Vol. 15, No. 45, Winter 2026, pages 23-34

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

Research article

Optimum mine dump design in Wardha Valley coalfields using finite difference numerical methods

Radhakanta Koner[1]*

1- Dept. of Mining Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad, India

*Corresponding author: E-mail: *rkoner@iitism.ac.in*

(Received: *February 2025*, Accepted: *September 2025)*

DOI: 10.22034/ANM.2025.22754.1665

Keywords

Mine dump
Dump Height
Slope Angle
Stage dumping
Dynamic loading
Factor of Safety

Abstract

The Wardha Valley coalfields are experiencing an acute shortage of dumping space for ongoing open-pit projects. This creates barriers to expanding the life of the projects and to developing the coal in greater depth. The acquisition of new land to dispose of waste material is challenging in the present socio-economic conditions of the region. The project administration cannot afford to lose large amounts of coal at greater depths. So, it is necessary to optimise the geometry of the waste dump slope. A steep slope can lead to a potential failure, and a flat slope may not be an economically viable option, so a balance must be found between these two aspects. In this study, a finite-difference numerical tool was used to account for the multiple factors contributing to the stability of mine dumps. The analysis was considered as a static and dynamic analysis using the FLAC2D finite-difference numerical modelling tool. The study proposed a viable alternative to waste dump geometry to optimise the use of natural resources in the Wardha Valley coalfields. The work showed that double-stage dumping is more advantageous. This study also showed that mining companies could accommodate 18% more waste rock in the available space without compromising safety by following this analysis.

1. INTRODUCTION

Large-scale mechanization and big opencast mining projects emerged in India after the 1990s. The open-pit project is prevalent in different coal mining projects in the country, with the increasing demand for coal [1]. Mining depths are increasing day by day due to the exhaustion of shallow deposits. The lifetime of projects increases with deep open-pit mines; thereby, efficient planning and design of the bench slope, pit slope, access roads, etc., become essential for the life of projects. The need for stability analysis becomes very important due to steep bench slopes, overall pit slopes, and increased bench heights. The volume of overburden removed last year was around 1926.34 million cubic meters [1]. This volume will soon increase due to the anticipated growth of open-pit coal mining projects. Hence, dumping such a large volume of overburden in the proper place and stabilizing the dump slope is also a challenging technical and economic problem for coal mining enterprises. Shortly, 500-800 m deep coal deposits may be exploited by India's opencast coal mining method. So, a large-scale study of the mine dump stability should be carried out before implementing such projects.

Experience has shown that since open-pit projects began, the material has been dumped in stages, keeping some free space within limited reach. So, a common practice in Indian open-pit projects is to maintain benches in the mine dump. This facilitates efficient management of the mine dump. The stage dumping allows the mining department to better handle the mine dump by adhering to several safety regulations. The limited space within the leased area and the management of the huge volume of waste rock have forced the mining authority to adopt the heightening of mine dumps beyond the permissible limits. In this particular situation, there are only a few alternatives for the miners. One is to run the mine with an increasing stripping ratio and at the same time, maintain the safety of the mine dump. This necessitates a revised parametric study to optimize the mine dump geometry with all prevailing external boundary conditions taken into account. A mining region in India with an acute shortage of dumping space and several other restrictions imposed from time to time by the regulatory authority was chosen for the study. Open-pit mining projects dominate this mining area, and guidance on dumping patterns is needed to run these mines.

This investigation thereby focuses on considering three alternative modes of dumping: single stage, double stage, and triple stage. In the stages, the bench height is limited to 30 m, but to cover the whole domain of viable alternatives, it has been increased to 90 m in some cases. The analysis takes into account the gravity load as the self-weight of the waste rock and the dynamic loading conditions to which these dumps are often subjected during major earthquakes. When designing a dump, there are many ways to assign values and combine various geometric and dimensional parameters while respecting safety and environmental constraints. The total tonnage capacity required can have as many geometrical representations as its limitations allow. In this situation, building a mathematical optimization model is the best option to interrelate certain vital variables. Given the broad scope of numerical applications available today, it has become essential for engineers to fully understand the varying strengths and limitations inherent in each of the different methodologies. When assessing slopes, geotechnical engineers use a factor of safety value to determine the stable/unstable conditions of slopes. The marginal equilibrium technique is the most commonly used conventional analysis method. However, with the help of recent significant advancements in computational and memory resources, geotechnical engineers, given the low-cost implications, have found the finite difference method (FDM) to be powerful and valuable, a viable alternative for all pre-field applications. Although there are certain limitations to the applicability of this method in capturing the actual field conditions, especially in cases of enormous discontinuity associated with the foundation of a large dump slope mass.

This work deals primarily with finding the optimum dump height and slope angle combination for safe overburden dumps. A parametric study has been conducted to analyze the effect of seismic vibration on dump stability.

1.1. Dump Design Considerations

A mine dump can be defined as a massive structure formed by placing large amounts of material in lifts of a restricted vertical expansion that lie one on top of the other and create a stable slope at the angle of repose. However, the formed dump needs a horizontal base, built by pushing dumping material from a specific elevation and leveling off the required footprint area.

Typically, this first phase in the construction of a dump construction takes the irregular shape of the terrain where it is placed. The height of the subsequent lift is constant, although it is limited to prevent shear stresses in the foundation and is a factor in control of consolidations and permeability variations [2]. The total height of the dump is also limited by the formation mechanism [3-9] and limitations of the carrying capacity [10, 11]. As with most the large open-pit operations, haulage is performed by heavy trucks. Access to the successive dump lifts is achieved by installing ramps of suitable width, superelevation, and gradient ramps to minimize the travel distance and reduce transportation costs. In dump designing, costs may be governed by any or all of the following factors:

1.1.1. Geometry

The dumps were usually designed to handle the total capacity throughout the life of mine. Over-sizing can cause the underutilization of valuable areas. Undersizing can increase the total haulage distances.

1.1.2. Operating costs

The costs result from fuel, energy, maintenance, and labour of the haul trucks.

1.1.3. Haulage distances

To minimize the total haulage distance while maintaining the required capacity by strategically placing ramps, exits, entrances, and dumping sequences.

1.1.4. Stability control

It will define the angle of repose and the nature of the underlying material. Maintaining the stability of the dump may require the relocation of waste rock or geomaterial, especially if water is present [12, 13].

1.1.5. Acquisition of the land

The dumping space requires a permit for dumping purposes, as specified by law.

1.1.6. Environmental factors

Costs of implementing and maintaining effective systems to reduce and eliminate losses. In the design considerations to maintain long-term stability, erosion control [14] should avoid rehandling costs [2] for reclamation and closure. Although every dump is unique [15], and some of its cost may be due to its factors, the above description includes all the general concerns that must be elaborated to develop the most economical dump design. Many of the parameters influencing mine dump slope design and optimizing the slope geometry are more economical when executing the project-specific guideline in the field. A finite-difference-based numerical toolbox is a good aid for modeling these options and possibilities and finding the best possible alternatives. In the dump design, it was observed that mine dump geometry optimization would meet many of the parameters that we have already discussed. Here is the importance of undertaking the present study.

2. MATERIALS AND METHODOLOGY

Slope stability analysis is an important area of geotechnical engineering for an open-pit project. Most textbooks on soil mechanics include several methods of slope stability analysis. A detailed review of equilibrium methods of slope stability analysis is presented by Duncan [16-18]. These methods include the ordinary practice of slices, Bishop's modified method, the force equilibrium methods, Janbu's generalized procedure of slices, Morgenstern-Price method, and Spencer's method. These methods, in general, require the soil mass to be divided into slices. The directions of the forces acting on each slice in the slope are assumed. This assumption plays a crucial role in distinguishing one limit equilibrium method from another. The limit equilibrium methods require a continuous surface for the soil mass to pass through. This surface is essential in calculating the minimum factor of safety (FOS) against sliding or shear failure. Before figuring slope stability using these methods, some assumptions, such as side forces and their directions, must be artificially set to build the equilibrium equations.

The finite difference approach in the analysis of slope stability problems does not assume the shape or location of the failure surface, slice side forces, and directions [18][19]. The method can be applied to complex slope configurations and soil deposits in two or three dimensions to model virtually all types of mechanisms. General soil material models that include Mohr-Coulomb and many others can be used. Equilibrium stresses, strains, and corresponding shear strengths in the soil mass can be computed very accurately. The critical failure mechanism developed can be extremely general and need not be simple circular or logarithmic spiral arcs. The method can be extended to account for seepage-induced failures, brittle soil behavior, random field soil properties, and engineering interventions such as geo-textiles, soil nailing, drains, and retaining walls. This method can inform about the deformations at working stress levels and monitor progressive failure, including overall shear failure [20].

2.1. Failure Mechanisms

The different failure modes that occur in mine waste dumps have been summarized by Caldwell and Moss [21], who reviewed these analysis methods. The typical mine dump of the Wardha Valley coalfields is shown in Figure 1. Surface or edge landslides may occur as the material moves down the slope. This failure mode is most likely to occur in crest-tipped embankments and is best evaluated by equations describing the stability of an infinite slope. A shallow landslide may occur if enough water enters the slope mass and flows parallel to the surface. Dumps placed on a flat surface of competent soil are the least likely to fail. However, if a thin layer of soft material covers the flat ground, base failure may occur. If the ground is inclined, base failure is more likely to occur. This mode of failure has been observed in both end-dump and embankments laid in layers.

Fig. 1. Mine dumps of Wardha Valley coalfields.

Block translation can occur where a dump is formed on inclined ground, and the soil cover is relatively thin and weak. An unusually high water table in a dam, earthquakes, or organic material decay beneath the dump may start such a failure. Circular arc failure through the dump material is most common where the dump material contains a significant percentage of fine-grain soil. Similarly, a circular arc failure surface can develop through a deep foundation soil deposit of fine-grained soil. In the Wardha Valley coalfields, it has been observed that the circular mode of failure is prevalent; thereby, the primary focus in this study will be on this direction.

2.2. Deformations As An Indication Of Failure

Deformations occur in a slope due to stresses and shear displacements in the mass of material forming the dump. Some of these deformations, such as consolidation, are not indicative of failure, while others, such as shear displacement along the failure surface, are. It is necessary to distinguish deformations that indicate failure from those that do not to predict failure. This requires an understanding of the failure mode and the deformations that accompany it. Analytical techniques currently available to analyze dump deformations are cumbersome and not sufficiently accurate to enable pre-construction estimates of consolidation and failure deformations. Instead, failure criteria are usually based on experience gained as the dump is constructed. The rate of deformation and change of the pace of deformation are generally good indicators of the behavior of a slope. They were used to establish criteria indicative of failure. We used the observed deformation rate, rate of movement, and acceleration pattern parameters to assess the failure in a mine dump [22].

2.3. Mine Site

In this investigation, an extensive geotechnical characterization of the dump geomaterial was initiated to estimate various properties. The locations of nine of the eleven selected mines and the land cover map for the present study are presented in Figure 2. It can be observed that they all belong to the Kamtee series of coal formations available in this part of the country. They are characterized by a top layer of black cotton soil of varying thicknesses of 4 to 8 m.

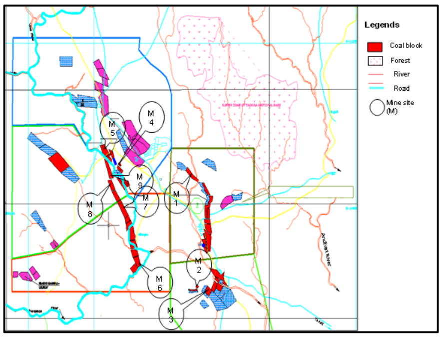

Fig. 2. Location of Mine Sites at Wardha Valley Coalfields.

2.4. Waste Rock Sampling Scheme

The variations in the soil and rock characteristics, and the varying complexity of dump conditions existing in the mines of the Wardha Valley coalfields considered in the present study, necessitated sampling methods of utmost importance. The dumps of these mine sites are of different categories, and a uniform sampling pattern of eight samples per dump was used to generalize the approach of sampling from each of the stages (benches) found in these dumps. Five samples were collected, following the standards, from the bottom and top benches, one from the middle bench and two from the top of the dump as shown in Figure 3, which is just representative and does not match the scale and shape of the existing dumps. Although a more rigorous sampling design might have proved better, we followed this sampling pattern due to the time and other resources of this study [23-25]. Thus, 252 samples were collected instead of 264 (i.e., eight samples per dump x 3 categories of dump per mine x 11 mine sites) because of the absence of a particular type of dump in some of the selected mines.

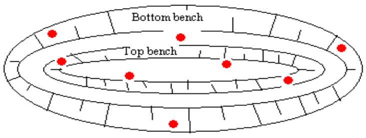

Fig. 3. Schematic Sample Collection Program from a Particular Dump (eight samples per dump).

2.5. Geotechnical Laboratory Interpretation

The materials constituting the mine dumps were collected from the fields, and they were mainly mixtures of broken rocks and loose soil. The proportion of loose soil was greater for the samples collected from the upper part of the dump than those collected from the lower part. Waste rock properties have mainly been attributed to the age of mine dumps, and mine dumps are divided into three categories.

a) Running dumps: Where active waste rock dumping is being carried out, further dumping will stop after reaching a certain desired height over a specific planned area.

b) Old dumps: Dumping here has been stopped for several years, and the mines have no plan to dump in the near future.

c) Vegetated dumps: Green reclamation has already been adopted/ achieved here, and there are no further plans for dumping.

Hence, this categorization will help the study team understand the diverse geotechnical nature of waste rock due to its age, changes in material properties due to compaction, and biological changes in the geo-materials that make up these dumps, etc., since a detailed investigation of material characteristics and site conditions forms the first part of any geotechnical study. We followed the detailed methods outlined in [26, 27].

Accurate determination of the representative shear strength of dump materials is essential for a meaningful slope stability analysis. However, the value of shear strength determined by laboratory testing depends on many factors, particularly the type of soil, the quality of the test samples, the size of the test samples, and the test methods. In a direct shear test, the plane of shear failure is predetermined. The test is usually carried out in a box split into two halves; hence, it is a shear box test. The equation can characterize the shear strength of cohesive soils.

$$\tau = \sigma tan\varphi + c \quad (1)$$

where σ is the normal stress, c is the cohesion, and φ is the internal friction angle. The results are summarised in Table 1.

Table 1. Average Cohesion and Internal friction angle of dump geomaterial of different mines

Name of the mines	Cohesion (kPa)	Internal friction angle (°)
Mine 1	0.00	38.56
Mine 2	0.00	48.65
Mine 3	13.97	27.95
Mine 4	26.87	32.58
Mine 5	26.89	22.25
Mine 6	0.00	33.64
Mine 7	0.00	31.40
Mine 8	0.00	36.74
Mine 9	0.00	33.40
Mine 10	49.63	24.13
Mine 11	100.03	19.74

2.6. The Geometry Of The Mine Dump

Slope stability analyses were performed along the cross-section of the dump slope. The cross-section includes stages of dumping (single, double, and triple stage dumps with heights of 90m, 45m, and 30m high benches respectively), slope angle from 20 to 45 deg., and berm width from 12 to 20 m between the stages of dumping. In this study, the homogeneous basement was considered as the natural rock prevailing at the dumpsite for study, excluding major geological features. Several combinations of the parameters mentioned above were studied in a dimensional optimization problem, and a total of 1936 model was analyzed.

2.7. Seismic Coefficients

The dynamic factors as the cause of instability of the external mine dump slopes were studied in detail, and a complete modeling analysis was performed. Seismic coefficient values were used in the numerical modeling.

2.8. Boundary Conditions

The length of the outer boundaries of the numerical models was varied to select the far-field boundary conditions. It was observed that the outer boundary of the mine overburden dumps in the numerical model should be extended to 50 m on both sides of the toe to achieve the far-field conditions. And, in the vertical direction, it was found that is should be around 30 m from the base of the dumps to reach the far-field condition. In the elastic-ideal-plastic numerical analysis of the external mine overburden dumps, conducted in the investigation, these conditions were taken into account for modeling. It was necessary to model the entire mine dump, rather than any particular part of the dump, because of the lack of symmetry in the site dump geometry in order to obtain accurate stresses and displacements. The boundary condition that appeared to work best was roller boundaries on both sides except for the bottom surface, i.e., in dump stability analysis, the side boundary elements were constrained with velocity in the x-direction equal to zero.

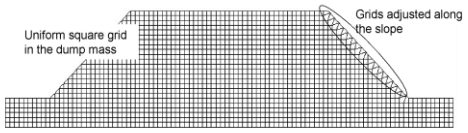

Fig. 3. A Single Stage Dump Section with Equal Grid Size.

And, the lowest boundary elements were constrained to zero velocity in both x- and y-. A uniform, quadratic grid with equal zone size was used, as shown in Figure 4, to minimize the effects of the grid in continuum modeling. The grids were adjusted along the slope surface to reduce the eccentricity of these elements, as depicted in Figure 4 — a similar grid pattern adopted in double- and triple-stage mine dump slopes.

2.9. Fully Dynamic Numerical Model

A fully dynamic analysis is recommended for higher acceleration levels. Dynamic numerical analysis using explicit time integration schemes poses a computational stability problem [28-31]. The time step between increments is kept below a critical value to ensure computational stability. Incremental displacements in the finite-difference grid are calculated from the velocity field of the previous step. However, stability and accuracy are two different issues. The fact that stability is maintained does not automatically guarantee that the analysis results will be accurate. With explicit time integration, stresses and displacements are calculated by extrapolating the velocity field of the previous step. This means that displacements and stresses change linearly between steps (i.e., a constant velocity between steps is assumed). It is argued that keeping the time steps small enough (like those small-time steps on the order of 10^{-6} seconds required for stability) will provide an accurate solution. The continuum model solves the equation of motion for mass-spring-dashpot systems in the time domain with incremental time steps. The calculated incremental displacements are related to the incremental stresses associated with chosen constitutive relationships the program uses explicit time step integration between consecutive steps. A critical time step is chosen to maintain computational stability [32]. The critical time step is selected 1.1×10^{-6} in this study. For simplicity, dry conditions were assumed, and a simple constitutive model was used; hence, the elements were modeled as elastic perfectly plastic Mohr-Coulomb materials. It should be noted that Rayleigh damping was used. Vertical displacement was fixed at the boundary since it was assumed that a very stiff in-situ layer exists at a depth of 30 m. The displacements are bound together at the lateral boundaries in both directions [33]. Assuming that waves radiating from the boundaries can be neglected, the coupled boundary condition with coupled degrees of freedom accurately models the free-field response at the lateral boundaries [34].

2.10. Input Ground Motion

The stability of the created and existing dumps for different mine sites was analyzed with different ground motion conditions. The El Centro time history recorded at 117 (USGS) station during the Imperial Valley earthquake was used in the analysis (Fig. 5). The study considered three acceleration time histories of the 1941 Imperial Valley earthquake. We used the PEER strong-motion database. The acceleration time histories were applied incrementally to all nodes along the lower boundary of the finite-difference model. It should be noted that the low-frequency components of earthquake motion usually dominate the displacement response [35]. Thus, displacement histories at different monitoring points were computed to assess the effect of numerical dissipation on the low-frequency response. After observing the response frequency, it can be assumed whether inaccurate high frequencies have been introduced into the solution.

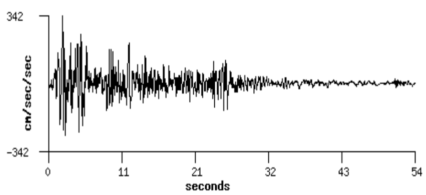

Fig. 5. Ground Acceleration Time histories of the records in the analyses – El Centro Earthquake CA - Array Sta 9; Imperial Valley Irrigation District - 302 Commercial, United States Geological Survey.

3. RESULTS AND DISCUSSION

In the analysis, a constant height of 90 m was used. The bench height and slope angle were varied, and the combinations of a large number of the models were analyzed.

A total of 1,936 models have been analyzed in three different dumping patterns: single stage, double stage, and triple stage dumping, shown in Table 2. This study was conducted to fulfill the main purpose of this research work. The summarised results (Table 2) showed a corresponding increase in volume accommodation capacity for a total base dump slope angle of 28.5° at a constant total height of 90 m and berm width of 12 m in all the cases. The changes in cross-sectional area at a constant total height and the same base area were calculated for these three different dumps to assess the volume of accommodation. For the lower bench height, the inclination may be increased, which prevails in the analysis. The double-stage dumping is advantageous because of the total waste rock accommodation capacity on the same base area, after comparing the results shown in Table 2. On average, it is about 1.5 times greater compared to the triple-stage dumping as a whole.

3.1. Static Condition

When analyzing the static stability, the safety factor was calculated and assumed 1.25 as a long-term factor, and the results correspond to those shown in Table 2.

The increase in capacity of the design dumps is calculated relative to the 28.5-degree dump slope limit set by the competent authority in Indian mining conditions, projecting an increase in the scope of dumping at the specific mine locations saving precious land.

3.1.1. Effect of Dump Parameters on Stability

The parametric analysis investigated the effects of dump height, soil strength, and the dump slope angle on permanent displacements of the base case slope. The values of the base case parameters were increased and decreased to create a range of observed behavior.

Table 2. Results of static analysis with FLAC tool

Name of the mines	Configuration Analyzed	Dump Slope Angle (in degrees)	Percentage of increase of volume
Mine 1	Single stage	30	5.95
	Double stage	32.63-37.04	7.15-13.18
	Triple stage	30.54-34.43	3.5-9.15
Mine 2	Single stage	35	22.45
	Double stage	41.42	18.07

	Triple stage	38.29	13.73
Mine 3	Single stage	25	0
	Double stage	31.55-35.69	5.27-11.10
	Triple stage	26.57-30.54	0-3.5
Mine 4	Single stage	35	22.45
	Double stage	37.04-41.42	13.18-18.07
	Triple stage	34.43-38.29	9.15-13.73
Mine 5	Single stage	20-25	0
	Double stage	23.70-26.85	0
	Triple stage	25.37-26.57	0
Mine 6	Single stage	28.5	0
	Double stage	28.19-32.63	0-7.15
	Triple stage	26.57-30.54	0-3.5
Mine 7	Single stage	25	0
	Double stage	26.85-28.19	0
	Triple stage	26.57	0
Mine 8	Single stage	30	5.95
	Double stage	32.63	7.15
	Triple stage	30.54-34.43	3.5-9.15
Mine 9	Single stage	28.5	0
	Double stage	28.19-32.63	0-7.15
	Triple stage	26.57-30.54	0-3.5
Mine 10	Single stage	30	5.95
	Double stage	32.63	7.15
	Triple stage	30.54-34.43	3.5-9.15
Mine 11	Single stage	30	5.95
	Double stage	32.63-37.04	7.15-13.18
	Triple stage	34.43-38.29	9.15-13.73

3.1.2. Effect of Bench Height on Stability of Dump

The height of the mine dump affects the magnitude of permanent displacements, as shown in Table 3 for a standardized single stage dump with a slope angle equal to 28.5°. The displacement was found to increase as the slope height increased. The average maximum displacement magnitudes obtained from the different models are shown in Table 3. It is observed that as the slope height increased, the maximum displacements also increased. The locations of these displacements were intentionally ignored in this part of the analysis because we are performing only a parametric analysis, but we are not considering the area of instability. Increased displacements indicate a high possibility of failure of the slopes unless proper preventive measures are taken. It was observed that a change in the dump height from 50 m to 90 m with an overall deviation of ±20% caused a change in maximum displacement from 11.89 cm to 14.65 cm with an average deviation of ±11.5% (Table 3). The relationship between these two parameters remains linear for the ranges analyzed in this study.

Table 3. Results of static analysis with FLAC tool

Dump Height (m)	Average Maximum Displacement (cm)
50	11.89
60	12.32
70	13.43
80	14.27
90	14.65

3.1.3. Effect of Slope Angle on Dump Stability

The dump slope angle affects the magnitude of permanent displacements shown in Table 4 for a standardized single-stage dump of 90 m. Displacement decreased when the slope was flatter. The average values of maximum displacements obtained from the models analyzed are shown in Table 4. It was observed that the maximum displacement increases with the dump angle. The locations of these displacements were intentionally ignored in this part of the analysis. It was observed that a change in the dump angle from 20° to 40° with an overall deviation of ±10% caused the average maximum displacement to change from 14.08 cm to 26.92 cm with an average deviation of ±10% (Table 4), except for the last case where a deviation of 77% was observed. The relationship between these two indices remains non-linear for the ranges analyzed in this study. It was observed that for dump angles between 28.5° to 30° and 35° to 40°, the rate of change of the average maximum displacement with the slope angle increased rapidly.

Table 4. Average Maximum Displacement with the Corresponding Dump Angle

Dump Angle (°)	Average Maximum Displacement (cm)
20.0	14.08
25.0	14.53
28.5	14.65
30.0	15.67
35.0	16.33
40.0	26.92

3.1.4. Effect of Internal Friction Angle on Dump Stability

The values of the internal friction angles are assumed to reflect the strength of the soil. It was found that an increase in the soil strength results in an increase in resistance to permanent displacements. This part of the investigation was carried out for numerical dump models with 28.5° as the overall slope angle and a height of 90 m for a single-stage dumping mode. A considerable effect of the friction angle on the permanent displacements was observed, as shown in Table 5. The average maximum displacements in magnitudes obtained from the analyzed numerical models are shown in Table 5. It was observed that the maximum displacements decreased with an increase in the friction angle of the dump materials. The locations of these displacements were intentionally ignored in this part of the analysis. It was observed that a change in the friction angle of the dump materials from 31.40° to 48.65° with an overall deviation of ±26% caused a change in the maximum displacement from 14.65 cm to 164.90 cm with an average deviation of ±85.14% (Table 5). The observed relationship between the friction angle and maximum average displacement remains non-linear for the ranges analyzed in this part of the study.

Table 5. Average Maximum Displacement with the Corresponding Friction Angle

Internal Friction Angle (°)	Average Maximum Displacement (cm)
31.40	164.90
32.58	98.64
33.40	73.88
33.64	66.88
36.74	32.64
38.56	27.46
48.65	14.65

3.2. Pseudo-Static Analysis

The pseudo-static analysis is an extended limit equilibrium method and uses calculated dynamic earth pressure to assess the stability of slopes [16]. The magnitude of the dynamic force and the lateral inertia force per slope mass are evaluated using a seismic coefficient. Various methods and empirical recommendations make it possible to estimate the magnitude of dynamic earth pressures. Once the magnitudes of static and dynamic forces are estimated, different failure mechanisms, both external and internal, can be tested for stability. These mechanisms include sliding along the base and overturning.

The mine locations are not subject to strong seismic zones; instead, it is a low-seismicity area. The present study takes a seismic coefficient of 0.1 in the pseudo-static mode of study, and the results are shown in Table 6. It was found that the factor of safety decreased by 2-3 percent.

Table 6. Dynamic stability analysis of dumps

Name of the Mines	Configuration Analyzed	Slope Angle	Factor of safety
Mine 1	Single stage	30	1.16
	Double stage	32.63-37.04	1.12
	Triple stage	30.54-34.43	1.09
Mine 2	Single stage	35	1.11
	Double stage	41.42	1.13
	Triple stage	38.29	1.45
Mine 3	Single stage	25	1.10
	Double stage	31.55-35.69	1.14
	Triple stage	26.57-30.54	1.06
Mine 4	Single stage	35	1.09
	Double stage	37.04-41.42	1.22
	Triple stage	34.43-38.29	1.14
Mine 5	Single stage	20-25	1.11
	Double stage	23.70-26.85	1.05
	Triple stage	25.37-26.57	1.14
Mine 6	Single stage	28.5	1.02
	Double stage	28.19-32.63	1.10
	Triple stage	26.57-30.54	1.08
Mine 7	Single stage	25	1.11
	Double stage	26.85-28.19	1.02
	Triple stage	26.57	1.04
Mine 8	Single stage	30	1.13
	Double stage	32.63	1.09
	Triple stage	30.54-34.43	1.04
Mine 9	Single stage	28.5	1.06
	Double stage	28.19-32.63	1.12
	Triple stage	26.57-30.54	1.07
Mine 10	Single stage	30	1.08
	Double stage	32.63	1.12
	Triple stage	30.54-34.43	1.11
Mine 11	Single stage	30	1.14
	Double stage	32.63-37.04	1.10
	Triple stage	34.43-38.29	1.10

3.2.1. Effect of Horizontal Seismic Coefficient on Dump Stability

The impact of the varying horizontal seismic coefficient (HSC) on the dump stability is examined in this section. Figure 6 below shows a columnar representation of the varying safety factor with HSC for the running dump geometry of ten mine sites and material conditions. HSC values of 0.01, 0.03, 0.05, 0.08, and 0.1 were analyzed in this part of the study.

It is observed that the safety factor decreases with an increase in the HSC. The safety factor remains maximum for the static case compared to the safety factors obtained in the dynamic model.

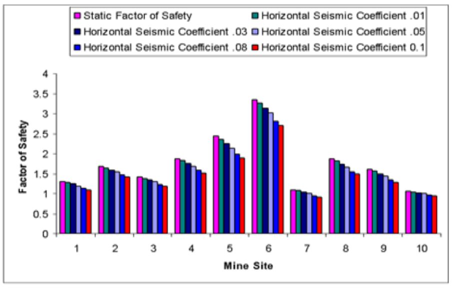

Fig. 4. Increasing Horizontal Seismic Coefficient Shows Decreasing Safety Factor.

3.3. Seismic Stability Analysis

It is necessary to investigate earthquakes, how the dump mass behaves during vibration, the magnitude of stress and deformation during and after vibration. The numerical analysis is performed for a 2D cross-section of the total dump mass. Analyses of the effects of ground failure/settlement are outside of the scope of this numerical study.

3.3.1. Effect of Input Accelerations on Displacements

The effect of input motion on the permanent average displacements was investigated in this part of the study. Four recorded earthquakes with different durations, amplitudes, and frequency contents were selected for analysis. For each of these recordings, the peak horizontal accelerations causing slope movement were scaled to match the El Centro base excitation (PHA= 0.2 g). Predicted displacements for each of these modified earthquake records were noted. The range of final displacements was from 0.7 cm to 8.7 cm, which was predicted for a numerical dump model of a single stage of 90 m high, with a slope angle of 28.5° having the same material conditions as mine site 2. This observation reflects the high level of record-to-record variability inherent in earthquake motion. This suggests that the design of dump slopes should not be based only on the analysis of a single ground motion record alone.

3.3.2. Effect on Stage Dumping

The present investigation compares combinations of different mine dump geometries and stage dumping to find the optimized one to make the best use of the available natural resources to the fullest extent. Thereby, we investigated all three types of dumps with dynamic load application and simulated the responses. Numerical models developed and analyzed for the different dump conditions were diagnosed under dynamic loading conditions. The selected models analyzed here represent stable configurations obtained from static analysis results and are shown in Table 2. All of these models analyzed for the material properties for mine site number two are shown below. Similar analyses have been carried out for all available configurations of material properties and the stable dump geometries. The results for the single, double, and triple stage configurations are presented below in sequence.

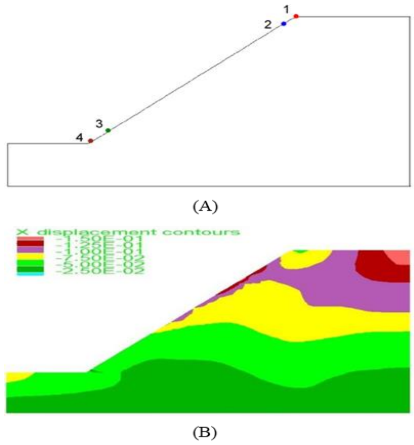

Fig. 7. Single Stage Dump Slope (90 m height and 35° slope angle with Four Monitoring Points (A); Horizontal Displacement Contours at Single Stage Dump Slope after 10 s of Dynamic Load (B).

Figure 7 shows the left side monitoring points in the studied dumps for the single stage with a 35° slope angle. The study used a double stage with 12 m berm distance and 40° stage angles; and a triple stage with 25 m berm distance and 30° stage angles for conducting a similar study. The numerical models used twice as many monitoring points with an equivalent number of points on the right side of each dump for analysis. The displacement time histories for monitoring points 1 and 4 have the same trend as points 2 and 3 for single-stage dumping with a maximum value of 18.74 cm and a minimum of 10.92 cm, as shown in Table 7. A similar character was observed for the the curves in time history of velocity and acceleration of these points. It was observed that the displacement and velocity remained neard zero until 0.5 s. In contrast, the acceleration remained insignificant up to 1.5 s after applying the excitation. The contour of the horizontal displacement vectors for the three stages indicated that the double-stage dumps had a smooth change in displacements. It was noted that the range of overall horizontal displacements was the smallest for the single-stage dumping, then the double-stage dumps, and then the triple stage dumps for mine site 2. Table 7 shows the range of magnitudes obtained by analyzing the effect of input acceleration for single, double, and triple stage dumps. The left monitoring points represent the horizontal displacement, horizontal velocity, and horizontal acceleration time histories.

Table 7. Displacement, Velocity and Acceleration at the Monitoring Points in the Dump Slope during Dynamic Loading

Sl. No	Type of Slope	Range of Displacement (cm) (Min to Max)	Range of Velocity (cm/s) (Min to Max)	Range of Acceleration (cm/s2) (Min to Max)
1	Single Stage Mine Dump Slope	-10.92 to 18.74	-40.08 to 40.94	-396.27 to 538.53
2	Double Stage Mine Dump Slope	-117.22 to 12.39	-78.24 to 38.61	-376.56 to 518.80
3	Triple Stage Mine Dump Slope	-285.81 to 7.43	-182.60 to 94.23	-1718.26 to 1468.48

4. OBSERVATIONS

From the plots and their time histories of horizontal velocity and acceleration over 10 s, as shown in Table 7 for the single, double, and triple stages of dumping, it is clear that changes in acceleration occurred more frequently in the triple-stage dumps, then in the double stage, and then single-stage dumping patterns. The range of change in the acceleration values was maximum for the triple-stage dumps, whereas a similar change was observed for the single- and double-stage dumps. For single-stage dumping, the maximum and minimum displacement, velocity, and acceleration values were (18.74, -10.92) cm, (40.94, -40.08) cm/s, and (538.53, -396.27) cm/s2, respectively, for the monitoring points mentioned above. A similar analysis for the double-stage dumping gave the maximum and minimum values of (12.39, -117.22) cm for displacement, (38.61, -78.24) cm/s for velocity, and (518.80, -376.56) cm/s2 for acceleration at the monitored points. Whereas for the triple-stage dumping, the maximum and minimum values of (7.43, -285.81) cm for displacement, (94.23, -182.60) cm/s for velocity, and (1468.48, -1718.26) cm/s2 for acceleration were obtained at the monitored points. The ranges of displacements, velocities, and accelerations obtained for the single-, double-, and triple-stage dumps were (28, 129, 293) cm for displacements, (86, 116, 276) cm/s for velocities, and (934, 904, 3176) cm/s2 for accelerations.

Although it is difficult to compare the changes in the displacements, velocities, and accelerations obtained with the static and dynamic modes of analysis, it was observed that the overall range of displacement changes at similar monitoring points showed higher displacement values for the dynamic analysis model compared to the corresponding static mode of analysis. The same was observed when comparing double and triple stages of dumping patterns for all three parameters, namely displacement, velocity, and acceleration values. The overall dump slope angles were unequal in the above models (35.0° for single-stage, 41.4° for double-stage, and 24.0° for triple-stage dumping), although the height was constant (90 m). It may be noted that the observed x-displacements differ in the three cases. It should not be concluded that single-stage dumping is safer (as seen in the x-displacement plots) than the double-stage dumping. It may be noted that even at a dump slope angle of 40°, the single-stage dump became unstable in the static analysis under the present conditions.

5. DISCUSSION

Mines 1, 2, 4, and 11 have higher slope angles than the other mine dumps due to their higher frictional characteristics of the mine dumps material. A maximum 41.42 degree dumps slope is possible with the present characteristics of the overburden material with a volume gain of 18.07%. These mines will benefit from a longer project life and compared to production expansion. The highest gain of volume accommodation was obtained for mine number two, at 22.45% for single-stage dumping. It was also observed that a mine dump with a 41.42º slope angle would remain safe under prevailing seismic conditions. In a worst-case scenario analysis, it was found that the obtained slope angle would remain stable over the longer term of the project. The study showed that optimization analysis using a parametric comparison of different field parameters and site conditions plays an influential role in good project planning and optimization of land resources. In the deformation study, the peak permanent deformation ranges from 11.89 cm to 14.65 cm for the dump heights of 50 m to 90 m. Similarly, it ranges from 14.08 cm to 26.92 cm for a dump slope angle of 20º to 40º. And for the available material characteristics of the angle of internal friction 31.4º to 48.65º, the deformation decreases from 164.9 cm to 14.65 cm. So, it was observed that deformation under pseudo-static loading is more sensitive to the material friction properties.

6. CONCLUSIONS

The following conclusions can be drawn from the results of this investigation:

1. The dumping pattern has an impact on the stability characteristics of the external overburden dumps. Double-stage dumping shows a higher factor of safety than single- and triple-stage dumping. It is possible to make the overall

dump slope angle steeper without sacrificing the safety factor in the case of double-stage dumping.

2. The influence of average seismic intensity showed very little effect on the stability of the dumps since the stable and safe dump slope angles differ by at most 1%-3% in relation to the angles obtained from the static analyses.

3. The impact of dynamic loading due to blast vibration and earthquakes causes more deformation in the toe side of the dump slope than in the crest of the dump. Vibration amplitudes in this area are more accentuated than in the crest area. The duration of these loads has an adverse effect on the dump slope stability (length of duration varies from 2 to 10 s). Every second of increasing time increment leads to a7.6% increase in dump slope displacement.

4. Dynamic analysis shows that the height and slope angle negatively affect the dump deformation in the analyzed range of 50–90 m and 20°-40°, respectively, with the observed deformation range of 11.9-14.7 cm and 14.1-26.9 cm. The material friction angle analyzed in the 31.4°-48.7° range showed significant potential for influencing the deformational dump characteristics observed in the 164.9-14.7 cm range. Ground motion input with a scaled peak amplitude of 0.2g showed that El-Centro seismic input affected the deformational dump characteristics more than Loma-Prieta, Friuli, and Kobe, with a change of 0.7-8.7 cm.

5. The failure surface in the dump slopes obtained from static and dynamic analyses was found to be circular. Parameters such as shear strain, displacement, and yield point plots were efficiently used as indicators to predict circular failure. In the absence of direct failure plane analysis as a result of continuum-based numerical modeling, they had a good agreement with each other.

Data Availability Statement

All data and computer codes used in this work will be provided by email to the corresponding author upon reasonable request.

Declaration of Competing Interest

The author states that he has no known competing financial interests or personal relationships that would affect the work presented in this paper.

Acknowledgments

The author is thankful to IIT(ISM) Dhanbad for conducting this research. This work was supported by the IIT(ISM) Dhanbad [grant number FRS (108)/2016-17/ME, 2020].

REFERENCES

[1] Provisional Coal Statistics, Ministry of Coal, Government of India, http://coal.gov.in/sites/default/files/2021-06/Provisional-Coal-Statistics-2020-21_0.pdf Accessed last June 2021

[2] Jorge Puell Ortiz, Methodology for a dump design optimization in large scale open-pit mines, Cogent Engineering, 4:1, 1387955, (2017) http://dx.doi.org/10.1080/23311916.2017.13879.

[3] J.R. Metcalf, Angle of repose and internal friction, Int. J. Rock Mech. Min. Sci. 3 (1966) 155–161. https://doi.org/10.1016/0148-9062(66)90005-2.

[4] S. Sujatono, The determination of mine waste dump material properties through back analysis, J. King Saud Univ. - Eng. Sci. (2021). https://doi.org/10.1016/j.jksues.2021.02.008.

[5] K.M. Khan, G. Bushell, Comment on "rolling friction in the dynamic simulation of sandpile formation," Phys. A Stat. Mech. Its Appl. 352 (2005) 522–524. https://doi.org/10.1016/j.physa.2005.01.019.

[6] S. Supandi, Geotechnical profiling of a surface mine waste dump using 2D Wenner–Schlumberger configuration, Open Geosciences 13.1, (2021) 335–344. DOI: 10.1515/geo-2020-0234.

[7] P. Zou, X. Zhao, Z. Meng, A. Li, Z. Liu, W. Hu, Sample Rocks Tests, and Slope Stability Analysis of a Mine Waste Dump, Advances in Civil Engineering 2018, (2018). https://doi.org/10.1155/2018/6835709.

[8] S. Liu, H. Wang, W. Xu, Z. Cheng, Z. Xiang, W. Xie, Numerical Investigation of the Influence of Rock Characteristics on the Soil-Rock Mixture (SRM) Slopes Stability, 24 (2020) 3247–3256. https://doi.org/10.1007/s12205-020-0034-1.

[9] Zhang, D., et al. (2014) Study on Formation Mechanism of Dumping Piles on Dumping Area Stability, Open Journal of Geology, 4, 161-175. http://dx.doi.org/10.4236/ojg.2014.44012.

[10] Peng, C., Ji, D., Zhao, L., Ren, F.H., 2013. Study on Limit Height and its Stability of Open-Pit Dump Based on Basement Bearing Mechanism. AMM 405–408,177–181. https://doi.org/10.4028/www.scientific.net/amm.405-408.177

[11] AK Bharati, A. Ray, R. Rai, A Stability Classification System for the Dragline Dump Slope, Mining, Metallurgy & Exploration 38.2,(2021) 1095–1109. https://doi.org/10.1007/s42461-021-00409-8.

[12] Russell, M. (2008) So you want to have the best possible waste rock dump, in Proceedings First International Seminar on the Management of Rock Dumps, Stockpiles and Heap Leach Pads (Rock Dumps 2008), A.B. Fourie (ed), 5–6 March 2008, Perth, Australia, Australian Centre for Geomechanics, Perth, pp. 117–128.

[13] M. Water, A.K. Singh, Quality Assessment of Mine Water in the Raniganj Coalfield Area, India Quality Assessment of Mine Water in the Raniganj

Coalfield Area, India, (2010). https://doi.org/10.1007/s10230-010-0108-2.

[14] Pantelis, G., Ritchie, A.I.M. and Stepanyants, Y.A., 2002, A conceptual model for the description of oxidation and transport processes in sulphidic waste dumps. Applied Mathematical Modeling, v. 26, p. 751-770.

[15] Petra Zástěrová, Marian Marschalko, Dominik Niemiec, Jan Durďák, Roman Bulko, Jozef Vlček, Analysis of Possibilities of Reclamation Waste Dumps after Coal Mining, Procedia Earth and Planetary Science, Volume 15, 2015, Pages 656-662, https://doi.org/10.1016/j.proeps.2015.08.077.

[16] C. Zienkiewicz, C. Humpheson, R.W. Lewis, Associated and non-associated visco-plasticity and plasticity in soil mechanics, Geotechnique 25.4, (1975) 671–689. https://doi.org/10.1680/geot.1975.25.4.671.

[17] M. Ghadrdan, A.P. Dyson, T. Shaghaghi, A. Tolooiyan, Slope stability analysis using deterministic and probabilistic approaches for poorly defined stratigraphies, Geomech. Geophys. Geo-Energy Geo-Resources. 3 (2021). https://doi.org/10.1007/s40948-020-00189-3.

[18] Duncan, J. M. (1996). State of the Art: Limit Equilibrium and Finite-Element Analysis of Slopes. Journal of Geotechnical Engineering, 122(7), 577–596. https://doi.org/10.1061/(asce)0733-9410(1996)122:7(577).

[19] Kaerbek Rafkatovich Argimbaev, 2016. Simulation of Rock Mass Stress-Strain Behavior Using the Method of Equivalent Materials During Ore Deposit Open-Pit Mining. Research Journal of Applied Sciences, 11: 894-899. doi: 10.36478/rjasci.2016.894.899.

[20] Radhakanta Koner, Debashish Chakravarty, Numerical analysis of rainfall effects in external overburden dump, International Journal of Mining Science and Technology, Volume 26, Issue 5, 2016, Pages 825-831, https://doi.org/10.1016/j.ijmst.2016.05.048.

[21] S. Liu, Z. Su, M. Li, L. Shao, Slope stability analysis using elastic finite element stress fields, Eng. Geol. 273 (2020) 105673. https://doi.org/10.1016/j.enggeo.2020.105673.

[22] Griffiths. D. V. and Lane. P. A.; (1999), Slope Stability analysis by finite elements, Geotechnique, 49(3), 387-403, https://doi.org/10.1680/geot.1999.49.3.387.

[23] R. Brummer, P. Andrieux, C. Detournay, R. Hart, FLAC and Numerical Modeling in Geomechanics 2003, FLAC Numer. Model. Geomech. 2003. (2003). https://doi.org/10.1201/9781439833490.

[24] Hekmat, M. Osanloo & Akbarpour M. Shirazi, New approach for selection of waste dumpsites in open-pit mines, Mining Technology, 2008, 117:1, 24-31.

[25] MC He, J.L.Ã. Feng, X.M. Sun, Stability evaluation and optimal excavated design of rock slope at Antaibao open-pit coal mine, China, 45 (2008) 289–302. https://doi.org/10.1016/j.ijrmms.2007.05.007.

[26] Okagbue, C.O., 1984, The geotechnical characteristics and stability of a spoil heap at Southwestern Pennsylvania coal mine, USA: Engineering Geology, v. 20, p. 325– 341.

[27] Koner, R., Chakravarty, D. (2016) Characterisation of overburden dump materials: a case study from the Wardha valley coalfield. Bull Eng Geol Environ 75, 1311–1323. https://doi.org/10.1007/s10064-015-0830-x.

[28] Rezaiee-Pajand, M., and Karimi-Rad, M. (2016) A New Explicit Time Integration Scheme for Nonlinear Dynamic Analysis, International Journal of Structural Stability and Dynamics, Vol. 16, No. 09, 1550054 (26 pages), https://doi.org/10.1142/S0219455415500546.

[29] Liang Lu, Zongjian Wang, Xiaoyuan Huang, Bin Zheng, Katsuhiko Arai, (2014) "Dynamic and Static Combination Analysis Method of Slope Stability Analysis during Earthquake", Mathematical Problems in Engineering, vol. 2014, Article ID 573962, 13 pages. https://doi.org/10.1155/2014/573962.

[30] Lisjak, A., and Grasselli, G. (2011) Combined finite-discrete element analysis of rock slope stability under dynamic loading, Pan-Am CGS Geotechnical Conference, October, 2-6, 2011, Toronto, Ontario, Canada, http://geoserver.ing.puc.cl/info/conferences/PanAm2011/panam2011/pdfs/GEO11Paper473.pdf

[31] Wei, W., Zhao, Q., Jiang, Q., Grasselli, G. (2018) Three new boundary conditions for the seismic response analysis of geomechanics problems using the numerical manifold method, International Journal of Rock Mechanics and Mining Sciences, Volume 105, Pages 110-122. https://doi.org/10.1016/j.ijrmms.2018.03.009.

[32] Noferesti, H., Hazegh, A. (2018). 'Comparison of pseudo-static, Newmark and dynamic response analysis of the final pit wall of Sungun copper mine', International Journal of Mining and Geo-Engineering, 52(2), pp. 141-147. https://doi.org/10.22059/ijmge.2018.229315.594661.

[33] A. Johari, A.R. Khodaparast, Analytical stochastic analysis of seismic stability of infinite slope, Soil Dyn. Earthq. Eng. 79 (2015) 17–21. https://doi.org/10.1016/j.soildyn.2015.08.012.

[34] CR Mcgann, P. Arduino, P. Mackenzie-Helnwein, Computers, and Geotechnics A stabilized single-point finite element formulation for three-dimensional dynamic analysis of saturated soils, Comput. Geotech. 66 (2015) 126–141. https://doi.org/10.1016/j.compgeo.2015.01.002.

[35] S.P. Pradatta, Analytical expressions for determining the stability of cohesionless soil slope under generalized seismic conditions, Journal of Mountain Science 15.7, (2018): 1559-1571. https://doi.org/10.1007/s11629-017-4780-6.