Influence of interface and induced seismicity on overburden dump slope stability

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A large volume of overlying waste material is removed to access deep-seated mineral deposits and stored near mines or eventually dumped as backfill. Overburden is stored in stacked dumps due to space constraints and high stripping ratios. The height and slope of these overburden dumps are enormous. This study is a parametric evaluation of the impact of interface and blasting-induced seismic loading on the stability of dump structures having total heights varying between 60 and 120 m. The study reveals that for 20° of internal friction of the interface, a factor of safety (FoS) of the slope structure increases with increasing cohesion (10–30 kPa). However, as the friction angle increases from 20° to 25°, the relative increase in FoS is reduced. Thus FoS remains unchanged with increasing cohesion for a friction angle of 29°. The stability of the dump reduces when subjected to blasting-induced seismic loading. The damage is more due to the shock waves imposing seismic loading in the horizontal direction than in the vertical direction.

Keywords: Coal, induced seismicity, interface, overburden dumps, slope stability.

INDIA ranks second among the top coal-producing countries in the world. The contribution of opencast mining dominates underground mining, which accounted for only 4.36% of the annual coal output during 2020–21 (ref. 1). The contribution of the coal mining industry is critical for sustained energy security in India, as it consumes more than 50% of the total production[2]. After the shallow deposits have been worked out, miners move deeper into deposits that may be mined either underground or on the surface. Surface mining is the most common method because the percentage of minerals extracted is significantly higher[3].

Opencast mining entails the removing and safely disposing of a large amount of waste to extract the mineral. The handling of overburden is proportional to the scale of production and is related to the stripping ratio, i.e. volume of waste generated per unit tonne of ore extracted. In 2020, 1925 million m^3 of overburden was removed[1]. Heavy earthmoving machinery is employed to meet these high output goals. High-intensity ground vibrations are produced due to bulk charging and heavy blasting of explosives in large-diameter blast holes. High-intensity blast vibrations significantly impact these massive spoil dumps as they destabilize the dump slopes. These blast vibrations increase the shear stress due to blast-induced seismic load and peak ground acceleration (PGA). PGA is the maximum ground acceleration during the induced seismic activity of blasting. Over time, the base of spoil dumps also deteriorates with the permeation of rainwater and the huge body weight of spoil dumps. This creates a slushy and weak layer beneath the dump slope, rendering it liable to failure[4].

The dump slopes, in general, are of enormous heights with steep slopes and they are exposed to heavy blast vibrations, as well as the self-acting load of the dump and water permeation, making them vulnerable to collapse. It has also been observed that top layers of soil are dumped in the vicinity as it is economical to do so. However, these topsoil layers are not competent to bear the load of the gigantic spoil dumps in the long run. There have been several incidents of dump failure in the past, resulting in injuries, fatalities and loss of property. Most of these incidents had some precursor signs before failure. So far, 23 incidents of slope failure have resulted in 143 fatalities[5].

The generation of colossal overburden dumps has posed a significant threat, increasing the danger of dump failure. Hence, it becomes vital to quantify the effects of blasting-induced seismicity and the impact of interface strength to ensure the stability of these dumps. The outcome would help design steeper dump slopes to accommodate more volume of dump material in a smaller area.

Here, a parametric study has been carried out to assess the influence of interface strength and blasting-induced seismic loading on the stability of dump slopes. The shear strength of the interface has varied in terms of its cohesion and friction for the height of dump slopes varying from 60 to 120 m. The cohesion of the interface has varied from 10 to 30 kPa, while the internal frictional angle from 20° to 29°. Similarly, blasting-induced seismic loads are applied along the x- and the y-directions. Seismic loads of 0.08 and 0.351 g have been applied along the x- and the y-direction respectively. The overall dump stability has been evaluated in terms of its factor of safety (FoS) and maximum displacement.

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Factors influencing slope stability

The geometry of the slope comprises the overall slope angle and dump height. It is also evident that considerable dump heights and steeper slopes render the dump slope unstable[4]. According to Regulation 108 of the Coal Mines Regulations, 2017 (ref. 6), the natural angle of repose of the spoil dump material dictates the overall slope angle. Preferably, it should not exceed 37.5° and no deck of the dump slope should exceed 30 m in height.

The shear strength of the spoil dump depends on the cohesion and friction angle of the dump material. Cohesion is the intermolecular attraction between particles holding them together. In contrast, the angle of internal friction measures the capacity to resist shear stress. The friction angle is measured between the normal force and the resulting force when the failure occurs only in response to shear stress. If the shear strength of the dump material is high, the slope of the spoil dump is competent and more stable[3,7,8]. The degree of compaction is entirely dependent upon the dumping method. Dragline dumping results in better compaction as the material is released from a fixed height uniformly, unlike non-uniform dumping in shovel and dumper combination. It affects the degree of compaction, with poor compaction leading to the instability of dump slopes[9].

Hydrological conditions are one of the most significant factors influencing dump stability, which are often overlooked. Overburden comprises broken/blasted rock fragments highly porous in nature because of the dumping methods. These porous rock fragments allow water to quickly percolate through the spoil dump to its bottom layers, potentially resulting in water collection if suitable drainage pathways are not established. Water accumulation in dumps can be hazardous, resulting in colossal dump slope failure, one of the causes of the Jayant Opencast Mine in Singarauli Coalfield spoil dump failure. Hydrostatic pressure is created due to the weight of water, and it increases the effective overall stress acting on the dump slope. Porosity and permeability are two distinct but critical aspects of the hydrology of a dump slope. There are unconnected pore spaces in the dump slopes it is porous and non-permeable. When the pore spaces are connected, the dump slope is porous and permeable. As there is water in the gap between the spoil dump materials, pore pressure is formed, which might take suction pressure or drive the overburden particles to move away from each other. Also, oversaturation of the dump leads to a decline in the cohesion of the dump material. This results in decreased shear strength of the dump material and renders the dump liable to failure.

The moisture content of the dump material plays a vital role in dump slope stability. An increase in moisture increases the weight of the spoil dump material, thus increasing the overall shear stress acting on the dump slope and making it susceptible to failure[9]. The impact of rainfall is another crucial aspect influencing dump stability. Rainwater can either percolate the dump material or run-off the dump slope surface depending upon its porosity and permeability. These erosions can block the drains of the dump slope, and the percolation of rainwater can create a weak slushy base, thus destabilizing the dump. To mitigate this, vegetation on dump slopes seems to have better stabilizing rates as the roots bind the loose dump material together[9].

Most of these factors are conventionally studied for their influence on slope stability. However, factors such as the influence of interface and induced seismicity blasting are seldom studied. Nevertheless, the present dump slopes have enormous heights and steep slope angles, making the slopes more vulnerable. Moreover, this augments the need to study the influence of interface and induced seismicity for a safe and stable design.

Interface

The existence of an interface has caused the failure of several dump structures in the past. The interface assumes a separation plane based on its physical and mechanical properties. Its geotechnical properties differ from the surrounding material. Numerous factors such as seismic load, groundwater or rainfall infiltration, susceptibility to moisture, external disturbances or ground conditions result in deterioration of geotechnical properties and formation of the interface. Such occurrences lead to the sliding of dump material along the slip face, making the slope structure unstable. A non-consolidated floor also forms a sliding surface between the waste dump and its foundation[10]. A saturated or near-saturated sand–gravel layer of silt and clay between the dump and the floor or within the dump causes a weak layer[7]. Moisture softens the dump material, creating an interface between the template and the floor layer. Even deformation due to the presence of water can lead to the formation of sliding/weakening planes due to the mobilization of residual forces[8,11]. In this study, the interface is considered as the plane between the foundation of a dump structure and its floor. Weak interfaces can cause the massive failure of the dump structure. The shear strength of the interface is controlled by friction and cohesion parameters[12].

Effect of seismicity

Seismic loading on dump slopes is mainly due to the heavy blasting in open-cast mines[4]. The most significant risk to dump stability during seismic activity is the liquefaction of the foundation, which leads to unavoidable progressive destruction. The intensity of the shock wave dictates its impact on the failure of the slope surfaces of the spoil dump. Seismic waves generated during blasting cause ground vibrations to propagate different waves from one point to another[13]. Although several models are available for analysing the dynamic behaviour of dump slopes, the exact effect on their stability is still controversial, mainly due to the unpredictable energy transfer from the ground to the spoil dump and its consequences[14]. Depending on the principal direction of energy dissipation, propagation of such waves produces seismic loading having different end effects on nearby structures[10]. The dynamic stability analysis for the Malugou dump under the influence of production blasting in Jinduicheng molybdenum mine, China showed that the safety factor of the dump decreased linearly with an increase in acceleration due to ground vibration[15]. Heterogeneous soil rock slopes are more liable to failure compared to homogeneous soil slopes[7,16]. Slope structures with static FoS < 1.1 can face a significant risk of instability due to any seismic activity[17]. Less than 20 mm of maximum displacement may cause a lower risk, while greater than 100 mm may trigger a higher risk of failure.

Methodology

Numerical simulation of dump slopes was performed to understand the impact of interface and induced seismicity on dump slope stability under various conditions of interface strength and seismic load. The numerical model considered deck width and height of 30 m each. The slope angle of each tier was 38°, while the total dump height varied from 60 to 120 m forming 2–4-tiers of equal height. Table 1 shows data for the dump and foundation material.

The benchmark model considered dump slope without any interface and dynamic loading. Its results were compared with the models having an interface of varied strengths based on their friction angle and cohesive strength. Similarly, different values of PGA were considered to evaluate the influence of seismic load on the dump slopes of different heights. Table 2 shows the interface strength properties used in the present study[18,19].

As the blasting phenomenon is restricted to a very small duration, the dynamic analysis was conducted using the pseudo-static approach. It considered two levels of seismic loads triggered in the *X*- and *Y*-directions based on PGA that may develop in different directions during blasting (Table 3), as acquired from experimental mine blasts.

Table 1. Properties of dump and foundation material

Property	Dump	Foundation
Density (kg/m^3)	1800	2200
Cohesion (kPa)	50	2130
Friction angle (°)	28	40
Shear modulus (GPa)	0.14	2.23
Bulk modulus (GPa)	0.42	5.38
Dilation (°)	0	5
Tension (MPa)	0	0.38

Table 2. Strength properties of the foundation–dump interface[18,19]

Interface strength	Cohesion (kPa)	Friction angle (ϕ, °)
Low	10	29
Moderate	20	25
High	30	20

Table 3. Seismic load (*g*) on the dump slopes

Along *X*-axis	Along *Y*-axis
0.08	0.08
0.351	0.351

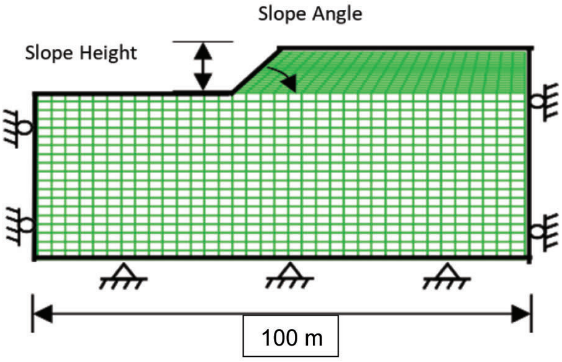

Figure 1. Boundary conditions for static analysis[12].

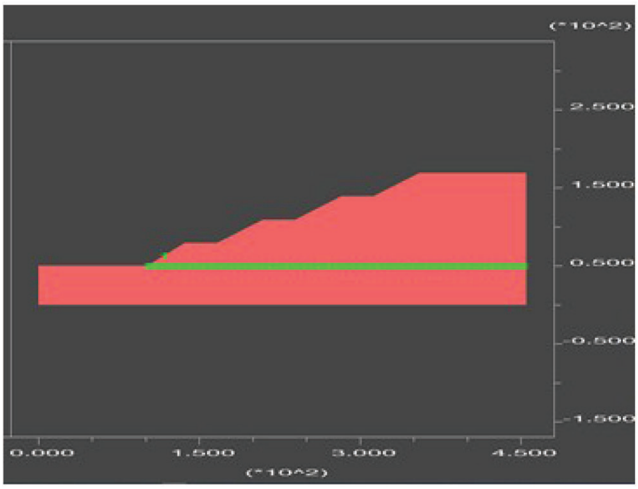

Figure 2. The 120 m dump model with interface between the foundation and dump slope.

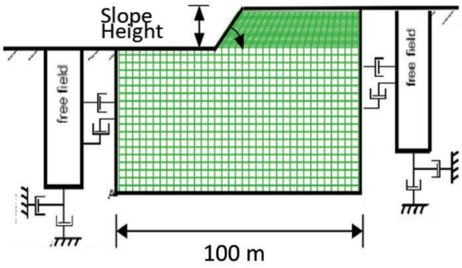

Figure 3. Boundary conditions for the dynamic slope model[12].

Table 4. Factor of safety (FoS) and displacement for 60–120 m dump slope for different cohesion values and friction angles

Dump height (m)	60			90			120		
	FoS for different friction angles								
Friction angle (°) Cohesion (kPa)	20	25	29	20	25	29	20	25	29
10	1.64	1.65	1.69	1.56	1.59	1.61	1.54	1.56	1.57
20	1.65	1.69	1.69	1.59	1.61	1.61	1.56	1.57	1.57
30	1.69	1.69	1.69	1.61	1.61	1.61	1.57	1.57	1.57
	Displacement for different friction angles (mm)								
Friction angle (°) Cohesion (kPa)	20	25	29	20	25	29	20	25	29
10	15.54	10.53	4.46	20.97	13.54	7.65	22.81	14.62	8.6
20	10.27	5.69	3.38	15.34	7.99	6.01	16.77	9.08	6.98
30	6.39	3.50	2.92	10.41	6.46	5.68	11.55	8.74	8.75

Model formulation

The formulation of the numerical model involved defining the model geometry according to its deck height, width, slope angle and total dump height. Suitable material properties were assigned in terms of cohesion, friction and density for floor and dump material. Boundary conditions were applied to the model after allocating the material properties to the dump slope and its floor. The boundary conditions included a rigid boundary along the bottom of the foundation. A roller boundary was applied along the side boundaries, allowing displacement only along the vertical axis (Figure 1). Figure 2 shows the dump model of 120 m in height with an interface between the foundation and dump slope.

For pseudostatic analysis, the boundary conditions included free field conditions (Figures 3 and 4). Such treatment of boundary conditions represents a region of material subjected to external dynamic loading at the model boundary. Wave reflections at model boundaries may be reduced by specifying viscous or free-field boundary conditions. In this way, plane waves propagating upwards suffer no distortion at the boundary because the free-field grid supplies conditions identical to an infinite model[12]. Constant PGA was applied in the horizontal and vertical directions to simulate the effects of seismic activity at the model boundary. The final step involved the evaluation of FoS using the strength reduction method.

Strength reduction technique

The strength reduction technique was used to calculate FoS by gradually decreasing the shear strength of the dump material to attain the state of limiting equilibrium when the shear stress was the same as the shear strength. In this condition, the slope is on the verge of moving as it can undergo failure at any moment. The Mohr–Coulomb failure criterion was used with the strength reduction technique. The FoS F is defined as follows

$$c^{\text{trial}} = \frac{c}{F^{\text{trial}}}, \tag{1}$$

$$\phi^{\text{trial}} = \left[\tan^{-1} \left\{ \left(\frac{1}{F^{\text{trial}}} \right) \tan \phi \right\} \right]. \tag{2}$$

Several iterations with trial values of F were made either by gradually decreasing the cohesion c and friction angle ϕ, unless slope failure occurred. In case the slope was initially unstable, c and ϕ were incrementally increased unless the limiting condition was attained[12].

Results

The influence of interface strength on the stability of the dump was evaluated by changing the shear strength properties of the interface through variable friction angle and cohesive strength and correlating it with the resultant FoS and the maximum displacement. Three categories of interface shear strength were considered by changing the angle of internal friction from 20° to 29° and cohesive strength from 10 to 30 kPa (ref. 19). The influence of interface strength on the stability of 60–120 m high dump was evaluated in terms of FoS and peak displacement (Table 4). The variation in FoS and peak displacement is plotted in Figure 5 *a–c* for dump height of 60–120 m. The results show that the weak interface produced the lowest FoS of the dump slope, which also reduced further with increasing dump height, as expected. However, the effect was more pronounced in terms of the maximum displacement.

The results indicate that the FoS of the dump slope had a marginal increase of 0.61% to 2.42%, while the peak displacement decreased by 57.64% to 12% with respect to

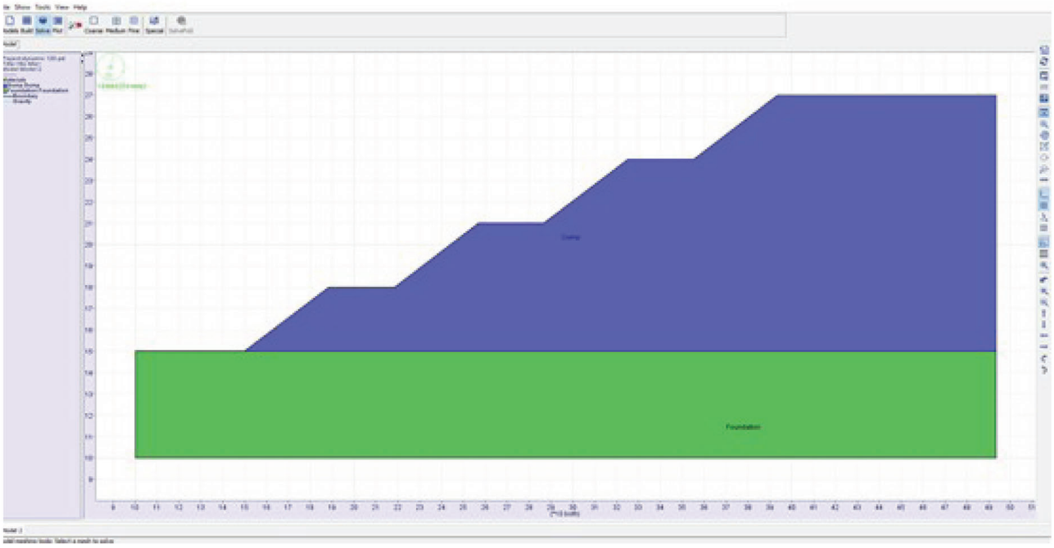

Figure 4. Dump model subjected to seismic loading along the *X*- and *Y*-axes.

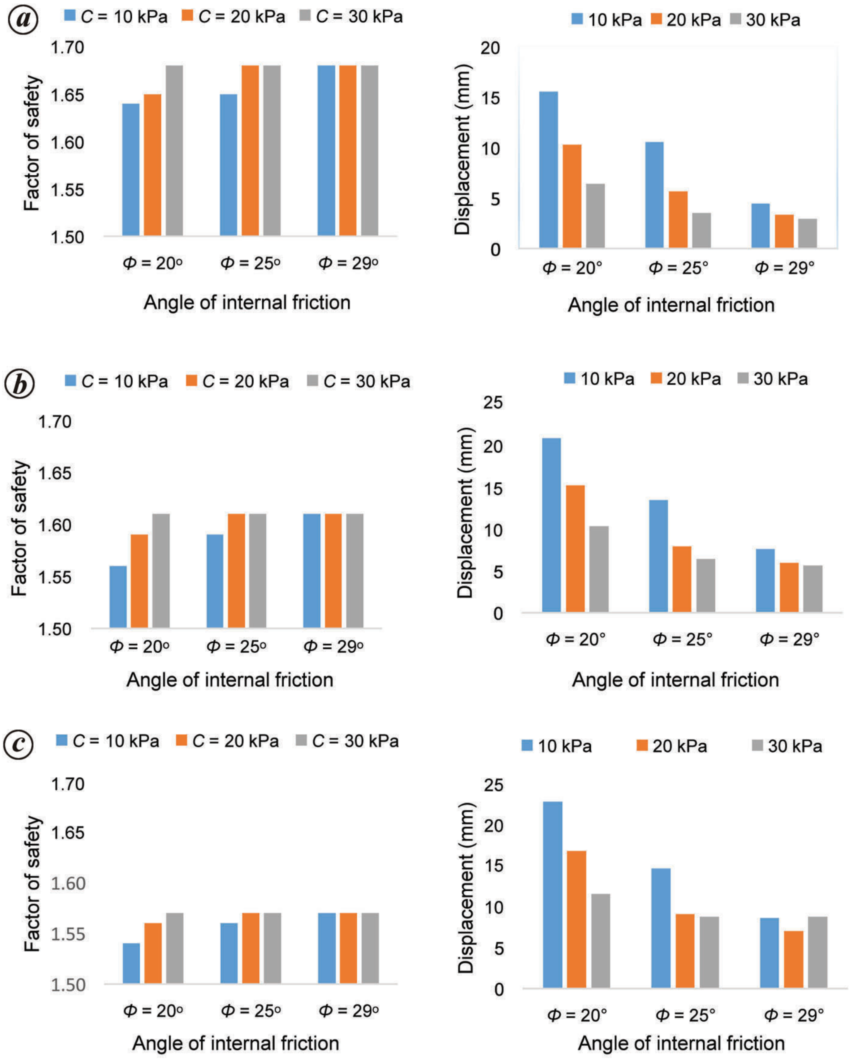

Figure 5. Bar chart of factor of safety (FoS) and maximum displacement for varying shear strengths of interface in dumps of 60–120 m.

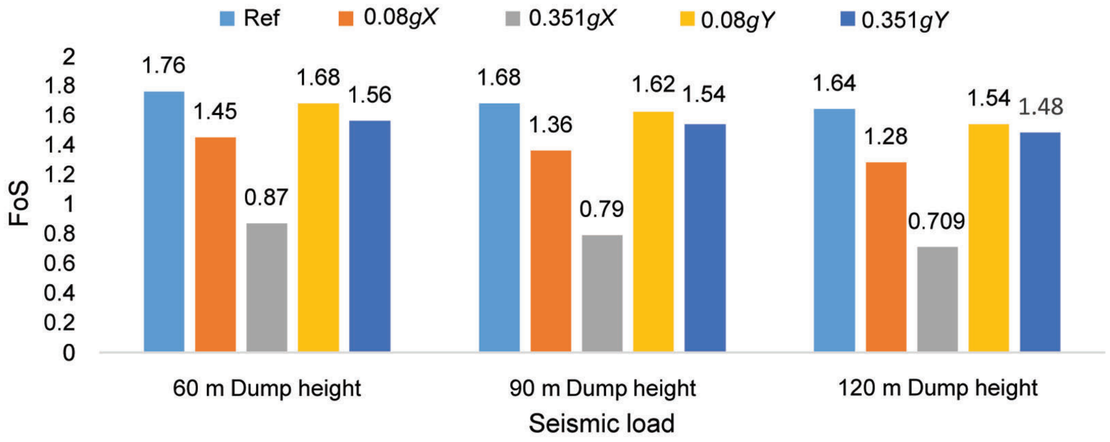

Figure 6. FoS of different dump slopes under seismic loading of 0.08–0.35 *g*.

their benchmark values depending on the interface shear strength. Interface of low shear strength caused higher displacement having the potential to create an instability-prone condition in spite of the overall FoS being higher than the acceptable limit for the safe performance of such structures. The results also confirmed that for high friction angle, the effect of the change in cohesion on the stability of the dump was insignificant in terms of FoS and displacement.

Figure 6 shows FoS of 60–120 m high overburden dumps under seismic loading of 0.08–0.351 *g* in the horizontal (*X*) and vertical (*Y*) directions. The benchmark FoS of the dump slope without a seismic load in each condition is also given. The reference FoS was 1.78 for 60 m dump, 1.68 for 90 m dump and 1.64 for 120 m dump. Under the influence of a seismic load of 0.08 *g* along the *X*-axis, FoS reduced to 1.45 for 60 m dump, 1.36 for 90 m dump and 1.28 for 120 m dump, with the percentage reduction varying from 17.8 to 21.8. The most significant decrease in FoS was observed when the slope structures were subjected to PGA of 0.351 *g* along the *X*-axis. The percentage reduction in FoS varied from 50.8 to 56.7 for the dump of 60–120 m in height.

The decrease in FoS due to seismic loading in the *Y*-direction was significantly smaller than that observed in the *X*-direction. For PGA of 0.08 *g*, the reduction in FoS was 3.5–6.1% only for dumps of 60–120 m in height. For a higher PGA of 0.351 *g*, FoS decreased in the range 9.7–11.3%.

Conclusion

The stability of dump slopes under variable interface strength and blasting-induced seismic loading for dump height of 60–120 m was evaluated. FoS of the dump slope showed only a marginal improvement of 0.61% to 2.42%, while the peak displacement decreased from 57.64% to 12% compared to their benchmark values based on the shear strength of the interface.

The present study reveals that for a low friction angle of the interface, an increase in cohesion improves the dump slope stability. However, such an increase in FoS of the dump is not significant if the interface already has a high angle of friction. The slopes of different heights attain a limiting value of FoS at high friction angle, which does not improve further with increased cohesion. This study also reveals that the impact of shear strength on the maximum displacement is significantly higher than that of FoS.

The reduction percentage of FoS ranged from 50.8 to 56.7 for spoil dumps of 60–120 m height when subjected to PGA of 0.351 *g* along the *X*-axis. In contrast, similar loading along the *Y*-direction showed only a marginal percentage decrease in FoS ranging from 9.7 to 11.3. The lower PGA of 0.08 *g* along the *X*-direction resulted in a 17.8–21.9% reduction in FoS for dumps of 60–120 m in height. Similar loading initialized in the *Y*-direction yielded a 3.5–6.1% reduction in FoS.

The higher values of PGA imposed in the *X*-direction were more damaging to the structural stability of the dump as compared to the load imposed in the *Y*-direction. An increase in PGA showed a significant decrease in FoS of dump slopes with enormous height. This work will be helpful in the improved design of dump slopes for their long-term stability.

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Received 23 April 2022; revised accepted 22 July 2022

doi: 10.18520/cs/v123/i6/797-803