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Full Length Article

Granular characterisation of coal spoil dump using unmanned aerial vehicle data to enhance stability analysis

Sureka Thiruchittampalam [a], Bikram Pratap Banerjee [b], Nancy Fraser Glenn [c], Alison McQuillan [d], Simit Raval [a,*]

[a] School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney, NSW, 2052, Australia
[b] School of Surveying and Built Environment, University of Southern Queensland, Toowoomba, Queensland, 4350, Australia
[c] Department of Geosciences, Boise State University, Boise, ID, USA
[d] Rocscience, Southport, QLD, Australia

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A B S T R A C T

Open pit mining operations generate significant spoil dumps that need to be characterised for stability to identify potentially unstable slopes. However, the current subjective practice for spoil characterisation often involves tedious and risky field work. To this end, this study demonstrated the use of periodically acquired unmanned aerial vehicle (UAV)-based images over a coal mine spoil dump in New South Wales, Australia. A granular approach that captures the variability of each truck offload pile on a dump was adopted through morphology-based segmentation and ensemble algorithm-based classification which consolidates predictions from multiple classifiers. Overall accuracy of over 90% in the material characterisation based on the classification framework was achieved. The two-dimensional classification outcome was then transformed into three-dimensional (3D) block models using a point-based interpolation approach for stability analysis. The factor of safety derived from the granular approach offered improved assessment of failure risk compared to the conventional approaches, which treat the entire dump as a uniform category. This rapid classification and assessment method proposed in this study will help reduce the uncertainty associated with the variability of spoil dumps in slope stability assessments, thereby enhancing the safety and efficiency of mining operations.

1. Introduction

The extraction of coal through open pit mining operations necessitates the excavation and accumulation of substantial quantities of spoil, resulting in the formation of extensive dumps at designated sites (Wei et al., 2018). The configuration of waste dumps is often, in the first instance, based on economics (i.e. spoil fit and circuit time). However, geotechnical considerations are critical to include in the dump design to reduce the potential for slope failure (e.g. oversteepening, sliding on weak foundations, and dumping into water). Further, dumps need to be routinely monitored for risk management.

Conventional methods in dump monitoring are limited to visual inspections and terrestrial surveys. The BHP Mitsubishi Alliance coal (BMAC) spoil framework, proposed by Simmons and McManus (2004), is deemed a reliable and less complex alternative to laboratory tests for spoil characterisation. This task necessitates a certain level of expertise, including an understanding of spoil properties, the skill to visually and tactilely evaluate them, and the capability to physically access and examine the spoil. However, the demands of this task make it impractical to manually inspect every batch of spoil throughout the mining process, whether during handling or after dumping. Uncharacterised spoil materials, if disposed of in an unstable manner in a dump, could potentially lead to instability and other complications. Further, this results in the dumping of spoil, which deviates from the initial plan, as mining operations prioritise flexibility and efficiency. The complexity of retracing steps to determine the placement of each material only becomes apparent when an issue arises.

Unmanned aerial vehicle (UAV) equipped with red-green-blue

* Corresponding author.
E-mail address: simit@unsw.edu.au (S. Raval).
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(RGB) sensors have emerged as a promising solution to acquire data for monitoring landform stability (Park and Choi, 2020; Zhou et al., 2024). To optimally utilise the UAV data, a robust and repeatable methodology must be developed that is suitable for the constantly changing dynamic dump terrain.

Spoil pile characterisation (in this paper, the term "characterisation" is used to describe the end-to-end process involved in assigning geomechanical properties to categories of spoil. The term "classification" refers to the process of categorising individual spoil piles into specific categories using classification algorithms) using UAV images is a recently developing area with studies currently limited to only two-dimensional (2D) analysis. Thiruchittampalam et al. (2023b) utilised RGB images to characterise spoil piles at the pixel level (a method where classification is done on a per pixel level, using only the information available for that individual pixel), leveraging spectral and textural descriptors. This approach was further refined with introduction of object-based characterisation (a method where classification is done on a localised group of pixels, taking into account the spatial properties of each pixel as they relate to each other) (Thiruchittampalam et al., 2023a, 2024b). Collectively, these studies underscore the feasibility and potential of using RGB images for spoil pile characterisation. However, they exhibit limitations in their scope, as they focus solely on a single time point and lack a three-dimensional (3D) perspective. The conversion of 2D classification into 3D necessitates the development of interpolation techniques to bridge the gap between two surface layers captured from a UAV. Nagendran et al. (2019) remarked that the utilisation of 3D data acquired from UAV marks a significant stride in stability analysis. Specifically, integrating 3D data from UAVs with machine learning-based classification improves the accuracy (Thiruchittampalam et al., 2024b; Wei et al., 2024) of stability analyses and demands a fundamental shift in the approach to stability assessments. By addressing the complexities and spatial variability associated with 3D mine dumps, engineers can effectively apply 3D stability analysis methods, including 3D limit equilibrium (LE) methods (Bar et al., 2021; Bar and Teleu, 2023; Zhang and Rensburg, 2023). On multiple occasions, 3D analysis has been demonstrated to capture more realistic failure mechanisms, particularly where slope geometry is nonlinear (McQuillan and Bar, 2023; Zhang and Rensburg, 2023). Hence, it is evident that the development of a methodology to convert 2D data into 3D data, which the existing stability analysis software can handle, would provide an improved stability analysis for mining dumps using UAV data. This would add significant value to the mining industry.

To this end, this study aims to enhance 3D stability analysis of coal spoil dumps by incorporating machine learning-based classification, utilising multitemporal high-resolution UAV data. It accurately measures spoil variability across multi-layer dumps and characterises the geomechanical properties of the dumped material, thereby enhancing the precision of stability assessments. The approach used in this study derives the 3D dump profile from 2D UAV derived data, which is then entered into 3D LE models to assess the stability of dumps. Comparisons are made between the stability of dumps characterised by a conventional approach and a granular approach. The conventional approach often assumes uniform spoil categories. This assumption can overlook the potential variability and complexity within the spoil, thereby potentially compromising the accuracy of the slope stability analysis. On the other hand, the granular approach is the characterisation method developed in this study. It takes into account the potential variability and complexity within the spoil, aiming to improve the accuracy of the slope stability analysis. Results show that the stability of dumps can be either underestimated or overestimated when the characterisation of spoil dump material is simplified to one category. This is in contrast to the methodology introduced in this paper, which provides an improved estimation of dump stability.

2. Methodology

2.1. Methodological overview

This study employed UAV data-based characterisation to visualise the 3D evolution of a spoil dump, encompassing its geotechnical (e.g. geomechanical) characteristics. The mapping was carried out based on the BHP Mitsubishi Alliance coal spoil (BMAC) framework. In this framework, spoil is categorised into four categories. These range from Category 1 (Cat-1), which has the lowest shear strength parameters, to Category 4 (Cat-4), which has the highest shear strength parameters. The categorisation is based on visual tactile attributes such as particle size distribution, relative density, and fabric structure (Simmons and McManus, 2004). At the end of this process, a stability analysis was conducted using 3D LE analysis methods. A flow chart summarising the method applied is presented in Fig. 1. UAV images were systematically captured over seven time points, and orthomosaics and digital surface models (DSM) were generated using the structure from motion (SfM) algorithm. The application of object-based characterisation was executed through a sequential process involving segmentation and subsequent classification for each scene. This method employed machine learning algorithms that were trained on ground truth data, which had been collected over a span of time. The accuracy of the classification process was upheld through the application of scene-to-scene calibration of orthomosaics prior to classification, employing pseudo-invariant targets specifically for radiometric correction. Classified maps were merged, and points representing spoil piles were extracted with uniform grid sizes (x and y directions) and their BMAC categories. Corresponding elevation values were extracted and assigned to the points, and gaps were filled using equal-sized grids in the z direction. Finally, the block models were created using 3D classified points. The study used the generated block model of spoil piles along with shear strength parameters obtained from the BMAC framework to determine potential critical slip surfaces using general limit equilibrium (GLE) method (Firincioglu and Ercanoglu, 2021). The study compared slip surfaces and factor of safety (FoS) maps of identical dump configurations. These were characterised using two different approaches: the conventional approach, which often assumes uniform spoil categories, and the granular approach, which is the characterisation method developed in this study. The comparison provided insights into the importance of incorporating spatial variability and spoil pile scale level information in slope stability analysis.

2.2. Data collection of the study area

An aerial survey was conducted employing a DJI M300 RTK drone, which was equipped with a DJI Zenmuse P1 optical camera. This setup facilitated the capture of high-resolution imagery, enabling a detailed examination of spoil piles within a specified coal mine site in New South Wales, Australia. Data collection occurred on seven time points (November 9, 2022, January 1, 2023, January 8, 2023, January 14, 2023, January 21, 2023, February 10, 2023, and February 18, 2023), scheduled around local solar noon for consistent optimal lighting conditions.

To ensure accurate georeferencing, five ground control points (GCPs) were strategically placed, and their coordinates were

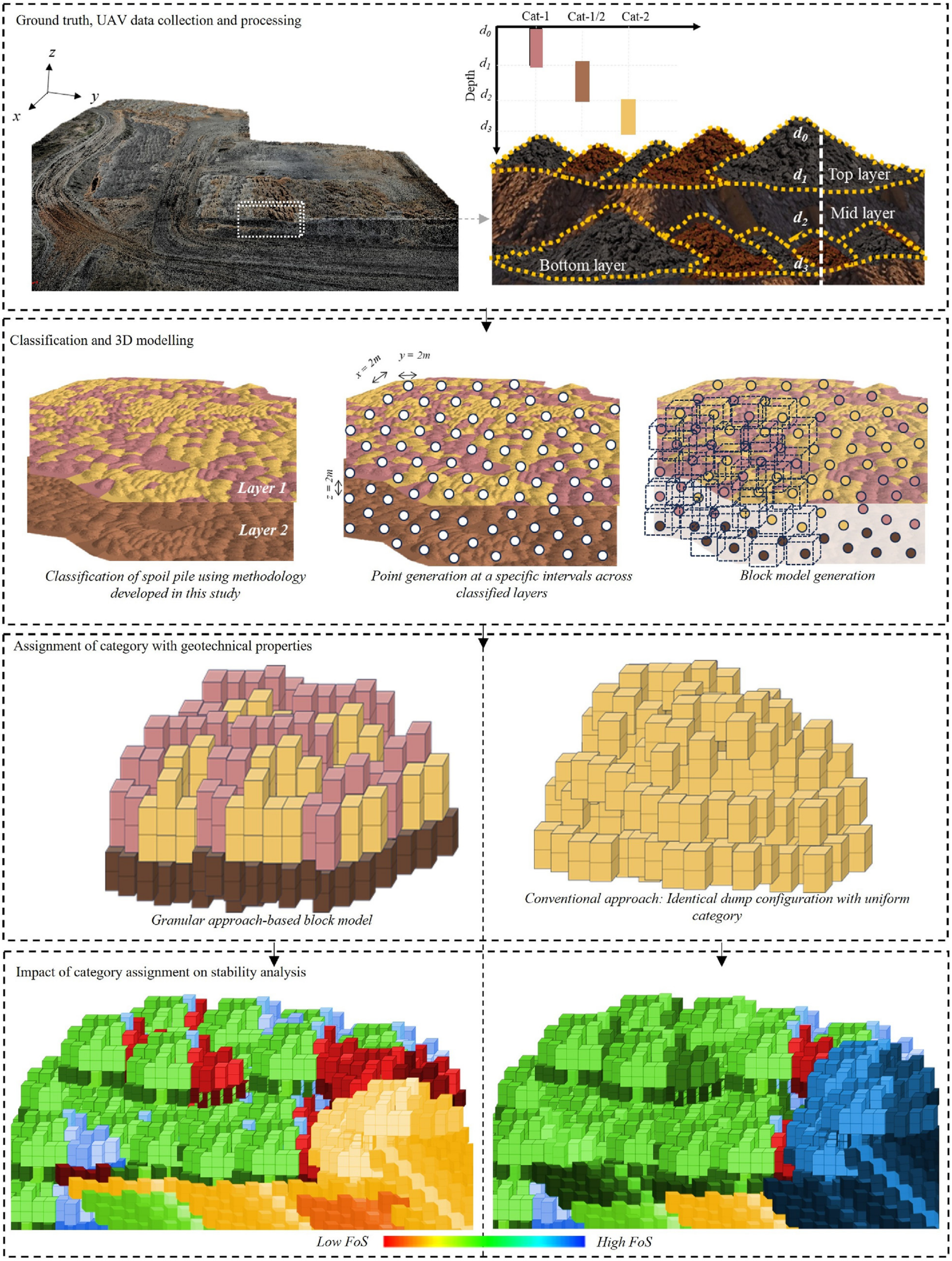

Fig. 1. Flow chart documenting the methodology applied to this study. Machine learning-based spatio-temporal mapping is applied to classify spoil dump variability based on BMAC spoil categories. 3D LE analysis then completed to assess variation in FoS with single or variable spoil configuration.

measured using an Emlid Reach RS2 global navigation satellite system (GNSS) receiver with a networked transport of radio technical commission for maritime services (RTCM) via Internet Protocol (NTRIP) correction service. This setup ensured precise positioning, crucial for high-quality and accurately georeferenced aerial imagery. The UAV's operations were managed through the DJI Pilot app, flying at an altitude of 80 m above ground level to optimise imaging conditions.

The fieldwork involved categorising and surveying 247 spoil piles in a dump area, with 117 piles falling under Category 1 (Cat-1) and 130 piles under Category 2 (Cat-2), each characterised using the BMAC framework (Simmons and McManus, 2004). Due to the geological characteristics of the mining site, the available spoil categories are limited to certain types. The mid layer comprised a mixture of Category 1/2 (Cat-1/2). The shear strength parameters for these categories were derived from the BMAC framework and are presented in Table 1.

2.3. UAV data processing

The raw optical images obtained from the UAV aerial survey underwent processing through Pix4Dmapper, an SfM-based photogrammetric stitching package. The processing included stitching and referencing of GCPs to create a georeferenced 3D mosaic. Seven distinct orthomosaics and DSM were generated in total from each of the seven UAV flyovers completed at the case study site. The resultant orthomosaics exhibited a ground sampling distance (GSD) of approximately 1.22 cm at an altitude of 80 m. The orthomosaics were reconstructed to a spatial resolution of 0.25 m and the spatial resolution of DSMs was 0.5 m.

To obtain the DSM of the middle layer, the DSM of the final day (18th February 2023) was utilised, and the spoil piles on the top layer of the paddock were subtracted. The inverse distance weighted (IDW) interpolation method (Shirowzhan and Sepasgozar, 2019; Liu et al., 2021) was then employed to fill the gaps resulting from the deduction. IDW estimates cell values by averaging the values of the sample data points in the neighbourhood of each processing cell, with the influence or weight determined by the proximity of a point to the center of the cell being estimated.

The ability to accurately evaluate temporal changes is impeded by the temporal inconsistency present in UAV imagery. This inconsistency can be attributed to radiometric errors in UAV-based sensing (Thiruchittampalam et al., 2024a). To this end, the study employed scene-to-scene correction with invariant targets for orthomosaic calibration. Pseudoinvariant targets, unchanged spoil piles, established the connection between consecutive images using robust regression. The calibration utilised regression equations for subsequent images in each orthomosaic. Pseudo-invariant targets are utilised due to the dynamic changes in the dump environment, making it impractical to set up reflectance targets. Moreover, the implementation of any field procedure to rectify this in the mining field is laden with risks. Fig. 2 shows how the mine dump changes in 3D over time and across different layers.

Table 1
BHP Mitsubishi Alliance Coal (BMAC) framework spoil categories and their shear strength parameters (adapted from Simmons and McManus, 2004).

Category	Unsaturated spoil		
	γ (kN/m^3)	c' (kPa)	ϕ' (°)
1	18	20	25
1/2	18	25	26.5
2	18	30	28

2.4. Granular approach for coal spoil characterisation and 3D dump creation

The workflow used in this study, referred to as the “granular approach”, takes into account each truck offload pile on a dump. This is followed by the generation of a 3D block model, which is based on the 2D characterisation outcomes from the three tiers of the dump.

This study employed object-based characterisation methodology to classify truck paddock-tipped spoil piles. The procedural sequence comprises of successive phases, including segmentation, feature extraction, the derivation of zonal statistics, and machine learning-based classification (Thiruchittampalam et al., 2024b).

The investigation utilised morphology-based segmentation, Voronoi-based segmentation techniques to delineate spoil piles, employing DSMs as input data (Thiruchittampalam et al., 2023a). The Voronoi tessellation-based segmentation technique addressed irregular shapes through noise reduction, seed point detection, background seed point removal, and pile polygonisation. Gaussian blurring was employed to enhance segmentation accuracy by smoothing out small irregularities in the DSMs. During segmentation, local maxima detection and Otsu's thresholding method played pivotal roles in seed point selection and distinguishing between background and spoil piles.

Following the segmentation process, a comprehensive analysis of object characteristics and their interrelations was conducted through the utilisation of various features. The study categorised these features into four distinct groups: spectral, textural, structural (edge), and statistical features (Table 2).

Notably, textural, structural, and statistical features were derived from individual bands (red, green, and blue) of the orthomosaics to extract maximal information from the dataset. Initially, 300 features were extracted through zonal statistics (mean and standard deviation computations) within each Voronoi-based segment. After eliminating features with null values, the retained features were reduced to 232. Feature extraction was performed on calibrated datasets for each of the seven orthomosaics.

The spoil pile classification employed Ensemble (subspace discriminant) (Ashour et al., 2018; Zeng et al., 2023). This machine learning algorithm was recognised as an effective algorithm for spoil characterisation, utilising calibrated RGB data from UAVs (Thiruchittampalam et al., 2024a). Data partitioning, particularly the segregation of training and test sets, significantly influenced model performance. A five-fold cross-validation approach (Wu et al., 2024) ensured robust generalisation, designating one part for testing and the remaining four for training iteratively, with results averaged for overall performance evaluation. The predictive capabilities of the model for coal spoil categories were evaluated using overall accuracy (Eq. (1)). This metric measures the proportion of correct predictions to total classifications.

$$Overall\ accuracy = \frac{TN + TP}{TN + TP + FN + FP} \tag{1}$$

where TN represents the correctly identified negatives, TP represents the correctly identified positives, FN represents the positives wrongly classified as negatives, and FP represents the negatives wrongly classified as positives. Thematic maps for BMAC spoil categories were generated based on the trained model.

To facilitate the construction of a block model for stability analysis (Lashgari and Ozturk, 2021), 2D map data were transformed into a set of 3D points. To this end, classified maps were merged, and points were created with uniform grid sizes (2 m × 2 m) in both x and y directions, along with their BMAC categories (Wang et al., 2020a). Elevation values corresponding to

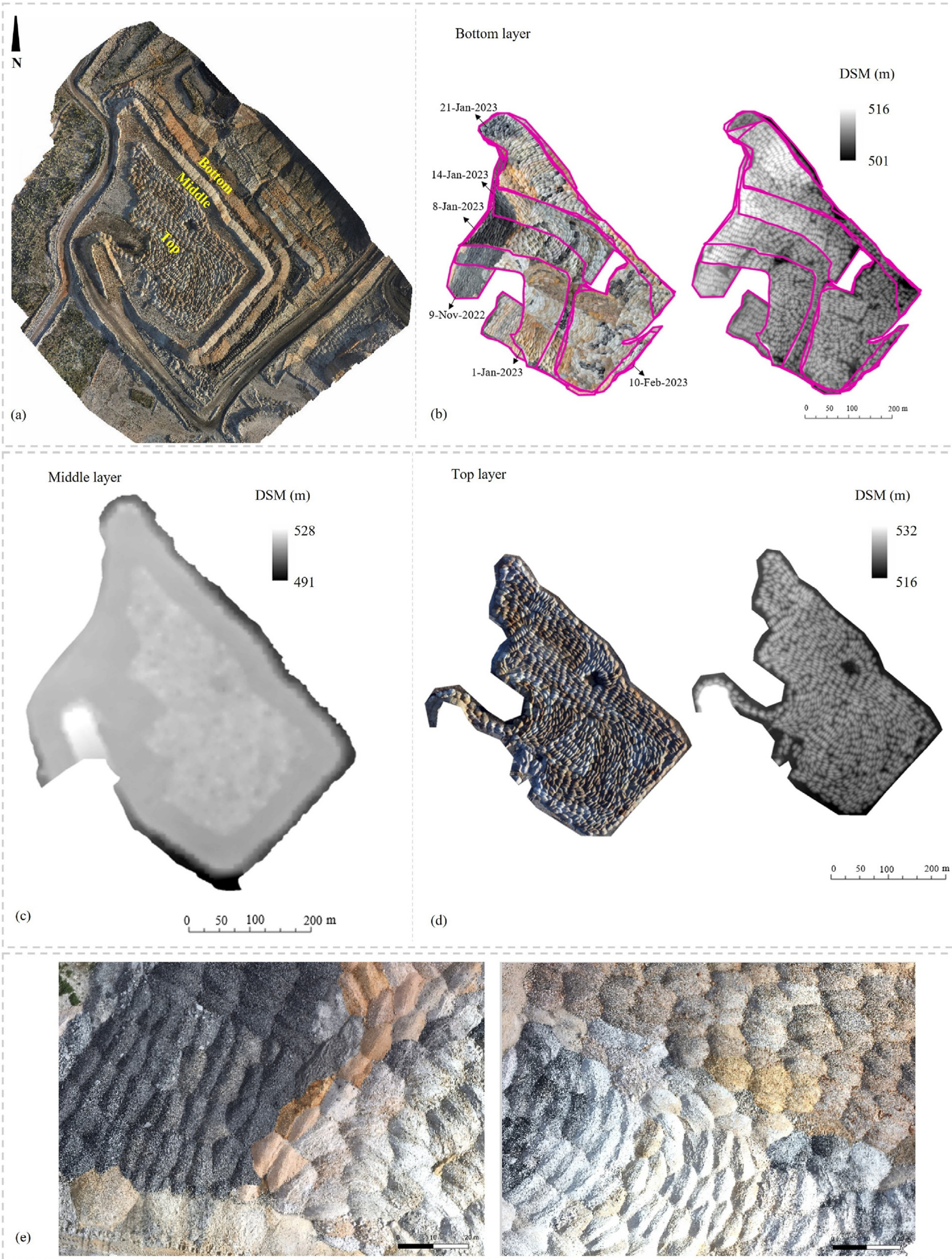

Fig. 2. Plan view of the mine dump and its 3D evolution across different layers and time frames: (a) Orthomosaic of the mine dump captured on the final day, showcasing bottom, middle, and top layers; (b) Merged and calibrated orthomosaic and DSM of the bottom layer created over seven time points, with polygons delineating dumps formed on different days; (c) DSM of the middle layer established through deduction of DSMs and interpolation; (d) Orthomosaic and DSM of the top layer; and (e) Zoomed view of individual spoil piles in UAV images.

Table 2
Features extracted for characterisation (Thiruchittampalam et al., 2024a).

Feature category	Feature
Spectral	Red, Green, Blue, Red-Green ratio, Green-Blue ratio, Red-Blue ratio
Textural	Haralick features [Energy, Entropy, Correlation, Inverse Difference Moment, Inertia, Cluster Shade, Cluster Prominence, Haralick Correlation: kernel sizes - (3 × 3)]
	Gabor: θ values of 0, $\pi/4$; σ values of 1 and 3; λ values of 0, $\pi/4$, $\pi/2$, $3\pi/4$, and γ values of 0.05 and 0.5
Structural (Edge)	Sobel, Prewitt and Scharr use 3 × 3 kernel and Roberts edge operators use 2 × 2 kernel
	Canny: Minimum and maximum values for double thresholding are chosen at 100 and 200, respectively
Statistical	Gaussian: σ values of 3 and 7
	Median: 3 × 3 kernel.

the points were assigned from DSM, and voids in the z-direction were filled by generating new points at equal intervals of 2 m between layers in the z-direction. The category values of the newly generated points were assigned based on the category of the nearest existing point. Due to the typical dimensions of the spoil pile in the dump being 2 m, a block model with a block size of 2 m × 2 m × 2 m was constructed utilising a total of 1.1 million points for the stability analysis using Rocscience Slide3 software (Rocscience, 2020).

2.5. 3D LE slope stability analysis

The 2D LE simplifies slope safety analysis by assuming plane strain conditions, leading to potential inaccuracies for complex geometries. Conversely, the 3D LE provides a more thorough analysis by considering the full spatial geometry of slope. Hence, in this study, 3D LE was used to capture the complexities in spoil dumps.

To achieve this, we assessed the dump slope stability of varying spoil configurations using Rocscience's 3D LE Slide3 software and the block model build function. The LE method in 3D employs a column-based approach to compute the FoS on a stochastically generated 3D slip surface. This technique is particularly effective when used in conjunction with optimised metaheuristic search algorithms. Notably, the Cuckoo and Particle Swarm algorithms (PSO) are designed to calculate Non-Uniform Rational B-Splines (NURBS) slip surfaces. These advanced algorithms frequently demonstrate superior performance over simpler search methods, such as those that calculate spherical and ellipsoid slip surfaces. This superiority is particularly evident when the objective is to identify the slip surface with the lowest FoS in the region of interest. The enhanced performance of these algorithms underscores their value in facilitating more accurate and efficient slope stability analyses. Hence, the Cuckoo search method was utilised as the optimised metaheuristic search algorithm in the analysis. Further, surface altering optimisation (SAO) was also applied to augment the degrees of freedom in the geometric approximation of slip surfaces to enhance the robustness of global surface search (Zhang and Rensburg, 2023).

In this study, analyses were conducted using the GLE (Morgenstern-Price) method. In detail 3D slope stability analysis, the slope's potential failure mass is divided into columns. Fig. 3 shows internal and external forces on each column at equilibrium. For computational simplicity, we assume the weight of soil and vertical load act at each column's center, which is acceptable if the column width is narrow. Assumptions include the validity of the Mohr–Coulomb failure criterion, secondly, in adherence to Morgenstern–Price's method, the determination of the FoS relies on the sliding direction, where factors of safety concerning force and moment are equal. Lastly, it is assumed that the sliding direction remains consistent across all spoil columns.

In accordance with the Mohr–Coulomb criterion, the global FoS, denoted as F, is defined as follows:

$$F = \frac{S_{fi}}{S_i} = \frac{C_i + N_i' \tan \phi_i'}{S_i} \tag{2}$$

In the context of column analysis, S_{fi} represents the ultimate resultant shear force present at the base of column i. Meanwhile, N_i' denotes the effective base normal force, where C_i is defined as the product of c' and A_i. Here, c' represents the effective cohesive strength, and A_i corresponds to the base area of the column. The base shear force (S_i) and base normal force (N_i) are articulated as components of forces aligned with the x-, y-, and z-directions for column i.

Search limits were applied to the models to ensure adequate search coverage in all four zones of the dump, i.e. north (Zone-1), east (Zone-2), south (Zone-3), and west (Zone-4), in order to report the FoS. Three models were generated to assess the variation in the FoS. This was done by applying single BMAC categories (i.e. Cat-1 and Cat-2) according to the conventional approach to the entire dump profile. This was then compared to the FoS calculated when varying spoil categories were applied. These categories were determined from a granular approach and applied to the three-tier dump profile.

3. Results

3.1. Granular approach for coal spoil characterisation and 3D dump creation

Thematic maps corresponding to the bottom, middle, and top layers are presented in Fig. 4. These maps offer a detailed visual representation of spoil pile classifications obtained from calibrated RGB data highlighting the dynamic and rapid changes occurring within spoil piles. The calibrated RGB data demonstrates superior performance, achieving an overall accuracy of 90.7% in the classification of spoil piles based on the BMAC framework. This accomplishment is attributed to the utilisation of an ensemble (subspace discriminant) as the classifier. The algorithm's efficacy is rigorously assessed through per-class accuracy metrics, including precision, recall, and F1-score. Notably, the F1-score consistently exceeds 0.9 when features derived from calibrated data are employed, highlighting the robustness and reliability of the adopted approach.

Using classified spoil piles in two dimensions, 1.1 million points were generated at regular intervals of 2 m along the x, y, and z axes in 3D space. Fig. 5 illustrates a 3D dump exhibiting different orientations with corresponding classifications. This visualisation encapsulates the volumetric arrangement of the spoil piles and serves as a valuable tool for discerning the spatial patterns and relationships embedded within the classified data. Fig. 6 illustrates

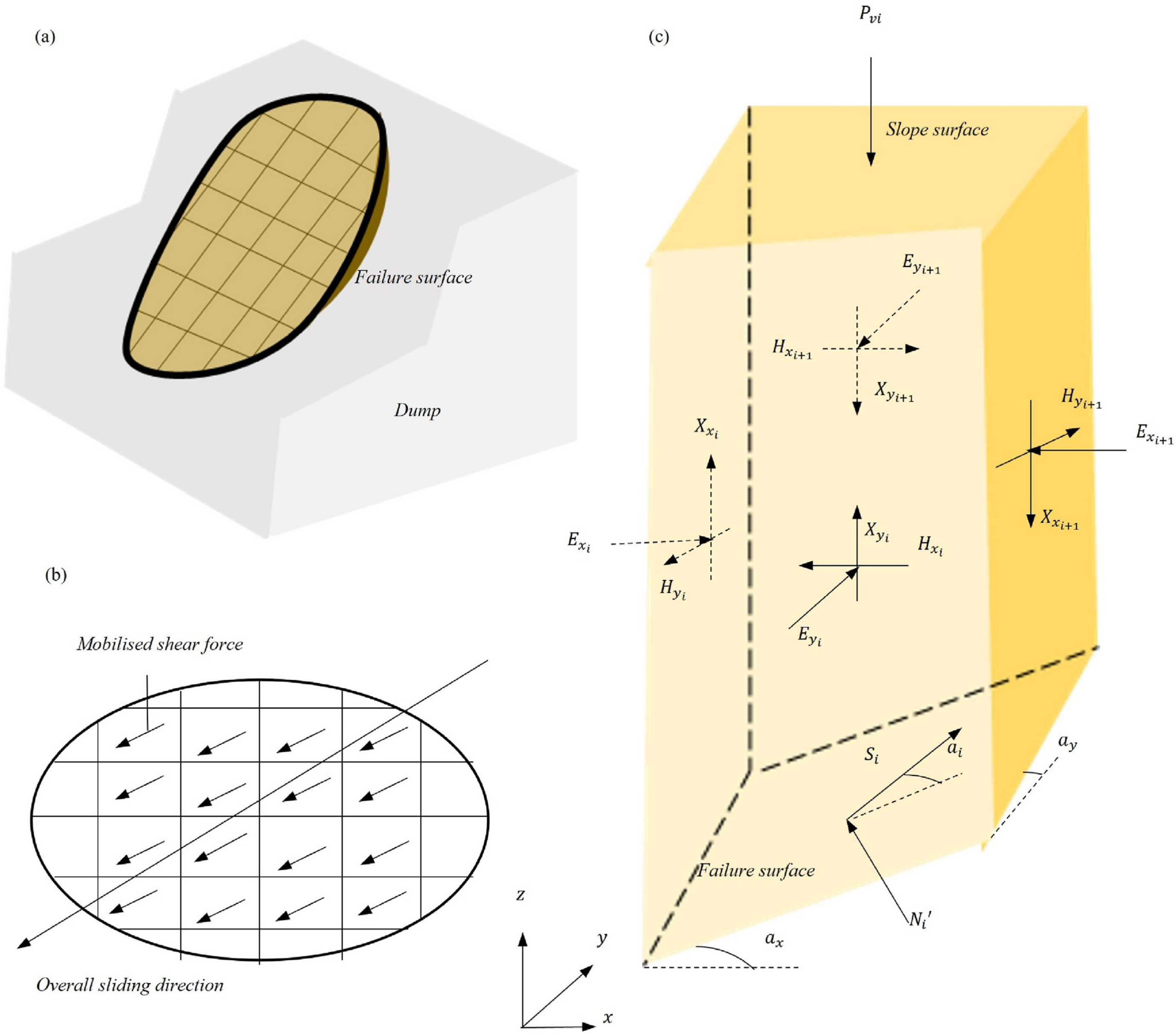

Fig. 3. (a) Dump with failure surface, (b) Sliding orientations for all columns within the plan view, and (c) The examined forces on a spoil column. The space sliding angle denoted as a_i is the angle of sliding with respect to the direction of the slide projected onto the *x*-*y* plane. The base inclinations along the *x*- and *y*-directions, represented as a_x and a_y, respectively, are measured at the center of each column. The intercolumn normal forces in the *x*- and *y*-directions are denoted as E_{x_i} and E_{y_i}, respectively, while the lateral intercolumn shear forces in these directions are represented as H_{x_i} and H_{y_i}. The effective normal force is symbolized as N_i'. The vertical external force and the base mobilized shear force are represented as P_{vi} and S_i respectively. Lastly, the vertical intercolumn shear force in the plane perpendicular to the *x*- and *y*-directions are denoted as X_{x_i} and Y_{y_i}. These forces collectively influence the behavior and stability of the spoil column *i*.

the results of each stage in the point-based interpolation method, depicted in 3D for a spoil dump. In Fig. 6a, the 3D points generated from a 2D classification are shown. This approach only captures the surface of the dump's three tiers. However, the 3D points interpolated using the IDW method represent the entire structure. They effectively fill the gaps between the surfaces of the dump's three tiers at equal intervals, meeting the format requirements of stability analysis software. Fig. 6b offers a sectional view of both the surface-level points and the interpolated points for each zone in the dump. This comprehensive representation facilitates a more detailed understanding of the dump's structure. The interpolated 3D point model, with equal intervals, is utilised to generate a block model in Slide3 for stability analysis.

3.2. Slope stability analysis

The results of 3D LE modelling are summarised in Table 3 and presented as FoS contour maps in Fig. 7.

Of most importance, the results show that, by simplifying the categorisation of spoil into a single category (i.e. Cat-1 or Cat-2) through conventional approach, the FoS can be over- or underestimated, compared to the newly developed granular approach (i.e. scenario where the spoil was classified by its actual composition, down to a 2 × 2 × 2 m scale). This is evident in the results, where the Cat-1 only scenario typically results in a lower (arguably conservative) FoS than the granular approach scenario, and the Cat-2 only scenario typically results in a higher (arguably optimistic)

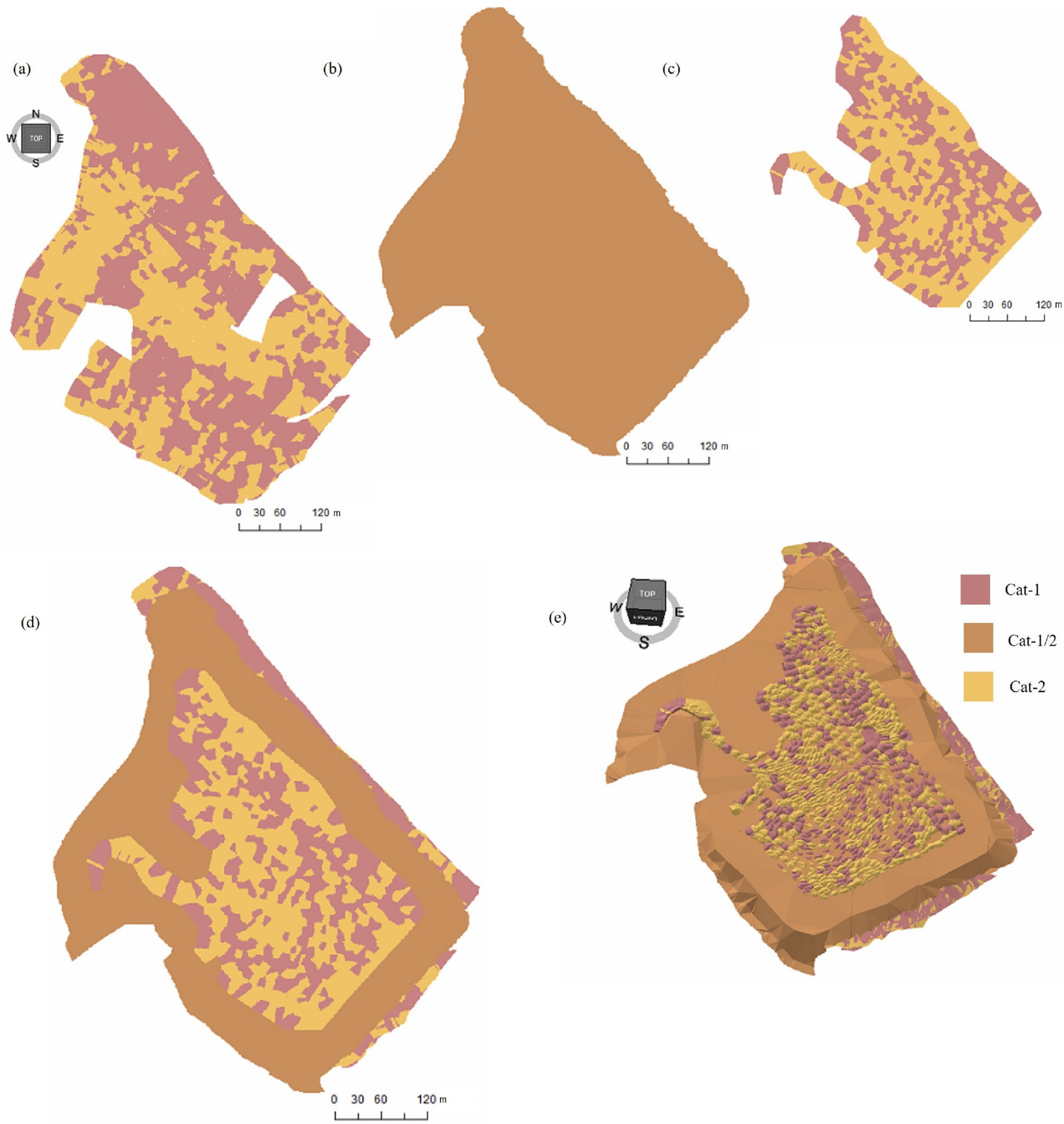

Fig. 4. Thematic maps illustrating (a) merged classified spoil piles over seven time points, (b) middle layer with mixed Cat-1/2, (c) classified spoil piles of the top layer, and (d) plan view of classified spoil piles in bottom, top, and middle layers. (e) 3D view of classified spoil piles.

FoS compared to the granular approach scenario.

The results also show that the FoS calculated for Cat-2 dump composition was typically higher than the FoS calculated for Cat-1 dump composition. The higher FoS observed is expected and is attributed to the higher Cat-2 shear strengths, as shown in Table 1.

All but one scenario assessed returned a FoS of less than the industry accepted design acceptance criteria (DAC) of 1.2. The absolute FoS calculated in this study was not the focus of the results, where the purpose of the analysis was to compare the FoS calculated with varying internal dump spoil configurations. However, it is worth relating the calculated FoS to actual dump stability. At the time of the UAV surveys, the spoil dump under investigation showed no signs of instability, indicating the dump likely has a FoS greater than 1.0, yet the 3D LE analysis typically returned FoS less

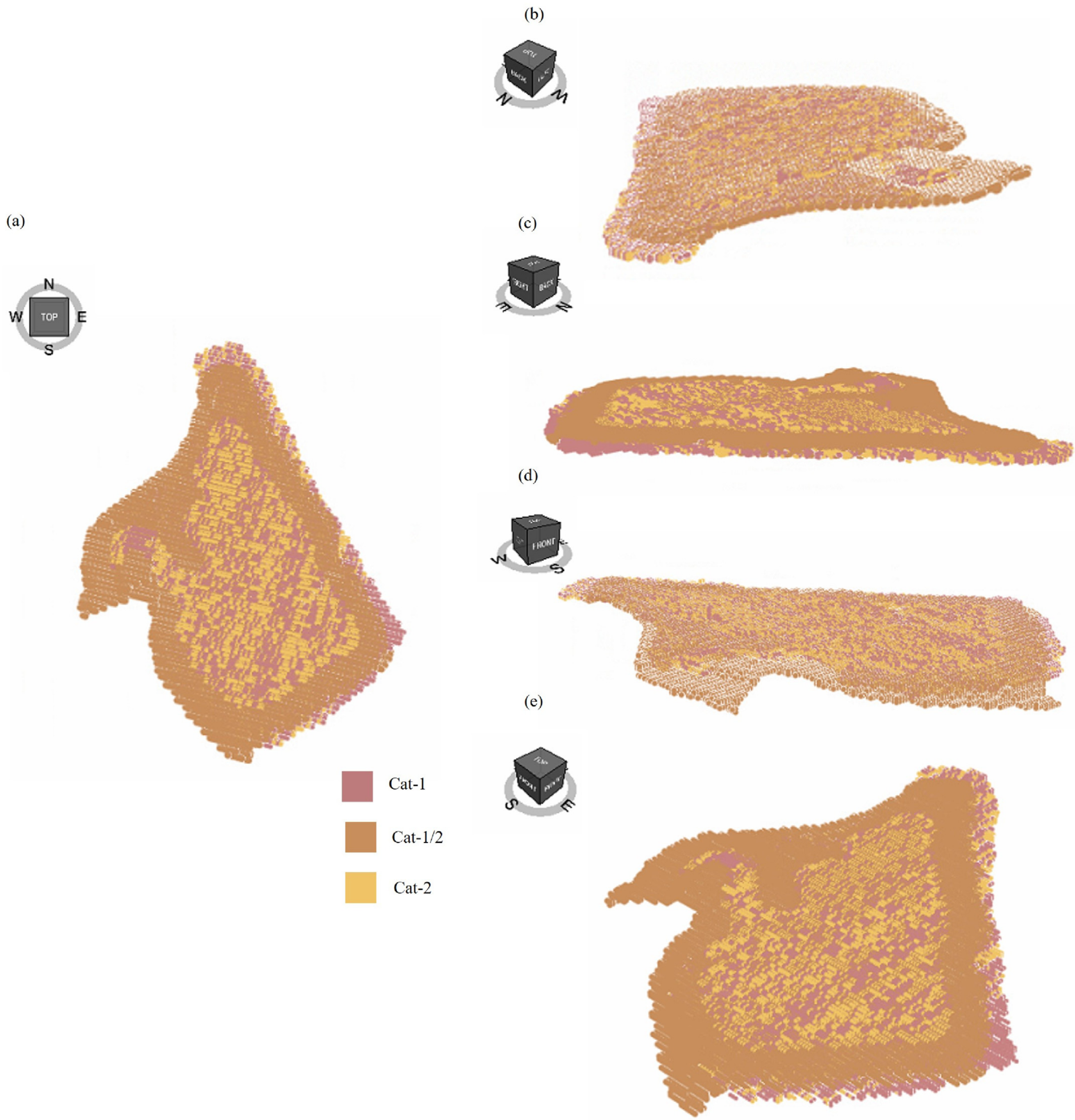

Fig. 5. 3D representation of a spoil dump as discrete points. (a) Plan view illustrating the dump with orientations in four directions, and (b), (c), (d), (e) dump profiles in specified orientations.

than 1.0 ± 0.05. These results indicate that the spoil properties applied to 3D analysis are likely conservative. This exercise has highlighted that the shear strengths applied to BMAC spoil categories should be reviewed for 3D analysis, as applying the current BMAC spoil properties, historically derived from the back analysis of 2D LE analysis, in this instance, underestimate the likely spoil strength.

4. Discussion

4.1. Discussion of results

UAVs equipped with RGB sensors have become increasingly prevalent within mining environments, primarily employed for efficient data acquisition. These technological advancements allow

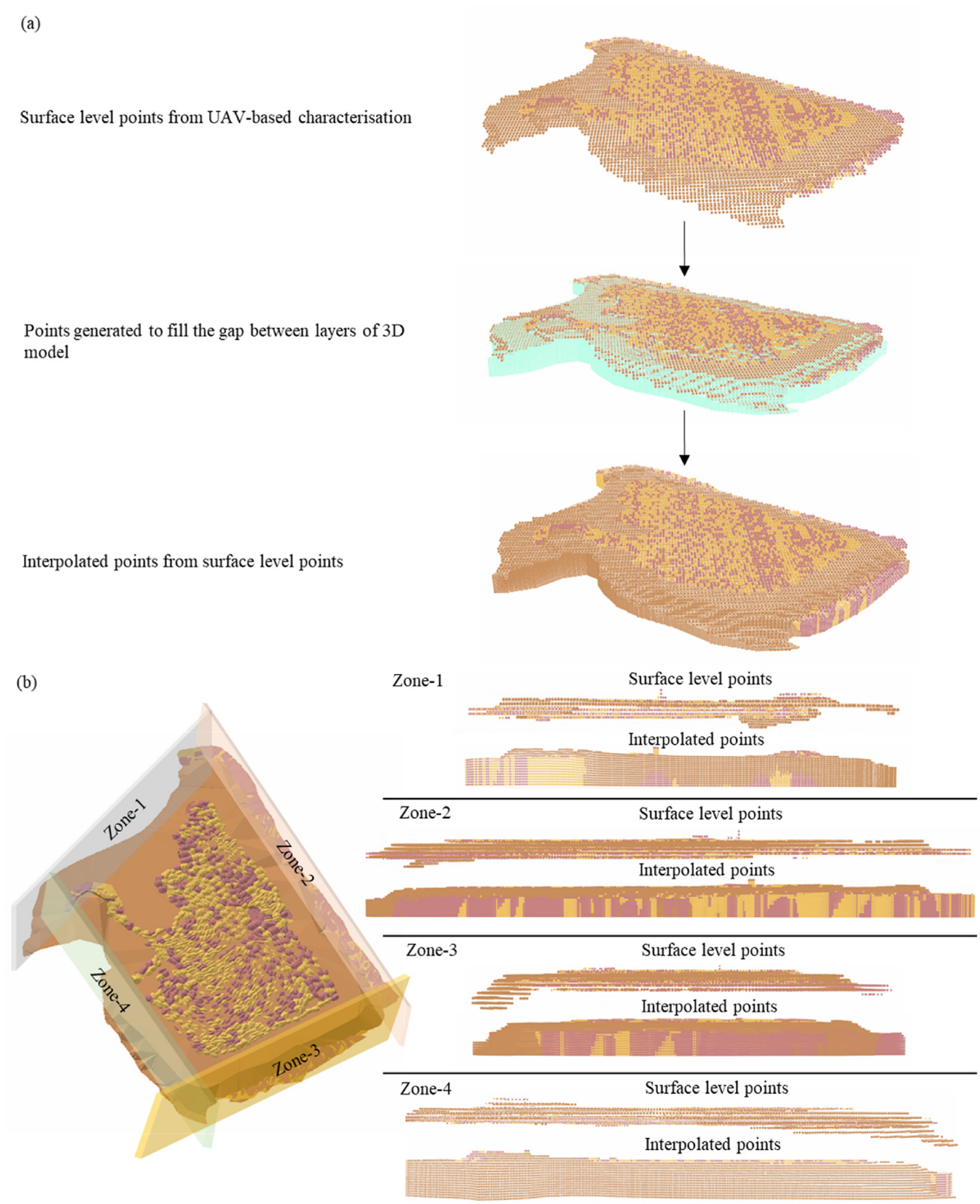

Fig. 6. (a) Outcomes at each step of the point-based interpolation approach, represented in three dimensions for a spoil dump; and (b) A sectional view of the surface-level points and interpolated points for each zone in the dump is provided.

for the rapid and comprehensive aerial imaging of mine sites. However, the efficacy of these acquired images in translating into meaningful outcomes that contribute to the stability analysis of dump sites, for long-term monitoring, presents a critical challenge. The complex topography of mine environments, such as dumps are coupled with the intricate interplay of factors influencing stability, necessitates robust and transferrable methodology. This study will not only bolster the accuracy and reliability of stability analyses but also contribute to the sustainable, long-term monitoring of mining dump sites.

The amalgamation of Voronoi-based segmentation (Thiruchittampalam et al., 2023a) and machine learning classification (Thiruchittampalam et al., 2023b, 2024b), particularly when applied to features derived from calibrated data, represents a

Table 3
Calculated FoS for varying dump composition.

Dump composition	FoS			
	Zone-1	Zone-2	Zone-3	Zone-4
The granular approach	0.67	1.14	0.81	0.67
Cat-1 only	0.58	1.09	1.04	0.66
Cat-2 only	0.74	1.26	1.01	0.67

robust methodology for spoil pile classification. The calibrated RGB data, in particular, exhibit a noteworthy performance advantage, achieving an exemplary overall accuracy of 90.7% within the BMAC classification framework for spoil piles. This noteworthy accomplishment is realised through the strategic deployment of an ensemble, specifically the subspace discriminant, as the classifier. Ensemble algorithms operate by consolidating predictions from a

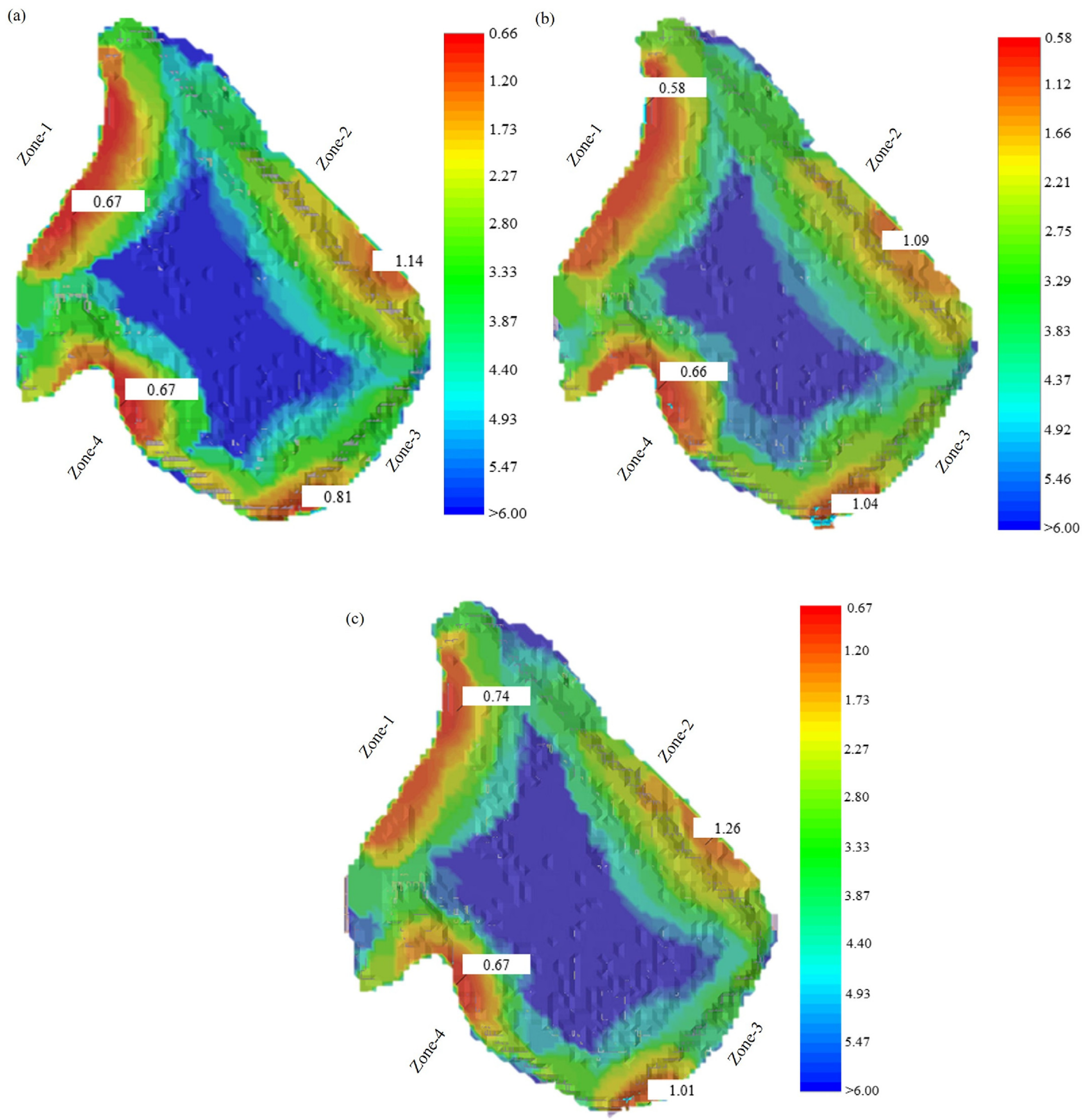

Fig. 7. Plan view maps showing FoS contour maps of the different scenarios analysed in 3D LE modelling: (a) Spoil piles characterised by the granular approach, (b) Cat-1 only and (c) Cat-2 only.

suite of classifiers to categorise unclassified data (Ashour et al., 2018). The subspace discriminant augments the accuracy of its base learners, discriminants in this context, through the implementation of the random subspace algorithm. The investigation into feature selection methodologies presents a viable strategy to counteract the "curse of dimensionality" and improve the accuracy of classification (Wang et al., 2020b; Thiruchittampalam et al., 2024b). Nevertheless, such an exploration falls beyond the purview of the current study. The implementation of the recommended workflow in this study has yielded classified spoil piles in 2D outcomes, thereby generating a dataset encompassing 1.1 million data points. These data points are systematically distributed at 2 m intervals within the confines of the 3D space. Each individual block represents the offload of spoil from a single truck. These blocks are set at a 2 m interval, reflecting the typical dimensions of the spoil pile in the dump, which also measures approximately 2 m. The smaller the interval, the higher the accuracy of interpolating points between three tiers. This is attributed to the increased density of data points, enabling a more precise interpolation of neighbouring points, hence precise depiction of the spoil pile's structure. This 3D depiction provides a comprehensive perspective of the topography of the spoil piles, facilitating enhanced management of dump sites and improved safety assessments. Moreover, the quantitative attributes inherent in the dataset permit a detailed stability analysis, thereby facilitating the detection of potential failures. Although smaller intervals yield more accurate representation for analysis, they demand more computational resources. This is crucial when determining block interval size.

The majority of scenarios assessed in this study did not meet the industry's accepted DAC, with the calculated FoS consistently falling below 1.2. However, when we compared three identical dump geometries, each with different spoil configurations, we observed a variation in the FoS. This variation can be attributed to the stratigraphic arrangement of categories within the critical slip surfaces. For instance, according to the methodology developed in this study, the primary constituents of the lowermost stratum in the identified critical slip surface zones of the characterised dump are identified as Cat-1 spoil piles. Progressing vertically through the layers, the intermediate layer displays spoil piles with Cat-1/2, characterised by higher shear strength parameters. The observed sequential deposition pattern in these zones, marked by the transition from predominantly Cat-1 spoil piles at the base to a blend of Cat-1 and Cat-2 spoil piles in the mid-layer, introduces a structural vulnerability to this zone. To elucidate, this heterogeneity, coupled with the sequential deposition, heightens the susceptibility to failure mechanisms within these zones. Consequently, the discernible layers within these zones necessitate consideration in geotechnical assessments and the formulation of risk management strategies to alleviate potential failures and ensure the stability of the stratified system. In summary, the observed variation in FoS values suggests misclassification or reliance on assumptions regarding the categorisation of spoil piles within the dump configuration may yield an inaccurate representation of the FoS, emphasising the need for a more precise categorisation approach to ensure an accurate safety assessment. In other words, the identification of critical slip surfaces or unidentified failure risk, with different material assignments to the same dump geometry, emphasises the pivotal role of material characterisation in the broader context of stability analysis. This underscores the necessity for thorough characterisation processes to prevent overlooking potential critical slip surfaces or the identification of incorrect critical slip surfaces that require action. This observation emphasises the significant influence of category assignment on the stability analysis of the dump and further highlights the complexity of the interactions at play.

The current investigation into the dump stability, despite the FoS values from 3D LE analysis being below 1.0, has revealed no signs of instability during field investigation. This suggests that the spoil properties used in the analysis might be overly conservative. The exercise has highlighted the shear strengths exerted on the BMAC spoil categories, indicating the need for a comprehensive reassessment of this framework. The use of prevailing BMAC spoil properties, traditionally derived from 2D LE analysis appears to underestimate the expected spoil strength (Xie et al., 2011). Therefore, a re-evaluation of these properties is necessary to ensure accurate 3D analysis results.

The incorporation of machine learning classification with high-resolution UAV data in 3D LE analysis presents a potent tool for the identification of accurate dump failure risks in mining operations. This methodology not only reduces the necessity for extensive on-site investigation, thereby diminishing associated risks, but also delivers a comprehensive 3D characterisation of dump failure risks. This is of utmost importance for the efficient management of risks in mining operations. Additionally, it furnishes spatial, stratigraphic, and temporal information regarding the deposition. This information assists in identifying areas with a higher probability of failure, thus further enhancing the safety and effectiveness of mining operations. Hence, this integrated approach transforms risk management in the mining industry by offering a safer, more efficient, and data-driven technique for the identification of dump failure risks.

4.2. Study contribution and scope for future work

This study presents a transferable, end-to-end workflow for monitoring the stability of spoil dumps using UAV imagery. This approach addresses the limitations of traditional in-field spoil characterisation methods, which are often time-consuming and require constant expert presence. As a result, these traditional methods are frequently neglected or only assumed after a failure has occurred. To overcome these challenges, the study leverages the often-underused UAV images that are regularly captured at mining sites. However, it is important to note that UAV-based characterisation also has its own limitations, particularly when it comes to 3D profiling of dumps using images. Image-based methods are typically limited to surface materials and may not detect subsurface features, thus necessitating interpolation. Further, integrating image-based workflows with existing stability assessment systems presents a significant challenge. This task requires the development of protocols for seamless data transmission across various systems and the assurance that the results of image analysis are compatible with the formats used in current stability analysis systems.

In this study, a three-tier spoil dump is examined. Prior to the creation of the 3D dump, an object-based approach is used to carry out a 2D characterisation of each pile in the dump. This process ends with a classification based on machine learning. Scene-to-scene calibration is employed to adjust for changes in lighting conditions and other environmental factors in the dump environment. Assuming that each spoil pile has the same material composition down to the bottom layer, the study introduces a point-based interpolation method. The gap between two layers is filled with points at equal intervals, and the IDW method is employed. Through this approach, the study enables comprehensive spoil characterisation from UAVs, overcoming the limitations of traditional methods and fully utilising available UAV imagery. The constructed 3D profile is subsequently used to analyse the stability of the dump by examining 3D slip surfaces. The study also demonstrates practical applications of the developed 3D profile to improve the understanding of mine dump stability by integrating it with available stability assessment software.

One of the significant limitations of this study pertains to the resolution of UAV imagery and the intervals between points for 3D profiling. The resolution and interval selection are critical factors that influence the balance between computational resource utilisation and the accuracy of characterisation and stability analysis. Therefore, the adaptability of the workflow to different resolutions remains a constraint in this study. Future research could focus on two key areas. The first is investigating variations in resolution, which could have a significant impact on the accuracy and computational efficiency of the 3D profiling process. This process could involve the use of variable block sizes or the implementation of advanced modelling techniques. The goal would be to represent the actual boundaries of the spoil pile more accurately. Such an approach could offer a more detailed understanding of the stability and structure of the spoil pile. The second is the creation of a resource-efficient workflow that can handle a higher number of blocks. Insights gained from these areas could be invaluable in optimising the workflow and addressing its current limitations.

In conclusion, this study makes a significant contribution to the field of spoil dump stability monitoring by offering a more efficient, effective, and accessible solution. This approach has the potential to revolutionise the way we monitor and manage spoil dumps in the mining industry.

5. Conclusions

UAVs equipped with RGB sensors are increasingly being utilised in the mining sector to efficiently gather data through aerial imaging. However, effectively translating these images into meaningful outcomes for stability analysis of dump sites poses a significant challenge due to the intricate mine topography and various factors that influence stability. The objective of this study is to enhance the accuracy and reliability of stability analyses and contribute to the long-term monitoring of mining dump sites, thereby advancing the effectiveness of UAVs with RGB sensors in the management of mine waste. The combination of Voronoi-based segmentation and machine learning classification, particularly when applied to calibrated data, offers a robust methodology for the classification of spoil piles. The use of calibrated RGB data achieves an overall accuracy of 90.7% in the classification framework. By implementing an ensemble algorithm, specifically the subspace discriminant, the accuracy is further improved by consolidating predictions from multiple classifiers. A comparison of three identical dump geometries with different spoil configuration revealed a variation in the FoS due to the stratigraphic arrangement of categories within the critical slip surfaces. The observed variation in FoS values suggests the importance of developed granular approach to ensure an accurate safety assessment and prevent potential failures. This approach reduces the necessity for extensive on-site investigation and provides a comprehensive 3D characterisation of along with failure risks. As a result, this integrated approach transforms risk management in the mining industry by offering a safer, more efficient, and data-driven technique to identify dump failure risks.

CRediT authorship contribution statement

Sureka Thiruchittampalam: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bikram Pratap Banerjee:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Nancy Fraser Glenn:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Alison McQuillan:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Simit Raval:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Sureka Thiruchittampalam received her BSc degree from the Department of Earth Resources Engineering, University of Moratuwa, Sri Lanka. She is currently working toward the PhD in minerals and energy resource engineering at the University of New South Wales, Sydney, Australia. Her research interests include remote sensing for mine environments, UAV-based multispectral imaging, and sustainable mining.