American Journal of Mining and Metallurgy, 2014, Vol. 2, No. 1, 1-7
Available online at http://pubs.sciepub.com/ajmm/2/1/1

DOI:10.12691/ajmm-2-1-1

Optimisation of Dump Slope Geometry Vis-à-vis Flyash Utilisation Using Numerical Simulation

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Received January 10, 2014; Revised March 29, 2014; Accepted March 31, 2014

Abstract Stability of waste dump is now gaining importance due to increasing depth and size of mine. Management of dump nearby mining areas is one of the most critical and crucial task for mine management due to limited land and other governing laws related to environment and forest conservation. In this paper, a study was conducted to establish the effect of slope angle on the stability of waste dump for accommodation of flyash is carried out. Based on numerical simulation, it was found that the dump slope of 60 m height with 36° slope can be critically stable with 20% flyash randomly mixed with overburden materials whereas flatter slopes provide higher factor of safety. Keeping other parameters constant, the optimum slope of 32° is the best possible to accommodate the mine dump for its long term stability. These findings were further supported by study of maximum velocity vectors and shear strain rates in every case and the extent of damage zone due to tensile pull. It is hoped that this technical note will find utility wherever a design of dump of chosen material type is being planned where the wastes can be managed alongside ulitisation of flyash.

Keywords: *dump, dump slope, factor of safety (FoS), finite difference method (FDM), FLAC/Slope*

Cite This Article: S.P. Pradhan, V. Vishal, T. N. Singh, and V.K. Singh, "Optimisation of Dump Slope Geometry Vis-à-vis Flyash Utilisation Using Numerical Simulation." *American Journal of Mining and Metallurgy*, vol. 2, no. 1 (2014): 1-7. doi: 10.12691/ajmm-2-1-1.

1. Introduction

Mining industries are one of the oldest industries on this earth, next to agriculture and are the basic examples of harnessing the mother Earth for the benefit, development and growth of mankind. Demand for raw materials to meet the growing needs has led to exploitation of earth resources since centuries of years. With decreasing near surface deposits, the demands are being met by gradual deepening of the crust to obtain the ores. This in turn leads to a large scale removal of overburden materials. Large dump accumulations are therefore formed in and around the mining areas. Studies on management of mine waste and dumps have increased in the last decade since it has been established that the waste do play a significant role in mine functioning and mining economics [25]. Several approaches have been utilised and case studies discussed for development of better dumps and landfills [12,13,26].

In India, a large number of surface mines are functional where economic deposits are extracted by several operations viz. drilling, blasting, and excavation, loading and dumping called as mining cycle. All these parameters play significant role in the economics of excavation [15]. The overburden has to be removed and transferred to an internal or external spoil heap. The dumping of overburden is itself a tedious task and formation of spoil heap and its stability is crucial for the progress of the mine. The dumping has to be done judiciously to ensure optimum use of ground and to reduce chances of any slide back or to avoid dangerous accidents in future. There are several parameters that affect the stability of dump slope like dump geometry, strength of the underlying rocks, mining methods, hydrological conditions, etc [16,22,23]. Once the location for dump accumulation is determined, it is mainly the design parameters that can be modified as per the existing foundation conditions. Dumps with low height and flatter slopes are ideal from the stability point of view but these not only occupy lot of ground space but also prove to be expensive due to transport and other handling costs involved. Hence, it is necessary to obtain a benchmark for an allowable dump height, slope angle and number of benches for a long term stable dump accumulation of the material type and should also be most economical. This not only provides with safe and stable conditions of mining but also minimizes the ill effects that a slope failure may have on the surrounding ecosystem [17,19,20,21,24].

Coal is a major source of energy and is believed to remain so for decades to come particularly in India. This is because nearly 64% of power generation in India is mainly based on coal production. Deeper and deeper coal deposits are being looked for and exploited to meet the needs of India's growing economy, industrialisation and population. The large amounts of fly ash generated from the capture power plants are a major environmental concern now a day [16]. Although methods of reutilizing these are being implemented, yet, large quantities need to be kept in the waste systems to achieve the goal of zero waste discharge. In this work, the stability of flyash wastes has been studied to understand and minimise the chances of devastating slope failures which is quite possible due to low cohesion of such materials. A fixed percentage of flyash is mixed with coal mine dump materials for long term safe containment of both of them.

Waste dump management is of prime concern today mainly as a consequence of many cases when slope failures have hampered the regular process of mine production which directly affects the mine economics. The consequence of slope failure can be very devastating when men and heavy earth moving machines work or come closer to the unstable zone [1,7,20]. Moreover, such failures cause severe damage to the niche of the surrounding ecosystem. Hence, prior testing of waste dump and flyash generated must be carried out to obtain their strength characteristics and accordingly a safe, stable and cost effective solution in the form of optimised dump slope design must be proposed and implemented with regular monitoring. The studies for the dump slopes with varying dump height and its effect on change in safety considerations have been carried out as a part of the detail dump slope analysis by Vishal et. al (2010) [26]. Apart from other parameters such as foundation strength, ground conditions, water conditions and dynamic forces, dump slope geometry needs to be critically analysed for elimination of chances of failures.

There are various methods of assessment of dump slope stability like limit equilibrium methods, stress analysis, kinematic analysis, physical modelling, numerical modelling etc. In this paper, we present the numerical modelling of combined slope (waste + flyash) to obtain the most appropriated and optimum solution with respect to dump geometry which can accommodate more and more dump material and yet remain stable. A two dimensional Finite Difference model was used to simulate various situations to see the behaviour of dump with increasing the dump slope for a most economical and stable solution of the problem in question.

2. Numerical Simulation of Dump

Numerical modelling for the purpose of dump slope stability has several advantages over the other methods. They not only have a shorter running time but also get quite detailed solutions with simple assumptions. They enable more number of trials in the design and other parameters. One major advantage of numerical simulation is that it provides information well in advance to take care of dump at a particular point during actual working. Keeping in view, a two dimensional dump slope analysis was performed in different geo-mining conditions to understand not only failure but also what best can be done to prevent it and protect the accumulation for long term stability. Variations in constituent size and types of material are not distributed uniformly. As a result of which the assessment of the internal strength of the waste dumps is difficult and often challenging due to inadequate engineering design for such type of dumps [28]. Hence, for the purpose of simulation, a homogenous material property equivalent to the average of those composing the dump accumulation has been calculated from laboratory tests and assigned to the material type used [8,9]. The rock properties play a significant and an important role in any kind of research involving geomaterials [14,18,22,27].

2.1. Slope Design

To calculate the individual bench stability for a dump slope can be expressed as Girard and McHugh (2000):

$$\tan A = 1 / \left[\left(W / H \right) + \left(1 / \tan B \right) \right] \tag{1}$$

where;

A = overall (average) slope angle;
B = bench face angle;
H = vertical height of bench and
W = horizontal width of bench.

2.2. Factor of Safety (FOS) and Strength Reduction Factor (SRF)

There are several methods to analyze slope which fails because its material shear strength on the sliding surface is insufficient to resist the actual shear stresses. Factor of safety is a value that is used to examine the stability state of slopes. In other words, it is the ratio of collapse load to working load. A better definition for FOS will be the ratio of maximum available shear strength to the shear strength needed for equilibrium. For FOS values greater than unity means the slope is stable, whereas, values lower than unity means unstable conditions. In accordance to the shear failure, the factor of safety against slope failure is simply calculated as:

$$FOS = \frac{\tau}{\tau_f} \tag{2}$$

Where τ is the shear strength of the slope material, which is calculated through Mohr-Coulomb criterion as:

$$\tau = C + \sigma_n \tan\Phi \tag{3}$$

C stands for material cohesion where as Φ is the angle of internal friction.

Where τ_f is the shear stress along the sliding surface. It can be calculated as:

$$\tau_f = C_f + \sigma_n \tan\Phi_f \tag{4}$$

where the factored shear strength parameters C_f and Φ_f are:

$$C_f = \frac{C}{SRF} \tag{5}$$

$$\phi_F = \tan^{-1}\left[\frac{\tan\phi}{SRF}\right] \tag{6}$$

where SRF is strength reduction factor. This method has been referred to as the 'shear strength reduction technique'. To achieve the correct SRF, it is essential to trace the value of FOS that will just cause the slope to fail.

This technique is employed where the state of effective stresses in slope is calculated [2,4]. By the use of this method, factor of safety calculations are done by progressively reducing the shear strength of the material to bring the slope to a state of limiting equilibrium.

A series of simulations are made using trial values of factor F^{trial} to reduce the cohesion, C, and friction angle, Φ, until slope failure occurs. In the used numerical tool, namely FLAC/Slope, a bracketing approach similar to that proposed by Dawson et al (1999) is used [4].

2.3. FLAC/Slope

FLAC/Slope is a mini-version of FLAC (Fast Langrangian Analysis of Continua) that is designed specifically to perform factor-of-safety calculation for slope-stability analysis. This version is operated entirely from FLAC's graphical interface (the GIIC) which provides for rapid creation of models for soil and/or rock slopes and solution of their stability condition [10]. It provides an alternative to traditional "limit equilibrium" programs to determine factor of safety. Limit equilibrium codes use an approximate scheme — typically based on the method of slices — in which a number of assumptions are made [11]. Several assumed failure surfaces are tested, and the one giving the lowest factor of safety is chosen. Equilibrium is only satisfied on an idealized set of surfaces.

The procedure in FLAC/Slope is as follows:

First, the code finds a "characteristic response time", which is a representative number of steps (denoted by Nr) that characterizes the response time of the system. Nr 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 factor of safety, F, Nr steps are executed.

If the unbalanced force ratio is less than 10^{-3}, then the system is in equilibrium. The factor-of-safety solution stops when the difference between the upper and lower bracket values becomes smaller than 0.005. The strength reduction technique gives FOS with respect to geo-material shear strength [5,6]. It gives the advantage of automatic critical failure mechanism for dump.

3. Modelling of Dump Using FLAC/Slope

In the present study, the explicit two-dimensional finite difference program FLAC/SLOPE version 4.00 has been used for the analysis by simulating the similar geometrical condition [3]. Assuming FDM techniques to be the most rigorous method, it has been chosen here to investigate the stability of dump slope under gravity loading. The geometrical and geotechnical parameters used were determined in the field as well as laboratory as per standards [8,9].

Figure 1 shows the general geometry of a model of dump slope having a height of 60m and overall slope angle equal to 28°. The dump slopes were evaluated at this constant dump height, base width and bench width, while the slope angle was varied as 30°, 32°, 34°, 35°, 36°, 37°, 38°, 39°, 40°. The shear strain rates and the velocity vector distribution of the dump material were evaluated at each inclination. The factor of safety is found to decrease with the increase in dump slope inclination. Although this fact is known like a thumb rule but it is important to quantify the rate at which FoS decreases and particularly to help in deciding the critical slope angle along with the FoS. In this article, the results of dump having dump slope angle of 28°, 30°, 32°, 34° and 36° are discussed. Cases with yet higher angles of slopes have not been shown as under normal conditions the dump with same material types and dump height, increase in dump slope only leads to further reduction in FOS close to 1 or even less. This implies an unstable condition and the dump slopes would fail unless the material cohesion is increased using various methods such as biostablisation which itself needs yet another optimisation study as carried out by Pradhan et al (2013) [16]. The samples collected from the field site are investigated for the following geomechanical properties which are used as input parameters for simulating a real environment model using. These include porosity, permeability, density, elastic modulus, tensile strength, cohesion.

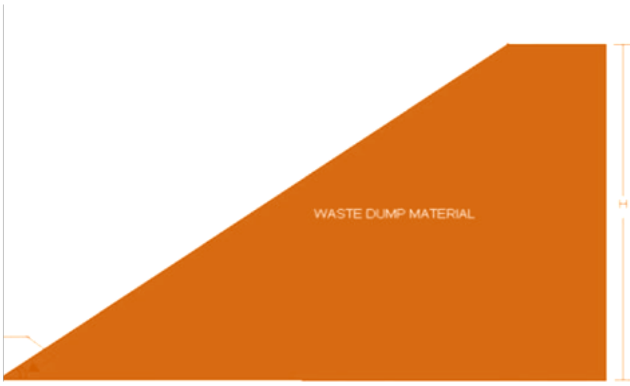

Figure 1. General Geometry of dump slope with Height, H = 60m

Dump slopes should be designed in accordance with the dump material characteristics, the availability of moisture as well as other operational features which may hamper its stability without giving much time for rectification. With progressive mining and exploitation of near surface ore deposits, as the mining advances deeper, more and more waste materials are taken out. These conditions of increasing stripping ratio results in generation of large quantities of dump which need to be managed with a scientific approach.

In first case, as shown in Figure 2, a 60 m high dump with 28° slope angle was simulated using the geomechanical properties of flyash and dump material to understand the failure behaviour of slope. The Factor of Safety obtained is very high i.e. 4.47 with a maximum shear strain rate equal to 8.00E-06 s^{-1} and maximum velocity vector equal to 1.247E-05 m/s. It can be seen that the shear strain rate and velocity values are quite low indicating imperceptibly low displacement of material particles. The distribution of velocity vectors is along most parts of the slope showing that the slopes although stable are not a static entity and hence monitoring at every stage is important. This is mainly because the materials are weak with low cohesion values unlike the rock cut or open pit slopes with intact rock masses. Yet the slope angle and height are optimised in this case and most coherent in the standards for maintaining the dump slopes which leads to a stable accumulation of dump materials as indicated by the FoS values. The concentration of higher shear strain rate is along the toe of the dump slope. Few tension cracks are developed at the top of the dump. Due to gravity loading, there are plastic deformations in the rear end of the dump indicates settlement of dump material.

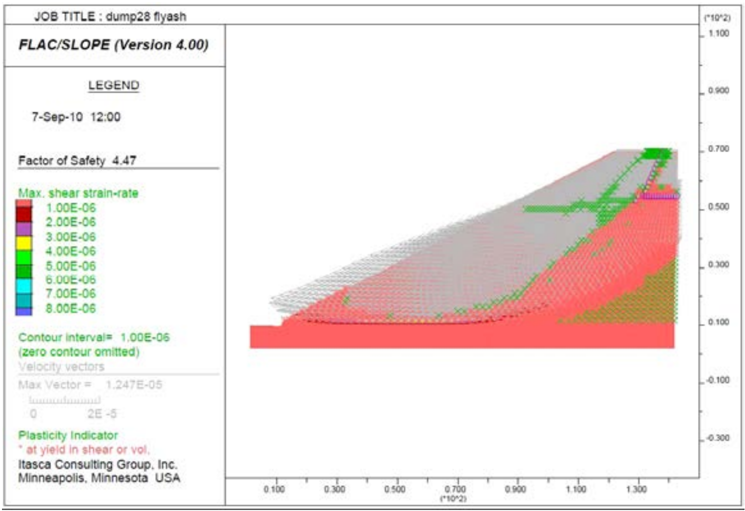

Figure 2. Simulated model for dump slope with H = 60 m and slope angle = 28°

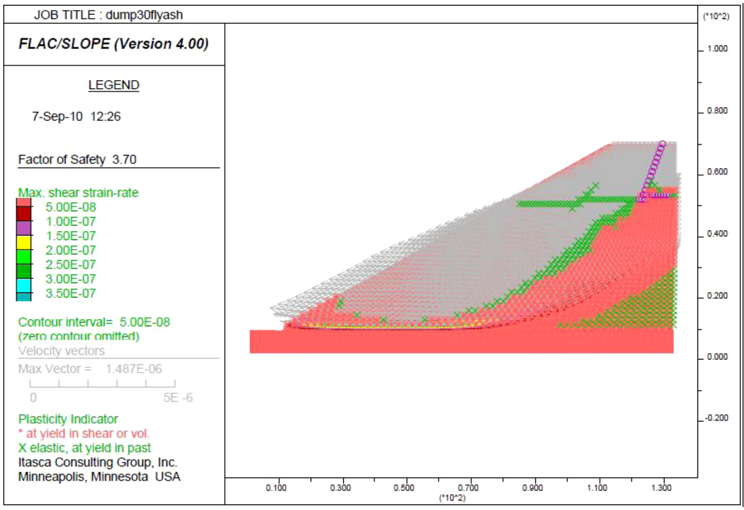

Figure 3. Simulated model for dump slope with H = 60m and slope angle = 30°

In the second case, the slope angle is increased by two degrees, equal to 30° while the slope height remains 60 m (Figure 3). This case clearly indicates the drop in factor of safety values from the previous case. Yet, the model is quite similar in outlook. This is because the dump material itself is weak unconsolidated heap of crushed rock grains. Hence, some movements are noticed in most of the parts of the dump. Yet it is noticeable that though the maximum velocity vector is less as compared to first case, the numerical value being 1.487E-06 m/s, the shear strain rate has increased almost ten times and the maximum shear strain rate in the model equals to 3.50E-07 s^{-1}. The tensile domain developed at the top rear end of the slope is due to the increased rate of shearing and the material is slowly being pulled out through the free slope surface. The slope at this angle is also quite stable.

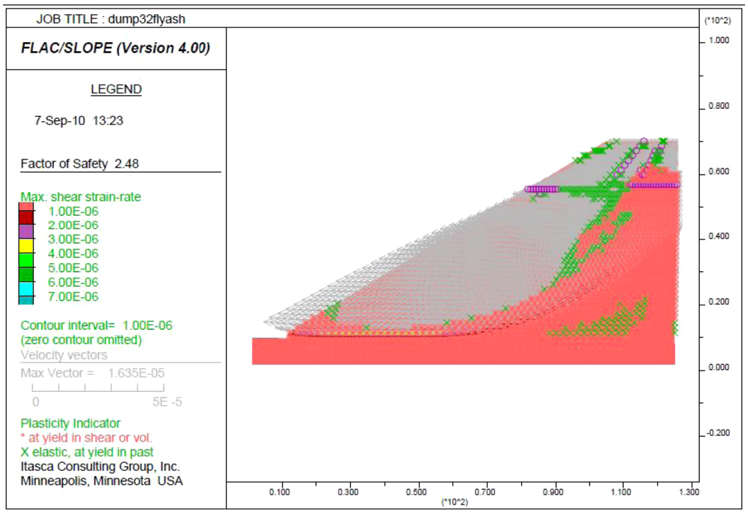

Figure 4. Simulated model for dump slope with H = 60m and slope angle = 32°

The slope angle is further increased up to 32° while keeping the base and dump height constant, the factor of safety is found to decrease up to 2.48, the value dipping by almost 45% from the 28° dump slope. The maximum velocity vector is found to be higher than the previous cases 1.635E-05 m/s while the maximum shear strain rate equals to 7.00E-06 s^{-1} (Figure 4). The tension cut off points form tension zones parallel to the slope at the top rear of the slope. The distribution of velocity vectors indicate a typical circular failure pattern according to which the health of slope with passage of time is evaluated. In this case, it is also worthy to notice that the disposition of shear strain rate also predicts a development of weak plane parallel to the face of the slope which may lead to a combination type of failure comprising of a planar slide along with circular failure. This situation if adopted may remain stable unless very heavy and sudden torrential rainfall suddenly weakens the frontal portion of the slope and reduction in FoS may occur.

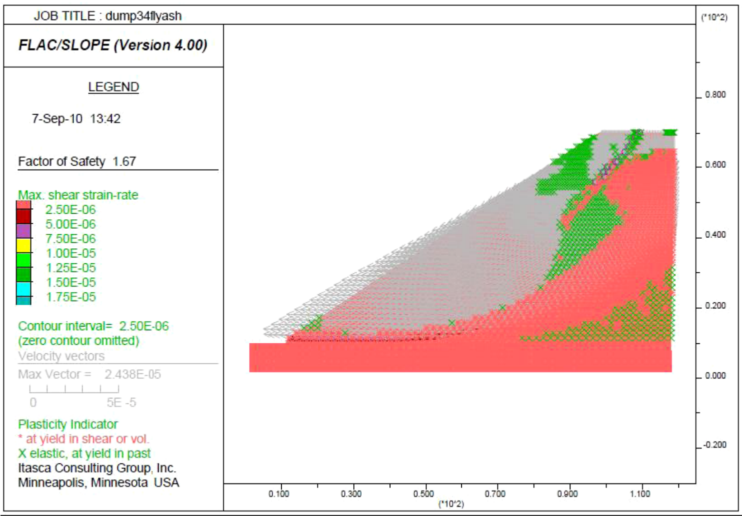

Figure 5. Simulated model for dump slope with H = 60m and slope angle = 34°

In fourth case, the flyash mixed dump slope was yet steepened to 34°. Here, Factor of Safety substantially reduces to 1.67 (Figure 5). The concentration of shear strain rates all along the dump has increased significantly and several weak zones are developed. The magnitude of maximum velocity vector and maximum shear strain rate are 2.438E-05 m/s and 1.75E-05 s^{-1} respectively. It is also noticed that some significant velocity vectors of constituent particles in this simulated model have developed on the rear end of the slope indicating the increased vulnerability of the dump slope where weakening is encroaching on the rear side as well. The velocity vectors have although been moving out with high magnitudes along the lower part of the slopes in each case but in with the increase in slope angle to 34°, the velocity vectors have become significantly higher in the top frontal portions as well. This demonstrates that the slope is slowly weakening and once these vectors are of sufficient magnitude as well as quantity in the major portions of the dump, more and more failure zones may develop and eventually the slope may fail due to contributions from every part of the slope.

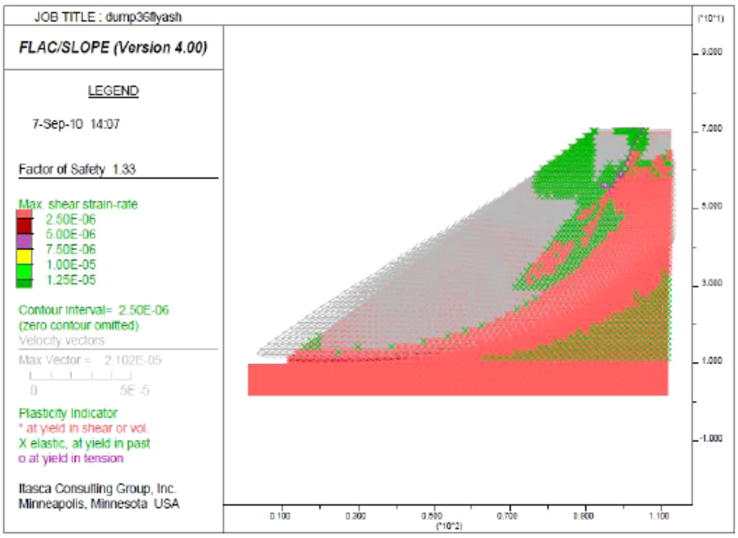

Figure 6. Simulated model for dump slope with H = 60m and slope angle = 36°

The fifth case studied is of a dump slope with 20% flyash mixing estimated at a slope angle equal to 36° for the same material types. In this case the factor of safety has decreased to a nearly critical state, the value equal to 1.33 (Figure 6). The quantity of velocity vectors with sizeable magnitude has increased significantly. The maximum velocity vector is equal to 2.102E-05 m/s while the maximum shear strain rate is equal to 1.25E-05 s^{-1}.

There as more distinct zones of increased shear strain rates in various parts of the slope and high abundance of elastic and tension points. The velocity vectors of particles are more spread out affecting larger domains including the rear end of the slope as well. This is the most vulnerable condition of maintaining the dump slope stable at 36° slope angle as the already-not-so-high FoS value may decrease fast in case of increase in moisture content of the dump material during rainfall and with time.

The results show that there is a drastic change in the safety conditions as the slope of waste accumulations in a mine site is increased keeping other parameters like slope height and material types constant. The changes in FOS as a function of dump slope angle for mine wastes generated are plotted in Figure 7.

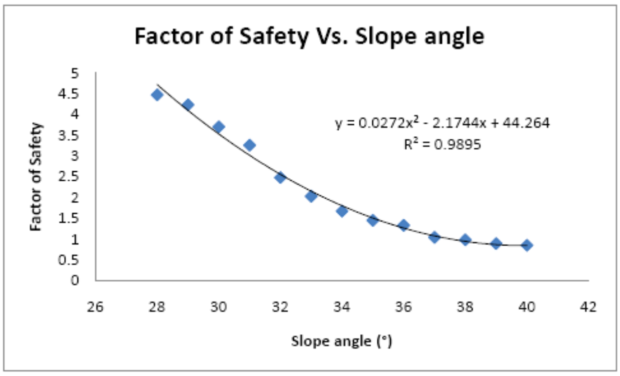

Figure 7. Variation of FOS values as a change in dump slope angle

The FoS vs. slope angle curve clearly indicates a strong correlation between the dump slope angle and Factor of Safety (Figure 7). The relation obtained has a high second order correlation. However, this relationship must be used with due care as site specific studies are always preferred and suggested for safe disposal of mine wastes.

4. Conclusions

The FLAC/Slope simulated results establish that for a dump of specific material type and keeping other parameters constant, the angle of dump slope can only be increased to a certain level beyond which it becomes critically stable and can lead to a major failure and hamper the surrounding establishments, men and machinery.

From this study, it is clear that high angle slopes are not recommended and dump slopes for any given choice of dump materials (as in this case coal mines) should not be made steeper than 36° under any circumstance to prevent large scale failure of the slope which will hamper the regular operations of waste disposal from the mine. The gravity of the situations may increase in case of in pit mining conditions where the space is limited and the process of coal extraction and waste management are interdependent and operate hand in hand. The quantification helps in considerations for optimum design of dump geometry. The cases where the ground conditions are weak, having low bearing capacity or more moisture saturated, the climate is moist and temperature variations high, the dump slope angle should be maintained well within the stable limits and kept low, preferable close to 32°. Even without external driving forces like blast induced vibrations or rainfall, dump with steeper slopes may fail under its own weight without giving much prior signal. Hence, the standards must be maintained to achieve safety and stability of mine and mine waste containment systems for regular and progressive mining and uninterrupted productivity of the mine. Careful monitoring and safe slope design by qualified geotechnical engineers at mine sites is important. Additionally, proper bench design, safe blasting patterns should be followed to minimize the adverse effects of nearby dump slopes.

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