Optimisation of Overburden Dump Capacity using Limit Equilibrium and Finite Element Techniques

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***Abstract*— In India, majority of coal demand is met by opencast mining production. The continuously increasing demand of coal has led to rapid opencast mining activities with high stripping ratio of 1:12 to 1:15, in turn requiring large quantities of overburden to be mined and its storage poses serious problem. Recently, few dump failures have taken place. Destabilisation of overburden dump hampers the production of the mine. On the other hand, under utilisation of storage capacity of the dump gives rise to additional land requirement. Therefore, for efficient functioning of dump, it is important to optimally utilise its capacity commensurate with stability. In this study, an internal dump at one of the mines of Coal India Limited has been studied. Two different techniques have been used to simulate and analyse the existing dump for its storage capacity and safety. The dump has been optimised maintaining the stability and safety requirements of the slope, and has been studied for its stability using different methods. A comparison of its factor of safety obtained from each method of analysis has been presented. From the study, an increase in the dump capacity of about 14% has been proposed by the numerical modelling technique, which further encourages possible savings in land. Hence, the paper seeks to optimise the existing dump and provide an economical and safe solution to the issues of land acquirement in India for overburden storage.**

Keywords*— Stability; Safety; Economy; Optimised Dump; Dump Stotage Capacity; Factor Of Safety; Savings In Land

I. INTRODUCTION

India is the fourth largest producer of coal in the world accounting for around 3.9% of total world production of coal. Table I ranks different countries on the basis of their annual coal production. The Indian coal industry aspires to reach the 1.5 billion tonne mark by the year 2020 (ICC, 2006) and in order to meet the increasing power generation needs of the country; there has been an unprecedented increase in the surface coal mining activities. As the production from opencast mines is going up, the coal deposits close to the earth's surface are depleting rapidly, which requires to go deeper for coal mining and to adopt underground mining methods. However, open cast mining is preferred over underground mining due to a number of factors. Open cast mining allows easy access to workers and machinery along with a safer working environment. Upon comparing the results of the statistical analyses of the mining methods given by Hedberg (1981), it can be said that materials and supply costs of underground mining are 50% more than those of opencast mining along with five times higher labour cost. Additionally, capital costs are found to be higher in the former case. Large scale operation in opencast mines implies high production at relatively low cost.

TABLE I. LIST OF COUNTRIES BY COAL PRODUCTION IN 2014, BASED MOSTLY ON THE STATISTICAL REVIEW OF WORLD ENERGY PUBLISHED IN 2015 BY BRITISH PETROLEUM, RANKING COUNTRIES WITH COAL PRODUCTION LARGER THAN 10 MILLION TONNES

Rank	Country/Region	Coal production (Million Tonnes)	Share of total (%)
1	Unites States	3,874.0	46.9
2	China	906.9	12.9
3	Australia	644.0	6.2
4	India	537.6	3.9
	European Union	491.5	7.1
5	Indonesia	458.0	7.2
6	Russia	357.6	4.3
7	South Africa	260.5	3.8
8	Germany	185.8	1.1
9	Poland	137.1	1.4
10	Kazakhstan	108.7	1.4
TOTAL	WORLD	8,164.9	100.0

In order to meet the coal requirement, the mining projects have been compelled to adopt stripping ratios as high as 1:15 to 1:20 and to go as deep as 300m (DGMS, 2010). This translates into the problems of overburden dumps and accommodation thereof has posed another challenge that needs attention. Mined out overburden is dumped either within the worked out part of the pit or outside the pit limits. If the dump is constructed within the worked out part of the pit, then it is called as internal dump. In case, the dump is constructed outside the pit limits, it is called as external dump. External dumping requires additional land away from the mining site. However, acquiring even a small piece of land is a complicated and time consuming affair. Besides this, very high transportation cost and material handling cost involved in external dumping which will increase the cost of coal production substantially, stability and reclamation at the site pose serious problems (Singh et al., 2011).

British Columbia Mine Waste Rock Pile Research Committee (1991) has discussed various stability aspects in its Investigation and Design Manual for Mined Rock and Overburden Piles. Potential environmental impacts many times control dump design. Requirements of sedimentation facilities in case of external dumps tend to favour one site over the other. During rains, the sediments at the bottom of external dump tend to get washed away to nearby fields and their deposit threatens field's yield capacity. Besides this, stability considerations may also depend on period of exposure of the dump (i.e. short term (during construction) vs. long term (abandonment)). Issues such as environmental protection, resource conservation, native land claims, aesthetics and archaeological significance and competing land uses are given more attention in public and political arenas.

It is not possible to exclusively practise internal dumping. As spoil dumps get higher, where overburden is stored in-pit, probability of slope failure becomes disproportionately greater (Bradfield et al., 2013). A number of cases of dump failure and slides have been reported which have caused casualties, damage to machinery and interrupted the production. Table II and III mention some of the major dump failure accidents that have taken place in India and rest of the world respectively. The Northern Coalfields Limited (NCL, 2006) has reported that their mine accidents of 10/02/97, 28/05/97 and 12/01/2000 were a result of high dump slope heights of 83.7, 82.5 and 88m respectively and very high slope angle.

TABLE II. LIST OF SLOPE FAILURES IN INDIAN MINES

Sr. No.	Date	Location	Type/Cause	Loss	Reference(s)
1	June 20, 2000	Kawadi Opencast mine, M/s WCL	31 m overburden dump slope failure	10 persons died	DGMS, 2010
2	December 09, 2006	Tollem Iron Ore Mine, Goa	30 to 46 m high dump failure	6 persons died	
3	December 17, 2008	Jayant Opencast Project, M/s NCL	Portion of dragline dump (135 m long,70 m high along slope side, 6 to 19 m high across slope) failed suddenly	Killed 5 persons, buried a shovel	
4	June 04, 2009	Sasti Opencast Coal Mine, M/s WCL	Failure of 73 m high dragline overburden dump	2 persons died, 2 excavators buried	
5	February 25, 2010	Hamsa Minerals and Export Granite Mine	Mass of granite stone (30 m long, 35 to 45 m high, 10 m thick) fell on pit floor	Buried 18 persons, fatally injured 14	

TABLE III. LIST OF SLOPE FAILURES IN MINES ACROSS THE WORLD

Sr. No.	Date	Location	Type/Cause	Loss	Reference(s)
1	2007	Crandall Canyon Mine, Utah, U.S.		Killed 9 miners and buried 6	*https://en.wikipedia.org/wiki/Mining_accident*
2	April 2010	Upper Branch Mine, West Virginia, U.S.		Killed 29 miners	
3	April 17, 2007	Tri-Star Mining, Inc., Barton, Allegany County, Maryland	Massive highwall collapse	Buried 2 miners under 93,000 tons of rock	Hem and Caldwell, *2013*
4	November 13, 2002	Master Aggregates Toa Baja Corp., Cantera Isabela, Puerto Rico	Collapse of portion of highwall onto bulldozer operator	Death of operator	Hem and Caldwell, *2013*

Evaluation of recent accidents, majority of these resulted from internal dumps, has revealed that lack of scientific designs and inefficient implementation of procedures have caused these accidents (DGMS, 2010). Parameters of resource recovery, mining cost, safety and environment are influenced by overburden dump instability. With growing emphasis on open cast mining, the problems have aggravated (Chaulya, 1995). Hence, it is imperative to address dump stability simultaneously with capacity optimisation of internal dumps. This shall significantly reduce the surface land requirement and provide a safe working environment.

In this paper, analysis has been performed on one of the internal dumps of Western Coalfields Limited. Methods of limit equilibrium and finite element code have been used for the analysis. The paper shall discuss stability parameters of the optimised dump laid down by different techniques. Limit equilibrium method describes failure surfaces and gives factor of safety. But the results shall be used only as guidelines due to the ambiguity in their results and further analysis must be conducted using numerical modelling techniques. Strength reduction was carried out by finite element method (Dawson et al., 1990; Griffith and Lane, 1999; Hammah et al., 2004) until the solution becomes non-convergent and the factor of safety so obtained is called critical factor of safety (FS) or Strength Reduction Factor (SRF).

II. FACTORS AFFECTING SLOPE STABILITY

In spoil dumps, the slope dimensions are substantially greater than the dimensions of spoil/rock fragments, which is a favourable condition for a circular failure to occur. The shape of the circular failure is influenced by geological conditions in the slope mass. Slopes composed of soft, weak, loose and closely fractured rock have three basic failure geometries viz. slope failure, toe failure and base failure. Fig. 1 illustrates these three types of failures. Geological conditions associated with the three types of failures are:

- Slope failure occurs when the arc of failure meets the slope above its toe. This is possible only when soil at the floor of the dump has a higher strength than that of the spoil mass and when the slope angle is very steep.
- Toe failure occurs when the soil above the base of the slope and below it is mainly homogeneous.
- In case of base failure, the slope angle is very low and the strength of material below the base of the slope is lower than that of the dump material.

Factors affecting the stability of a dump are broadly classified as (Singh and Chaulya, 1992; Singh et al., 1994; Singh and Singh, 2006):

- Spoil dump geometry and strength
- Foundation material strength
- Hydro-geological and rain water conditions of dumping site
- External loading conditions and dynamic forces

The presence of clay mineral imparts anisotropy to the dump material, causing its stress-strain behaviour to be quite unpredictable (Bishop, 1955; Morgenstern and Price, 1965; Dawson, 1999). Presence of water imparts visco-elastic property to the dump material. As the pore water pressure rises, the waste dump material loses its shear strength. This is often followed by static liquefaction, which is absolute loss of strength (Chowdhury, 2009). Flow of water may increase seepage force, which causes formation and propagation of tension cracks. Consolidation and compaction, owing to the uneven size distribution are other key factors. Dump slope stability is directly influenced by the bearing capacity of the foundation ground. A sloping ground with low bearing capacity destabilises the dump due to failure of foundation. Dynamic forces such as blasting and earthquake liquefy the dump material, reducing its shear strength.

Erosion changes the waste dump slope geometry (Matsukura and Mizuno, 2006) and morphological characters (Norris and Back, 1990). The weathering and attrition of material at the toe of a slope reduces the restraining force that may destabilize the slope. Cohesion among grain boundaries is reduced due to erosion of void filling material or zones of percolation, which notably reduces the material shear strength. This decrease in shear strength gives rise to potential movement in dump slope along weak plane. Besides, localized erosion may also result in increased permeability and ground water flow, leading to failure due to formation of gully and deep flow channels in dump.

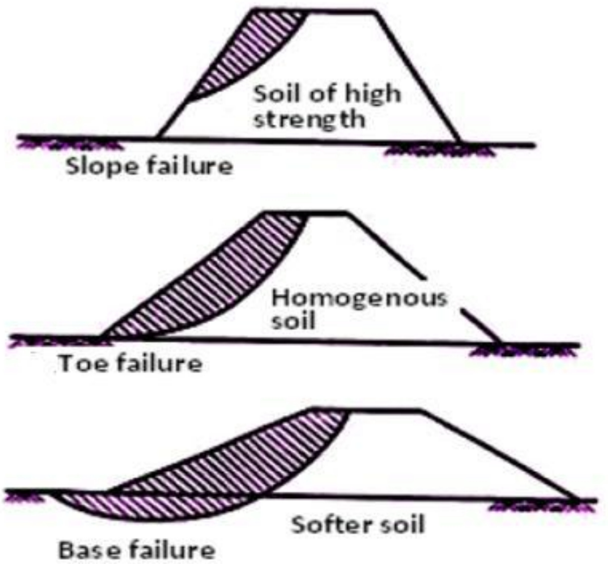

Fig. 1. Different types of dump slope failures (Murthy, 2002)

III. TECHNIQUES ADOPTED FOR SLOPE STABILITYANALYSIS

Limit equilibrium method (LEM) and finite element method (FEM) are the popular techniques of slope stability analysis. They have been used to simulate and study the existing dump slope. The physico-mechanical properties obtained from the testing of dump samples were used as inputs for stability evaluation.

A. Limit Equilibrium Method

Traditional LEM techniques are the most commonly used for slope stability analysis. This technique determines two very important aspects, namely factor of safety and location of failure surface (Chaulya, 1995). The most widely used LEM technique is method of slices, where the mass above an assumed failure surface is divided into a number of, usually vertical, slices and the value of factor of safety (FS) is obtained:

$$FS = \frac{\tau_a}{\tau_m} \qquad (1)$$

where, τ_a is the actual available shear strength of the material, and τ_m is the mobilised shear strength or the average shear strength on the hypothetical failure surface mobilised to maintain the body in equilibrium (Berisavljevic et al., 2014).

In order to render the analysis, certain assumptions are made. Shear strength is fully mobilised all along the failure surface at the instance of failure and the forces acting thereon are assumed to be in static equilibrium (Aruna, 2009; Singh et al., 2013; Cheng et al., 2003; Krahn, 2003). LEM assumes a simple failure surface, which restricts its use to simple geometry and strata. It lacks in incorporating stress-strain relations and in situ stresses and does not indicate the instability mechanisms. The LEM analyses are performed assuming linear Mohr-Coulumb failure criterion. Thus, three input parameters are needed, namely, total unit weight of material, cohesion and angle of friction (Berisavljevic et al., 2014). Despite its inherent shortcomings, LEM has been widely used as guidelines for stability analysis. Further analysis is required using numerical techniques.

The limit equilibrium analysis was conducted using the Rocscience limit equilibrium software, Slide, using techniques of Ordinary Method of Slices, Bishop Simplified, Janbu Simplified.

B. Finite Element Method

The Finite Element Method is a continuum model which can be used for analysis of complex geometries, stress modelling and material behaviour (Singh et al., 2011). The method is able to predict stresses and deformations of support element at failure and it is also possible to visualize the development of failure mechanisms (Hammah et al., 2005). The material behaviour is described by an elastic, perfectly plastic model complying with the Mohr-Coulumb failure criterion, taking into account shear strength and deformation parameters (Brinkgreve and Bakker, 1991).

FEM divides the problem domain into discrete elements called as finite elements (Zienkiewicz and Cheung, 1967), interconnected at nodes and boundaries of continuum. Algebraic equations are individually obtained for each element and assembled together to solve for unknown variables at nodes. Results are obtained in the form of stresses, strains and displacements at nodes. Nodes have nodal (vector) displacements or degrees of freedom which may include translations or rotations. Upon displacement, nodes drag the elements in a certain manner dictated by the element formulation. In simple words, displacements of any points in the element will be interpolated from the nodal displacements. This is the main reason for the approximate nature of the solution (Singh et al.., 2011). It theoretically satisfies all the requirements to be met for a complete solution of a slope stability problem (Potts and Zdravkovic, 1999).

A major advantage of FEM is that, it does not require any assumption on failure mechanism and it overcomes a number of shortcomings of LEM (Singh et al.., 2010; Kasmer et al.., 2006; Yang et al.., 2014). The Shear Strength Reduction (SSR) technique (Dawson et al.., 1999, Griffith and Lane, 1999, Hammah et al.., 2004) enables this method to calculate factor of safety for slope. However, due to limited experience of geotechnical engineers with the tool and limited information published on the quality of its results, FEM is not very commonly used for routine slope stability analysis. Recently, by the virtue of significant computing and memory resources and low costs, FEM has become a powerful slope analysis tool (Hammah et al.., 2005).

The Rocscience software Phase2 was used for two dimensional stability analysis of the dump slope.

IV. DUMP SLOPE GEOMETRY AND FIELD INVESTIGATIONS

The internal dump, made up of three benches, is constructed over a floor inclined at an angle of 7˚. The bottom two benches are 25 m high and 25 m wide while the top bench is 10 m high. The bench slope angle provided for each bench is 70˚ while the overall slope angle is 40˚. Dump material samples were collected at different sections of the dump and were tested for their physico-mechanical properties in the laboratory as per the ISRM standards (ISRM, 1972; 1977; 1981). The analysis has been carried out for monsoon season of the year when the dump material possesses least strength.

V. SLOPE STABILITY ANALYSIS

A. Stability Analysis of Existing Dump

Fig. 2 shows the geometry of the existing dump.

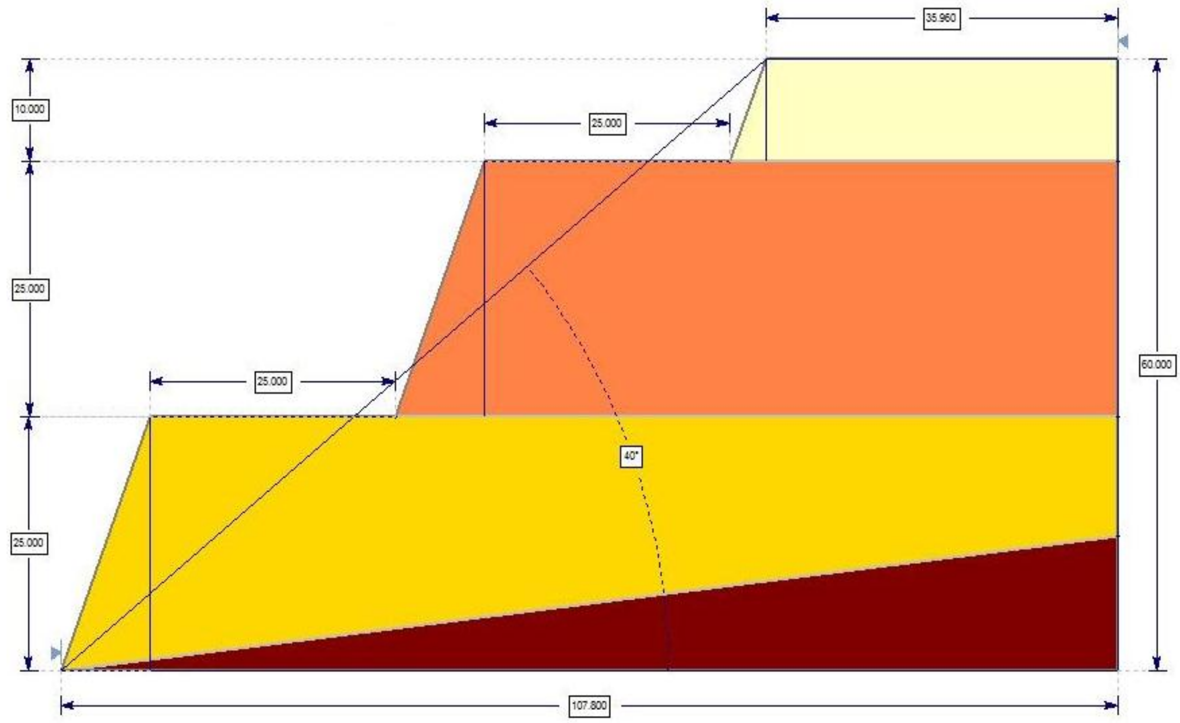

Fig. 2. Geometry of existing overburden dump slope

The limit equilibrium analysis was conducted using the Rocscience limit equilibrium software, Slide, using techniques of Ordinary Method of Slices, Bishop Simplified, Janbu Simplified.

Table IV gives the storage capacity of existing dump and values of factor of safety obtained from various analysis methods and table V gives a comparison FS values from various LE methods with that obtained from FEM.

TABLE IV. FACTOR OF SAFETY OBTAINED FROM VARIOUS METHODS OF ANALYSIS

Method of analysis	Capacity of dump (m^3) per metre length of existing dump	FS from analysis
OMS	4687.8	1.536
Bishop Simplified	4687.8	1.57
Janbu Simplified	4687.8	1.515
FEM	4687.8	1.49

TABLE V. CHANGES IN FS OBTAINED FROM DIFFERENT ANALYSIS METHODS COMPARED TO FEM ANALYSIS

Method of analysis	FS from various methods	FS from FEM	% change in FS from FEM
OMS	1.536	1.49	3.087
Bishop Simplified	1.57	1.49	5.369
Janbu Simplified	1.515	1.49	1.678

B. Optimisation of Existing Dump and its Stability Analysis

The value of factor of safety has been maintained at 1.3 throughout the optimisation process. The Investigation and Design Manual presented by the British Columbia Mine Waste Rock Pile Research Committee (1991) considers FS of 1.3 to be safe. The height and angle of the dump have been increased in small increments while keeping the dump within the bounds of given land surface area. Fig. 3 shows the geometry of the optimised dump with details of the same tabulated in Table VI. The optimum capacity of the dump comes out to be 5349.661 m^3 per metre length of dump at a height of 76m and overall slope angle of 43˚.

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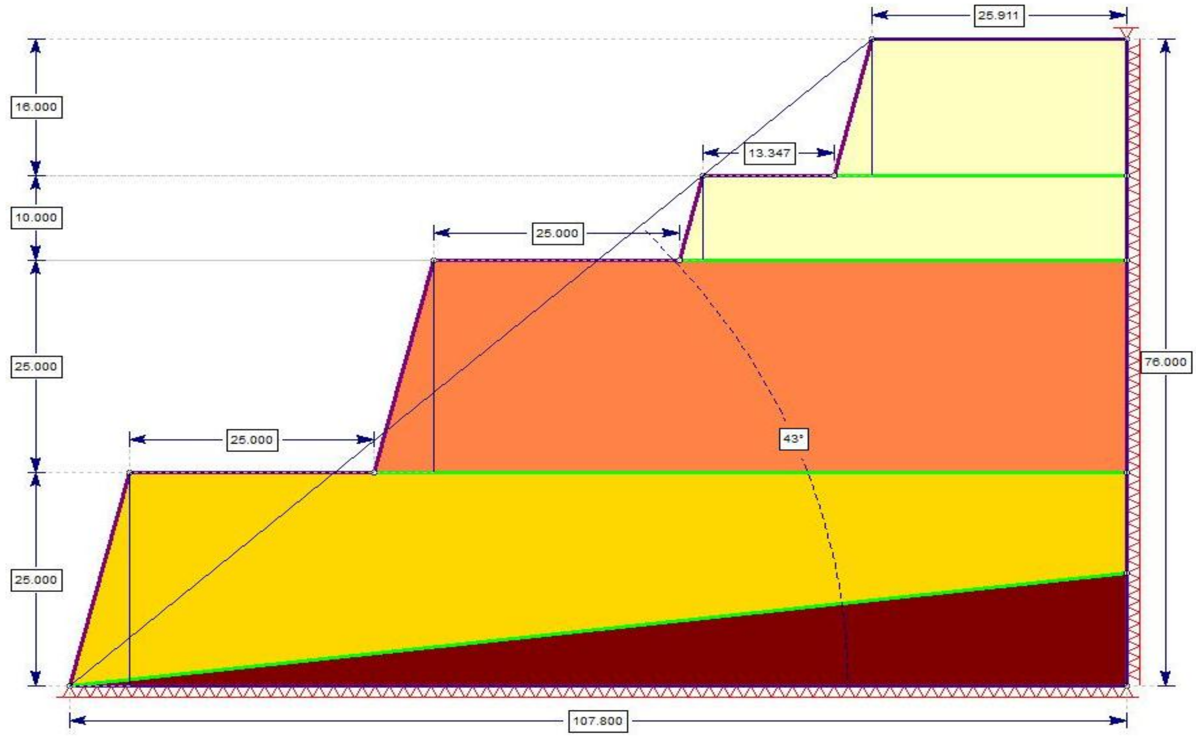

Fig. 3. Geometry of optimised overburden dump slope

TABLE VI. DETAILS OF OPTIMISED OVERBURDEN DUMP SLOPE

FS (from FEM)		Height (m)		Slope angle (˚)		Capacity (m^3) per meter length of dump		% increase in capacity
Existing dump	*Optimised dump*	*Existing dump*	*Optimised dump*	*Existing dump*	*Optimised dump*	*Existing dump*	*Optimised dump*	
1.49	1.3	60	76	40	43	4687.8	5349.661	14

VI. RESULTS AND DISCUSSIONS

A. Limit Equilibrium Method

A two dimensional LE analysis was carried out using Slide software. OMS or Fellenius method (Fellenius, 1936), Bishop simplified method (Bishop 1955) and Janbu simplified method (Janbu, 1957; 1973) were carried out to evaluate FS of circular failure surfaces. Fig. 4, 5and 6 illustrate the location of critical slip circle provided by the three methods along with their respective FS for existing dump as well as optimised dump.

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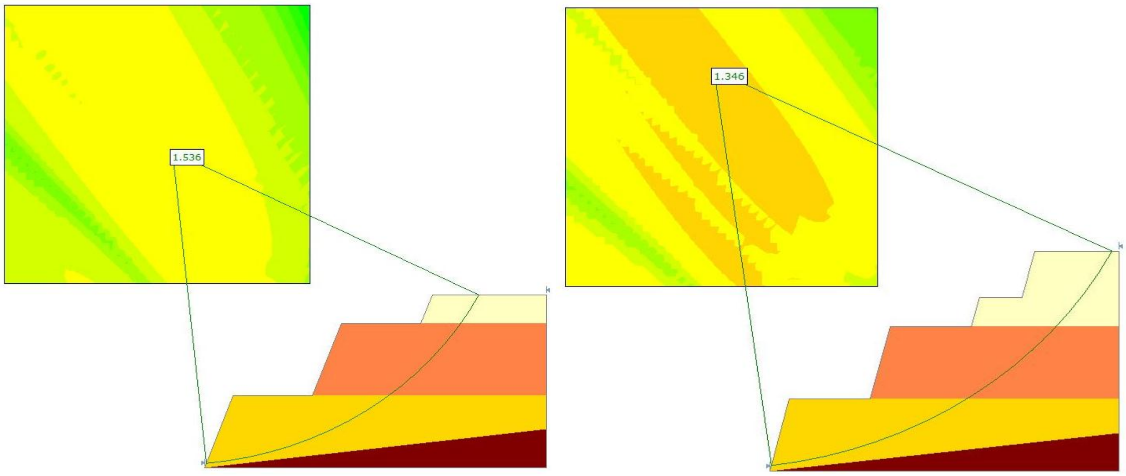
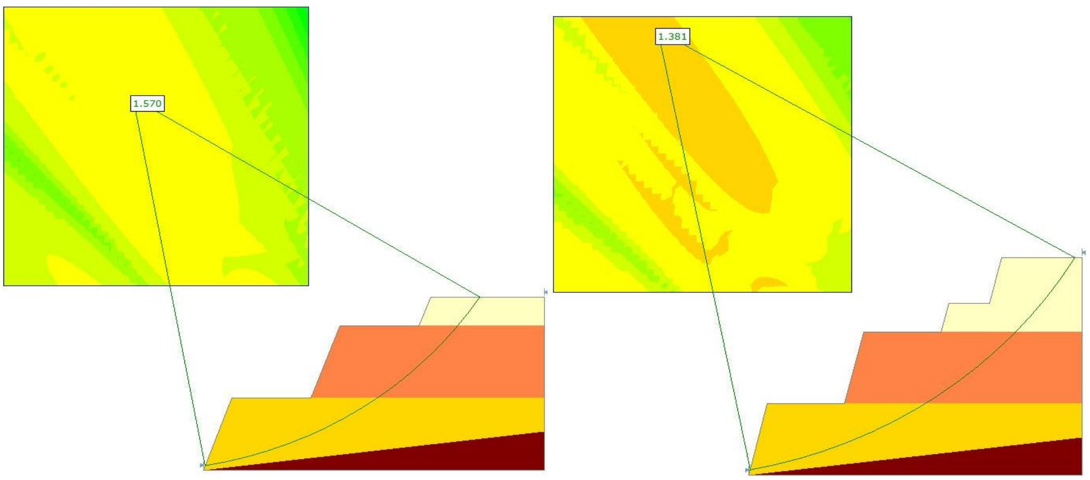
The failure surfaces provided by the different methods for both existing and optimised dumps strike the slope between its crest and toe and their values of FS are well above 1.3. There is a marginal difference between the values of FS given by the three methods. This is because each method is based on certain assumptions (Douglas and Bailey, 1981; Jiang and Magnan, 1997; Mansour and Kalantari, 2011). This indicates the LEM results are ambiguous and provide little information about material behaviour. Hence, numerical analysis has been conducted to further comprehend the stability of the waste dump to understand the behaviour of deformations in the dump



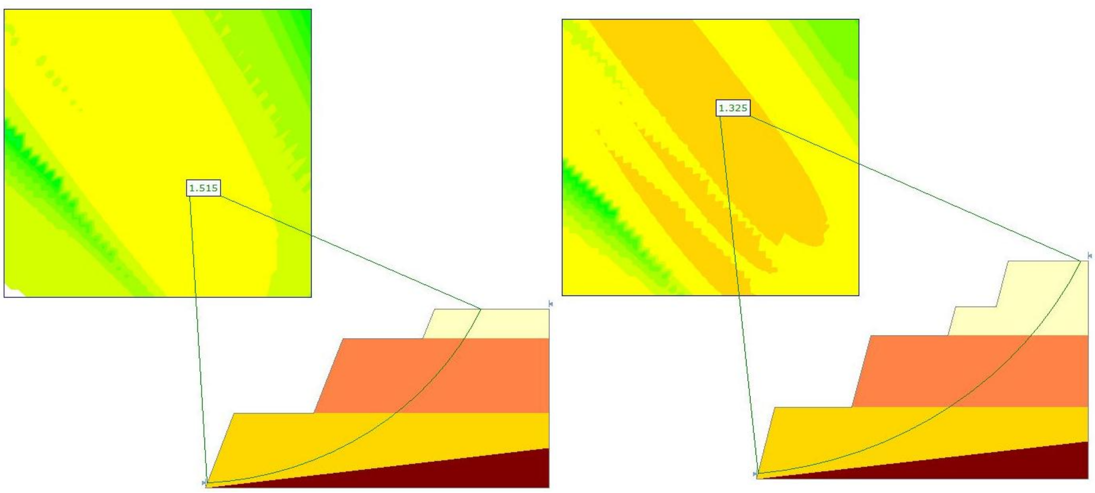
(a) Existing dump (FS = 1.536) (b) Optimised dump (FS = 1.346)

Fig. 4. OMS/Fellenius method



(a) Existing dump (FS = 1.57) (b) Optimised dump (FS = 1.381)

Fig. 5. Bishop simplified method



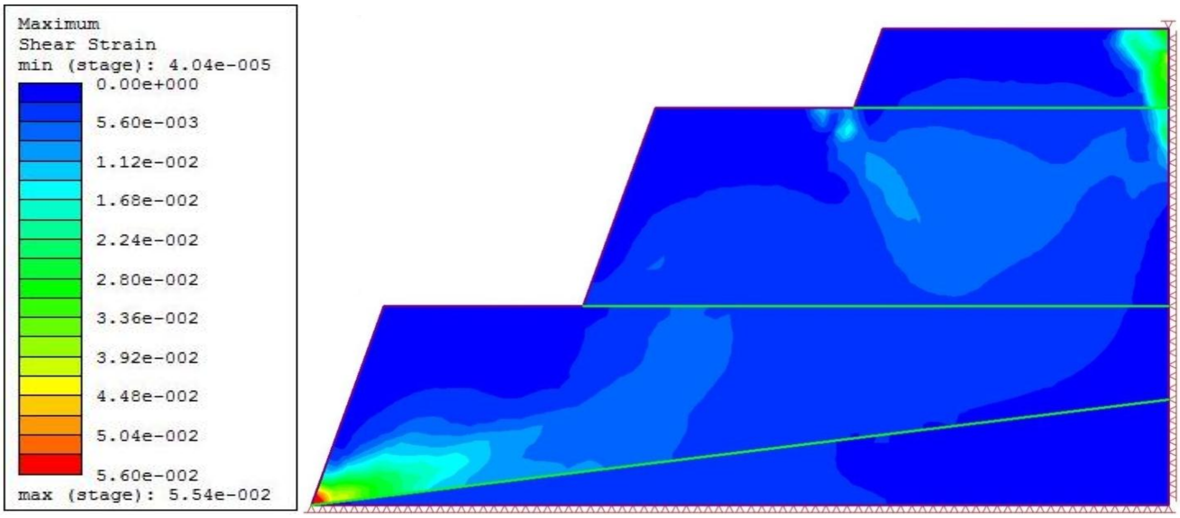
(a) Existing dump (FS = 1.515) (b) Optimised dump (FS = 1.325)

Fig. 6. Janbu simplified method

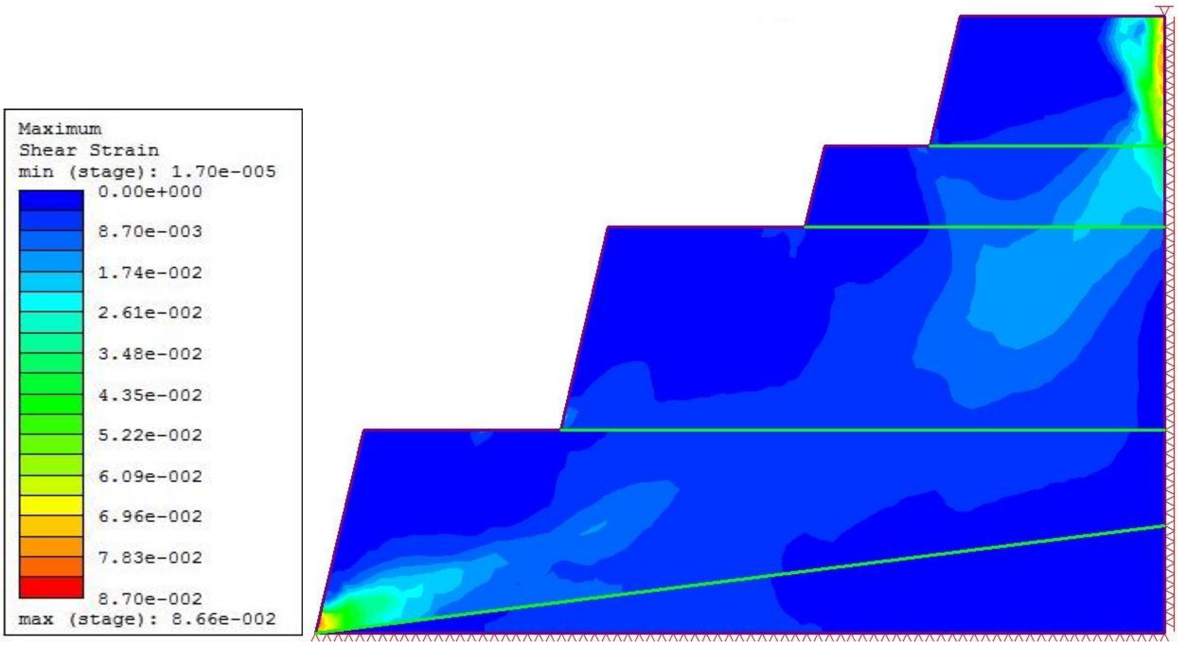
B. Finite Element Method

A two dimensional FEM model was simulated using Phase^2 software. Mohr-Coulumb failure criterion was incorporated to analyse the stability. The method makes use of shear strength reduction (SSR) technique to calculate FS and other strength parameters (Dawson et al., 1999; Griffith and Lane, 1999; Hammah et al., 2004).

The initial estimate of SRF for the first SSR iteration, by default is set to 1 and an appropriate step size is automatically selected by the software for every SSR iteration to obtain the SRF. When the difference in SRF between two iterations of the SSR method is less than the SRF and the stress analysis has converged for the SSR iteration with lower SRF but does not converge for the next iteration with higher SRF, the value of SRF is taken as the critical SRF value for the analysis. It was found that the FEM analysis for the existing dump converges at critical SRF=1.49 giving a maximum displacement of 0.43 m while the convergence for the optimised dump occurs at critical SRF=1.3 giving maximum displacement of 0.25 m. This implies that the optimised dump experiences lesser displacement than the existing dump even though the FS was reduced from 1.49 to 1.3. Fig. 7 (a) and (b) illustrate maximum shear strain distribution in existing and optimised dump, respectively.



(a) Existing dump (FS = 1.49)



(b) Optimised dump (FS=1.3)

Fig. 7. Distribution of shear strain

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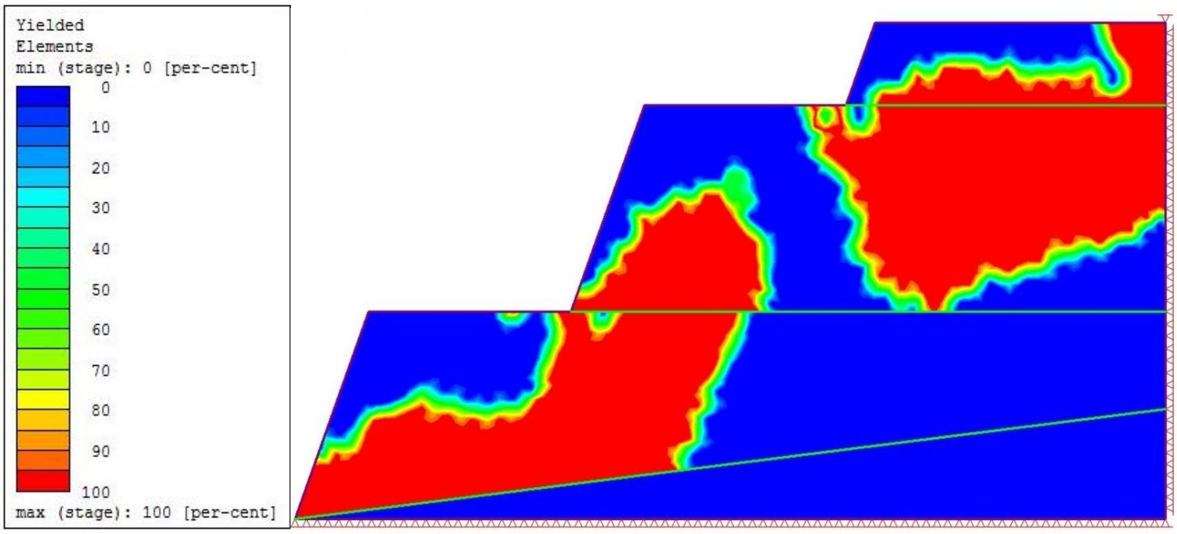
The strain distributions of both the dumps are almost identical. In case of optimised dump, the strain has increased marginally close to the toe region and at the crest region. The overall intensity of strain has increased in case of optimised dump compared to the existing dump. However, the dump slope is overall stable in both the cases. Maximum values of strain in the analyses of existing dump and optimised dump have been found to be 0.0554 and 0.0866, respectively. Table VII further presents the details of the results obtained from the stability analysis.

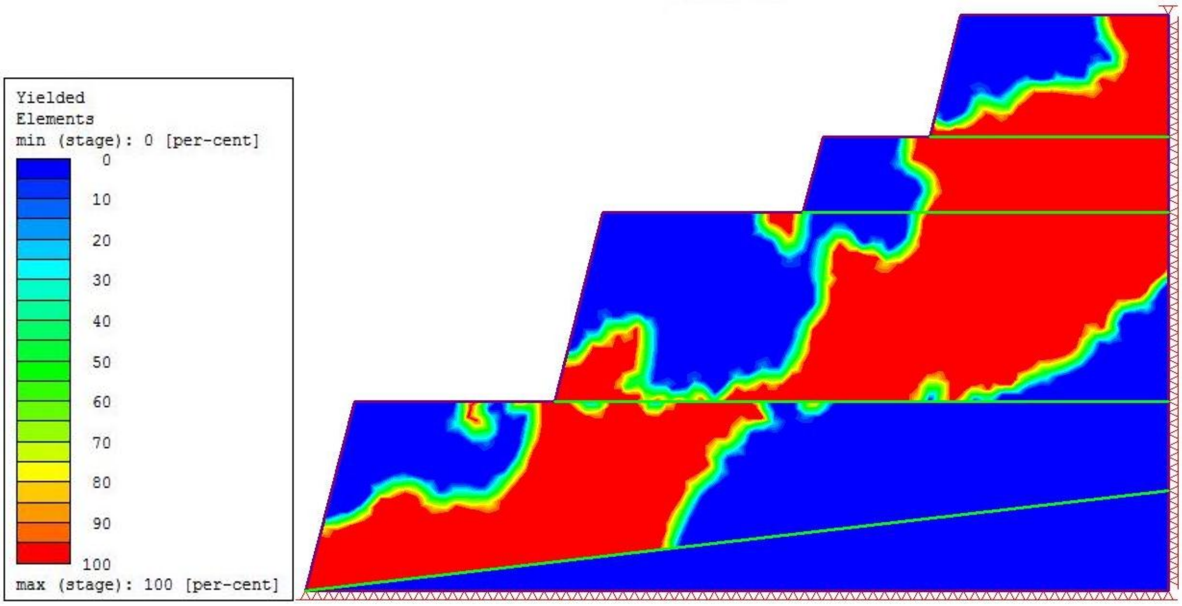
TABLE VII. COMPARISON OF MAXIMUM VALUES OF DIFFERENT PARAMETERS OBSERVED DURING THE ANALYSIS

σ_1 (kPa)		σ_3 (kPa)		Horizontal displacement (x 10^{-2} m)		Vertical displacement (x 10^{-2} m)		Total displacement (x 10^{-2} m)	
Existing dump	*Optimised dump*	*Existing dump*	*Optimised dump*	*Existing dump*	*Optimised dump*	*Existing dump*	*Optimised dump*	*Existing dump*	*Optimised dump*
1326.3	1501.32	1134.55	1354.47	4.25	2.53	2.09	1.48	2.29	3.03

Fig. 8 (a) and (b) show yielded elements in the existing and optimised dump, respectively.



(a) Existing dump (FS=1.49)



(b) Optimised dump (FS=1.3)

Fig. 8. Yielded elements

For the bottom most bench, the yielding pattern is similar in both the dumps. However, in case of the second bottom bench near its toe region, the yielded area has reduced in the optimised dump compared to the existing bench. This is due to the redistribution of stresses that has taken place in the optimised dump by the virtue of increase in the number of benches and of the improved geometry of the dump. Hence, optimised dump has improved the overall stability of the dump.

The top 43 m zone of optimised dump and 33 m zone of existing dump are occupied by completely yielded elements, which may initiate tension cracks and accelerate failure. Circular failure may occur due to high concentration of these tension cracks and their increasing depth. The area lying near the toe is also occupied by completely yielded elements, zone of which being 19 m in optimised dump and existing dump. The yielded elements are interconnected to give rise to circular failure. However, the floor of the dump is sufficiently strong and does not give way to any subsidence. Thus, in the event of destabilisation, the movement of dump material will take place over the dump floor and the material in the surrounding zone of toe will face shear strength reduction. Consequently, this will form a weak zone of crushed material. These conditions will favour translational movement of toe parallel to the base of the dump floor directed towards the dip of the floor, giving rise to planar failure mode. It can be deduced that the upper part of the dump will undergo circular failure while the interface between the dump floor and the dump material will undergo planar failure, giving rise to compound failure.

VII. CONCLUSION

Land requirement in mine waste dumping is a major issue in India. Being a tedious and time consuming process, land acquirement hampers the overall economy of the mine project. Therefore, it is imperative to ensure that the dump storage is fully utilised for its capacity.

In the present work, following conclusions can be drawn out from the study:

- The existing overburden dump has been optimised up to 14% increase in the dump storage capacity.
- The results obtained from LEM and FEM analyses show that the optimised slope gives a FS of 1.49 and 1.3, respectively. Hence, the storage capacity of the dump can be fully utilised without compromising its stability.
- Evaluation of dump stability requires rigorous techniques as simple techniques like LEM overestimate the FS.
- Limit equilibrium analysis results shall be used as guidelines only. Numerical analysis is required to be conducted to obtain a better insight into slope stability.
- Numerical modelling techniques provide different parameters to measure slope stability and predict failure modes.
- FS value of 1.3 was found to be optimum for long term stability of the internal dump even under saturated condition.
- Slope stability analysis is a complex phenomenon. It is suggested to incorporate more than one technique to evaluate dump stability as each technique is based on different principles and assumptions. This ensures a comprehensive and a more reliable slope stability analysis.

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