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Internal Mine Dump Slope Stability and Failure Zone Identification using 3D Modelling

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Abstract

In open-pit mine, safety of internal dumps is a significant pointer on the economic perspective of the overall project. It has been found in several studies that unplanned and random deposition of the overburdened material is the main reason for mishaps and failure. The study utilized unmanned aerial vehicles (UAVs) to map the mine dumps, and the precise 3D geometry of the same was reconstructed to evaluate the safety using numerical methods. A framework is proposed to assess and identify the potential zone of instability in the mine dumps. The study was conducted at the open-pit mine at the Raniganj coalfield of Paschim Bardhaman in West Bengal, India. The study assessed the internal dump safety using a 3D limit equilibrium method and numerical methods. Finally, optimum parameters are suggested for the mine dumps geometry under the prevailing geo-mining conditions of the mine site. The framework proposed here for assessing critical zones in mine dumps is cost-effective, easy to use, quick, and efficient.

1. Introduction

Coal demand has expanded in the recent years for industrial and domestic needs. The coal mining industry contributes 70% of our country's energy demand, and greatly helps the economy's growth. In India, 90% of coal is extracted using open-pit mining [1]. Coal is excavated by removing the overburden through drilling and blasting. The shovel-dumper combination handles the loose, overburdened materials [2]. The removed overburdened material is deposited in the external and internal dumps of the mine [3]. Overburdened materials are increasing, and the dump slope susceptibility to failure is increasing due to unplanned dumping. Internal dumping is practiced in the excavated space of the open-pit, thus saving a substantial amount of conveyance cost of the dumping, and vis-à-vis de-coaled areas were backfilled, which finally economically benefits the industry [4]. Internal dumping also reduces the costs of post-reclamation operations. Therefore, the safety of these internal dumps is an essential issue for smooth mining operations. Failure of the dumps hampered the production operation, which may be a reason for the mine closing. Several dump slope failures have occurred, and many fatalities have occurred due to slope failure [5]. Fourteen people were killed in 2013 when the dumps failed at the Basundhara mines in Odisha [6]. In 2016, 25 people were killed in the Rajmahal open-pit mine due to a dumps failure [1]. Therefore, dumps stability and critical failure zone identification are essential, so that we can redesign the mine dumps, reduce mine accidents and avoid disasters.

Over the years, substantial work has been done on existing mining dumps in terms of stability studies [6][9][16] and dump stabilization [17][18][19]. Two-dimensional (2D) slope stability analysis is one of the most commonly used approaches for evaluating slope stability. Simple generalization and extended history are the basis of this method for slope stability analysis [7]. However, this strategy does not consider the effects

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that occur in real-world situations. However, this stability analysis approach is helpful in geo-technical engineers for preliminary investigations. Many researchers have used 2D numerical modelling for slope stability assessment [8][9].

Therefore, there is a continued need to apply modern surveying and data collection methods and to develop methods for accurately analysing slope safety problems. The structure-from-motion (SfM) approach was used for digital elevation model reconstruction using photogrammetry, and is a low-cost and effective tool for geoscience applications [20]. Compared with terrestrial laser scanners, SfM photogrammetry using an unmanned aerial vehicle (UAV) provides a rapid and cost-effective method for mapping mine dumps slope [24]. LiDAR and photogrammetry have been widely used and accepted as standard practices in the recent years [21]. Kong used UAV-SfM photogrammetry to characterise rock mass discontinuities quantitatively [22]. For rapid and robust slope failure appraisal, aerial photogrammetry, and modelling have been used for mine-pit slopes [23].

Traditional numerical modelling tools often require more computational power and a longer time for slope stability analysis. The conventional infrastructure set for slope health monitoring has been altered regarding safety, flexibility, and simplicity of use provided by UAV platforms owing to the emergence of new tools, data collection platforms, and advanced analytical processing techniques. The UAV strengthens the numerical modelling for more detailed 3D model generation and slope stability analysis. Dumps slope stability was analysed by Layak *et al*. [2022] using numerical modelling with a UAV [1]. Rock slope stability was recently analysed using the 3D limit equilibrium method [10]. This study provides an approach to slope stability assessments, failure zones, and using UAVs in overburden material management practices. This study proposes an internal dump stability assessment methodology using UAV and 3D modelling. UAVs have various benefits over conventional monitoring techniques including the capacity to gather high-resolution images, access difficult-to-reach locations, and collect data regularly and cheaply [25][26]. UAV-Digital Photogrammetry reduces measurement risk and time expense and provides abundant data for the precise reconstruction of 3D geological models [27].

The Coal Mine Regulation 2017 of India mandates regular safety audits of the mine dumps and corrective action on the part of the mining company in cases it is found to be susceptible to failure. In the mine site, regular data collection may often interfere with the production process; therefore, some alternative touchless remote sensing-based approach would fit the requirement. Satellite-based data collection would not fit the purpose due to several limiting conditions, and UAVs have the potential to meet this gap. The purpose of the mine dumps safety audit is to understand the state of conditions of the stress-strain distribution in the dumps mass regarding possible chances of failure. The failure in the mine dumps is often a local phenomenon, and identification of susceptible zone is crucial in taking remedial action and reducing load and flattening the slope. The present investigation aims to quickly appraise the high-risk zone in terms of slope angle on the higher side from the slope contour map prepared in this study. The framework proposed in this work has the flow of pipeline work involving the identification of the potential and critical failure zone, thereby helping the mining management in quick action mode.

This study uses 3D modelling for internal mine slope stability analysis under the present dumps condition. The aerial data generated a realistic 3D model for failure zone identification. The collected data were used for 3D model generation and dump slope stability analysis using a 3D limit equilibrium analysis. LEM and FDM analysed the detailed stability in 2-dimensional as well. We proposed optimum geometric parameters for a stable slope for an internal dump. Finally, the dump stability and failure zone were identified as safety measures. The last section of the research work presents vital results and conclusions regarding the approaches used to examine slope stability and safety. It should be noted that similar approaches, albeit described for dumps slopes, may be used for the stability study of other slopes such as highway slopes located near high-risk landslide areas, which cause concerns such as nuisances, property damage, and loss of life.

2. Material and methodology

The assessment of the safety factor of the mine dumps using numerical analysis principally relies on the geometry, geotechnical parameters, and constitutive criteria considered in the modelling [31]. The first parameter assumed significant importance in view of the fact that dumps geometry is irregular and extraction of the geometry from the mine map compromised to a large extent due to scale effect and sparse spacing of the data point. The actual 3D geometry would be the need of today's analysis toolbox to achieve a better safety perception of the mine dumps. Considering the large extent of the open-pit mines and sporadically distributed mine dumps in the mines needs a highly mobile, portable, and quick data acquisition technology to serve faster analysis and assessment of safety factors. The present study utilised UAV technology for the data collection, and used a few photogrammetry techniques to generate 3D data sets in the spatial extent of the mine. The second parameter was evaluated from the sample collected from the dump site in the IIT(ISM) Dhanbad lab. The Mohr-Coulomb (M-C) failure criteria were considered in view of the M-C characteristics shown by the sample tested in the lab plotted in the x-y space in *normal stress vs. shear stress* plot. In loose material congregates of dumps, the alignment of the slope and its angle is vital in the context of lower frictional resistance of the material and angle of repose. A quick appraisal of the safety notion of the 3D dump mass was assessed from the slope angle contour using Geographical Information System (GIS) toolbox. This opens the scope of focusing on the relatively higher computational work using numerical analysis. Mega open-pit mines with many dumps would reap the benefit of prioritising the scale high to low susceptibility of the potential failure probability of the mine dumps.

In the first stage, we assessed the safety factor considering the self-weight of the dump mass. The safety factor above 1.25 is relatively safe in the context of the mining conditions and dumping pattern of the loose material. Steep dumps would save a large extent of the space requirement for the dumping of overburdened rock, thereby inviting higher risk in the safety notion of the mass for the higher chances of failure. The data collection strategy is described in the following sections. The research methodology is presented in Figure 1.

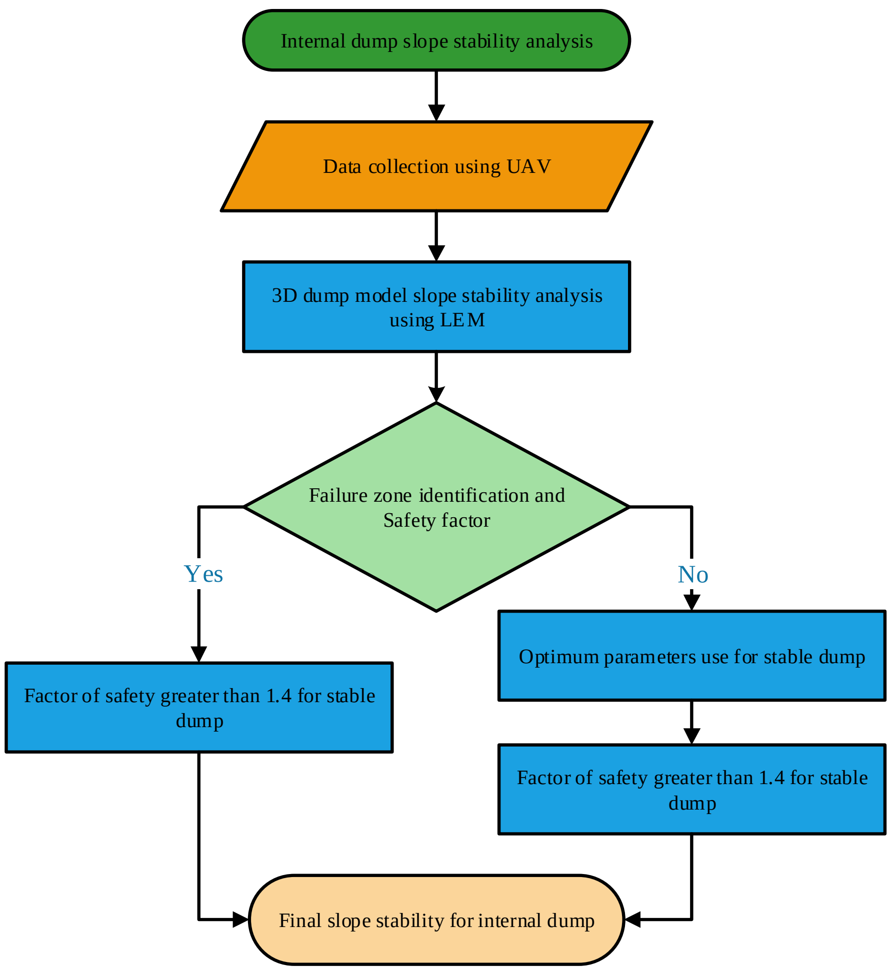


Figure 1. Methodology used for the dump slope stability analysis.

2.1. Data collection

The data acquisition planning is done before the actual visit of the mine site with the base data of Google map to optimize the path planning in the form of a grid to cover the whole area and ascertain 75% front overlap, and 65% side-overlap in the area concern in the mine site. The restriction in the mine site was checked to strictly adhere to flying the UAV within the leasehold boundary of the mining organization. In addition, the optimum fly height was assessed based on the pilot run, required point-cloud average spacing, i.e. achieving ground zero resolution and availability of the spare batteries. In this study, 75 – 100 m flying height was maintained to achieve 13 cm point cloud average spacing between the points. The dense point clouds, orthomosaics, digital elevation models (DEM), and digital terrain models (DTM) are constructed from the aerial images acquired using UAV [11].

Ground Control Points (GCPs) in temporary stations were erected throughout the length and breadth of the area, where the UAV is acquiring data to minimize errors. Based on similar studies and experiences, we have taken images with eight GCPs. These GCPs were located in different elevations to address the relief displacement correction. Global Navigational Satellite System (GNSS) and total station were used to map the GCPs in the spatial extent of the area concerned, and later used as the master file to geo-reference the whole data set.

2.2. 3D model reconstruction

Multiple image data were used for 3D model reconstruction. The image processing software *Pix4D* and *CloudCompare* were used for the 3D model reconstruction. Image scale accuracy was enhanced using the data of GCPs. In the current SfM workflow, the use of GCPs is very time-intensive. Initially, a substantial amount of field effort was required to implement and assess the GCPs during data collection [28]. Post-processing requires more time and labour to identify GCPs in the images, although some progress is being made in automatic GCP identification [29]. Recent advancements in UAV onboard orientation sensors such as real-time kinematic global navigation satellite systems (RTK-GNSS) provide promising alternatives to GCPs for direct georeferencing [30]. A conventional survey collects ground control point data using a total station. Finally, the reconstructed 3D model was used for slope stability estimation. Figure 2 shows the 3D reconstruction of the internal dump of the mine.

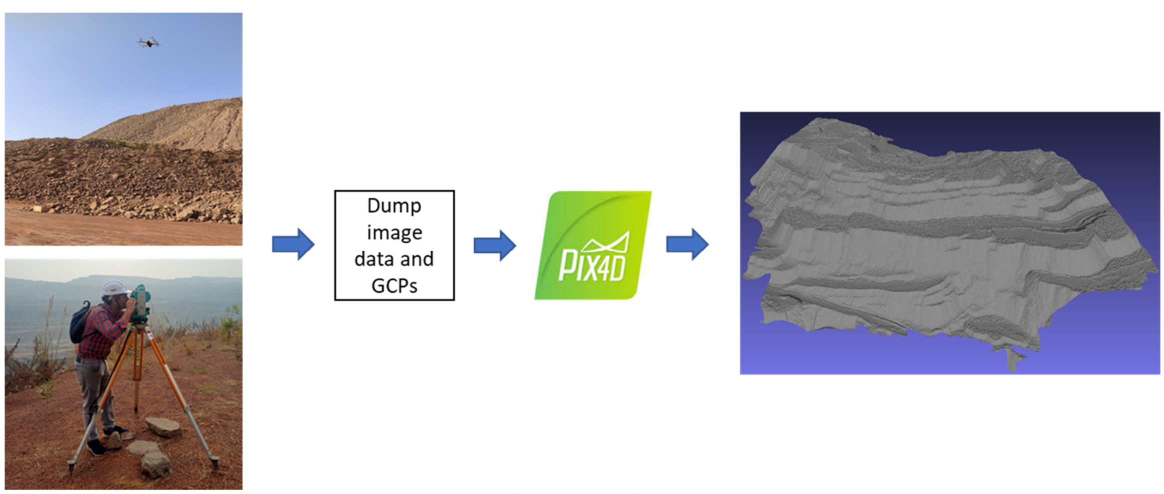


Figure 2. Methodology flow chart for 3D reconstruction.

2.3. Model geometry and material properties of the overburden

The overall dump height was 90–110 m, and the slope angle was 35°–38°. Figures 3 and 4 show the internal dump's detailed view and geometry. The M-C failure criteria were used for slope stability analysis. A clear projection view of the dumps is shown in Figure 3. The whole mass of the dump was considered uniform cohesion, friction angle, and density, as mentioned in Table 1. Table 1 shows the geo-mechanical properties of the dump's material used for the slope stability analysis.

Table 1. Overburden material properties

Sl. no.	Properties	Value
1	Density (kg/m^3)	1800
2	Cohesion (kPa)	50
3	Friction angle (degree)	27

2.4. Limit equilibrium method

The static limit equilibrium approach has been developed to comprehend the stability of slopes. The LEM is the predominant approach in slope stability analysis, and is a well-known method for assessing the strength of natural and man-made slopes [12] [13]. This approach is based on the concept of slices, where the slope is divided into several slices. The safety factor is determined by analyzing each slice's force and moment equilibrium before summing all slices to find the safety factor. Several LEMs have been developed for slope stability analysis, including Bishops (1955), Janbu (1954), Morgenstern-Price (1965), Spencer (1967), and the Generalised Limit Equilibrium (GLE) approach. Popular techniques include the simplified Bishop, Janbu, GLE, and Morgenstern-Price methods because the factor of safety value can be easily computed for slip surfaces.

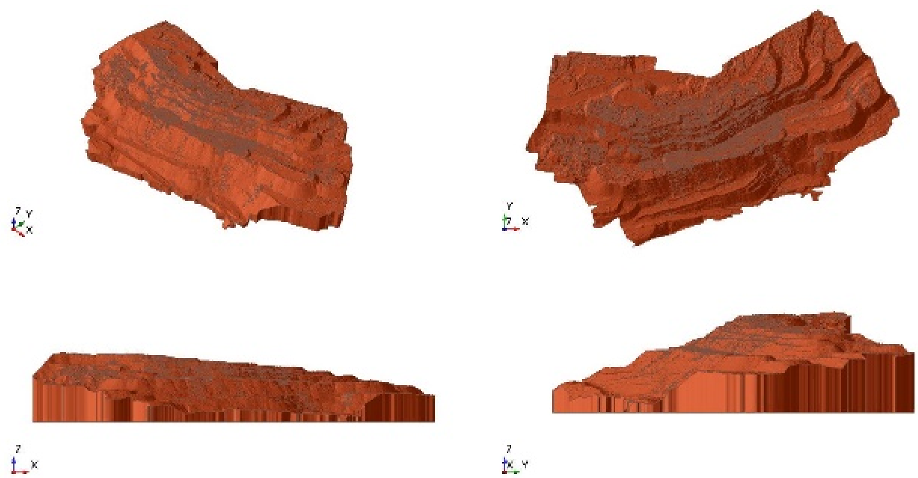


Figure 3. Detailed view of the internal dump.

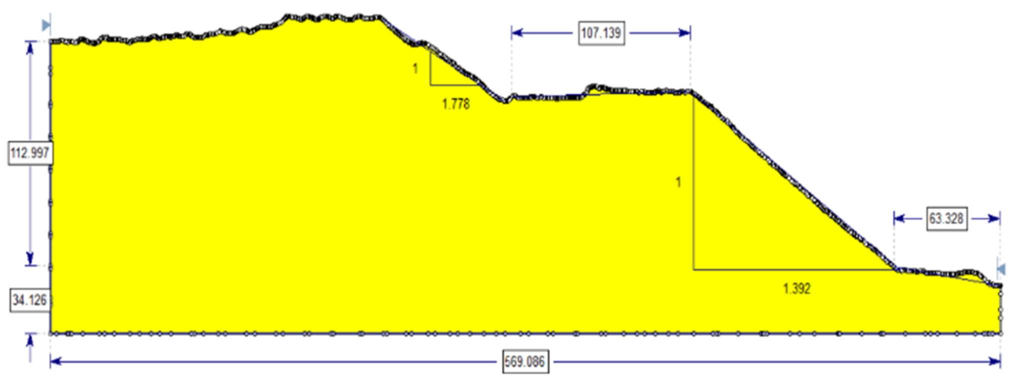


Figure 4. Geometry parameter details for the critical section.

The Bishop simplified technique is typically used for circular slip surfaces. Janbu's simple approach is used for both circular and non-circular failure surfaces, with the factor of safety determined by horizontal force equilibrium [13].

Models were constructed using SLIDE-3D software (2022), and the slope stability was analyzed. LEM analysis was performed under both static and dynamic conditions.

2.5. Numerical modelling

The *FLAC* of Itasca Inc., a finite difference solver based on continuum numerical modelling, was used to assess the state of stress and strain distribution in the dump mass under prevailing boundary conditions and was also used to compare the safety factor obtained through LEM approaches. The shear strength reduction (SSR) method was used for dump slope stability evaluation in 2-dimensional and 3-dimensional dump slopes. Typically, SSR is utilized in factor-of-safety calculations by progressively decreasing the material's shear strength to achieve limiting equilibrium on the slope. The safety factor was defined according to the following equation (1 & 2):

$$c^{trial} = \frac{c}{F^{trial}} \quad (1)$$

$$\phi^{trial} = arctan\left(\frac{\tan\phi}{F^{trial}}\right) \quad (2)$$

3. Results of DUMP stability analysis

This study conducted the analysis under gravity loading conditions, with height and slope angle under prevalent field conditions. Figure 5 presents the sensitive zone with a factor of safety, 1.24, under the gravitational loading condition. This shows a relatively stable dumps slope. External factors such as seismic conditions affect dumps slope stability [14]. It has been considered and analysed to assess the influence on the present dumps. The investigation region lies in earthquake zone II, and its horizontal seismic coefficient (k_h) is 0.16. Under pseudo-static analysis, the safety factor is calculated as 1.0. The profile under the pseudo-static condition of the slope is shown in Figure 6. The analysis was conducted to assess the safety factor under various seismic coefficients, and Figure 7 shows the variation in the y-axis with decreasing value with increasing seismic coefficient in the x-axis. Table 2 presents the results of the static dump slope safety factor with 2D sections. Furthermore, the entire dump slope failure zone was identified using 3D modelling also.

Figure 8 presents the critical sections of the dump slope, which were selected for detailed stability analysis. These data were exported from the *SLIDE-3D* software for stability analysis. The global critical slip surface approach has been used for 2D and 3D modelling. Ten sections were generated from the zone of interest with a higher potential towards failure for further investigation and detailed study. The 3D and 2D models assigned uniform material properties for the analysis.

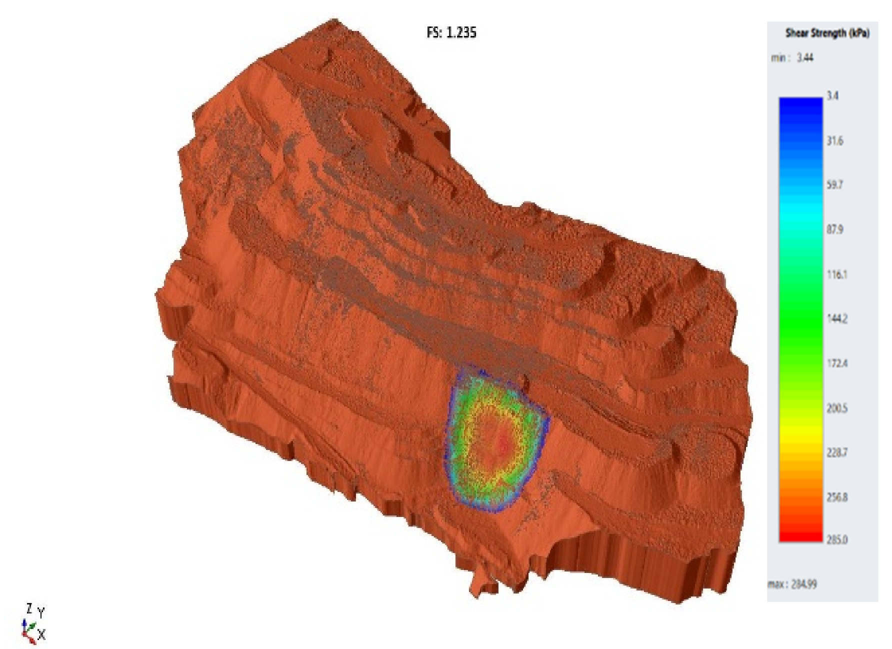


Figure 5. Slide-3D model showing the critical zone of failure.

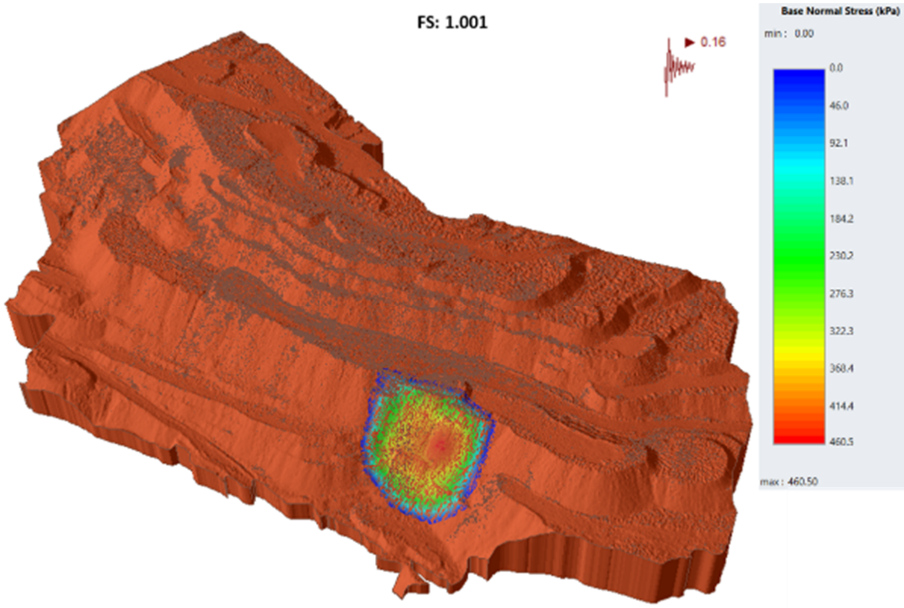


Figure 6. Slope stability analysis with seismic loading.

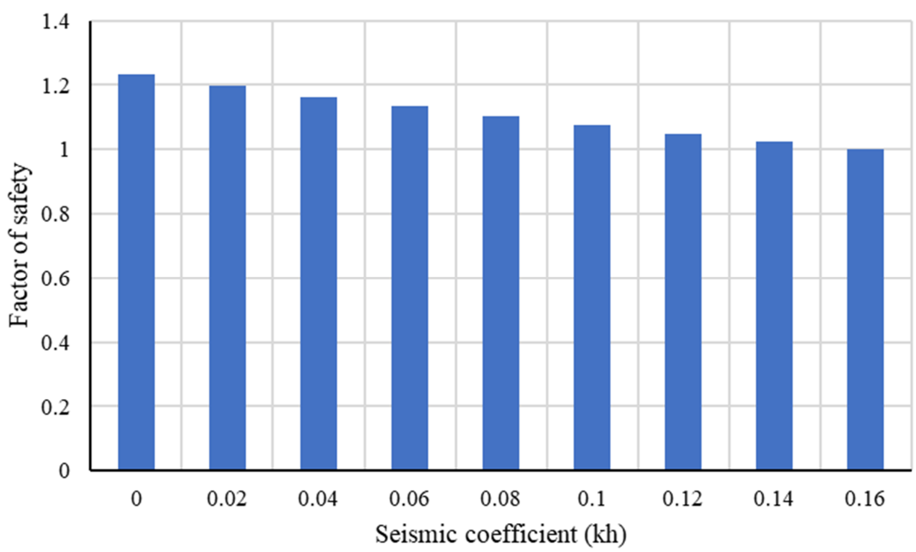


Figure 7. Slope stability variation with seismic coefficient.

3.1. Dump slope stability for the failure zone

We selected ten sections, and conducted a detailed analysis using 2D approaches in LEM and numerical methods. We observed that the factor of safety value in the 2D analysis was greater than the value obtained in the 3D analysis in a few sections. However, in sections 7, 8, and 10, it was observed that the safety factor is of higher value in 3D analysis than the 2D methods. In view of comparing results under LEM and numerical methods, Section 3 was considered, and similarity in the potential failure plane was observed in Figure 11.

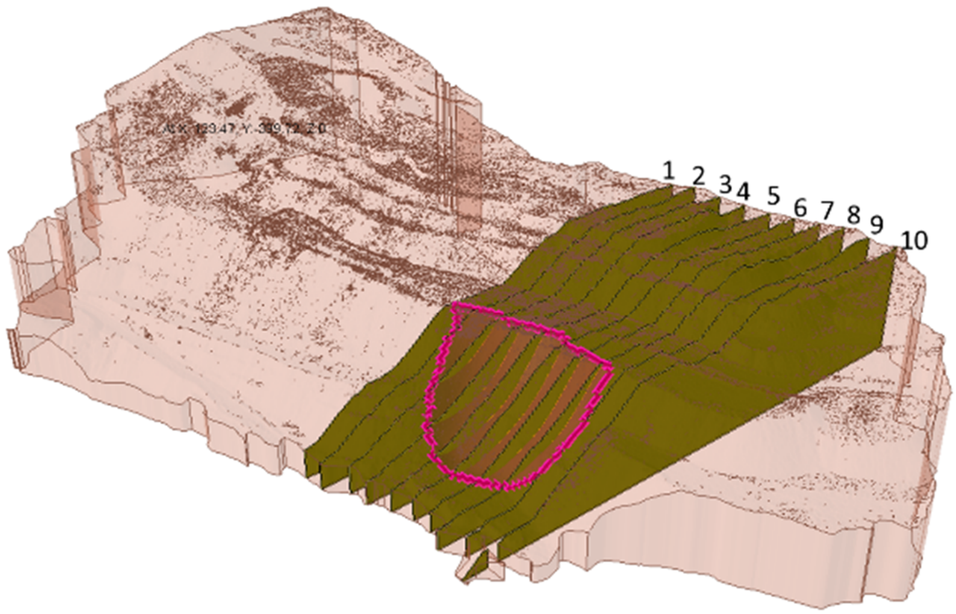


Figure 8. Failure zone along section created for the detailed slope stability analysis.

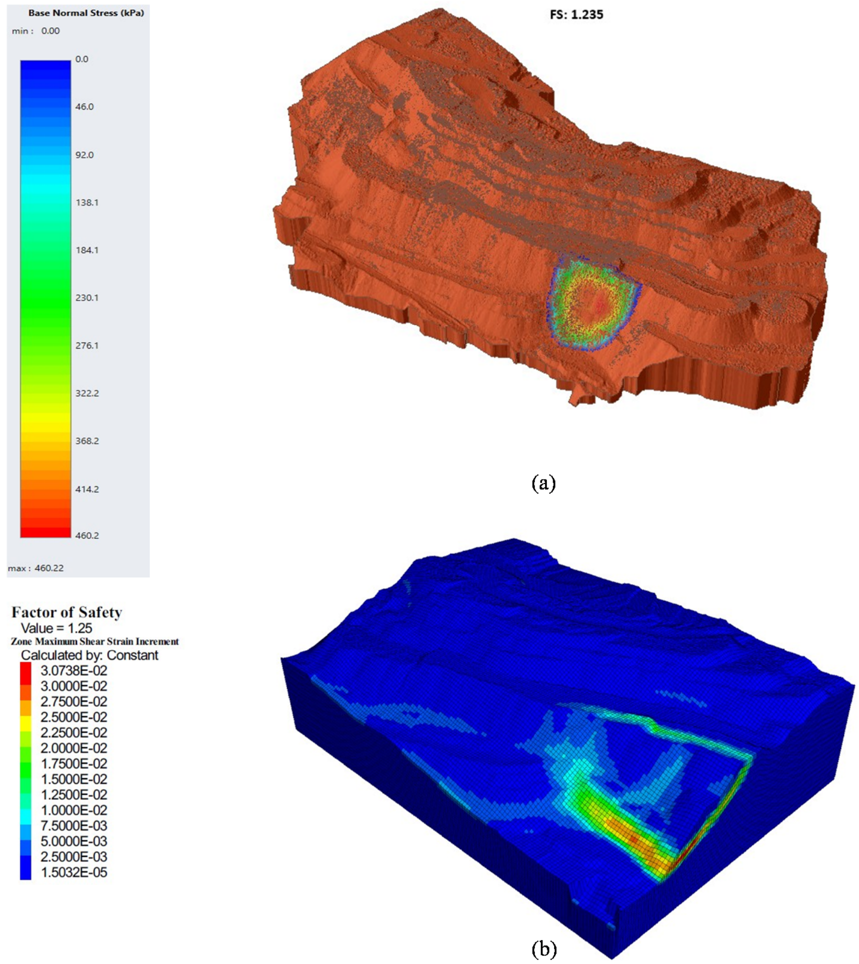
3.2. Critical zone validation using numerical modelling

This study used a numerical modelling method for identifying critical zone within the dumps. The shear strength reduction (SSR) method was used for the calculation of the factor of safety. LEM approach and numerical analysis identified the zone of potential failure for the same dump geometry. It was found that it indicates the critical zone lies within the geometry, and both approaches zoom in the same area with accuracy. The critical zone identified using numerical approaches is shown in Figure 9, and it is seen that the factor of safety is 1.25. The overall displacement within the critical zone is 0.47 m, shown in Figure 10.

As discussed in the first part of this work, once a critical zone within the dump mass is identified, the next task of the field engineers is to take appropriate action, particularly the remedial measures, to make dumps more stable for the future. The strategy is evolved by combining the outcome observed in the LEM and numerical approaches and implemented in the field. The cumulative displacement shown in Figure 10 of around 0.47 m happens to be addressed in view of effectively guarding the dumps mass for further movements.

Table 2. Failure zone along slope stability results

Sections	Bishop Simplified	Janbu Simplified	Spencer	Numerical modelling
Section-1	1.47	1.38	1.46	1.38
Section-2	1.50	1.41	1.50	1.42
Section-3	1.48	1.39	1.48	1.41
Section-4	1.34	1.25	1.33	1.26
Section-5	1.24	1.16	1.23	1.17
Section-6	1.21	1.14	1.21	1.14
Section-7	1.17	1.10	1.16	1.10
Section-8	1.21	1.14	1.20	1.12
Section-9	1.24	1.16	1.24	1.14
Section-10	1.21	1.15	1.21	1.14



(a)

(b)

Figure 9. Numerical validation of failure zone.

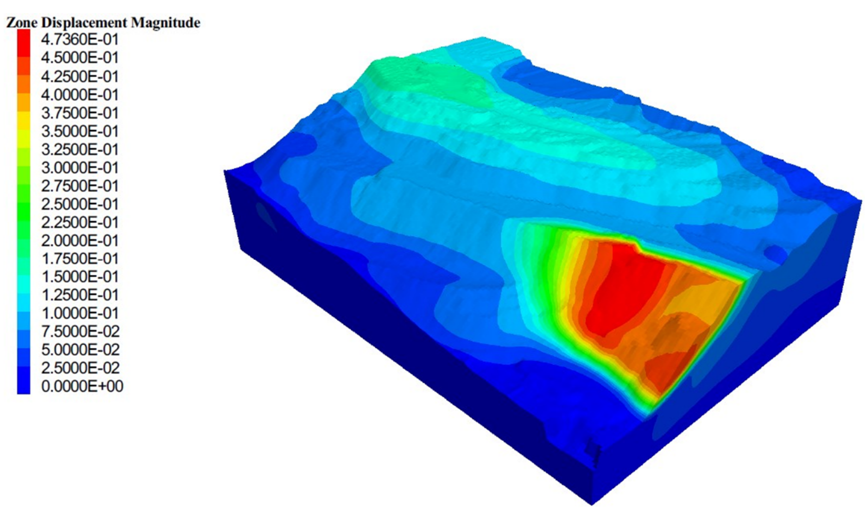
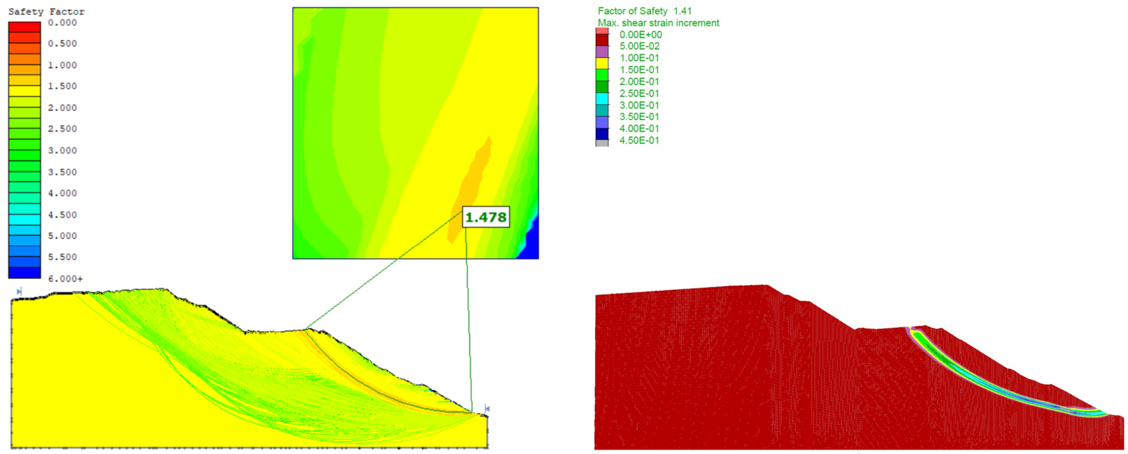


Figure 10. Critical zone overall displacement.



(a) (b)

Figure 11. Slope stability analysis for dump Section 3 (a) limit equilibrium analysis, and (b) finite difference analysis.

3.3. Slope stabilisation approach

The initial estimates for section number 7 geometry within the critical zone had a safety factor of 1.17. We have identified to work out how much improvement of the safety factor would be in view of addressing changes in the geometry pattern for further dumping within the space. Thus synthetically material was filled on the sloping side of the geometry, and numerical simulation was carried out to understand the state of change of stress-strain pattern and safety factor. Many possible combinations of changes in the geometry were undertaken to assess the optimality of the factors critically influencing. The target was to develop an optimal combination of the geometry parameters so that the study can effectively suggest field engineers for possible dumping in the following stages achieving a higher safety factor.

Three parameters on the geometry have been considered in this part for the simulations: slope angle, bench height, and safety width between the benches. The results in Figure 12 show all possible combinations of the safety width within the dumping benches. It is found that a 20 m safety width would be optimal in all possible combinations. The bench height was a maximum of 30 m for these combinations of the study, and the slope angle may be kept below 38°.

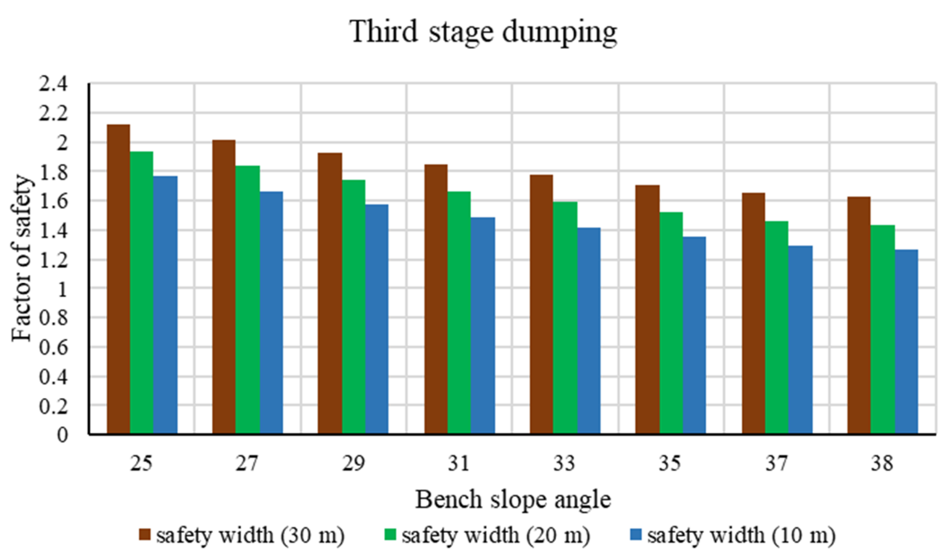


Figure 12. Slope parametric study for the stable slope design.

Considering the above analysis, the proposed geometry for Section 7 with optimal combinations of the geometry shown in Figure 13 (b) and factor safety is enhanced to 1.63, and it has been compared with the original Section 7 before changes of the geometry were undertaken in Figure 13 (a).

4. Discussion

The investigation has followed a framework to devise a solution for the field engineers for quick safety appraisal of the dumps. It has been tried with tested approaches, namely LEM and FDM. The 2D-based approaches considering plane-strain approximation overlook many important stress components within the 3D actual dumps mass. Therefore, the need for better approaches using 3D-based methods was felt and worked out in this study.

The factor of safety estimation using the LEM approach considers the upper and lower bound in calculating the safety factor. In the numerical analysis, the shear strength reduction technique is followed to progressively observe how the shear strength values' reduction impacts the state of conditions within the dumps mass, as shown in Equations 1 and 2. 3D-based approaches in this study have considered a realistic simulation of the dump's mass behaviors under the self-weight and the external loading factors.

This investigation helps identify failure zones in the dump's mass. This method is cost-effective and relatively cheaper than slope stability radar (SSR) systems and other systems used in the mines for dumps monitoring. The set-up used in this study conforms with the carbon-neutral approach and is very fast in data acquisition. The mobility, portability, and preciseness in the data accuracy are the potential pointers that this approach will be helpful for field applications.

This study introduces a quick, efficient slope stability estimation method involving a lower computational facility. It comes up with the identification of critical failure zone in the mine dumps, which will be a helpful way for the field mining engineers to manage the dumps in safer ways.

The methods proposed pipeline approaches using high precision UAV data of the actual mine dump 3D geometry and seamlessly fitting into the numerical modelling toolbox and providing a quicker insight about the safety and stability of the mine dumps.

This approach may change how slope stability analysis has been done in the past and propose a low-cost method. Usage of 3D reconstruction method from 2D images is not very much used in the mine dump stability analysis, and we have included the 3D reconstruction method used in the back-end of the investigation with some details (Figure 2) and an additional 3D numerical modelling tool is used for the critical zone numerical validation.

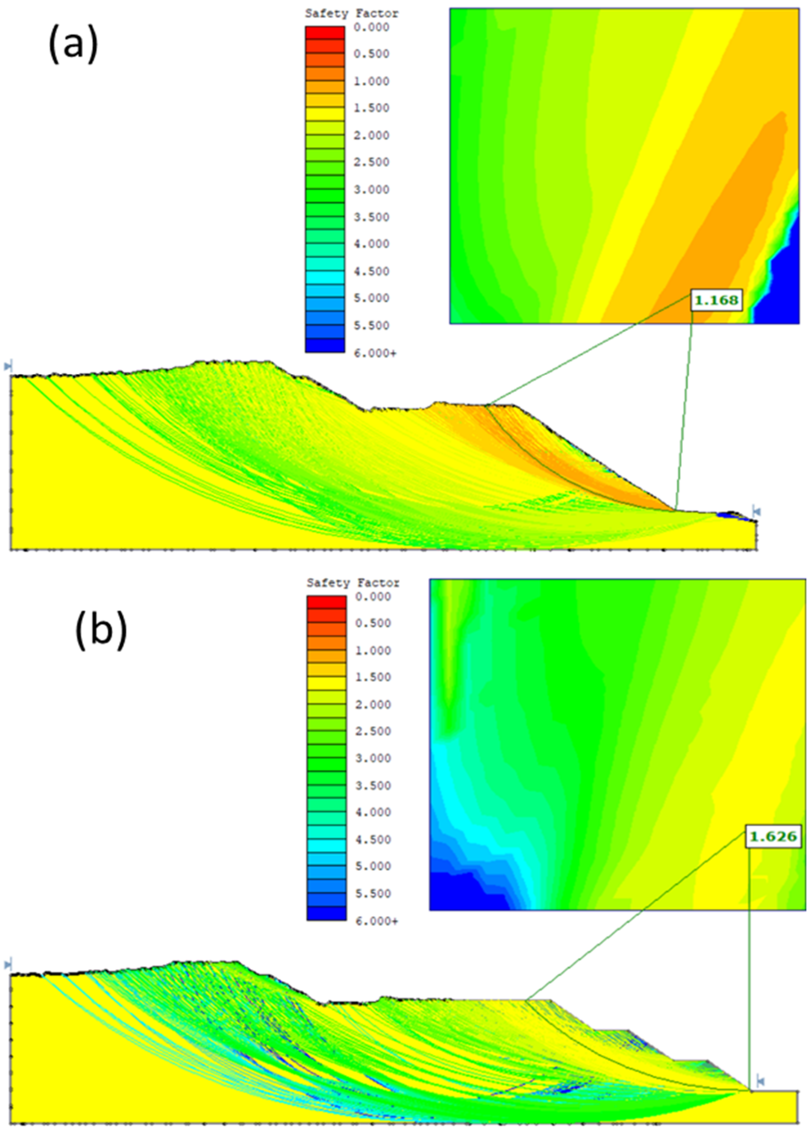


Figure 13. 2D slope stability analysis of the dump slope for section 7 (a) present condition (b) stable slope after optimum parameter design.

5. Conclusions

Based on this study, the following conclusions were drawn:

The stability of the internal dump depends on the overburden material shear strength, the dump height, and the slope angle. The study has come out with a swift approach and smooth system for a quick appraisal of the state of stability of the dump mass by identifying potential failure zone within the spatial extent of the geometry. The point cloud average spacing between the points in 3D space for the present system was 13 cm.

The stability analysis of the 2D section was observed insufficient for determining the area of failure zone identification. Hence, 3D modelling is essential for slope stability analysis. Hence, 3D approaches for LEM and numerical study were followed and done for the present mine dumps.

The internal dump was stable under static conditions; its safety factor was 1.24. The seismic loading reduces the factor of safety to 1.0. Therefore, there is a need for slope stabilisation.

The parametric study shows optimum geometric parameters: a bench height of 30 m, a bench slope angle of 38°, and a safety width between the two benches of 20 m. The optimum dump slope safety factor is 1.6, indicating better slope stability performance.

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References

[1]. S. Layek, V. G. K. Villuri, R. Koner, and K. Chand, "Rainfall & Seismological Dump Slope Stability Analysis on Active Mine Waste Dump Slope with UAV," *Advances in Civil Engineering*, Vol. 2022, 2022.

[2]. T. Gupta, R. Rai, A. Jaiswal, and B. K. Shrivastva, "Sensitivity Analysis of Coal Rib Stability for Internal Mine Dump in Opencast Mine by Finite Element Modelling," *Geotechnical and Geological Engineering*, Vol. 32, No. 3, pp. 705–712, Jun. 2014.

[3]. D. Verma, A. Kainthola, S. S. Gupte, and T. N. Singh, "A Finite Element Approach of Stability Analysis of Internal Dump Slope in Wardha Valley Coal Field," *American Journal of Mining and Metallurgy*, Vol. 1, No. 1, pp. 1–6, 2013, doi: 10.12691/ajmm-1-1-1.

[4]. A. K. Bharati, A. Ray, M. Khandelwal, R. Rai, and A. Jaiswal, "Stability evaluation of dump slope using artificial neural network and multiple regression," *Eng Comput*, Vol. 38, pp. 1835–1843, Aug. 2022.

[5]. A. K. Dash, "Analysis of accidents due to slope failure in Indian opencast coal mines." Current Science (00113891). 7/25/2019, Vol. 117 Issue 2, pp 304-308. 5p.

[6]. P. Kumar Behera, K. Sarkar, A. Kumar Singh, A. K. Verma, and T. N. Singh, "Dump Slope Stability Analysis-A Case Study," 2016.

[7]. M. D. Fredlund, D. G. Fredlund, and L. Zhang, "Moving from 2D to a 3D Unsaturated Slope Stability Analysis."

[8]. R. Rai, S. Kalita, T. Gupta, and B. K. Shrivastva, "Sensitivity Analysis of Internal Dragline Dump stability: Finite Element Analysis," *Geotechnical and Geological Engineering*, Vol. 30, No. 6, pp. 1397–1404, Dec. 2012.

[9]. R. Koner, "Estimation of Optimum Geometric Configuration of Mine Dumps in Wardha Valley Coalfields in India: A Case study," *Journal of Mining and Environment*, Vol. 12, No. 4, pp. 907–927, Sep. 2021.

[10]. S. S. C. Congress and A. J. Puppala, "Geo-technical slope stability and rockfall debris related safety assessments of rock cuts adjacent to a rail track using aerial photogrammetry data analysis," *Transportation Geotechnics*, Vol. 30, Sep. 2021.

[11]. S. S. C. Congress, A. J. Puppala, P. Kumar, A. Banerjee, and U. Patil, "Methodology for Resloping of Rock Slope Using 3D Models from UAV-CRP Technology," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 147, No. 9, Sep. 2021.

[12]. A. Falamaki, A. Shafiee, and A. H. Shafiee, "Under and post-construction probabilistic static and seismic slope stability analysis of Barmshour Landfill, Shiraz City, Iran," *Bulletin of Engineering Geology and the Environment*, Vol. 80, No. 7, pp. 5451–5465, Jul. 2021.

[13]. B. Poulsen, M. Khanal, A. M. Rao, D. Adhikary, and R. Balusu, "Mine Overburden Dump Failure: A Case Study," *Geotechnical and Geological Engineering*, Vol. 32, No. 2, pp. 297–309, Apr. 2014.

[14]. R. Koner and D. Chakravarty, "Evaluation of Seismic Response of External Mine Overburden Dumps." *In Proceedings of the 5th International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, California.*

[15]. Chai, S., 2022. Maximum height estimation for mine waste dumps. *Journal of the Southern African Institute of Mining and Metallurgy, 122(10*), pp. 579-586.

[16]. Hao Wang, Jianhong Zhang, and Honglin Lin (2022) Satellite-based analysis of landfill landslide: the case of the 2015 Shenzhen landslide, *International Journal of Geotechnical Engineering, 16:3, 293-300.*

[17]. Rai, R., Khandelwal, M., and Jaiswal, A. Application of geogrids in waste dump stability: a numerical modeling approach. Environ Earth Sci 66, 1459–1465 (2012).

[18]. Tarun Kumar Rajak, Laxmikant Yadu, Sandeep Kumar Chouksey, and Pankaj Kumar Dewangan (2021) Stability analysis of mine overburden dump stabilized with fly ash, *International Journal of Geotechnical Engineering*, 15:5, 587-597, DOI: 10.1080/19386362.2018.1503780.

[19]. Ranjan, V., Sen, P., Kumar, D. *et al*. Enhancement of mechanical stability of waste dump slope through establishing vegetation in a surface iron ore mine. Environ Earth Sci 76, 35 (2017).

[20]. Westoby, M.J. *et al.* "'Structure-from-Motion' Photogrammetry: A Low-Cost, Effective Tool for Geoscience Applications." *Geomorphology, Vol. 179, 2012, pp. 300-314*.

[21]. Lato, M. *et al*. "Rock Bench: Establishing a Common Repository and Standards for Assessing Rockmass Characteristics Using LiDAR and Photogrammetry." *Computers & Geosciences, vol. 50, 2013, pp.* 106-114, https://doi.org/10.1016/j.cageo.2012.06.014. Accessed 5 Jul. 2023.

[22]. Kong, Deheng *et al*. "Development and Application of UAV-SfM Photogrammetry for Quantitative Characterization of Rock Mass Discontinuities." *International Journal of Rock*

Mechanics and Mining Sciences, Vol. 141, 2021, p. 104729.

[23]. Bar, Neil *et al*. "Rapid and Robust Slope Failure Appraisal using Aerial Photogrammetry and 3D Slope Stability Models." International Journal of Mining Science and Technology, Vol. 30, No. 5, 2020, pp. 651-658.

[24]. Kumar, N.S. and Ismail, M.A.M., 2020, May. 3D limit equilibrium method for rock slope stability analysis using generalized anisotropic material model. In Proceedings of the 2020 International Symposium on Slope Stability in Open-Pit Mining and Civil Engineering, Australian Centre for Geomechanics, Perth, WA, USA (pp. 12-14).

[25]. E. Kotsi *et al*., "Using UAS-Aided Photogrammetry to Monitor and Quantify the Geomorphic Effects of Extreme Weather Events in Tectonically Active Mass Waste-Prone Areas: The Case of Medicane Ianos," Applied Sciences, Vol. 13, No. 2, p. 812, Jan. 2023.

[26]. Valkaniotis, Sotiris *et al*. "Mapping an Earthquake-Induced Landslide Based on UAV Imagery; Case Study of the 2015 Okeanos Landslide, Lefkada, Greece." Engineering Geology, vol. 245, 2018, pp. 141-152. Accessed 5 Jul., 2023.

[27]. J. Hao, X. Zhang, C. Wang, H. Wang, and H. Wang, "Application of UAV Digital Photogrammetry in Geological Investigation and Stability Evaluation of High-Steep Mine Rock Slope," Drones, Vol. 7, No. 3, p. 198, Mar. 2023, doi: 10.3390/drones7030198.

[28]. Eltner, A., Kaiser, A., Castillo, C., Rock, G., Neugirg, F., and Abellán, A., 2016. Image-based surface reconstruction in geomorphometry–merits, limits and developments. Earth Surface Dynamics, 4(2), pp. 359-389.

[29]. Chen, L. C., Lo, C. Y., Liu, C. L., and Chen, A. J.: Orientation modelling by matching image templates of a GCP database, Proc. 21st ACRS, 21, 2000.

[30] Nesbit, P.R. and Hugenholtz, C.H. Enhancing UAV–SfM 3D Model Accuracy in High-Relief Landscapes by Incorporating Oblique Images. Remote Sens. 2019, 11, 239.

[31]. Chand, K., Koner, R. Failure Zone Identification and Slope Stability Analysis of Mine Dump Based on Realistic 3D Numerical Modeling. Geotech Geol Eng (2023).

پایداری شیب انباشتگاه داخلی باطله معدن و شناسایی منطقه شکست با استفاده از مدل سازی سه بعدی

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چکیده:

در معدن روباز، ایمنی زباله‌های داخلی یک نکته مهم در چشم‌انداز اقتصادی کل پروژه است. در چندین مطالعه مشخص شده است که رسوب بدون برنامه ریزی و تصادفی مواد بیش از حد، دلیل اصلی حوادث ناگوار و شکست است. این مطالعه از وسایل نقلیه هوایی بدون سرنشین (پهپادها) برای نقشه برداری از زباله‌های مین استفاده کرد و هندسه سه بعدی دقیق آن برای ارزیابی ایمنی با استفاده از روش‌های عددی بازسازی شد. چارچوبی برای ارزیابی و شناسایی منطقه بالقوه ناپایداری در زباله‌های معدن پیشنهاد شده است. این مطالعه در معدن روباز در میدان زغالسنگ Raniganj در Paschim Bardhaman در بنگال غربی، هند انجام شد. این مطالعه ایمنی تخلیه داخلی را با استفاده از روش تعادل حد سه بعدی و روش‌های عددی ارزیابی کرد. در نهایت، پارامترهای بهینه برای هندسه زباله‌های معدن تحت شرایط غالب ژئومعدنی سایت معدن پیشنهاد می‌شود. چارچوب پیشنهادی در اینجا برای ارزیابی مناطق بحرانی در زباله‌های معدن مقرون به صرفه، آسان برای استفاده، سریع و کارآمد است.

کلمات کلیدی: انباشتگاه باطله معدن، پایداری شیب، مناطق بحرانی، ضریب ایمنی، روش تعادل حدی.