

Evaluation of Pillar Stability Across Different Extraction Depths Using FLAC3D Numerical Modeling: a case study on Kakatiya Khani No. 5 Incline located in the Godavari Valley Coalfield, Telangana

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ABSTRACT

Coal pillar stability is one of the most critical factors governing the safety, productivity, and economic viability of underground coal mining operations employing the bord-and-pillar mining method. As mining activities progress to greater depths, the stress environment surrounding underground excavations becomes increasingly complex, resulting in higher pillar loading, stress concentration, and potential instability. The present study investigates the influence of extraction depth on coal pillar stability through three-dimensional numerical modeling using FLAC3D software. A detailed case study was conducted based on the geological and geotechnical conditions of Kakatiya Khani No. 5 Incline, operated by Singareni Collieries Company Limited (SCCL), Telangana, India.

A three-dimensional numerical model representing the roof-pillar-floor system was developed using the Mohr–Coulomb constitutive model. Mine-specific geological parameters, material properties, pillar dimensions, and boundary conditions were incorporated into the simulation framework to replicate actual field conditions. Parametric analyses were performed for five different depths of working, namely 240 m, 280 m, 300 m, 330 m, and 360 m, while maintaining constant pillar geometry and gallery dimensions. The study evaluated stress distribution patterns, pillar strength characteristics, failure mechanisms, and factor of safety (FOS) values under varying overburden loading conditions.

The simulation results revealed a significant increase in pillar stress with increasing depth of extraction. The average pillar stress increased from approximately 17.5 MPa at a depth of 240 m to about 21.1 MPa at 360 m depth. Stress concentration was predominantly observed along the pillar edges and corners, indicating these regions as the most vulnerable zones for failure initiation. Although pillar strength exhibited a marginal increase due to confinement effects, the rate of stress increase was substantially higher, resulting in a gradual reduction in the factor of safety with increasing depth. The numerical analysis further demonstrated that deeper workings are associated with higher risks of pillar instability, localized yielding, and potential roof control problems.

Statistical evaluation of the simulation results established a strong positive correlation between extraction depth and induced pillar stress, confirming the significant influence of overburden loading on pillar performance. The findings emphasize the necessity of adopting depth-dependent pillar design methodologies rather than relying on conventional empirical approaches. The study demonstrates that FLAC3D-based numerical modeling provides a reliable and effective tool for evaluating pillar behavior, optimizing pillar dimensions, and improving mine safety in underground coal mines.

The outcomes of this research contribute to the understanding of depth-related pillar behavior and provide valuable guidelines for mine planners, design engineers, and safety professionals in developing scientifically sound pillar design strategies for deep underground coal mining operations.

Keywords: Coal Pillar Stability; Bord and Pillar Mining; FLAC3D; Numerical Modeling; Underground Coal Mining; Factor of Safety; Stress Distribution; Pillar Design; Geotechnical Engineering; Mine Safety; Extraction Depth; Rock Mechanics.

1. Introduction

Coal remains one of the most important sources of energy worldwide and continues to play a vital role in the economic development of many countries, including India. A significant portion of coal reserves is extracted through underground mining methods, among which the bord-and-pillar method is the most widely practiced due to its operational flexibility, safety, and suitability under varying geological conditions. In this method, a network of roadways is developed while leaving coal pillars intact to support the overlying strata. The stability of these pillars is critical for maintaining underground safety, preventing roof collapses, and ensuring uninterrupted mining operations.

As mining activities progress to greater depths, the stress conditions acting on underground excavations become increasingly severe due to the weight of the overburden. Increased vertical and horizontal stresses result in higher loads on coal pillars, which may lead to pillar deformation, spalling, yielding, or catastrophic failure if not adequately designed. Therefore, understanding the influence of extraction depth on pillar behavior is essential for developing safe and efficient mine designs. Traditional pillar design methods are primarily based on empirical relationships and field observations. Although these methods have been successfully applied in many mining situations, they often fail to capture the complex interactions between geological conditions, stress redistribution, and pillar response at greater depths.

Recent advancements in computational techniques have enabled the application of numerical modeling for analyzing rock mass behavior and pillar stability under different mining conditions. Numerical methods provide a powerful tool for simulating realistic stress environments and evaluating the performance of pillars under varying geotechnical conditions. Among these methods, FLAC3D has emerged as one of the most reliable software packages for analyzing underground excavations due to its ability to model complex rock mass behavior and stress-strain relationships.

The present study focuses on evaluating pillar stability across different extraction depths using FLAC3D numerical modeling. A case study of Kakatiya Khani No. 5 Incline, operated by Singareni Collieries Company Limited (SCCL), Telangana, India, has been selected for analysis. Numerical simulations were conducted for depths ranging from 240 m to 360 m to investigate stress distribution, pillar strength, and factor of safety. The outcomes of this study provide valuable insights into depth-dependent pillar behavior and contribute to the development of scientifically sound pillar design guidelines for deep underground coal mining operations.

1.1 Background

The extraction of coal seams using the board and pillar mining method presents significant challenges in maintaining pillar stability and ensuring safety during the depillaring process. The depillaring operation becomes particularly problematic when dealing with strong and massive roof strata, as increasing the depth of working can lead to a dilution in strength. This dilution can fail barrier pillar and goaf overriding, posing serious risks to underground mining operations.

To address these challenges, this Thesis focuses on investigating the variation in pillar strength and evaluating the factor of safety in the context of depillaring of coal seams by increasing the depth of working. The Thesis aims to enhance the understanding of pillar strength variation and its impact on the depillaring process, ultimately leading to more effective and safer underground mining operations.

1.2 Aim of the Study

To evaluate the stability of pillars across different extraction depths using numerical modeling, investigating the effects of depth on pillar strength, stress distribution, and failure mechanisms, and providing insights for optimizing pillar design and ensuring safe and efficient mining operations.

The goal of the present investigation is to evaluate the factor of safety of the Bord and Pillar working of a local colliery. The goal is achieved by following specific objectives.

1.3 Objectives

The specific objectives of this Thesis are as follows:

- Creating a three-dimensional model of the pillar by using FLAC3D Assessment of the strength of the pillars at different depths of workings.
- Assessment of FOS of pillars at different depths of workings.
- To develop a numerical model that simulates pillar behavior at varying extraction depths.
- To investigate the effects of depth on pillar strength and failure mechanisms.
- To analyze the relationship between extraction depth and pillar stability.

2. Study area and Mine Details

The present study was carried out at **Kakatiya Khani No. 5 Incline (KTK-5 Incline)**, an underground coal mine operated by **The Singareni Collieries Company Limited (SCCL)** in the Jayashankar Bhupalpalli district of Telangana, India. The mine forms part of the **Bhupalpalli Block-I of the Godavari Valley Coalfield**, one of the most important coal-producing regions in South India. Geographically, the mine is located between latitudes **18°25'00"N and 18°26'30"N** and longitudes **79°50'38"E and 79°52'32"E**, approximately 66 km from Warangal city.

- | | | |
|------------------------------|----|---|
| a) Name of mine | :- | Kakatiya Khani No. 5 Incline |
| b) Geological Block | :- | Bhupalpalli block I of Mulugu coal belt. |
| c) Topo&Co-ordinates | :- | Topo sheetNo.56N/15 |
| | | Latitude: N18-25'-00''to18-26'-30'' |
| | | Longitude: E79-50'-38''to79-52'-32'' |
| d) Permissions / AP approval | :- | Kakatiya Khani 5 Incline is the second mine in |
| | | Bhupalpalli area. The feasibility report of Project |
| | | was prepared in October 1989. |

2.1Board approval: - Board of SCCL was approved on15-12-1989 for an annual targeted production of 2.75Lakh tons with capital investment of Rs.1966 lakhs and the targeted production was to be achieved in 1994-95. But due to adverse general lawandordersituationininitialyearsofprojectconstructionresultedinslow progress of tunnelling and other construction activities.

The cost of over run of project had well exceeded the sanctioned capital by more than 20%. So revised cost estimate of KTK5 Incline has been prepared for annual targeted production of 4.10 Lakh tons with capital expenditure of Rs. 4,019 lakhs and the targeted production was to be achieved in 2003-04.

a) Mining lease: -For 172.65 Ha. Land Letter No. G.O. MS No. 230, Dt. 31-05-1988.

Renewal G.O. MS No. 14, Dt. 09-03-2010. For 144 Ha. Forest Land G.O. MS.

No. 155 Dt. 26.5.2003

b) **Mining plan approval:** -Govt. of India was approved vide Ministry of coal letter dated 1107- 1997.

Date of opening: -KTK5 Incline was opened in April 1993

KTK-5 Incline was commissioned in **1993** and employs the conventional **bord-and-pillar mining method** for coal extraction. The mine contains nine coal seams, namely 1A, 1, 2 (Top), 2 (Bottom), 3A, 3B, 3, 4A, and 4, of which Nos. 1, 2 (Top), 2 (Bottom), and 3 seams are economically workable. The depth of workings varies from **50 m to 420 m**, while the present operational depth is approximately **340 m**. The mine possesses geological reserves of about **28 million tonnes**, with extractable reserves estimated at **15.91 million tonnes**.



The immediate roof strata mainly consist of sandstone with fair to good rock mass quality ratings (RMR 57–64), providing moderate roof stability conditions. The mine is classified as a **Degree-I gassy mine** and operates under semi-mechanized mining conditions. These geological and geotechnical characteristics make KTK-5 Incline a suitable case study for evaluating pillar stability under varying extraction depths using numerical modeling techniques.

2.1.1 Geotechnical Details

KTK-5 Incline is having total 9 seams viz. 1A, 1, 2(top), 2(bottom), 3A, 3B, 3, 4A, and 4 seams in descending order in the lease hold area of the mine, of which the No.1, No.2(top), No.2(bottom) and No.3 seams are found to be persistent throughout the area with workable thickness. 1A and 4 seams attained workable thickness only over certain patches

Sl. No	No./Name of the seam	Depth of workings		Gradient	Grade	Thickness	Balance extractable Reserves as on 31.03.2011
		Minimum	Maximum				
1	No.1Aseam	virgin		1in2.5	D	1.6m	0.06m.t. with 1.6mw.s.
2	No.1Seam	50m	350m	1in2.5	E	2.8m	2.4m.t.
3	No.2(top) Seam	80m	120m	1in2.5	E	1.8m	0.4m.t. with 1.8mw.s.
4	No.2(bottom) Seam	50m	300m	1in2.5	E	4.2m	3.3m.t. with 2.8w.s.
5	No.3Seam	50m	420m	1in2.5	B	3.0m	2.0m.t.
6	No.4Seam	virgin		1in2.5	B	1.8m	0.06m.t. with 1.8m.w.s.

Table 2.1 : Depth of Working Seams

Gassiness: -Degree I

IMMEDIATE ROOF OF WORKING SECTION: -

Seam	Roof	Compressive Strength	Classification	Final R.M.R
1	Stone	210Kg/Sq.cm.	III(Fair)	57.60
2T	Stone	144Kg/Sq.cm.	IIIB(Fair)	60.04
2B	Stone	460Kg/Sq.cm.	IIIB(Fair)	59.96
3	Stone	270Kg/Sq.cm.	IIA(Good)	63.54

Table 2.2: Immediate Roof of Working Section

2.1.2 RESULTS OF CHEMICAL ANALYSIS OF COAL SAMPLES

Sl.No.	Seam No.	Crossing Point		Ignition Point in Oxygen °C
		In Oxygen °C	In Air °C	
01	1	168	190	183
02	2	171	196	183
03	3	166	195	175

Table 2.3 Results of Chemical Analysis of Coal Samples

1	Name of the Project	:	KakatiyaKhani-5Incline
2	Organization	:	Singareni Collieries Company Limited
3	Coalfield	:	Godavari Valley Coal Field

4	Type of Mine	:	Underground Coal Mine Project
5	Technology	:	Semi-Mechanization
6	Environmental Clearance	:	
	A Letter No &date	:	. Ir.no. J-11015/312/2007-IA. II(M), dated:31.10.2008
	B Sanction capacity	:	Normative:0.30MTPA Peak:0.60MTPA
	C Mining Lease Area	:	316.65ha
	D Date of Public Hearing	:	11.04.2008
7	Location of the Project	:	
	A Village	:	Bhupalpalli
	B Tehsil	:	Bhupalpalli
	C District	:	Jayashankar
	D State	:	Telangana

	E Latitude	:	18°30'00"to18°31'31"
	F Longitude	:	79°44'49"to79°46'39"
	G Topo Sheet	:	56 N/15
	H Nearest railway station	:	Warangal
	I Nearest Airport	:	Shamshad Hyderabad
	J Nearest town	:	Warangal

8	Address for Correspondence		:	
	A	Name	:	Sri J. Rajashekar
	B	Designation	:	Dy. General Manager
	C	Address	:	O/agent, KTK-5Incline, Bhupalpalli, Dist.: Warangal
	D	Pin Code	:	506169
	F	E-mail ID	:	agt_klp_bhp@scclmines.com
	G	Telephone No.	:	7382608945
	H	Fax No.	:	08713-220208
9	Life of the Project		:	
	A	Date of Opening	:	1993
	B	Total life of the project as per EMP	:	52Years
	C	Balance Life	:	22years
10	Seams		:	
	A	Total Seams Present	:	9 (no's)
	B	Seams being worked	:	3
11	Depth		:	
	A	Minimum Depth(m)	:	32m

	B	Maximum Depth(m)	:	430m
	C	Present working depth(m)	:	340m
12	Reserves		:	
	A	Total Geological Reserves	:	28 MT

	B	Total Extractable Reserves	:	15.91MT
	C	Reserves already Extracted	:	7.138MT
	D	Balance Reserves	:	8.772MT
	E	Coal production during as t year	:	3,40,000T
13	Land Requirement			
	A	Non-forestland		172.65ha
	B	Land acquired so far (Surface rights)		145.29 ha
14	Statutory Clearances		:	
	A	Ground Water Clearance		No.1862/T/2003-04/755, Dated05-11-2005
	B	Consent for Establishment	:	No:60/PCB/CFE/RO- WGL/HO/2009/590, DT.04.06.2009
	C	Consent for Operation	:	Order No. APPCB/10471/ZO- HYD/HO/CFO/2013-5675 dt.18.12.2013, Validuptodt.30.06.2015
	D	Forest Clearance	:	VideGO.MS.No:44, Dt:13.05.2002
	E	Mining Lease	:	BhupalpalliminingleaseG.O.Ms.No.14, dt .09.03.2010for20Yearsfrom04.06.2009to 03.08.2029
	F	Others (Specify)		-
15	R&R Involved		:	-

3. METHODOLOGY

The present study was conducted to evaluate the stability of coal pillars at different extraction depths using numerical modeling techniques. A systematic methodology was adopted to investigate the influence of depth on pillar strength, stress distribution, and factor of safety (FOS) under underground mining conditions. The methodology consisted of data collection, model development, numerical simulation, result analysis, and validation.

3.1 Data Collection and Mine Characterization

The first stage involved collecting geological, geotechnical, and operational data from Kakatiya Khani No. 5 Incline (KTK-5 Incline), operated by Singareni Collieries Company Limited (SCCL), Telangana. Information regarding seam thickness, depth of workings, pillar dimensions, gallery width, roof and floor characteristics, rock mass properties, and mining geometry was gathered from mine records and technical reports. Geotechnical properties such as Young's modulus, Poisson's ratio, density, cohesion, friction angle, and tensile strength were used as input parameters for the numerical model.

3.2 Development of Numerical Model

A three-dimensional numerical model was developed using FLAC3D (Fast Lagrangian Analysis of Continua in Three Dimensions), a widely used software for rock mechanics and geotechnical analysis. The model represented the roof-pillar-floor system of the underground mine and was designed to simulate actual field conditions. The geometry of the model consisted of a coal pillar surrounded by galleries, with roof and floor strata extending sufficiently beyond the excavation boundaries to minimize boundary effects.

The dimensions adopted in the model included a pillar width of 40 m, pillar height of 3 m, gallery width of 4 m, and roof and floor dimensions of 44 m × 44 m. The model was discretized into finite difference zones to ensure accurate stress and deformation calculations. A finer mesh was used near the pillar and excavation boundaries where stress concentration was expected.

3.3 Material Properties and Constitutive Model

The Mohr–Coulomb constitutive model was selected to represent the behavior of coal and surrounding rock strata. This model is widely accepted for simulating elastic-plastic behavior of rock masses. Material properties assigned to the roof, pillar, and floor included Young's modulus, density, cohesion, friction angle, Poisson's ratio, and tensile strength. These parameters were obtained from mine-specific geotechnical investigations and published literature.

3.4 Boundary Conditions and Stress Initialization

Appropriate boundary conditions were applied to simulate in-situ stress conditions. The bottom boundary of the model was fixed in the vertical (Z) direction, while lateral boundaries were constrained in the horizontal directions (X and Y). Roller boundary conditions were applied to allow realistic deformation while preventing rigid body motion.

The in-situ vertical stress was calculated based on the overburden depth using:

$$\sigma_v = 0.025H$$

where:

(σ_v) = Vertical stress (MPa)

(H) = Depth of working (m)

The horizontal stress was determined using:

$$[\sigma_h = 2.4 + (0.01H)]$$

where:

(σ_h) = Horizontal stress (MPa)

These stress values were applied to simulate the loading conditions at different mining depths.

3.5 Simulation Scenarios

A parametric study was performed by varying the depth of working while maintaining constant pillar geometry and gallery dimensions. Five simulation cases were considered at depths of 240 m, 280 m, 300 m, 330 m, and 360 m. For each case, stress distribution, deformation characteristics, pillar strength, and failure patterns were analyzed.

The factor of safety (FOS) was calculated using:

$$[FOS = \frac{\sigma_p}{S_p}]$$

where:

(σ_p) = Pillar strength (MPa)

(S_p) = Stress acting on the pillar (MPa)

Pillar strength was estimated using the Sheorey pillar strength equation, which incorporates pillar dimensions, depth of cover, seam height, and coal strength.

3.6 Analysis and Validation

The simulation results were analyzed by examining stress contours, pillar stress concentration, and factor of safety values. Comparative analysis was carried out among all depth scenarios to identify trends in pillar behavior. The obtained results were compared with established rock mechanics principles and findings reported in previous studies to validate the reliability of the numerical model.

The adopted methodology provided a comprehensive framework for assessing the impact of extraction depth on coal pillar stability and developing recommendations for safe pillar design in deep underground coal mines.

4.0 Model Preparation

In order to prepare the model, we have to write code to run in FLAC 3D software. At first, the code is prepared in a text document. The code is developed by using fish language. The numerical procedure consists of grid generation, appropriate material behaviour- or model selection as follows. In grid or mesh generation, the mesh size and mesh ratio are given in X Y Z direction, i.e., $10 \times 10 \times 10$ and 1 1 1, respectively.

The model geometry values are

❖ Floor values Width 44 m Length 44 m

Height 10 m

❖ Pillar values width 40 m, length 40m

height of pillar 3 m gallery values 4 m

❖ roof values width 44 m length 44 m

❖ height 240, 280, 300, 330 360M

The floor, pillar, roof is attached by the zone attach command.

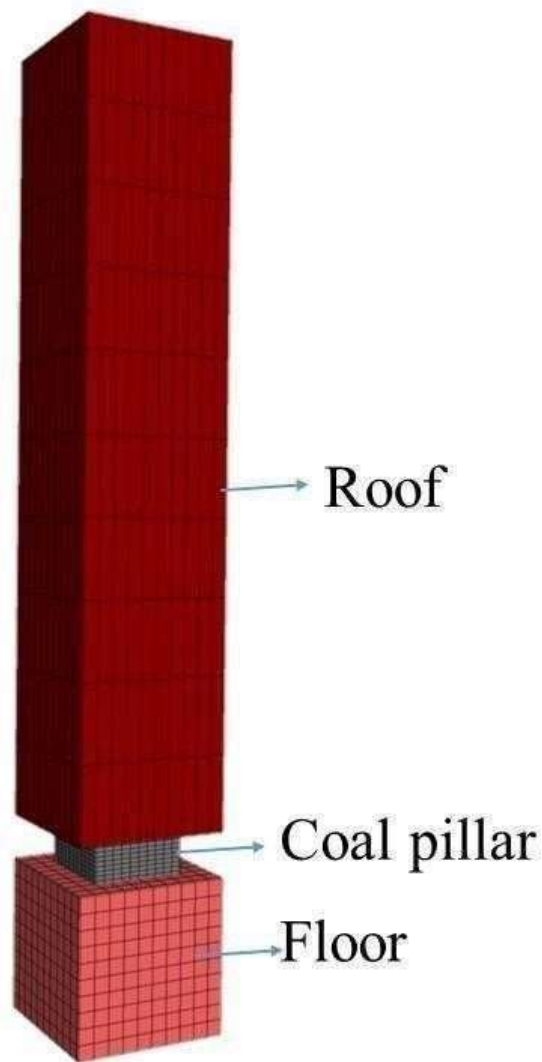


Fig. 3.1: Three-dimensional discretized view of a model

4.1 Material Properties

The material properties are taken for analysing the stress acting on the pillar in Z position ranges the properties in below table.

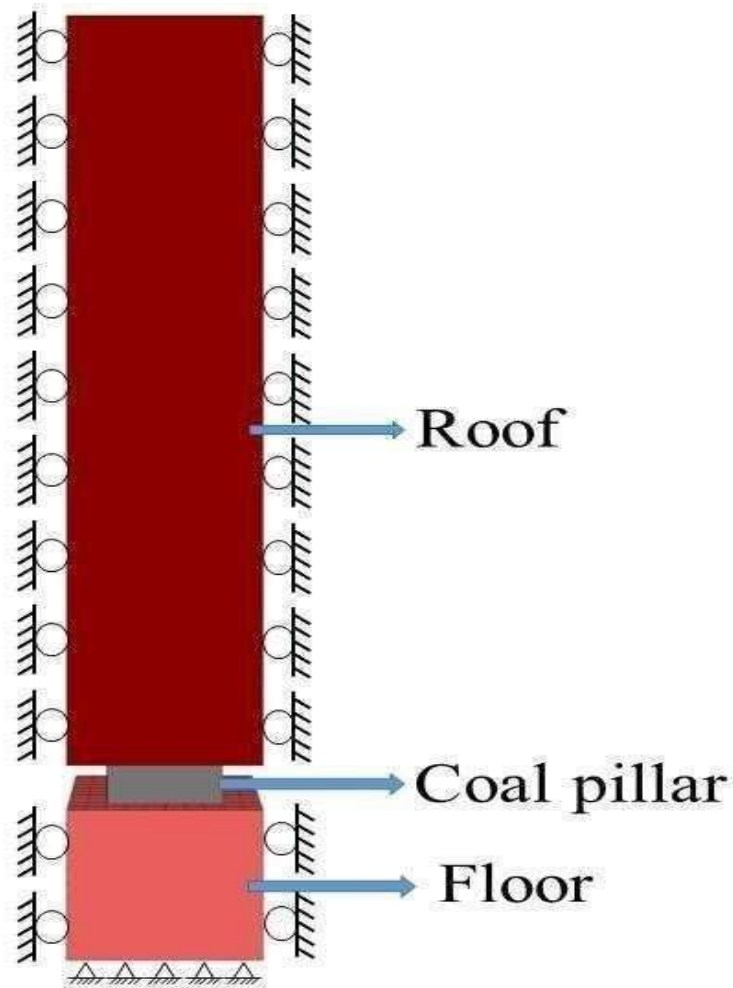
Table 5.1: Material properties used in FLAC 3D Software

Strata	Thickness In meters	Youngs modulus (GPa)	Poisson's ratio	Density Kg/m ³	Cohesion (MPa)	Friction	Tension (MPa)
Floor	10	2	0.25	2500	10	25	0.2
Coal pillar	2.5 – 4.5	2	0.25	1400	3	25	0.2
Roof	350	2	0.25	2500	10	25	0.2

The Mohr-coulomb constitutive model is applied to the model.

4.2 Boundary Conditions and Stress Initialization

The boundary conditions are applied in Z, X, and Y directions. The boundary condition in the numerical model has been defined so that the vertical wall of the model is fixed in the



X and Y directions, and the model's floor is fixed in the Z direction. Roller boundary condition was applied to the model in lateral X and Y directions. Fixed boundary condition was applied to the model in the Z direction.

```
;;slope failure;;

model new
program threads 8
model largestrain of
model gravity 10

zone create brick size 10 10 10 ratio 1 1 1 ...
point 0 0,0,0 ...
point 1 44,0,0 ...
point 2 0,44,0 ...
point 3 0,0,10 ...group 'floor'

zone create brick size 10 10 10 ratio 1 1 1 ...
point 0 2,2,10 ...
point 1 42,2,10 ...
point 2 2,42,10 ...
point 3 2,2,13 ...group 'pillar'

zone create brick size 10 10 10 ratio 1 1 1 ...
point 0 0,0,13 ...
point 1 44,0,13 ...
point 2 0,44,13 ...
point 3 0,0,253 ...group 'roof'

zone attach by-face

;;material properties;;

zone cmodel assign mohr-coulomb range position-z 0 10
zone property young = 2e9 poisson = 0.25 density =2.5e3 cohesion = 10.0e6 friction 25 tension 0.2e3 range position-z 0 10

zone cmodel assign mohr-coulomb range position-z 10 13
zone property young = 2e9 poisson = 0.25 density =2.5e3 cohesion = 2.0e6 friction 25 range position-z 10 13

zone cmodel assign mohr-coulomb range position-z 13 253
zone property young = 2e9 poisson = 0.25 density =2.5e3 cohesion = 1.0e6 friction 25 tension 0.2e3 range position-z 13 253

;;boundary conditions;;

zone face apply velocity-z 0.0 range position-z 0.0

zone face apply velocity-x 0.0 range position-x 44
zone face apply velocity-x 0.0 range position-x 0

zone face apply velocity-y 0.0 range position-y 0.0
zone face apply velocity-y 0.0 range position-y 44

model factor-of-safety
model save "ppl"
```

Fig 4.1: Flac 3D Software code text document

5.1 Scheme of Simulation

The scheme of simulation is presented in a flow chart as shown below

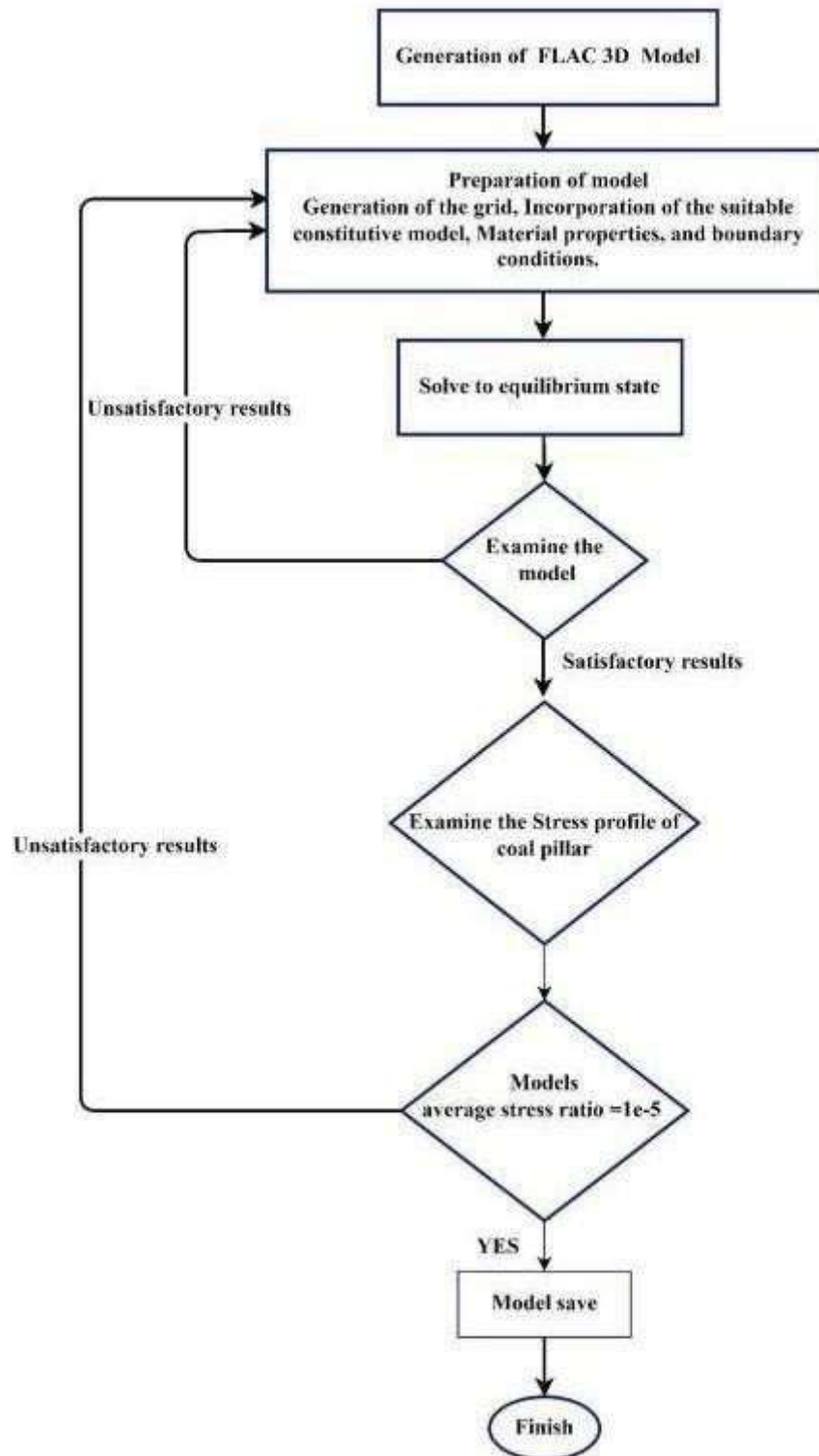


Fig. 5.1: Scheme of simulation

Results and discussion:

6.1 Parametric Study

After the case study, we did a parametric study by increasing the depth of work and keeping the size of the pillar and gallery width constant. Initially, we took the depth of working from 240 m, then increased up to 360 m. The results were impressive. They were observed keenly and thoroughly. We drew the graphs by taking the depth of working- stress load values strengths values- and factor of safety. And the equations are created to know the relationships between each of them.

6.1.1 Case No 1: 240 m Depth of Working Model

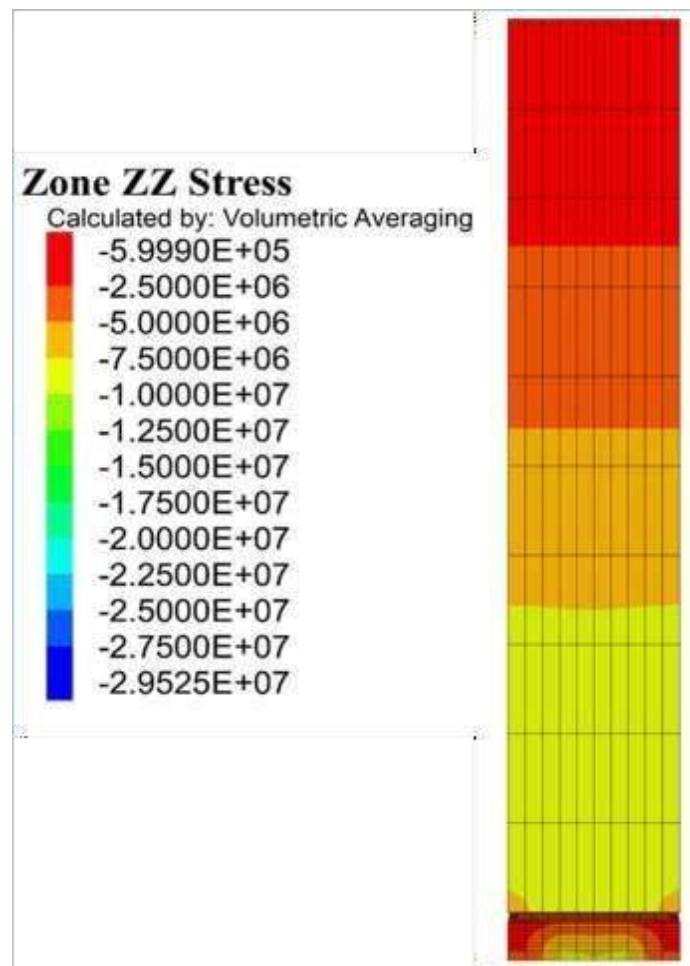


Figure 6.1: Side view of 240 m model

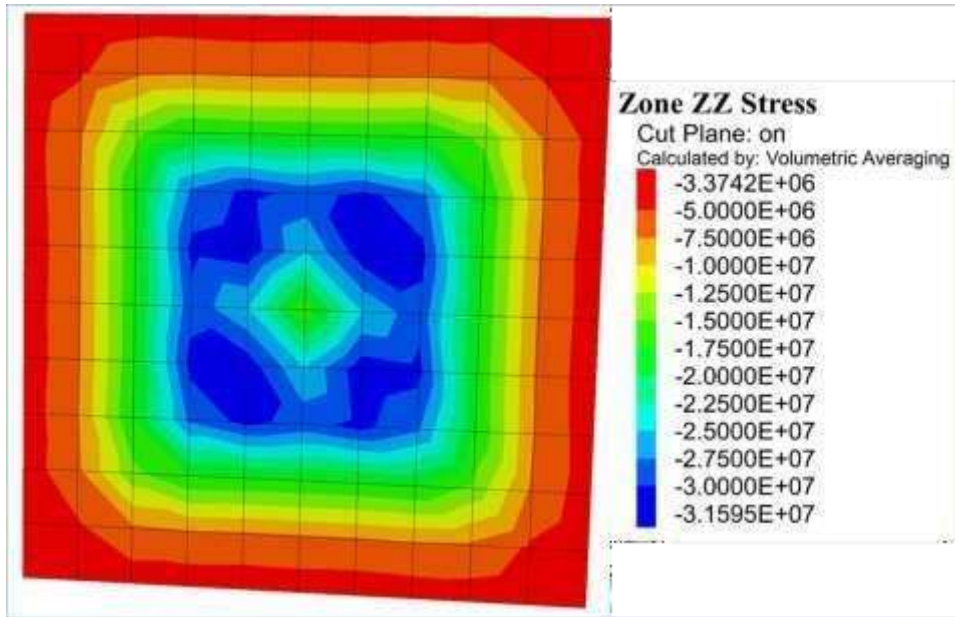


Figure 6.2: Stress profile at middle of pillar at a depth of 240 m

6.1.2 Case No. 2: 280 m Depth of Working Model

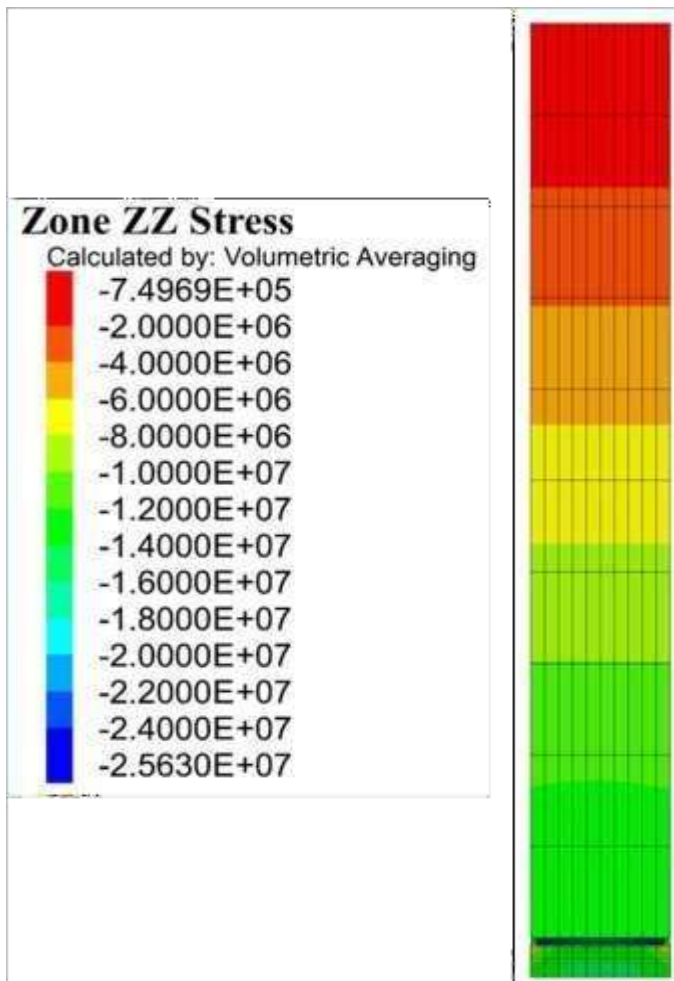


Figure 6.3: Side view of 280m model

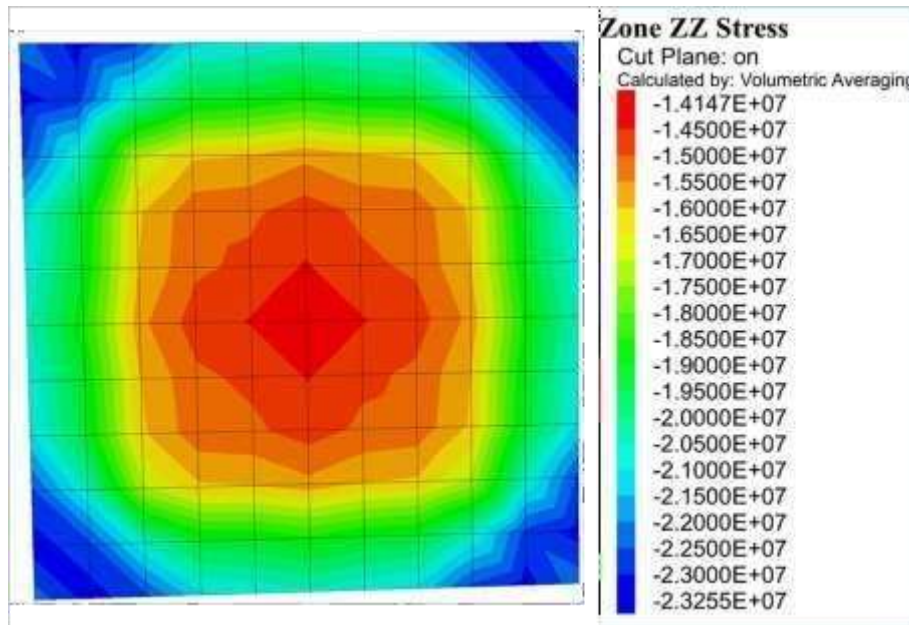
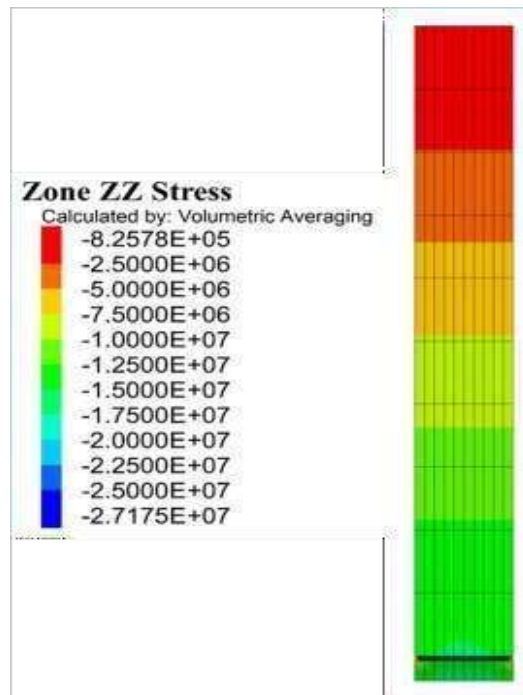


Figure 6.4: Stress profile at middle of pillar at depth of 280m

In this case the depth of working is taken as 280m and the stress value is obtained from the FLAC 3D software and the stress value is 18.17 MPa.

6.1.3 Case No.3: 300 m Depth of Working Model

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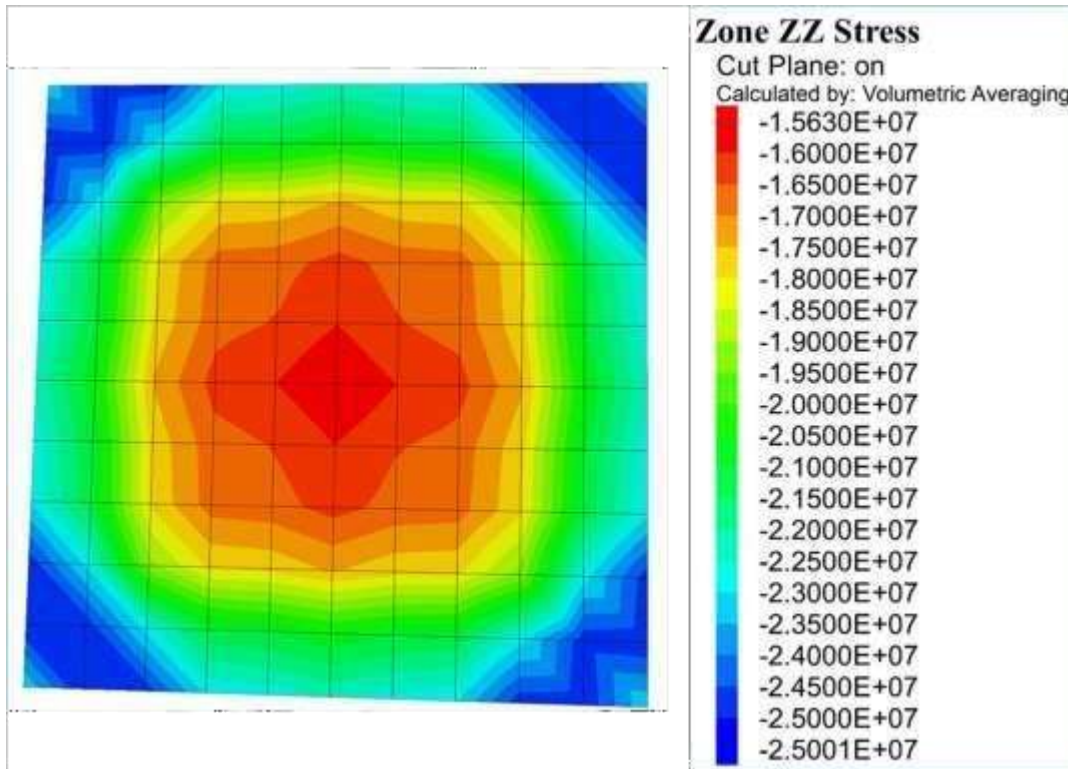


Figure 6.5: Side view of 300 m model

Figure 6.6: Stress profile at middle of pillar at depth of 300m

In this case the depth of working is taken as 300 m and the stress value is obtained from the FLAC 3D software and the stress value is 18.74 MPa.

6.1.4 Case No 4: 330 m Depth of Working Model

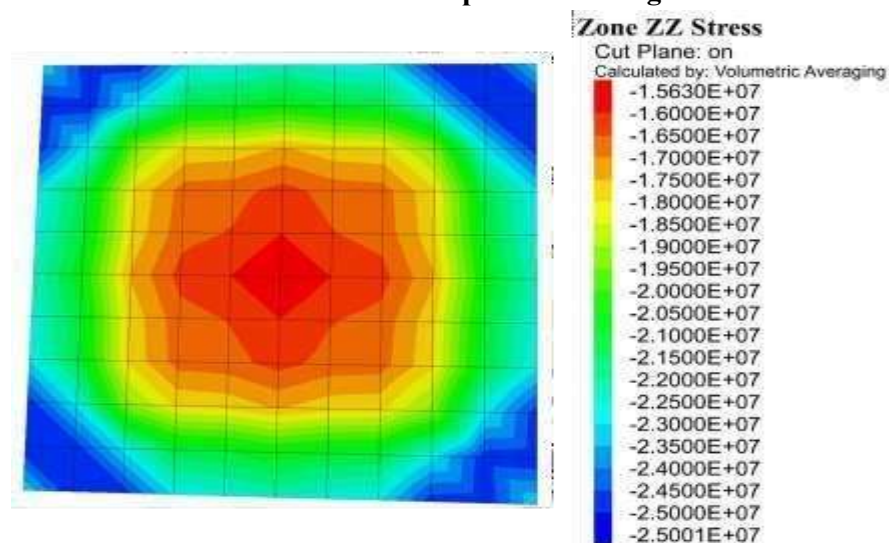
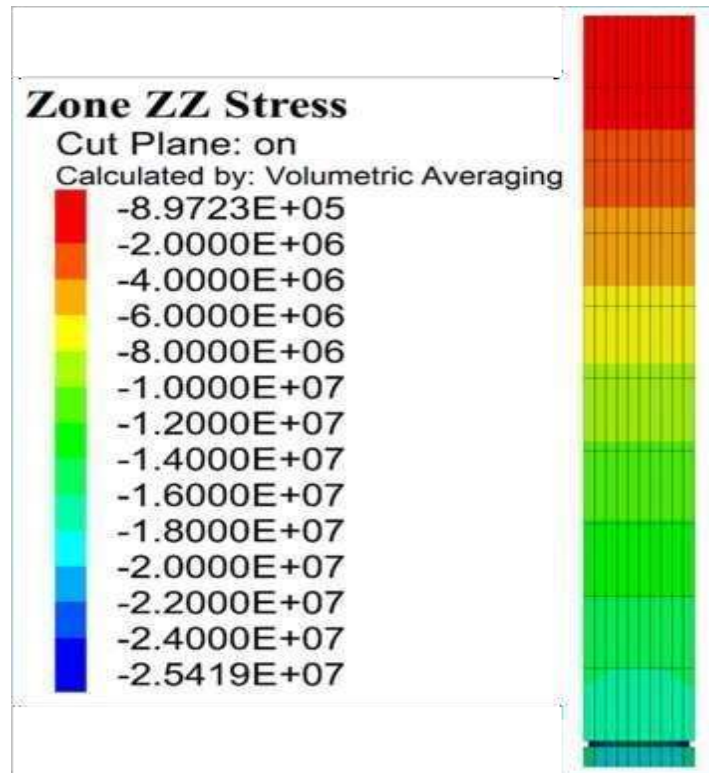


Figure 6.7: Stress profile at middle of pillar at depth of 330m

In this case the depth of working is taken as 330 m and the stress value is obtained from the FLAC 3D software and the stress value is 20.48 MPa.



6.1.5 Case No 5: 360 m Depth of Working Model

Figure 6.8: Side view of 360m model

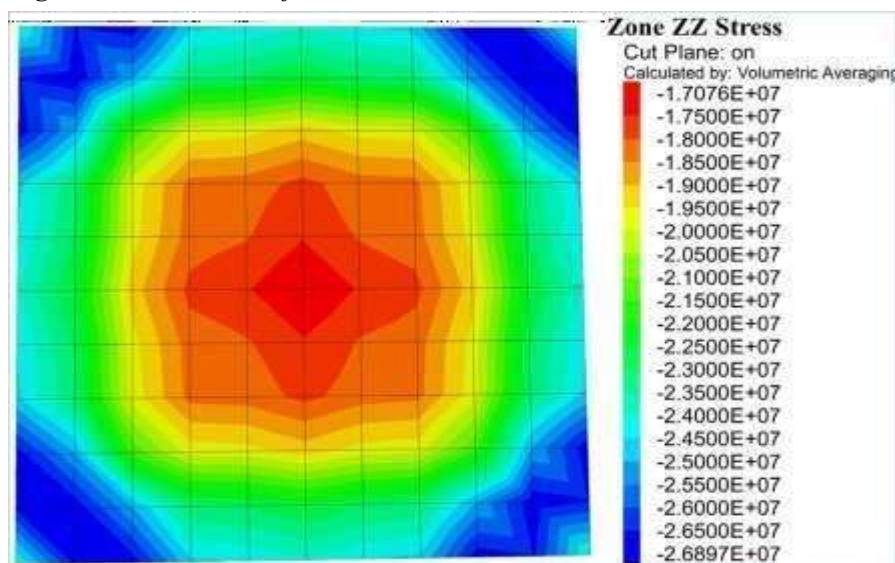


Figure 6.9: Stress profile at middle of pillar at depth of 360m

In this case the depth of working is taken as 360 m and the stress value is obtained from the FLAC 3D software and the stress value is 21.1 MPa.

6.2 : Discussions

The following observations have been made from the analysis: -

- As depth of working increases the factor of safety of the pillar is decreases.
- At greater depths the pillar tends to fail at corners.
- By increasing depth of working the stress on the pillar increases.
- Various cases are analyzed and are shown in below table
- For each case the pillar width and gallery width & pillar height were kept constant, i.e., pillar width is 50 m, gallery width is 4 & pillar height is 3 m.

S.NO	DEPTH (m)	STRESS(MPa)	STRENGTH(MPa)	FOS
1	240	17.5	24.86	1.420571
2	280	18.17	27.94	1.5377
3	300	18.74	29.48	1.573106
4	330	20.48	31.8	1.552734
5	360	21.1	34.11	1.616588

Table 6.1: Numerical values of various cases

- The Sheorey formula was used to calculate the pillar strength. The stresses corresponding to their particular depth of mining was calculated. Graph was plotted for stress vs. depth of working, Strength vs. depth of working & FOS vs. depth of working. These were pertinent with the existing conditions in the mine.
- After plotting the graph equations are formed which distinguish the relationship between them.

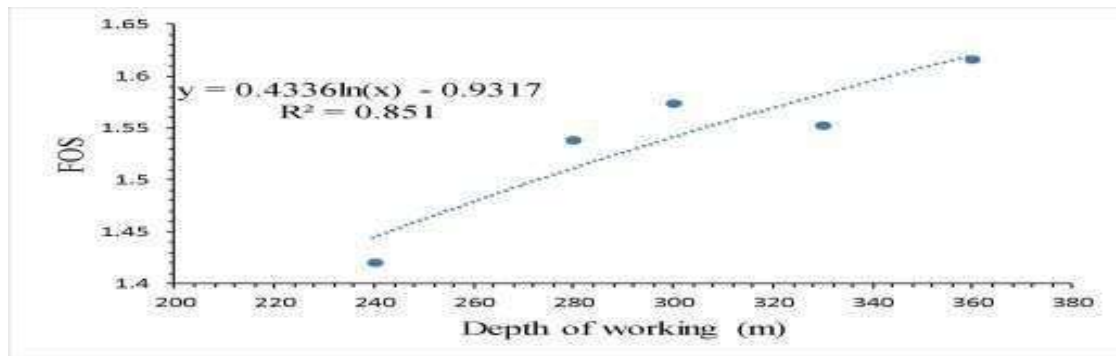


Fig.6.2.1 Graphical representation of FOS with respect to depth of working.

7.1 Conclusion

The aim of the investigation was to evaluate the design of pillar in an underground coal mine. In this study the following conclusions have been made:

- Regular Bord and pillar method of working was followed; Pillar was assumed to be of square shape. The gallery width and height of working did not change throughout Modelling.
- The numerical stress values of the pillar from the output in each case can be validated manually by the average stress formula
- Using DGMS specification for minimum pillar dimension for all approaches, safety factors were found to, at different depths and at particular width of opening.
- Simple linear equations were developed from graph and are analysed and taken into considerations.

7.1.1 Overall Summary:

- It is observed that strength of the pillar is directly proportional to the depth of cover for the particular size of pillar and height of extraction.
- Stress induced on pillar is directly proportional to the depth of working.
- It is observed that factor of safety is indirectly proportional to the depth of working. i.e., when the depth of cover increases the factor of safety decreases

7.2 Recommendations

- The above investigation was carried out in a limited manner, it considered uniform loading, assumed the Poisson's ratio to be 0.25 for pillar and 0.3 for roof and strata and did not consider the effect of increasing moisture content, variation in surface topography and effect of blasting, etc.
- The overburden has different material throughout and hence exhibit different density values. Pillar loading should consider these values instead of one uniform value assumed here.

References:

- [1] E. Hoek and J. W. Bray, *Rock Slope Engineering*, 3rd ed. London: Institution of Mining and Metallurgy, 1981.
- [2] B. H. G. Brady and E. T. Brown, *Rock Mechanics for Underground Mining*, 3rd ed. Dordrecht: Springer, 2006.
- [3] D. C. Wyllie and C. W. Mah, *Rock Slope Engineering: Civil and Mining*, 4th ed. Boca Raton, FL: CRC Press, 2004.
- [4] J. C. Jaeger, N. G. W. Cook, and R. W. Zimmerman, *Fundamentals of Rock Mechanics*, 4th ed. Oxford: Wiley-Blackwell, 2007.
- [5] A. Palmström and E. Broch, *The Q-system for Rock Mass Classification in Tunnel Design*, London: Taylor & Francis, 2006.
- [6] L. R. Alejano and A. M. Ferrero, "A brief review of some numerical models for rock slope stability analysis," *Geotech. Geol. Eng.*, vol. 23, no. 4, pp. 343–356, 2005.
- [7] T. N. Singh, A. Kainthola, and D. Verma, "Numerical modeling of bench slope stability using FLAC3D," *Int. J. Earth Sci. Eng.*, vol. 5, no. 3, pp. 528–533, 2012.
- [8] Q. Feng and Y. Liu, "Stability analysis of open-pit mine slope using FLAC3D," in *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 170, p. 022046, 2018.
- [9] W. Hustrulid, M. K. McCarter, and D. Van Zyl, *Open Pit Mine Planning and Design*, Rotterdam: A.A. Balkema, 2001.
- [10] L. J. Lorig and P. Varona, "Practical slope stability analysis using numerical methods," in *Slope Stability 2000*, 2000.
- [11] Itasca Consulting Group, *FLAC3D Version 7.0 User's Guide*, Minneapolis, MN: Itasca Consulting Group Inc., 2019.
- [12] Itasca Consulting Group, *FLAC3D Theory and Background*, Minneapolis, MN: Itasca Consulting Group Inc., 2019.
- [13] L. J. Lemos, "Application of FLAC3D to analyze slope stability in open-pit mines," in *Proc. 46th US Rock Mech./Geomech. Symp.*, 2012.
- [14] Itasca Consulting Group, *FLAC3D Example Problems Manual*, Minneapolis, MN: Itasca Consulting Group Inc., 2014.
- [15] P. Varona, "Three-dimensional slope stability modeling with FLAC3D," in *FLAC and Numerical Modeling in Geomechanics*, 1999.
- [16] R. Sharma, "Numerical analysis of slope stability in an open-pit mine using FLAC3D," M.Tech thesis, IIT Roorkee, 2020.
- [17] M. Rajasekhar, "Stability analysis of benches in an opencast mine using numerical methods," B.Tech project report, NIT Rourkela, 2018.

- [18] R. Kundu, "Analysis of bench stability in iron ore mines using numerical simulation," M.Tech thesis, IIT Kharagpur, 2019.
- [19] M. P. Rao, "Investigation of geotechnical parameters affecting bench design in Indian opencast mines," M.Tech dissertation, NIT Durgapur, 2021.
- [20] H. Patel, "Numerical modeling and analysis of open-pit slope failure using FLAC3D," M.Tech thesis, SVNIT Surat, 2022.
- [21] Bureau of Indian Standards, IS 14811: Design and Construction for Slopes and Benches in Surface Mines, New Delhi: BIS, 2000.
- [22] Directorate General of Mines Safety, Guidelines for Geotechnical Investigations and Slope Stability Study in Opencast Mines, Dhanbad: DGMS, 2020.
- [23] ISRM, "Suggested methods for rock characterization, testing and monitoring," Int. Soc. Rock Mech., 2007.
- [24] Bureau of Indian Standards, IS 875 Part 5: Code of Practice for Structural Safety – Foundation and Slope Design, New Delhi: BIS, 2013.
- [25] X. B. Li and H. B. Li, "An overview of slope stability analysis using numerical techniques," J. Rock Mech. Geotech. Eng., 2007.
- [26] J. Read and P. Stacey, Guidelines for Open Pit Slope Design, Collingwood, Australia: CSIRO Publishing, 2009.
- [27] R. Anbalagan, "Landslide hazard evaluation and zonation mapping in mountainous terrain," Eng. Geol., vol. 32, pp. 269–277, 1992.
- [28] R. Bhasin and E. Grimstad, "The use of the Q-system and numerical methods for stability analysis of tunnels in jointed rock," Tunn. Undergr. Space Technol., 1996.
- [29] B. Singh and R. K. Goel, Rock Mass Classification: A Practical Approach in Civil Engineering, Amsterdam: Elsevier, 1999.
- [30] Z. Zhang and Q. Zhang, "Analysis of factor of safety for mine slope based on limit equilibrium and numerical method," Safety Sci., 2016.
- [31] G. Q. Qiu and Y. M. Cheng, "A study on the effects of bench height and slope angle on open pit stability," Int. J. Rock Mech. Min. Sci., 2010.
- [32] Q. H. Yao et al., "Comprehensive analysis of slope instability using numerical and physical modeling," Eng. Geol., 2019.
- [33] S. Singh et al., "Influence of geological structures on bench stability in an opencast mine," J. Min. Metall., 2015.
- [34] R. Ghosh, "Impact of slope geometry on factor of safety in opencast mines," J. Geol. Soc. India, 2017.
- [35] W. Zhou et al., "Numerical analysis of the influence of bench parameters on slope stability using FLAC3D," J. Rock Mech., 2020.