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Assessment of stability of a panel in an Underground Coal Mine using Numerical Modelling

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Abstract: Mining is one of the most important sectors for the progressive development nation. In which underground coal mining is of two types, the longwall method and bord and pillar method. That Bord & pillar mining is most commonly used in India. The extraction of coal from underground sources is filled with many uncertainties. Underground coal mining involves problems like panel stability, roof control, spontaneous heating of coal, mine fire, explosion, and many others. Bord and pillar method of working is generally adopted for a seam with a thickness greater than 1.5 m. Coal being the major producer of electricity from underground, coal mining cannot be avoided totally. In these many years, scientists and researchers have worked on the issue of creating a safe atmosphere underneath the surface. At greater depths, this bord and pillar method becomes uncontrollable as effects of ground pressure which are not easily predictable, the problem of pillar failure was encountered. Hence, A detailed parametric study is conducted using the FLAC^{3D} (Fast Lagrangian Analysis of Continua) to analyze the panel stability of an underground coal mine for varying geo-mining conditions.

Keywords: Panel Stability, Numerical Modelling, Underground Coal Mining, Local Mine Stiffness, Post Failure Stiffness, Strain Energy.

1. INTRODUCTION

The Bord and Pillar technique of mine development entails driving a series of thin parallel roads separated by solid coal blocks and connecting them with a second set of narrow parallel roadways driven practically at right angles to the first set. The development of first working stage at which a network of roadways is developed, and these roadways are named as Bord or Gallery. Pillars are substantial blocks of coal which are left around the gallery after it has been constructed. Depillaring is a later stage of extracting coal from pillars, which occurs after the development of the mine area. During underground mining, pillars support a large weight of overlying strata. Ground control is impossible without stable pillar. Several mines designed their pillars using local rules of thumb based on experience during the 1990s. Around 25% of all roof collapse fatalities occurred underground as a result of pillar recovery operations [1].
Strata control issues affect pillar extraction operations. If the processes are not designed scientifically, there is a risk of major strata movement, which could result in pillars being overridden and premature collapse. Pillar failures can be categorized into two types:

A. control pillar failure occurs gradually and typically over a prolonged period of time, resulting in a slow progressive deterioration of the pillar, which creates delayed surface subsidence and also causes damage to the pillars, leading them to fail, which is known as creep or squeeze.

B. Uncontrolled pillar failure occurs violently and over a short period of time, resulting in pillar collapse and surface damage, which is associated to fatal accidents. It cannot be preceded by any

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weakening of the pillar due to the rapid failure. [2].

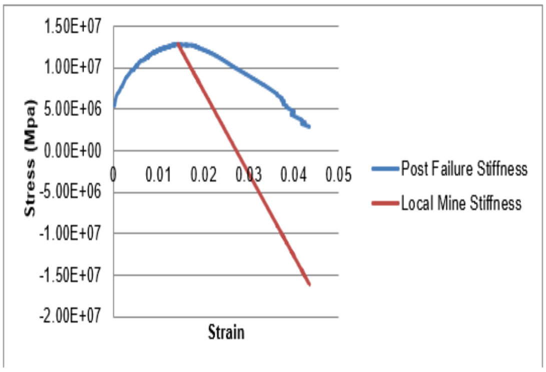

Fig.1: Schematic representation of stable nonviolent failure

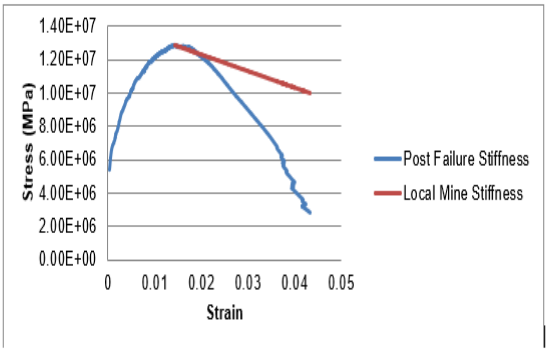

Fig.2: Schematic representation of unstable violent failure

Stable, nonviolent failure occurs when local mine stiffness > post- failure stiffness as shown in figure.1

Unstable, violent failure occurs when local mine stiffness < post- failure stiffness as shown in figure.2

The Controlled and uncontrolled pillar failures depend on two main factors: local mine stiffness and post-failure stiffness. The w/h ratio is the main controllable parameter that governs the post-failure stiffness of the pillars while the local mine stiffness may vary due to many reasons: mine layout, major geological structures, extraction ratio [3].

Traditional methods for calculating local mine stiffness and post-failure stiffness are both costly and time-consuming. One can easily determine the local mine stiffness and post-failure stiffness using numerical modelling, by using the software Fast Lagrangian Analysis of Continua in Three Dimensions (FLAC^{3D}). Numerical models with well-quantified geotechnical characteristics can be effective in this situation. Other influencing parameters of pillar stability, such as contact conditions, floor behaviour, the effect of horizontal discontinuities, and water and/or gas content in the rock mass, can also be analysed using these numerical models [3].Computer simulations aim to replicate an abstract representation of a system. Dynamical systems, statistical models, differential equations, and game-theoretic models are just a few aspects of models.. Engineers frequently use a mathematical model to analyse a system that needs to be implemented or upgraded. Engineers would be using the results of the study to establish a descriptive model of the system as a hypothesis for how the system would work, or to try to predict how an unforeseeable event could affect the system.. FLAC was designed specifically for geotechnical and mining engineers, but now it has a wide range of capabilities for solving the complex mechanical issues. There are several built-in constitutive models that can be used to generate extremely nonlinear, irreversible responses that are characteristic of geology or analogous materials which has a several advantages when it comes to engineering field [4].

II. METHODOLOGY

Product concept designs can be traditionally dominated by a parametric research that perturbs design variables in the product design study to assess the design alternatives. A parametric analysis has the added benefit of allowing you to choose which parameters to analyze, define the parameter range, provide design limitations, and understand the implications of each parameter modification.. A parametric study with numerical modelling provides an efficient

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tool for this project. Numerical modelling is known for its high efficiency in solving complex problems quickly.

These are the following steps used in numerical modelling:

1. Defining element types
2. Defining material parameters
3. Applying in Software
4. Creating the geometry model
6. Solution
7. Analysis of results

Numerical modelling has been used to predict/investigate pillar failure proneness by estimating the amount of strain energy released, or by determining the local mine stiffness and comparing with the post-failure stiffness, or by large/rapid deformation of the roof, or based on stress-strain analysis, or energy release ratio [5]. Utilizing FLAC3D, numerical modelling can be performed to estimate the impact of the specified parameters on post and pre-mining stresses on strata contributing to coal bumps using geo-mining conditions [4].

2.1. Selection of Parameters

The modelling is done employing mining parameters from Tata Steel Limited's Digwadih colliery, where depillaring is occurring in the 2S Panel of the IX seam at a depth of 483 m. Through using conventional bord and pillar mining with a gallery width of 4.8 m and an extraction height of 3.02 m, the 2S panel of the IX seam, with a thickness of almost 3.02 m, was developed. The immediate roof is made up of a 5.37-meter thick layer fo shale and sandy shale. The roof's RMR is calculated to be 35.5, ranking it in the poor roof category. Table 1 lists the properties of the digwadih colliery used in the modeling [6].

Table.1: Rock Mass Properties Used for Different Formations

Formation	Thickness of seam (m)	Young's Modulus (GPa)	Density (kg/m^3)	Uni-axial Compressive Strength (MPa)	Tensile Strength (Mpa)	RMR
Shale	50	7.5	2578	95.7	8.84	51
Coal Seam	3.02	2,3,4	1606	32.55	3.5	35-65
Shale	0.8	3.98	2578	60.6	4.83	44
Fgsst	0.82	4.54	2278	95.7	8.84	42
Shale	1.21	4	2575	70.7	7	37
Cgsst	13.06	6.49	2158	38.4	3.88	55
Mgsst	39.9	6.99	2378	40	4.4	60

2.2 Selection of Suitable Material Model

The change in stress caused by an increase in strain is determined using a constitutive law. Within FLAC3D, various constitutive material behaviours can be permitted, even though only elastic, Mohr-Coulomb (plastic), and Mohr-coulomb strain-hardening/softening (brittle/weakening) models are used. In mining, induced loading or stress is frequently observed to exceed the rock mass's strength. Constitutive laws that can represent the behaviour of the rock mass in the post-peak condition also are necessary for the realistic representation of stresses and deformation in such circumstances [6]. The stress-strain behaviour of an unconsolidated rock mass is described using a modified Mohr-Coulomb constitutive model. The modification is based on changes in the internal friction angle and cohesion generated by plastic strain, i.e. activated strength properties. The modification is done to represent the hardening and softening-strain of the rock mass character [4].

2.3. Determination of MCSS Parameters by the Single Pillar Test Run

Determining strain-softening by Mohr-coulomb parameter in real practice is more difficult, which is done easily by the test run model. The number of test trials is carried out to the single pillar with difference in width and height ratios and suitable representativestrain-softening parameters by Mohr- coulomb are estimated as by back analysis. The Mohr-Coulombstrain-softening properties like

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Cohesion, friction angle, and dilation angle is obtained by a single pillar test run the model. This method of determining the MCSS parameters considered to be best practice [7]. A single pillar test run model is given in figure 3.

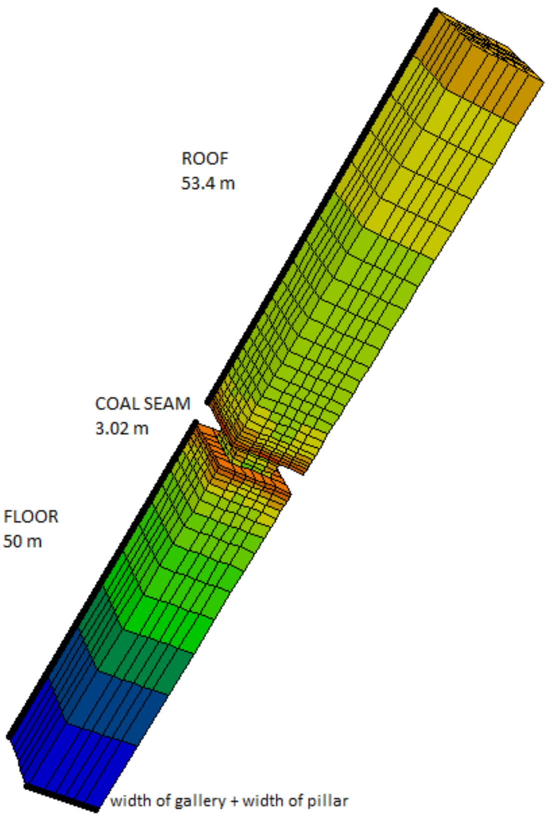

Fig.3: Numerical model for a singlepillar

As shown in figure 2.2, the analysis was done on a single pillar with varying width to height ratio, the maximum stress obtained in the pillar before failure was assumed to represent the strength of that pillar [3]. This indicates that once the stress exceeded the strength, the pillar failed. The strength obtained from the pillar is then compared with strength obtained from formulas such as Sheorey's formula.

If the strength obtained in FLAC^{3D} does not match with the one calculated from formulas, then the modifications on cohesion, dilation, and frictional angle are done and the procedure is repeated for varying width to height ratios. An acceptable range of error is from -0.05 to +0.05. The values are shown in table.2.

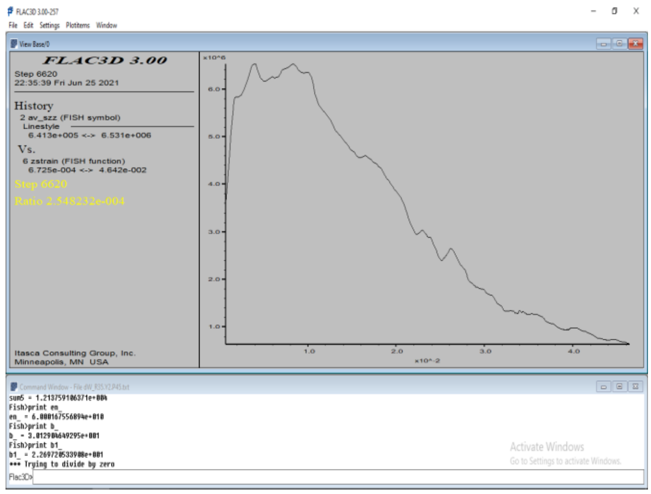

Fig.4: Average stress vs strain of a single pillar with w/h ratio of 2.

Table.2: Comparison of strength using Sheorey's formula and using FLAC3D.

Compressive strength of coal (MPa)	Height of the pillar (m)	Depth of cover (m)	w/h	Width (m)	Strength of pillar using Sheorey's formula (MPa)	Stress obtained in FLAC3D (MPa)
32.55	3.02	300	2	6.04	8.103537	8.095
32.55	3.02	300	2.5	7.55	9.203537	10.22
32.55	3.02	300	3	9.06	10.30354	11.83
32.55	3.02	300	3.5	10.57	11.40354	12.95
32.55	3.02	300	4	12.08	12.50354	13.69
32.55	3.02	300	4.5	13.59	13.60354	14.13
32.55	3.02	300	5	15.1	14.70354	14.42

2.4. Study for Panel Stability

Once the Mohr-Coulomb strain-softening parameter are obtained, during running the main model the same parameter is used for the development of the gallery (4.8m). After the development of the gallery, the load/average stress on the middle pillar is obtained. Using a FISH (an in-built programming language of FLAC3D) file the average vertical stress concentration on the pillar and the average convergence (roof and floor) is determined. Out of 15

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pillars in the coal seam of the model, the middle pillar is removed as shown in figure.6 to determine the average convergence between roof and floor [6].

2.5. Development of the Models

In this project, a panel of 15 pillars and 10 barrier pillars is considered for modelling. A panel of dimensions is considered. The models were created in FLAC 3D from the bottom to top the height of the model was 108.61m from -50 to 58.61 being the coal pillar at 0 to 3.02m covered with galleries on four sides after the development.

The model's top is maintained in the vertical direction after the roadways are developed, and a constant velocity of 10-5 m/s is applied. Other boundary conditions used in the model include zero vertical displacements at the model bottom and zero horizontal displacements at the four vertical symmetry planes as shown in figure.5.

The stored strain energy before failure and the released strain energy after failure are determined using the stress-strain curve to estimate a mine's pillar failure for a specified geo-mining conditions. The mine may be considered unstable if the accumulated strain energy is higher than the released strain energy [8].

The core pillar is taken out, leading the pillar to collapse. The pillar's collapse is a gradual process; as seen during the model run, the pillar began to fail from the outside edges and continues to the core's centre, with little horizontal stress due to the pillar's crushing. as shown in Figure.6 [9].

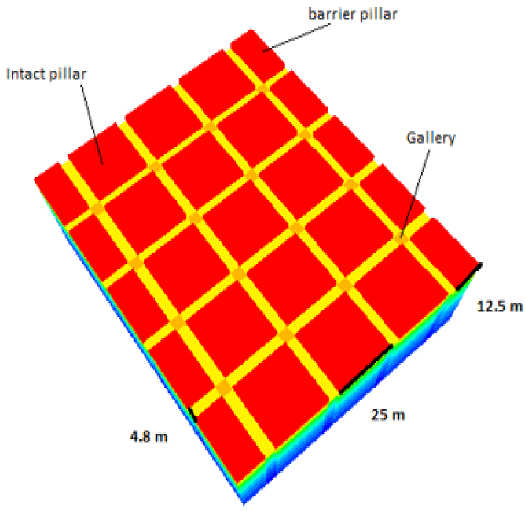

Fig.5: The numerical model using FLAC^{3D} for the developed coal seam

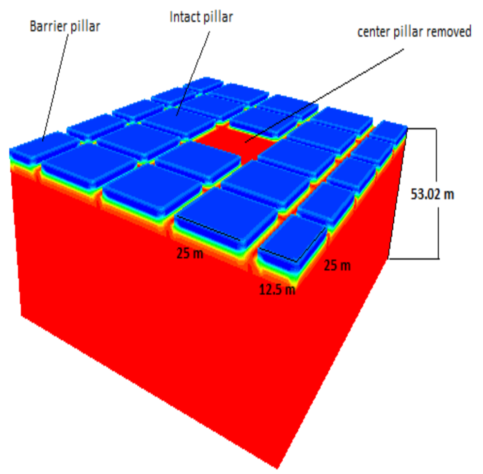

Fig.6: The numerical model using FLAC^{3D} for the developed seam where the middle pillar is removed

Using the properties, numerical models were simulated in FLAC^{3D} with different widths and height ratios ranging from 2 to 5. The models were run till they reached.A fish file is used to determine the average stress and average strain and plotted using the history function in the FLAC^{3D} [6].
The models give the roof-to-floor convergence C_p with the pillar in place, roof-to-floor convergence C_e with the middle pillar removed and σz the average vertical stress on the pillar. Then, the local mine stiffness is calculated from the equation given below.

$$K = \frac{\sigma_Z \times A}{C_e - C_p}$$

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The results were imported to excel and the graphs of different width to height ratios of post-failure characteristics are plotted. The steepest part of the post-failure characteristic is the post-failure stiffness [10].

2.6. Parameters Considered

The parameters considered in this project are shown in table 3.4 below where at each respective depth, RMR of 35,45,55 and 65 is considered with a change in young's modulus of 2,3,4 with every RMR.
The stress and convergence of the panel and each pillar are determined by changing the depth, RMR, and Young's modulus respectively.

Table.3: Parameters considered

Depth (m)	Pillar size (m)	Rock Mass Rating (RMR)	Young's modulus (GPa)
300	25	35, 45, 55, 65	2, 3, 4
	35	35, 45, 55, 65	2, 3, 4
	45	35, 45, 55, 65	2, 3, 4
600	25	35, 45, 55, 65	2, 3, 4
	35	35, 45, 55, 65	2, 3, 4
	45	35, 45, 55, 65	2, 3, 4
900	25	35, 45, 55, 65	2, 3, 4
	35	35, 45, 55, 65	2, 3, 4
	45	35, 45, 55, 65	2, 3, 4

III. RESULT AND ANALYSIS

The local mine stiffness is plotted against the post-failure characteristics as shown in figure 7 and 8.

Table.4: Tabulation of local minestiffness and post-failure stiffness for the panel at depth 300, RMR 35 and different pillar size and young'smodulus

DEPTH (m)	RMR	Young's Modulus (GPa)	Pillar Size (m)	Stress (MPa)	Average convergence with pillar (mm)	Average convergence without pillar (mm)	Local mine stiffness (MPa)	Post failure stiffness
300	35	2	25	10.257606	1.17E-02	8.08E+01	79.39153	383.6199
300	35	2	35	9.4213163	6.31E+00	8.51E+01	146.4281	360.99
300	35	2	45	8.9448066	3.41E+00	9.57E+01	196.194	292.5954
300	35	2	55	8.6420455	2.43E+00	1.08E+02	246.7774	246.3695
300	35	3	25	10.267504	9.20E+00	7.73E+01	94.17425	455.05
300	35	3	35	9.4217511	4.79E+00	8.23E+01	148.9832	367.2891
300	35	3	45	8.9425984	2.43E+00	9.30E+01	199.8334	298.0231
300	35	3	55	8.6407329	1.77E+00	1.06E+02	251.9046	251.4882
300	35	4	25	10.279335	8.11E+00	7.60E+01	94.60407	457.1269
300	35	4	35	9.4143442	4.09E+00	8.10E+01	149.9438	369.6573
300	35	4	45	8.941716	1.99E+00	9.15E+01	202.3993	301.8498
300	35	4	55	8.6422621	1.45E+00	1.04E+02	254.5354	254.1147

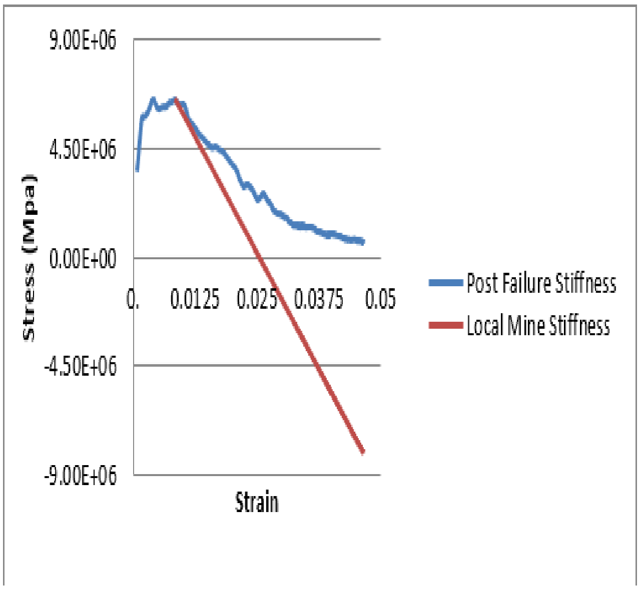

Fig.7: Stable or unstable failure for w/h = 2 with pillar size 25*25 at depth 300

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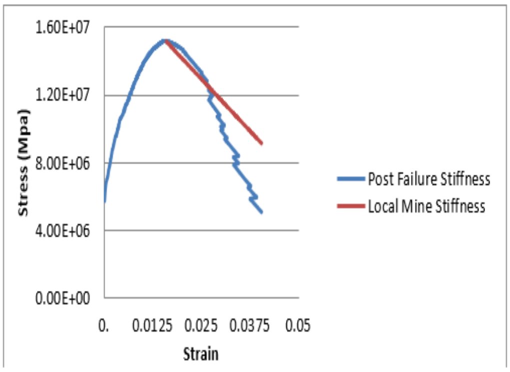

Fig.8: Stable or unstable failure for w/h = 5 with pillar size 55*55 at depth 300

3.1. Pillar Size Wise Analysis

For pillar of size 25*25, comparing the w/h ratio from 2 to 5, the local mine stiffness is lesser than the post-failure stiffness in all the graphs in figure.9 (a to g). Hence, it can be stated, the failure in this condition would be stable (i.e., not abrupt and violent) and there is no chance of sudden pillar failure at pillar size 0f 25*25 at depth of 300 as per the geo-mining parameters used in the model.
For pillar size 55*55 at depth 300, the local mine stiffness obtained from the numerical modelling is almost near to the post-failure stiffness as shown in figure.10 (a to g). It can bestated that there is a chance of violent failure of the pillar in the mine. As per the field observation stated earlier, the pillar of size 55*55 should be near to the unstable category, but little over estimated may be due to the assumption of several physic-mechanical properties and in-situ stresses in the numerical models.

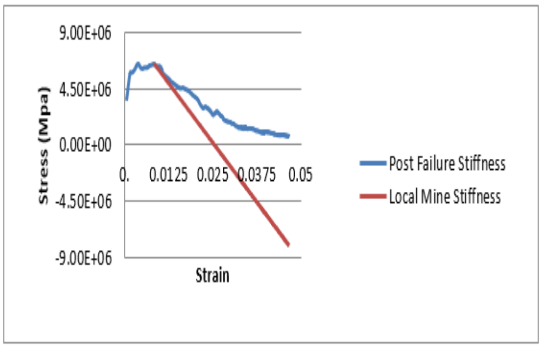

Fig.9 (a) Stable or unstable failure for w/h = 2 with pillar size 25*25

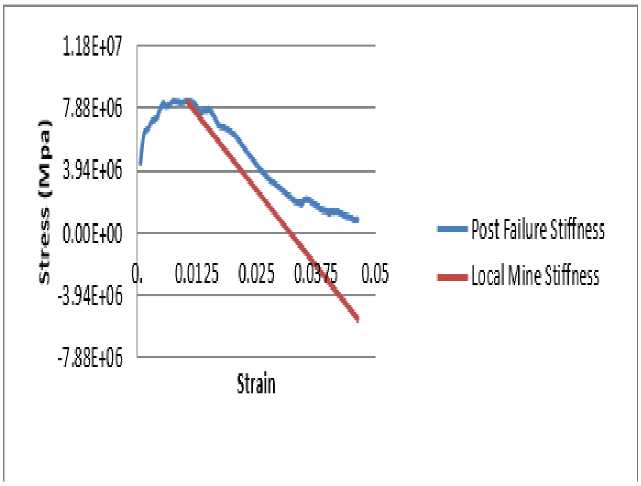

Fig.9 (b) Stable or unstable failure for w/h = 2.5 with pillar size 25*25

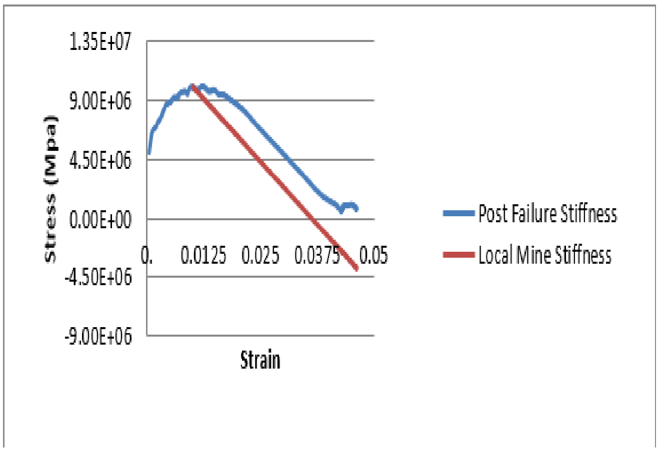

Fig.9 (c) Stable or unstable failure for w/h = 3 with pillar size 25*25

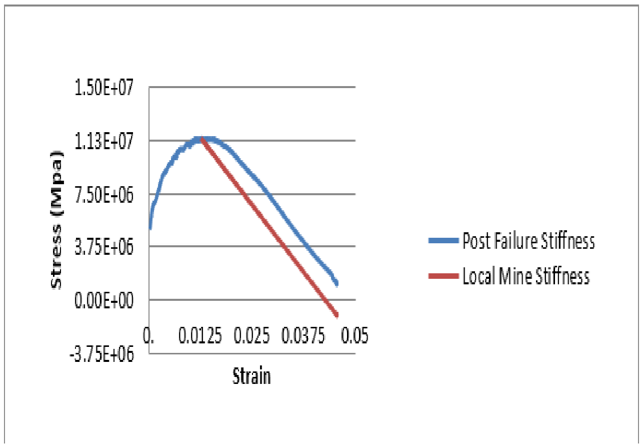

Fig.9 (d) Stable or unstable failure for w/h = 3.5 with pillar size 25*25

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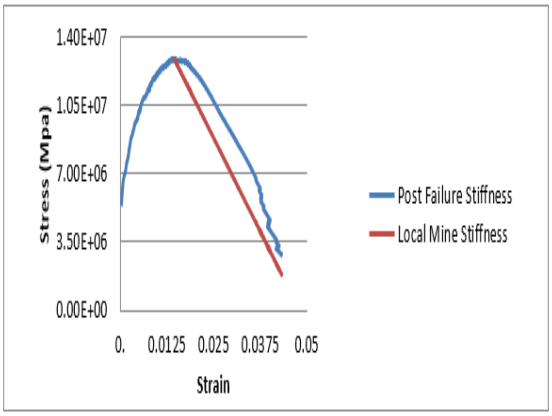

Fig.9 (e) Stable or unstable failure for w/h = 4 with pillar size 25*25

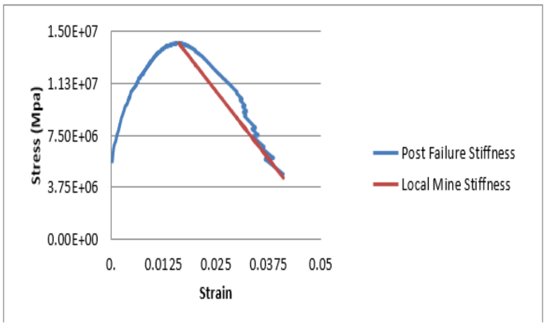

Fig.9 (f) Stable or unstable failure for w/h = 4.5 with pillar size 25*25

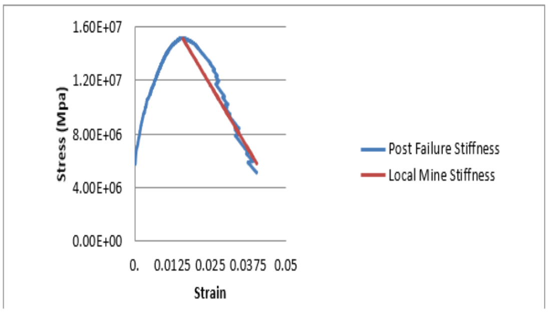

Fig.9 (g) Stable or unstable failure for w/h = 5 with pillar size 25*25

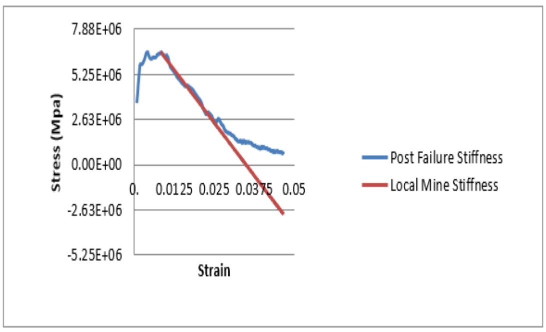

Fig.10 (a) Stable or unstable failure for w/h = 2 with pillar size 55*55

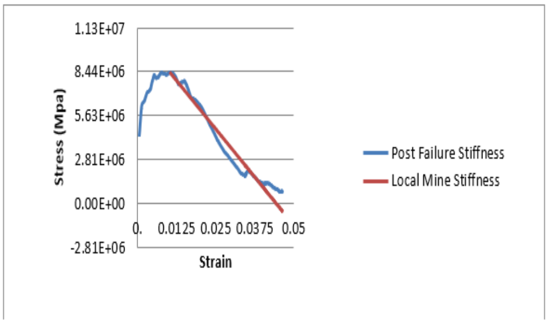

Fig.10 (b) Stable or unstable failure for w/h = 2.5 with pillar size 55*55

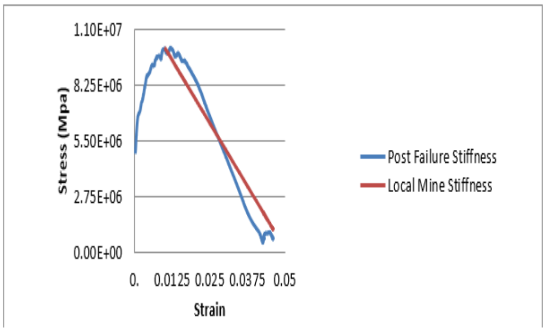

Fig.10 (c) Stable or unstable failure for w/h = 3 with pillar size 55*55

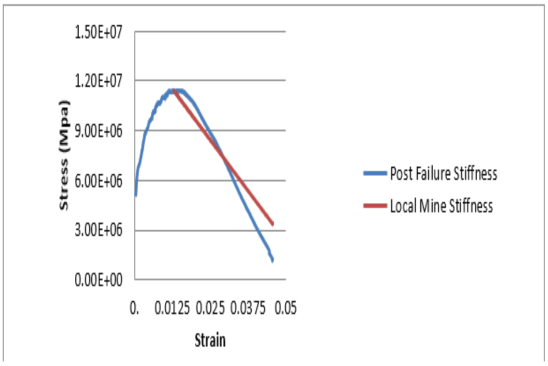

Fig.10 (d) Stable or unstable failure for w/h = 3.5 with pillar size 55*55

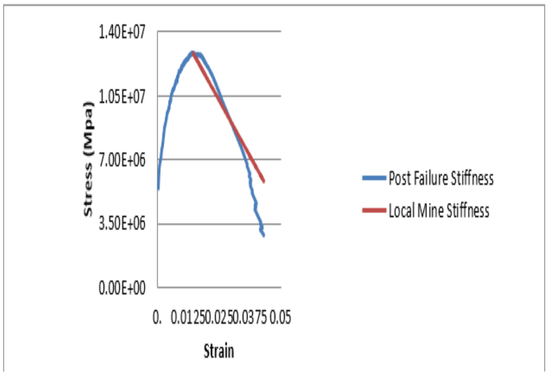

Fig.10 (e) Stable or unstable failure for w/h = 4 with pillar size 55*55

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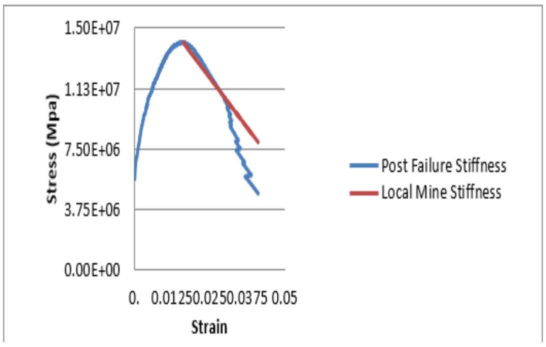

Fig.10 (f) Stable or unstable failure for w/h = 4.5 with pillar size 55*55

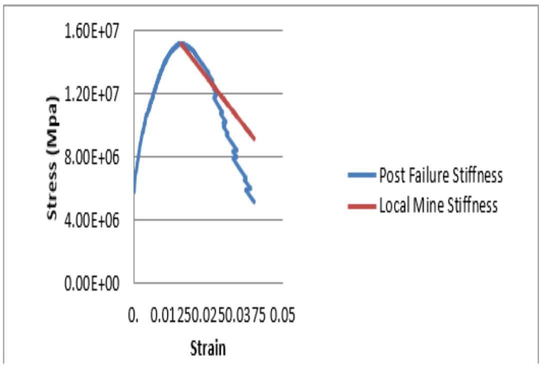

Fig.10 (g) Stable or unstable failure for w/h = 5 with pillar size 55*55

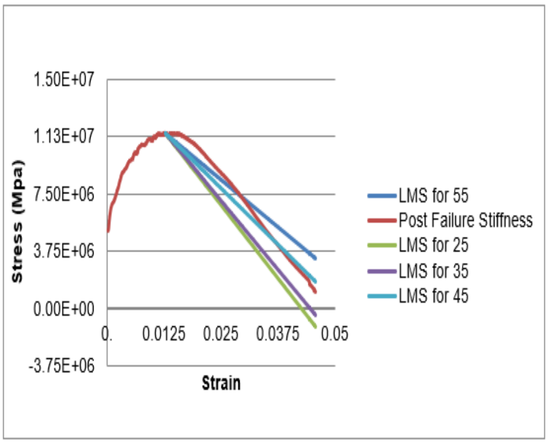

Fig.11: Stable or unstable failure for pillar size 25,35,45,55 at depth 300, RMR 35 and youngs modulus 2.

The plotting for local mine stiffness for different pillars and post-failure stiffness is done. Figure.11 shows the stress vs strain graph, the depth is taken as 300m, RMR 35 and Young's modulus of 2. For pillar of size 25*25, stable failure of the pillar happens. For pillar of size 55*55, unstable violent failure will occur. From the study, it can concluded that, as pillar size increases proneness for unstable violent failure increases.

3.2. Youngs Modulus Wise Analysis

Plotting of local mine stiffness and post-failure stiffness is done for the pillar of size 25, w/h ratio 5 and at different youngs modulus is shown in figure.12 (a to c). From the study, unstable failure can happen in the case of youngs modulus 2 and stable failure can happen in the case of youngs modulus 4. From the study, it can be concluded that, when youngs modulus increases proneness for stable non-violent failure increases.

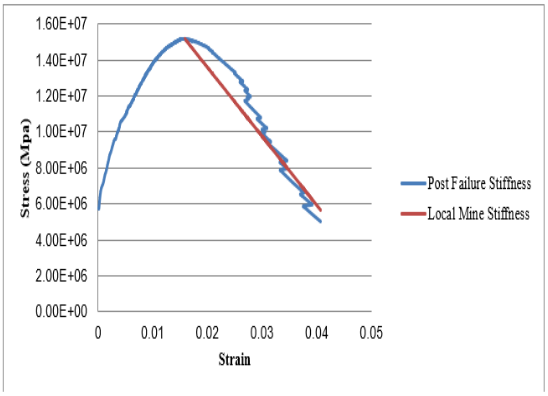

Fig.12 (a): Stable or unstable failure for w/h = 5 with youngs modulus 2 at depth 300 and RMR 35

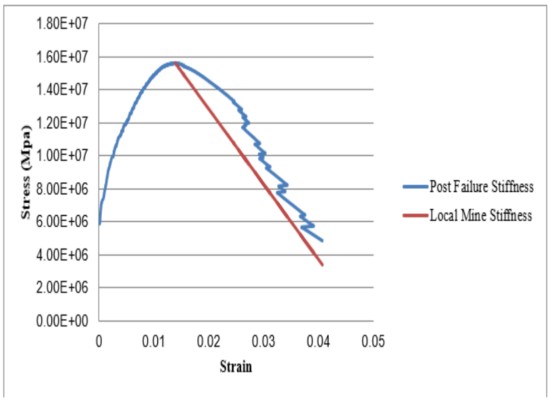

Fig.12 (b): Stable or unstable failure for w/h = 5 with youngs modulus 3 at depth 300 and RMR 35

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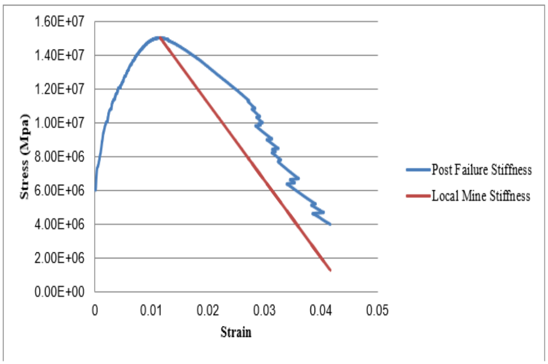

Fig.12 (c): Stable or unstable failure for w/h = 5 with youngs modulus 4 at depth 300 and RMR 35

IV. CONCLUSION

The focus of this research was to use numerical modelling to improve the effectiveness and standard safety of dealing with the bord and pillar methods of mining. The pillar stability was evaluated using the details of the digwadith colliery case analysis. For the above-mentioned case study, models were constructed utilising different characteristics and qualities of the coal in the FLAC 3D software.

According to the studies, when violent pillar failure occurs during the development or depillaring stages occur at a rapid rate. If the panel's stability is determined before the development stage, a suggestion for a viable and effective support system can be provided in advance. Perhaps if the coal is extracted in this manner, accidents can be prevented and improve output, productivity, and also increasing the safety of the workers. Differentiating parameters such as width to height ratio, RMR, youngs modulus and pillar size are used in this study. Local mine stiffness and post failure stiffness for different conditions are obtained from the study.

The conventional way of evaluating the post-failure characteristics is a time-consuming, costly, and ineffective procedure. Now it can be easily determined by the advancement of numerical modelling techniques. When the local mine stiffness is equal or lesser than the post failure stiffness, the pillar fails in an unstable manner. Which is determined and compared using FLAC3D. Due to non-available data such as physiomechanical characteristics, institute stresses, and so on, the outcome may vary slightly. However, if all of the essential data is available, numerical modelling can be used to reasonably predict the stability of a panel in advance.

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