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Optimisation of internal dump capacity and stability analysis in a coal mine — a case study

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Abstract

In India, accelerated demand of coal resulted in rapid development of open pit mines. This has resulted into adoption of stripping ratios ranging between 1:15 to 1:25 and mine depths of open pit mines greater than 300 m, from topographic surface, being reached. All this requires removal of huge quantities of overburden material needing to be accommodated in properly planned and designed containment systems within the worked out part of the mine. In any open pit mining venture, transportation cost is approximately 40% of the mineral mining cost. In-pit dumping of overburden material is always preferred to minimise the cost of transportation. However, destabilisation of internal dumps, as seen in the recent past, hampers the smooth functioning of mining operations and severely affects economics. To ensure long-term stability, vis-à-vis enhanced capacity of internal dumps, scientific understanding and practical know-how is necessary.

In this study, detailed stability analysis of internal dumps was done at one of the coal mines of Western Coalfields Limited, India. Pertinent physico-mechanical properties of the dump material were determined and used as inputs for numerical simulation. Four different methods were used in simulating and analysing the existing and optimised dump slopes. Stability analysis of dump slopes was carried out for monsoon season of the year, when dump material possesses least shear strength. Factor of Safety determined by different analytical techniques is presented. Also, distribution of stresses, strains, plastic points, tensile zones along with various failure surfaces were determined. Based on the results of numerical modelling, an increase of nearly 22% of the existing dump capacity is recommended, whilst maintaining a safe range of Factor of Safety.

1 Introduction

Increasing demand of coal, by the power sector, has led to an increase in surface mining of coal seams. This has compelled mining companies to adopt higher stripping ratios of up to 1:15 to 1:25, while working depths could be greater than 300 m. As a result, huge quantities of overburden materials are removed during coal mining, which needs to be handled and stored efficiently and safely. This overburden material is partly stored in internal dumps, while the remainder is stored in external dumps. Efficiently enhancing the capacity of internal dumps would result into lesser surface land requirements and substantially reducing transportation cost.

Accident statistics in open pit mines revealed that dump failures are indicating an upward growing trend in recent times. Some of the recent fatal and dangerous occurrences in open pit coal mines, involving dump failures, are quite alarming. The analysis indicates that a lack of scientific designs and improper implementation of procedures has caused dump failures (DGMS 2010). The majority of these accidents resulted from failures of internal dumps.

Hence, stability and capacity optimisation of internal dumps need to be addressed simultaneously. Dump stability has close links to safety, while optimisation of these slopes is linked to the economics. This paper shall discuss stability analysis, along with dump capacity optimisation for an internal dump of one of the coal mines of Western Coalfields Ltd. (WCL), India. It was observed that chart solutions given by Hoek and Bray (1981) are only good for preliminary investigation. Limit equilibrium method (LEM) mark failure surfaces but show ambiguity in results and hence, should be used as guidelines only. Due to this limitation, dump stability analysis was done further using numerical analysis methods, finite difference analysis and finite element analysis. It is possible to make out locations of local failures and compound failures with numerical methods, which otherwise goes unnoticed (Singh et al. 2013; Vishal et al. 2010a).

Dump slopes and civil embankments have some similarities, both planned for long-term with later having very high Factor of Safety (FS). Therefore, designing dumps on similar lines will not be feasible for mining projects. Economically, stable dump design requires a thorough understanding of parameters affecting its stability.

The dump stability study needs to be focused on three critical factors: geometry, moisture and material strength (Khandelwal & Mozumdar 1987; Singh et al. 2008; Singh 2011). Water content in a dump is one of the most important factors affecting its stability severely, it brings changes in material properties and reduces angle of internal friction. Material strength involves type of dump material depending on clay content, spoil placement method, zonation, grain size, compaction, Atterberg limits, dynamic forces generated by seismic activity or blasting etc.

2 Stability analysis methods

For any open pit mining activity, stability of slopes forms an important part of the study, both for working slopes and for dump slopes. Kinematic analysis, slope mass rating, analytical as well as numerical methods, may be adopted for detailed studies (Singh et al. 2012; Umrao et al. 2011). To validate the existing mine slope conditions, and to evaluate the response of slopes in different conditions, numerical solutions can be used. The following analysis techniques were adopted in the study, their limitations have been highlighted.

2.1 Chart solution

The use of slope stability charts is for preliminary analysis. Chart solutions provide approximate FS and also rapid checks on the results of analysis. The circular failure charts were prepared by running a search routine to find the most critical combination of slide surface and tension crack for each, in a wide range of slope geometries, ground water conditions considering slope material to be homogenous. Provisions were made for the tension crack location, either at the upper surface or in the face of the slope. The chart solutions given by Hoek and Bray (1981) are considered as comprehensive and, hence, preferred in the study, although there are several other chart solutions available in the literature for conducting slope analysis (Janbu 1954, 1968; Spencer 1967; Taylor 1937).

2.2 Limit equilibrium method

The conventional stability analysis of dump slopes is based on the LEM. It is postulated that the slope might fail as a mass of soil sliding over a failure surface. At the instance of failure, the shear strength is fully mobilised all along the failure surface and overall slope, and each part of it are assumed to be in static equilibrium (Aruna 2009; Cheng et al. 2007; Ranjan & Singh 2004; Richards et al. 1981; Singh et al. 2013; Ulusay & Aksoy 1994). There are a number of methods proposed, by various researchers, to calculate FS and failure surface using the LEM approach. The mostly practiced and popular LEM methods are ordinary method of slices (Fellenius 1936), simplified Bishop method (Bishop 1955) and Janbu corrected method (Janbu 1957, 1973).

2.3 Finite difference method

Finite difference method (FDM) is being used widely, for analysis of slope by various researchers (Rassam & Williams 1999; Singh et al. 2013; Trivedi et al. 2012; Tutluoglu et al. 2011). In this method, problem domain is divided into an assembly of discrete interacting nodes to which governing equations are applied. It includes the following equations the differential equations of equilibrium, the strain-displacement relationship and the stress-strain equations. With this exercise approximate numerical solutions are obtained by the governing equations at an array of points within the problem domain. Hence, this method provides an approximate solution to an exact problem (Brown et al. 1983; Jing 2003).

Fast Lagrangian Analysis of Continua (FLAC) is a two-dimensional FDM code from Itasca (2005), providing the stress-strain response of a continuum material (overburden material) under loading environment (static or dynamic). Failure state of points in the model can be examined based on plasticity, where failure is defined under tension or in shear. Plasticity indicators must be reviewed in the context of overall behaviour before definite conclusions can be drawn (Duncan & Christopher 2001). FS can be computed applying the shear strength reduction technique (Dawson et al. 1999). The strength of material is progressively reduced by the strength reduction factor (SRF) until the solution becomes non-convergent. The maximum value of SRF at which convergence was achieved, is called critical SRF or FS.

2.4 Finite element method

Finite element method (FEM) is a two-dimensional approach, based on plane strain solution. It includes a rock material model, which allows for yielding in shear, via a Drucker-Prager yield criterion and its associated rule. Goodman-type joint element is also available for modelling major rock faults in the slope. The concept of piecewise-continuous functions in a sub-domain has been introduced by Courant (1943). FEM is the most versatile numerical method to solve complex rock mechanics problem. It can handle inhomogeneity and anisotropy, complex boundary and dynamic problems, together with moderate efficiency while dealing with complex constitutive models and fractures (Jing 2003). This method overcomes the various shortcomings of LEMs (Aruna 2009; Kasmer et al. 2006; Rassam & Williams 1999; Richards 1982; Vishal et al. 2010b).

Basically FEM divides the soil continuum into discrete units, so called as, finite elements (Zienkiewicz & Cheung 1967). The elements are interconnected at their nodes and at boundaries of the continuum. In geotechnical applications displacement method of formulation of FEM is typically used and results are obtained in the form of displacements, stresses, and strains at the nodal points. To find out the stability of dump slopes using FEM, the Rocscience software Phase2, two-dimensional finite element program, was used to calculate stresses, displacements and plasticity state within dump mass. The software computes stress, strain, displacement, plasticity, deformed boundaries, deformation vectors and yielded elements (Richards 1982; Richards et al. 1981).

3 Field and laboratory investigations

In a WCL surface mine, located in the Wardha Valley Coalfield, internal dump stability and capacity optimisation studies were performed. The area lies in the Chandrapur district of Maharashtra. The average annual rainfall is about 1,270 mm. The area experiences extreme climate, the maximum temperature during summer is 47°C, while winter reaches 9°C.

The coal bearing Barakar formations do not outcrop in the region due to complete overlapping of Barakars by Kamthis and recent detrital mantle. Like other coal bearing blocks of Wardha Valley Coalfield, only one composite coal seam is seen. The average thickness of the composite coal seam, in the existing open pit mine area, is 22 m of which the top section, about 3 m thick, is banded with shale, carbonaceous shale and streaks of coal. The middle seam is 4.5 to 5 m thick, on an average. The bottom part has an average thickness of about 10 m. The general dip of the coal seam is towards west and the rate of dip is about 1 in 13.

Top capping of soil is mined in the strips of 70 m width and 1,200 m length. Height of the block varies between 3 to 4.5 m. This soil is stacked separately for future use. Once, soil bench has advanced sufficiently then it will be followed by a 24/96 dragline bench, of height 30 m. Still 5 m of overburden thickness is left over the coal, which is mined by a shovel-dumper combination. Now, the coal seam is exposed. The coal seam is mined by a shovel-dumper combination in two number of benches. The area where the coal is mined from is called a void. Overburden removed by a dragline is thrown in the void, also from overburden bench immediately above the coal seam. This forms an internal dump in the mine, the area where from coal has been removed. Ten cuts have been completed and two more cuts are yet to be achieved. Mine is working at a stripping ratio of 1:5.8. Future planning is for a stripping ratio of 1:15. The mine has produced

1.75 Mt of coal and 4.83 mcm of overburden in the financial year 2010–2011. Presently overburden mined out goes completely in refilling.

The internal dump is constructed over a floor, which is inclined at an angle of 7°. It consists of three benches, two bottom benches having a height of 25 and 25 m and a width of 25 m. The height of the top bench is 10 m. The bench slope angle for the benches is 70°. Overall dump slope angle is 40°. The length, width and height of the dump is 250, 120 and 60 m respectively. The geometry and layout of internal dump used in simulation is shown in Figures 1 and 2 respectively. Dump samples were collected from various locations along different sections are marked in Figure 2, namely A-A', B-B', C-C' and D-D'. Following tests were performed to determine unit weight, cohesion, angle of internal friction, Young's modulus and moisture content. The geo-technical properties of the dump material were determined in the laboratory as per the International Society for Rock Mechanics (ISRM) standards (ISRM 1972, 1977, 1981). The results of dump material are presented in Table 1 for monsoon season, when shear strength is least.

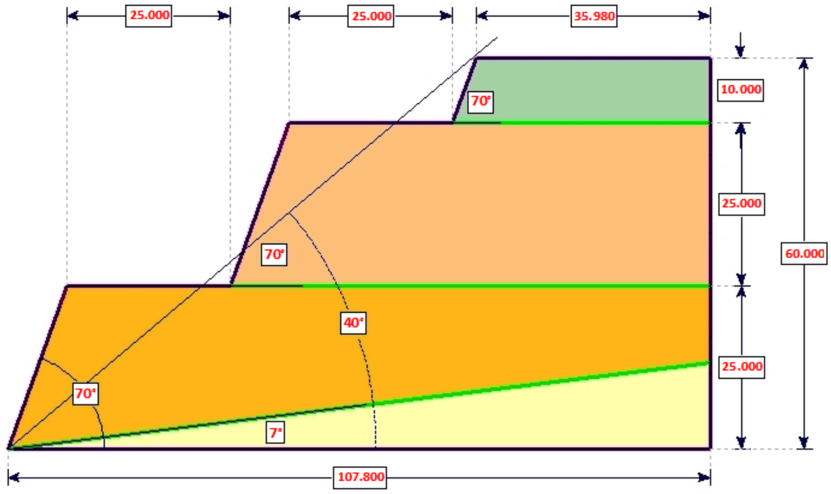


Figure 1 Geometry of existing dump (all distances are in metres)

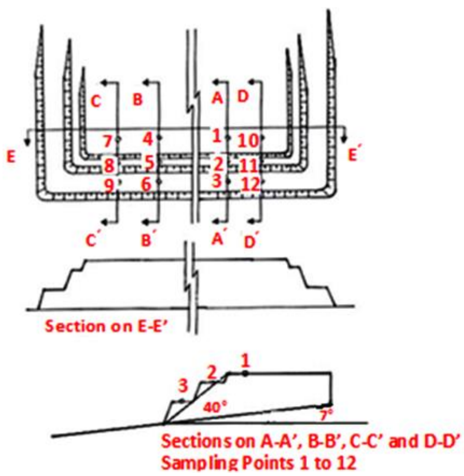


Figure 2 Layout of mine in schematic (not to scale)

Table 1 The average geomechanical strength of the dump material

	Unit weight (kN/m³)	Cohesion (kPa)	Internal friction angle (°)	Young's modulus (MPa)	Poisson's ratio	Moisture (%)
Mean	20.89	113.66	24.66	4.908	0.30	9.20
Standard deviation	0.63	9.54	1.50	0.17	0.01	0.31

4 Slope stability analysis

Numerical methods were also used to conduct slope stability studies in respect to existing dump, as well as, for optimised dump. The summary of findings is shown and discussed in terms of FS, which is considered to be the popular means.

4.1 Stability analysis of existing dump

The dump stability was analysed using methods like chart solution method, LEM, as well as numerical methods. In Table 2, calculated FS for all sections during monsoon season is given. It was found that shear strength of the dump material is least during monsoon so is the FS. A comparison of FS evaluated using four different methods is shown in Table 3. Based on chart solution, LEM, FEM and FDM results of FS, it is found that section A-A’ has the lowest FS for rainy season. Hence, section A-A' was considered as the reference for dump slope optimisation.

Table 2 Factor of Safety values were determined using all methods during monsoon

Section	FS					
	FEM	FDM	OMS	Simplified Bishop method	Janbu’s corrected method	Chart solution
Monsoon						
A-A'	1.430	1.510	1.487	1.520	1.542	0.790
B-B'	1.460	1.530	1.541	1.575	1.601	0.790
C-C'	1.470	1.550	1.598	1.590	1.645	1.235
D-D'	1.450	1.530	1.511	1.546	1.573	0.800

Table 3 A comparison of Factor of Safety values obtained for section C-C′

Method of analysis	FS from different methods	FS from FEM	% change
FDM	1.550	1.470	5.440
OMS	1.598	1.470	8.700
Bishop simplified	1.590	1.470	8.160
Janbu corrected	1.645	1.470	11.900
Chart solution	1.235	1.470	-15.980

4.2 Optimisation of existing dump slope and its stability

Standard procedure was used to find out the optimised dump capacity (Coates & Yu 1977). From stability point, FS equal to 1.30 is considered as safe. Hence, a safe range of FS equal to 1.30 was maintained during optimisation. Optimisation was performed based on section A-A' for which FS was the lowest and equal to 1.43. The volume of dump for slope optimised at different dump heights is shown in Figures 3 and 4 maintaining FS of 1.30. In case, external dumps are designed for FS equal to 1.10 to 1.15, they have moderate risks of instability. It is observed that, external dumps designed for a FS less than 1.10 are subjected to greater risk of failure due to deviation in dump height, material strength and presence of clay. Such conditions may result in fluctuations of FS by ± 10% (Khandelwal & Mozumdar 1987). In India, mine regulations do not specify any FS for internal dumps. As per British Columbia Mine Waste Rock Pile Research Committee (1991), the FS of 1.30 is considered as safe. The details of optimised dump, in respect of capacity and conditions, are given in Table 4. It was found that the optimum capacity of dump is about 6,500 m^3/m length of dump for 90 m dump height with dump slope angle equal to 37°.

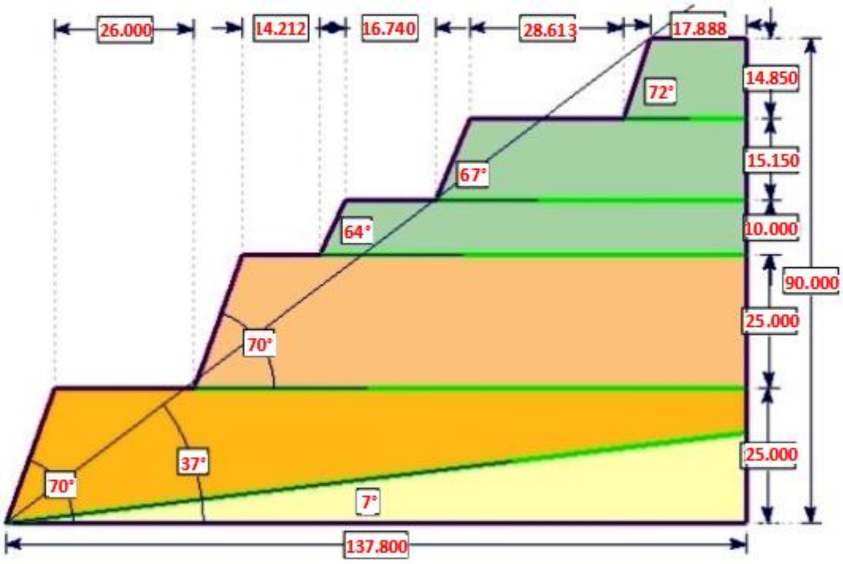


Figure 3 Dimensions of optimised dump slope simulated using FEM (height = 90 m and slope = 37°)

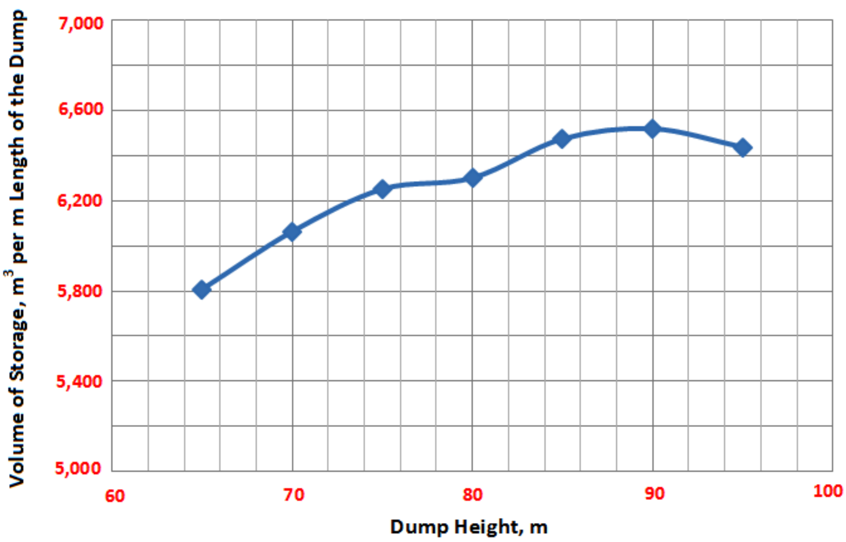


Figure 4 Dump height versus volume of dump, FS = 1.3

Table 4 Details of optimised dump configuration

Existing dump FS	Existing dump height (m)	Optimised dump height (m)	Present capacity, m³ per metre length of existing dump	Optimised capacity, m³ per metre length of optimised dump	Increase in capacity (%)
1.43	60 (dump slope angle 40°)	90 (dump slope angle 37°)	5,300	6,500	22

5 Result and discussion

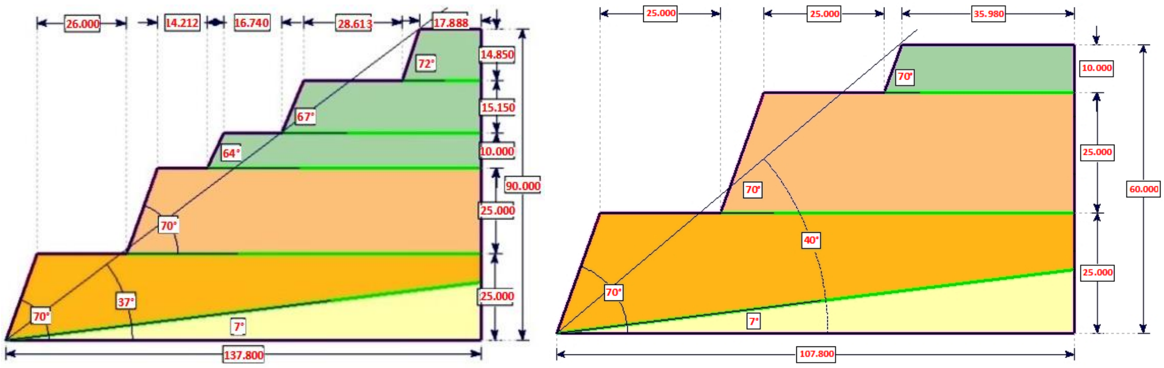
The stability of saturated dump slopes was analysed in terms of stress, strain and displacement changes apart from FS.

5.1 Chart solution

This empirical approach was useful for calculating FS quickly and easily, however, their utilities are limited and have low reliability (Table 2). The comparison of FS, calculated using chart solution, and FEM is presented in Table 3 along with other methods. It was found that chart solution overestimates the FS as much as 16%. It may be due to a high amount of subjectivity associated in locating various points on the chart.

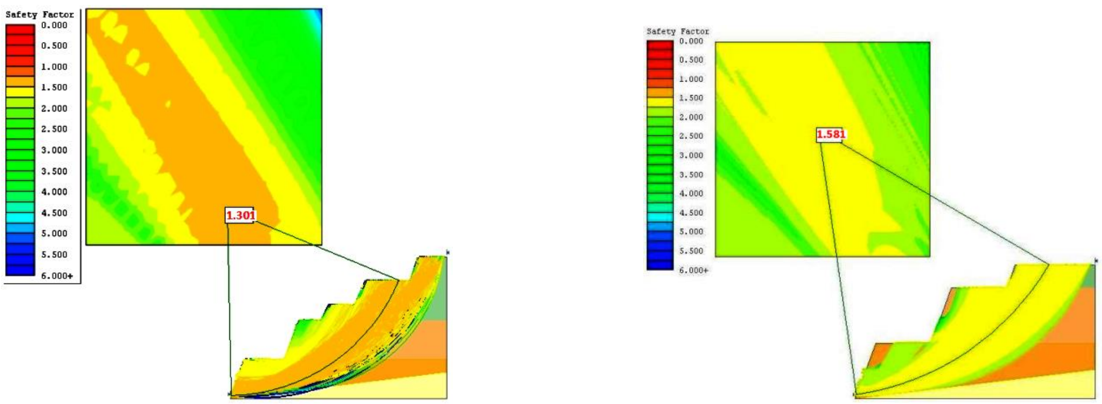
5.2 LEM analysis

Limit equilibrium analysis was conducted using a two-dimensional limit equilibrium slope stability program for evaluating FS of circular failure surfaces. Optimised and existing dump slopes were analysed using Slide software with OMS or the Fellenius method (Fellenius 1936), simplified Bishop method (Bishop 1955) and Janbu's Corrected Method (Janbu 1957, 1973). The FS computed using LEM analysis ranging between 1.487 and 1.645 in the case of existing dump. The FS computed using LEM analysis ranging between 1.301 and 1.371 in the case of optimised dump. FS of existing and optimised dumps with LEM method was found above 1.3. For comparison of optimised dump and existing dump, both have been shown in Figures 5(a) and 5(b). LEM analysis results with OMS, Bishop's Simplified method and Janbu's Corrected method for optimised and existing dumps are shown in Figures 6, 7 and 8 respectively.



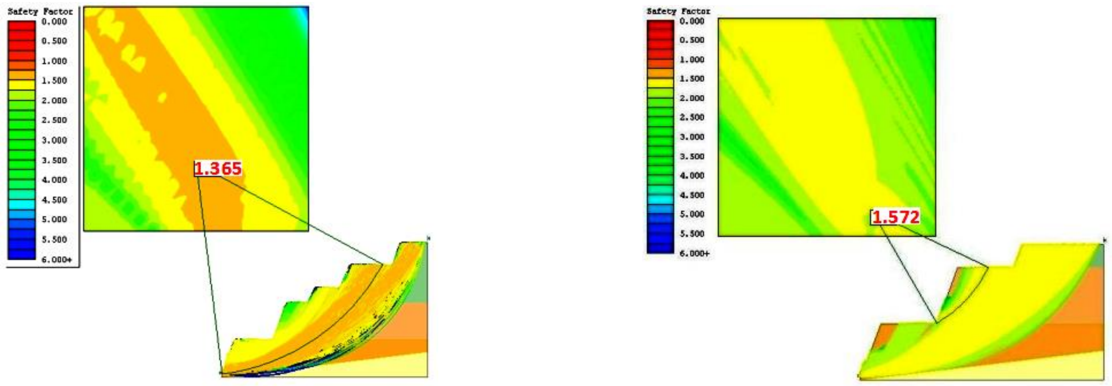
(a) (b)

Figure 5 (a) Optimised dump height = 90 m and slope = 37°; (b) Existing dump height = 60 m and slope = 40°



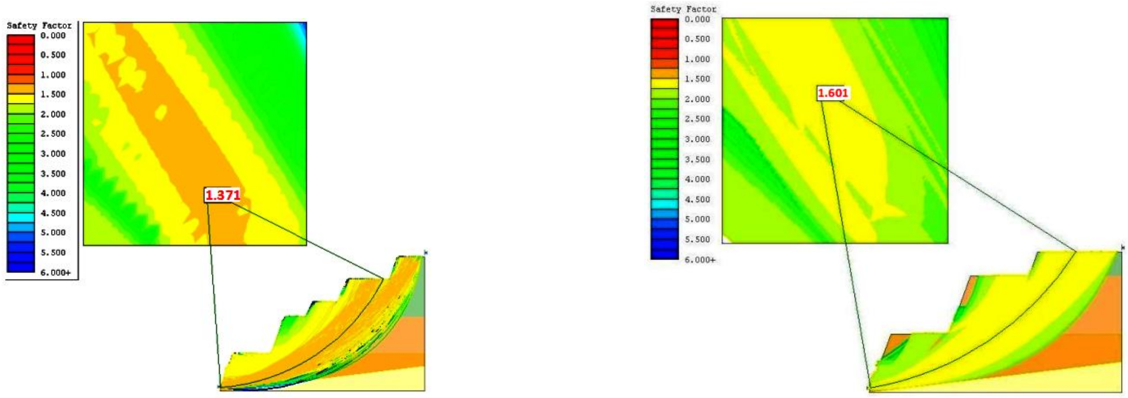
(a) (b)

Figure 6 (a) OMS method for optimised dump FS = 1.301; (b) OMS method for existing dump FS = 1.581



(a) (b)

Figure 7 (a) Bishop simplified method for optimised dump FS = 1.365; (b) Bishop simplified method for existing dump FS = 1.572



(a) (b)

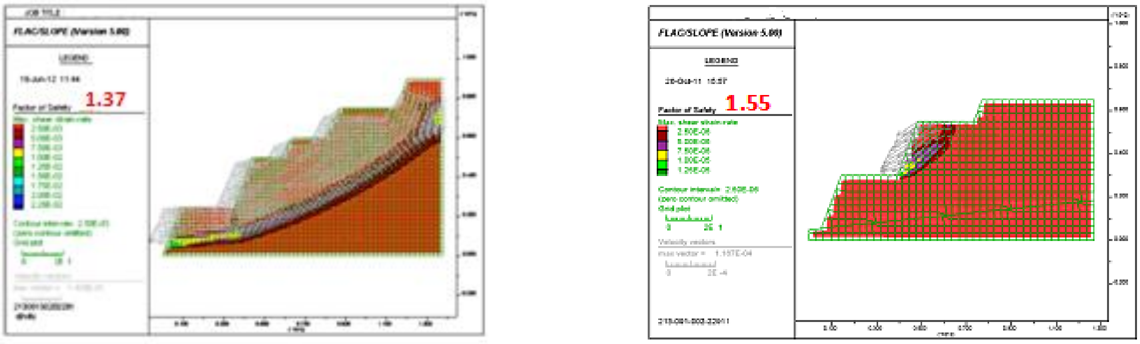
Figure 8 (a) Janbu corrected method for optimised dump FS = 1.371; (b) Janbu corrected method for existing dump FS = 1.601

All LEM methods provide location of optimum slip circle. Based on these results, it is inferred that both existing and optimised dumps are stable, since the computed FS in all cases are higher than 1.3. For optimised dump, LEM methods show failure surface between crest and toe. There is little variation in its FS. In the case of existing dump, failure surface is seen between toe and crest of the dump in OMS and Janbu's Corrected method, whereas, Bishop's Simplified method locates failure surface between toe and crest of middle bench. The FS calculated has marginal variation in all three LEM methods. This has happened because each method is based on certain assumptions (Douglass & Bailey 1981; Jiang & Magnan 1997; Mansour & Kalantari 2011). The results indicate that for crucial study of dump, LEM does not provide enough confidence.

However, the information provided by LEM results does not completely comprehend the stability of waste dump, and at times there is an ambiguity. Griffiths and Lane (1999), and Hammah et al. (2005) cautioned while using LEMs. LEMs give little information about the deformational behaviour of the material. Hence, established numerical methods were chosen for further analysis to understand deformational behaviour of dump under various environments.

5.3 FDM analysis

FLAC Slope software was used for the dump stability analysis to locate the critical slip surface. The FDM provided relatively higher FS (1.55) for existing dump and 1.37 for optimised dump. Duncan and Christopher (2001) suggested norms were used to find out the stability of the dumps (Table 5). Condition of optimised dump and existing dump is shown in Figures 9(a) and 9(b), respectively. In Table 6, the output in terms of displacement and velocity vectors are presented. From the results it is found that the slopes are stable; however, the velocity range exhibits a contradictory inference. Thus, more information is required to make a conclusion. In existing dump, middle bench shows that it is approaching towards destabilisation. In optimised dump, this destabilisation section was vanished due to proper distribution of stresses within the dump mass. In comparison with existing dump, overall stability has improved in case of optimised dump.



(a) (b)

Figure 9 Stability analysis of slopes using FDM: (a) optimised dump FS = 1.37; and, (b) existing dump FS = 1.55

Table 5 Stability status based on norms (Duncan & Christopher 2001)

Parameter	Status of parameter	Status of stability
Displacement and velocity	Increasing displacement and velocity	Unstable state
Displacement and velocity	Steady displacement and decreasing velocity	Stable state
Displacement and velocity	Constant displacement and velocity	Failure
Velocity (ms^{-1})	Below 1e-6	Indicates stability
Velocity (ms^{-1})	Above 1e-5	Indicates instability

Table 6 Shear strain rate velocity vector and FS in optimised and existing dumps

Parameter	Optimised dump		Existing dump		Middle bench (existing dump)	
Shear strain rate (s^{-1})	1.00×10^{-2} At the toe of the dump	5.00×10^{-3} Between toe of the dump and top bench	2.50×10^{-6} At the toe of the dump	2.50×10^{-6} At the toe of middle bench	1.00×10^{-5} In the toe area	5.00×10^{-6} Between toe and crest
Maximum velocity vector (ms^{-1})	1.458×10^{-1}		1.163×10^{-4}		1.156×10^{-4}	
FS	1.37		1.55			

5.4 FEM analysis

A two-dimensional FEM model was used for incorporating Mohr–Coulomb failure criteria for conducting dump stability analysis. The SRF technique was used to calculate stress and displacement (Zienkiewicz & Cheung 1967) in the dumps. The distribution of strain obtained from simulation for both optimised dump and existing dump, is shown in Figures 10(a) and 10(b). Figure 11 indicates SRF and maximum displacement. Tables 7 and 8 illustrates strain, total displacement, horizontal displacement, vertical displacement, major and minor stresses within optimised and existing dumps respectively. In existing dump, shear strain is highest at the toe area and varies between 0.041 at the crest to 0.373at the toe of the dump. In optimised dump, shear strain is highest at the toe area and varies between 0.023 at the crest to 0.500 at the toe of the dump. Strain distribution in optimised dump has increased marginally in the vicinity of the toe in comparison with the existing dump. It shows that the toe of the dump experiences higher strain. Therefore, the toe region, in both cases, is subjected to high stress conditions and further increase of strain may lead to complete yielding of dump and accelerate failure.

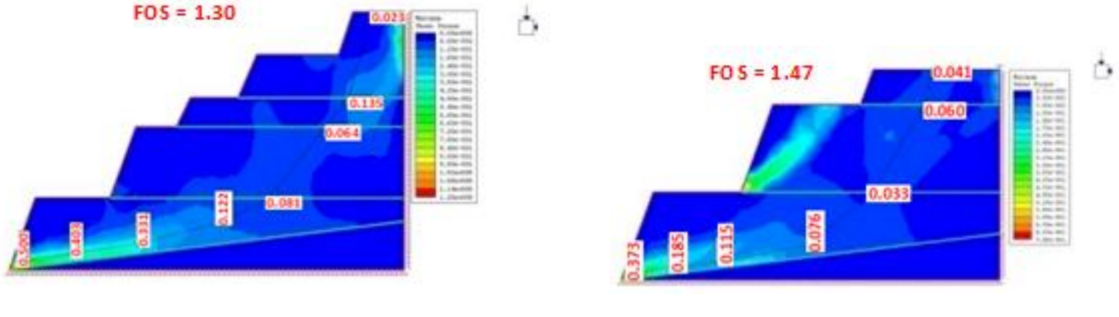


Figure 10 Distribution of strain at different points on: (a) optimised dump; and, (b) existing dump

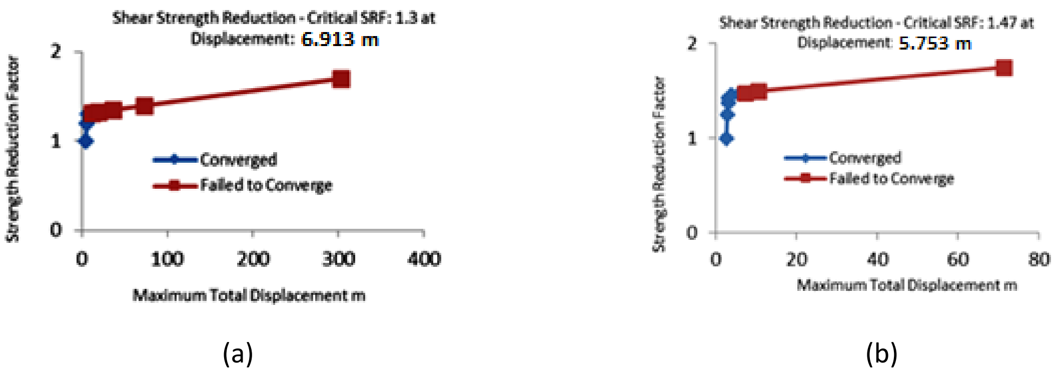


Figure 11 Strength reduction factor at 10 points with maximum total displacement for: (a) optimised dump; and, (b) existing dump

Table 7 Details of FEM analysis (point 1 is toe) optimised dump

Point	Vertical distance (m)	Strain	T (m)	H (m)	V (m)	σ_1 (kPa)	σ_3 (kPa)
1	4	0.500	2.79	2.73	0.634	320.53	47.65
2	6	0.403	1.62	1.62	0.235	669.82	213.34
3	8	0.331	1.25	1.24	0.272	955.10	354.86
4	20	0.122	0.561	0.503	0.250	1,292.80	521.98
5	25	0.081	0.575	0.544	0.185	1,246.85	580.75
6	50	0.064	1.02	1.01	0.354	684.20	224.42
7	60	0.135	1.36	1.23	0.643	506.23	118.95
8	90	0.023	1.53	0.577	1.41	32.42	14.66

T - Total displacement (absolute), H - Horizontal displacement (absolute), V - Vertical Displacement (absolute)

Table 8 Details of FEM analysis (point 1 is toe) existing dump

Point	Vertical distance (m)	Strain	T (m)	H (m)	V (m)	σ_1 (kPa)	σ_3 (kPa)
1	2	0.373	1.24	1.21	0.302	300.67	42.32
2	4	0.185	0.322	0.314	0.085	651.32	215.17
3	5	0.115	0.256	0.255	0.027	752.95	263.92
4	8	0.076	0.129	0.116	0.034	1,049.14	443.35
5	25	0.033	0.185	0.184	0.025	688.54	389.67
6	50	0.060	0.295	0.197	0.215	234.87	20.36
7	60	0.041	0.442	0.348	0.272	18.52	0.99

FEM analysis gives the plot between maximum deformation and SRF. As SRF increases, the strength properties decrease, reaching a maximum displacement of 6.913m, in the case of optimised dump, and 5.753 m, in the case of existing dump. It is a point of non-convergence that defines critical SRF and called FS. In the case of analysis using SRF method, when interpolation functions satisfy the defined mathematical requirements, a finite element solution for a particular problem said to be converges to the exact solution of the problem. This is inferred that, as the number of elements increased and the physical dimensions of the elements are decreased, the finite element solution changes incrementally. The incremental changes keep on decreasing with the process of mesh refinement and eventually lead to the exact solution asymptotically. For slope stability, strength reduction technique is the basis for calculating the FS. For each SRF, the solution does not converge, meaning the solution of governing equations do not approach the exact solution. The highest value of the SRF, for which the solution converges, is termed as critical SRF or FS. It is observed that, negligible changes in the strain of existing and optimised dumps indicating the overall stability of the dump has improved.

The displacements, total, horizontal and vertical, for the optimised and existing dump are shown in Tables 7 and 8 respectively. The displacement is due to loading and settlement of the material. Any displacement beyond the limit indicated in SRF and displacement plot initiates destabilisation of dump. Stress distribution within the optimised and existing dump are also shown in Tables 7 and 8 respectively. There is marginal increase in displacement and stresses, in the case of optimised dump slope, which is not significant, so it is within safe level.

The distribution of strain and stress at 2 m height above the floor for optimised and existing dump is indicated in Tables 9 and 10 respectively. In the case of optimised dump, strain increased marginally in the region, which is closed to the toe. It is high, up to 43 m in existing dump and up to 70 m in optimised dump. Therefore, intensity of strain and its distribution over the floor has increased in the case of optimised dump, as compared to existing dump. This feature point out that the area will expand under possible failure zone.

Table 9 FEM analysis of optimised dump-parallel to floor

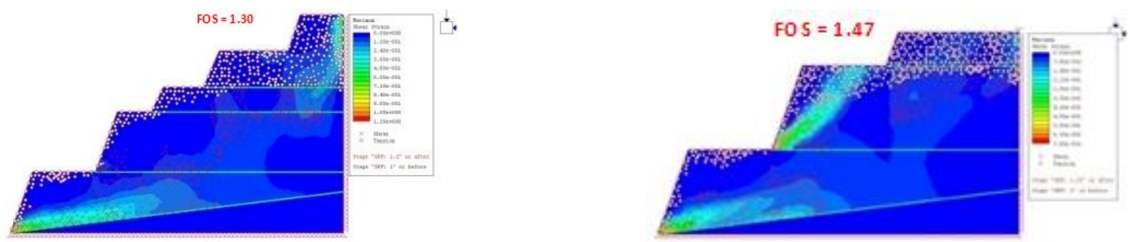
Point	Inclined distance parallel to floor from toe and 2 m above the floor	Strain	σ_1 (kPa)	σ_3 (kPa)
1	2	0.547	334.860	52.080
2	18	0.413	674.390	215.680
3	38	0.354	884.260	319.170
4	58	0.186	1,240.580	497.280
5	70	0.138	1,374.350	562.490
6	100	0.077	1,425.350	814.250
7	138	0.023	1,397.580	1,224.580

Table 10 FEM analysis of existing dump-parallel to floor

Point	Inclined distance parallel to floor from toe and 2 m above the floor	Strain	σ (kPa)	σ_3 (kPa)
1	2	0.384	281.660	36.190
2	12	0.236	586.580	183.570
3	25	0.119	734.170	255.170
4	43	0.107	1,015.830	392.940
5	55	0.075	1,049.640	465.350
6	85	0.032	955.280	707.860
7	108	0.008	849.490	774.420

In optimised dump, major stress increased up to the height of 100 m from the toe and similar pattern is observed for minor stress. The maximum values of major and minor stresses obtained were 1,425.35 and 1,224.58 kPa respectively. In the existing dump, similar trend was observed with the highest values of major and minor stresses equal to 1,049.64 and 774.42 kPa respectively. The area next to the floor of the dump is subjected to high stress level. This may cause failure of dump material in the lower part of the dump, which will lead to reduced material strength in this zone. As a consequence, this part of the dump may yield to initiation of planar failure over the floor of the dump, which is competent.

The plasticity of optimised and existing dump in FEM is shown in Figures 12(a) and 12(b). These results are almost identical for both the dumps. The upper 10 m zone in existing dump and 30 m in optimised dump are completely occupied by tension elements, which may initiate formation of tension cracks and accelerate failure in this zone. Due to high concentration and depth of tension cracks, top portion of both the dumps may follow the circular failure mode. The area in the vicinity of toe of the dumps is occupied by shear elements. The height of this zone is 15 and 25 m in existing and optimised dumps, respectively. In both the dumps, tension zone and shear zone are interconnected. The lateral extension of shear zone over the floor of the dump is 40 and 80 m in case of existing and optimised dumps respectively towards rise side. According to Kasmer et al. (2006), the geometry of floor is critical as it facilitates movement of overburden material towards dip side of the dump floor and this may prove to be one of the important contributors to instability. Dump floor is sufficiently strong to take up the load without any subsidence. In case of destabilisation of dump, movement of dump material will take place over the dump floor. Also, reduction of material shear strength in the zone takes place in the surrounding area of toe as the material is subjected to high level of stresses. This consequently forms a weak zone of crushed material, which is a favourable situation for planar failure to take place. In case of destabilisation of dump, the circular failure will be initiated first from the top, rear end of the dump. As a result, the toe shall undergo translational movement parallel to the base of the dump floor and directed towards dip of the dump floor. This suggests a complex failure consisting of a circular sliding surface passing through the dump material in the upper part of the dump and a planar surface along the interface between overburden material and dump floor. Thus, two different modes of failure may take place in the same dump, called a compound failure.



(a) (b)

Figure 12 Plasticity values and distribution in: (a) optimised dump; and, (b) existing dump

6 Conclusion

The presented study provides useful information about the existing internal dump slope.

- The dump stability is a complex phenomenon and simple analyses techniques always overestimate the FS.
- The numerical simulations using FDM/FEM provide better insight of the dump slope and indicate scope for sufficient space for accommodation of further dump material with greater safety.
- A 22% capacity can be enhanced in the present existing dump without hampering the present mine working schedule.
- FS equal to 1.30 was found optimum for long-term stability of dump, even under saturated condition for internal dumps.
- The analysis using FDM indicates maximum velocity vector of dump material equal to 1.163E-04 and 1.458E-01 ms^{-1} for existing and optimised dump respectively, while a maximum displacement of 6.913m, in the case of optimised dump, and 5.753m, in the case of existing dump, was obtained from the FEM results. Based on displacement stability of the dump can be inferred.
- Stability of dump improves due to appropriate re-distribution of stresses within the dump. It is seen in case of existing dump where middle bench is unstable, the same has vanished in optimised dump.
- It will always be advisable to follow more than one tool or technique to estimate stability of any dump. FS of a critical dump, the lowest value of FS should be chosen for safety, sustainability and variability of the internal dump.

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