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STUDY OF STRATA MOVEMENT BASED UPON DEVELOPED ROOF FALL WARNING INDEX DURING FINAL EXTRACTIONS IN UNDERGROUND COAL MINING UNDER EASILY CAVABLE ROOF FORMATIONS

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ABSTRACT

Roof strata tend to have sagging effect due to gravity loading, in the zone of extraction under bord and pillar underground coal mining with caving, with subsequent development of mining induced stress which keeps on increasing gradually with extractions. Such induced stress may influence workings as dynamic loading effect, posing as a threat to stability of working geometries. In general, when the cavable roof strata are considerably weak in formations, such loading effect remains within the goaved out area, resulting to a safer caving scenario. But, under such situation, presence of any weaker working geometries nearby, such as rib extraction zone, geologically disturbed places etc. may attract the dynamic load to get released with possibilities of sudden premature strata failures. The effective preventive measure for such adverse situation is to go for proper study of strata movement to predict / apprehend the peak limits, so that suitable control measures including roof & side support actions may be actuated. This is a study for analysis of strata behavior under weak roof formations during depillaring with caving and predicting / apprehending the safe limits of strata movement by working over the ‘Roof Fall Warning Index’, already developed by the principal author. For the study, information were used on different main falls from the depillaring panels of two different underground coal mines with weak and easily cavable roof strata.

Keywords: underground coal mining, roof strata, caving, loading effect, induced stress and weak roof.

INTRODUCTION

Roof strata tend to have sagging effect due to gravity loading, in the zone of extraction under bord and pillar underground coal mining with caving (Lokhande R. D., *et al*., 2015). The sagging effect leads to strain along the bedding planes of the cavable roof formations, further leading to formation of mining induced stress. Such stress keeps on increasing during mining and becomes ultimate, before a main / major fall occurs. Such induced stress may influence workings as dynamic loading effect (Kumar N et al., 2011), posing as a threat to stability of weaker working geometries. In general, when the cavable roof strata are considerably weak in formations, such loading effect remains within the goaved out area, resulting to a safer caving scenario. But, under such situation, presence of any weaker working geometries nearby, such as rib extraction zone, geologically disturbed places etc. may attract the dynamic load to get released with possibilities of sudden premature strata failures, further leading to unsafe mining scenario. The effective preventive measure for such adverse situation is to go for proper study of strata movement to predict / apprehend the peak limits, so that suitable control measures may be actuated. The control measures may include support actions for roof and sides, induced caving of goaf, following suitable working methodologies etc. This study is on analysis of strata behavior under weak roof formations during depillaring with caving and predicting / apprehending the safe limits of strata movement by working over the ‘Roof Fall Warning Index’, already developed by the principal author.

BACK GROUND

Literature review was done, studying number of models relating to strata control issues of underground coal mining, already developed by different authors. Ten, out of the studied models are relating to dynamic loading and effect of induced stress during bord and pillar depillaring. The models are, Heasley, 1998, Wang C. *et al*., 2000, Singh R. *et al*., 2004, Jayanthu S. *et al*., 2004, Nemcik J., *et al*., 2006, WANG J. *et al*., 2009, Poulsen, 2010, Kushwaha A. *et al*., 2010, Singh R. *et al*., 2011, Singh A. K., *et al.* 2011.

Out of the ten, models Heasly, 1998, Poulsen, 2010 and Singh A.K., *et al*., 2011 are having similarity on approach with the continuing research. Model, Heasly, 1998 is related to dynamic loading aspects of laminated roof only, which limits itself for inclusion in this study. In model Poulsen, 2010, assessment of ultimate induced stress is based upon extraction ratio and the model is having suitability for weak and easily cavable roof formations, while in the Model Singh A. K., *et al*., 2011, cavability index is the principal input for assessment of such stress. The model works more appropriately when roof formations are strong enough with caving constraints. So, both of these models are included in this research study for assessment of induced stress.

From the literature review, also it was observed that none of the models include strata control

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instrumentation outcomes such as locally monitored stress convergence etc. for analysis of strata movement during bord and pillar extractions. So, in this research study, strata movement is apprehended with help of 'Roof Fall Warning Index (RFWI)', already developed by the principal author. The principal inputs for the model include the geo-mining parameters, physico-mechanical properties of formations and strata control instrumentation values such as monitored stress, convergence etc.

STUDY AREA

For the study, information were used on different main falls from two of the depillaring panels of two different Indian underground coal mines with weak and easily cavable roof strata. The study panels are the CM-6 depillaring panel of Pinoura UG mine and M-7 depillaring panel of Mahamaya UG of South Eastern Coalfields Limited (SECL), India. Details of the study panels are given on Table-1 as under.

Table-1. Data table (Basic information of the study panels).

Panel→ Parameters↓		**Pinoura CM-6**	**Mahamaya M-7**
Geo-mining Information	H (m)	110	54
	h (m)	3	3
	Pillar (m)	26 X 26	25 X 25
	Gallery (m)	6.5	4.5
	A (m^2)Fall 1,2…	4056, 2704	8750, 3125, 1550, 2000
	e	0.6	0.69
	Mechanisation	CM	SDL
Physico-mechanical Parameters	σc (MPa)	32.50	13.59
	σt (MPa)	0.8	1.77
	σtc (MPa)	2	2
	ρ (Kg/ m^3)	2270	2540
	ν	0.2	0.271
	νc	0.27	0.2
	Ec (Gpa)	4	3.6
	E (Gpa)	2	3.2
	Cr (MPa)	0.5	3.17
	Cc (MPa)	1.8	0.8
	Φr (Degree)	30	37
	Φc(Degree)	39	38
	I	1657	1970
Strata control Instrumentation (Maximum Cumulative Value)	Str (Kg/ cm^2) Fall 1,2…	2.45, 1.97	-
	Di (mm)Fall 1,2…	15,13	-
	Cv (mm)Fall 1,2…	-	85, 54, 45, 39
	CL (Te)Fall 1,2…	-	6.57, 3.58, 2.21, 2.25

Where,

H = Depth of cover
h = Thickness of working
A = Area of fall
e = Extraction ratio
σc = Weighted Uniaxial compressive strength of roof rock
σt = Weighted Tensile strength of roof rock
σtc = Tensile strength of coal
ρ = WeightedDensity of roof rock
ν = WeightedPoisson's ratio (rock)
νc = Poisson's ratio (coal)
Ec = Elastic modulus of coal
E = WeightedElastic modulus of roof rock
Cr = WeightedCohesion of roof rock
Cc = Cohesion of coal
Φr = Weighted Angle of friction of roof rock
Φc = Angle of friction of coal
I = Cavability Index
Str = Cumulative stress
Cv = Cumulative roof convergence
CM = Continuous Miner
SDL = Side Discharge Loader

Information on dynamic loading during two main falls in CM-6 Panel of Pinoura UG and four main falls in the M-7 depillaring panel of Mahamaya UG were considered for the research study. Strata control instrumentation monitoring was being done in the CM-6 Panel of Pinoura UG with stress cells and Tell Tales while it was being done with Convergence Recorders and Load Cells in the M-7 depillaring panel of Mahamaya UG. Following Figures 1 & 2 show the working plans of both the panels with fall details and cross section of cavable roof.

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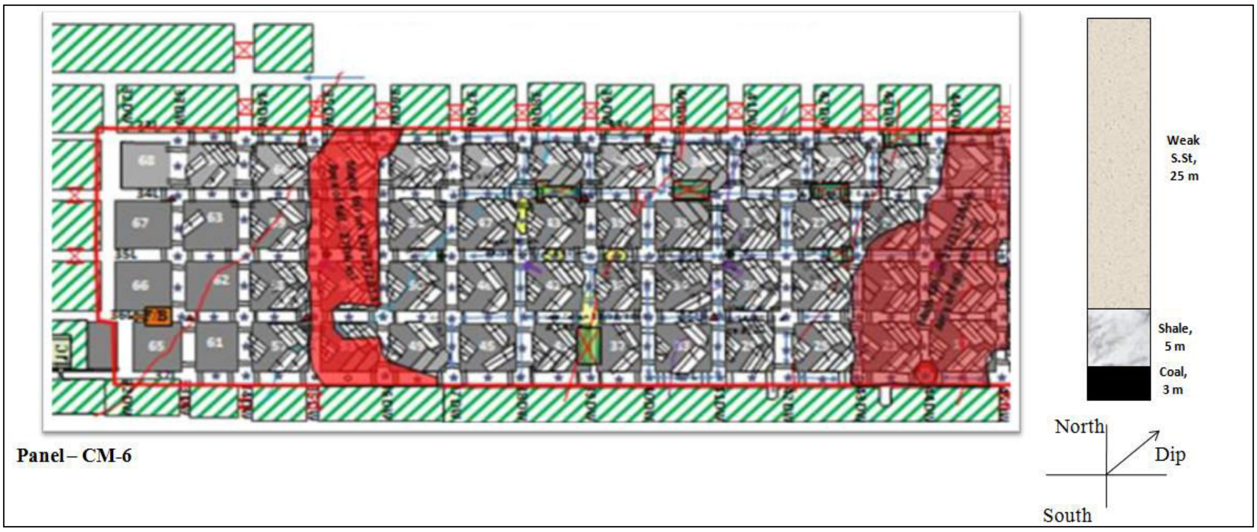

Figure-1. Working plan of CM-6 Panel, Pinoura UG with cross section of roof formations including coal seam.

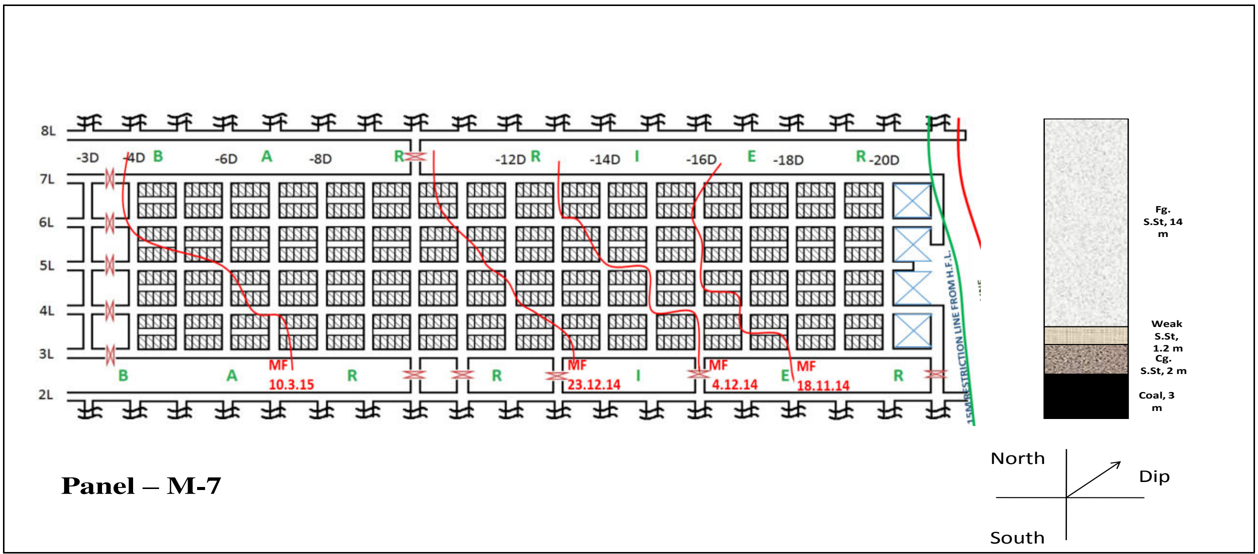

Figure-2. Working plan of M-7 panel, Mahamaya UG with cross section of roof formations including coal seam.

Main fall details, drawn from both the working plans are tabulated as Table-2 as under.

Table-2. Main fall details.

Panel	Main fall	Date	Area of fall (m^2)
Pinoura, CM-6	Fall-1	17.11.2014	4056
Pinoura, CM-6	Fall-2	28.12.2014	2704
Mahamaya, M-7	Fall-1	18.11.2014	8750
Mahamaya, M-7	Fall-2	04.12.2014	3125
Mahamaya, M-7	Fall-3	23.12.2014	1550
Mahamaya, M-7	Fall-4	10.03.2015	2000

ASSESSMENT OF INDUCED STRESSES

Final extraction, tend to formation of dynamic loading from goaf roof, which leads to increase in mining induced stress continuously. Such induced stress reaches to a peak and become ultimate before any main / major roof fall occurs. So, assessment of such peak / ultimate induced stress is an important aspect for apprehension of strata movement leading to roof falls and also organizing control measures. Such ultimate mining induced stress can be assessed either by working out already developed mathematical models or deriving from numerical simulations. Also, mining induced stress can be monitored by installing stress cells at strategic locations in the underground. Such monitored stress remains place specific and bears smaller value with respect to assessed ultimate induced stress and have limitations to be the true representative of the stress profile of the dynamic loading of entire goaf. Rather it works as an indicative parameter of state of dynamic loading. So, the strata control instrumentation outcomes including stress, convergence, load etc. are included as input parameters for development of the 'Roof Fall Warning Index', the predictive model for apprehension of strata movement. In this research study, the resultant ultimate induced stress, which is generally predominant with vertical component, the gravity loading has been taken into assessment in following ways.

a) Mathematical assessment, using existing models, Poulsen, 1998 and Singh A.K., *et al.,* 2011.
b) Numerical simulations / modeling.

Mathematical models

As per model, Singh A. K., *et al*., 2011

In this model, ultimate induced stress (Su) is assessed making cavability index and depth of cover as the principal inputs and is explained as Eq. (1), follows:

$$Su = 0.0033I + 0.059H – 9.85MPa \quad (1)$$

Where,

I = Cavability index
H = Depth of cover in m
I = $(\sigma l^n t^{0.5}) / 5$
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 Equation. (2),

$$R = 0.106I + 0.1H – 12.45m \quad (2)$$

For depth of cover less than 200m, as Equation. (3), follows:

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

Subsequent Range of influence, as Equation. (4)

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

m = Elastic modulus of cover rock

As per model, Poulsen, 1998:

As per the model, ultimate mining induced stress is the peak pillar stress, assessed making extraction ratio, the principal input, given as Equation. (5).

$$\text{Pillar stress} = \rho gH / (1- e) \quad (5)$$

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 was assessed for the main falls, for each study panel, using both the models and are shown on Table-3, given further.

As per numerical simulations / modeling:

Also the peak / ultimate induced stress was 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 was considered to be a strain-softening material. Failure criterion for immediate roof was considered to be of Mohr Coulomb principle, while main roof and floor were considered to be elastic in nature. Goaf was considered as linearly elastic as suggested by Jaiswal and Shrivastva, 2009, with the following mathematical relationship as Equation. (6).

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

Where
E = Young's modulus
I = Cavability Index

Boundary conditions

The bottom of the model was restricted in downward direction whereas sides were restricted in normal direction.

Stress initialization

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

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

Horizontal stresses have been estimated by using Sheorey formula (Sheorey*et al*., 2001) as Equation. (8) given below:

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

Where, σ_v is vertical stress, $\sigma_h$is the horizontal stress and H is the depth of cover.

Feeding the values of parameters in the above equation, the generalized horizontal stress formula can be represented as Equation. (9):

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

Modelling was done for the main falls, two from Pinoura, CM-6 depillaring panel and four from Mahamaya, M-7 panel of the study area using the input parameters given on Table-1 and excluding the strata control parameters and the outcomes are as follows.

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Pinoura, CM-6 depillaring panel

Following Figure-3 shows the numerical simulation during extraction before first main fall with the peak induced stress of 6.50 MPa and the Figure-4 shows the subsequent failure/yield profiles in the working geometry. From the yield profile it was observed that impact of dynamic loading on workings was least with favourable mining conditions due to soft and easily cavable roof.

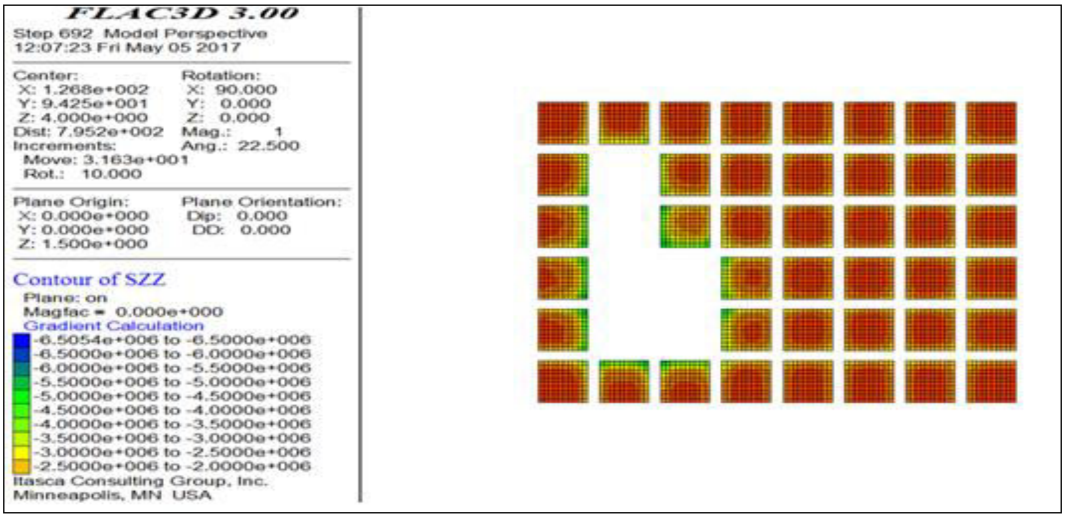

Figure-3. Pinoura-CM.6-Fall-1 (Ultimate induced stress).

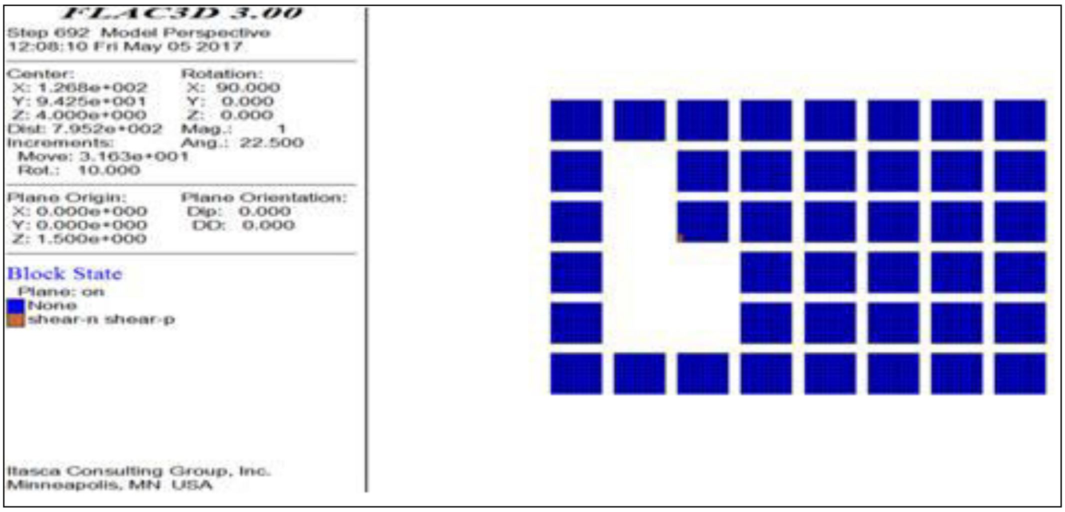

Figure-4. Pinoura-CM.6-Fall-1 (Yield profile).

Similarly the ultimate induced stress during the second main fall was observed as 6.81 MPa from the respective numerical simulations and also the failure profile was observed with negligible impact upon workings.

Mahamaya, M-7 depillaring panel

Figure-5 and Figure-6 show the numerical modeling for ultimate induced stress and yield profile during first main fall in the Mahamaya UG, M-7 depillaring panel. As per the simulations, the peak / ultimate induced stress before the fall was 4.4 MPa with negligible yielding impact upon workings.

Similarly, numerical simulation was done for the next three main falls in the panel, observing the ultimate induced stress and yield profile. Simulations show the peak / ultimate induced stress of 4.2 MPa, 4.17 MPa and 4.23 MPa for Fall-2, 3 & 4 respectively. Yielding effect of such stress workings was the minimal during all these falls, which says about easily cavabile characteristic of roof formations. Ultimate induced stress assessed as per different models are summerised in the Table-3.

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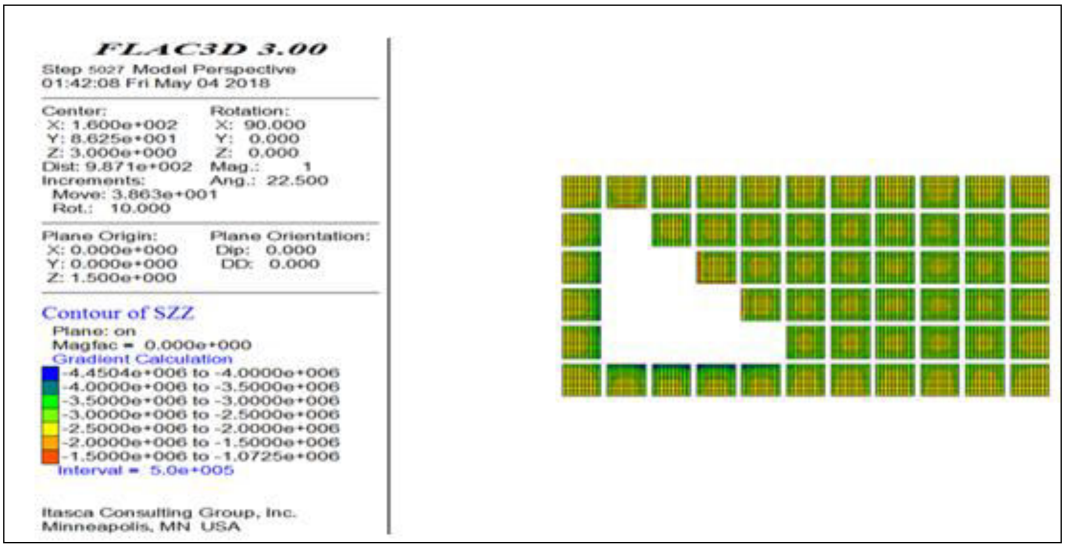

Figure-5. Mahamaya-M-7-Fall-1 (Ultimate induced stress).

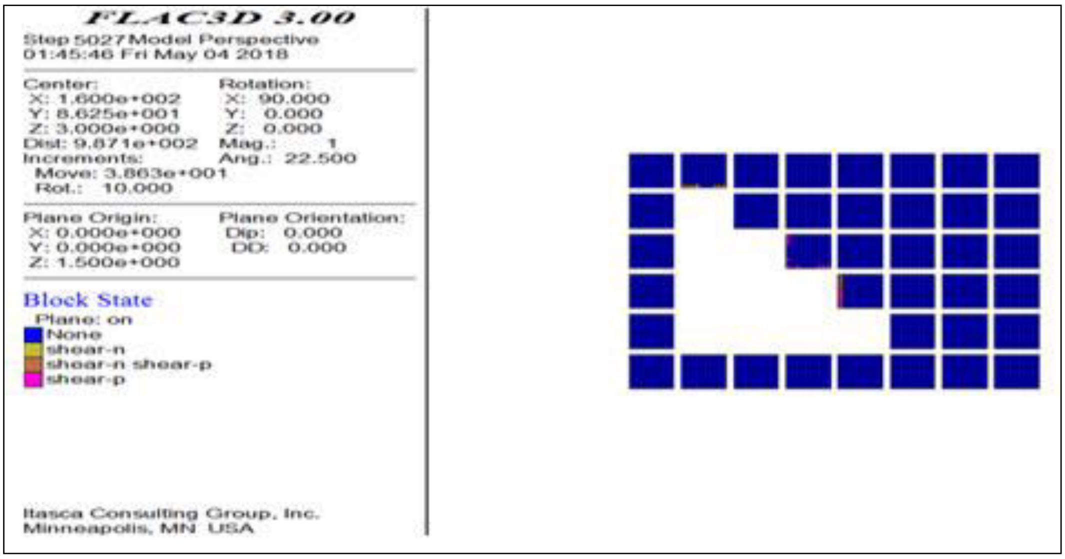

Figure-6. Mahamaya-M-7-Fall-1 (Yield profile).

Table-3. Summerisation of values of ultimate induced stress.

Panel	Main Fall	(Su) **Ultimate induced stress** (MPa)			
		Singh A.K. *et al.*	**Poulsen**	**Nu. Modelling**	**Nu. Modelling (Av.)**
Pinoura, CM-6	Fall-1	2.11	6.01	6.50	6.65
Pinoura, CM-6	Fall-2	2.11	6.01	6.81	6.65
Mahamaya, M-7	Fall-1	3.47	4.26	4.4	4.25
Mahamaya, M-7	Fall-2	3.47	4.26	4.2	4.25
Mahamaya, M-7	Fall-3	3.47	4.26	4.17	4.25
Mahamaya, M-7	Fall-4	3.47	4.26	4.23	4.25

Referring Table-3 it was observed that the ultimate induced stress assessed as per model Singh A. K., *et al.*, 2011 were less with respect to other form of assessment. It is because in both the study areas, cavability index was too low and the roof formation was easily cavable. In case of Mahamaya UG, apart from low cavability index, weighted uniaxial compressive strength of cavable roof formation was also very low. The values of induced stress assessed as per the model, Poulsen 2010 in both the panels were 6.01 MPa and 4.26 MPa respectively, which were too close to that of as per numerical models, average values, i.e., 6.65 MPa at Pinoura, CM-6 Panel and 4.25 MPa at Mahamaya M-7 panel. This says that the stress value derived as per Poulsen model[11] works more appropriately with weak roof formations.

PREDICTION / APPREHENSION OF STRATA MOVEMENT

Extraction induced stress reaches to a peak before the roof breaks for fall. Such peak / ultimate induced stress is also directly proportional to other geo-technical parameters as follows.

Su α *H*

Su αA (Where '*H*' is the depth of cover and Á' 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 instrumentation parameters, such as convergence, Load and monitored stress. These geo-technical parameters are identified as the critical parameters for the study influencing ultimate induced stress and subsequent strata movement. For better apprehension of 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)

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 was developed by the 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 Equation. (10), under.

Roof Fall Warning Index, $C = I / (\sum K/n)^{0.5}$ (10)

Where, I = Cavability Index & n = nos. of critical parameters taken into consideration

ANALYSIS AND DISCUSSIONS

The worked out values of 'Roof Fall Warning Index (C)' in the study panels are summerised in Table-4 as follows. Values of the ultimate induced stress included in the 'Roof Fall Warning Index, were assessed as per the model Poulsen, because the roof formations were too weak and with easy on caving.

Table-4. Summery for derivation of roof fall warning Index.

Panel	Cavability index (I)	(Su) Ultimate induced stress (MPa)				Roof fall warning index
		A.K.S *et al.*	Poulsen	Nu. modelling (For validation)	Nu. modelling (Av.)	
Pinoura, CM-6	1657	2.11	6.01	6.50	6.65	1148
Pinoura, CM-6	1657	2.11	6.01	6.81	6.65	1113
Mahamaya, M-7	1970	3.47	4.26	4.4	4.25	2468
Mahamaya, M-7	1970	3.47	4.26	4.2	4.25	2261
Mahamaya, M-7	1970	3.47	4.26	4.17	4.25	2075
Mahamaya, M-7	1970	3.47	4.26	4.23	4.25	2080

Referring the values on Table-4, it is observed that cavability index of roof formation for both the study panels, Pinoura, CM-6 and Mahamaya, M-7 are 1657 and 1970 respectively, which are included under 'Easily cavable weak roof' with cavability index range of 0-2000. 'Roof Fall Warning Index', worked out for different main falls were 1148 and 1113 at Pinoura, CM-6 panel and 2468, 2261, 2075 and 2080 respectively at Mahamaya, M-7 panel.

CONCLUSIONS

Final extraction with caving during bord and pillar coal mining and related dynamic loads are too complex to understand and workout. Such loading impact is highly situation specific and governed by many known and unknown parameters. Minimisation of loading impact on workings and related control measures are the bare requirement for a safer scenario of mining, which is possible only the terminal strata pressure and movement are apprehended properly. Working out with 'Roof Fall Warning Index', the outcome of this research definitely adds to appropriateness of apprehension of vulnerable strata movement in advance.

Concluding the study, it is ascertained that both the study panels were having cavability index under the category, 'Easily cavable weak roof' with range of 0-2000. Under such circumstances, the 'Roof Fall Warning Index (RFWI)', worked out for different main falls were 1148 and 1113 at Pinoura, CM-6 panel and 2468, 2261, 2075 and 2080 respectively at Mahamaya, M-7 panel, which can be clubbed in a range of 1000-2500. This implies that when 'Roof Fall Warning Index (RFWI)' is worked out within a range of 1000-2500, active to peak strata movement can be apprehended for extraction under 'Easily cavable weak roof' formations. Such working out of roof fall warning index can be explored with different limits to different geo-mining situations, extending the research further.

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