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INFLUENCE OF THICKNESS OF WEAK BEDDING PLANES AT VARIOUS POSITIONS WITHIN PILLAR HEIGHT ON STRENGTH: A NUMERICAL MODELLING STUDY

Efficient extraction of coal from an underground mine is mainly done under the protection of different forms of coal pillars. It is observed that the coal seams and its host rock contain different geological discontinuities such as weak beds (bands), which affect the strength of pillars. The weak bed creates weak bedding planes. The available pillar strength formulae are based on the width-to-height ratio, depth of cover, and strength of intact coal, and they do not consider the effects of discontinuities. A numerical simulation study on the quarter symmetry model is carried out to assess the impact of weak beds with their positional variation and thickness. The strength of the pillar without discontinuities estimated through the simulation study was validated with those obtained by the indigenous empirical strength formula. A weak bed of 0.2 m, 0.3 m, 0.4 m, and 0.5 m thick was incorporated into the model within the pillar height at different positions and studied its impact on pillar strength. A simulation study revealed that the presence of a weak bedding plane at different positions in the pillar system reduces the strength of the pillar from 3.50% to 15%. However, it was found that the strength is reduced more in the case of a weak roof-pillar interface.

Keyword: Coal pillar; Weak bedding planes; Pillar strength; Field study; Numerical modelling

1. Introduction

The bord and pillar mining method (BPMM) is the most dominant and popular technique of underground coal extraction in India. It will continue to dominate in future considering prevailing geological discontinuities and techno-economical aspects. Galleries and pillars in BPMM are generally designed as per the Coal Mines Regulations 2017 [1] in India. The stability of the pillar [2] especially at the goaf edges during depillaring decides the efficacy of this method. The strength

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of a coal pillar is influenced by the nature of the material which forms it. Coal contains many natural discontinuities including weak bedding planes in pillar systems, which adversely affect its strength. It has been found that these pillars are frequently affected by natural discontinuities such as weak clay/shale band within pillar height, weak host strata (interfaces), cleats, slips, etc. which may deteriorate pillar strength and cause instability [3] during underground coal mining.

Further, these factors also influence the performance of the fender and rib/snook [4] during depillaring. It is therefore necessary that these discontinuities should be considered during its design. Inspection of coal mine workings has indicated that the intensity of discontinuities including the nature of host strata within the pillar system is highly variable. These create instability issues threatening the lives of miners and machinery, especially during pillar extraction when high values of induced stresses are observed over the pillars at higher depths. The presence of a clay band along with water creates the probability of sliding the whole pillar along this weak plane in an underground working environment. Knowledge of the behaviour of such pillars in terms of their strength and interaction with different natures of host strata would help in avoiding safety issues due to the premature failure of a pillar/fender/snook. The strength of a pillar affected by the discontinuities will be smaller as compared to the strength of an intact coal pillar, but it has not been quantified yet for the Indian coalfields. Efforts have been made in the past by foreign researchers [5] to study the shear strength of discontinuities in coal through laboratory testing without any field implications of pillar design. Researchers [6] have speculated about the adverse impacts of discontinuities on the strength and stability of coal pillars. The rock mass classification has also been utilised by researchers to investigate the impact of fractures on the stability of coal pillars.

Previous numerical modelling studies [7-9] found that the effects of discontinuities become more visible as the width-to-height (w/h) ratio of the pillar decreases. A numerical modelling study [10] was carried out for pillar strength estimation without considering discontinuities and observed that the strength of the pillar increases linearly with the w/h ratio, however, the post-failure modulus of the coal pillar was found to be non-linear. Further, pillar strength is found to be more sensitive to the strength of the interfaces between the coal pillar and the host rock strata, even at larger w/h ratios [5,11]. Therefore, it is required to determine the strength of the pillars affected by discontinuities for the safety of underground workings. Further, appropriate safety precautions and arrangements can be made for such vulnerable pillars during depillaring [12-13]. The possibility of the global collapse of the whole panel/district poses a major safety hazard to operating coal mines, which can be alleviated by the effective design of such coal pillars [14]. The available empirical formula for the estimation of coal pillar strength does not explicitly consider the effects of discontinuities (TABLE 1).

The performance of coal pillars can be strongly impacted by geological conditions, such as the inclination of the coal seam, the strength of the rock strata at the roof and floor, and the interfaces between the coal pillar and dirt band within the pillar height [3]. Additionally, it is reported that cohesive and frictional qualities affect coal strength, which aids in understanding how various pillar sizes behave under various geo-mining circumstances. According to Ran et al. [21], failure along weak interfaces at the roof-floor level can result from a pillar developed along the inclined coal seam under significant lateral stress. Considering the impact and safety threat issues due to discontinuities in the coal pillar, it is required to evaluate through field, laboratory, and numerical simulation studies. The outcomes of this study would prove to be useful for mining academicians and practitioners in designing coal pillars/fenders affected by discontinuities during development. Further, it would result in increased recovery with enhanced safety during the final pillar extraction.

TABLE 1

Available empirical approaches for pillar design

<table>
<tr><th>Sl. No.</th><th>Researcher (s)</th><th>Formula</th><th>Parameters</th><th>Remarks</th></tr>
<tr><td>1</td><td>Salamon and Munro [15]</td><td>$S_p = 7.2\frac{w^{0.46}}{h^{0.66}}$</td><td rowspan="3">$w$ – Effective width
h – Height of working</td><td rowspan="3">Based on in-situ strength of coal.

Discontinuities were not considered.</td></tr>
<tr><td>2</td><td>Madden [16]</td><td>$S_p = 5.24\frac{w^{0.63}}{h^{0.78}}$</td></tr>
<tr><td>3</td><td>Galvin [17]</td><td>$S_p = 6.88\frac{w^{0.5}}{h^{0.7}}$</td></tr>
<tr><td>4</td><td>Bunting [18]</td><td>$S_p = 6.9\left(0.7 + 0.3\frac{w}{h}\right)$</td><td rowspan="3">$w$ – Effective width
h – Height of working
H – Depth of cover
k – UCS of intact rock</td><td rowspan="3">Based on UCS of intact rock.

Developed irrespective of depth of cover except Sheorey, 1992.</td></tr>
<tr><td>5</td><td>Sheorey [19]</td><td>$S_p = 0.27kh^{-0.36} + \left(\frac{H}{250} + 1\right)\left(\frac{w}{h} - 1\right)$</td></tr>
<tr><td>6</td><td>van der Marwe [20]</td><td>$S_p = 5.47\frac{w^{0.8}}{h}$</td></tr>
<tr><td>7</td><td>Maleki [6]</td><td>$S_p = 32\left(1 - \exp\left(-\frac{0.339\,w}{h}\right)\right)$
[Confinement control]

$S_p = 26\left(1 - \exp\left(-\frac{0.264\,w}{h}\right)\right)$
[in structural control]</td><td rowspan="2">w – Effective width
h – Height of working</td><td>Considered weak and strong rock/coal mass.</td></tr>
<tr><td>8</td><td>Prassetyo et al. [5]</td><td>$S_p = 2.7\left(0.12 + 0.88\frac{w}{h}\right)$
[for low interface]</td><td>Developed based on interface friction study in the laboratory.</td></tr>
</table>

2. Field study

Seam No. I of Godavarikhani No. 11 Incline Mine of M/s Singareni Collieries Company Limited (SCCL), India is selected for the study. This coal seam contains different dirt bands such as shale, dull coal, clay, and carbonaceous clay (Fig. 1). Major portion of the panel was developed long back using conventional semi-mechanised technology with 2.5 m height and 3.6 m width along the middle horizon of the seam. As the panel was developed along the middle horizon, the roof coal band of around 2.5 m was found to be fractured during the field investigation. To accommodate the CM, the existing gallery is widened up to 6 m in width and heightened up to 5 m. The gallery's height and width are extended more than the statutory provisions [1] for manoeuvring of the CM with special permission from the Directorate General of Mines Safety, India. The stability of the proposed widened and heightened pillar is examined through empirical approaches and finite difference-based numerical modelling techniques. Brief geo-mining conditions of the considered Panel No. C-2 (Fig. 2) are given in (TABLE 2).

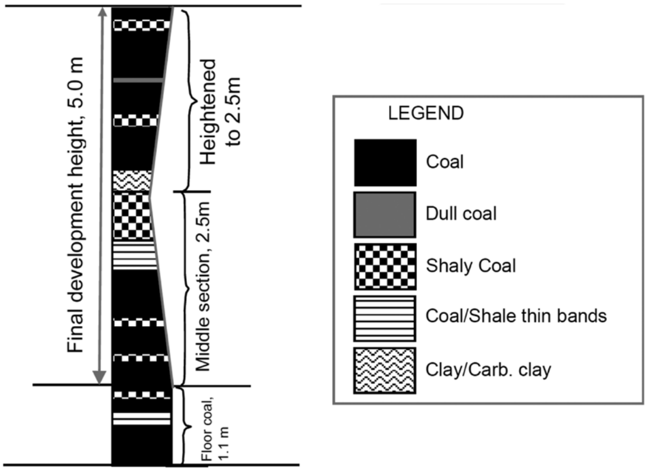

Fig. 1. Section of Seam No. 1 of Godavarikhani No. 11 Incline Mine

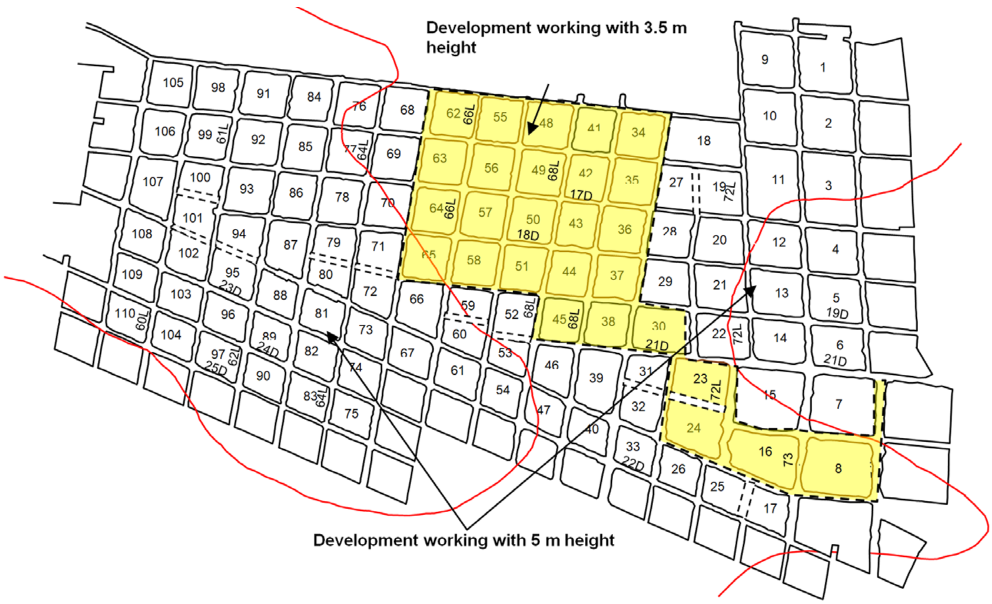

Fig. 2. Panel No. C-2 for widening and heightening using continuous miner

3. Study of Pillar Stability

Pillar stability is assessed through the factor of safety and effective width-to-height ratio using available empirical and laboratory-based formulations (TABLE 1). Numerical modelling is also done to find out the strength of a modelled pillar. Details of the pillar stability evaluation are mentioned below.

TABLE 2

Geo-mining details of CM Panel No. C-2

Parameter	Description
Name of the working seam	1
Seam thickness	6.10 m
The gradient of seam	7°-8° towards N60°E
Size of pillar (centre to centre)	36.5 m×41.5 m
Number of Pillar	110
Depth (m)	240 m to 291 m
Existing gallery size (width×height)	3.6 m×2.5 m
Gallery size after widening and heightening	6 m×5 m
RMR of immediate roof strata • Without adjusted • With adjusted (10% reduction due to conventional BPMM)	 61.31 55.18
Discontinuities/weak planes within pillar system	Shale/mudstone/carb. shale bands present within pillar height

3.1. Study on coal pillar design at selected mine using empirical approaches

Empirical and laboratory-based approaches [5-6,15-20] are used for estimation of pillar strength. The tributary area method is used to calculate load over the pillar. The factor of safety (FOS) of each pillar is estimated considering the pillar strength formula [19], which is established in Indian coalfields including the effective width-to-height ratio (TABLE 3). The formation of a pillar by driving galleries all around disturbs the state of virgin stresses, keeping the total weight of the overlying strata γH constant. Normally, it is assumed that the entire weight overlying strata with zero stiffness is coming over solid pillars. The stress on pillar (P) is estimated using the tributary area method as given in Eq. (1).

$$P = \frac{\gamma H}{1-e}, \text{ MPa} \tag{1}$$

where,

e – recovery $= \dfrac{\left[(W_1+B)(W_2+B)-(W_1W_2)\right]}{(W_1+B)(W_2+B)}$,

H – depth cover (m),
B – width of the gallery (m),
W_1 – length of pillar (m),
W_2 – width of pillar (m),
γ – unit rock pressure (0.025 MPa/m).

It is observed that each heightened (5 m) pillar seems to be squat, as the effective width-to-height ratio is more than the critical value of 5 [22-23]. Confinement and frictional resistance develop in the pillar due to the development of micro-cracks under the influence of the redistribution of stresses. It may behave as a transition mode (ductile to pseudo ductile) for bit

TABLE 3

Stability assessment of each heightened (5 m) pillar of panel C2

Pill No.	Length (m)	Width (m)	Height of pillar (m)	Effective Width-to-height ratio	Load (MPa)	Strength unbolted pillars (MPa)	FOS of unbolted pillars	Strength bolted pillars (MPa)	FOS of bolted pillars
1	2	3	4	5	6	7	8	9	10
1	35.9	44.6	5.00	7.96	8.79	18.29	2.1	20.68	2.4
2	35.9	44.2	5.00	7.92	8.80	18.23	2.1	20.60	2.3
3	35.9	59.3	5.00	8.94	8.53	20.33	2.4	22.98	2.7
4	35.9	37.2	5.00	7.31	9.00	16.95	1.9	19.17	2.1
5	35.9	36.7	5.00	7.26	9.01	16.85	1.9	19.05	2.1
6	35.9	36.5	5.00	7.24	9.02	16.81	1.9	19.01	2.1
7	45.3	46.2	5.00	9.15	8.49	20.75	2.4	23.46	2.8
9	35.8	44.3	5.00	7.92	8.80	18.22	2.1	20.59	2.3
10	35.8	44.4	5.00	7.93	8.80	18.23	2.1	20.61	2.3
11	35.8	59.3	5.00	8.93	8.53	20.30	2.4	22.95	2.7
12	36.2	37.2	5.00	7.34	8.99	17.02	1.9	19.24	2.1
13	35.9	36.7	5.00	7.26	9.01	16.85	1.9	19.05	2.1
14	35.9	36.2	5.00	7.21	9.03	16.75	1.9	18.94	2.1
15	46.0	46.1	5.00	9.21	8.48	20.88	2.5	23.60	2.8
17	28.0	29.2	5.00	5.72	9.72	13.68	1.4	15.46	1.6
18	51.0	35.9	5.00	8.43	8.66	19.26	2.2	21.78	2.5
19	26.2	36.6	5.00	6.11	9.49	14.48	1.5	16.37	1.7
20	32.6	36.8	5.00	6.91	9.14	16.14	1.8	18.25	2.0
21	35.9	36.9	5.00	7.28	9.01	16.89	1.9	19.10	2.1
22	35.9	36.8	5.00	7.27	9.01	16.87	1.9	19.08	2.1
25	28.9	31.3	5.00	6.01	9.55	14.28	1.5	16.14	1.7
26	28.9	31.8	5.00	6.06	9.53	14.37	1.5	16.25	1.7
31	27.6	26.4	5.00	5.40	9.92	13.02	1.3	14.71	1.5
32	27.4	24.6	5.00	5.18	10.06	12.58	1.3	14.22	1.4
33	29.0	31.1	5.00	6.00	9.56	14.26	1.5	16.12	1.7
39	27.2	45.1	5.00	6.79	9.18	15.88	1.7	17.95	2.0
40	27.7	31.7	5.00	5.91	9.60	14.08	1.5	15.92	1.7
46	26.7	35.7	5.00	6.11	9.50	14.49	1.5	16.37	1.7
47	26.9	32.0	5.00	5.85	9.64	13.94	1.5	15.76	1.6
52	28.9	36.5	5.00	6.45	9.33	15.19	1.6	17.17	1.8
53	28.4	24.5	5.00	5.26	10.01	12.73	1.3	14.40	1.4
54	28.2	31.6	5.00	5.96	9.58	14.18	1.5	16.03	1.7
59	30.0	24.1	5.00	5.35	9.95	12.91	1.3	14.59	1.5
60	30.2	24.0	5.00	5.35	9.95	12.92	1.3	14.60	1.5
61	30.5	30.5	5.00	6.10	9.51	14.46	1.5	16.35	1.7
66	30.1	40.0	5.00	6.87	9.15	16.05	1.8	18.15	2.0
67	30.1	30.5	5.00	6.06	9.53	14.38	1.5	16.26	1.7
72	29.0	30.3	5.00	5.93	9.60	14.11	1.5	15.95	1.7
73	28.3	31.1	5.00	5.93	9.60	14.11	1.5	15.95	1.7
74	28.6	30.5	5.00	5.90	9.61	14.06	1.5	15.89	1.7

1	2	3	4	5	6	7	8	9	10
75	28.5	28.9	5.00	5.74	9.70	13.72	1.4	15.51	1.6
76	28.0	36.3	5.00	6.32	9.39	14.92	1.6	16.87	1.8
77	28.0	37.1	5.00	6.38	9.36	15.05	1.6	17.01	1.8
78	28.1	37.3	5.00	6.41	9.35	15.10	1.6	17.08	1.8
79	28.3	24.9	5.00	5.30	9.98	12.81	1.3	14.48	1.5
80	28.7	24.9	5.00	5.33	9.96	12.88	1.3	14.56	1.5
81	28.8	30.9	5.00	5.96	9.58	14.18	1.5	16.03	1.7
82	28.6	30.7	5.00	5.92	9.60	14.10	1.5	15.94	1.7
83	28.7	28.8	5.00	5.75	9.70	13.74	1.4	15.54	1.6
84	27.0	36.4	5.00	6.20	9.45	14.67	1.6	16.59	1.8
85	27.2	37.2	5.00	6.28	9.41	14.85	1.6	16.78	1.8
86	27.3	37.4	5.00	6.31	9.40	14.90	1.6	16.85	1.8
87	27.4	42.9	5.00	6.69	9.22	15.68	1.7	17.72	1.9
88	26.7	30.5	5.00	5.69	9.73	13.63	1.4	15.41	1.6
89	27.2	29.9	5.00	5.70	9.73	13.63	1.4	15.41	1.6
90	27.5	29.3	5.00	5.67	9.74	13.59	1.4	15.36	1.6
91	31.7	36.4	5.00	6.78	9.19	15.86	1.7	17.93	2.0
92	31.8	37.5	5.00	6.88	9.15	16.08	1.8	18.18	2.0
93	31.5	37.5	5.00	6.85	9.17	16.01	1.8	18.09	2.0
94	31.4	29.8	5.00	6.12	9.50	14.50	1.5	16.39	1.7
95	31.1	30.9	5.00	6.20	9.46	14.67	1.6	16.58	1.8
96	30.0	29.2	5.00	5.92	9.60	14.09	1.5	15.93	1.7
97	30.0	29.5	5.00	5.95	9.59	14.15	1.5	16.00	1.7
98	29.2	36.5	5.00	6.49	9.32	15.27	1.6	17.26	1.9
99	29.1	37.5	5.00	6.55	9.29	15.40	1.7	17.41	1.9
100	29.2	27.2	5.00	5.63	9.77	13.50	1.4	15.26	1.6
101	29.1	26.5	5.00	5.55	9.82	13.33	1.4	15.06	1.5
102	28.9	31.6	5.00	6.04	9.54	14.34	1.5	16.21	1.7
103	29.4	28.6	5.00	5.80	9.67	13.84	1.4	15.65	1.6
104	29.3	29.7	5.00	5.90	9.61	14.05	1.5	15.88	1.7
105	29.1	36.5	5.00	6.48	9.32	15.24	1.6	17.23	1.9
106	29.0	37.7	5.00	6.56	9.29	15.41	1.7	17.42	1.9
107	28.9	45.6	5.00	7.08	9.07	16.48	1.8	18.63	2.1
108	28.9	31.8	5.00	6.06	9.53	14.37	1.5	16.25	1.7
109	28.9	28.0	5.00	5.69	9.73	13.62	1.4	15.39	1.6
110	28.8	30.0	5.00	5.88	9.62	14.01	1.5	15.83	1.7

strain hardening characteristics. Considering the heightened pillars and lower factor of safety, each pillar is supported by the application of glass-fibre reinforced plastic bolting. It will help in confinement from the surroundings of the pillar and will control induced stress-driven spalling in the heightened pillars. Further, pillar strength is also increased after application of the side bolting [22], which is mentioned in TABLE 3.

An attempt is made to estimate the strength of the heightened pillar considering the average size (36.50 m × 41.50 m, centre to centre), depth and other geo-mining conditions (TABLE 4) of the pillar using the formulations mentioned in TABLE 1. The estimated pillar's strength and factor of safety using the available empirical approaches are given in TABLE 5 and Fig. 3.

TABLE 4

Geo-technical details of the pillar

Mine/Panel	**Average pillar size (m × m) (centre-to-centre)**	W_1 **(m)**	W_2 **(m)**	W_e **(m)**	B **(m)**	h **(m)**	**Average Depth (m)**	σ_c **(MPa)**	P **(MPa)**	W_e/h
GDK-11/C2	36.50 m × 41.50	30.5	35.5	32.81	6	5	266	30.5	9.30	6.56

TABLE 5

Factor of safety of developed pillars

Empirical approach	**Strength**	**FOS**
Prassetyo et al. [5]	15.92	1.71
Maleki [6]	21.40	2.30
Sheorey [19]	16.09	1.73
Salamon and Munro [15]	12.40	1.33
Madden [16]	13.47	1.45
Galvin [17]	12.77	1.37
van der Marwe [20]	17.86	1.92
Bunding [18]	18.41	1.98

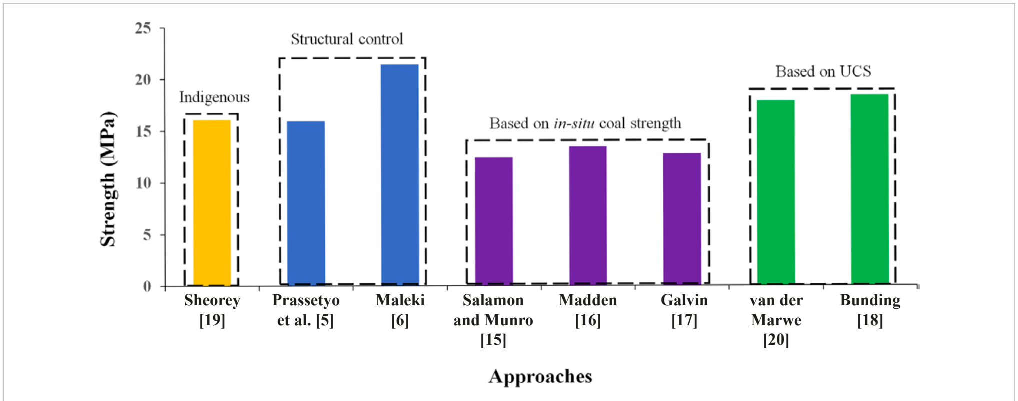

Fig. 3. Comparison of estimated coal pillar strength using available pillar design approaches

The comparison of estimated coal pillar strength using available pillar design approaches revealed that, except for in-situ coal strength, most of the empirical approaches exhibit FOS greater than 1.5, which is appropriate for stability during depillaring at this mine [12]. Although the approaches [5,6] are based on structural control, there is a notable difference in the estimated strength (Fig. 3). The fact that tested the UCS of coal specimens made by adding weak layer at interfaces rather than intact coal is one of the main drivers of this disparity [5], Sheorey's empirical approach [19] is well accepted in Indian coalfields for strength determination as it also incorporates the depth of cover, but the effect of geological discontinuities is lacking. Hence, this paper determines the effect of weak bedding planes over the pillar and its positional effect with numerical modelling.

3.2. Study on Coal Pillar Behaviour Using Numerical Modelling

Simulation study on numerical models is a versatile approach for designing different forms of natural support of an underground mine [7-10]. The selection of a suitable constitutive model is an important factor for any simulation study to design competent natural supports like coal pillar, fender and snook. Deformation in a natural support depends on the depth of working, redistribution of stresses during the mining activities, levels of pre-mining elastic accumulated energy etc. The gallery is driven to form a natural support that causes the dissipation of accumulated energy which leads to fracturing/spalling in the support surrounding the excavation [24]. The fracturing/spalling in the natural supports is subjected to the aperture, frequency, orientation of geological discontinuities [25], and rock mass rating [26-27] which is exaggerated due to redistribution of stresses especially at greater depth and during pillar extraction. Considering the findings of field observations, a finite difference-based software tool employing Mohr-Coulomb Strain Softening (MCSS) is chosen for the working seam, while elastic constitutive properties are considered for other strata.

The conversion of intact rock strength to rock mass was done as per Sheorey's failure criterion. The failure criterion has been developed indigenously [28] by testing the varying strength of coal measure formations in a laboratory at different confining strengths. It was found to be deviating from the in-built Mohr-Coulomb Strain Softening (MCSS) failure criterion in FLAC3D. Therefore, a FISH function was developed in FLAC3D to incorporate this failure criterion instead of MCSS to find out the strength of the coal pillar. This criterion is based on Beniawski's rock mass rating [26] for the reduction of the strength of intact rock to the corresponding rock mass. The criteria are outlined below:

$$\sigma_1 = \sigma_{cm}\left(1+\frac{\sigma_3}{\sigma_{tm}}\right)^{b_m} \tag{2}$$

$$\sigma_{cm} = \sigma_c \exp\left(\frac{RMR-100}{20}\right) \tag{3}$$

$$\sigma_{tm} = \sigma_t \exp\left(\frac{RMR-100}{27}\right) \tag{4}$$

$$b_m = b^{RMR/100};\ b_m < 0.95 \tag{5}$$

where,

σ_1 – major principal stress of rock mass (MPa),
σ_3 – confining stress or minor principal stresses (MPa),
σ_c – compressive strength of intact rock (MPa),
σ_t – tensile strength of the intact rock in MPa,
b – exponent of intact rock,
m – stands for the rock mass.

Shear strength (τ_{sm}) coefficient (μ_{0m}) and the friction angle (ϕ_{0m}) of the rock mass can be obtained using the Eqs. (6-10).

$$\tau_{sm} = \left(\sigma_{cm}\, \sigma_{tm} \frac{{b_m}^{b_m}}{\left(1+b_m\right)^{1+b_m}} \right)^{1/2} \tag{6}$$

$$\mu_{0m} = \frac{{\tau_{sm}}^2 \left(1+b_m\right)^2 - {\sigma_{tm}}^2}{2\tau_{sm}\sigma_{tm}\left(1+b_m\right)} \tag{7}$$

$$\phi_{0m} = \tan^{-1}(\mu_{0m}) \tag{8}$$

$$\tau_{sm(residual)} = 0 \tag{9}$$

$$\phi_{0m(residual)} = \phi_{0m} - 10° \tag{10}$$

The values obtained through the above-mentioned equations were used in numerical models. Nevertheless, these factors were modified marginally as a numerical tool (FLAC^{3D}) for the study based on the linear Mohr-Coulomb failure criterion, whereas the Sheorey failure criterion is non-linear. To compensate for the disparity in nature, the estimated values of shear strength and friction angle based on the Sheorey failure criterion were increased by 10% and decreased by 5°, respectively (Fig. 4), before being used as Mohr-Coulomb parameters [29].

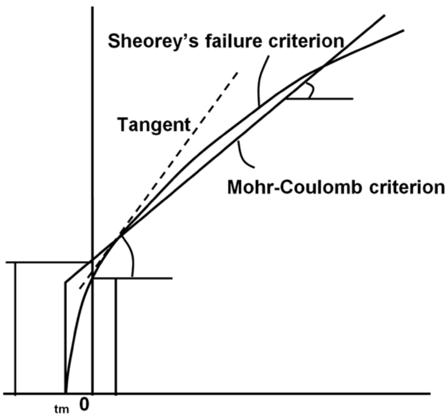

Fig. 4. Non-linearity of Sheorey criterion against the linear Mohr-Coulomb criterion adopted in the simulation package [28]

3.2.1. Assessment of strength without weak bedding planes in pillar system

At the outset, an attempt is made to evaluate pillar strength through numerical modelling without the incorporation of weak bedding planes and its validation with available indigenous empirical approaches [19]. A block of 20 m×18 m×105 m is generated for quarter symmetry modelling to examine the strength of the coal pillar without weak bedding planes (Fig. 5). This model is developed considering rock mass properties including geo-mining conditions of a coal seam of GDK-11 Incline Mine. The depth of cover of the selected coal seam is 266 m. The thickness of the coal seam considered in the model is 5 m and developed with 5 m height and 6 m width of gallery. A truncated load of 0.025H MPa (H = depth of cover) for the unmodelled portion of the overlying strata is applied over the top of the model. The strength of the quarter symmetry pillar is estimated to be similar to a coal sample's strength determined in the laboratory using a Universal Testing Machine. It is adopted for the estimation of pillar strength through simulation by applying a constant velocity of 8.25×10^{-5} m/s on top of the model. The sides of the model (at 0 m and 20 m along the x-axis & at 0 m and 18 m along the y-axis) are kept on rollers, the bottom boundary is fixed, and the top one is kept free as shown in Fig. 5.

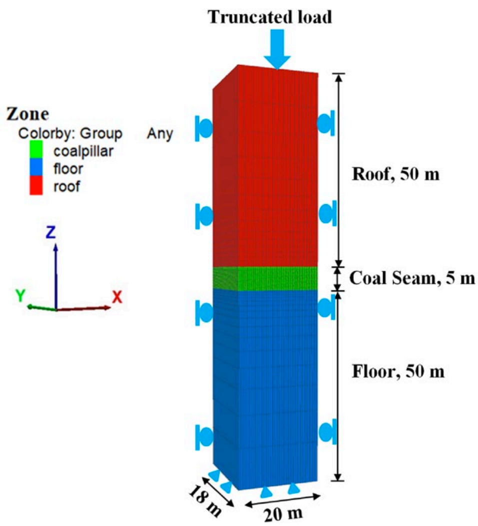

Fig. 5. In-situ quarter symmetry model for evaluation of pillar strength

3.2.2. Calibration of model

The properties of materials obtained through laboratory testing are fine-tuned through the results of different initial test models of a quarter symmetry of the pillar. The obtained values of strength (Fig. 6) from numerical simulations of a quarter symmetry of a pillar are compared with the value obtained by the empirical pillar strength [19] formula (Eq. 11).

$$S = 0.27\sigma_c h^{-0.36} + \left(\frac{H}{250}+1\right)\left(\frac{w_e}{h}-1\right), \text{ MPa} \tag{11}$$

where,

S – pillar strength in MPa,
σ_c – uniaxial compressive strength of coal in MPa,
h – working height in meter,
H – depth of cover in meter,
w_1 – length of the pillar (corner to corner) in meter,

w_2 – width of the pillar (corner to corner) in meter,
effective pillar width (w_e) = $4A/P_c$,
area of the pillar (A) = $w_1 \times w_2$ and
perimeter of the pillar (P_c) = $2 \times (w_1 + w_2)$.

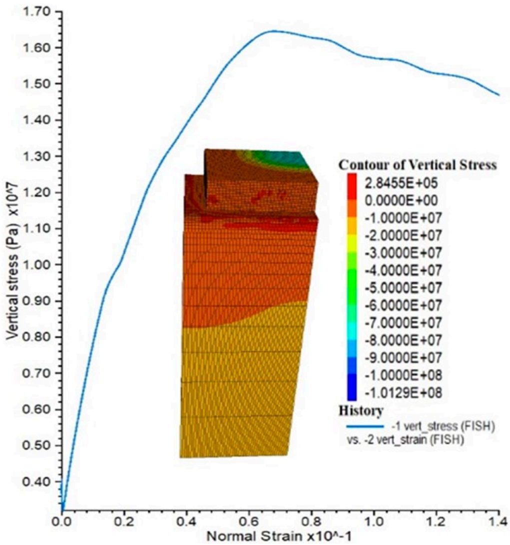

Fig. 6. Strength of coal pillar based on stress-strain behaviour without discontinuities

The adopted failure criterion has helped in calibrating the numerical models by considering the best representative set of MCSS parameters (cohesive strength and its variation with strain and frictional angle and its variation with strain rate) for Indian geo-mining conditions. After calibrating the numerical model, pillar strength was estimated in FLAC^{3D} by replicating the servo-controlled laboratory testing in FLAC^{3D}. Pillar strength estimated in FLAC^{3D} is found to be matching with the strength estimated using the empirical formula developed by Sheorey [19] for Indian geo-mining conditions. It is to be mentioned here that Sheorey [19] developed an empirical formula to estimate coal pillar strength based on failed and stable cases in Indian coal mines. A set of properties (TABLE 6), which provided good agreement between the empirical and numerical values of the strength, are finally selected for the simulation.

TABLE 6

Properties used for modelling of coal pillars

Strata	**Young's modulus (E) MPa**	**Poisson's ratio (v)**	**Bulk modulus (K) GPa**	**Shear modulus (G) GPa**	**Density of rock mass (d) Kg/m^3**	**UCS of intact rock (σ_c) MPa**	**Tensile strength (σ_t) MPa**	**Rock mass rating (RMR)**
Coal	2	0.25	1.33	0.80	1400	30.5	3.05	48
Shale	7.68	0.14	3.56	3.37	2292	47	4.7	47
Sandstone	7	0.25	4.67	2.80	2250	30	3	48
Discontinuities	0.5	0.25	0.33	0.20	1000	5	0.5	20

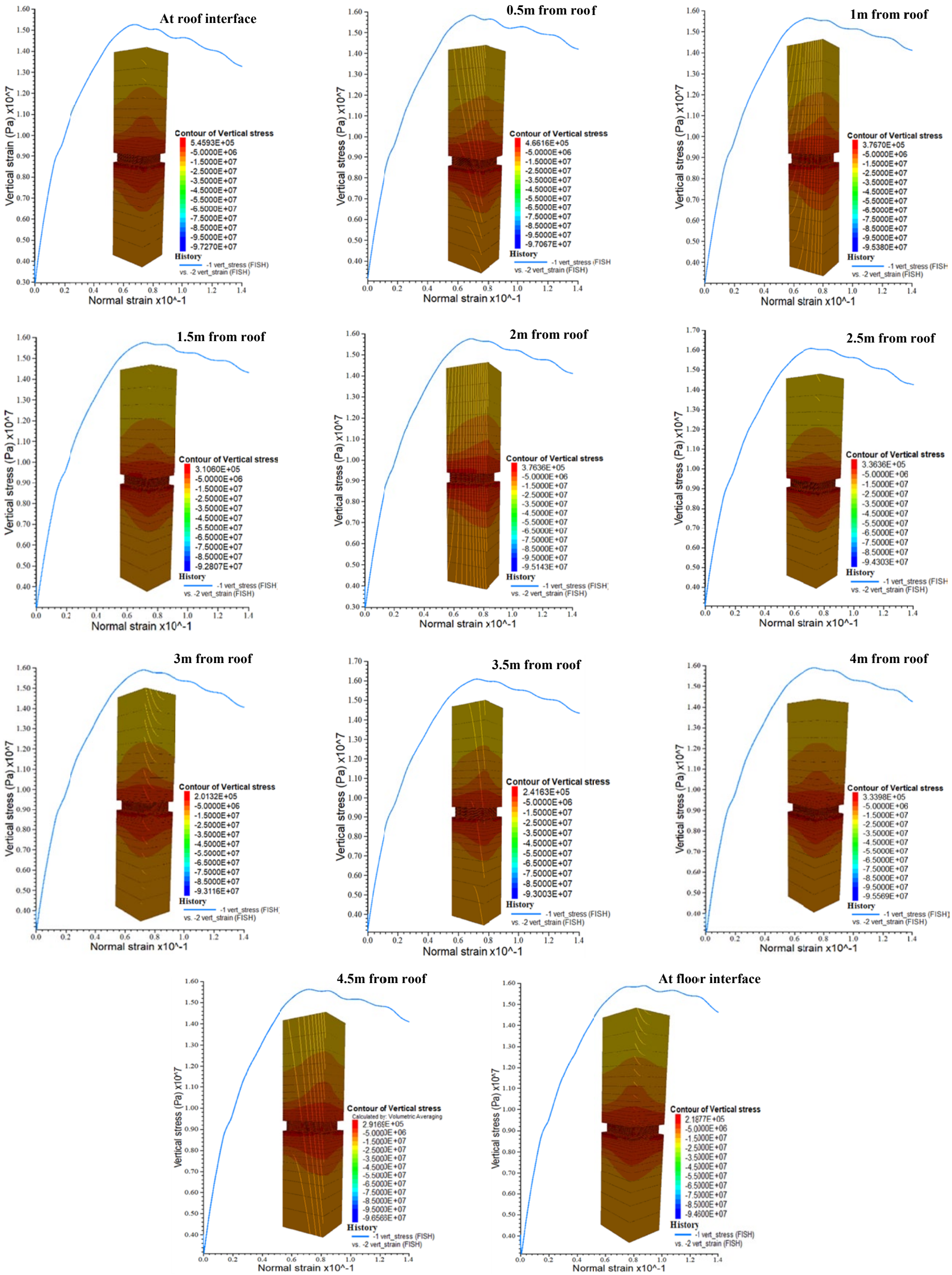

Fig. 7. Variation in stress-strain behaviour including strength of pillars having 0.2 m thick weak bedding plane at different positions in pillar system

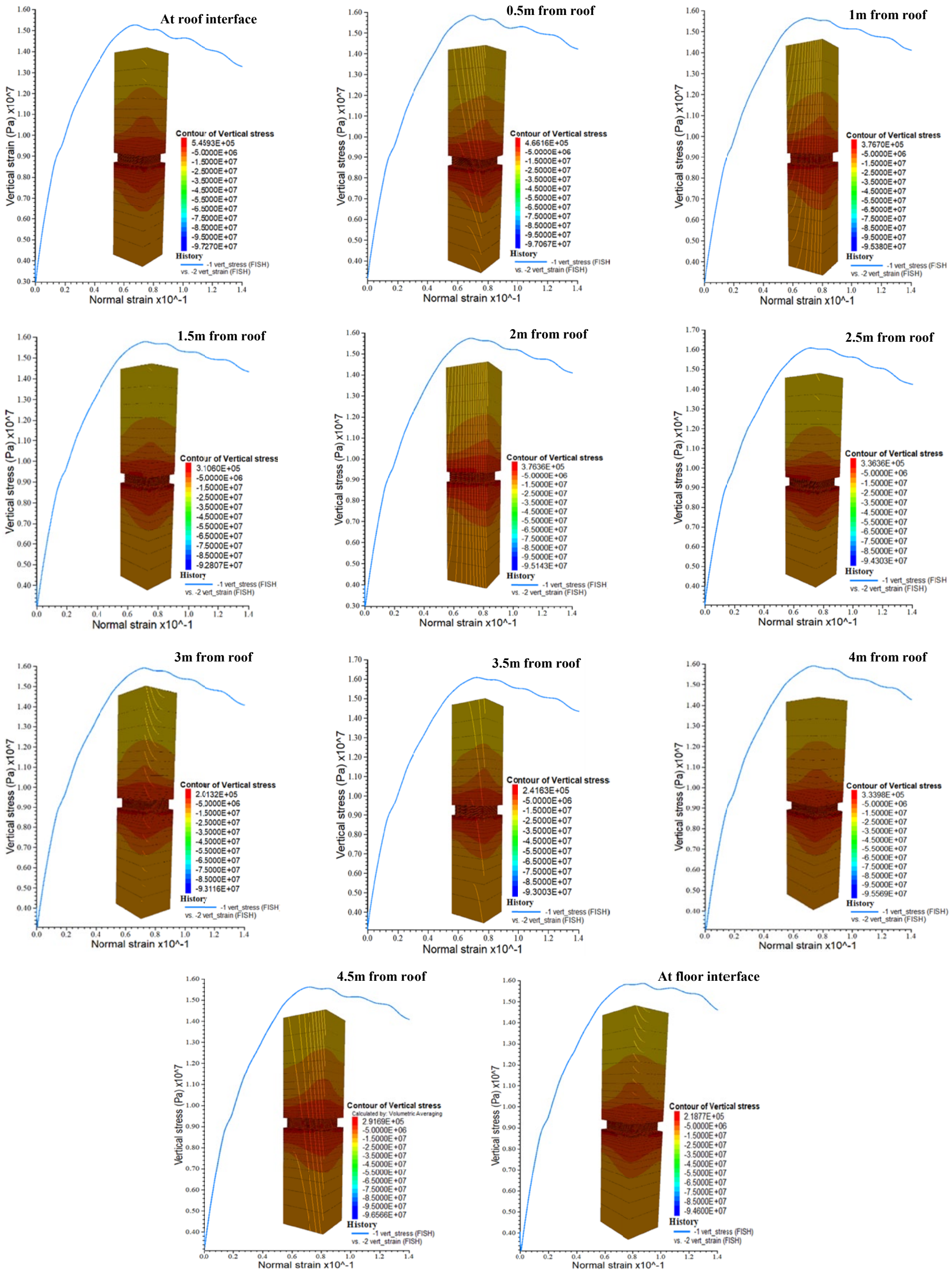

Fig. 8. Variation in stress-strain behaviour including strength of pillars having 0.3 m thick weak bedding plane at different positions in the pillar system

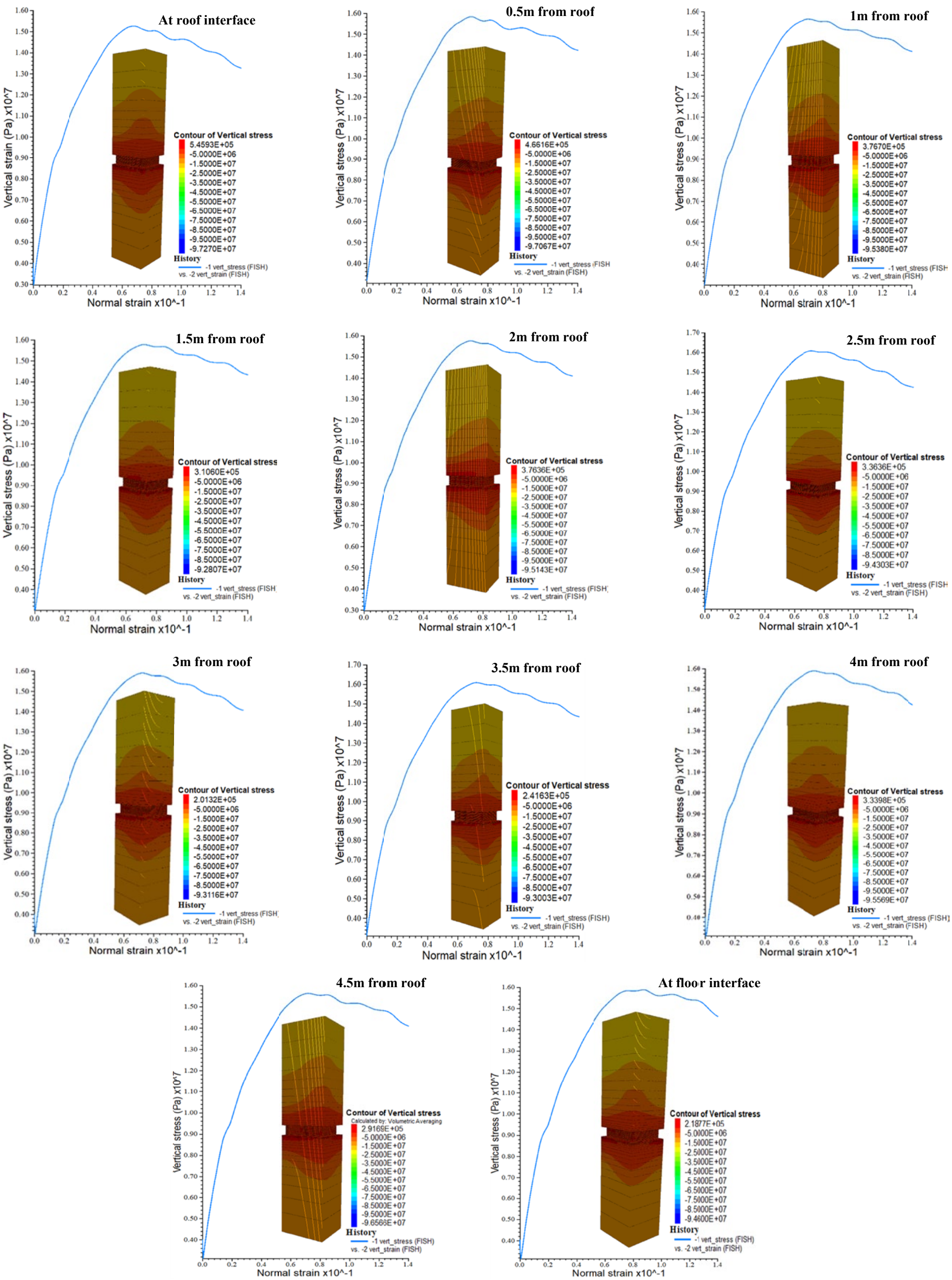

Fig. 9. Variation in stress-strain behaviour including strength of pillars having 0.4 m thick weak bedding plane at different positions in the pillar system

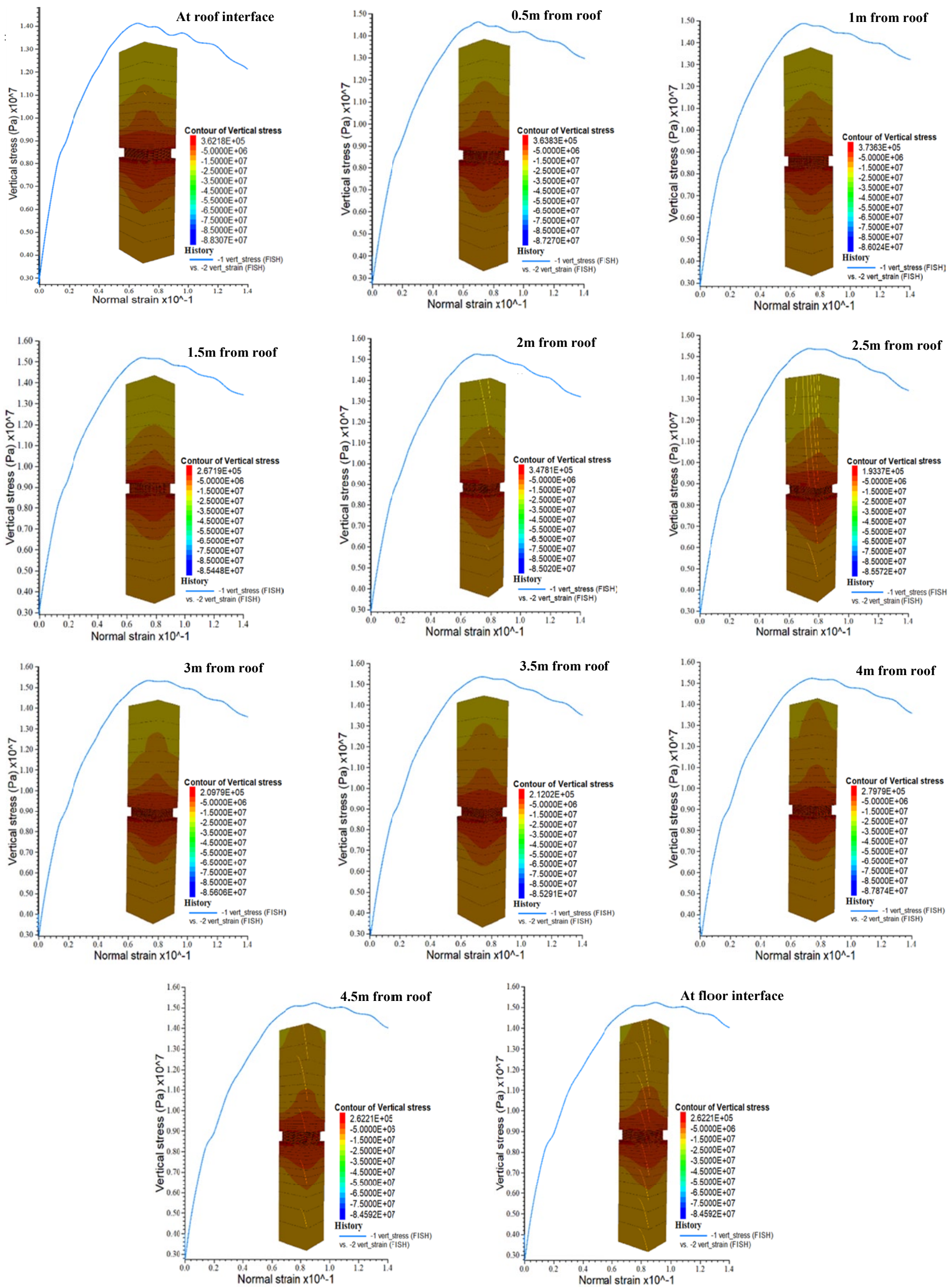

Fig. 10. Variation in stress-strain behaviour & strength of pillars with 0.5 m weak bedding plane at different positions

3.2.3. Impact of discontinuities on pillar strength

After the validation of simulation results with those of the indigenous empirical approach, an attempt is made to visualize the impact of weak bedding planes (discontinuities) in the pillar system. Weak bedding planes of 0.2 m, 0.3 m, 0.4 m, and 0.5 m thick at different positions within pillar height are incorporated separately to know the thickness and positional effects on strength (Figs. 7-14).

There are a total of 11 different positions of weak bedding planes considered within 5 m development height for numerical simulation study including roof-pillar-floor interfaces. The impact of the weak plane is examined by varying its position at 0.5 m intervals within the pillar height. Results of the numerical simulation study revealed that the pillar strength was reduced by 3.5-15% for the considered thickness and positions of weak planes in the pillar system as given in TABLE 7. Pillar strength is minimal when the weak bedding plane is present at the roof-pillar interface while maximum at the middle horizon (2.5 m below the roof) of the pillar.

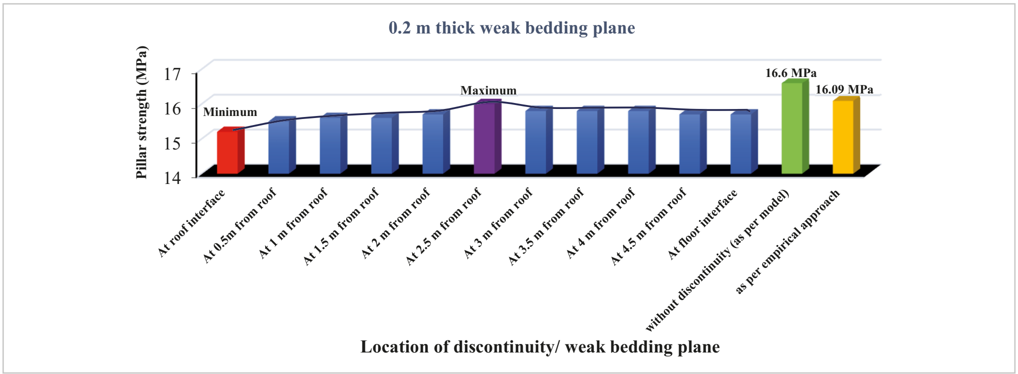

Fig. 11. Variation in strength of pillar with weak bedding plane of 0.2 m at different positions in the pillar system observed through numerical modelling

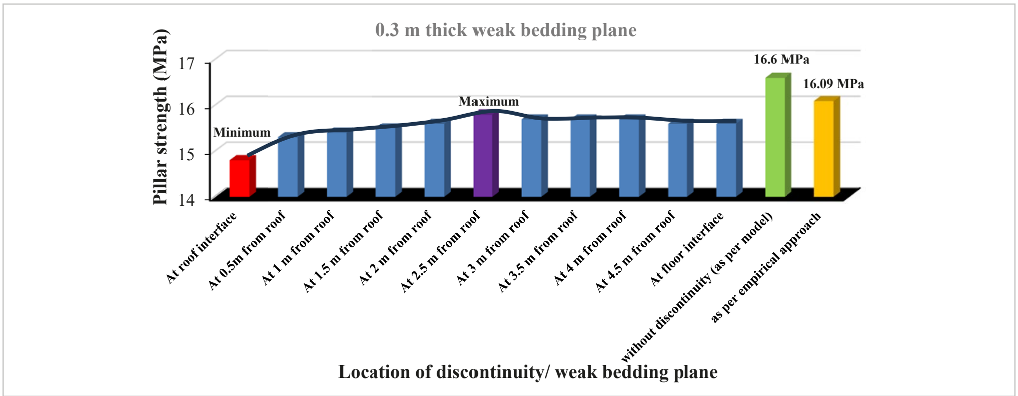

Fig. 12. Variation in strength of pillar with different position of weak bedding plane of 0.3 m in the pillar system observed through numerical modelling

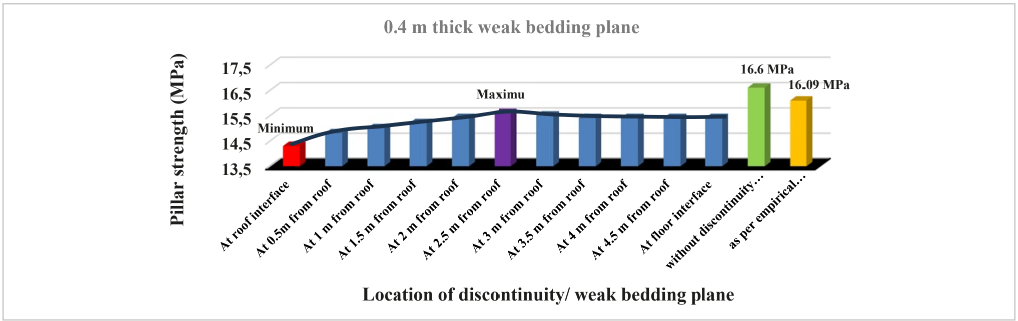

Fig. 13. Variation in strength of pillar with different position of weak bedding plane of 0.4 m in the pillar system observed through numerical modelling

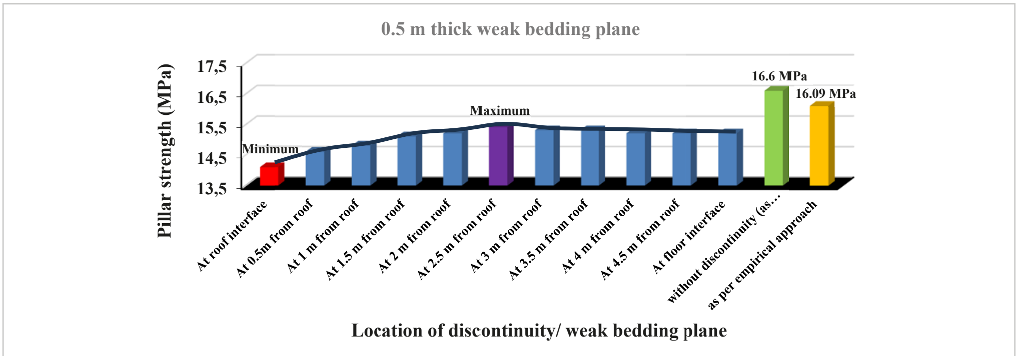

Fig. 14. Variation in strength of pillar with different position of weak bedding plane of 0.5 m in the pillar system observed through numerical modelling

4. Results and discussion

Non-uniform vertical and horizontal in-situ stress distribution developed on roof-pillar-floor interfaces during the formation of a coal pillar. The average vertical stress due to the overlying strata, also known as average pillar stress, acts as normal to the roof-pillar interface resulting in an increase in its shear strength. The lateral movement towards the surrounding gallery of a pillar depends on the properties/nature of the interfaces. The presence of weak bands at the interface creates weak bedding planes, which help in the lateral straining of a pillar resulting into reduced confinement around the pillar core. Finally, the strength of a coal pillar reduces due to the weak bedding planes.

Further, the presence of weak bedding planes at different horizons of pillar height causes a reduction in its strength. Development of the pillar stress is dependent on the depth of cover, width of the surrounding gallery of a pillar, pillar area, and cohesive & frictional properties of the weak bedding planes. Required friction and cohesion properties at the interface are essential for transferring loads from the roof to the pillar and preventing the lateral squeezing of a pillar. A simple numerical simulation study with variation in thickness of the weak bands and their positions within pillar height including the roof-pillar-floor interfaces is carried out and assesses

TABLE 7

Results of numerical modelling by varying the location of discontinuity in the pillar system

S. No.	Location of discontinuity	Impact of weak bedding planes over Pillar strength in model (MPa)				Pillar strength without discontinuity in model (MPa)	Pillar strength [19] (MPa)	Remarks
		Thickness of weak bedding plane						
		0.2 m	0.3 m	0.4 m	0.5 m			
1	At roof-pillar interface	15.20	14.80	14.30	14.10	16.60	16.09	Presence of discontinuity reduces the pillar strength. 0.2 m = 3.5-8.5% 0.3 m = 4.5-11% 0.4 m = 6-14% 0.5 m = 7-15%
2	0.5m from roof	15.50	15.40	14.80	14.60			
3	1 m from roof	15.60	15.40	15.00	14.80			
4	1.5 m from roof	15.60	15.60	15.20	15.10			
5	2 m from roof	15.70	15.60	15.40	15.20			
6	2.5 m from roof	16.00	15.80	15.60	15.40			
7	3 m from roof	15.80	15.70	15.50	15.30			
8	3.5 m from roof	15.80	15.70	15.40	15.30			
9	4 m from roof	15.80	15.70	15.40	15.20			
10	4.5 m from roof	15.70	15.60	15.40	15.20			
11	At pillar-floor interface	15.70	15.60	15.40	15.20			

their impact on pillar strength. The presence of weak bedding planes within the coal pillar significantly influences its strength. The results of the numerical simulation study incorporating the weak bedding planes are shown in Fig. 15.

Pillar strength reduction varies from 3.5% to 15%, depending on the thickness of the weak bedding plane and its position in the pillar system. The weak bedding plane at the roof-pillar

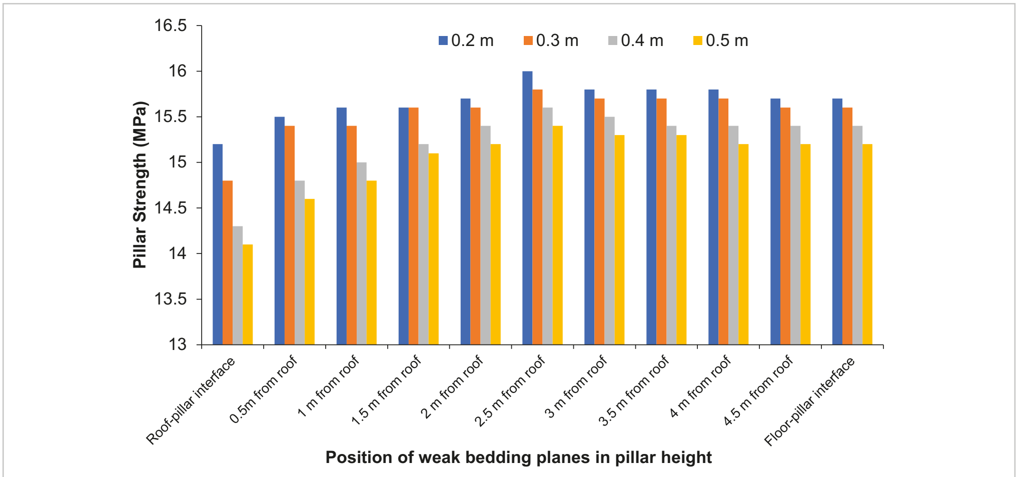

Fig. 15. Results of Numerical modelling studies incorporating weak bedding planes of varying thickness at different positions within pillar height

interface caused the most significant reduction in pillar strength. The maximum reduction of 15% is observed for a 0.5 m thick weak bedding plane at the roof-pillar interface. The roof-pillar interface is a critical zone where induced overburden vertical stress concentrations lead to the initiation of considerable lateral movement and weaken the pillar strength (Fig. 15).

A weak plane at this juncture disrupts this load transfer, leading to a reduction in the overall strength of the pillar due to poor confinement. As the weak bedding plane was positioned away from the roof, its impact on pillar strength gradually decreased. The presence of weak bedding planes at the pillar-floor interface also caused a reduction in pillar strength but it was relatively less in comparison to the roof-pillar interface. Further, it is observed that the presence of weak bedding planes above the middle horizon of a pillar is found to be more vulnerable to strength reduction concerning the other conditions. The reduction in pillar strength due to weak bands is also influenced by their thickness, with thicker bands causing more substantial reductions.

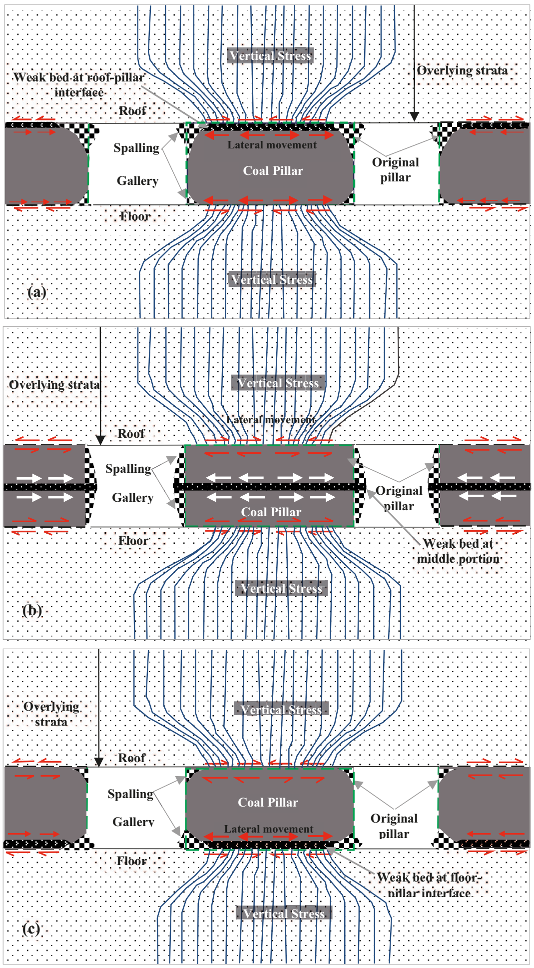

Fig. 16. Conceptual model for strata mechanics considering weak beds at three different horizons of a pillar: a) Weak bed at roof-pillar interface, b) Weak bed at middle portion, and c) Weak bed at floor-pillar interfac

An attempt is also made to develop conceptual models for lateral movement considering weak bands at three different positions in pillar height (Fig. 16). It indicates that lateral movement with weak bands at the roof-pillar interface is relatively more in comparison to the other positions.

The findings suggest that current indigenous empirical methods [19] for pillar strength assessment, which do not account for geological discontinuities, may overestimate the strength of coal pillars having weak bedding planes. This study emphasizes the necessity for integrating numerical modelling techniques to account for such discontinuities, thereby providing a more accurate estimation of pillar strength for safe mining. This insight can guide the design of coal pillars, particularly in areas with known geological weaknesses, ensuring safer and more efficient mining operations. This study provides a framework for further research and practical application, enabling the development of more robust and reliable coal pillar design methodologies that can consider the complex geological conditions often encountered in coal seams.

5. Conclusions

The strength of a coal pillar is reduced due to geological discontinuities within the pillar system. A review of the relevant literature revealed that most available empirical approaches are based on the w/h ratio and strength of coal/coal mass. Few foreign researchers have evaluated the effect of interface friction on pillar strength based on laboratory investigations. However, consideration of geological discontinuities within the pillar system is lacking. Field study shows that the geological settings of the pillar system contain a wide range of diversity that is yet to be quantified in the strength calculation for competent design.

Results of a simple numerical simulation study with positional variation of 0.2 m, 0.3 m, 0.4 m, and 0.5 m thick weak bedding planes within the pillar height revealed that its strength was reduced from 3.50% to 15%. Further, it was found that more strength is reduced in the case of a weak bedding plane at the roof-pillar interface. When a weak bedding plane/discontinuity is positioned away from its roof, its effect on pillar strength gradually decreases.

If the weak bedding plane is in the middle of a pillar and the roof-pillar-floor interfaces are free from weak planes, there is relatively less impact over the pillar. Pillar strength is inversely proportional to the thickness of a weak bed. This study will help academicians and engineers to design coal pillars which are affected by weak bands.

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