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The 6th Victor de Mello Goa Lecture: Development of large direct shear facility for geotechnical characterization and stability assessment of opencast mines dumps

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Lecture

Keywords
Large direct shear box
Over burden dumps
Slope stability
Slide2
GALENA

Abstract

As opencast coal production increases, a crucial challenge is safeguarding the stability and management of overburden dumps while prioritizing both safety and cost-efficiency. Determining the optimal stable dump slope dimensions during and after mining remains a key challenge for mining operations worldwide. Assessing the stability of overburden (OB) dumps is necessary to maintain them at the steepest possible angle without compromising stability. Understanding the shear strength, including cohesion and angle of internal friction, of the heterogeneous dump mass is crucial for this assessment. To evaluate the shear strength behaviour of OB materials, a large direct shear machine (LDSM) was designed and developed at Central Mine Planning and Design Institute, Ranchi. The LDSM features a shear box with dimensions of 1000 mm × 1000 mm × 1000 mm to facilitate testing materials with larger particle sizes. It can test large specimens with a thickness up to 500 mm and a maximum particle size (D_{max}) of 80mm in accordance with ASTM D3080-98. Seven different OB materials from Magadh Coalfields, India were collected and tested for their shear strength. Using the obtained shear strength parameters, various slope profiles are assessed for stability using 2D limit equilibrium software such as Slide2 and GALENA. Probabilistic modelling is employed to generate a statistically distributed factor of safety (*FoS*) instead of a deterministic value, accounting for uncertainties related to input parameters. This paper aims to forecast the maximum safe height for OB dumps based on the determined shear strength parameters.

1. Introduction

India is the third largest producers of coal in the world. In the year 2022-23, 96.10% of coal production in India was from open cast mines (858.342 MT) and the rest 3.90% was from underground mines (34.848 MT). Opencast mining operation involves excavation of overburden (OB) material which comprise of waste rock and barren materials that must be excavated to access the coal seams. Heavy earthmoving machineries such as draglines, shovels and dumpers are used to excavate the overburden materials. For opencast coal mining in 2022-23, Coal India Ltd (CIL), the single largest coal producing company in the world, owned by the government of India had removed a massive 1.66 billion cubic meters of overburden, translating to a stripping ratio of 2.43. This translates to 2.43 cubic meters of overburden removed for every tonne of coal extracted. Majority of OB material is backfilled to the de-coaled area as internal dump and remaining is dumped outside of the mine as external dump. Coal production and OB Removal (OBR) by CIL in the last three years is shown in Figure 1.

Geotechnical characterization of OB materials across coal mines in India revealed that, materials forming these dumps vary from silt and clay size (<75 μm) to coarse grained soil particles (>75 μm) including sands and gravels as well as large size cobbles (150-300 mm) and boulders (>300 mm). The OB dumps in most of the opencast coal mines are usually formed by end dumping method which results in formation of dumps with relatively low density and where the outer slope is just stable under the static loading conditions at angle of repose of 37-38°.

The materials are subjected to wide range of environmental and climatic changes including erosion, ageing, wet dry cycles, seasonal temperature fluctuations and cyclic loading due to earthquakes, machine movement. These processes result in degradation of strength properties of geomaterials and fragment sizes resulting in generation of fines.

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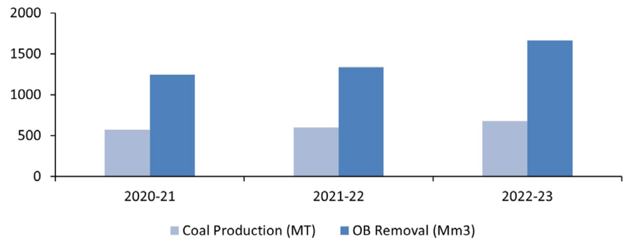

Figure 1. Coal production and OB removal by Coal India Ltd.

The preparation of large-sized dumps is becoming a challenging task for the mine management from two important perspectives. First, the limited availability of surface leasehold land for dumping materials and the second, associated problems of slope stability with the increasing heights of dumps due to increase in stripping ratio. Any instability in the dump can affect the production rate and safe mining operations. Hence, slope stability analysis of dumps is an important element in mining operations. The research work presented in the paper deals with uncertainties in the shearing behaviour of high overburden dumps (OB dumps), existing and planned. It seeks to offer reliable shear strength parameters for OB dump design, achieved through development of a large direct shear machine. The study aims to determine the maximum safe height for these dumps by analysing their stability using acquired strength properties.

2. Existing framework for stability assessment and design of dumps

For the design and stability analysis of dumps, reliable and direct measurement of shear strength of OB materials has always been limited by the scale of the available testing equipment. There is lack of available data on representative OB materials for Indian coal mines. Mine planners could no longer rely on experience-based models to establish design criteria with confidence.

In India, the design regulations for overburden (OB) dumps are stipulated by the Coal Mine Regulations Act (CMR) of 2017 and enforced by the Director-General of Mine Safety (DGMS). According to these guidelines, the slope of individual OB dump benches must conform to the natural angle of repose of the material, not exceeding 37.5°. Any inclination steeper than this angle requires scientific justification approved by the DGMS. OB dump exceeding 30 m in height shall be benched so that no bench exceeds 30 m in height and the overall slope shall not exceed 1 vertical to 1.5 horizontal.

For external dumps situated outside the mine, the maximum permissible height is 90 m above ground level, structured in three distinct benches. Additionally, a minimum distance of 100 m is mandated between the dump toe and any mine openings, railways, public works, roads, buildings, or other permanent structures not owned by the mine operator.

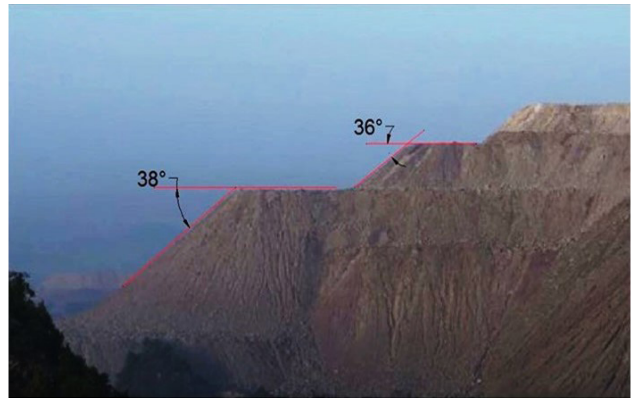

Figure 2. Individual bench angles of external OB dump at Northern Coalfields Limited.

These regulations aim to ensure safe and compliant OB dump construction and operation within the Indian mining industry.

The dump formation in Indian opencast coal mines primarily involves end dumping. This practice of end dumping makes individual benches attain a slope equivalent to the material's angle of repose, which may vary between 37-40° (Coal India, 2021). Some Coal projects of Northern Coalfields Limited and Central Coalfield Limited show the same trend from where the sample collection was carried out and the dumps have reported different values of the bench angles (Figure 2) ranging from 35° to 45°.

2.1 Issues with existing apparatus

The analysis of major accidents due to dump failure in Indian coal mining industry converged on one common conclusion that is the lack of scientific design and monitoring of the pit and dump slopes in mines.

Design and stability analysis of OB dumps involves obtaining data, applying engineering principles to derive an appropriate and acceptable design. The major constraints for carrying out such studies are the limited test data and non-availability of the testing facilities equipped to test full-scale samples or simulate the higher loading conditions normally associated with the deeper mining conditions and higher OB dumps.

In the current practice, strength properties are derived from small conventional test data with a linear Mohr-Coulomb envelope. These appear to be reliable for small OB dumps of height only up to 60 m considering normal load constraints of regular laboratory direct shear test. A very nominal data of characterization for Indian coal mine dumps are reported in the literature. This may be due to significant costs and time involved with the design, construction, and operation of large and robust equipment to test representative OB samples at field scale. This relative lack of attention can also be attributed to the small economic value of dumps or the approach of mine management to accept higher risks for temporary slopes in the coal mining projects.

2.1.1 Scale effects on shear strength

One of the debated subjects among mine geotechnical practitioners is the degree to which shear strength measurements obtained from conventional laboratory testing equipment can be confidently relied upon to predict the shearing behaviour of actual OB dumps. Standard 60-100 mm sized shear boxes are suitable for testing the majority of soils for civil engineering applications and 300 mm shear boxes are routinely used for handling more granular materials such as reinforced earth wall backfill (QTMR Q181C-2002) and rockfill. For soils tested in boxes up to 300 mm in size, a maximum normal stress of around 1 MPa is the norm for 'off-the-shelf' equipment and scalping of oversize particles is usually not required. Standard laboratory equipment can provide reliable shear strength data for soils and stress ranges comparable to field conditions, for most civil engineering applications. The reliability of the data is questionable when materials tested contain "oversize" particles, or particles deemed to be too big for the equipment being used. In such cases, samples require scalping to be performed to meet particle size restrictions of test standards. The reliability of data is also questionable when tests are performed under non-representative stress ranges. For coal mine dumps, a compliant specimen can often be a specimen that is scalped to a fine fraction that is distinctly dissimilar to its original material. In addition to this, the effective vertical stress near the base of even a 90 m-high dump is likely to be greater than the 1 MPa stress capacity of standard available test equipment.

The ambiguity about the relevance of scale-effects is one of the reasons why mine planners are hesitant to use shear strength parameters generated using normal laboratory testing equipment. There are two noteworthy scale effects:

- The first is the extent to which an OB sample's grading must be downscaled to meet device capacity, so that the influence of prototype-sized particles on shear strength is not abnormal;
- The second relates to the normal stress limits of the test apparatus; and if the failure envelope developed from measured strengths can be reliably extrapolated out to the 'much-higher' stress ranges to simulate field-conditions for dumps of current and future heights.

2.2 Design and development of LDSM

To overcome the limitations associated with estimation of strength parameters a detailed geotechnical characterization of the OB materials forming the dumps was carried out to decide the direct shear box size and load capacity that can accommodate representative OB material samples and test at field scale.

2.2.1 Geotechnical characterization

The stability of OB dump primarily depends upon the geotechnical characteristics of the OB material i.e., both physical and engineering properties of the overburden soil. As the dump formation involves several sequential mining operations (e.g drilling, blasting, loading, transportation, dumping, grading, and levelling), the OB material is subjected to several physical and chemical processes like abrasion, crushing, weathering, degradation, etc. due to this, soil characteristics of OB dump significantly vary from that of their geological formation. Therefore, a detailed study of geotechnical characteristics of OB materials is essential to the proper design and development of sustainable OB dump approaches.

Site investigations were carried out on OB dumps for the sample collection from the coal fields. Samples were collected at different heights and with a defined spatial variation, to cover the randomness/heterogeneity of sample (Figure 3).

The geotechnical characterizations indicate that there is extreme spatial variation of particles in a dump mass. Younger dumps have comparably lesser fine contents (<75 µm) than aged dumps (Figure 4). It is also found out that presence of coarse gravel (20-80 mm) contributes approximately 50% of the mass of dump material which classifies the dump material as coarse-grained gravel. Testing the coarse gravel material in conventional small direct shear machine does not yield actual strength properties and scalping OB materials to match the constraints of standardized laboratory equipment, will result in an inaccurate estimation of strength properties (Figure 5).

2.2.2 Design considerations for large direct shear machine

The main problems with using standard laboratory equipment to test mine dump related to the scale effects, both in terms of device volume and available stress limits. To overcome these limitations, a direct shear machine for coarse grained dump specimens and high applied stresses has been designed and constructed at the Central Mine Planning and Design Institute (CMPDI).

Shrivastava & Rao (2013) designed and developed a large direct shear machine with shear box of size each 300 mm × 300 mm × 448 mm at IIT Delhi. This equipment

Figure 3. View of different materials with varying particle sizes that contribute to the formation of a dump.

Figure 4. Sieving of through 30 mm sieve and amount retained and passed through 30 mm sieve.

is servo controlled and has capability to apply normal load up to 500 kN and shear load up to 100 0kN. A data acquisition software was also developed to acquire the test data and store in computer system for further analysis. Later, Niktabar et al. (2017) has modified this machine to achieve automatic cyclic shearing. This fundamental basis was kept in mind while working in the design and development of Large Direct Shear machine at CMPDI (Figures 6 and 7). The large direct shear machine (LDSM) at CMPDI was structurally and mechanically designed and was externally peer reviewed by an instrument manufacturing and engineering consulting firm (M/s Hydraulic Engineering Instruments Co., HEICO, New Delhi). Since, very large forces were required to generate the target stress capacities for the largest practically achievable test specimen hence, both the compressive and shear loads were considered as being applied through a self-supported reaction/loading frame, using commercially available actuators with suitable load capacities and strokes (Fityus et al., 2014; Niktabar et al., 2017; Rao et al., 2009). In addition to meeting the high-stress and large-specimen criteria, the LDSM was designed with the following aspects considered (Figures 8, 9 and 10):

- A split shear box with relatively rigid walls to limit sidewall deflection and associated volume changes and reduce specimen rotation during a test.
- A shearing system able to:
  a) Maintain a constant rate of shear displacement during testing;
  b) Shear at rates as low as 0.001 mm/sec;
  c) Achieve relative shear displacements of 20%;
  d) Allow measurement of shear stresses independently of sliding friction between the box and the frame;
  e) Ability to change the spacing between the upper and lower shear boxes;
  f) Facilitate to test 300 mm × 300 mm size specimen also.
- A compression system able to:
  a) Maintain a constant normal stress during testing;
  b) Minimise tilt of the top-plate and keeping equal stress at the top.

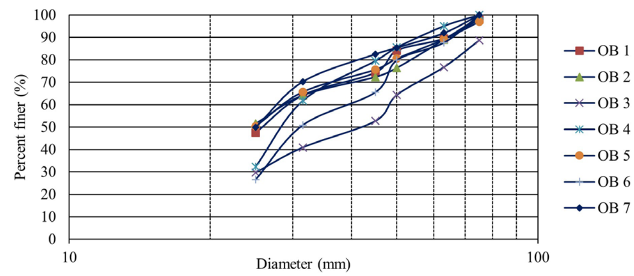

Figure 5. Grain size distribution of OB materials for particle size >25 mm.

- A free-standing self-supported reaction frame which allowed for all forces within it to be balanced and equilibrized.

2.3 Technical specifications of the large direct shear machine

The large direct shear machine (LDSM) for large specimens and high applied stresses has been designed to accommodate approximately full-scale specimens (from clay to gravel i.e., $D_{max} \leq 80$ mm) with greatly reduced requirements for scalping and to apply normal stresses sufficient to simulate field stress conditions for OB dumps of up to 250-300 m height. The normal and shear load capacity of the machine are 2500 kN each (Table 1). An EOT crane meant for placing top plate over the shear box system is also a part of this facility, which meant that for each test performed for this research a hydraulic crane was used for placing the top plate.

The large direct shear machine (LDSM) that has been developed in the course of this research work, can test over a normal stress range that is almost 5 times greater than that offered by standard direct shear boxes and of the order of the stresses in the highest OB dumps created by current mining operations.

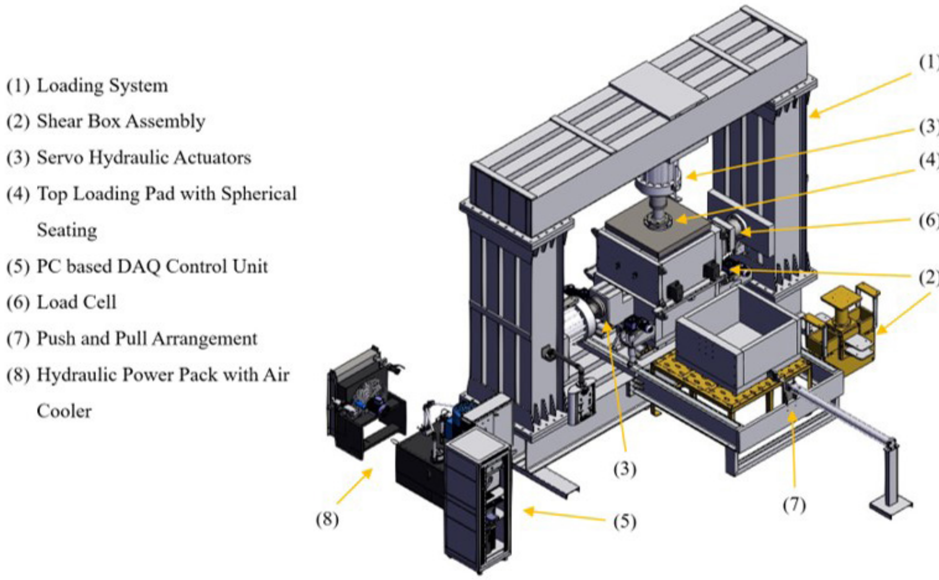

Figure 6. Solid Works conceptual drawing of LDSM assembly.

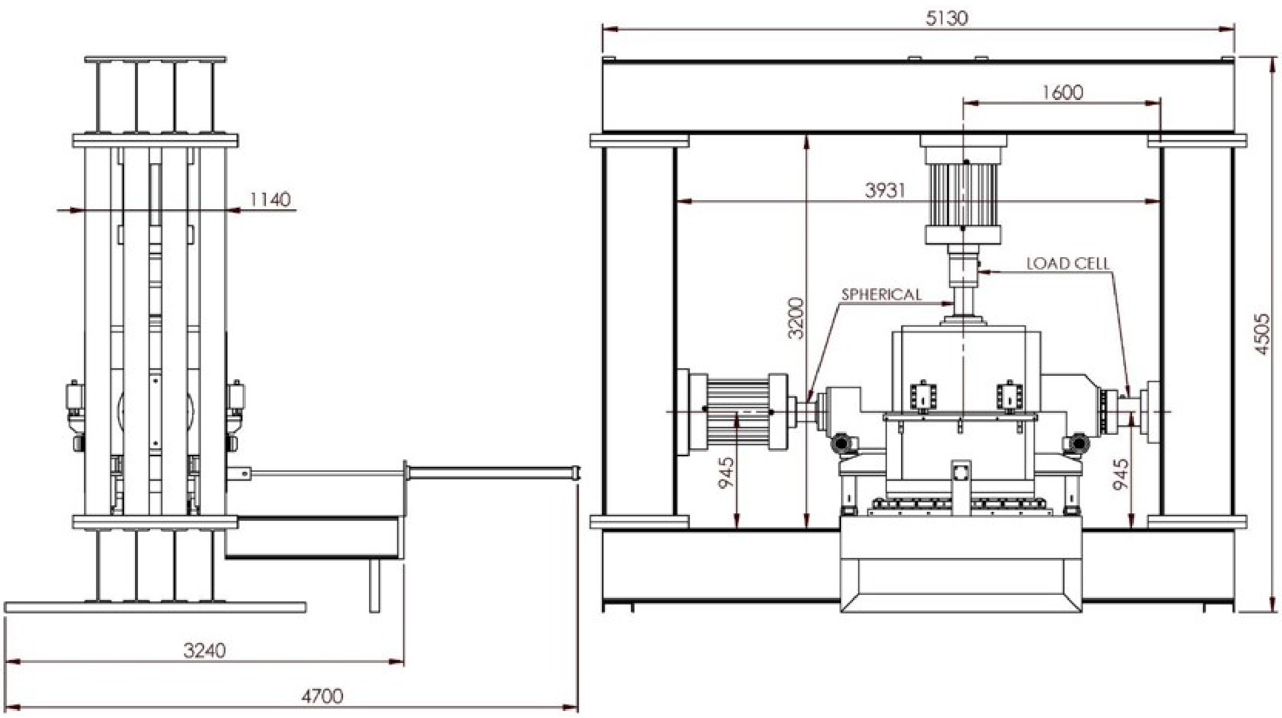

Figure 7. Line diagram of LDSM (all dimensions are in mm).

3. Scheme of stability analysis

From the geotechnical characterization of OB materials, it was observed that particle sizes ranging from 25 mm-80 mm are present in abundance. These contribute approximately 50% of the mass of OB dump materials (Figure 5). Standard laboratory direct shear test (DST) with specimen size of 60 mm × 60 mm × 25 mm permits the maximum particle size D_{max} < 4.75 mm. Hence, to accommodate the higher particle size i.e. D_{max} < 80mm, shear strength parameters were obtained using LDSM with specimen size of 1000 mm × 1000 mm × 500mm (LDST) and D_{max} < 80 mm (Coal India, 2021). Shear strength parameters of seven OB materials determined from DST and LDST are analysed to understand the effect on slope stability of the OB dumps for various profiles (Gara, 2021). To ascertain the possibility of the

Table 1. Technical specifications of LDSM.

Sr. No.	Technical Detail	Specification
1	Maximum normal load	2500 kN
2	Maximum shearing load	2500 kN
3	Normal load range	10-2500 kN
4	Shear strain rate	0.001 mm/sec – 1 mm/sec
5	Sample size	1000 mm × 1000 mm × 1000 mm, 300 mm × 300 mm × 300 mm
6	Normal load cell capacity	2500 kN
7	Shear load cell capacity	2500 kN
8	Safe over load	150% of rated capacity
9	Ultimate over load	300% of rated capacity
10	Displacement speed	≤ 10 m/s
11	Mechanical stroke (C.M.)	C.E.U + 10

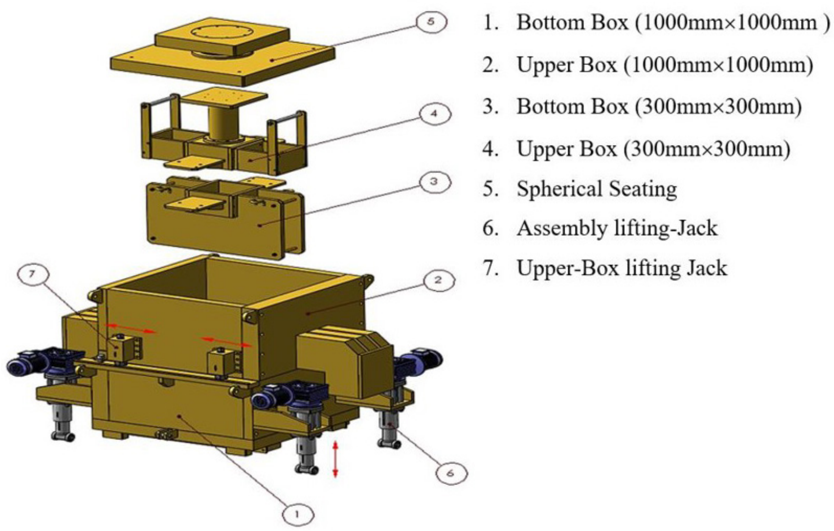

Figure 8. Shear box assembly with all its components.

enhancement of dump capacity and assessment of dump stability under high stress conditions, the stability analysis of the OB dumps is carried out for the cases shown in Table 2.

3.1 Slope stability analysis using Slide2 and GALENA

Stability analysis is carried out by a 2D limit equilibrium-based software Slide2 from Rocscience group (Rocscience, 2023) and GALENA (Clover, 2012). First, using Slide2, the analysis is carried out for deriving the factor of safety using Bishop simplified and Janbu simplified method, and probability analysis is carried out using Latin-Hypercube sampling method. Then, these results are affirmed with the results obtained using GALENA. As the observations of past failures suggest that the predominant failure pattern is circular in OB dumps, hence failure surface is assumed circular. While Slide2's comprehensive analysis takes care for local and global failures, individual failure surfaces need to be defined for each, global and local failures, in GALENA.

Figure 9. View of the large direct shear machine installed at CMPDI.

Slide2 helps in avoiding the uncertainties in the manual failure surface selection through grid search. The concept of restraints is used to focus the investigations on meaningful failure surfaces during analysis in GALENA. In practice, failures nearly always pass through, or near, the toe of the slope. Hence, X-LEFT, X-RIGHT and RADIUS system in GALENA is used to define and explore the area of interest.

The horizontal seismic coefficient is incorporated in the analysis for pseudo static conditions. Seismic forces are considered as per Indian standard criteria for Earthquake Resistant Design of Structures IS 1893 - Part 1 (IS, 2002). Seismic force/coefficient *αh* is calculated as per the above IS Code by two methods named Seismic Coefficient Method and Response Spectrum Method, and a higher value is taken for slope stability calculation.

Shear strength properties of 7 samples of Magadh OCP derived from DST and LDST are taken for this analysis (Gara, 2021). The dump is the composition of all the collected materials; hence, statistical analysis is carried out for deriving mean and standard deviation for strength properties. The shear strength properties, i.e., cohesion (c) and friction (ϕ) used in the stability analysis are shown in Table 3. In the case of cohesion of the material, standard deviation (*SD*) is high because the composition of soil in OB dumps is ranging from clay to sand and higher. It's impact on the analysis is less because the slope stability of material with higher particle size depends more on the clast formation and inter particle locking (Bradfield et al., 2014) which is a function of internal friction

Table 2. Cases considered for stability analysis.

Dump Height (*M*)	Bench angle	Strength properties
90, 120, 150	37.5°, 39°, 40°	DST and LDST

Unit weight is considered uniform throughout the dump, and it is taken as 18 kN/m^3. Uniform strata condition for the foundation is assumed for the analysis. To account for the effect of water, the phreatic surface is considered at the base of the dump. Material properties of the dump are assigned for inclusion within the simulations, based on a normal distribution derived from a mean and standard deviation.

4. Results and discussion

Factors of Safety (*FoS*) are derived for dump sections with varying dump heights of 90 m, 120 m, and 150 m and varying dump face slope angles of 37.5°, 39°, and 40°. Furthermore, *FoS* calculation is carried out for both local and global scenarios for each case. Typical results from the stability analysis viz Model with the height of 120 m, analysed using strength parameters from LDST for local and global failure analysis are presented here in Figures 11 to 13.

A total of nine Slide2 Models (SM) and nine GALENA Models (GM) of dumps sections are prepared for the analysis. Each model is prepared for a certain bench angle and overall height. Shear strength properties from both DST and LDST (Table 3) are considered in each model. Afterwards, each model is analyzed based on failure surface assumption for local and global failure and then, *FoS* for critical failure circle and probability of failure (*PoF*) for the critical failure surface is carried out. A summary of results for critical *FoS* required, mean *FoS* from model analysis and its standard deviation (*SD*) are presented in Tables 4 to 9.

Table 3. Shear strength parameters used in the analysis.

	c_{mean} (kN/m^2)	ϕ_{mean} (°)	*SD* c (kN/m^2)	*SD* ϕ (°)
DST	6.32	35.58	2.03	1.74
LDST	6.91	42.23	5.23	1.96

Figure 10. (a) shear box in position for loading of the sample; (b) shear box in position for application of normal and shear loads.

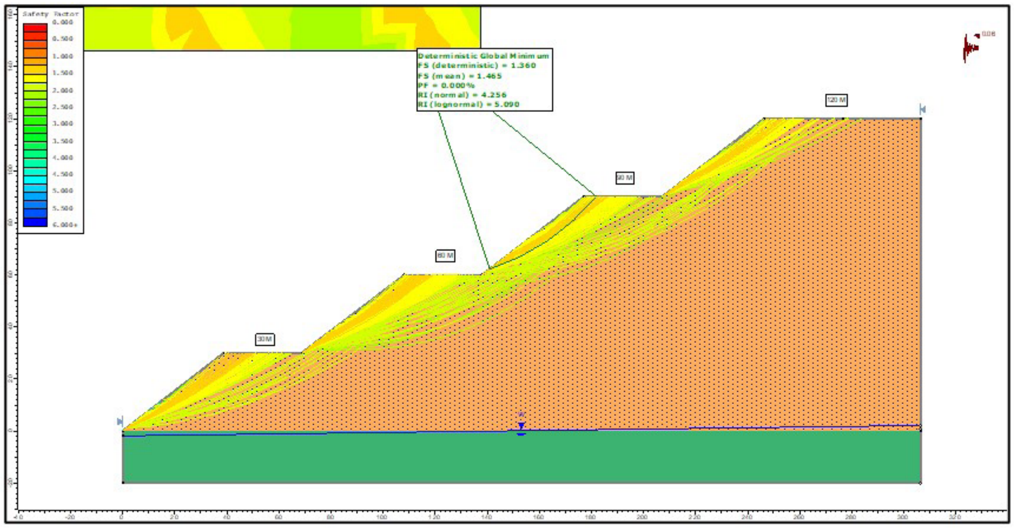

Figure 11. SM2: Slide2 analysis results for dump height 120 m and bench angle 37.5° with LDST parameters.

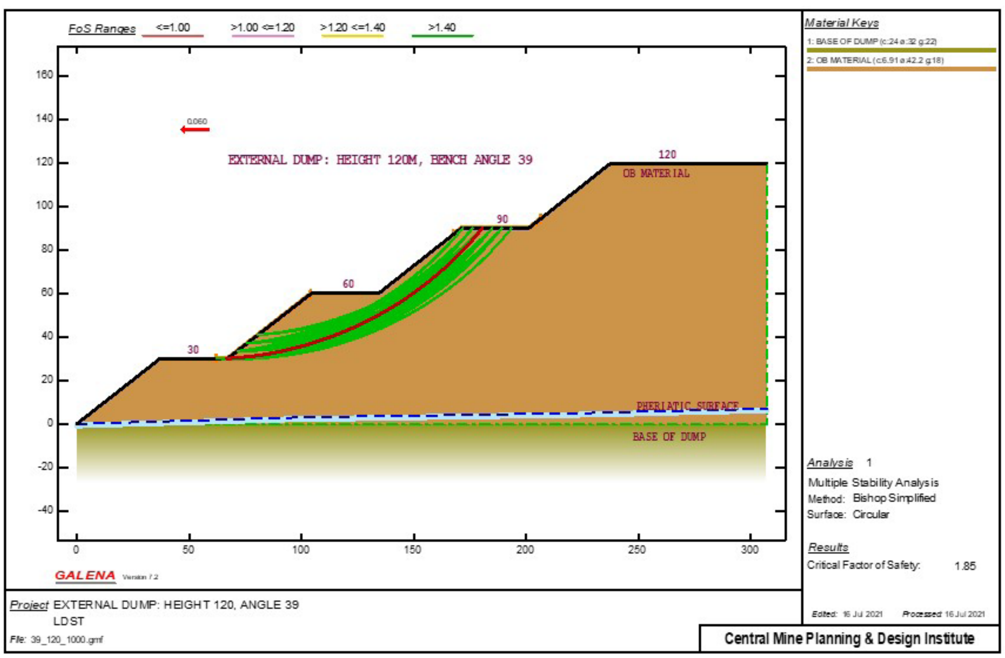

Figure 12. GM5: GALENA analysis result for critical *FoS* for local failure for dump height 120 m and bench angle 39° with LDST parameters.

Table 4. OB dump with 37.5° bench angle.

Model	Height (m)	*FoS* (DST)				*FoS* (LDST)			
		Bishop	Janbu	Mean	*PoF*	Bishop	Janbu	Mean	*PoF*
SM1	90	1.08	1.05	1.08	13.8	1.34	1.30	1.47	0
SM2	120	1.09	1.06	1.09	11.7	1.36	1.32	1.46	0
SM3	150	1.20	1.18	1.07	13	1.507	1.47	1.43	0

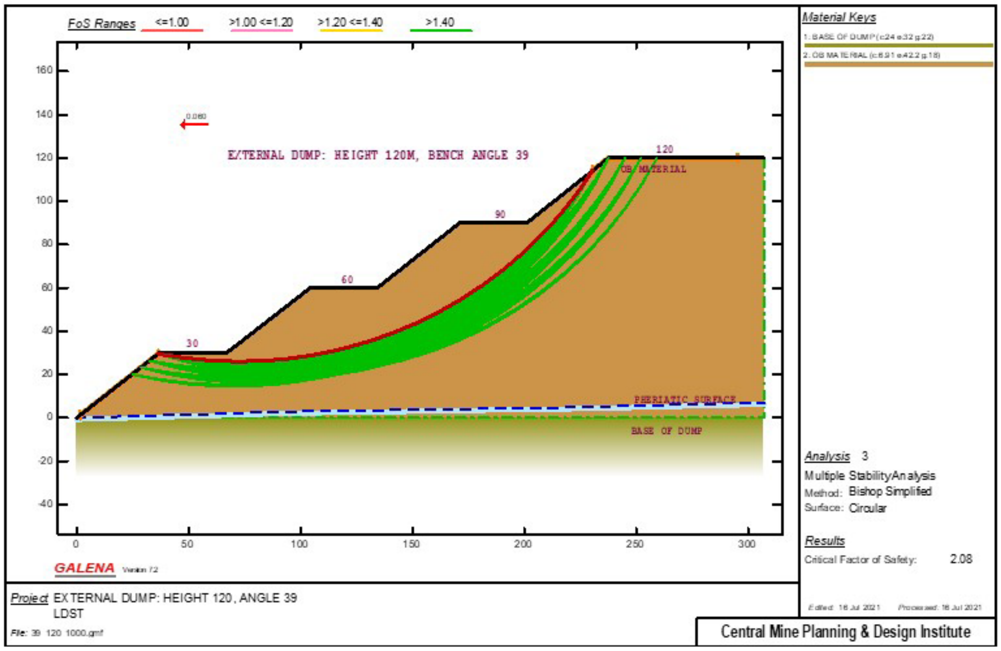

Figure 13. GM5: GALENA analysis results for critical *FoS* for global failure for dump height 120 m and bench angle 39° with LDST parameters.

Table 5. OB dump with 39° bench angle.

Model	Height (m)	*FoS* (DST)				*FoS* (LDST)			
		Bishop	Janbu	Mean	*PoF*	Bishop	Janbu	Mean	*PoF*
SM4	90	1.04	1.03	1.04	25.9	1.30	1.27	1.41	0
SM5	120	1.05	1.03	1.05	26.4	1.3	1.27	1.42	0
SM6	150	1.07	1.05	1.07	20.08	1.32	1.30	1.45	0

Table 6. OB dump with 40° bench angle.

Model	Height (m)	*FoS* (DST)				*FoS* (LDST)			
		Bishop	Janbu	Mean	*PoF*	Bishop	Janbu	Mean	*PoF*
SM7	90	1.00	0.97	1.00	44	1.36	1.32	1.46	0
SM8	120	1.03	1.01	1.03	32.3	1.27	1.26	1.42	0
SM9	150	1.04	1.025	1.040	27.3	1.30	1.27	1.42	0

Table 7. OB dump with 37.5° bench angle.

Model	Height (m)	Analysis	*FoS* (DST)			*FoS* (LDST)		
			Critical	Mean	*SD*	Critical	Mean	*SD*
GM1	90	Local	1.17	1.16	0.087	1.47	1.49	0.135
		global	1.65	1.65	0.120	2.17	2.12	0.157
GM2	120	Local	1.57	1.56	0.118	1.98	1.99	0.151
		global	1.59	1.58	0.117	2.02	2.03	0.154
GM3	150	Local	1.50	1.51	0.112	1.91	1.93	0.149
		global	1.65	1.66	0.116	2.10	2.12	0.161

Table 8. OB dump with 39° bench angle.

Model	Height (m)	Analysis	*FoS* (DST)			*FoS* (LDST)		
			Critical	Mean	*SD*	Critical	Mean	*SD*
GM4	90	Local	1.05	1.06	0.092	1.32	1.36	0.142
		global	1.59	1.59	0.120	2.02	2.05	0.158
GM5	120	Local	1.45	1.46	0.105	1.85	1.86	0.142
		global	1.63	1.63	0.115	2.08	2.09	0.157
GM6	150	Local	1.45	1.45	0.106	1.84	1.86	0.144
		global	1.74	1.74	0.131	2.22	2.23	0.187

Table 9. OB dump with 40° bench angle.

Model	Height (m)	Analysis	*FoS* (DST)			*FoS* (LDST)		
			Critical	Mean	*SD*	Critical	Mean	*SD*
GM7	90	Local	1.04	1.03	0.085	1.31	1.33	0.135
		global	1.61	1.61	0.125	2.05	2.06	0.165
GM8	120	Local	1.37	1.36	0.099	1.73	1.75	0.149
		global	1.61	1.62	0.119	2.06	2.07	0.144
GM9	150	Local	1.45	1.45	0.110	1.85	1.85	0.142
		global	1.73	1.74	0.135	2.22	2.23	0.167

Comparison plots for *FoS* from GALENA are prepared for *FoS* for DST and LDST of OB dumps for local and global failure in Figures 14 and 15.

The analysis results show that *FoS* is invariably high for the analyses with the shear strength parameters from the large direct shear test when compared with the analyses with shear strength parameters from the conventional Direct Shear Test. The mean and *PoF* values derived from the Slide2 indicate that the dump height of 90 m, 120 m, 150 m with individual bench angles 37.5°, 39 and 40° result in a safer mean *FoS* with zero *PoF* for all case with strength parameters derived from LDST. These results are in confirmation with the results obtained from GALENA. Though it is evident from Tables 4 to 9 that for same section of slope model, Slide2 tends to give conservative result than GALENA. It is due to efficient algorithm of Slide2 which automatically looks for the critical surface. The manual search of potential critical surface in GALENA sometimes may deviates from the actual critical surface.

For all cases, the large direct shear test (LDST) has reported higher *FoS* than that of direct shear test (DST) by a factor of at least ~1.5 times (Figures 14 and 15). Hence, one conclusion is that the shear strength parameters derived from the DST underestimate the stability of the dumps. The shearing mechanism remains the same in varying particle sizes but the zone of influence of shear is higher with a bigger particle size which aids in shear strength parameters (Bradfield et al., 2014).

It is observed that local failure reported lesser *FoS* values when compared to that of global failure (Figure 13), suggesting that local failure is critical for dumps up to a height of 150 m. Furthermore, in the case of local failures,

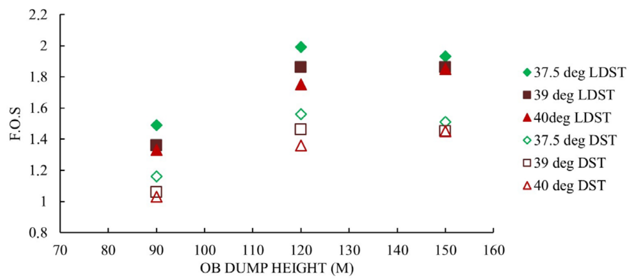

Figure 14. Variation of *FoS* w.r.t dump height and slope angle of OB dumps for local failure on DST and LDST.

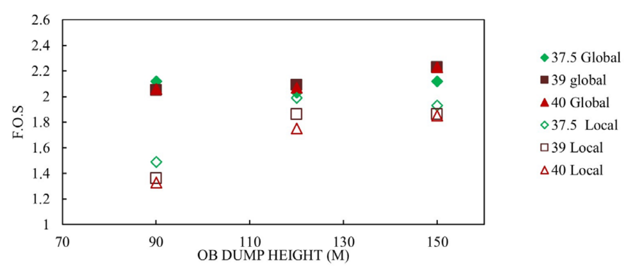

Figure 15. Variation of *FoS* w.r.t dump height and slope angle of OB dumps for local and global failure on LDST.

it is observed that *FoS* is increasing with the increase of dump height for local failures up to 150 m. This can be attributed to the lower normal stresses generated due to the lower height of the dump.

Dump sections of three different bench slope angles, 37.5°, 39° and 40° were considered to assess the significance of slope angle on *FoS*. Although dump sections with 37.5°

slope angles have shown slight incremental *FoS* for local failure but no such variance is observed in the global failure scenario. However, it can be ascertained that the dump slope angle has minimal impact on the dump stability up to the max considered slope angle of 40°.

5. Conclusions

a) Geotechnical characterizations reveal extreme spatial variation of particles within dump masses, with younger dumps containing comparably less fine content (<75 µm) compared to aged dumps. Coarse gravel (20-80 mm) constitutes approximately 50% of the dump material, classifying it as coarse-grained gravel, which poses challenges for conventional small direct shear machine testing;
b) Testing coarse gravel material using standard laboratory equipment may lead to inaccurate estimations of strength properties, emphasizing the need for appropriate testing methods;
c) The study identifies scale effects on apparatus size, necessitating the development of a large direct shear machine (LDSM) with specific parameters in terms of specimen, shear box volume, and load capacity to accurately represent in-situ conditions;
d) The LDSM designed and developed at CMPDI, Ranchi, has a normal and shear load capacity of 2500kN each and a box size of 1000 mm × 1000 mm × 1000 mm, enabling testing of particles up to 80mm for direct shear as per ASTM D3080-98 standards (ASTM, 2011);
e) Slope stability analysis using strength parameters of overburden material from LDSM, indicate that dump height can be safely extended up to 150 m above ground level keeping 30 m bench height, while maintaining an adequate Factor of Safety (*FoS*), thereby increasing dumping capacity within regulatory limits;
f) Extending dump height beyond 150 m may also can be considered, however it may lead to increased land acquisition demands due to larger surface area requirements at ground level, alternatively, after reaching 150 m height, transitioning the external dump further inward as an internal dump is recommended. This balances stability concerns with land use efficiency;
g) The study underscores the site-specific nature of optimum dump material, necessitating individualized geotechnical characterization, assessments considering local attributes and bearing capacity;
h) Future research directions include exploring advanced optimization techniques such as incorporating geosynthetics and advanced slope monitoring systems to enhance stability and potentially extend dump height further.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Sravan Kumar Gara: conceptualization, metodology, data curation, visualization, writing - original draft. K. S. Rao: conceptualization, data curation, methodology, writing - reviewing and editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols and abbreviations

C.E.U	Center of elasticity]
DST	Direct shear testing
FoS	Factor of safety
GM	GALENA Model
LDST	Large direct shear testing
SD	Standard deviation
SM	Slide2 model

References

ASTM D3080-11. (2011). *Standard test method for direct shear test of soils under consolidated drained conditions.* ASTM International, West Conshohocken, PA.

Bradfield, L., Koosmen, K., Fityus, S., & Simmons, J. (2014). Practical considerations for direct shear testing of mine spoils. In *Proceedings of the 10th ANZ Young Geotechnical Professional's Conference* (pp. 123-130), Queensland. Wellington: New Zealand Geotechnical Society.

Clover. (2012). *GALENA slope stability analysis system, version 6.00.* Robertson, NSW: Clover Technology.

Coal India. (2021). *Annual report.* Coal India. Retrieved in February 19, 2024, from https://www.coalindia.in/

Fityus, S., Robertson, H., & Simmons, J. (2014). Compression induced saturation in coal mine spoil piles. In *Proceedings of the 6th International Conference on Unsaturated Soils* (pp. 1515-1520), Sydney, Australia. Leiden, The Netherlands: CRC Press. http://dx.doi.org/10.1201/b17034-221.

Gara, S.K. (2021). *Geotechnical characterisation and stability analysis of coal mine overburden dumps in India* [PhD thesis]. Indian Institute of Technology Delhi.

IS 1893-1. (2002). *Criteria for earthquake resistant design of structures.* Bureau of Indian Standards, New Delhi.

Niktabar, S.M.M., Rao, K.S., & Shrivastava, A.K. (2017). Effect of rock joint roughness on its cyclic shear behavior. *Journal of Rock Mechanics and Geotechnical Engineering*, 9(6), 1071-1084. http://dx.doi.org/10.1016/j.jrmge.2017.09.001.

Rao, K.S., Shrivastava, A.K., & Singh, J. (2009). Development of an automated large scale direct shear testing machine for rock. In *Proceedings of the Indian Geotechnical Conference* (pp. 238-244), Guntur. IGS.

Rocscience. (2023). *Slide2: 2D limit equilibrium analysis for slopes, version 9.027.* Toronto, ON: Rocscience Inc.

Shrivastava, A.K., & Rao, K.S. (2013). Development of a large-scale direct shear testing machine for unfilled and infilled rock joints under constant normal stiffness conditions. *Geotechnical Testing Journal*, 36(5), 670-679. http://dx.doi.org/10.1520/GTJ20120155.