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Stability Assessment of Coal Mine Waste Dumps Using Numerical Modelling: A Parametric Study

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Abstract

Aim: *This study employs numerical modeling techniques to assess the stability of coal mine waste dumps, utilizing the Strength Reduction Factor (SRF) method to compute the Factor of Safety (FoS).* ***Methods:*** *By integrating FLAC/Slope software, a comprehensive parametric study is conducted to evaluate the influence of key geometrical and geotechnical parameters on waste dump stability.* ***Results:*** *The analysis indicates that the FoS decreases with increasing slope angle, highlighting the critical role of slope geometry in determining stability. Steeper slopes exhibit a heightened risk of failure, emphasizing the need for careful design considerations. The study underscores the significance of shear strength parameters - cohesion and the angle of internal friction in enhancing slope stability. The result presents a strong linear correlation between increases in these shear strength parameters and improvements in the FoS. A threshold is identified in the relationship between shear strength parameters and overall stability. Beyond a specific value of cohesion or internal friction, the slope approaches a critical instability point, marking the boundary between stable and unstable conditions. This finding is valuable for the design and management of coal mine waste dumps, ensuring that material properties are optimized to prevent failures.* ***Conclusion:*** *By improving predictive modelling and risk mitigation strategies, this study provides essential guidance for maintaining safe operational conditions in coal mines. These findings not only aid in enhancing dump design but also support regulatory compliance and sustainable mining practices.*

Major Findings: *The stability assessment uses the Strength Reduction Factor (SRF) technique to calculate the Factor of Safety (FoS) gives an accurate representation of the stability. Parametric study with FLAC/Slope shows that the FoS decreases as the slope angle increases. The study demonstrates that when any of the shear strength parameters, such as cohesion and angle of internal friction, increase, the FoS follows a straight line. This suggests that enhancing material quality can increase waste dump slope stability. The relationship identifies a critical threshold: above a particular value of these shear strength parameters, the slope approaches critical instability.*

Keywords: Numerical Modelling, Parametric Study, Slope Stability, Waste Dump Stability

1.0 Introduction

In opencast mining operations, the dumping of waste rock is a prominent aspect of mining processes. The waste rock facility encompasses a substantial part of the project entire footprint, frequently exceeding the dimensions of the mine itself. The stripping ratio in opencast mining, which determines the volume of waste rock that must be excavated to reach the ore, is dependent upon critical elements. The factors include the geometry and proportions of the ore body, the ore value, and the pit design, all of which may be affected by slope stability issues. The resultant waste rock, or overburden, is extracted during excavation and transported by trucks

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or conveyance systems to specified disposal locations, creating what is referred to as waste dumps[1]. Waste dumps are classified as internal or external depending upon the location of material deposition. An external waste dump is located beyond the mine or quarry periphery, often elevated over the surrounding terrain. An internal dump is situated within the pit or quarry, positioned above the de-coaled area (the mine floor from which coal or minerals have been extracted). The geometrical and geotechnical parameters, such as dump slope angle, dump height, cohesion, and angle of internal friction, affect the stability of waste dumps[2]. By adjusting input parameters, such as cohesion, angle of internal friction, slope angle, and height, engineers can simulate and evaluate the FoS for each condition. The study aims to achieve the following objectives:

a. **Understanding the Concept behind FLAC Software Application**: To provide a comprehensive understanding of FLAC (Fast Lagrangian Analysis of Continua) software used to model the behaviour of dump slopes. This entails acquainting oneself with the software capabilities, the necessary input parameters for precise simulations, and the interpretation of the results to evaluate stability;
b. Making Numerical Models of Dump Slopes: The study will make numerical models of waste dump slopes that include changes in slope angle, dump height, cohesion, and the angle of internal friction. These models will help us identify the key factors that affect dump stability and enable the evaluation of potential failure conditions. The study will provide the design of waste dumps, helping to optimise slope angles and parameters to minimise the risk of waste dump slope failure; and
c. **Parametric Variations and Stability Assessment**: Parametric studies of numerical modelling refer to the systematic variation of key input parameters to evaluate their effect on the stability of coal mine waste dumps. Changes in important parameters, like slope angle, height, cohesion, and angle of internal friction, will be done to see how these affect the stability of the waste dump. FDM has been employed to investigate the impact of factors like dump height, slope angle, and material properties on the stability. The method is known for its ability to handle large deformations and for its relatively simple implementation, making it suitable for parametric studies[3,4].

2.0 Literature Review

The study by focused on the estimation of critical parameters that influence slope instability in in-pit mine dumps[5]. The research concluded that key factors such as soil cohesion, friction angle, and external environmental conditions significantly affect the stability of mine dump slopes. The study emphasized the importance of accurately estimating these parameters for the proper assessment and mitigation of slope failure risks. It was found that variations in material properties and external forces, such as rainfall or seismic activity, can alter the stability of waste dumps. The research also highlighted the role of slope geometry, particularly the height-to-slope ratio, in determining failure susceptibility. By conducting a detailed parametric study, the authors demonstrated that maintaining an optimal combination of these parameters is crucial for preventing instability. The findings underscored the need for careful monitoring and management to enhance the long-term stability of mine waste dumps.

The study concluded that FDM provides a comprehensive approach to evaluating the stability of coal mine waste dumps, particularly when examining the effects of material properties and slope geometry[6]. The study found that both cohesion and the internal friction angle of waste materials significantly influence the stability of the dumps. Higher cohesion and friction angles lead to greater stability, while lower values increase the risk of failure. The study also emphasized the critical role of slope angle in determining stability, with steeper slopes (greater than 35°) significantly raising the risk of failure, especially when the height of the dump is increased. It highlighted the importance of optimizing the height-to-slope ratio to ensure long-term stability.

The study concluded that numerical analysis is an effective tool for evaluating the stability of coal mine waste dumps under varying loading conditions[7]. The research highlighted that external load, such as added waste material or environmental factors like rainfall, significantly influence the stability of the dumps. The study found that increases in dump height or external loading led to higher

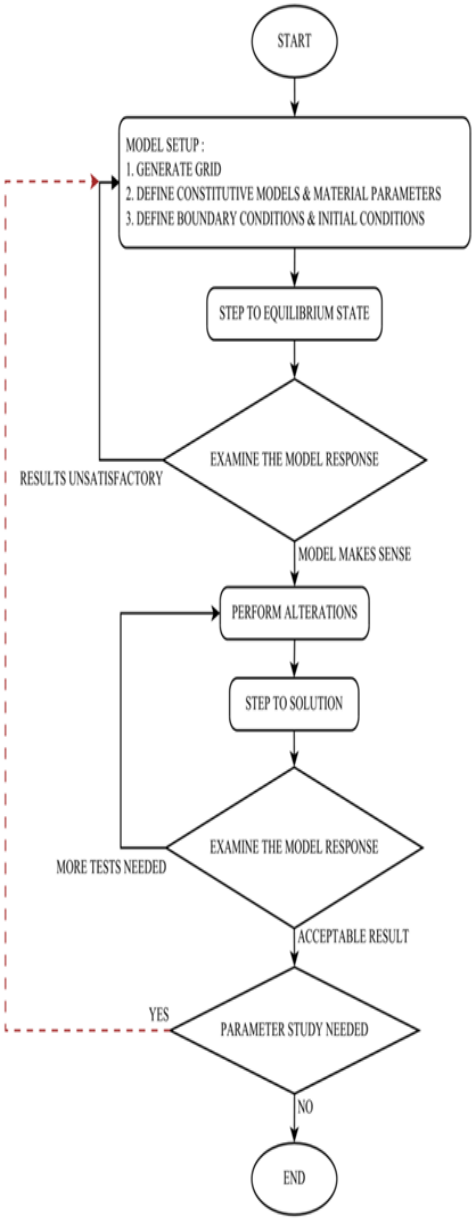


Figure 1. Flowchart of methodology for parametric study using FLAC/Slope.

stress concentrations at the base of the waste dump, which can increase the risk of slope failure. Additionally, the study emphasized the importance of considering both the material properties and external loading conditions when assessing stability. It was also noted that the application of appropriate reinforcement measures or changes in slope geometry could improve the overall stability of waste dumps. The findings reinforced the need for a thorough understanding of loading conditions to design safer and more stable waste dumps in coal mining operations.

The study concluded that the slope angle plays a crucial role in determining the stability of coal mine waste dumps, with steeper slopes significantly increasing the likelihood of failure[8]. Using FDM the research demonstrated that slope angles greater than 35° elevate the risk of instability, especially when the height of the waste dump is increased. The study found that the combination of high slope angles and tall dumps leads to increased stress and strain at the base, exacerbating the potential for slope failure. Furthermore, the research emphasized the importance of optimizing the slope angle to ensure long-term stability, as slopes that are too steep can lead to excessive shear forces and material sliding. The findings highlight the need for careful design and management of waste dump geometry, specifically focusing on the slope angle, to improve overall safety and stability in coal mining operations.

The study concluded that the angle of repose and dump geometry significantly influence the stability of coal mine waste dumps[9]. The research highlighted that the angle of repose, which defines the steepest slope at which the waste material can remain stable, is a critical factor in preventing slope failure. Waste materials with low cohesion and high porosity tend to have a lower angle of repose, making them more susceptible to instability when placed at steeper angles. The study found that the geometry of the dump, the height and slope configuration play a key role in determining overall stability. As the height of the dump increases, so does the potential for excessive stress at the base, leading to possible failure. The study concluded that proper consideration of the angle of repose and optimized dump geometry are essential for ensuring the safe and stable design of coal mine waste dumps.

The study investigated the rapid flow slides of coal mine waste in British Columbia, Canada, and concluded that such catastrophic events are primarily triggered by a combination of steep slopes, high moisture content, and weak material properties[10]. It was found that the geometry of the waste dumps, including slope angle and dump height, significantly influenced the risk of such events. The authors concluded that effective monitoring, material characterization, and the implementation of stabilization

measures are essential to mitigate the risk of rapid flow slides in coal mine waste dumps.

The present study uses FLAC, based on the FDM which divides the physical domain of a slope into a grid of elements, enabling the calculation of critical parameters such as stress, strain, and displacement at each point within the model. This approach provides a comprehensive understanding of slope behaviour by simulating how material properties, geometry, and loading conditions influence stability. FLAC/Slope, a specialized tool within the FLAC software suite, enhances the capability to perform complex stability analyses and parametric studies for slope stability projects[4]. It integrates multiple analyses, making it an invaluable resource for evaluating the safety of waste dump designs. A critical component of the stability analysis process is the strength reduction factor (SRF) technique[11-13], which calculates the FoS. By gradually reducing the material strength until failure occurs, the SRF technique provides an accurate representation of the slope stability. In validation cases, the SRF technique has been proven effective in reproducing observed instabilities, demonstrating its ability to accurately predict the failure mechanisms of slopes. This validation reinforces the reliability of FLAC/Slope and its capacity to predict real-world failures, thus serving as a powerful tool for ensuring the safe design and management of coal mine waste dumps. The use of FLAC and FLAC/Slope allows mining engineers to conduct comprehensive, reliable stability analyses, optimizing the safety of mining operations[14].

3.0 Mine Study Area

Table 1 shows the overburden dump stability parameters of Singareni Collieries Company Limited (SCCL) Srirampur OCP-II project. The mine is located in the southern section of the Somagundem-Indaram coal belt, between north latitude $18^0$49'04" and $18^0$51'12" and east longitude $79^0$31'18". Table 2 summarizes the lithological properties of the overburden of SRP OCP-II. Table 3 lists the physico-mechanical properties of the overburden at SRP OCP-II. Table No. 4 shows the dump material properties under drained condition. The material characteristics data used in the FDM system study were collected from the Srirampur OCP-II mine and are provided in Table 4[15]. The Srirampur OCP-II case study

Table 1. Overburden dump stability parameters

Stability parameters	Study site (Srirampur OCP-II)
Dump slope	37.5°
Dump height	90m
Dump material quality	Medium grain sandstone (moderate)
Foundation type	Competent
Foundation slope	Flat
Dumping method	Shovel-dumper
Dynamic force	Moderate
Dumping rate	Slow

Table 2. Lithological characteristics of overburden of SRP OCP-II

Strata	Lithology	Thickness (m)
Above I seam	Medium to coarse grain grey sandstones	45-75
Parting between I and II seam	Medium grained grey sandstones	10-36
Parting between II and III-B seam	Fine grained to Medium grained grey sandstones	25-50
Parting between III-B and III-A seam	Fine grained to Medium grained white sandstones	6-19
Parting between III-A and III seam	Fine grained white sandstones	9-35

incorporated the variables into the modelling process, acknowledging that the composition of the overburden material can change significantly across different sections of the dump. The inclusion of variability ensures that the model closely mimics real-world conditions, leading to more reliable predictions of slope behaviour. Figure 2[10] shows how the variation in the material is taken into account by changing the input parameters used in

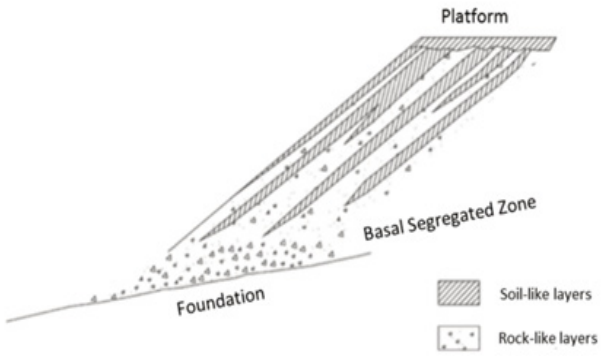


Figure 2. Idealisation of waste dump in the slope stability. Stratigraphy seen in an end-dumped waste dump.

numerical simulations with the adaptive continuum FDM system. The proposed dump slopes at Srirampur OCP-II follow geometry and dimensional guidelines based on the characteristics of the waste material and the operational requirements of the mine. The study objective is to assess the stability of the proposed dump overburden bench Srirampur OCP-II external waste dump as shown in Figure 3.

The study of these benches as part of the overall slope design helps to ensure that the dump can accommodate the increasing load of waste material over time without failure. This includes testing the behaviour of the dump under different material characteristics, including cohesion and internal friction, as well as varying dump heights and slope angles. With the use of the numerical results to adjust the design parameters, ensuring the slopes remain stable throughout the mine operational life. Over the course of the mine life, opencast mining manages its waste material through external dumping and then in-pit dumping. Initially, the mine uses external dumping to deposit overburden material outside its boundaries. As mining progresses, the overburden material is increasingly deposited inside the mine, forming internal dumps. The accumulation of waste rock during mining activities forms the bench, a stepped feature. It serves as a stabilising mechanism that enhances slope safety by preventing material from sliding or collapsing. The creation of these benches helps to manage the waste material efficiently, ensuring that the slope maintains its integrity over time. By terracing the slope into manageable sections, the benching process reduces the risk of erosion and landslides, contributing to both the safety of mining operations and the surrounding environment. Geotechnical assessments of the site guide the design and size of the benches with precision. Proper bench design and slope profile are essential for

Table 3. Physico–mechanical properties of overburden of SRP OCP- II

Sl. No.	Strata	Density gm/cc (Dry)	Compressive strength (MPa)	Cohesion kg/cm^2	Friction angle (degree)
1	Medium to coarse grained grey sandstones	1.91 to 2.13	7.82	32 - 48	30
2	Medium grained grey sandstones	2.12	17.9	38 - 55	40
3	Fine grained grey sandstones	2.03	18.0	55	36
4	Coarse grained white stones	1.91 to 2.03	10.98	45	35.5
5	Medium grained white stones	2.12	14.8	38	38
6	fine grained white stones	2.17	23.48	37	42

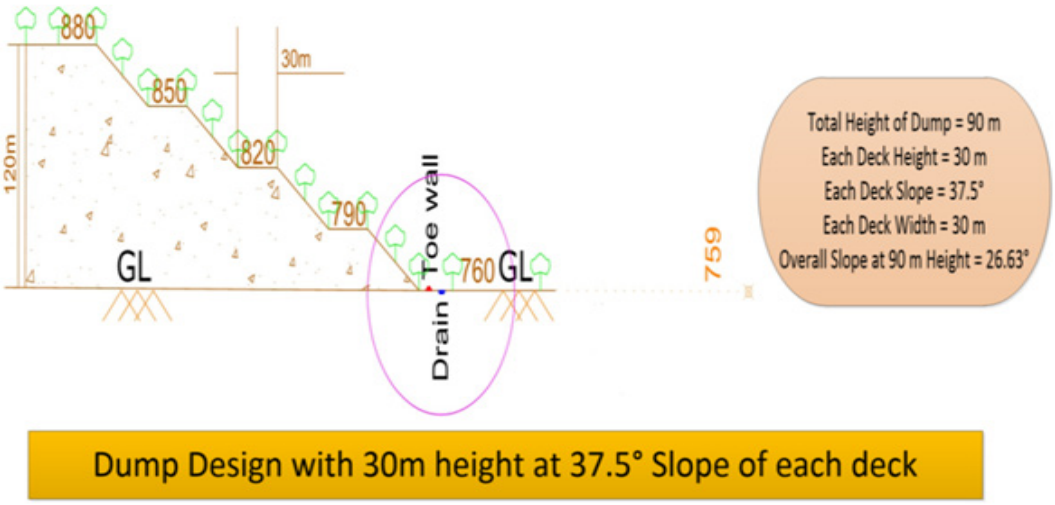


Figure 3. Section of overburden dump bench.

Table 4. Dump material properties under drained condition

Symbol	Quantity	Value
γ	Dry Density (kg/m^3)	2100kg/m^3
φ	Internal angle of friction (°)	30°
c	Cohesion (kPa)	55 kPa

distributing the weight of the overburden material evenly and preventing localised failure.

4.0 Numerical Modelling - Mine Waste Dump Stability

In opencast mining at the Srirampur OCP-II site, numerical simulations of slope stability are key for ensuring the operational safety of waste rock disposal. The material characteristics of the waste rock are key inputs to these simulations, as they directly influence the shear strength and stability of the coal mine dump slopes. The objectives of this study are to evaluate the stability of the dump slopes and to estimate the key shear strength parameters at which the slope becomes unstable using numerical modelling based on the Mohr-Coulomb failure criterion. According to Mohr-Coulomb criteria, the shear strength of a material is related to the normal stress acting on the shear plane, cohesion, and the internal friction angle of the material. We can express the law mathematically as follows[3,16]:

$$\tau = c + \sigma_n \tan\varphi$$

where: τ is the shear stress along the shear plane at failure, c is the cohesion, a measure of the material internal stickiness,is the normal stress acting on the shear plane, and φ is the internal friction angle, which describes the resistance to sliding between particles. The Mohr-Coulomb model requires six primary material parameters for its implementation in numerical simulations: the friction angle (φ), cohesiveness (c), dilation angle (ψ), Young modulus (E), Poisson ratio (v), and soil unit weight (γ). These parameters are critical for accurately modelling the shear strength and deformation characteristics of the waste material under loading conditions. For the purposes of this study, the focus is on three primary material parameters: the friction angle (φ), cohesion (c), and material unit weight (γ). These three parameters directly affect the shear strength and stability of the dump slope, making them the most relevant for evaluating slope behaviour. By leaving out the secondary parameters and the dilation angle (ψ), the model stays simple and easy to use while still showing the main factors that cause slope failure[16].

Material properties for each element within the model grid are assigned based on the measured characteristics

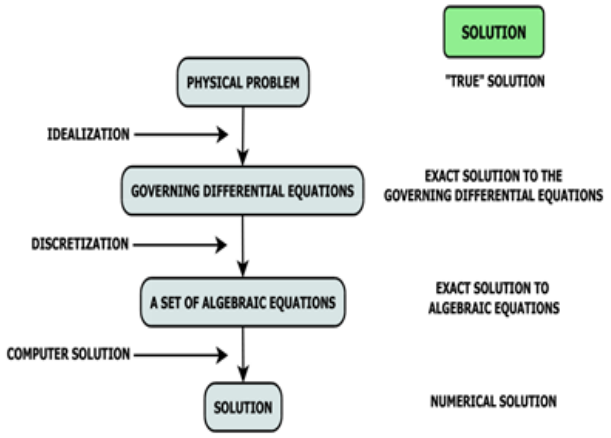


Figure 4. FDM steps and solutions.

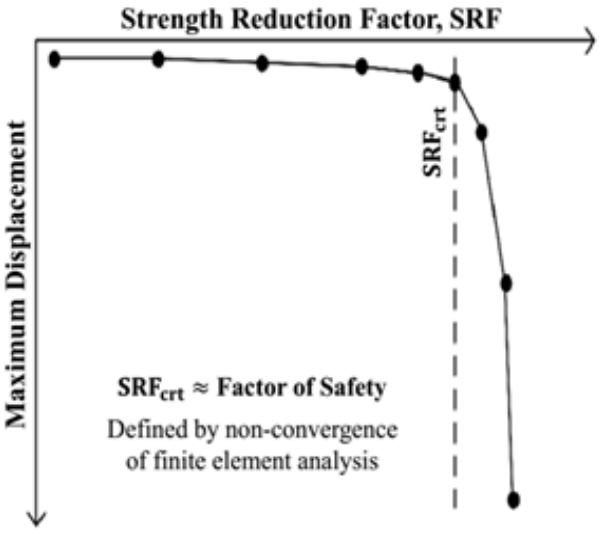


Figure 5. Non-convergence failure criterion for strength reduction analysis.

from the Srirampur OCP-II mine. The elements are represented as quadrilaterals within the grid, and the shear strength is computed at each element using the Mohr-Coulomb criterion. The FDM is a numerical method used to analyze both static and dynamic stability for assessing the stability of waste dumps in opencast mining[3,16]. The method involves replacing the derivatives in governing equations with approximate "finite difference" relations at discrete nodal points arranged on a grid or mesh. These relations are used to convert the continuous governing differential equations into a set of algebraic equations, which can then be solved computationally[3,4,17,18]. The FDM approach allows to model behaviour and interactions within a rock or soil mass, providing valuable insights into potential failure mechanisms and the overall stability of the waste dump slopes. When applying FDM to waste dump analysis, it is to understand that the accuracy of the solution depends on types of errors, including discretization error, numerical error (due to round-off), and total error. These errors can impact the results, but they can be minimized by refining the grid resolution and carefully selecting numerical techniques[18].

As illustrated in Figure 4[18], a balance between computational efficiency and accuracy must be maintained to obtain reliable results. As illustrated in Figure 5[11-13], this non-convergence indicates that the system has exceeded its stable loading capacity and is experiencing failure. At this stage, some parts of the model undergo plastic deformation, and the system is unable to reach equilibrium. This failure is an aspect of the numerical simulation, as it signifies that the slope has reached a critical failure condition. In Figure 6[11-13], global failure is depicted as the point where the numerical solution fails to converge, showing signs of instability. Factors such as poor grid resolution, inappropriate material models, or incorrect boundary conditions can cause non-convergence. The model requires refinement to optimise grid spacing and time intervals for stability and convergence.

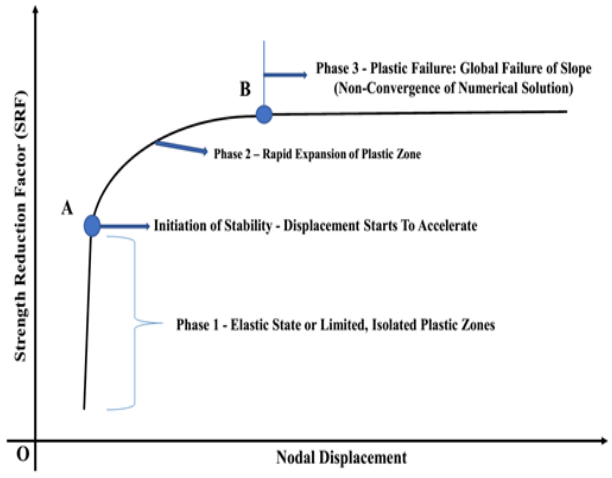


Figure 6. Global failure non-convergence of numerical solution.

For waste dump stability, the strength reduction method is utilised. This method involves a progressive process of reducing the strength of the rock mass and geological structures. For each reduction step, the fulfilment of the equilibrium criterion at each node of the model is checked. The SRF is determined at the point where the equilibrium criterion is no longer satisfied. The reduction in the strength of the rock mass and geological structures is based on an SRF. The reduction according to SRF is defined by Equation[13,19].

$$c_r = \frac{c_0}{SRF}$$

$$T_r = \frac{T_0}{SRF}$$

$$\varphi_r = \text{degrees}\left(\text{atan}\left(\frac{\tan(\text{radian}(\varphi_0))}{SRF}\right)\right)$$

where:

SRF = reduction factor. For this study, the SRF is the value of the factor of safety.

c_r, c_0 = reduced cohesion and original cohesion of the Mohr-Coulomb model, respectively.

T_r, T_0 = reduced and original tensile strength, respectively.

φ_r, φ_0 = reduced and original friction angle of the Mohr-Coulomb model, respectively.

The equilibrium criterion is defined based on the velocities of each node in the analysed sector and is described by Equation[4,13,19].

$$\text{velocity}_{\text{nodal}} < 1^* 10^{-5}$$

The reduction process used in the analysis consists of a total of nine steps, starting with a reduction factor of 0.90 and increasing in intervals of 0.05 until a reduction factor of 1.30 is reached. Stability analysis is based on the FoS results obtained using the SRF technique for each analysis period, all geomechanically significant zones are identified and each zone is analysed independently[4,13].

In this study, the 2D-FDM software FLAC version 7.00, developed by Itasca Consulting Group Inc., was employed for the analysis. The strength reduction method in FLAC/Slope is based on systematically reducing the material strength properties until failure occurs, helping to determine the FoS. The procedure of strength reduction in FLAC/Slope is as follows[4]: First, the code finds a "characteristic response time", which is a representative number of steps (denoted by N_r) that characterizes the response time of the system. N_r is found by setting the cohesion and tensile strength to large values, making a large change to the internal stresses, and finding how many steps are necessary for the system to return to equilibrium then, for a given FoS, N_r steps are executed. If the unbalanced force ratio is less than 10^{-3}, then the system is in equilibrium. The FoS at which collapse occurs is found by bracketing and bisection method. The lower limit of bracket represents the current F_{trails} where the simulation converges. The initial upper limit of the bracket is any F_{trails} where the solution does not converge. The next value is selected by bisecting this interval (new F_{trails}). The process is repeated until the difference between the upper limit and lower limit of bracket values becomes smaller than 0.005. The strength reduction technique gives the FoS concerning geomaterial shear strength. It gives the advantage of automatic critical failure mechanism for the dump[3,4,14].

The analysis process in FLAC/Slope can be divided into four key stages[4]: (1) **Models Stage**: In this stage, users define the geometry, material properties, and boundary conditions of the model, specifying simulation parameters like slope dimensions, material types, and the analysis type (static or dynamic). (2) **Build Stage**: Here, the model is discretized into a mesh of elements, with material properties assigned to each element. Mesh resolution is crucial, as finer meshes yield more accurate results but require more computational resources. (3) **Solve Stage**: FLAC/Slope uses the finite difference method to solve algebraic equations, calculating stresses, strains, and displacements at each node. The solver adjusts shear strength parameters during strength reduction analysis to compute the Factor of Safety (FoS) and assess slope stability. (4) **Plot Stage**: In the final stage, graphical plots are generated to visualize results like stress distributions, displacement vectors, and the FoS, helping to identify failure zones and evaluate slope behaviour under loading conditions.

In this study, boundary conditions were applied as follows: (a) a **roller boundary** was applied to the back side of the dump. This boundary allows displacement

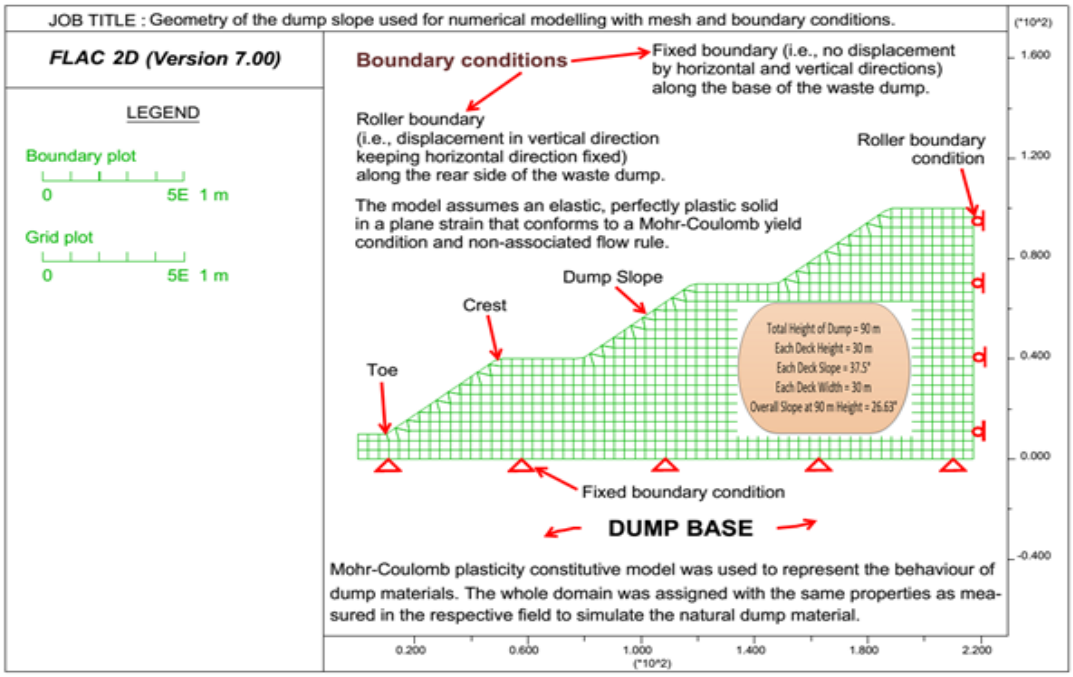


Figure 7. Boundary conditions with mesh for numerical modelling.

in the vertical direction, but fixes the horizontal displacement. This condition simulates the scenario where the dump is against a solid boundary as a natural slope or retaining structure, with no movement allowed in the horizontal direction; and (b) a **fixed boundary** was applied along the base of the dump, which means that there is no displacement in either the horizontal or vertical directions at the base. This boundary condition represents a rigid foundation, simulating the underlying rock or soil layer that does not move under the weight of the dump. To imitate the natural dump material, the entire domain was assigned the same attributes as those measured in the relevant field. The slope angle and height of the Srirampur OCP-II dump were observed to be 37.5°, with 30m evaluated for an overburden dump height of 90m. The base length of 237m was chosen after examining the dump design and the effects of stress. The boundary conditions were applied as a roller boundary (i.e., displacement in the vertical direction while keeping the horizontal direction fixed) along the backside of waste dump and a fixed boundary (i.e., no displacement in either horizontal or vertical directions) along the base as suggested and illustrated in Figure 7 for numerical modelling by[16].

5.0 Results and Discussion – Mine Waste Dump Stability and Parametric Study

The FDM numerical technique simulates the behaviour of slopes and waste dumps under loading conditions. Finite difference equations model the soil behaviour by discretising the entire domain into a grid of nodes. FDM has been employed to investigate the impact of factors like dump height, slope angle, and material properties on the stability of coal mine waste dumps. The method is known for its ability to handle large deformations and for its relatively simple implementation, making it suitable for parametric studies. FLAC/Slope is used for performing parametric studies, which involve varying one or more input parameters to assess their effect on slope stability.

The Srirampur OCP II waste dump stability study uses a parametric approach to examine the impact of various factors on the FoS for the dump slope stability. Key parameters considered in the analysis include the slope angle, dump height, cohesion, and angle of internal friction. The study investigates the influence of varying the slope angle of the waste dump, aiming to identify the optimal slope configuration for maintaining stability

throughout the operation. A numerical model, using FLAC/Slope, was employed to simulate the stability under different conditions. The model focuses on a waste dump with a height of 90m, structured with three benches, each measuring 30m in both height and width. This bench system plays a crucial role in controlling the overall stability of the dump by enhancing its structural integrity and facilitating the distribution of the stresses within the slope.

The parametric study starts with an initial slope angle of 37° and progresses in increments of 0.5°, up to 40°. The objective is to assess how incremental changes in the slope angle affect the FoS, which serves as a critical indicator of the safety and stability of the dump. For each slope angle, the FoS was calculated, and the results were recorded in Table 5. As expected, the numerical model revealed a clear trend: increasing the slope angle beyond a certain point resulted in a decreasing FoS, which correlates with a higher likelihood of slope failure. The FoS was highest at a 37° slope angle, indicating that this configuration offers the best stability under the given conditions.

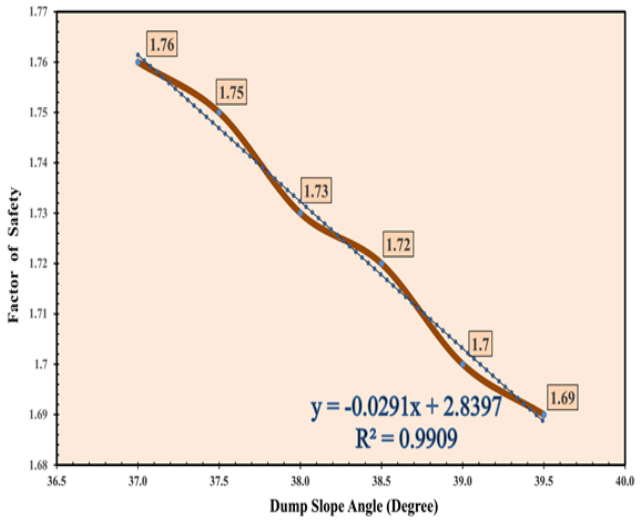


Figure 8. Variation in FoS vs. dump slope angle.

This trend emphasizes the delicate balance that must be maintained between maximizing the height of the dump for operational efficiency and ensuring that the slope angle remains within a safe range. Steeper slopes, while potentially allowing for greater waste volume, come with a significant risk of failure. The decrease in FoS with increasing slope angle suggests that a more gradual slope angle should be maintained to preserve the stability of the dump. Figure No. 8 further illustrates this relationship, showing a clear inverse correlation between the slope angle and the FoS. The parametric study highlights that slope angles beyond a certain threshold may result in an unacceptable reduction in FoS, thereby increasing the risk of failure. Further analyses can build on this study by incorporating other factors such as varying friction angles and cohesion values, to refine the understanding of waste dump stability under different conditions.

Quantifying the rate of slope failure is crucial for ensuring the safety of mining operations, particularly in opencast mining projects[14] like the Srirampur OCP-II. The FoS for the dump slope was evaluated under drained conditions, with a slope angle of 37.5° for each individual bench, which measures 30m in both height and width. The

Table 5. FoS vs. dump slope angle using FLAC/Slope

Sl. No.	Slope angle (^{0})	Density (kg/m^3)	Friction angle (^{0})	Cohesion (kPa)	FoS
1	37^0	2100 kg/m^3	30^0	55 kPa	1.76
2	37.5^0	2100 kg/m^3	30^0	55 kPa	1.75
3	38^0	2100 kg/m^3	30^0	55 kPa	1.73
4	38.5^0	2100 kg/m^3	30^0	55 kPa	1.72
5	39^0	2100 kg/m^3	30^0	55 kPa	1.70
6	39.5^0	2100 kg/m^3	30^0	55 kPa	1.69
7	40^0	2100 kg/m^3	30^0	55 kPa	1.68

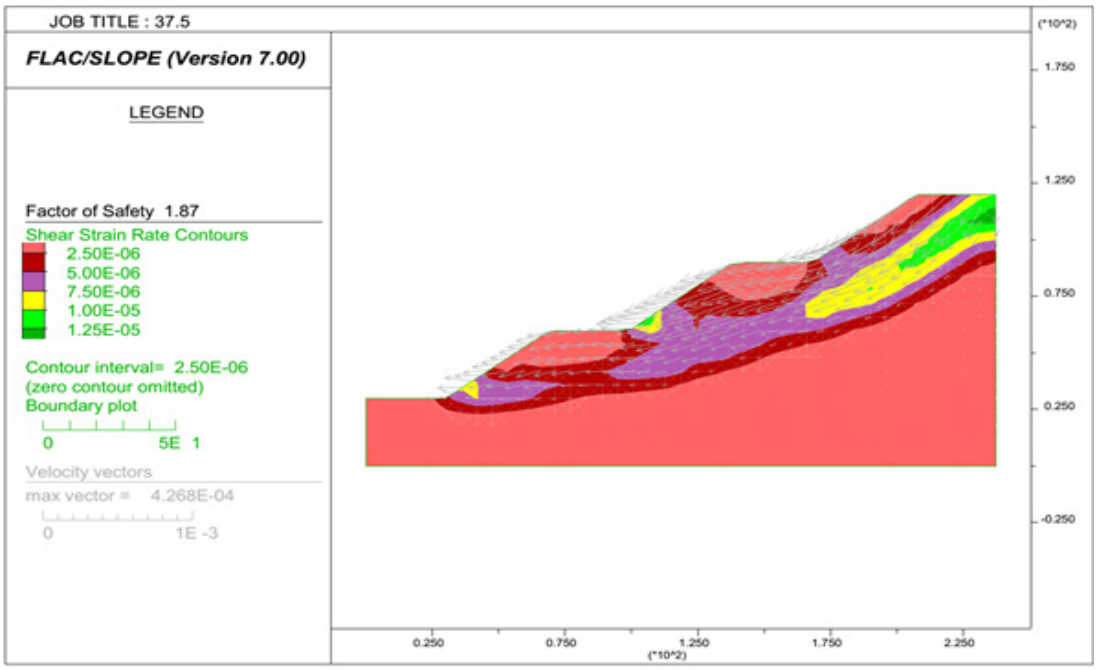


Figure 9. Limiting surface showing contours of maximum shear strain with FoS.

calculated FoS was found to be 1.87, which signifies a stable slope as it exceeds the threshold value of 1.5, a benchmark indicating that the slope is safe for operational activities. Additionally, the probability of failure was determined to be less than 1%, reinforcing the conclusion that the slope is highly stable under the existing conditions[3]. This analysis demonstrates that the slope is secure and meets the required safety standards for ongoing mining operations. The numerical modelling results shows that slope failure tends to occur along circular slip surfaces, with maximum shear strain contours forming a circular path near the slope toe. The greatest displacement occurs near the slope crest, suggesting that this region is the prone to failure. The crest, being the zone of maximum instability, is a critical area for monitoring and risk assessment (Figure 9)[15]. These findings indicate that while the overall slope is stable, focused attention is needed at the crest to prevent potential failure.

A parametric study plays a key role in modelling the behaviour of dump slopes, as material properties such as cohesion and the angle of internal friction are not fixed and can vary with environmental conditions and material composition[5]. The study focuses on understanding the results of cohesion and the angle of internal friction on the FoS with the increase in waste dumps heights. Cohesion (denoted as 'c') is a key factor in determining the shear strength of materials along dump slopes. It shows how particles are connected inside, and when it goes down, the material shear strength goes down too, which makes the slope more likely to fail[5]. Stability is achieved when the cohesion is at its smallest value, which ensures that

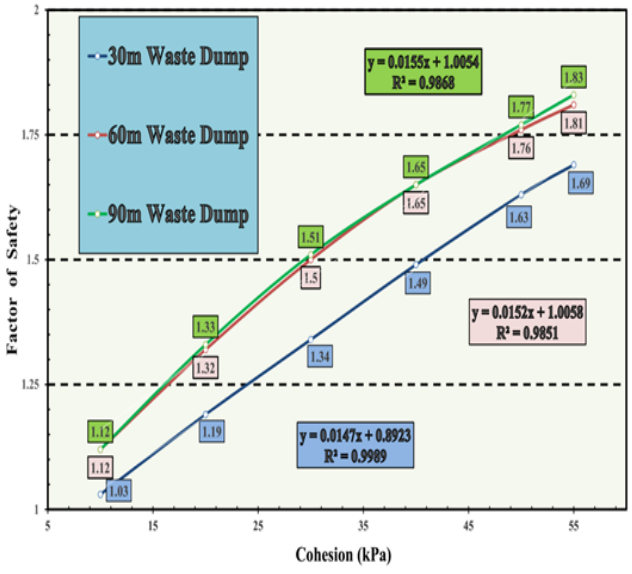


Figure 10. Variation in FoS with cohesion for increasing dump height.

Table 6. FoS with varied cohesion for increasing dump height

Sl. No.	Dump slope angle (^{0})	Dry density (kg/m^3)	Dump height (m)	Friction angle (^{0})	Cohesion (kPa)	FoS
1	37.5^0	2100 kg/m^3	30 m	30^0	10 kPa	1.03
2	37.5^0	2100 kg/m^3	30 m	30^0	20 kPa	1.19
3	37.5^0	2100 kg/m^3	30 m	30^0	30 kPa	1.34
4	37.5^0	2100 kg/m^3	30 m	30^0	40 kPa	1.49
5	37.5^0	2100 kg/m^3	30 m	30^0	50 kPa	1.63
6	37.5^0	2100 kg/m^3	30 m	30^0	55 kPa	1.69
7	37.5^0	2100 kg/m^3	60 m	30^0	10 kPa	1.12
8	37.5^0	2100 kg/m^3	60 m	30^0	20 kPa	1.32
9	37.5^0	2100 kg/m^3	60 m	30^0	30 kPa	1.5
10	37.5^0	2100 kg/m^3	60 m	30^0	40 kPa	1.65
11	37.5^0	2100 kg/m^3	60 m	30^0	50 kPa	1.76
12	37.5^0	2100 kg/m^3	60 m	30^0	55 kPa	1.81
13	37.5^0	2100 kg/m^3	90 m	30^0	10 kPa	1.12
14	37.5^0	2100 kg/m^3	90 m	30^0	20 kPa	1.33
15	37.5^0	2100 kg/m^3	90 m	30^0	30 kPa	1.51
16	37.5^0	2100 kg/m^3	90 m	30^0	40 kPa	1.65
17	37.5^0	2100 kg/m^3	90 m	30^0	50 kPa	1.77
18	37.5^0	2100 kg/m^3	90 m	30^0	55 kPa	1.83

grain contact is maintained and the material can still resist shear forces. The parametric study shows that cohesion changes, while the angle of internal friction, dry density, slope angle, and dump height are the same such that have an influence on the FoS of the waste dumps (see in Table 6). Figure 10 illustrates the variation of the FoS with changes in cohesion as the dump height increases. This highlights the critical role of cohesion in large dump design, where variations in cohesion can significantly influence the stability and overall safety of the waste dump slopes, requiring careful consideration.

The angle of internal friction (φ) plays key role in determining the stability of slopes. It is a material property that reflects the resistance to sliding between particles, and it is influenced by factors such as particle shape, size, and surface roughness[5]. In the study the angle of internal friction, in combination with factors such as cohesion, dump height, and dump slope angle are analyzed to evaluate its impact on the FoS (see in Table 7).

As in Figure 11, a direct relationship between the FoS and the angle of internal friction is evident. As the dump height increases, the FoS improves with an increase in the angle of internal friction. The study underscores the importance of this relationship, showing that even a minor reduction in the angle of internal friction leads to a substantial decrease in the stability of the dump slope. This observation aligns with the principles of the Mohr-Coulomb failure criterion, where the shear strength of a material is directly related to the angle of internal friction

Table 7. FoS with varied angle of internal friction for increasing dump height

Sl. No.	Dump slope angle (^{0})	Dry density (kg/m^3)	Dump height (m)	Friction angle (^{0})	Cohesion (kPa)	FoS
1	37.5^0	2100 kg/m^3	30 m	55 kPa	15^0	1.15
2	37.5^0	2100 kg/m^3	30 m	55 kPa	17.5^0	1.24
3	37.5^0	2100 kg/m^3	30 m	55 kPa	20^0	1.35
4	37.5^0	2100 kg/m^3	30 m	55 kPa	22.5^0	1.47
5	37.5^0	2100 kg/m^3	30 m	55 kPa	25^0	1.58
6	37.5^0	2100 kg/m^3	30 m	55 kPa	27.5^0	1.69
7	37.5^0	2100 kg/m^3	60 m	55 kPa	15^0	1.08
8	37.5^0	2100 kg/m^3	60 m	55 kPa	17.5^0	1.2
9	37.5^0	2100 kg/m^3	60 m	55 kPa	20^0	1.32
10	37.5^0	2100 kg/m^3	60 m	55 kPa	22.5^0	1.44
11	37.5^0	2100 kg/m^3	60 m	55 kPa	25^0	1.56
12	37.5^0	2100 kg/m^3	60 m	55 kPa	27.5^0	1.66
13	37.5^0	2100 kg/m^3	90 m	55 kPa	15^0	0.99
14	37.5^0	2100 kg/m^3	90 m	55 kPa	17.5^0	1.11
15	37.5^0	2100 kg/m^3	90 m	55 kPa	20^0	1.24
16	37.5^0	2100 kg/m^3	90 m	55 kPa	22.5^0	1.36
17	37.5^0	2100 kg/m^3	90 m	55 kPa	25^0	1.5
18	37.5^0	2100 kg/m^3	90 m	55 kPa	27.5^0	1.62

and cohesion[5]. The dashed line in Figure 11 highlights the critical FoS value of 1.25, which represents the minimum required angle of internal friction for maintaining theoretical stability under operational conditions. Values below this threshold indicate a risk of instability and potential failure. Therefore, accurate estimation of the angle of internal friction is key in designing safe and stable slopes. By ensuring the angle of internal friction meets the required threshold; mining engineers can mitigate the risks associated with slope failure and enhance the safety of the mining operations.

In SRP OCP-II, mechanical compaction is employed to enhance the shear strength of dump materials. The use of pneumatic compactor helps to compress the soil, reducing void spaces and increasing material density. This compaction improves particle interlocking, which enhances friction between the soil particles, resulting in increased shear resistance. The process effectively strengthens the dump material, making it more resistant to shear stresses and deformation under loading. In addition to mechanical compaction, chemical stabilization techniques are applied to further improve the shear strength. Fly ash is incorporated into the dump material to enhance cohesion and internal bonding. When mixed with soil, fly ash reacts with the soil particles to form cementitious compounds, which significantly strengthen the soil matrix. This chemical interaction not only improves cohesion between the soil particles but also

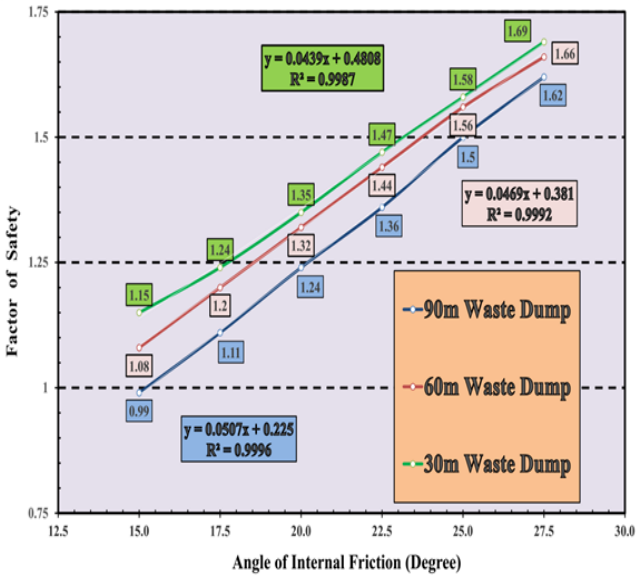


Figure 11. Variation in FoS with angle of friction for increasing dump height.

increases friction, further increases the shear strength parameters. By combining mechanical compaction with chemical stabilization using fly ash, a highly effective and durable solution is achieved for increasing the shear strength of the dump material. This dual approach enhances the stability of the dump, making it more resilient to failure under external loads, and improving its overall performance in the long term.

6.0 Conclusion

In conclusion, the Finite Difference Method (FDM) proves to be an effective and reliable tool for evaluating the stability of waste dumps in opencast mining. By incorporating the Mohr-Coulomb plasticity model, applying suitable boundary conditions, and meshing the model, FDM facilitates detailed stability analysis of complex waste dump structures. The Strength Reduction Factor (SRF) technique used in conjunction with FDM provides an accurate representation of the Factor of Safety (FoS), allowing for precise assessments of slope stability. The parametric study conducted using FLAC/Slope reveals a direct relationship between the slope angle and FoS, with the FoS decreasing as the slope angle increases. This finding emphasizes the importance of slope geometry in determining the stability of waste dumps, highlighting that steeper slopes are more susceptible to instability. Additionally, the study illustrates a strong linear correlation between shear strength parameters, such as cohesion and the angle of internal friction, and the FoS. This indicates that enhancing material quality by increasing these parameters can significantly improve slope stability. Furthermore, the analysis identifies a critical threshold in the relationship between shear strength factors and stability. When cohesion and internal friction exceed a particular value, the slope approaches critical instability, marking the boundary between stable and unstable zones. This insight is crucial for effective waste dump management, as it helps in identifying the specific conditions under which waste dumps may fail. The findings underscore the importance of controlling shear strength parameters to maintain safe operating conditions and prevent catastrophic failures in opencast mining operations. Overall, the study provides valuable guidance for improving the safety and stability of coal mine waste dumps.

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