

Numerical Evaluation of Coal Bench Stability at Different Bench Heights Using FLAC3D: A Case Study of JK-5 opencast Mine, Telangana, India

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Abstract

This research investigates the stability of coal benches in the JK-5 Opencast Mine using FLAC3D numerical modeling. Bench heights of 10, 12, 15, 20 and 25 m were analyzed. Geological, geotechnical and operational data from the mine were incorporated into a three-dimensional model. The study evaluates stress distribution, displacement and factor of safety (FOS) for different bench geometries. Results indicate that increasing bench height increases deformation and decreases stability. The study provides recommendations for safe and economical bench design in opencast coal mines. This research investigates the stability of coal benches in the JK-5 Opencast Mine using FLAC3D numerical modeling. Bench heights of 10, 12, 15, 20 and 25 m were analyzed. Geological, geotechnical and operational data from the mine were incorporated into a three-dimensional model. The study evaluates stress distribution, displacement and factor of safety (FOS) for different bench geometries. Results indicate that increasing bench height increases deformation and decreases stability. The study provides recommendations for safe and economical bench design in opencast coal mines. This research investigates the stability of coal benches in the JK-5 Opencast Mine using FLAC3D numerical modeling. Bench heights of 10, 12, 15, 20 and 25 m were analyzed. Geological, geotechnical and operational data from the mine were incorporated into a three-dimensional model. The study evaluates stress distribution, displacement and factor of safety (FOS) for different bench geometries. Results indicate that increasing bench height increases deformation and decreases stability. The study provides recommendations for safe and economical bench design in opencast coal mines.

Keywords

Coal Bench Stability, FLAC3D, Slope Stability, Numerical Modeling, Open Cast Mining, Factor of Safety, Geotechnical Engineering

1. Introduction

Slope stability analysis is usually performed to measure the safe and economical design of natural or human-made slopes (for example, water embankments, open pit mines, mining excavations, landfills, etc.) and equilibrium conditions. The term "slope stability" can be defined as the ratio of the resistance offered by the surface inclined to the failure due to sliding or collapse. The main objective of the stability analysis of slopes is to locate dangerous areas, to predict the stability of the slope, supervising potential failures mechanisms, the finding of the susceptibility of the slope to different trigger mechanisms, the design of optimal slopes concerning safety, reliability, and economy, designing possible protective measures, e.g., Barriers and stabilization.

2 .Study area:

Jawahar Khana Opencast (JKOC) is located in Yelland area of the Singareni Collieries Company Limited (SCCL), Bhadradi Kothagudem District Telangana. This mine consists of two workable seams namely Queen seam and King seam. The reserves of King seam were already exploited. At present, JKOC mine is extracting coal from Queen seam and average thickness of Queen seam is 14 m. The general gradient of the seam varies from 1 in 5 to 1 in 10 and the average gradient of the seam is 1 in 7. The minimum and maximum depths of the mine are 35m and 120 m respectively.

Location of mine

Latitude: 17°31'09" N to 17°34:39" N

Longitude: 80°19'27" E to 80°21*14" E

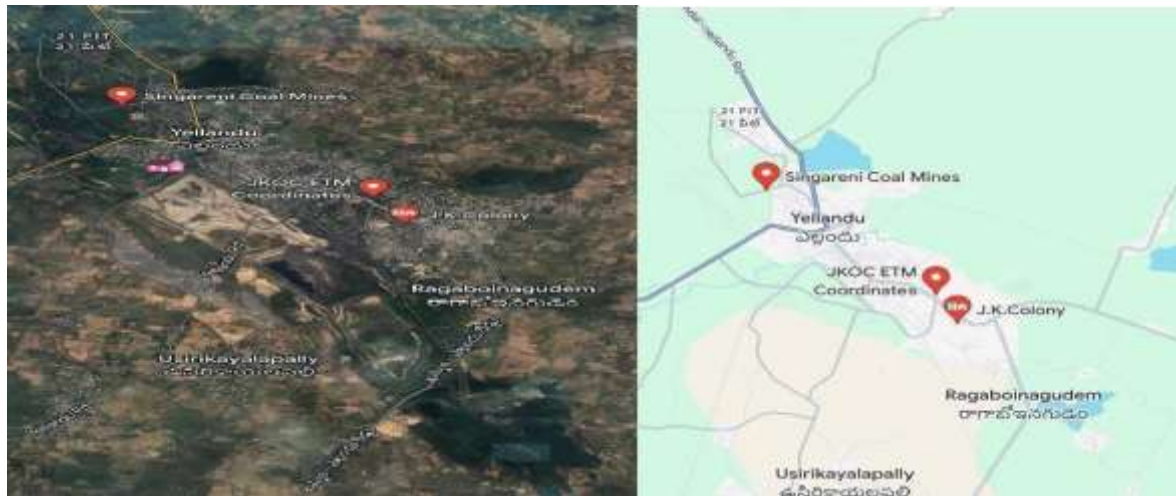


Figure 2. 1: Mine location

2.1 General Information of the Mine

• Name of the Mine	: -	JK-5 OC Mine
• Name of the Agent	: -	Sri.B. Venkateshwarlu
• Name of the Colliery manager	: -	Sri.P. Purnachandar
• Name of the Project Engineer	: -	Sri.M.Chinnaiah
• Location	: -	Yellandu
• District	: -	Bhadradi Kothagudem
• State	: -	Telangana 507123
• Mine started in the year	: -	1983
• JK5 Block started in	: -	1 st January 2012
• Depth of the Quarry	: -	Minimum 35m Maximum 120m
• Remaining Life of the mine	: -	6 Months
• Number of seams being worked	: -	1
• Average stripping ratio	: -	1:5.14
• Average gradient of mine	: -	1 in 7
• Average grade of coal	: -	G-15
• Geological reserves (coal)	: -	26.30 million tonnes
• Extractable reserves (coal)	: -	23.67 million tonnes
• Total OB removal	: -	110.20 million Cubicm
• OB Quantities in external dump	: -	47.65 million Cubicm
• OB Quantities in internal dump	: -	51.50 million Cubicm

- Height of external dump : - 60.00m
- Geological Block : - JK5 OCP block falls in the yellandu coal belt
- Topo & co-ordinates : - Survey of India Topo sheet No-65C/6

Latitude: 17°31'09" N to 17°34'39" N

Longitude: 80°19'27" E to 80°21'14" E

- Full dip gradient & direction : - full dip: 1 in 7 direction: S 62° 20' W
- Target of JK-5 OC Block : - 1.45 MTPA

Seam	Thickness in mts Min-Max	Partition (M)		Extractable Reserves (M.T)	Quality	
		Min	Max	As per FR	Avg UHV K.Cal/kg	Grade
"A" (Queen) seam	5.79 – 20.23	5	27	23.67 UE	1921	G-1
"B" seam	0.10 – 0.61	6	15	---	---	---
"C" seam	0.30 – 1.20	7	23	---	---	---
"D" seam	0.60 – 0.91	5	32	---	---	---
"E" (King) seam	0.15 – 3.00	---	---	Extract ed by British ers	---	--

Table 2.2 Details of coal seam

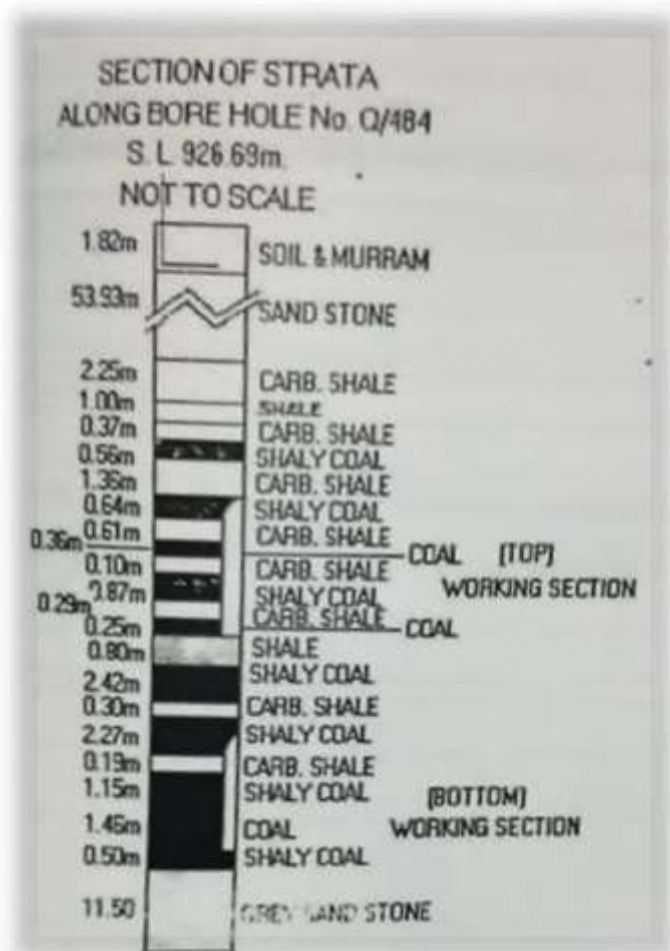
Sl.No.	BH. No	From	To	Thickness(m)	M%	A%	UHV	Grade
1	Q/457	55.9	68.20	12.26	2.54	49.67	1695	G
2	Q/458	30.8	42.95	12.06	3.39	45.75	2119	G
3	Q/493	72.7	88.25	15.52	2.38	48.45	1866	G
4	Q/494	84.7	98.70	13.94	2.61	44.10	2448	F
5	Q/495	74.4	91.78	17.33	2.24	50.68	1569	G

Table 2.3 Borehole wise thickness & Quality data

North West	Quarry surface is fixed about 100 – 200 m away from Railway track leading to 'Singareni collieries railway station'
South East	Yellandu Opencast Project, Block-D
North-east	Quarry floor aligns with in crop of Queen Seam.

South West	Quarry floor aligns with 120 mDepth line of Queen
	Seam

Table 2.4 Boundaries of the project



3.0 Methodology

A methodology is a system of methods used in a particular area of study or activity to fulfil the objective. A keen study in literature review helped in the selection of the method of slope stability, collection of data, analyzing the data, preparation of basic models, to run the models, simulation and analysis of the models. Before the computer age, stability analysis was performed graphically by using a hand-held calculator. Today, engineers have many possibilities to use analysis software that ranges from simple limit equilibrium techniques through computational limit analysis approaches (e.g. Finite element limit analysis, Discontinuity layout optimization) to complex and sophisticated numerical solutions (finite-/distinct-element codes). Each technique has its own limitations and are has been studied. For example, limit equilibrium is most commonly used and is a simple solution method, but it can become inadequate if the slope fails by complex mechanisms (e.g. internal deformation and brittle fracture, progressive creep, liquefaction of weaker soil layers, etc.). In these cases, more sophisticated numerical modelling techniques should be utilized.

3.1 Steps involved in Numerical Modeling

These are the following steps used in Numerical Modeling:

1. Creating a Mode
2. Meshing and Discretization

3. Boundary Conditions
4. Material Properties
5. Execute

The above-mentioned steps used in numerical modelling are included in a single program. In which each all the steps are interlinked with each other. The numerical modelling process for assessing the factor of safety (FoS) of a bench with varying heights using FLAC3D involves several key steps. Initially, the objective of the analysis is defined, focusing on evaluating the stability of mine benches at different heights. This is followed by the collection of detailed geological and geotechnical data, including rock type, unit weight, cohesion, angle of internal friction, and joint orientation. Using this information, a three-dimensional geometric model of the bench is developed in FLAC3D, with bench heights systematically varied while maintaining consistent boundary conditions. Appropriate material properties are then assigned based on constitutive models such as Mohr-Coulomb or Hoek-Brown. Boundary and initial stress conditions are applied, and the model is discretized into a finite mesh, with finer zoning near expected failure areas. If groundwater is present, pore pressure effects are incorporated into the model. The shear strength reduction (SSR) technique is then applied, where the shear strength parameters are gradually reduced until failure is observed; the reduction factor at failure gives the FOS.

3.1.1 Creating a Model:

Creating a model is a step-by-step process in which one need to identify the required geometry of the model and its shape. One of the main tasks when performing a FLAC3D analysis is building a numerical representation of the real-world situation. All FLAC3D models will have an outer boundary to which boundary conditions will be applied. The complex shapes which result from the intersections of non-continuous planes in space are difficult to create and visualize. The first rule is keeping the model simple. Usually, a numerical model is being developed because the real-life situation is too complex to understand. There is a tendency to attempt to include every possible feature in a numerical model. This results in a FLAC3D model that is also too complex to understand. The time required to calculate a solution also increases with increasing complexity. Therefore, it is to the modeler's advantage to start with a model that only includes the minimum of features. The complexity of the model can then be increased by adding features one at a time and noting the effect. By using this approach, the modeler has the best chance of gaining understanding of the parameters that are critical to the real-life situation.

➤ 3.1.2 Meshing the model geometry

FLAC3D has three main built-in methods for creating zones for grids: primitives, extrusions, and building blocks. Each is different. Each offers distinct advantages and disadvantages. For initial generation of grids, they are mutually exclusive (i.e., you cannot create one set of zones using primitives and an extrusion at the same time). However, the program offers commands that allow zones from any method to be further modified, combined, and so forth, as needed. The right path to the geometry of a model might involve an adept combination of these methods of zone generation.

3.1.3 Boundary Conditions

Boundary and initial conditions must not be applied until after all block-cutting is complete and the mesh for deformable blocks is generated. Mechanical boundary conditions are generally applied with the BOUNDARY command. This command is used to specify force, stress and velocity (displacement) boundary conditions. Boundary forces and stresses can be applied to both rigid and deformable blocks, but boundary velocities can only be applied to deformable blocks. Boundary conditions are an essential component of numerical simulations and modeling, including those performed using FLAC3D software. The purpose of boundary conditions can be summarized as follows:

1. Replicating the real system: Boundary conditions aim to replicate the real-world behavior of the system being modeled. They capture the interaction between the modeled domain and its external environment, such as applied loads, displacements, or constraints.
2. Constraining the problem: Boundary conditions help define the limits and constraints of the problem. They restrict the degrees of freedom and behavior of the system at its boundaries, simulating the physical conditions that are present in the actual system.
3. Controlling inputs and outputs: Boundary conditions enable the control of inputs and outputs in the simulation. They allow you to prescribe specific values or relationships at the boundaries, which may include fixed displacements, applied loads, fluid flow rates, or thermal conditions. By defining these conditions, you can study the response of the system under different scenarios.

3.1.4 Material Properties

The material properties are assigned to the blocks and joints. Block and joint properties are not assigned directly. Instead, a block material number and a joint material number are assigned (default is 1 in both cases). The properties of each material are then specified using the PROPERTY command.

The shear strength of the material, which is its ability to resist sliding or deformation, is a crucial factor. When the shear stress (the force causing the slope to slide) exceeds the shear strength, failure occurs. Various factors, including material properties, slope geometry, and external influences like water pressure and seismic activity, can affect both shear strength and shear stress, thus impacting slope stability. In essence, a slope fails when the forces trying to make it slide (shear stress) exceed the forces resisting the movement (shear strength). Understanding and quantifying these material properties and external influences is crucial for assessing and mitigating slope failure risks.

Material properties refer to the characteristics and behaviors of a material that determine its response to various external conditions and loads. In the context of numerical simulations and modeling, material properties are essential inputs that define the mechanical, thermal, and other relevant properties of the materials being analyzed. Here are some commonly considered material properties:

1. Density: Density is a physical property of matter that describes how much mass is contained within a specific volume. It is defined as the mass of an object divided by its volume and is usually expressed in units such as kilograms per cubic meter (kg/m^3) or grams per cubic centimeter (g/cm^3). In simple terms, density tells us how tightly the particles in a substance are packed together.
2. Bulk Modulus: Bulk modulus is a measure of a material's resistance to uniform compression. It defines how much a material will compress when subjected to external pressure applied equally in all directions. In other words, it indicates how difficult it is to change the volume of a substance under pressure. The bulk modulus is calculated as the ratio of the change in pressure to the resulting fractional change in volume and is expressed in units of pressure, such as pascals (Pa) or gigapascals (G Pa).
3. Shear Modulus: Shear modulus, also known as the modulus of rigidity, is a measure of a material's ability to resist deformation under shear stress. It defines how a material changes shape when a force is applied parallel to one of its surfaces while the opposite surface is held fixed. The shear modulus is calculated as the ratio of shear stress to shear strain and is expressed in units of pressure, such as pascals (Pa) or gigapascals (G Pa).
4. Friction Angle: Friction angle, also known as the angle of internal friction, is a measure of the shear strength of soils or rocks due to friction. It represents the maximum angle at which a material can resist sliding or shearing along a plane without failure. The friction angle is expressed in degrees and is a key parameter in geotechnical engineering for analyzing the stability of slopes, foundations, and retaining structures. A higher friction angle indicates greater resistance to shear and stronger interparticle locking, as seen in coarse-grained soils like gravel, while a lower friction angle suggests weaker resistance, typical of fine-grained soils like clay.

5. Cohesion: Cohesion is the measure of the internal bonding force that holds together the particles of a soil or rock mass.

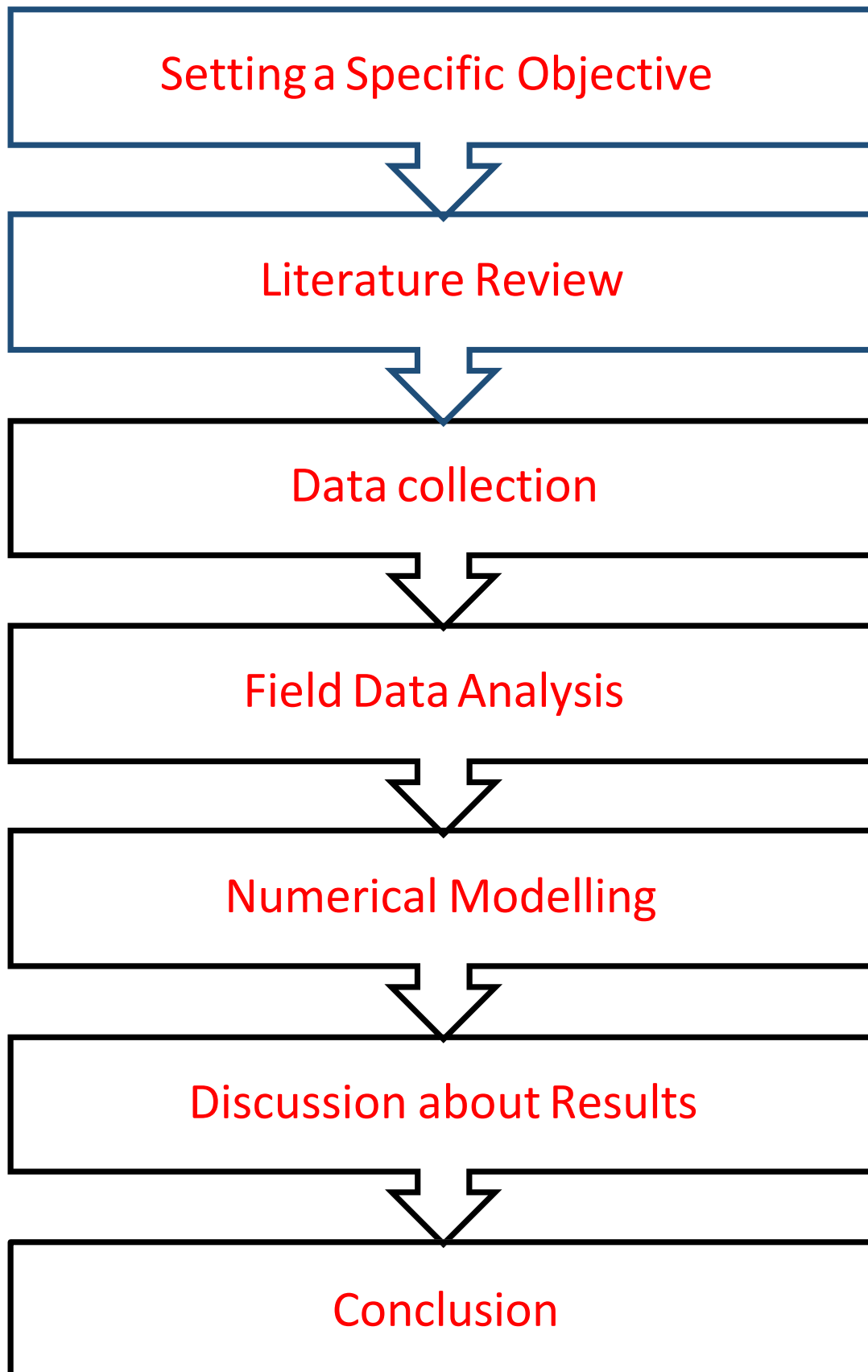


Fig.3.1: Flow chart of methodology followed in this thesis.

4.1 Model Preparation

The numerical procedure consists of grid generation and appropriate material behaviour 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 10 10 and 1 1 1, respectively.

The model geometry values are

- Floor values Width m, Length mand Height m
- Coal bench dimensions from the field
- Bench angle 10 m
- Bench width 15 m
- Simulated bench heights 10, 12, 15, 20 and 25 m.

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

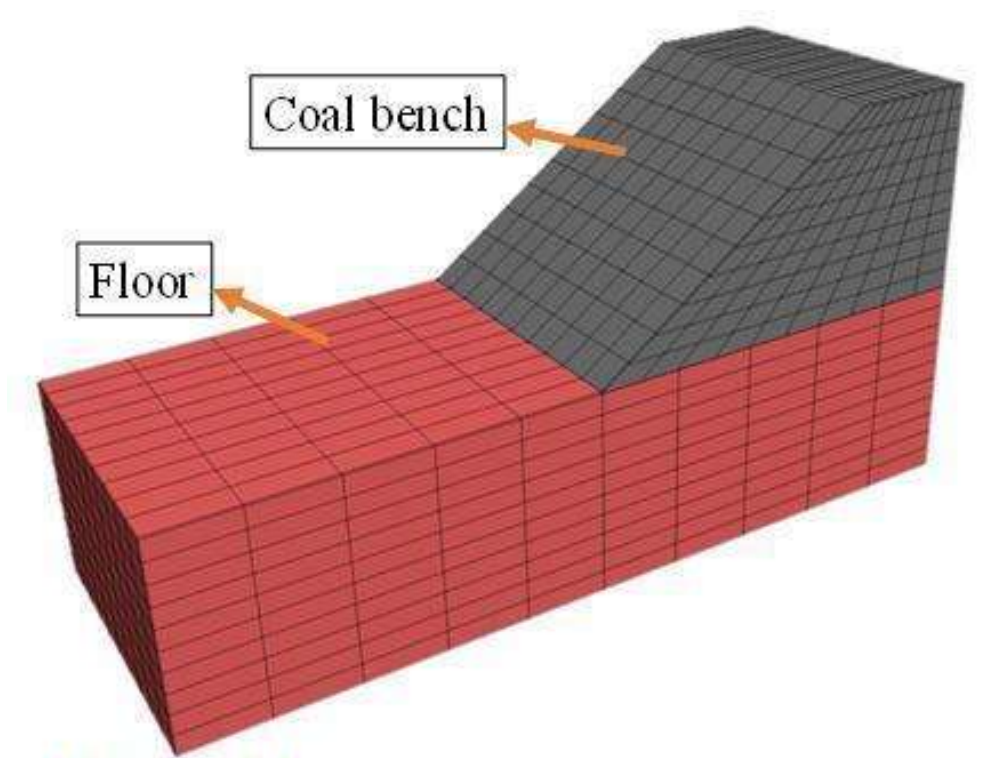


Fig. 4.1: Three-dimensional discretization of a coal bench

4.2 Material Properties:

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

Strata	Thickness	Youngs modulus (GPa)	Poisson's ratio	Density	Cohesion (MPa)	Friction	Tension (MPa)
Floor	5m	3	0.25	2530	0.5	25	0.2
Coal bench	2.5-6m	2	0.3	1400	0.5	25	0.2

Table 4.1: Material properties of pillar

4.3 Boundary conditions

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. As shown in Figure 5.2.

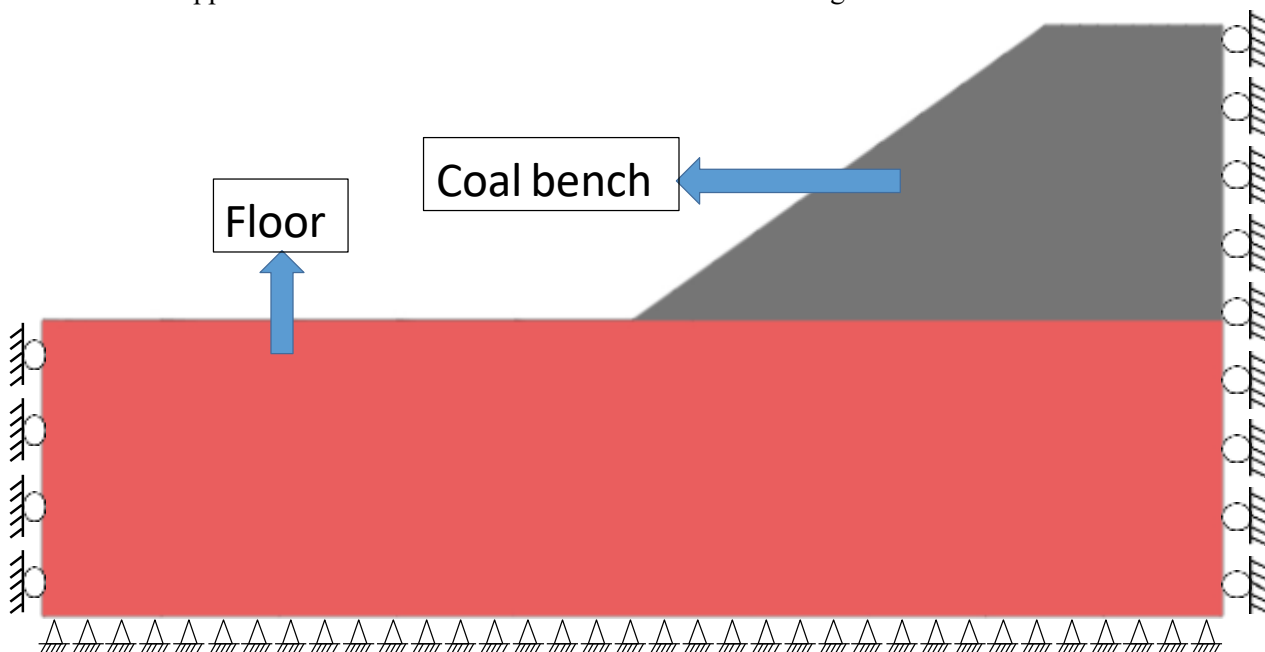


Fig. 4.2: Model with boundary conditions.

Scheme of simulation

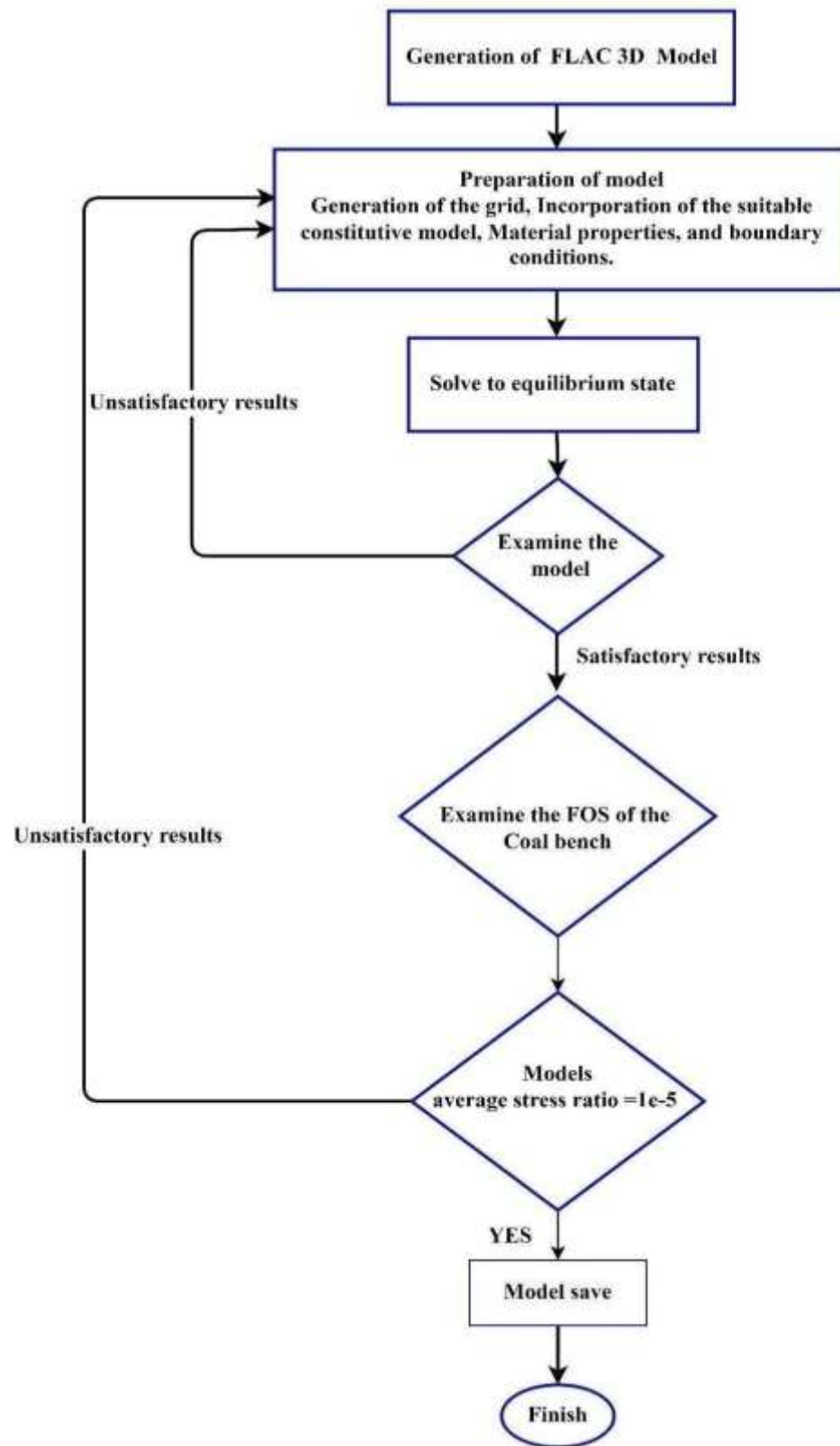


Fig. 4.3: Flow chart of scheme of simulation.

5.0 Results and Discussion:

5.1 Parametric Study

The parametric study is on the FOS of the coal bench by increasing height. In this, the width and angle of the bench and the height vary. The height of the bench varied from (10m to 25m) A total of 5 cases were considered, and the following cases give the FOS of the coal bench using the FLAC 3D model.

5.1.1 Case-I Height of the bench is 10 m

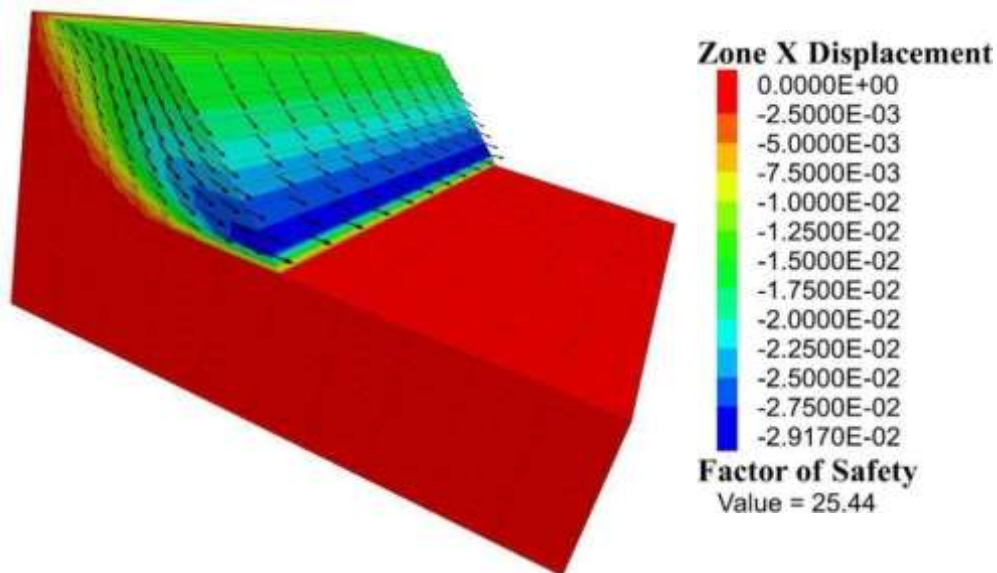


Fig.5.1: Displacement of coal bench at a height of 10 m

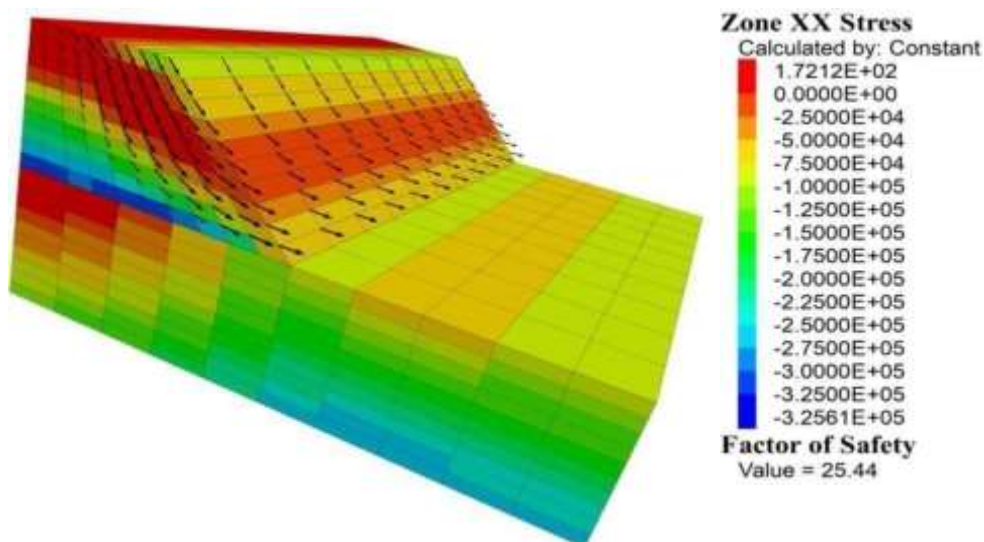


Fig.5.2: Stress profile of coal bench at height of 10 m

Case-I Height of the bench is 12 m

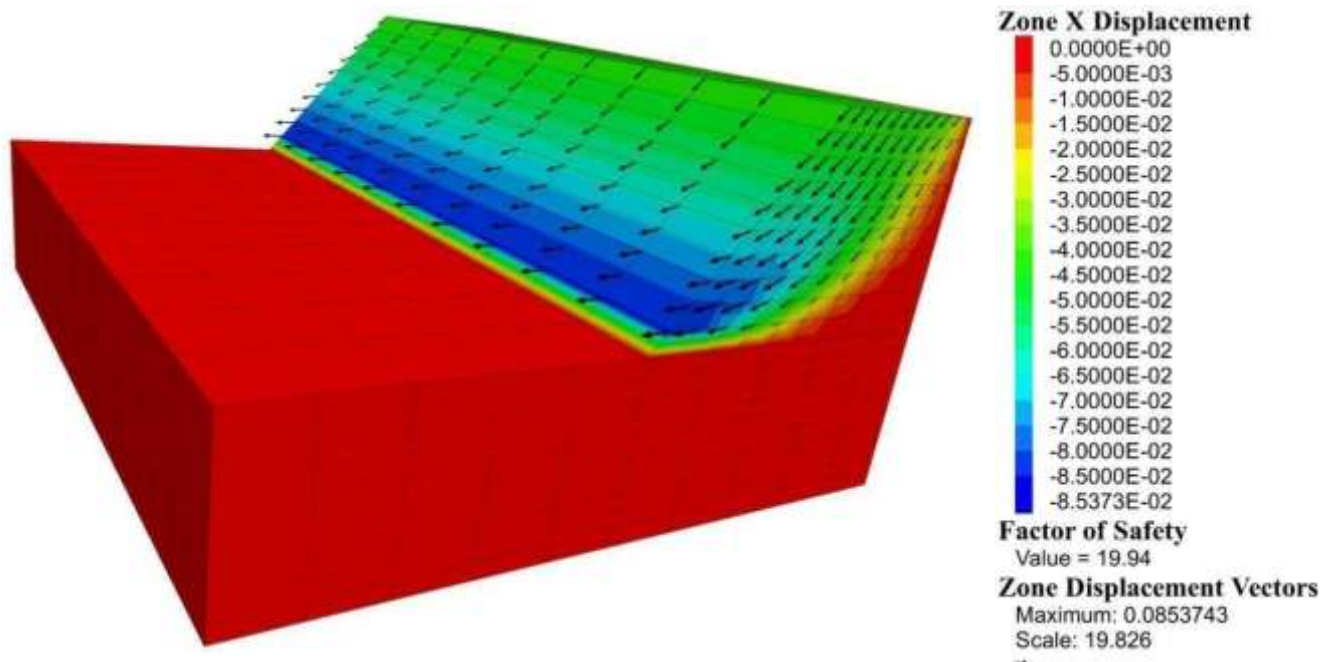


Fig.5.3: Displacement of coal bench at a height of 12 m

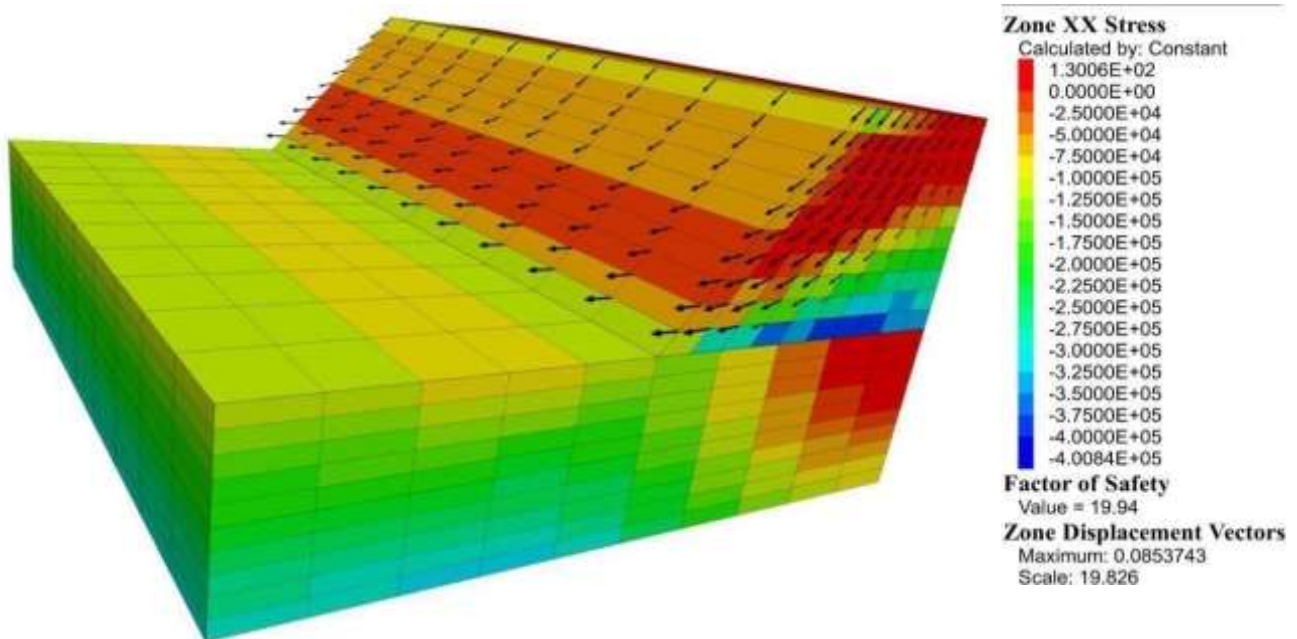


Fig.5.4: Stress profile of coal bench at a height of 12 m

Case-I Height of the bench is 15 m

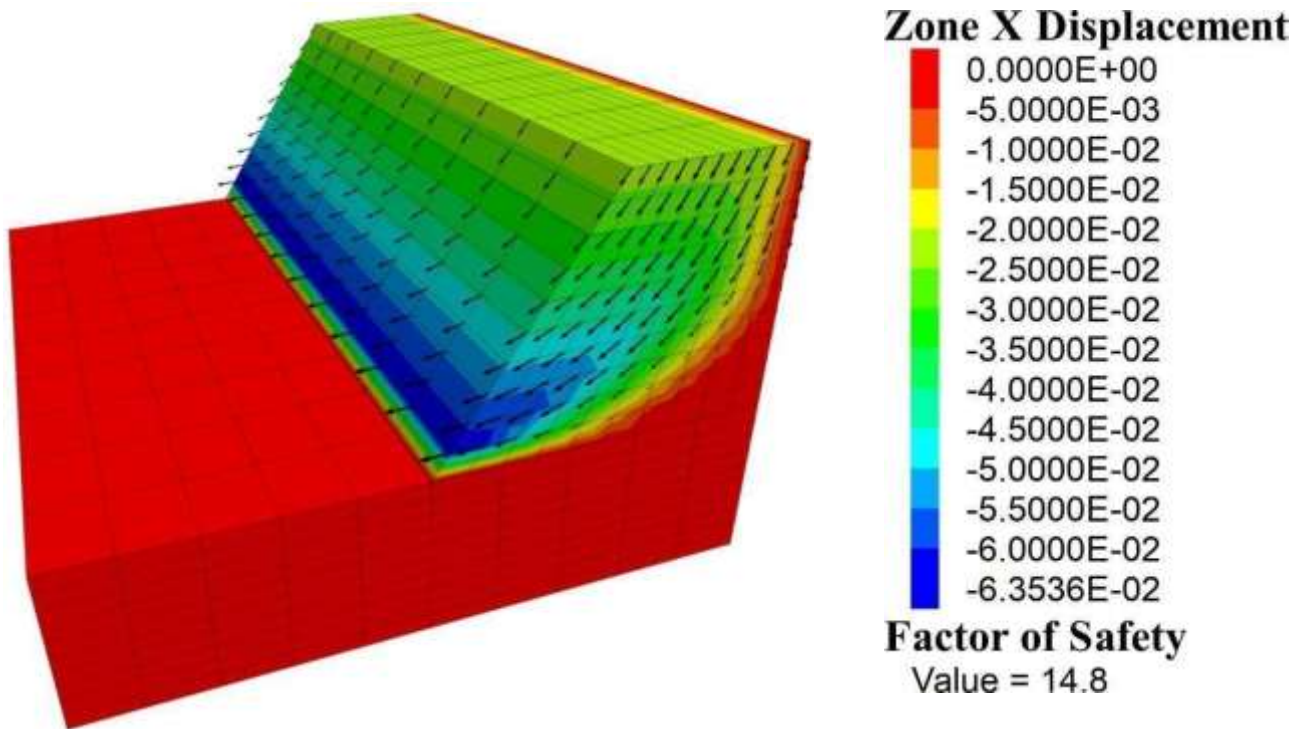


Fig.5.5: Displacement of coal bench at a height of 15 m

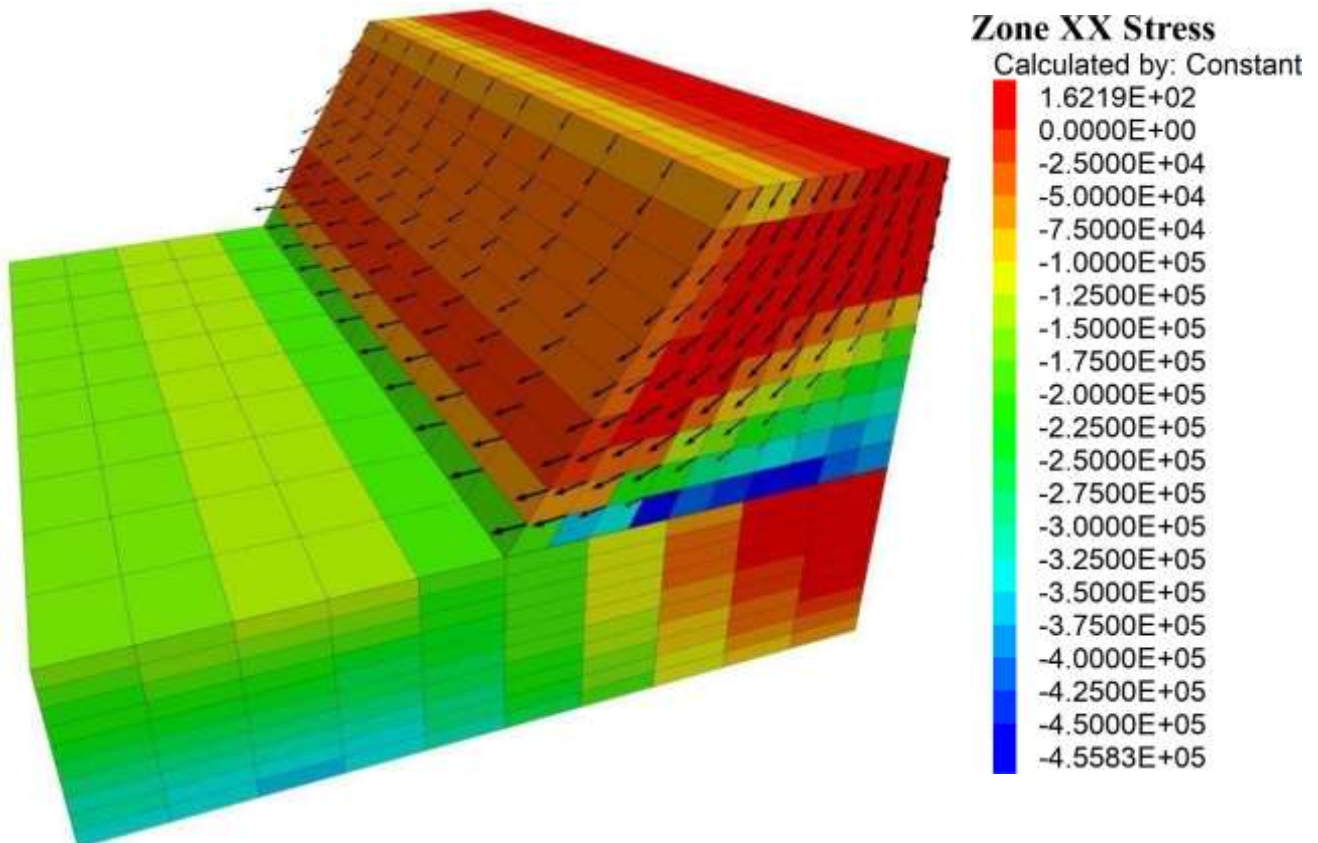


Fig.5.6: Stress profile of coal bench at height of 15 m

Case-I Height of the bench is 20 m

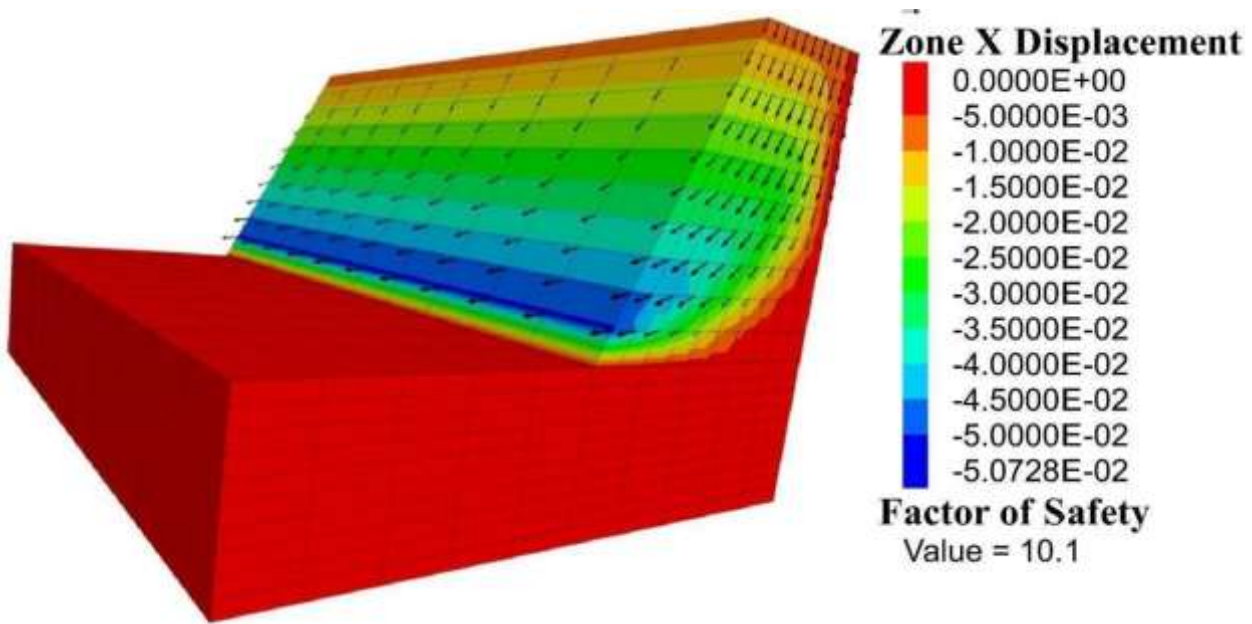


Fig.5.7: Displacement of coal bench at a height of 20 m

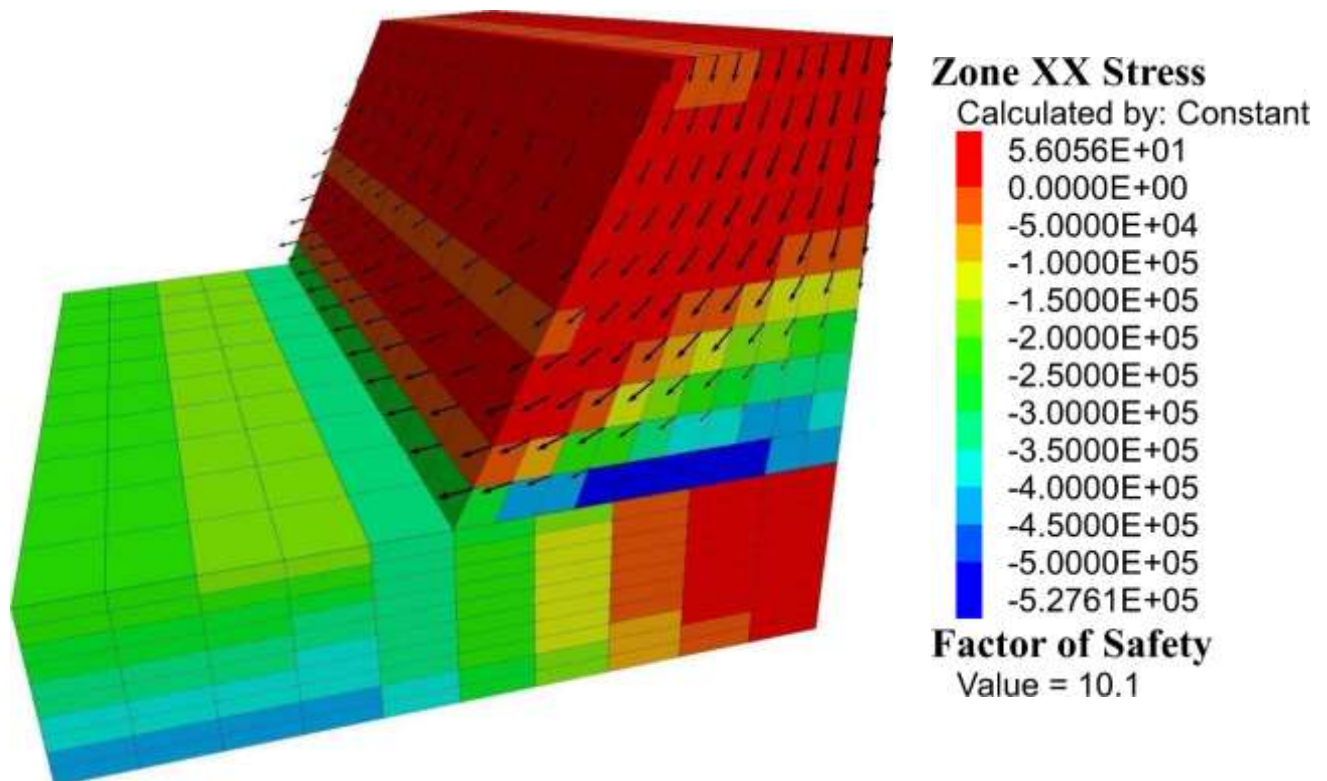


Fig.5.8: Stress profile of coal bench at height of 20 m

Case-I Height of the bench is 25 m

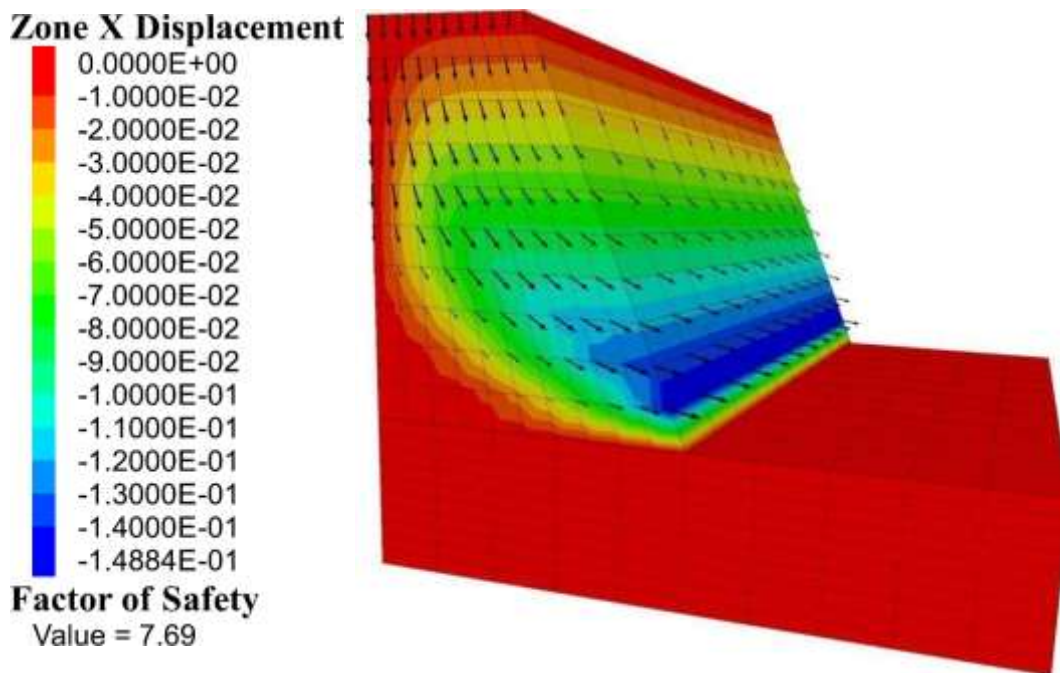


Fig.5.9: Displacement of coal bench at a height of 25 m

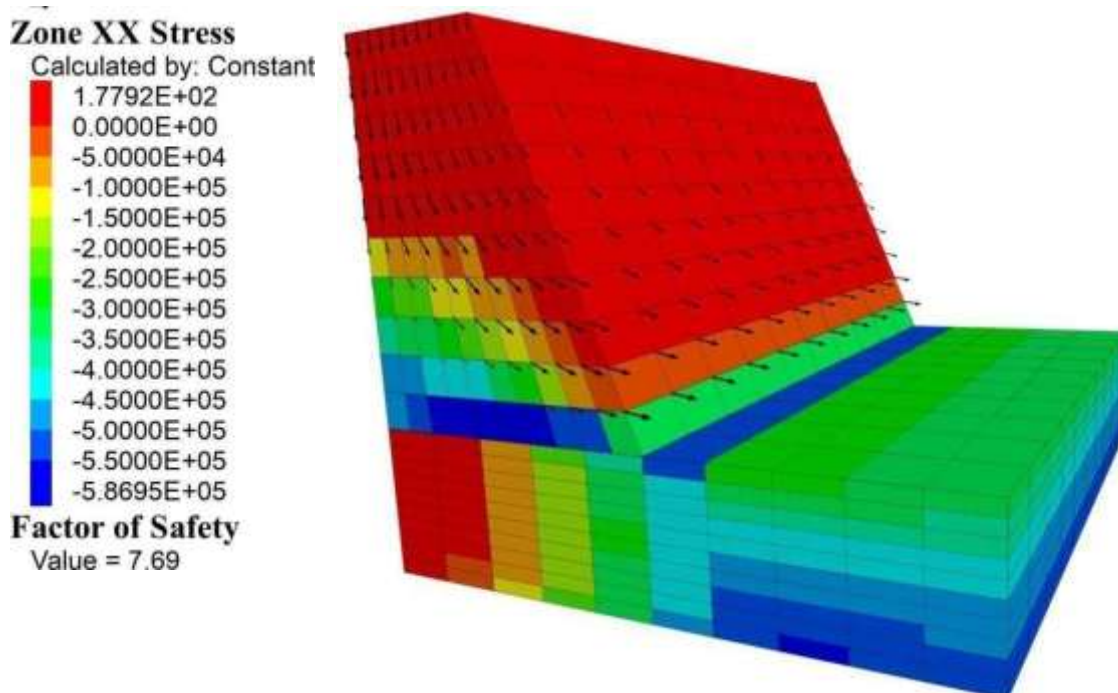


Fig.5.10: Stress profile of coal bench at height of 25 m

5.1.2 Discussion of the Result

Table 5.11: FOS of coal bench at various bench heights

S.NO	HEIGHT OF BENCH (m)	FACTOR OF SAFETY
1	10	25.44
2	12	19.94
3	15	14.78
4	20	10.1
5	25	7.6

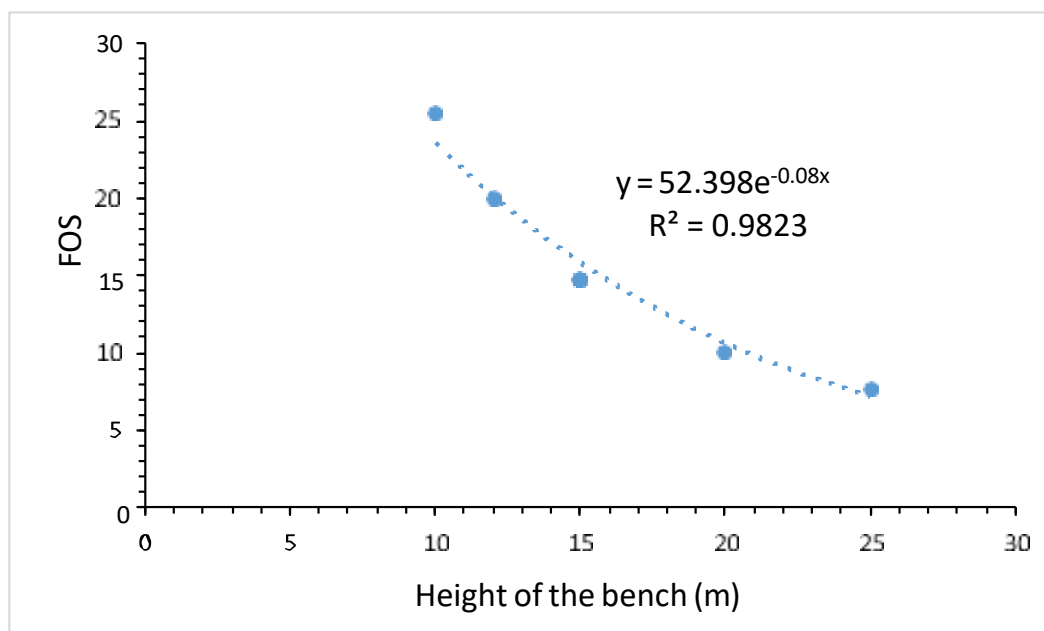


Fig 5.12: Graphical representation of FOS of a coal bench at different heights.

The results obtained from the numerical simulation were mentioned in table 6.2. the results are also presented in graphical way. Based on Table 6.2 it is concluded that as the bench height increases, the stability of the slopes decreases. Lower the bench height, higher is the stripping (mining of waste rock), which will in turn have direct consequences on the economy of the mining operation.

While running the numerical model FLAC3D it was observed that factor of safety changes with change in the resolution of the numerical mesh (coarse, medium and fine). In case of coarse mesh the factor of safety is quite approximate, while in fine mesh the factor of safety converges to the nearest possible value making it more accurate. However, calculation in coarse mesh is faster than in fine mesh. So, depending upon the requirement and time availability of modeler, the mesh has to be selected.

6.1 Conclusion

- 1) Opencast mining is a cost-effective method that allows a high grade of mechanization and large production volumes. Mining depths in open pits have increased steadily during the last decade, which has increased the risk of large-scale stability problems. It is necessary to assess the different types of slope failure and take suitable, cost-effective measures to prevent, eliminate, and minimize risk.
- 2) The parametric study, which was carried out by varying the bench height, showed that with an increase in bench height, the factor of safety decreases. Moreover, the bench parameters are important factors affecting slope stability. With the increase in both parameters, the stability decreases. Conduct of slope stability assessment in Indian mines is mostly based on empirical and observational approaches; hence, the effort is made by statutory bodies to have more application of analytical, numerical modelling in this field to make slope assessment and design scientific. This will ensure that suitable corrective actions can be taken on time to minimize slope failures and the associated risks.

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