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Estimation of Optimum Geometric Configuration of Mine Dumps in Wardha Valley Coalfields in India: A Case Study

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Abstract

The Wardha valley coalfields, situated in the western part of India, contribute to more than 7% of the national coal production. The open-pit mining methods are the modes of exploitation of coal in the majority of the mines in the area. Due to the increased depth of working and higher stripping ratio, the output of waste overburden is increased. The challenges are the scarcity of the available land for dumping waste overburden geo-material safely. Optimization of the mine dump slope geometry is the only available alternative in the hands of the management in order to increase the life of the projects and continue the production of coal. This investigation specifically addresses this issue, and proposes a combination of the optimum geometric configurations of the dump slope. This work utilizes the computational power of the numerical modeling technique in order to solve a large number of alternatives and zero them down to the optimum combination. The numerical modeling is considered as a major external factor that contributes to the mine dump's instability. This work shows an 18% increase in the dumping waste material volume in the present condition. This investigation also reveals that double stage dumping is comparably better in optimizing the dump slope configuration.

1. Introduction

Large-scale mechanization and big opencast mining projects came into existence after the 1990s in India. Since then, the open-pit projects have been widely prevalent for different coal mining projects in order to meet the increasing demand for coal [1]. Mining depth is increasing day by day with the exhaustion of shallow deposits. The lifetime of the projects is expanding with the deep open-pit mines; thereby, the efficient planning and design of the bench slope, pit slope, access roads, etc. are becoming essential for the entire life of the projects. The requirement for stability analysis is becoming very important with 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 increase soon with the anticipated growing tendency for the open-pit coal mining projects. Hence, dumping such a massive overburden in a proper place and stabilizing the dump mass is a challenging techno-economic problem for the coal mining enterprises. Thus the large-scale mine dump stability study would be essential before executing such projects.

Dumping waste overburden geo-material was done in stages, keeping some free space to accommodate local falls. Thus the general practice in the Indian open-pit projects is to maintain benches in the mine dump. It facilitates an efficient management of the mine dump. The stage dumping allows the mining authorities to handle the mine dump better, maintaining several safety regulations. The limited space within the lease-hold area and managing a massive volume of waste rock mining authority forced and adopted the heightening of the mine dumps. In this particular situation, there are only a few alternatives to the miners. The one aspect is to run the mine with

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increasing stripping ratio and maintain the safety of the mine dump simultaneously. It necessitates a re-examination of the parametric studies to optimize the mine dump geometry with all the prevailing external boundary conditions [2].

In this work, we chose a mining region in the western part of India with an acute shortage of dumping space vis-à-vis several other restrictions imposed from time to time by the regulatory authority. The open-pit projects dominate the mining area, and a guideline on maintaining waste rock and overburden slope need in the hour to run these mines.

This investigation, thereby, focuses on considering three alternative modes of dumping: single, double, and triple stage dumping. In general, the benches are 30 m in height. However, addressing the whole domain of the viable alternatives has been heightened up to 90 m in some cases. The analysis considers gravity loading as the self-weight of the waste rock and overburdens geo-material. The earthquake vibration is used to analyse the dynamic loading conditions on which these slope masses are exposed during seismic vibrations.

In designing the dump, there are many ways to assign the values and combine the different geometric and size parameters, while respecting the safety and environmental constraints [3]. 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 the numerical applications available today, it has become essential for the engineers to fully understand the varying strengths and limitations inherent in each different methodology [4]. In assessing the slopes, the geotechnical engineers use a factor of safety value in order to determine the stable/unstable conditions of slopes. The limit-equilibrium technique is the most commonly used conventional method. However, with the help of the recent significant advancements in computing and memory resources, the geotechnical engineers, with low-cost implications, have found the finite difference method (FDM) as a powerful and valuable technique as a viable alternative for all the pre-field applications, although there are certain limitations to the applicability of this method in capturing the actual field conditions, especially in the cases of enormous discontinuity associated with the foundation of large dump slope mass.

This work deals primarily with finding the optimum dump height and slope angle combination for safe overburden dumps. Analysing the effect of seismic vibration on dump slope is the second objective of the present investigation.

1.1. Dump design considerations

A mine dump is a massive structure formed by placing large amounts of overburden geo-material in lifts of a restricted vertical expanse laid on top of each other and create a stable slope at the angle of repose. However, a formed dump requires a horizontal base built by waste geo-material from a specific elevation and levelling off the required footprint area.

Generally, this first phase of the dump construction takes the irregular shape of the topography where it is placed. The subsequent lift height is constant, though it is restricted to prevent shear stresses on the foundation, and is a factor to control the consolidations and permeability variations [3]. The total height of the dump is also restricted by the formation mechanism [5] and carrying capacity limitations [6]. As in most of the large open-pit operations, haulage is performed by heavy trucks. Access to the successive dump lifts is achieved by establishing a suitable width, super-elevation, and gradient ramps in order to minimize the travel distance and reduce the travel distance haulage costs.

In dump designing, the costs may be governed by the following factors:

Geometry

They were usually designed to handle a total capacity throughout the life-of-mine. Over-dimensioning can cause underutilization of the valuable areas. Under-dimensioning can increase the haulage distances.

Operating costs

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

Haulage distances

Minimize the total haulage distance while meeting the required capacity by strategically placing the ramps, exits, entrances, and dumping sequence.

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 geo-material, especially if water is present [7].

Acquisition of land

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

Environmental factors

The costs of implementing and maintaining effective systems to reduce and eliminate losses. In the design considerations to maintain a long-term stability, the erosion control should avoid the re-handling costs [3] for reclamation and closure.

Although every dump is unique [8] and some of its cost maybe be given by its factors, the above description includes all the general concerns, and one would have to elaborate the most economical dump design.

The dump design elaboration observes that the mine dump geometry optimization would fulfil many facets of our already discussed parameters. Here is the importance of undertaking the present work.

2. Materials and methodology

The slope stability analysis is an important area of concern in geotechnical engineering for an open-pit project. Most textbooks on soil mechanics include several methods of slope stability analysis. A detailed review of the equilibrium methods of slope stability analysis has been presented by Duncan [9]. These methods include the ordinary practice of slices, Bishop's modified method, force equilibrium methods, and Janbu's generalized procedure of slices, Morgenstern and Price's 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 different forms of limit equilibrium methods. Here, requires a continuous surface to pass the slope mass. This surface is essential in calculating the minimum safety factor (FoS) against sliding or shear failure. Before figuring slope stability in these methods, some assumptions such as the side forces and their directions have to be given artificially to build the equilibrium equations.

The finite difference approach in the analysis of the slope stability problems does not assume the shape or location of the failure surface, slice side forces, and directions [10]. The method can be applied with complex slope configurations and soil deposits in two or three dimensions in order to model virtually all types of mechanisms. General soil material models that include Mohr-Coulomb and numerous others can be employed. The equilibrium stresses, strains, and the associated shear strengths in the soil mass can be computed very accurately. The critical failure mechanism developed is highly general and require not to be simple circular or logarithmic spiral arcs. It has extended to account for the seepage-induced failures, brittle soil behaviors, random field soil properties, and engineering interventions such as geo-textiles, soil nailing, drains, and retaining walls. This method shows the deformations at the working stress levels and monitors progressive failure including overall shear failure [11].

2.1. Failure mechanisms

The various failure modes that occur in mine waste dumps have been summarized by Caldwell and Moss [12], who reviewed these analysis methods. These failure modes are illustrated in Figure 1.

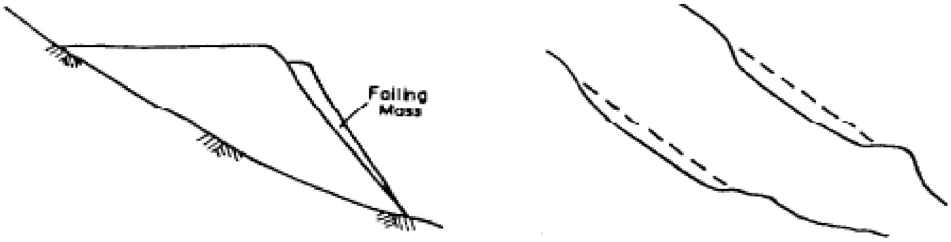
Surface or edge slides may occur as material moves down the slope. This failure mode is most likely to occur in crest tipped embankments, and is best evaluated by the equations describing the stability of an infinite slope. A shallow flow slide may occur if sufficient water enters the slope mass and flows parallel to the face.

Dumps placed on the flat ground of competent soil are least likely to fail. However, if a thin layer of soft material covers the flat earth, base failure may occur. If the ground is inclined, base failure is more likely to occur. This mode of failure has been experienced in both the end-dumped and layer-placed embankments [13].

Block translation can occur where a dump is formed on the inclined ground, and the soil cover is relatively thin and weak. Unusually high water tables in the dam, earthquakes or organic material decay beneath the dump may start such a failure.

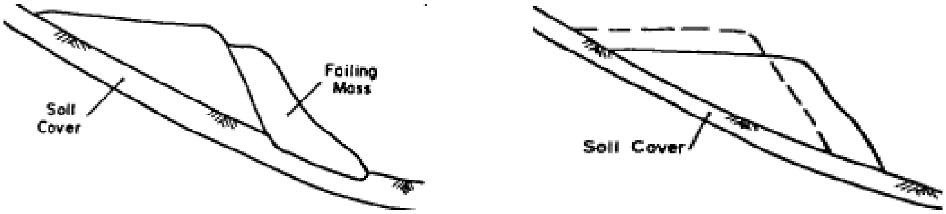
Circular arc failure through the dump material is most common where the dump material contains a significant percentage of fine-grain soil. Similarly, a circular arc failure surface may develop through a deep foundation soil deposit of fine-grained soils.

In the Wardha valley coalfields, it was observed that the circular mode of failure was widespread; thereby, the primary focus in this work will orient in that direction.



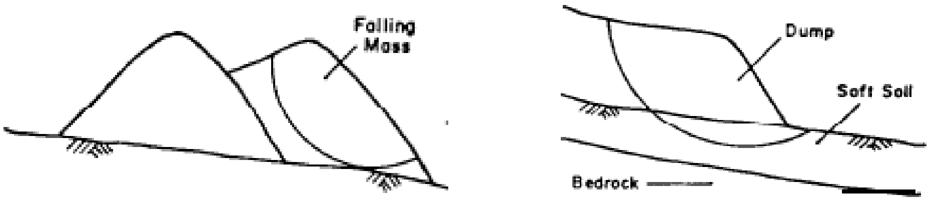
a. Surface or edge slide

b. Shallow flow slides



c. Base failure (spreading)

d. Block translation



e. Circular arc failure

f. Foundation circular failure

Figure 1. Mine dump possible failure modes [12].

2.2. Deformations as an indication of failure

Deformations occur in a slope due to normal and shear stresses acting in the mass of material forming the dump. Some of these deformations such as consolidation are not indicative of failure, while others such as shearing along the failure surface are. It is necessary to distinguish the deformations that indicate failure from those that do not predict failure. It requires an understanding of the failure mode and the deformations that accompany it [14].

The analytical techniques currently available to analyze dump deformations are cumbersome and not sufficiently accurate to enable pre-construction estimates to be made of the consolidation and failure deformations. Instead, the failure criteria are usually based on experienced gained as the dump is constructed. The rate of deformation and a change of the pace of deformation are generally good indicators of the behavior of a slope. It has been used to establish the criteria indicative of failure. We used observed deformation, rate of movement, and acceleration pattern parameters in order to assess the failure in the mine dump.

2.3. Mine site

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

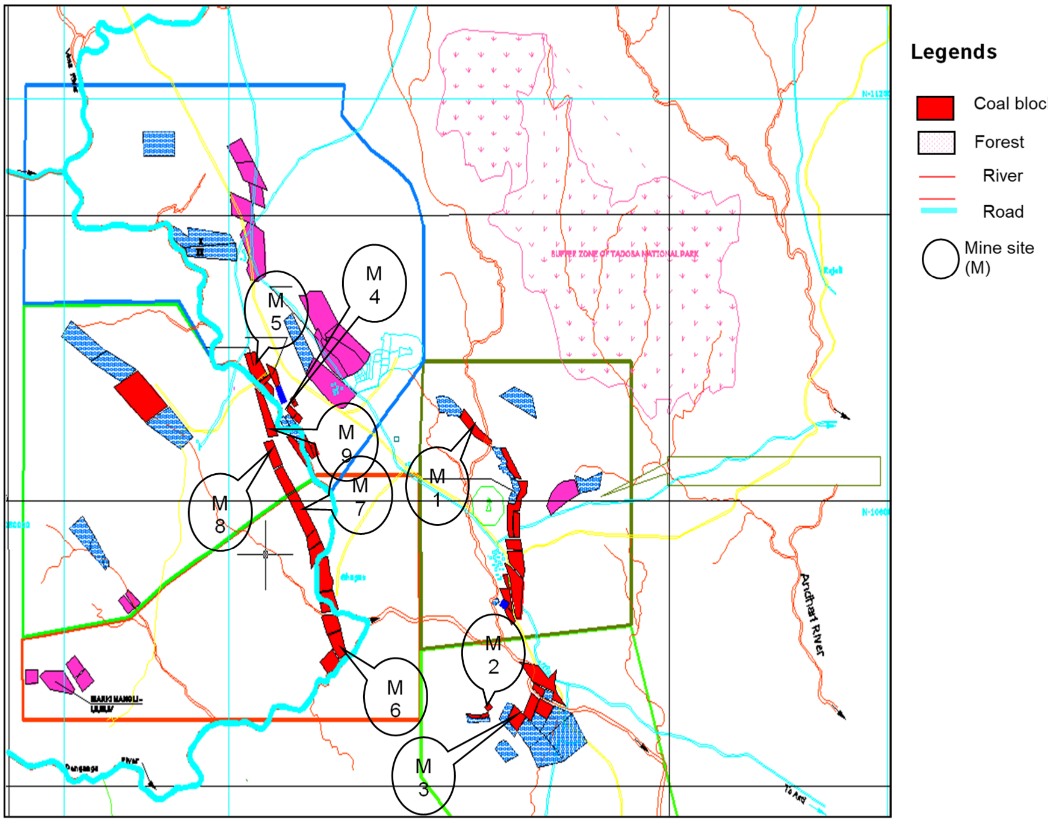


Figure 2. Location of the mine sites at the Wardha valley coalfields.

2.4. Waste rock sampling scheme

The variations in the soil and rock characteristics and the varied complexity of dump conditions existing in the mines of the Wardha valley coalfields considered for the present work made the selection of the sample collection methods of utmost importance. The dumps of these mine sites are of different categories and follow a uniform sampling pattern of eight samples per dump for a generalized approach of sampling from each one 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 a representative one, and not to 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 present study's time and other resource limitations. Thus there were 252 samples collected in place of 264 (i.e. eight samples per dump x 3 categories of dump per mine x 11 mine sites) due to the absence of a particular type of dump in some of the selected mines.

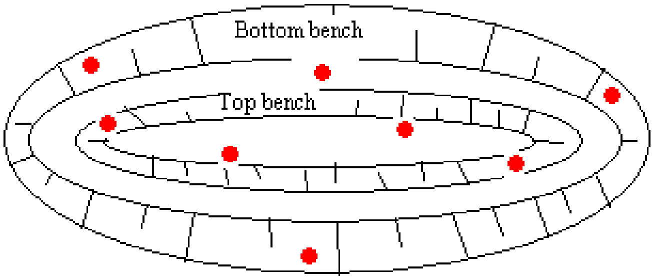


Figure 3. A schematic sample collection program from a particular dump (eight samples per dump).

2.5. Geotechnical laboratory interpretation

The materials constituting the mine dumps were collected from the field, and these were mainly mixtures of broken rocks and loose soil. The proportion of loose soil was more for the samples collected from the top portions of the dump than those collected from the bottom parts. The waste rock properties are mainly attributed to the age of mine dumps, and the mine dumps are categorized into three.

a) Running dumps

Where active waste rock dumping is being carried out, further dumping would be stopped after reaching a certain desired height over a specific planned area.

b) Old dumps

Here, dumping was stopped for a few years with no plan of dumping by the mine authorities soon.

c) Vegetated dumps

Here, green reclamation has already been adopted/achieved, and we have no further plans for dumping.

Hence, this categorization would help the study team to understand the varied geotechnical nature of the waste rock resulting from their age, change in material properties due to compaction, and biological changes in the geo-materials composing these dumps, etc. A detailed investigation of the material characteristics and the site conditions forms the first part of any geotechnical study. We followed the detailed methods laid in [15].

The 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 from the laboratory tests depends on many factors, particularly the type of soil, quality of the test samples, size of the test samples, and testing methods [16].

In a direct shear test, the plane of shear failure is pre-determined. The test is usually carried out in a box split into two halves; hence, it is a shear box test.

This equation can characterize the shear strength of the cohesive soils:

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

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

Table 1. Average Cohesion and internal friction angles of dump geo-material of different mines.

Name of mines	Cohesion (KPa)	Internal friction angle (°)
Mine 1	0.00	38.56
Mine 2	0.00	48.65
Mine 3	13.97	27.93
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. Geometry of 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 each of 90 m, 45 m, and 30 m high benches, respectively), slope angle from 20 to 45 deg., and berm width from 12 m to 20 m in-between stages of dumping. This study considered the uniform foundation as in-situ rock prevailing at the dumpsite for the study, excluding the major geological features. Several parameters mentioned above were studied in the dimensional optimization problem, and a total of 1936 models was analyzed.

2.7. Seismic coefficients

The dynamic factors for the cause of instability of the external mine dump slopes were studied at length, and complete model analyses were done. Seismic coefficients' values were used in the numerical modeling.

2.8. Boundary conditions

The extents of outer boundaries of numerical models were varied to select the far-field boundary conditions. The boundary of the mine dump extended 50 m on both sides to achieve the far-field condition, and in the vertical direction, it was 30 m from the base of the dumps to reach the far-field condition. In the elastic-perfectly-plastic numerical analysis of the external mine overburden dumps, followed in the investigation, these conditions were considered for modeling. It was necessary to model the entire mine dump, not any particular portion of the dump, due to the absence of symmetry in the site dump geometry to obtain accurate stresses and displacements. The boundary condition that appeared to work best was the roller boundaries on both sides, except the bottom surface, i.e. in the dump stability analysis, side-boundary elements were restricted with velocity in the x-direction to be zero.

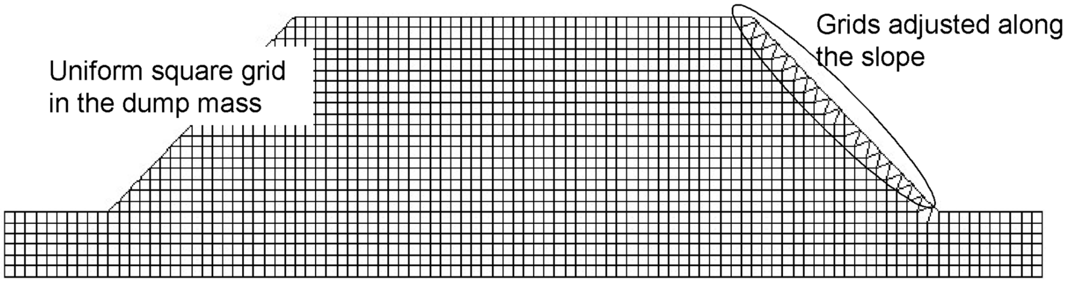


Figure 4. A single stage dump section with equal grid size.

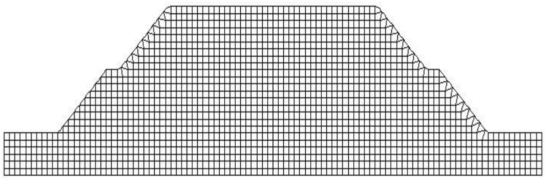


Figure 5. A double stage dump section with equal grid size.

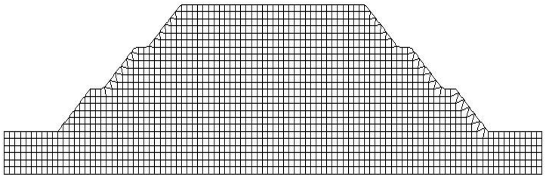


Figure 6. A triple stage dump section with equal grid size.

Moreover, the bottom boundary elements were restricted with both the x- and y-velocities to be zero. A uniform quadratic grid with equal zone size was used, as shown in Figures 4, 5, and 6 for single, double, and triple stage dumps, respectively, to minimize the effects of the grid in the continuum modeling. The grids were adjusted along the slope surface in order to reduce the eccentricity of these elements, as depicted in Figure 4.

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 [17]. The time step between the increments is maintained below a critical value to ensure the computational stability. The incremental displacements in the finite-difference grid are calculated from the velocity field of the previous step. However, the stability and accuracy are two distinct issues. The fact that stability is maintained does not automatically guarantee that the analysis results will be accurate. In the explicit time integration, stresses and displacements are calculated by extrapolating the velocity field of the previous step. It means that displacements and stresses vary linearly between steps (i.e. assuming a constant velocity between steps). It has been argued that keeping the time steps sufficiently small (like those small time steps in the order of 10-6 seconds that are required for stability) will maintain an accurate solution.

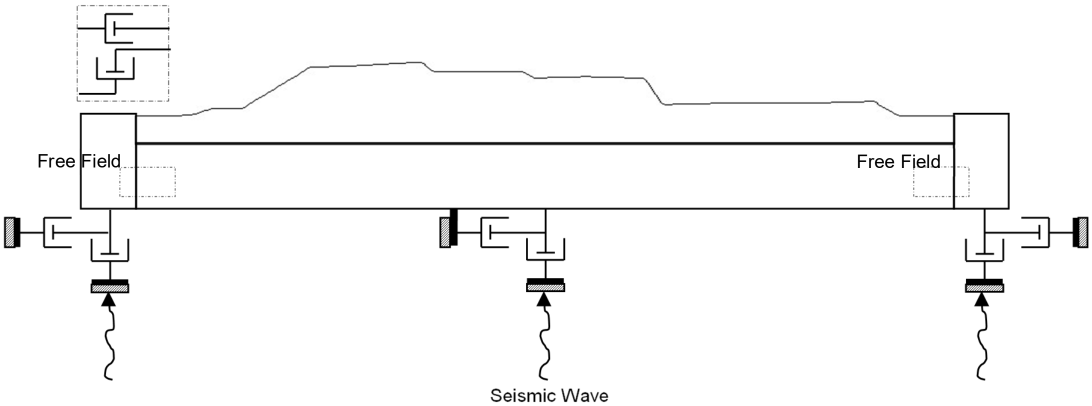


Figure 7. Model for seismic analysis of external dump slope and free-field mesh (details of the free field boundary are shown in the above-dotted box).

The continuum model solves the equation of motion for the mass-spring-dashpot systems (Figure 7) in the time domain with incremental time steps. The calculated incremental displacements are related to the incremental stresses connected with selected constitutive relationships—the program utilized explicit time step integration between consecutive steps. A critical time step is selected in order to maintain the computational stability [18]. The critical time step selected in the present work was 1.1x10-6.

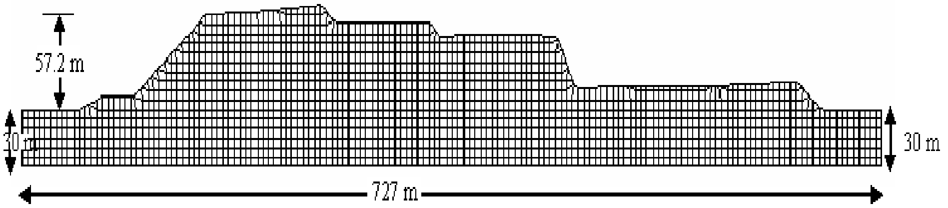


Figure 8. Overburden dump section from mine site 2 meshed with rectangular element.

Dry conditions were assumed, and a simple constitutive model was used; hence, the elements were modeled as elastic, perfectly plastic Mohr-Coulomb materials. Rayleigh damping was used in the model. Figure 7 also illustrates the boundary conditions employed in the dynamic analyses. In the model, vertical displacement was fixed on the boundary since a very stiff in-situ layer existed at a depth of 30 m. The displacements are tied together at the lateral boundaries in both directions [19]. The model ignores radiating waves going away from the boundaries, and the connected degrees of freedom accurately predict the free-field response at the lateral edges [20].

2.10. Input ground motion

The stability of the generated and the existing dumps for different mine sites were analyzed with different input ground motion conditions. The analysis used the El Centro time history recorded at 117 (USGS) station during the Imperial Valley earthquake (Figure 9). The study considered the three acceleration time histories of the 1941 Imperial Valley earthquake. We used the PEER strong motion database. Incrementally, the model applied the acceleration time histories to all nodes along the bottom boundary of the finite difference model. The low-frequency components of an earthquake motion generally dominate the displacement response [20]. Thus displacement histories of the different monitoring points were computed in order to assess the effect of numerical dissipation on the low-frequency response. After observing the response frequency, it can be postulated whether inaccurate high frequencies have been introduced into the solution.

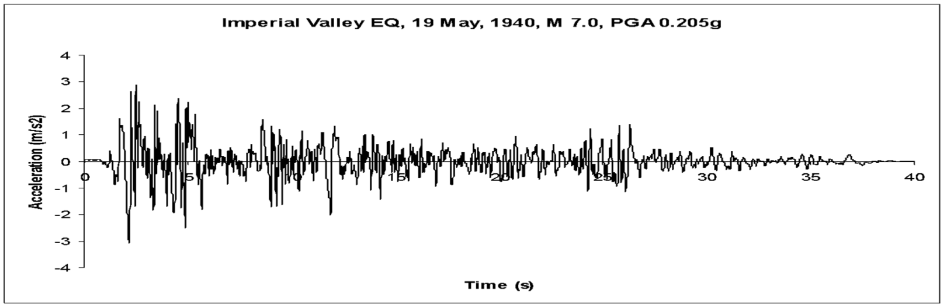


Figure 9. Ground acceleration time histories of the record used in the analyses – El Centro Earthquake 117 Station.

3. Results and discussion

A schematic diagram of different dump sections is shown in Figure 10. This was accomplished with varying heights and slopes. In the analysis, a constant height of 90 m was used, as shown below.

A total of 1936 models were analyzed in three different dumping patterns: single stage, double stage, and triple stage dumping, summarized in Table 2. This study was conducted to fulfill the principal objective of this research work. The summarized results (Table 2) show the corresponding increased volume accommodation capacity about the overall base dump slope angle of 28.5° with a constant total height of 90 m and a berm width of 12 m in all the cases. The variation in section area with constant total height and same base area for these three different types of dumps is shown in Figure 10. For a lower bench height, the inclination may be increased more as prevail in the analysis. Double-stage dumping is advantageous due to the total waste rock accommodation capacity for the same base area after comparing all the results shown in Table 2. It is an average, about 1.5 times more compared to triple-stage dumping on an overall basis.

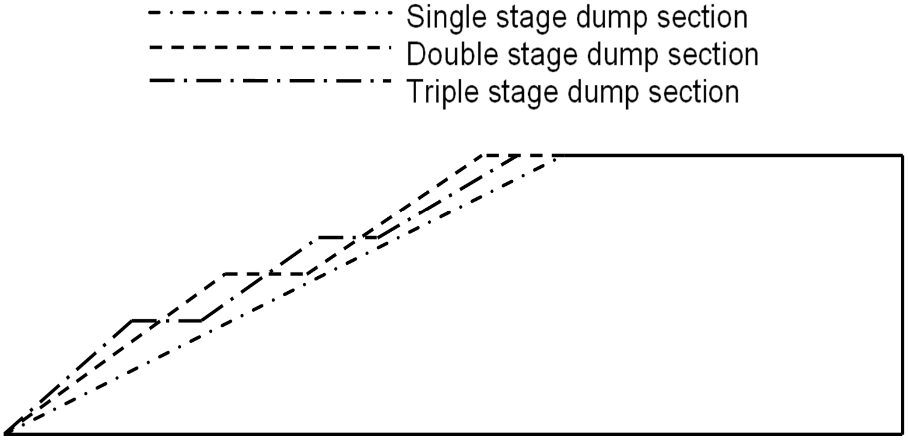


Figure 10. Cross-sections of dumping patterns.

3.1. Static condition

The static stability analysis tabulates the safety factor, and assumes 1.25 as a long-term factor, and hence, the results are followed as given in Table 2.

The increase in volume capacity of the design dumps is calculated about the limiting 28.5-degree dump slope angle specified by the competent authority in the Indian mining conditions, predicting the increased scope of dumping at the specific mine locations saving the precious land.

3.1.1. Influence of dump parameters on stability

The parametric analyses investigated the influence of dump height, soil strength, and dump slope angle on permanent displacements of the base case slope. The magnitudes of the base case parameters were increased and decreased to create a range of observed behaviors.

Table 2. Results of static analysis with FLAC tool.

Name of 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

3.1.1.1. Effect of bench height on stability of dump

The height of the mine dump influences the magnitude of permanent displacements, as shown in Table 3 for a standardized single-stage dump of slope angle equal to 28.5°. The displacement appeared to increase when the slope height was increased. The average maximum displacements in magnitudes obtained from the various models are displayed in Table 3. It is observed that as the elevation increases, the maximum displacements also increase. The locations of these displacements are deliberately ignored here for this part of the analysis because in this part, we have concentrates only on the parametric analysis but not on the region of instability. The increased displacements indicate a high possibility of failure of the slopes unless proper preventive measures are adopted. It was observed that a change in the dump height from 50 m to 90 m with an overall variation of ±20 % caused a change in the maximum displacement from 11.89 cm to 14.65 cm with an average variation of ±11.5 % (Table 3). The relation between the two was observed to remain linear for the ranges analyzed in this study.

Table 3. Average maximum displacement with the corresponding dump height.

Dump height (m)	Average maximum displacement (cm)
50	11.89
60	12.32
70	13.43
80	14.27
90	14.65

3.1.1.2. Effect of slope angle on dump stability

The dump slope angle influences the magnitude of permanent displacements shown in Table 4 for a standardized single-stage dump of 90 m. The displacement appeared to decrease when the slope was flatter. The average maximum displacements in magnitudes obtained from the analyzed models are displayed in Table 4. It was observed that the maximum displacement increased with the dump angle. The locations of these displacements were deliberately ignored here for this part of the analysis. It was observed that a change in the dump angle from 20° to 40° with an overall variation of ±10% causing a change in the average maximum displacements from 14.08 cm to 26.92 cm with an average variation of ±10% (Table 4), except for the last case, where 77% variation was observed. The relationship between the two was observed to remain non-linear for the ranges analyzed in this study. It was observed that for the 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.

3.1.1.3. Effect of internal friction angle on dump stability

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

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

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 an estimated dynamic earth pressure to assess the stability of slopes [21]. The magnitude of the dynamic force and the lateral inertia force on the slope mass are evaluated using a seismic coefficient. Various methods and empirical recommendations can estimate the magnitude of dynamic earth pressures. Once the magnitudes of the static and dynamic forces are estimated, different failure mechanisms, both external and internal, can be checked for stability. These mechanisms include sliding along the base and overturning. One example of the analyzed cases by the pseudo-static approach is shown in Figure 11, with safety factor contour on the right side of the diagram. This is very easy to handle and use for a quick appraisal of stability. In Figure 11, the two insets showed the existence of the failure surface and the factor of safety contours for a specified number of grid centers within the box having the same failure surface, respectively. The horizontal input component of the dynamic load is also depicted here. The dimensions of the dump are kept the same, as shown in Figure 8, having the material properties of mine site 2.

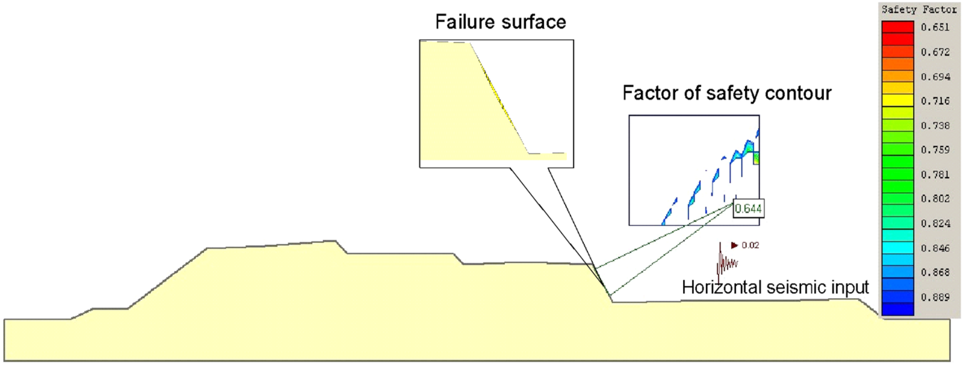


Figure 11. Pseudo-static slip surface at seismic coefficient 0.02 for existing dump (mine site 2).

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

3.2.1. Effect of horizontal seismic coefficient on dump stability

The impact of varying horizontal seismic coefficient (HSC) on the dump stability is discussed in this section. Figure 12 shows the columnar representation of the varying safety factor with HSC for the running dump geometry of ten mine sites and material conditions. The HSC values of 0.01, 0.03, 0.05, 0.08, and 0.1 were analyzed in this part of the study.

Table 6. Dynamic stability analysis of dumps.

Name of 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

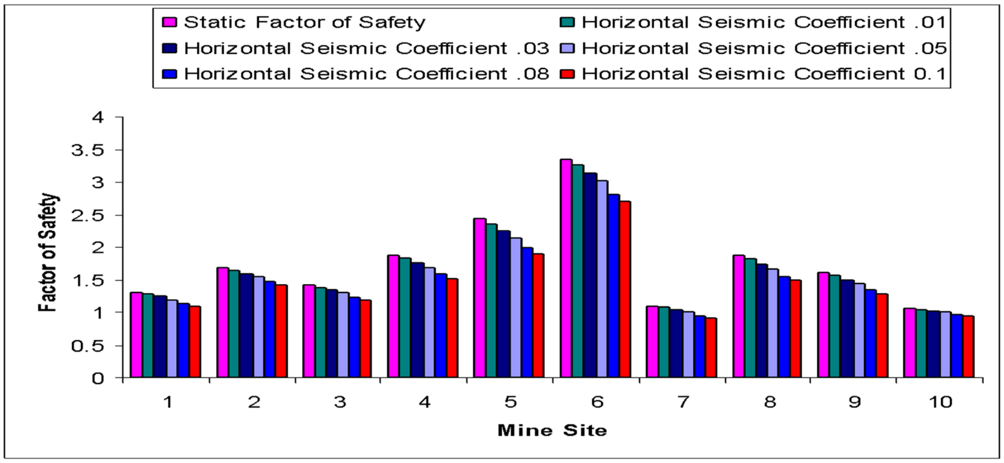


Figure 12. Increasing horizontal seismic coefficient showing decreasing factor of safety.

It was observed that the factor of safety decreased with an increase in HSC. The factor of safety remains maximum for the static case compared to those obtained in the dynamic model.

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. Numerical analyses were performed for a 2D cross-section of the total dump mass. The analyses of the effects of ground failure/settlement were not kept within the scope of this numerical study.

3.3.1. Effect of input accelerations on displacements

The effect of the input motion on the permanent average displacements was investigated in this part of the study. Four recorded earthquake motions of varying durations, amplitude, and frequency contents were selected for the analyses (Figure 13). For each one of these records, the peak horizontal accelerations causing slope movement were scaled to match the El Centro base excitation (PHA = 0.2 g).

The predicted displacements for each one of these modified earthquake records are shown in Figure 13. The displacement history for the base case acceleration is highlighted here with black line and other with blue, red, and gray colored lines. 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 the earthquake motion. It suggests that the design of dump slopes should not be based only on analyses of a single ground motion record.

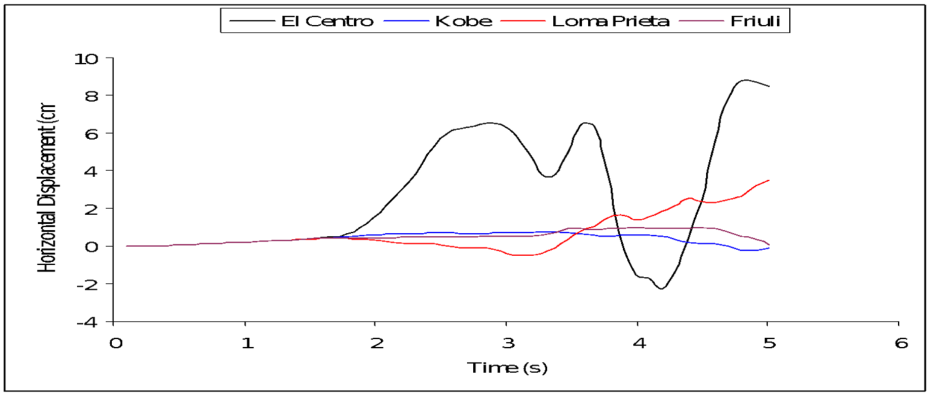


Figure 13. Acceleration time histories used to illustrate the influence of frequency content on the prediction of permanent displacements at monitoring point 1 shown in Figure 16.

3.3.2. Effect on stage dumping

The present investigation compares the combinations of various mine dump geometries and the stage dumping to find out the optimized one because of utilizing the available natural resources to the fullest extent. Thereby, we investigated all three types of dumping with dynamic load application and simulated the responses.

The numerical models developed and analyzed for the different dump conditions were diagnosed with dynamic loading conditions. The selected models analyzed here are the stable configurations obtained from the static analyses results and shown in Table 2. All these models analyzed for the material properties for mine site number 2 are displayed below. However, similar analyses were carried out for all the available configurations of material properties and the stable dump geometries. The results for the single, double, and triple stage configurations are provided below in sequence.

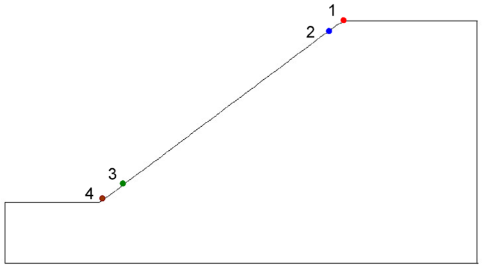


Figure 14. Single stage dump slope (90 m height and 35° slope angle) with four monitoring points.

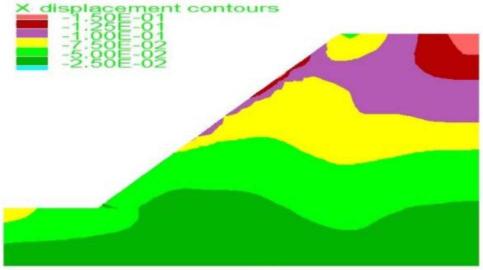


Figure 15. Horizontal displacement contours at single stage dump slope after 10 s of dynamic load.

Figures 14, 19, and 24 provide the left-hand side monitoring points in the studied dumps for the single-stage with 35° slope angle, double stage with 12 m berm distance, and 40° stage angles; and triple stage with 25 m berm distance and 30° stage angles for this part of the study, respectively. The numerical models used twice more monitoring points with an equivalent number of points on the right side of each of the dumps 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 shown in Figure 16. A similar nature is observed for these points' velocity and acceleration time history curves (Figures 17 and 18). It was observed that the displacement and velocity remained near around zero-till until 0.5 s.

In contrast, the acceleration was noticed to remain negligible till 1.5 s after applying the excitation. The contour of the horizontal displacement vectors for the three stages (Figures 15, 20, and 25) indicated that the double stage dumps had a smooth variation of displacements. The range of overall horizontal displacements is noted to be least for the single-stage dumping followed by the double-stage dumps, and then the triple-stage dumps for mine site 2.

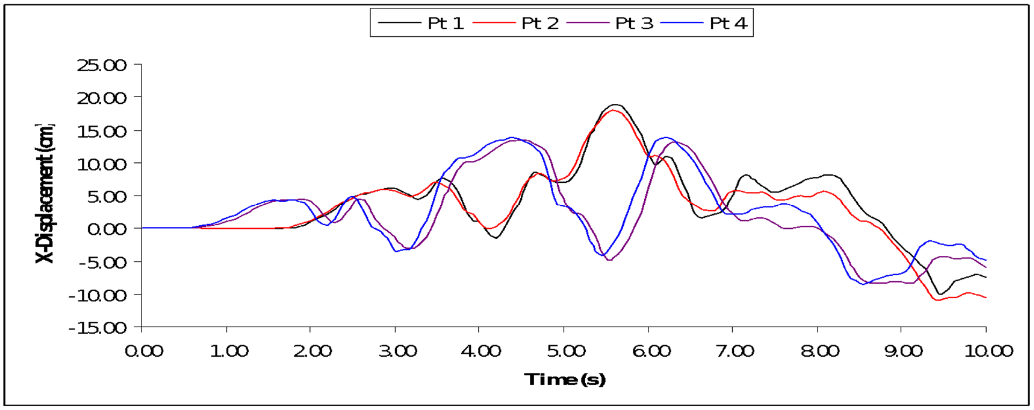


Figure 16. Horizontal displacement at four monitoring points.

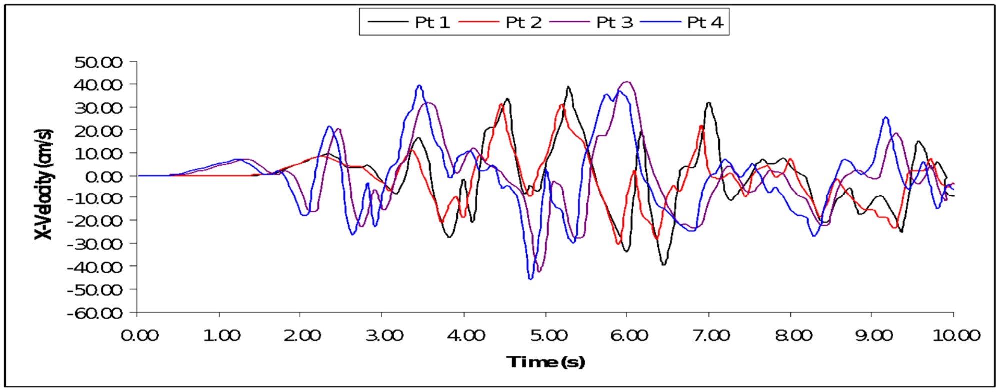


Figure 17. Horizontal velocity at four monitoring points.

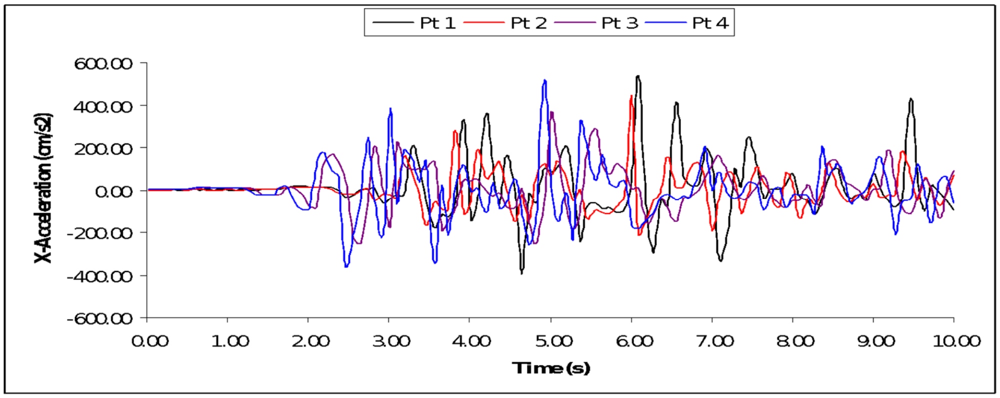


Figure 18. Horizontal acceleration at four monitoring points.

A representative result of the analyses on the effect of input acceleration for double-stage dumps is depicted in Figures 19 to 23. Figures 21, 22, and 23 have horizontal displacement, horizontal velocity, and horizontal acceleration time histories plotted for all the left-hand side monitoring points.

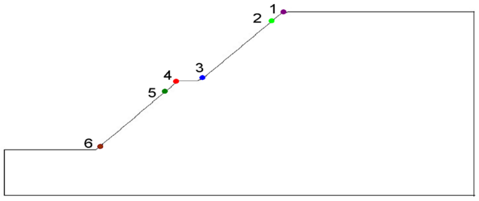


Figure 19. Double stage dump (90 m height and 41.14° overall slope angle) with six monitoring points.

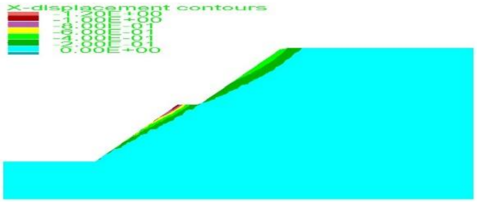


Figure 20. Horizontal displacement contours at double stage dump slope after 10 s of dynamic load.

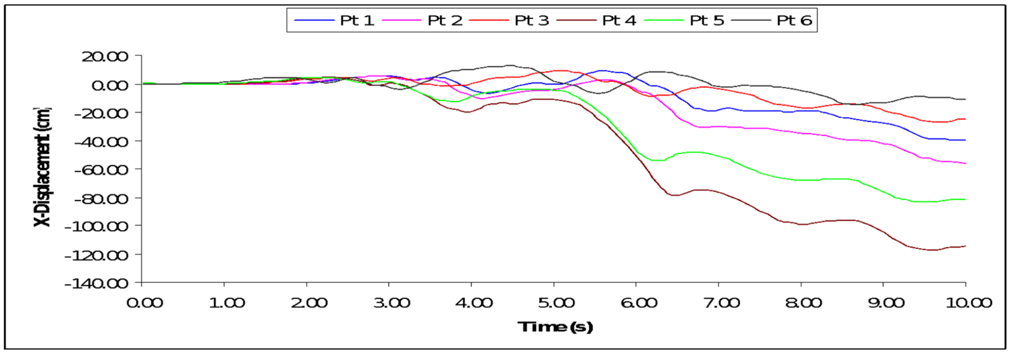


Figure 21. Horizontal displacement at six monitoring points.

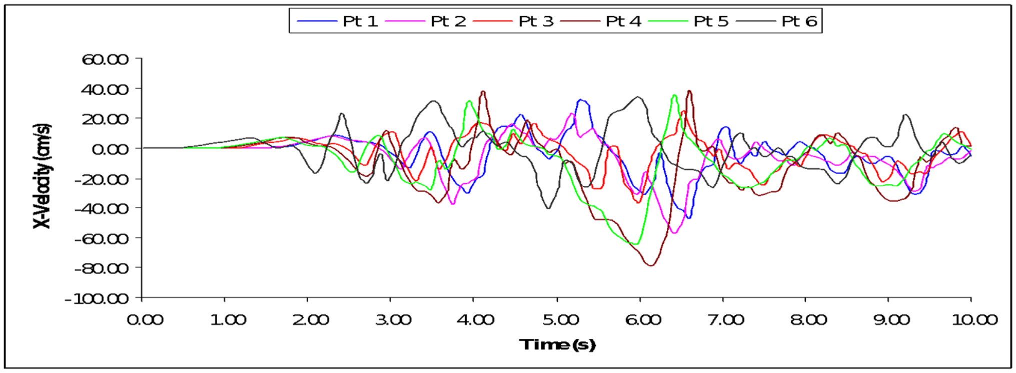


Figure 22. Horizontal velocity at six monitoring points.

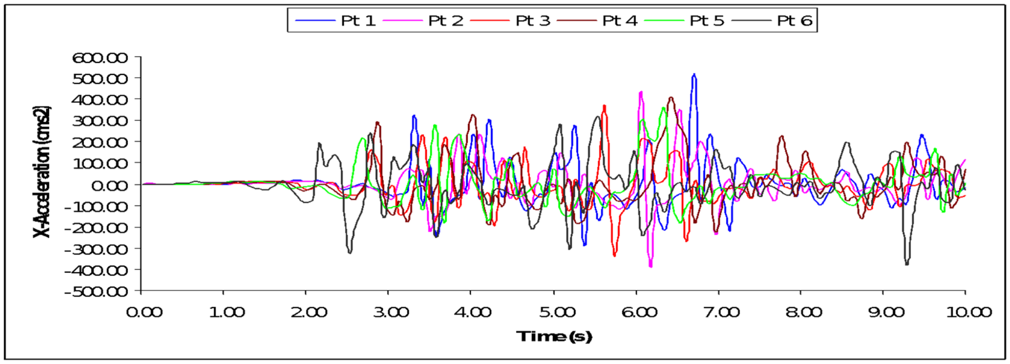


Figure 23. Horizontal acceleration at six monitoring points.

A representative result of the analyses on the effect of input acceleration for triple-stage dumps is depicted in Figures 24 to 28. Figures 26, 27, and 28 have the horizontal displacement, horizontal velocity, and horizontal acceleration time histories plotted for all the left-hand side monitoring points, respectively.

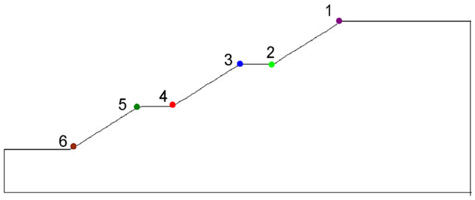


Figure 24. Triple stage dump (90 m height and 24° overall slope angle) with six monitoring points.

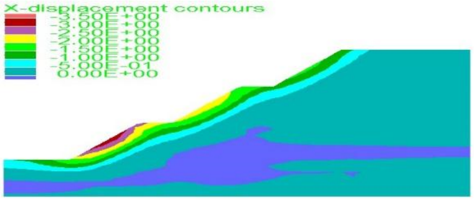


Figure 25. Horizontal displacement contours at triple stage dump slope after 10 s of dynamic load.

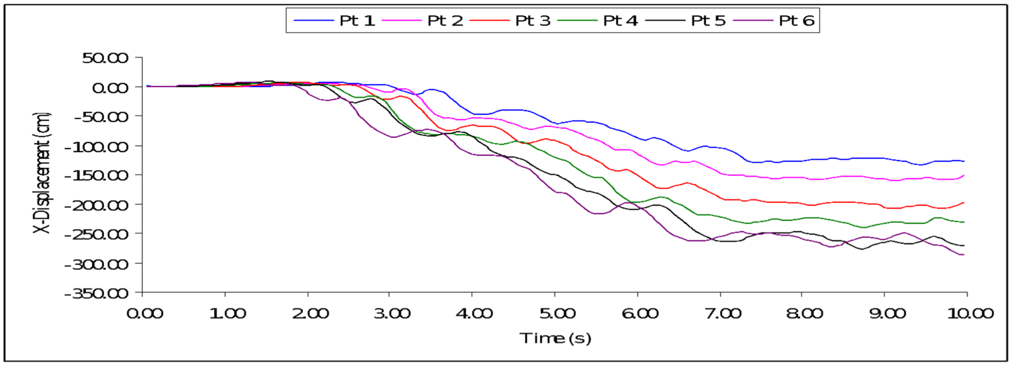


Figure 26. Horizontal displacement at six monitoring points.

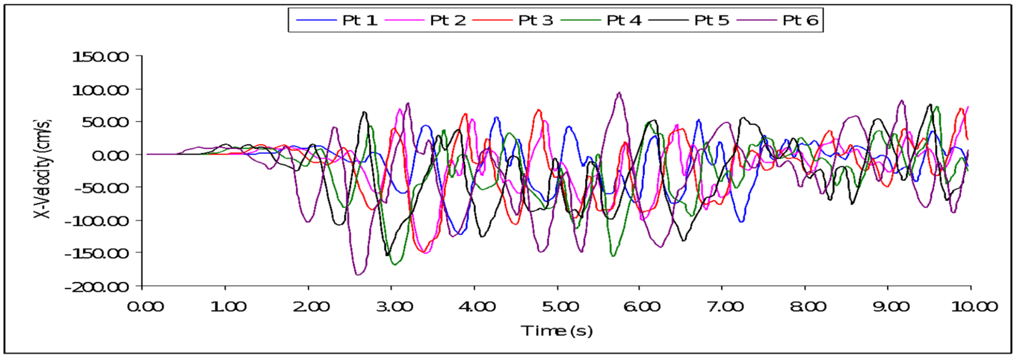


Figure 27. Horizontal velocity at six monitoring points.

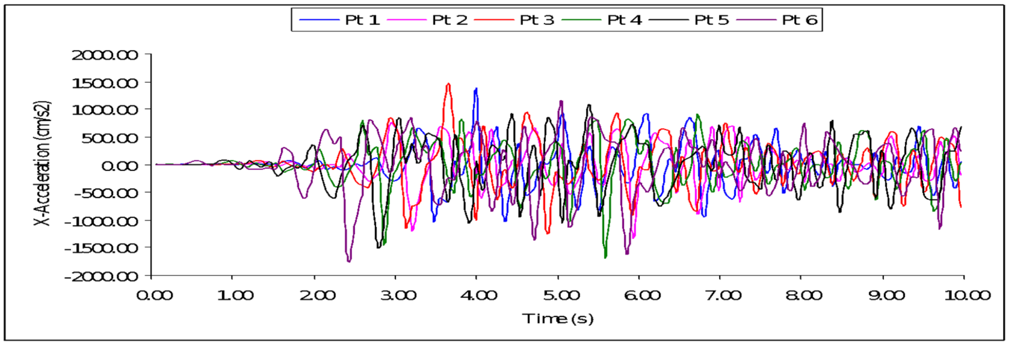


Figure 28. Horizontal acceleration at six monitoring points.

3.3.3. Observations

The plots of horizontal velocity and acceleration time histories for the 10 s time are shown in Figures 17, 18, 22, 23, 27, and 28 for the single, double, and triple stages of dumping. It can be observed that the changes in the acceleration are more frequent in triple-stage dumps followed by the double-stage and then the single-stage dumping patterns. The ranges of variation of the acceleration values were a maximum for the triple-stage dumps, whereas similar variation was observed for the single- and double-stage dumps. For the single-stage dumping, the maximum and minimum values for displacement, velocity, and acceleration are observed to be (18.74, -10.92) cm, (40.94, -40.08) cm/s, and (538.53, -396.27) cm/s^2, respectively, for the monitoring points mentioned above. A similar analysis for the double-stage dumping provided the maximum and minimum values as (12.39, -117.22) cm for displacement, (38.61, -78.24) cm/s for velocity, and (518.80, -376.56) cm/s^2 for acceleration along with the monitored points, whereas those for the triple-stage dumping provided the maximum and minimum values as (7.43, -285.81) cm for displacement, (94.23, -182.60) cm/s for velocity, and (1468.48, -1718.26) cm/s^2 for acceleration along with the monitored points. The ranges of displacements, velocities, and accelerations obtained for the single-, double-, and triple-stage dumps were found to be (28, 129, 293) cm for the displacements, (86, 116, 276) cm/s for the velocities, and (934, 904, 3176) cm/s^2 for the acceleration.

Although it is difficult to compare the variations of the displacements, velocities, and accelerations obtained between the static and dynamic modes of analyses, it can be observed that the overall range of variation of displacements at the similar monitoring points show higher displacement values for the dynamic model of analysis compared to the corresponding static mode of analysis. The same is observed to be true while comparing the double and triple stages of dumping patterns for all the three parameters, namely the displacement, velocity, and acceleration values.

The overall dump slope angles in the above models were not the same (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 in the three cases differ. It should not be concluded that single-stage dumping is safer (as found in the x-displacement plots) than double-stage dumping. It may be noted that even at a dump slope angle of 40°, the single-stage dump in static analysis became unstable with the present conditions.

3.4 Discussions

The study's objective was to optimize the dump slope geometry, and the results shown in the section above have rightly demonstrated the same. Mines 1, 2, 4, and 11 are found with higher slope angles than other mine dumps due to their higher frictional characteristics of the mine dump material. Maximum 41.42 deg. dump slope is possible with the present overburden material characteristics with volume gain of 18.07%. It is an achievement that more than 18% of the waste volume can be accommodated within the existing dump without changing much of the ground parameters. The increased accommodation capacity will benefit the mine management to endure the current projects due to the land scarcity.

The highest gain of volume accommodation was for mine number 2, with 22.45% for single-stage dumping. It can also be observed that mine dump with a 41.42° slope angle will remain safe under prevalent seismic conditions. Strategically, single-stage dumping might not be suitable considering the risk associated with that.

In the deformation study, peak permanent deformation ranges from 11.89 cm to 14.65 cm for the dump height 50 m to 90 m. Similarly, it ranges from 14.08 cm to 26.92 cm for dump slope angles 20° to 40°, and for the available material characteristics of the angle of internal friction 31.4° to 48.65°, the deformation reduces from 164.9 cm to 14.65 cm. Thus it can be observed that deformation in pseudo-static loading is more sensitive to material friction properties.

The study shows that, even during dynamic loading, the maximum deformation is observed to be within the limits of accommodate perception. Thus this analysis has substantially helped the mining engineers to quickly assess the extent of deformation in case of similar loading, and that too can also be efficiently handled.

4. Conclusions

The following conclusions can be summarized from this investigation:

1) The study's primary objective was fulfilled, and this work showed that a good amount of optimization of the dimensional parameters was achievable.
2) The investigation showed that considering the prevalent boundary condition in the dump slope, there was a scope for improving the accommodation capacity without compromising the safety aspect.
3) 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 the single- and triple-stage dumpings. It is possible to make the overall dump slope angle steeper without sacrificing the factor of safety in the case of double-stage dumping.
4) The effect of average seismic intensity shows very little influence on the stability of the dumps since the stable and safe dump slope angles differ by 1% to 3% maximum with respect to the angles obtained from the static analyses.
5) The impact of dynamic load due to blast vibration and earthquakes causes more deformation in the toe side of the dump slope than the crest of the dumps. The vibration amplitudes are more accentuated in this region than in the crest region. The length of duration of these loads has an adverse impact on the dump slope stability (length of duration varies from 2 s to 10 s). Every second of time increment causes a 7.6% increase in dump slope displacement.
6) The dynamic analysis shows that the height and slope angle negatively influence the dump deformation in the analyzed range of 50–90 m and 20°-40°, respectively, with the observed deformation ranges of 11.9-14.7 cm and 14.1-26.9 cm. The material friction angle analyzed in the range 31.4°-48.7° showed a significant potential for influencing the deformational dump characteristics observed in the range of 164.9-14.7 cm. The input ground motion with a scaled peak amplitude of 0.2 g showed that the El-Centro seismic input influenced the deformational dump characteristics more than Loma-Prieta, Friuli, and Kobe with a 0.7-8.7 cm variation.
7) The failure surface in dump slopes obtained from the static and dynamic analyses was found to be of a circular type. The parameters like shear strain, displacement, and yielding point plots were efficiently used as the indicators in order to predict the circular failure. In the absence of a direct failure plane analysis from the continuum-based numerical modeling, they had a good conformity amongst themselves.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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تخمین هندسه بهینه انباشتگاه باطله‌ی معدن در حوزه‌های زغالسنگ دره واردا در هند: مطالعه موردی

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IIT(ISM)، واردا، هند

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چکیده:

میدان‌های زغالسنگ دره واردا واقع در بخش غربی هند، بیش از ۷ درصد از تولید ملی زغال‌سنگ را تشکیل می‌دهند. زغالسنگ در اکثر معادن این منطقه بصورت روباز بهره برداری می‌شود. در نتیجه افزایش عمق معدنکاری و به طبع آن حجم باطله برداری افزایش یافته. چالش پیش آمده مربوط به کمبود زمین‌های مناسب جهت انباشت ایمن باطله‌های معادن است. بهینه‌سازی هندسه شیب سد باطله معدن تنها جایگزین موجود در دست مدیریت به منظور افزایش عمر پروژه‌ها و پیوستگی تولید زغالسنگ است. این تحقیق به طور خاص به این موضوع می‌پردازد و ترکیبی از تنظیمات هندسی بهینه شیب سد باطله را پیشنهاد می‌کند. این کار از قدرت محاسباتی تکنیک مدل‌سازی عددی برای حل تعداد زیادی گزینه جایگزین و صفر کردن آنها برای رسیدن به ترکیب بهینه استفاده می‌کند. مدل‌سازی عددی به‌عنوان یک عامل خارجی اصلی در نظر گرفته می‌شود که به ناپایداری سد باطله‌ی معدن کمک می‌کند. این کار افزایش ۱۸ درصدی را در حجم مواد باطله انباشت شده را در شرایط فعلی نشان می‌دهد. این بررسی همچنین نشان می‌دهد که تخلیه دو مرحله‌ای در بهینه‌سازی پیکربندی شیب سد باطله نسبتاً بهتر است.

کلمات کلیدی: انباشتگاه باطله معدن، ارتفاع انباشتگاه باطله، زاویه شیب انباشتگاه، بارگیری پویا.