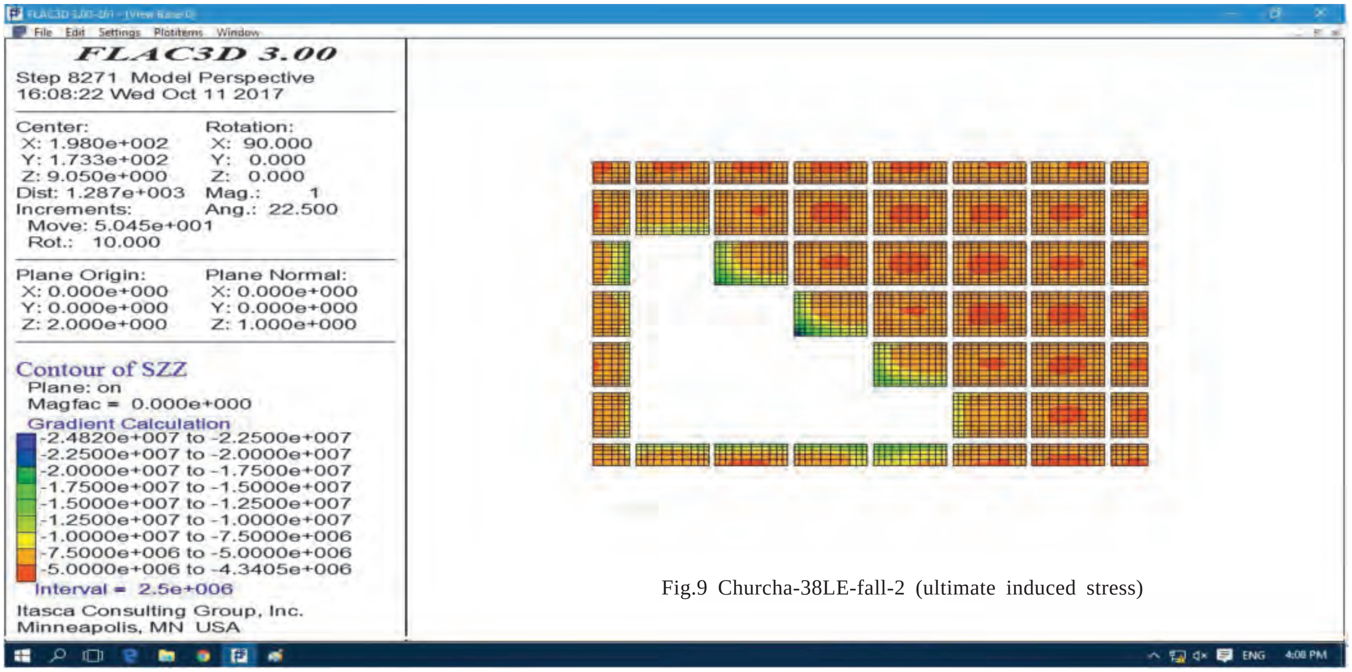


Fig.9 Churcha-38LE-fall-2 (ultimate induced stress)

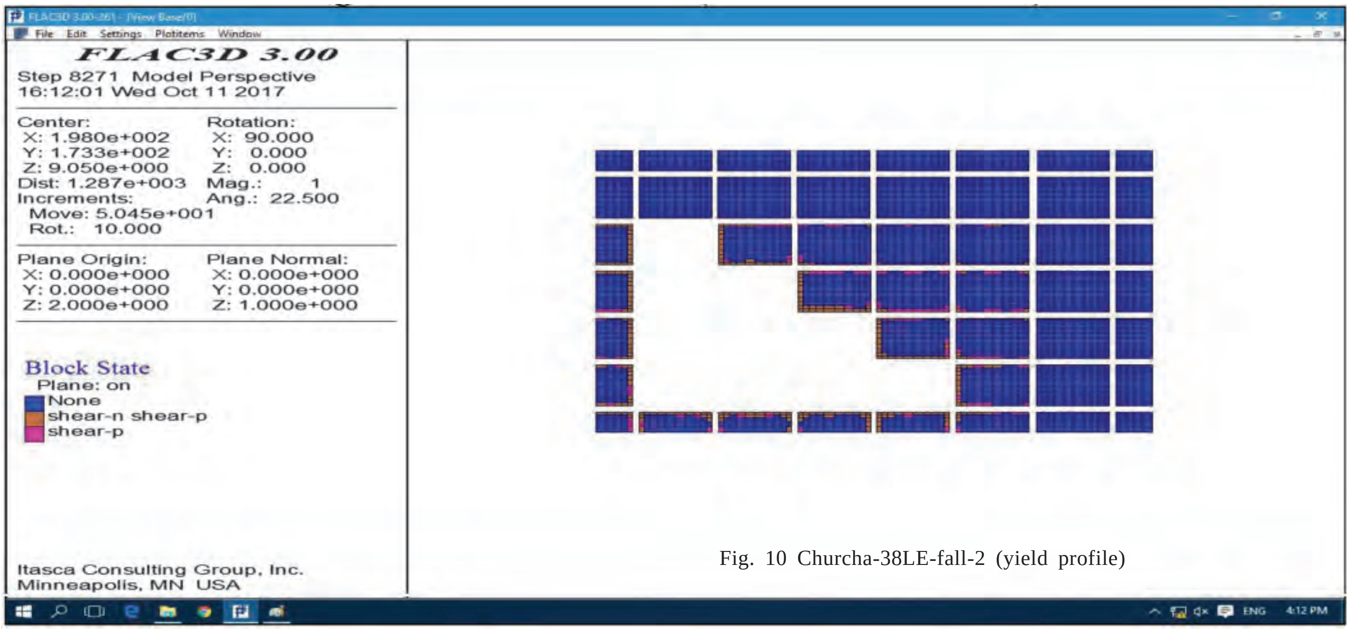


Fig. 10 Churcha-38LE-fall-2 (yield profile)

TABLE 5: SUMMERY FOR DERIVATION OF ROOF FALL WARNING INDEX

Panel	Main fall area (A) m^2	Cavability index (I)	(Su) Ultimate induced stress (MPa)				Roof fall warning index
			Singh A. K. et al. [10]	Poulsen [7]	Nu. modelling (for validation)	Nu. modelling (average)	
22 X	Fall-1, A-7179	9168	38.28	21.76	32.72	35.35	6095
22 X	Fall-2, A-7266	9168	38.28	21.76	37.99	35.35	6086
38 LE	Fall-1, a-23088	9168	34.33	16.95	30.79	27.80	6226
38 LE	Fall-2, A-7949	9168	34.33	16.95	24.80	27.80	6506

K4 = Su/peak cum. conv. (Cv), observed

K5 = Su/peak cum. load (Cl), observed

K6 = Su/peak cum. stress. (Str), observed

Where, K1, K2…Kn are the constants of corresponding ratios.

Based upon the mathematical relationship of critical parameters with ultimate induced stress (Su), a roof fall warning index is developed by the principal author to apprehend the danger of roof fall. The 'Roof Fall Warning Index (C)' is based upon the assessed values (assessed out of mathematical models) of ultimate induced stress, impending main fall in the goaf and is derived as Eq. (10):

$$\text{Roof fall warning index, } C = I/(\Sigma K/n)^{0.5} \quad \ldots \quad (10)$$

where, I = Cavability index and n = nos. of critical parameters taken into consideration.

6. Analysis and discussion

The worked out values of 'Roof Fall Warning Index (C)' in the study panels are summerised in Table 5. Values of the ultimate induced stress included in the 'Roof Fall Warning Index, are assessed as per the model Singh, A. K. et al. [10], because the roof is moderate to difficult on caving.

Referring Table 5, it is ascertained that cavability index of roof formation for both the panels, 22 X cut and 38 LE, Churcha UG mine is 9168, which comes under the Cavability Index range of 5000-10000, referring to roof category, caving with difficulty. Under this scenario of caving under strong roof characteristic, Roof Fall Warning Index (RFWI) for the main roof falls, two in each study panels are assessed as 6095, 6086, 6226 and 6506 respectively.

7. Conclusions

Situation of active dynamic loading before main fall under bord and pillar extractions with caving is a complex situation to understand and analyse. Many parameters, directly/ indirectly influence generation and propagation of strata pressure in the form of induced mining stresses. Roof fall is the prime most opportunity for release of such stress. Minimisation of release of strata pressure in the active workings leads to safer mining scenario for which strata movement need to be apprehended in advance. This requires simplification of studies and analysis rock mechanical complexities occur during dynamic loading hours. Development of Roof Fall Warning Index (RFWI) is an absolute effort in this regard.

Predicting/apprehending the peak strata movement in the study panels, 22 X cut and 38 LE of Churcha UG mine, where bord and pillar extraction is being done with caving under very hard strata and at higher depth of cover, the values of Roof Fall Warning Index (RFWI) become 6095, 6086, 6226 and 6506 respectively for the falls, two from each panel and constitute a range of value, 5000-7500 representing cavability index of 9168, which is in the range of 5000 – 10000, representing the situation of caving with difficulties. This derivation of roof fall warning index can be extrapolated with different limits to different geo-mining situations, exploring the research further.

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