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Mine Active Internal Dump Susceptible Zone Identification using MMO Technique

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Abstract

In open-cast mines, a dump stability analysis is tedious for engineers. In the past, dump slope disasters have caused a loss of human resources and mining machinery. Sometimes, the machinery is stuck in a debris flow. Therefore, Susceptible Zone Identification (SZI) and its treatment are essential for the mining industry. This study aims to identify multiple failure zones in a large dump using a Multi Model Optimization (MMO) technique. Realistic 3D modelling is essential for accurate stability evaluation. Researchers have used 2D numerical modelling for dump slope stability analysis in many studies. However, the geometry of mine dumps is irregular because of unplanned Overburden (OB) material deposition. If the real 3D geometry of the dump is not considered, the slope stability results may confound researchers. Therefore, this study aimed to analyze the stability of the Sonepur Bazari mine dump with multiple failure zones using realistic 3D modelling. The Limit Equilibrium Method (LEM) and Finite Difference Method (FDM) were employed for slope stability analysis. This study investigated different critical zones in the entire dump. The advantage of this combined approach is that large internal and external dump failure zones can be quickly identified, and decisions can be made for mitigation.

Keywords: *Dump Stability Analysis, 3D Modelling, Susceptible Zone Identification, UAV Photogrammetry*

1.0 Introduction

Large open-cast mine projects generate a massive Overburden (OB) in the active mining areas. The OB material is managed by internal dumping, also called internal dump. OB generation depends on the mine stripping ratio and coal production rate. Therefore, active internal dump monitoring is essential for the open-cast industry to avoid dump slope failure. Many dump slope failure disasters have occurred in India between 1920 and 2023 (Figure 1). Unplanned dumping causes dump slope failure. 2016 Rajmahal experienced dump slope failure due to unplanned dumping and weak ground floor conditions. Owing to debris flow, 23 mining persons were killed, and many mine machinery were stuck in the debris[1,2], as shown in Figure 2. Different types of dumping approaches are used for OB management, including internal and external. This man-made structure consists of loose and broken rock and soil materials. Therefore, this geo-structure had no natural strength. Therefore, a dump stability analysis is a basic requirement for human and machinery safety.

Recently, substantial work has been conducted on existing OB dumps, such as dump slope failure behaviour analysis[3], stability and deformation analysis[4], and dump critical zone identification[5]. Two-Dimensional (2D) and Three-Dimensional (3D) numerical modelling tools are widely used to evaluate slope stability. The advantages of 2D numerical simulation are its fast iteration process and easy slope stability analysis, and it does not require a high-end computing configuration. However, the 2D slope stability analysis results are

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Figure 1. Dump slope failure accident from 1921 to 2020.

useful for dump slope design. The 2D simulation did not identify the entire dump critical zone or its stability. Recently, many researchers have used 3D numerical modelling for dump and hill slope stability analyses[6,7]. 2D numerical simulation has some limitations for slope stability analysis, resulting in misleading researchers. Occasionally, the 2D numerical analysis results confound site engineers. Therefore, 3D numerical modelling is vital for identifying the entire dump susceptible zone.

Figure 2. Mine machinery is stuck in debris flow[8].

Dump slope monitoring using Slope Stability Radar (SSR) is popular in large open-cast projects[9]. However, capital investment in equipment is not feasible for open-cast mine projects that monitor OB dumps. The limitation of SSR is that it covers only a small area of the dump. This technology is unsuitable for the open-cast industry for rapid monitoring of the entire dump slope. Unmanned Aerial Vehicle (UAV) photogrammetry is popular for slope change detection and displacement monitoring[10]. For rock slope stability analysis, Congress used a UAV and 3D LEM[11]. The mine dump Area of Interest (AOI) was analyzed using a UAV and GIS[4]. UAV Photogrammetry and Structure from Motion (SfM) computer vision were used for mine slope 3D reconstruction and slope stability analysis[12]. Currently, UAV surveys are widely used to monitor infrastructure and geo-structural health.

A dump slope stability performance analysis under actual field conditions is challenging for geotechnical engineers. This study aims to develop a sustainable and reliable dump stability performance analysis methodology for actual field conditions. This study identified a large dump slope-susceptible zone using UAV photogrammetry and 3D modelling. The mine dump slope stability was analyzed using 3D and 2D numerical modelling, and the slope stability was analyzed using the 3D LEM and Shear Strength Reduction (SSR) method. This study used an intelligent particle swarm optimisation approach for dump susceptible zone identification. Slide-3D and Flac-3D numerical modelling applications were used for slope stability analysis and critical zone numerical validation. These results will be helpful for identifying the entire dump failure zone and their control measures based on dump site conditions.

2.0 Material and Methodology

An open-cast mine in the Eastern Coalfield was selected for this investigation. The locations of the study area are shown in Figure 3. The Sonepur Bazari Open-cast project covers the study area in the Eastern Raniganj Coalfields of Burdwan and West Bengal. It is easily accessible to the main transit lines 14 km from the G. T. Road. The average stripping ratio of the mine was 1:5.70, indicating effective extraction. As of April 1, 2015, the mineable reserve was 179.60 million metric tons, a significant energy resource. Mineable coal seams such as R-VII, R-VI, R-V, R-IV, and R-III/II, provide diversified and rich resources. The research area was 2,452.17 hectares, including the land needed for the extension to produce 8.0 MTY. This area is essential to the Eastern Part of Raniganj Coalfields' coal mining landscape and a centre of economic and industrial expansion.

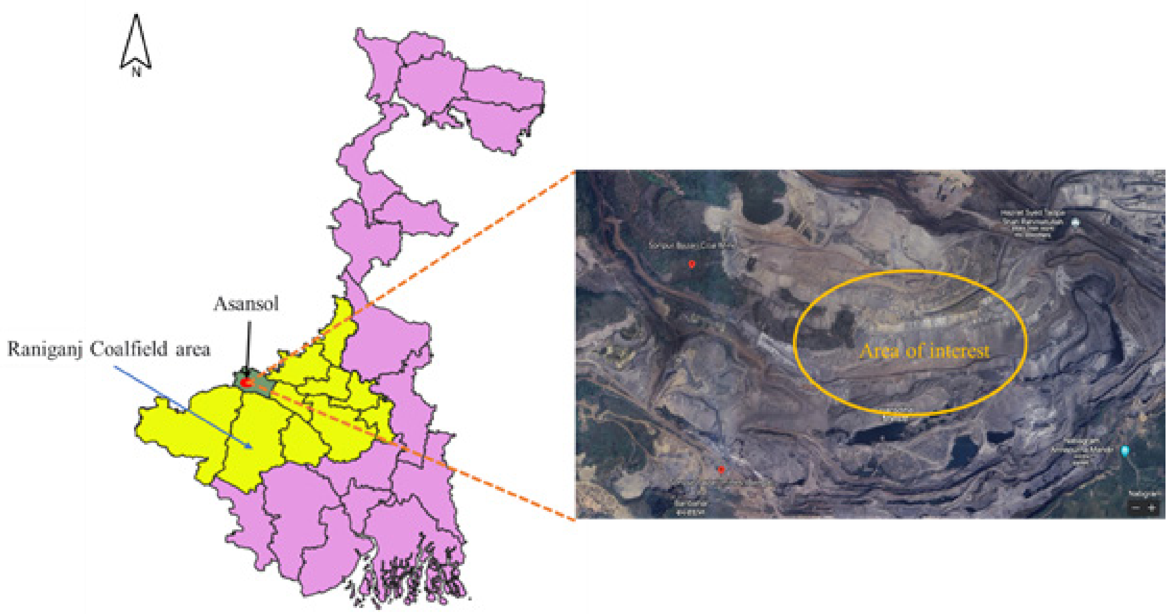

Figure 3. Location of the study area: Raniganj coalfield, West Bengal, India.

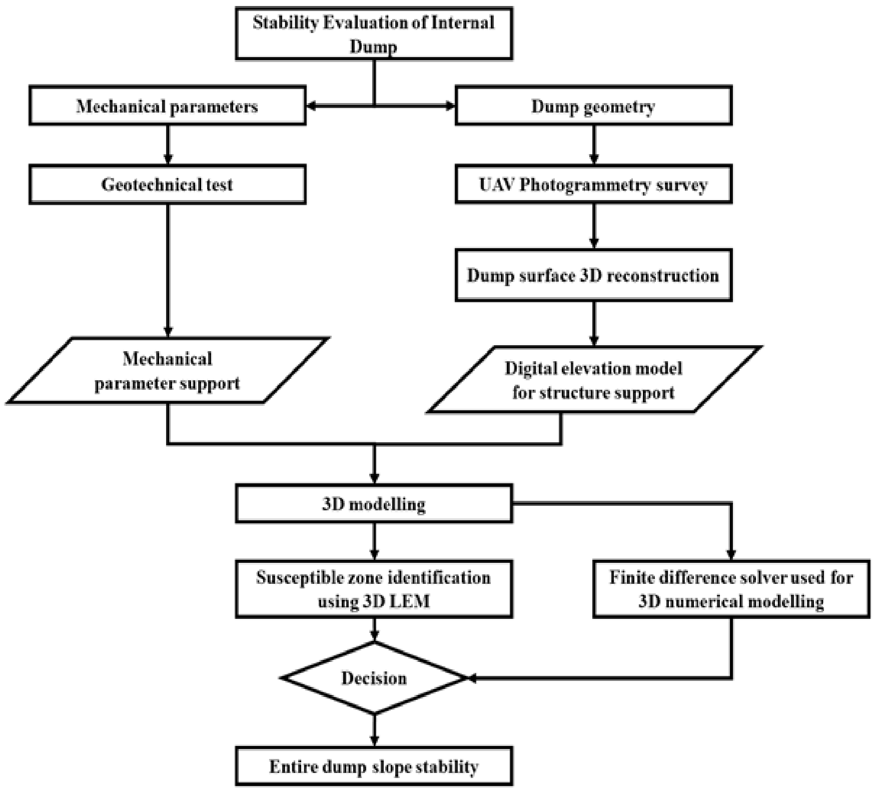

Figure 4. Scheme of large internal dump stability analysis

The aim of this study is to develop a sustainable approach for large dump failure zone identification using a combination of UAV technology and actual 3D modelling. Different types of investigations, such as geotechnical tests, UAV surveys, and 3D numerical modelling, are required to complete this task. An internal mine dump Digital Elevation Model (DEM) was generated using UAV photogrammetry. Finally, Slide-3D and Flac-3D numerical modelling tools were used to identify dump susceptible zones and calculate the Factor of Safety (FOS). As shown in Figure 4, the dump stability assessment scheme includes three steps: geotechnical investigation, UAV photogrammetry, and 3D modelling. The three steps are described below.

2.1 Geotechnical Test

Geotechnical investigations are essential for OB material strength analysis[13,14]. This study conducted OB material laboratory testing according to Indian standards. Compaction and soil triaxial tests were performed in the laboratory to determine density (kg/m^3), friction angle (°), and cohesion (kPa). Table 1 lists the dump material properties used in the numerical simulation.

Table 1. Properties of the OB dump material

S. no.	Properties	value	Test
1	Unit weight (kN/m^3)	18.45	Soil compaction
2	Friction angle (°)	26.5	Soil triaxial
3	Cohesion (kPa)	50	Soil triaxial

2.2 UAV Photogrammetry Survey and 3D Reconstruction

For accurate dump slope stability analysis under real field conditions, an accurate digital elevation model of the dump surface is required. Image processing software must be used for the dump surface 3D reconstruction. Generally, 2D numerical analysis only considers the plain-strain condition for dump slope stability and may confound slope stability results. For the dump digital model generation UAV photogrammetry survey, a Ground Control Point (GCPs) measurement survey (using the total station) and image processing were used to complete this task. This study used UAV photography technology to collect images of mine dump surfaces (Figure 5). After image collection, a dump surface 3D model was constructed using image processing tools (Pix-4D Mapper and CloudCompare). For the dump surface 3D reconstruction, SfM computing algorithm was used. Figure 6 shows the process of dump surface digital elevation model generation. The entire internal dump covers an area of 0.5 km^2 with a total height of above 60 m. The UAV technology involves carrying a digital camera to acquire images. The S-path is used for dump image collection, as shown in Figure 5. Using this path, the dump images easily overlapped by 75% in the horizontal direction and 65% in the vertical direction to increase image acquisition accuracy[15,16]. For image collection, the midday window time was used so that the RGB image could generate an accurate dump surface 3D reconstruction.

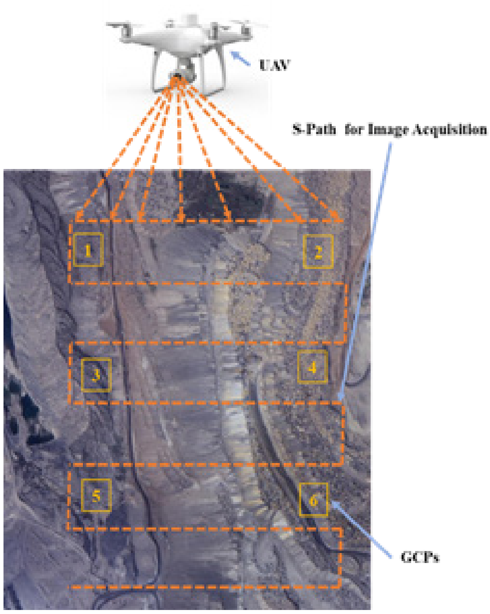

Figure 5. Dump image acquisition using the UAV survey.

Finally, the generated digital elevation model provided topographic structural support for 3D modelling. Image processing obtains three data streams: the (DEM), Point Cloud Data (PCD), and Standard Tessellation Language (STL). The manual dump measurement method requires considerable manpower and material resources, and risk-prone zones cannot be monitored through manual surveys. The failure problem of a dump slope becomes increasing serious over time. Therefore, it is necessary to develop a rapid and accurate survey method. This approach will be useful for generating a risky-zone digital elevation model.

2.3 Three-Dimensional Modelling

2D numerical modelling has been used in the past for dump slope stability[17–19]. 2D numerical modelling has some limitations. Hence, the primary objective of this study was to concentrate on the implementation of realistic three-dimensional numerical modelling. For the entire dump stability and critical zone identification, 3D modelling is significant. The surface model of the dump obtained by

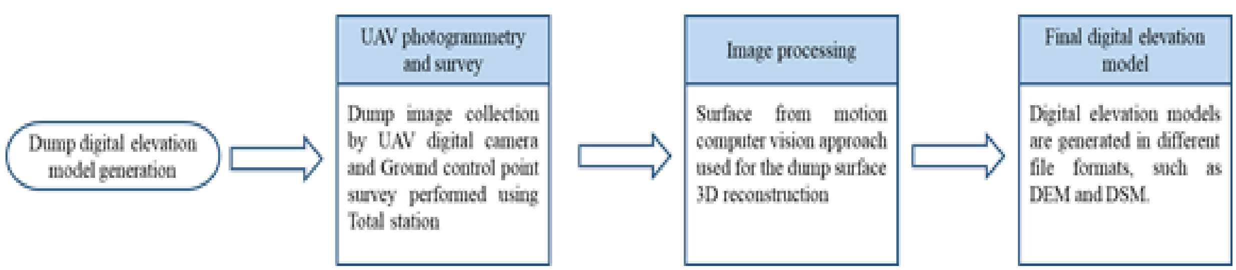

Figure 6. Dump surface 3D reconstruction process.

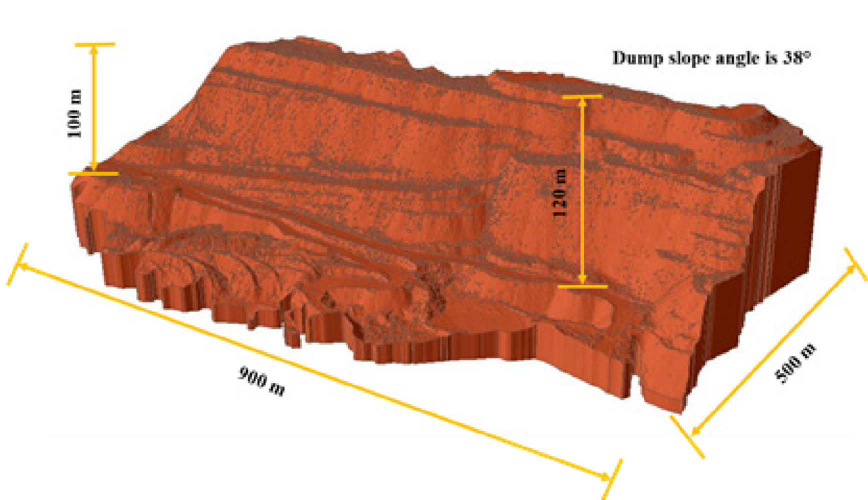

Figure 7. 3D modelling with dump geometry parameters.

photogrammetry was synthesized using stratum data, and Slide-3D and Flac-3D software were used for dump slope stability analysis. The AutoCAD file is imported into the modelling software for the realistic dump 3D model construction (Figure 7). A three-dimensional numerical model of the dump was established. The Slide-3D method evaluates dump slope stability using the MMO approach. The 3D limit equilibrium method was used. The Mohr-Coulomb failure criteria were used in the numerical modelling for slope stability analysis.

MMO approach was used for 3D slope slip surface analysis[20]. In this study, MMO approach was used for susceptible zone identification. This study used the spline search method for the slope slip surface, which is more flexible than other slip surface search methods. Particle Swarm Optimization (PSO) is a computational technique used in the swarm intelligence field. It is designed to efficiently locate an optimum solution within a given search space. MMO approach will help analyze the critical zone in a dump with a complex structure. Generally, slope stability analysis uses a single global minimum surface. However, slopes often contain multiple critical regions that can fail. A multi model PSO computing algorithm is used for multiple search surfaces.

The critical zone of the dump was validated using a finite difference numerical solver. The Shear Strength Reduction (SSR) approach was used to analyze the stability of the mine dump slope. Figure 7 shows the geometric parameters of the mine dump that directly reflect the safety factor of the dump slope and its critical zone.

In this study, the dump slope stability analysis included geotechnical tests, UAV photogrammetry, TS surveys, and 3D numerical modelling. Using the aforementioned geotechnical test and UAV photogrammetry, we obtained the mechanical parameters of the dump mass and its digital elevation model. We obtained the entire dump stability and critical zones after establishing a three-dimensional numerical model and conducting a numerical simulation.

3.0 Results

3.1 UAV Photogrammetry Survey and 3D Modelling

UAV photogrammetry technology was used to collect internal dump image data. The DJI Air 2S drone was selected for the dump image collection. The UAV completed photogrammetry of the entire dump over three flights, and the overall flight time was 50 min. For dump surface 3D reconstruction, 455 digital images were collected using a UAV digital camera. Each image was 20 megapixels in size. The entire area of the internal dump is covered in UAV photogrammetry, which is approximately 0.5 km^2. The flying height is 60 m above the top surface of the dump. A Ground Control Point (GCP) survey measured the actual RL level. Ground control point measurements are crucial for achieving precise reconstruction of the

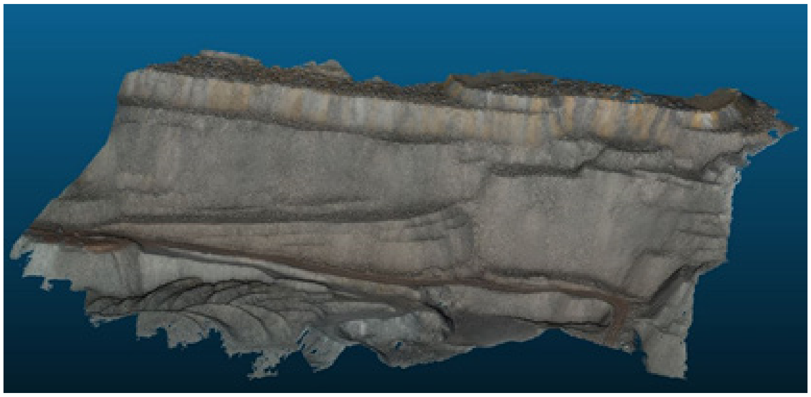

Figure 8. Dump surface 3D model generated using point cloud data.

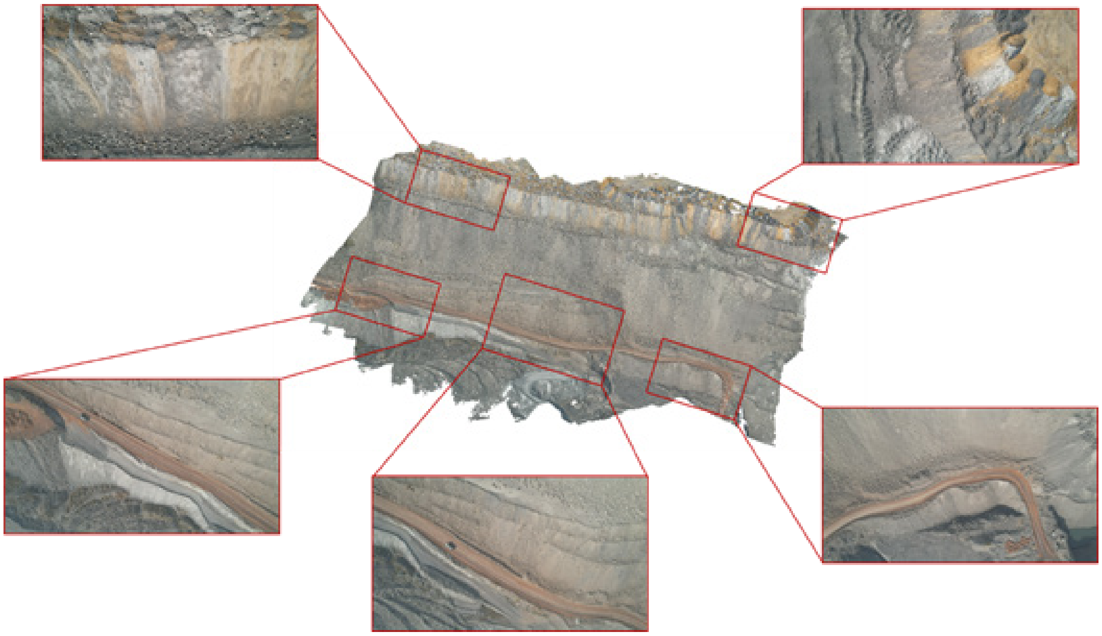

Figure 9. Dump surface 3D model with dump images.

(DEM) and generating point clouds [21]. Sokkia 330R Total Station (TS) was used in this investigation for the GCPs measurement. GCPs have been used to geo-reference digital 3D models. A minimum of three to four GCPs are needed to scale and enhance the accuracy of the 3D reconstructed model[15]. This work measured six GCPs using the TS survey over the dump slope region (Figure 5). These GCPs were imported into an image-processing tool to create a dump surface 3D reconstruction. In the three-dimensional model of the dump, the GCPs were used to correct the image control points, and finally, an accurate dump model was established, as shown in Figure 8. Figure 9 compares the dump surface 3D model with the dump images.

3.2 Dump Susceptible Zone Identification Using 3D Modelling

This study used the 3D LEM, and multiple susceptible zones were identified in the entire mine dump using the MMO approach. Figure 10 shows the three failure surfaces with a minimum FOS for the entire dump. Susceptible zone-1 has a minimum FOS, and zone-2 has a minimum FOS compared to zone-3. Six cross-sections were selected for

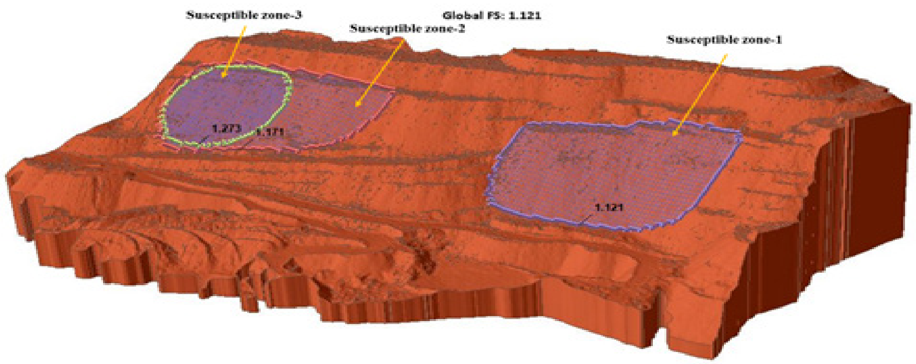

Figure 10. Identification of mine internal dump-susceptible zones using MMO.

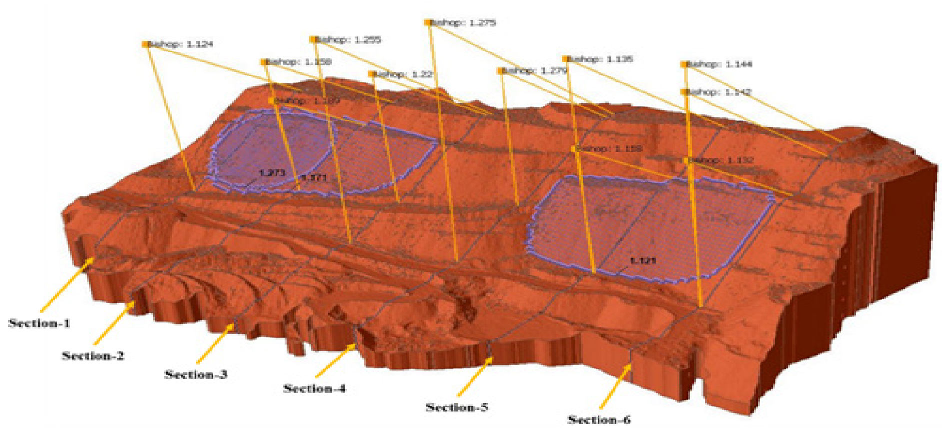

Figure 11. Entire dump stability with cross sections.

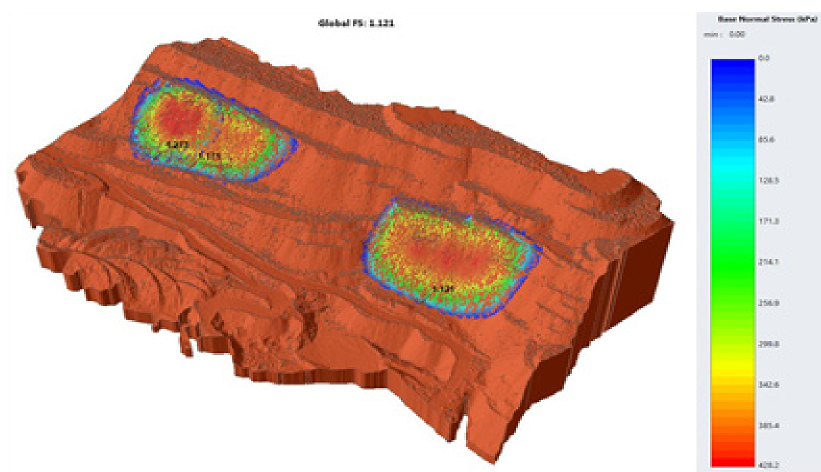

Figure 12. Shear stress of failure surfaces with three minimum FOS.

the slope stability analysis and MMO approach, as shown in Figure 11.

Figure 12 shows the shear stress for the three critical slip surfaces (the red and yellow regions correspond to high shear stress). In this figure, two susceptible zones (2 and 3) overlap between the two failure surfaces,

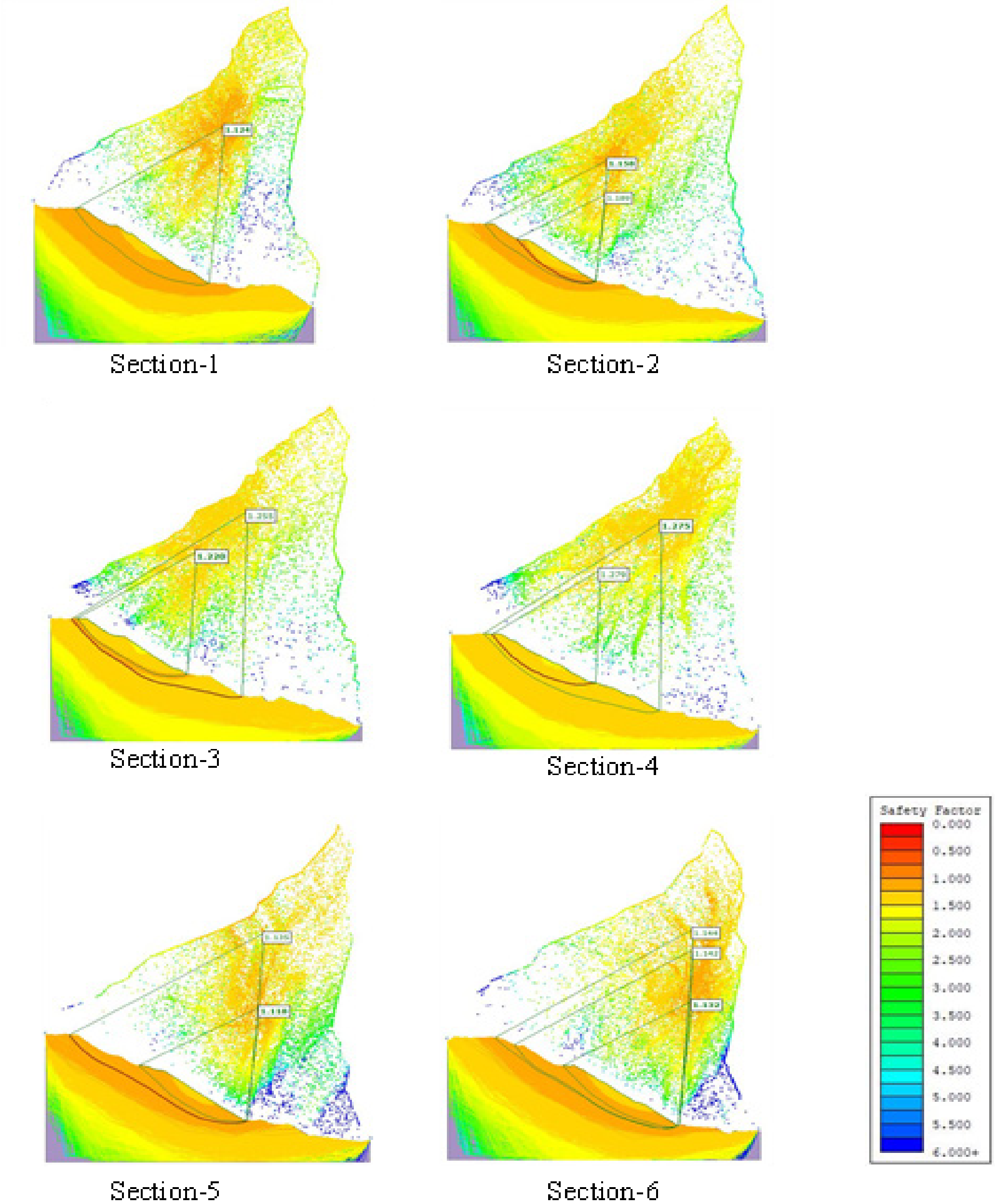

Figure 13. Dump 2D cross-section with stability analysis using MMO.

and in the third zone, there is high shear stress, which can be expected to represent the most critical region of the dump model.

This investigation observed that the 2D dump cross-sectional FOS was greater than that of the 3D modelling results. The 2D section shows only the slope-slip surface, as shown in Figure 13. 2D modelling is only capable of slope FOS analysis; however, failure zone identification and volume analysis 3D modelling are suitable for large dumps.

After the implementation of the MMO and failure zone identification for the entire dump, mining engineers can make decisions regarding slope stability. This study indicated that multiple failure zones exist in the dump.

The reason for the numerous failure zones is unplanned mine dumping.

3.3 Validation of Susceptible Zone

In this study, Flac-3D software was used for numerical validation, and the SSR method was used for dump slope stability (FOS) and critical zone identification. Three-dimensional stability analysis results were obtained, as shown in Figures 14 (a), (b), and (c). The legend column on the right in Figure 14 (a) shows multiple states or combinations of states, such as shear-n, shear-p, tension-n, and tension-p, among which shear is shear failure and tension is tensile failure. The red zone in the model represents the region with the highest risk and potential hazards. The primary failure mode observed in the bulk accumulation slope is shear failure. Consequently, the

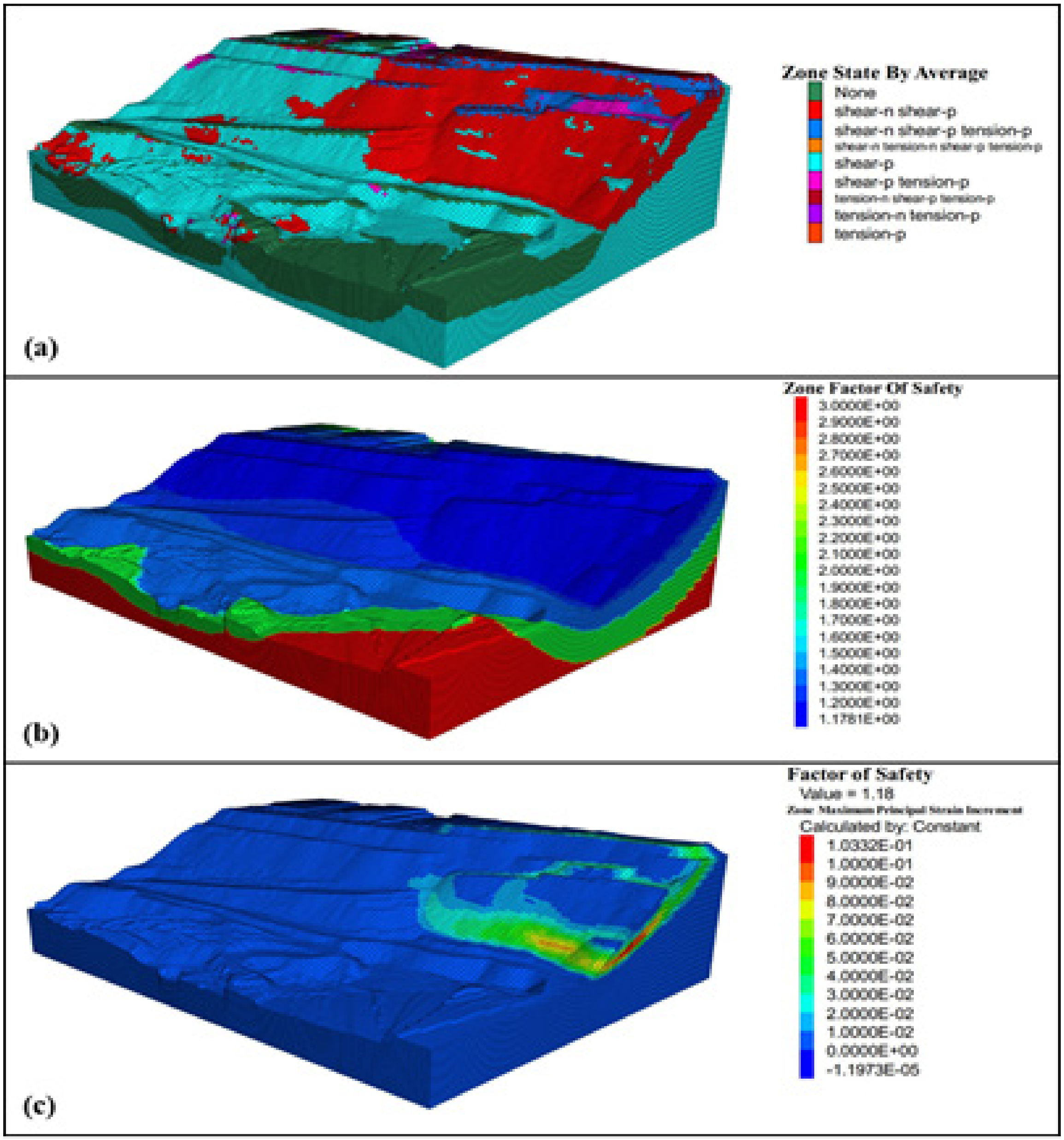

Figure 14. 3D numerical modelling: **(a)** entire dump shear zone analysis, **(b)** factor of safety contour mapping, and **(c)** susceptible zone identification using the SSR approach.

sky-blue and red zones include the shear-n and shear-p failure mechanisms. These two colours are concentrated at the highest position in the dump slope zone, indicating that the probability of shear failure in this zone is relatively high.

3D numerical modelling is a reliable approach for internal dump stability analysis. Figure 14 (b) shows the entire dump FOS contour map. The average safety factor for the entire dump slope was 1.178.

The three-dimensional analysis result reveals that the most hazardous region in the dump is a single bench formed by the OB dumping operation with a large height and bench angle. The stability coefficient of the entire dump is 1.18, which represents the stability coefficient of the location (Figure 14 (c)).

In this study, remote sensing photogrammetry technology was applied to rapid 3D reconstruction of the dump surface and identification of multiple failure zones in the dump. In addition, a three-dimensional dump surface digital elevation model was used for rapid modelling and slope stability analysis, which accurately grasped the stability of the large internal dump slope of the Sonepur Bazari coal mine and provided sufficient technical support for subsequent overburden disposal planning and slope failure mitigation.

4.0 Discussion

This investigation focuses on 3D modelling because the 2D numerical modelling tool provides only the slope slip surface and comprehensive stability. The stress profile also depends on geometry. Therefore, the 2D analysis approach was not chosen for the dump stability analysis. Multiple research investigations have provided evidence that the outcomes derived from three-dimensional stability calculations often exhibit a minor decrease compared to those obtained from two-dimensional calculations. This discrepancy may be attributed to the variations in the methods and dimensions used in the respective computations. The potential volume and area of debris failure may be calculated using a three-dimensional analysis, which provides a more precise representation of the geometric configuration and stress distribution of the slope (Figure 14(a)). The present work effectively constructed an accurate three-dimensional numerical representation of an internal dump inside a mine using a synergistic approach, including UAV technology and 3D modelling techniques.

In this investigation, the gravitational load was used for dump stability analysis. The actual field conditions were generated using computer vision for the identification of susceptible zones. This study did not include other factors that affect slope stability, such as rainfall and dynamic loading. The static loading condition was used for dump slope susceptible zone identification, and the dump FOS was 1.1. This indicates that the dump slope is stable under static conditions, but seismic events may be a trigger for failure. Therefore, the 1.2 FOS is significant for the dump's longer time stability under different conditions (rainfall and seismic)[22]. In this study, a digital elevation model was extracted from the results of UAV photogrammetry to establish a surface model of a mine's internal dump.

This combined approach is inexpensive for identifying the mine OB dump-susceptible zone. Dump risk-prone area stability can be easily analyzed without taking risks and going on the site. Large dump geometry data remotely accessed by UAV photogrammetry survey. To ensure precision and dependability, this study performed a comprehensive evaluation of the stability of the mine OB dump, verified the susceptibility zone FOS for the dump, and identified the stress state of the slope and the causes of failure.

5.0 Conclusion

The conventional approaches used in slope stability analysis aim to identify a single critical failure surface. However, it is often advantageous to explore several failure surfaces in real-world situations. This paper introduces and implements the MMO approach with 3D LEM analysis for a dump case. The susceptible zone results were compared with the 3D numerical modelling results.

Aerial photogrammetry technology was used to conduct a comprehensive survey and generate a three-dimensional model of the entire dump. This process involves the use of UAVs to capture aerial imagery, which is then processed to create a digital elevation model and three-dimensional representation of the dump. The complete investigation of dump stability used a methodology based on realistic 3D numerical modelling.

A stability study was conducted, resulting in a calculated stability factor of safety for the whole dump of 1.18. The stress-strain distribution law of the dump slope and the stress distribution structure were established via the process of cutting and comparative analysis of the data obtained from three-dimensional analysis. This study offers adequate technical assistance for further discharge planning and slope remediation.

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