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Numerical Investigation into Factors Affecting Stability of Opencast Coal Mine's Rise Side Highwall Slope

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Abstract

Open-pit coal mining accounts for 93% of India's total coal production, playing a significant role in meeting the nation's substantial energy needs. The success of an open-pit mine hinges on maintaining the steepest and deepest slopes that remain stable over the mine's lifespan. However, slope failure is a complex issue influenced by numerous factors. In the context of open-pit coal mines, the rise side highwall involves cutting through a rock mass containing various elements like an unconsolidated weathered mantle of sandstone, sandy clay, clay, carbonaceous shale and coal. Some opencast mines within the Godavari Valley Coal Field (GVCF), India have encountered significant pit slope failures. This paper uses a numerical modelling approach aimed at effectively assessing the stability of the rise side highwall, leveraging available geotechnical data from one of GVCF's largest opencast coal mines. The research investigates the impact of seven detrimental factors on slope stability, including dynamic loading due to blasting, employing a methodical One-Factor-At-A-Time (OFAT) approach. The study utilises Rocscience Phase2 version 9.0, a Finite Element Method (FEM) based numerical modelling software to gauge the sensitivity of each factor on the Factor of Safety (FoS). The numerical modelling results indicate that there is a linear decrease in FoS corresponding to the reduction in cohesion and an exponential increase in the FoS as the angle of internal friction rises. Furthermore, the analysis reveals significant impacts on the FoS due to groundwater and seismic loading from the blasting. This approach aims to comprehensively analyse and understand the intricacies of slope stability in the specific context of open-pit coal mining.

Keywords: *Godavari Valley Coal Field (GVCF), One-Factor-At-A-Time (OFAT), Rise Side Highwall, Slope Failure, Weathered Mantle*

1.0 Introduction

Coal stands as the foremost and most abundant fossil fuel in India, spread across 27 major coalfields and fulfilling 55% of the country's energy requirements[1]. Open pit mining technology constitutes a significant share of coal production, contributing to 93% of India's total coal output[1-3]. As the demand for coal in India is projected to continue rising until at least 2030 and potentially beyond, estimates suggest a total coal demand ranging between 1300 to 1900 million tons (Mt) by the year 2030[1-4]. To meet this anticipated surge in demand, Open-Cast (OC) mines will play a pivotal role. Open-pit mining proves highly cost-effective and enables substantial mechanisation allowing for the extraction of large production volumes[3,5,6]. However, a noteworthy trend is the increasing depth of these open-cast mines. In India, few opencast mines were designed to reach depths

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up to 400m, a testament to the progressive deepening of these operations over time[7,8]. This deeper exploration underscores the evolving landscape and challenges within India's open-cast coal mining sector[9].

The analysis of accidents and incidents in open-cast coal mines reveals a troubling trend with an increase in slope failures being observed in recent times[8]. Specifically, mines within GVCF such as Dorli OC-I, Srirampur OC-I, Gowthamkhani OC, Ramakrishnapur OC and Kakatiyakhani OC (Sector-I) have already encountered pit slope failures of rise side highwall[7,10,11]. This pattern necessitates a thorough investigation into the causes of these failures to prevent similar incidents in the future. Addressing this issue aligns with the recommendations of experts like Yue Li *et al*., who stress the urgency of conducting comprehensive studies on failure mechanisms and slope stability evaluation[12]. In line with Coal Mines Regulations 2017, proper planning, designing and scientific study of ultimate pit slope and monitoring stability become imperative for opencast mines[13]. Slope failure is a complex phenomenon influenced by numerous parameters. Evaluating the FoS is a common approach for slope design, with recommended values falling between 1.2 and 1.4 according to Wyllie and Mah[14]. These values vary based on different loads and geological conditions. While analytical modelling has been historically favoured, numerical modelling has gained traction recently, particularly in open-pit mining, due to its critical role in mine design, safety and economic impact[7,10]. This study uses a numerical modelling approach to effectively assess slope stability on the rise side highwall of one of GVCF's largest opencast coal mines.

By employing the FEM through Rocscience Phase2 version 9.0 software, the research aims to comprehensively analyse the sensitivity of seven detrimental factors on slope stability. Using the Strength Reduction Factor (SRF), the study evaluates each factor's impact on the FoS. The objective is to underscore the importance of understanding how various factors influence pit slope stability.

2.0 Sensitivity Analysis Through OFAT Approach

The sensitivity analysis method using the OFAT approach involves systematically altering individual factors to observe their specific impact on the output. This method allows for a clear understanding of how a change in a single factor directly influences the output without the complication of concurrent adjustments in multiple variables. By isolating one factor at a time, all other factors are maintained at their central or baseline values. This practice ensures better comparability of results and reduces the likelihood of software crashes, which can occur when numerous input variables are altered simultaneously. Additionally, the OFAT approach facilitates quick identification of the responsible input factor in case of model failure, aiding in immediate troubleshooting and corrective actions[15].

3.0 Location and Design Parameters of Opencast Coal Mine

The GVCF in Telangana state spans an extensive 350-kilometer stretch, housing substantial coal reserves. These proven geological resources amount to an impressive 10475Mt and extend to depths of up to 1200 meters[16]. Presently, GVCF hosts a total of nineteen operational Open-Cast (OC) mines contributing to coal extraction efforts[16]. Among these, the present OC mine occupies a central location within GVCF, situated in Telangana state, India. Commencing operations in 2017, this mine utilises the benching method, employing a shovel-dumper combination alongside drill and blast excavation techniques.

OC mine boasts several distinctive characteristics defining its operational parameters and resource potential. Spanning a strike length along the surface ranging from 2499 to 2712 meters and a surface width extending between 878 to 1054 meters, the mine operates within a quarry depth varying from 30 to 180 meters. Its floor area covers 168.21 hectares, with an excavation area on the surface encompassing 253.24 hectares. The total project area for mining activities encompasses 637.25 hectares covering quarry, spoil bank and infrastructure area. The coal seams exhibit a gradient ranging from 1 in 4.10 to 1 in 3.10, containing an extractable coal reserve estimated at 23.34 million tons. With a stripping ratio of 1:14, the mine predominantly holds G9 and G11 grade coal across 11 coal seams. Anticipating a tenure of 10 years, this mine's configuration and resource allocation delineate its strategic significance within the coal mining landscape.

The design strategy for the pit slopes at OC mine was primarily based on experience rather than a scientifically conducted study, catering to a rated capacity of 2.5 million tons per year (Mt/y). The mine's expansion occurred gradually, unfolding in stages along the strike, extending from the northern to the southern boundary. Initially, the quarry was opened through an initial box cut in an area concealing the outcrop of seam v, the bottom-most coal seam.

To facilitate access to the coal deposit along the strike, a primary haul road was established, connecting the concealed Seam-V outcrop to the incrop location. Local ramps were strategically laid out to enable the transportation of both coal and overburden. As the initial cut widened adequately, subsequent benches were systematically deepened by increments of 10 meters. The upper benches of Overburden (OB) progressed towards the dip side, creating necessary space for the quarry's gradual deepening and expansion. This progressive approach allowed for efficient extraction to maintain the planned coal production.

4.0 Occurrence of Slope Instabilities at OC Mine

The OC mine encountered several slope failures, initiated in September 2017 and recurring periodically, significantly impacting operations. Initially, the rise side highwall benches formed up to 30 meters in depth from the surface experienced failures across a 500 meter strike length at the northern part of the quarry. In response, adjustments were made by widening the benches from 5 meters to 10 meters at the central part of the quarry, flattening the slope to mitigate future incidents. A typical view of the rise side highwall slope of OC mine is shown in Figure 1.

Despite these modifications, slope failures reoccurred in September 2018 prompting further management actions. Benches were widened to 15 meters at the southern part of the quarry along a 600 meter strike length, aiming to enhance stability. Thus, the overall slope angle (for a 30m high highwall) of the rise side highwall decreased in stages from to . However, subsequent slope failures persisted in October 2019, raising concerns.

Geotechnical mapping of the exposed benches unveiled the extension of the bottommost coal seam (Seam-V) into the highwall, revealing variations in coal seam composition consisting of mainly shale and blackish clay. The overburden on the rise side highwall slope primarily comprises fractured and weathered brownish sandstone. Only Seam v was found in the studied section because it was the lowest seam and was encountered first during excavation because of geological reasons. Moreover, the mine boundary on the rise side (west) was set up to where the incrop of Seam-V, which is lying 30 meters deep in the GVCF. While, the incrops of the remaining upper seams would occur further ahead, i.e., towards the quarry's dip side property.

Figure 1. A view of the rise side highwall slope of OC mine.

Daylighting of Seam-V into the slope face is critical, causing many slope failures in the mine. To prevent these failures, the mine management modified the highwall by making it flatter. They did this by widening the benches from 5 meters to 15 meters. Additionally, to prevent slope failures, controlled blasting techniques like line drilling and pre-splitting were used when blasting near the rise side highwall benches. Mine authorities also limited the amount of explosives used per hole, the number of holes fired in a round of blasting and effective drainage measures were put in place. Wherever feasible, the mine authorities backfilled (internal dumping) immediately after the evacuation of coal to provide lateral support to the disturbed highwall.

The quarry floor limit line on the rise side was planned to reach up to the incrop of Seam-V. The ground beneath, up to a depth of 30m, consisted of an unconsolidated weathered rock mass. Because of the presence of a public road and poor quality of Seam-V incrop region had led the mine management to restrict the rise side highwall slope's surface excavation limit line of the quarry. This decision led to leaving behind Seam-V, which mainly consists of clay and shale and the same was revealed during subsequent geological mapping of highwall benches.

Notably, these slope instabilities predominantly occurred during the monsoon period, leading to increased stripping costs, alterations in haul road routes for coal and overburden transportation, production delays and safety hazards. The repetitive nature of these slope failures necessitates urgent attention and strategic interventions to address the ongoing challenges impacting the mine's efficiency and safety.

5.0 Formulation of a Typical Slope Model

The pit slope stability analyses have been meticulously conducted utilising Rocscience Phase2 version 9.0, a numerical modelling software that accurately mirrors the rise side highwall slope's field conditions (Figure 2). The modelled slope measuring 30 meters in height with an overall angle of 55°, encompasses various strata thicknesses and the inclination of the coal seam which dips at 16° into the excavation. The computational model takes into account the, weathered sandstone, sandstone and coal as the materials for analysis, all dipping towards the excavated pit.

In the studied section of the rise side highwall slope of OC mine, Seam V was the bottommost seam, whose incrop encountered at a depth of 30m from the surface. Hence, there were 3 benches each 10m in height with widths varying from 5m to 10m. Hence, in numerical simulations, a single slope of 30 m height with slope face stretching from the crest of the top bench to the toe of the bottom bench, was considered for analysis to investigate the effect of seven detrimental factors including slope angle on the stability of the slope.

Shear strength parameters play a pivotal role in numerical modelling for optimising pit slope design. Understanding the lithological units within the slope's construction is crucial as these units' engineering properties significantly impact slope stability analysis. To ascertain these properties, core samples were diligently collected from the mine and subjected to laboratory testing to determine density and shear strength

Table 1. Strength properties of rise side highwall slope material at OC mine

S.No.	Material	Cohesion (kPa)	Friction Angle (deg)	Unit Weight (kN/m^3)
1	Weathered Sandstone	95.00	21.00	22.00
2	Coal seam	105.00	19.00	15.50
Weighted average (Above Strata)		95.97	20.81	21.37
3	Sandstone	200.00	35.00	25.00

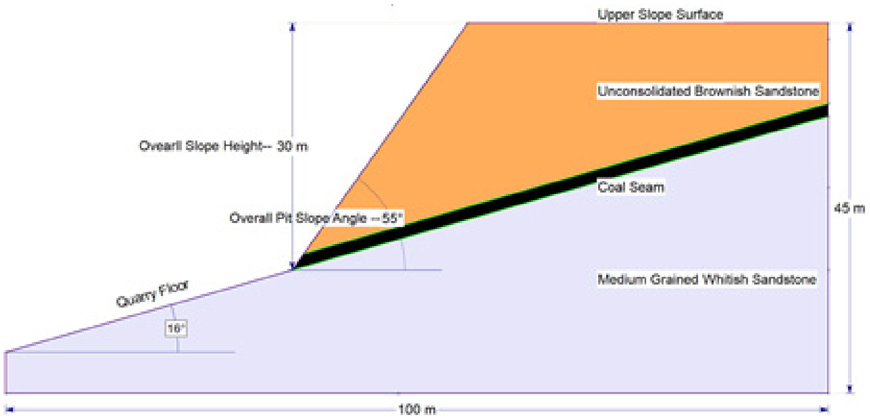

Figure 2. Model configurations and parameters employed in the numerical modelling.

parameters. Table 1 presents the pertinent strength properties, notably focusing on the weighted average properties and specifically the properties of sandstone. Sensitivity analysis of pit slope stability primarily considers the sandstone (representing the basement rock) for simulation, presuming its strength to be robust and anticipating no failure within this stratum. Confirming this assumption, the numerical modelling indicated that the failure plane does not intersect the sandstone strata present on the floor.

The model's left, right, and bottom edges are restricted in both X and Y directions while the top, bottom and slope faces remain unrestricted. The slope model's area was divided into 6-noded triangular elements (T6) with a consistent mesh. In total, there were 2591 elements and 5372 nodes within the slope model.

6.0 Sensitivity Analysis of Factors Affecting the Highwall Slope Stability

The repeated failures of the rise side pit slope at OC mine necessitate an immediate and comprehensive investigation into the contributing factors to prevent future occurrences and implement necessary precautions throughout the remaining lifespan of the

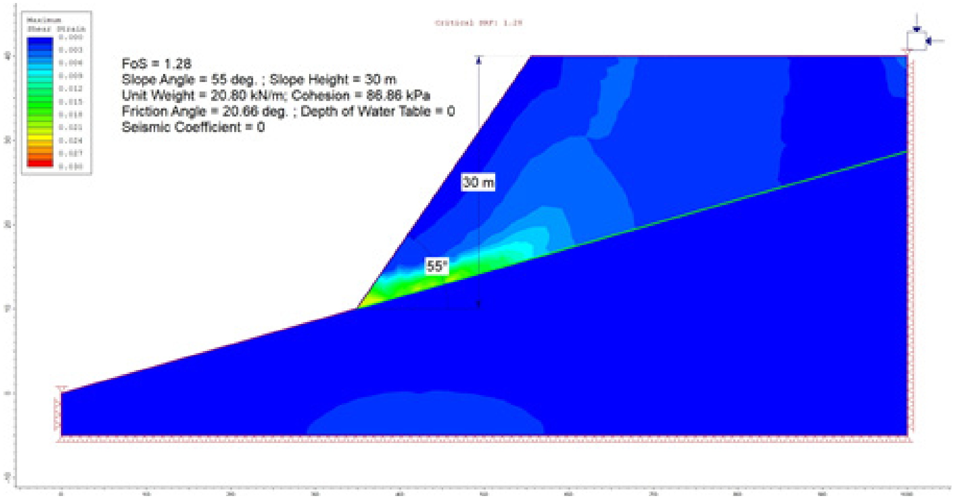

Figure 3. The critical failure surface and the Factor of Safety (FoS) of slope in a fully drained condition.

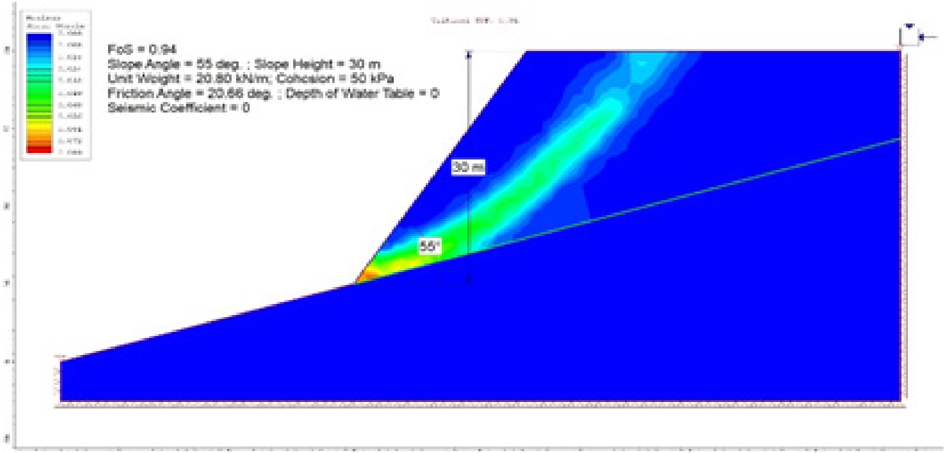

Figure 4. The critical failure surface and the Factor of Safety (FoS) of slope with reduced cohesion.

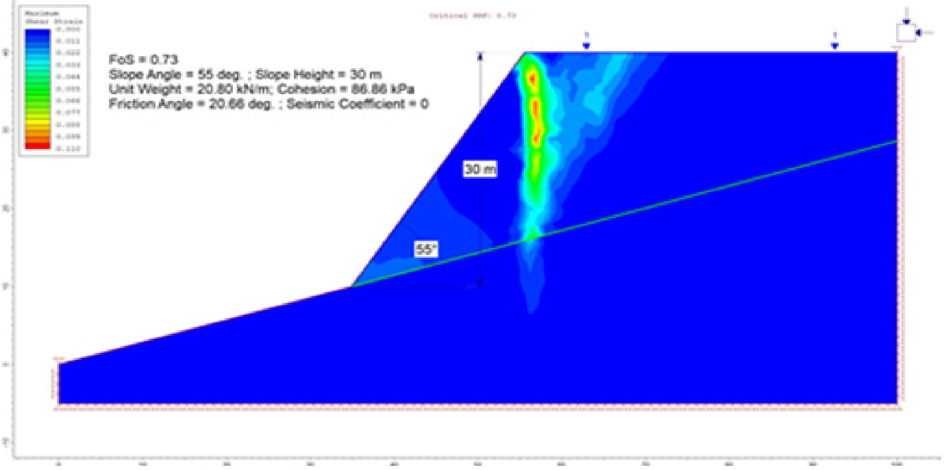

Figure 5. The critical failure surface and the Factor of Safety (FoS) of slope in undrained condition.

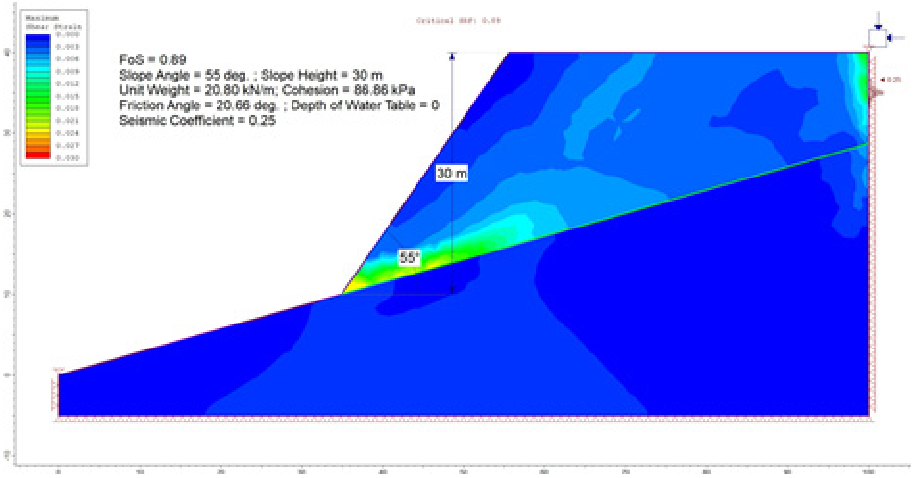

Figure 6. The critical failure surface and the Factor of Safety (FoS) of the slope with dynamic (seismic) loading due to blasting.

mine. Typically, slope failures stem from a multitude of causes rather than a single factor, often involving a combination of elements that collectively trigger the failure.

Various factors significantly influence the stability of the rise side highwall at OC mine, encompassing aspects such as topography, geological formations, lithology of strata, overall pit slope angle, rainfall and dynamic loading induced by blasting operations. Post-mining geological mapping unveiled the absence of significant joints during the pit formation, highlighting the need for a suitable numerical method for slope stability analysis. Consequently, a two-dimensional continuum modelling approach was deemed most appropriate for this scenario.

The estimated FoS obtained through FEM for the OC mine's rise-side pit slope under different scenarios is depicted in Figure 3, Figure 4, Figure 5 and Figure 6. The numerical analyses conducted under fully drained conditions except for investigation into the sensitivity of water table on slope stability, in which a piezometric head is added in numerical simulations indicate a critical situation, considering that a pit slope is unstable if its FoS is less than 1.2[10,17-18]. This finding corresponds with the observed field situation, signalling the present state of instability and the urgent need for remedial measures to mitigate further slope failures.

7.0 Results and Discussions

In this research, seven key factors, slope height, overall pit slope angle, strata weight, strata cohesion, angle of internal friction, groundwater level and seismic loading from blasting were investigated to understand their impact on pit slope stability. The analysis involved altering one factor at a time while maintaining the others constant, examining how each factor influences the FoS. For this study, FEM software specifically Phase2 version 9.0, was employed to assess the sensitivity of each factor on the FoS.

7.1 Sensitivity of Slope Height

The relationship between the FoS and the slope Height (H) is depicted in Figure 7. The assessment of the slope's FoS involved incrementally raising the slope height in 5-meter intervals, starting from 10 meters. Results indicated a gradual decline in FoS as the slope height increased from 10 meters to 55 meters. On average, there was a consistent 4.53% reduction in the safety factor for each unit increase in height.

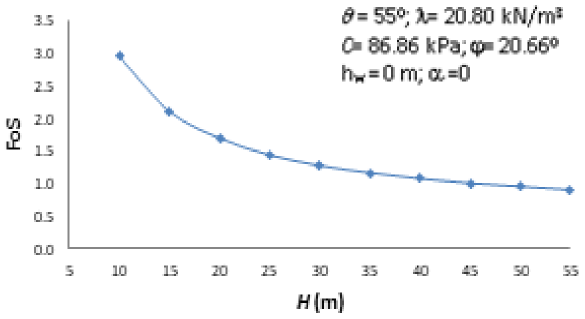

Figure 7. . Relationship between FoS and slope height

7.2 Sensitivity of Slope Angle

The analysis aims to investigate the impact of varying the pit slope angle (θ) on the FoS and to identify the critical pit slope angle. Using the computational model (Figure 2), the study assesses the influence of overall pit slope angles ranging from 25° to 70° on slope stability. The results, depicted in Figure 8, illustrate a notable trend. The safety factor experiences an exponential decline, dropping from 3.10 to 1.0 as the slope angle increases from 25° to 70°. On average, there's a consistent decrease

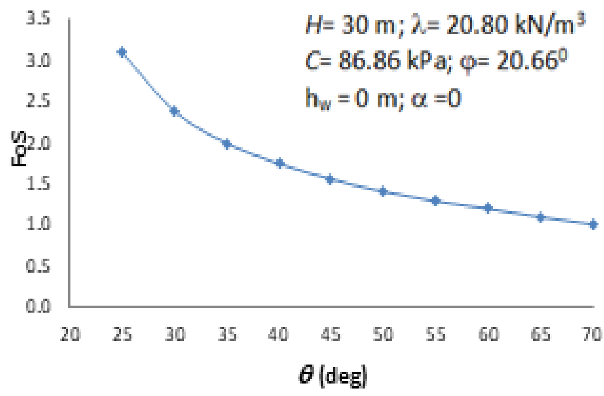

Figure 8. Relationship between FoS and angle of slope.

of 4.67% in the safety factor per unit increase in the slope angle.

7.3 Sensitivity of Unit Weight

The study aimed to assess the impact of unit weight (λ) on pit slope stability by systematically decreasing it in 3kN/m^3 increments from an initial value of 35kN/m^3. The relationship between the FoS and unit weight is visualised in Figure 9. The analysis showcased a non-linear decrease in slope safety factor with rising unit weight, particularly noticeable within the range of 5.0 to 17.0 kN/m^3. Notably, the safety factor exhibited a 16.07% decrease as the unit weight increased from 5.0 to 20.0 kN/m^3. On average, there was a 9.20% decline in the safety factor for each unit increase in unit weight. This highlights the direct and significant influence of unit weight on pit slope stability.

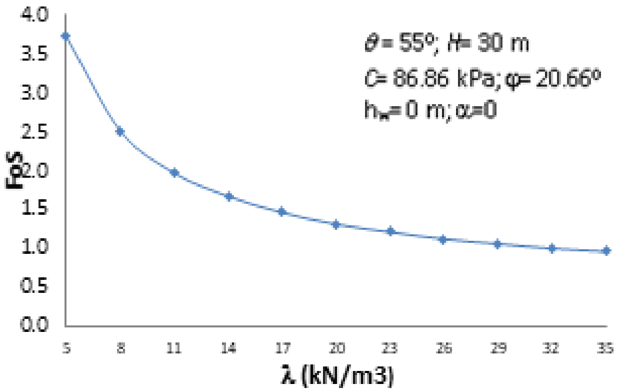

Figure 9. Relationship between FoS and unit weight, λ.

7.4 Sensitivity of Cohesion

The computational model was used to examine the impact of cohesion (decreasing in 10kPa increments from an initial value of 150kPa on slope stability. Figure 10 illustrates the relationship between the FoS and Cohesion (C). The graphical representation indicates a linear decrease in FoS corresponding to the reduction in C. Notably, the variations in FoS were relatively minor, displaying a consistent overall rate of decrease/increase of 0.91% for every unit decrease/increase in C. This linear relationship underscores the sensitivity of slope stability to changes in C, even though with relatively small fluctuations.

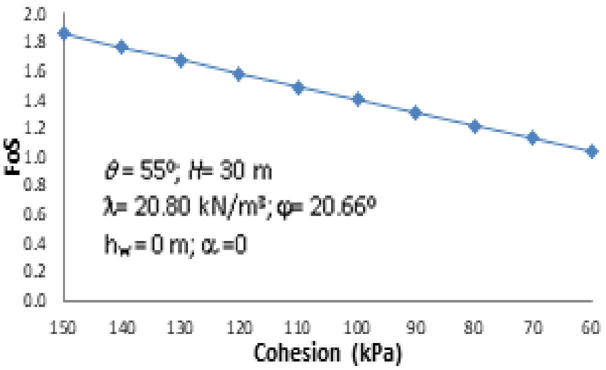

Figure 10. Relationship between FoS and cohesion of the slope.

7.5 Sensitivity of Friction Angle

The computational model was utilised to assess the impact of the angle of internal friction (decreasing in increments of from an initial value of f) on the stability of the rise-side highwall slope. Figure 11 represents the relationship between the FoS and the angle of internal friction (ϕ). Notably, the graphical depiction illustrates an exponential increase in the slope safety factor as the internal angle of friction rises. The variations in the safety factor were relatively substantial, with an overall rate of increase of 3.0% for every unit increase in the internal friction angle. This exponential relationship highlights the significant influence of the internal friction angle on slope stability, demonstrating considerable variations in the safety factor with alterations in this parameter.

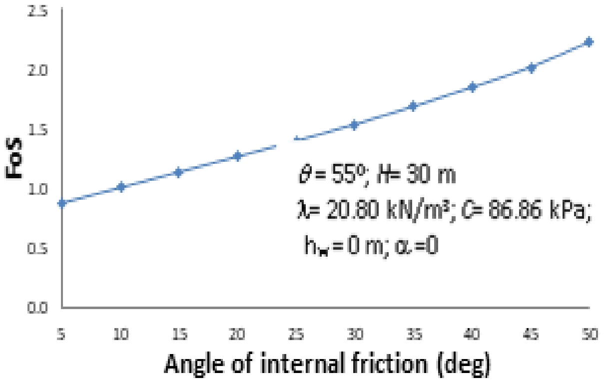

Figure 11. Relationship between FoS and friction angle.

7.6 Sensitivity of Water Table

The computational model (Figure 2) incorporating the water table, was employed to examine the impact of the depth of the water table from the surface (decreasing in 3-meter intervals from the surface) on the stability of the rise-side highwall slope. Figure 12 illustrates the relationship between the FoS and the depth of the water Table . Notably, the inclusion of the water table reduced the FoS to 0.73 from its dry condition value of 1.28 (as depicted in Figure 6) for the same computational model. This substantial drop of 42.96% in the slope safety factor underscores the remarkable influence of groundwater on slope stability.

The graphical representation illustrates a linear increase in the safety factor of the slope with a rise in the depth of the water table from the surface. Despite the increase, the variations in the safety factor are relatively minor, displaying an overall rate of increase of 1.83% for every unit increase in the depth of the water table from the surface. This linear relationship emphasises the sensitivity of the FoS of slope to changes in the depth of the water table.

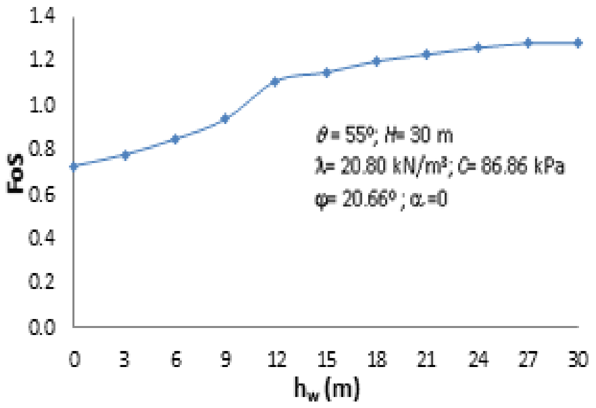

Figure 12. Relationship between FoS and depth of water table.

7.7 Sensitivity of Seismic Effect Due to Blasting

The computational model was utilised to assess the impact of the horizontal component of the seismic coefficient resulting from blasting (decreasing in increments of 0.05 from an initial value of 0.55) on the stability of the rise side highwall slope. Figure 13 illustrates the relationship between the FoS and the seismic coefficient (a) induced by blasting. The graphical representation reveals a linear decrease in the slope safety factor as the seismic coefficient caused by blasting increases. Significantly, the variations in the safety factor are relatively substantial, indicating an overall rate of decrease of 6.55% for every 0.05 increase in the seismic coefficient due to blasting. This linear relationship underscores the sensitivity of slope stability to changes in the seismic coefficient induced by blasting, highlighting notable fluctuations in the safety factor with alterations in this parameter.

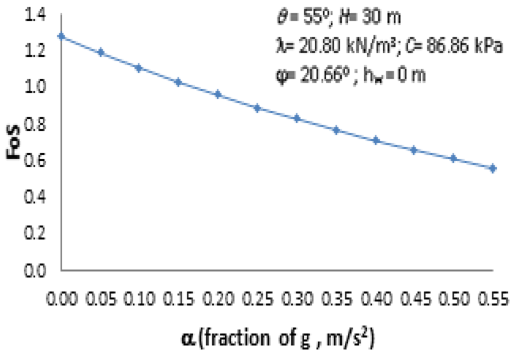

Figure 13. Relationship between FoS and Seismic coefficient due to blasting.

8. Conclusions

- In the present case study of pit slope stability analysis of a rise side highwall of 30 m height under the influence of seven major parameters has undergone thorough sensitivity analysis to assess open pit slope stability, both the model's geometry and computational setup, including boundary conditions, were established.
- The numerical modelling analysis reveals a linear decrease in FoS corresponding to the reduction in Cohesion and also illustrates an exponential increase in the slope safety factor as the internal angle of friction rises. Both these factors highlight their significant influence on slope stability. The analysis further reveals that factors pertaining to slope geometry such as slope height, overall pit slope angle and seismic loading from blasting

are controllable parameters, whereas unit weight, Cohesion, angle of internal friction and groundwater level are uncontrollable parameters. However, with effective drainage measures, the groundwater level can be controllable.

- The numerical modelling analysis revealed significant impacts on the FoS due to groundwater and seismic loading from blasting. Specifically, the inclusion of a water table led to a substantial 42.96% decrease while a 0.05 increase in the seismic coefficient resulted in a notable 6.55% drop in the slope safety factor within the computational model.
- The increasing order of most influencing parameters on the factor of safety of the slope is found to be as follows: height of water table, seismic coefficient, slope height, angle of internal friction and unit weight. slope angle and cohesion.
- In OC mines, it is very important and essential to pre-assess the stability of the pit slopes scientifically before the commencement of mining operations and the design of pit slopes should be optimised to ensure that the slopes are stable and economical.
- The analysis findings definitively confirm that pit slopes lacking a scientific basis in their design can lead to slope instabilities and subsequent occurrences of landslides.
- Implementing the results of these analyses can significantly contribute to the safe and economically sound design of pit slopes.
- To prevent slope instabilities, controlled blasting techniques like line drilling and pre-splitting should be strictly followed when blasting near the highwall benches to minimise the adverse impacts of dynamic loading. Mine authorities should also restrict the maximum charge per hole and the number of holes fired based in a round of blast on scientific basis.. Effective drainage measures should be put in place. Wherever feasible, back-filling (internal dumping) should be done immediately after the evacuation of coal to provide lateral support to the highwall.
- Further, the mine management should design the quarry in such a way that benches should be formed from downwards commencing from the outcrop of the coal seams, without leaving any coal seam to daylight in the slope face of the rise side highwall.
- Recommendations include implementing an efficient drainage system within and around open pits. Additionally, conducting real-time monitoring of pit slopes throughout the mine's operational life is advised to ensure continual stability and safety.

9.0 Acknowledgements

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