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Predictive Block Stability Analysis by Integrating UAV-Based Photogrammetry and Back Analysis

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Abstract

Determining in-situ joint shear strength properties through the back analysis of previously failed blocks is substantial in rock slope stability analysis since such back-calculated strength parameters not only reflect site-specific geological conditions but also enhance the reliability of forward stability predictions. The integration of UAV-based photogrammetry within this analytical workflow strengthens the process by providing high-resolution 3D models for detailed, contact-free structural mapping and geometrical analysis of discontinuity networks.

This study presents an extensive rock slope stability analysis on the south facing wall of an open pit mine, integrated with UAV-based photogrammetry. The study includes limit equilibrium based back analysis of earlier wedge failures and forward block stability analysis for slope hazard assessment. To identify discontinuities along the slope face, detailed structural geologic mapping was performed on the 3D model generated in ShapeMetriX by processing 959 overlapping aerial images acquired by an unmanned aerial vehicle (UAV). Kinematic analysis performed in Dips software utilizing mapped structural data confirmed that several wedges were kinematically admissible. Two previously failed wedges were also identified, one of which generated rock fragments that extended to the lower benches and near the access tunnel. The geometry, size and failure characteristics of this wedge were quantified on the 3D model. These inputs were used in limit equilibrium based back analysis in RocSlope2 to estimate joint shear strength parameters contributing to the failure. Theseestimatedparameters were then applied in forward block stability analyses in RocSlope3 to assess the potential for future block failures that could threaten the safety and mining operations.

This workflow enables fast and rigorous mapping of structures, reliable calibration of joint shear strength parameters, supports predictive rock slope stability evaluation, and provides a foundation for designing targeted mitigation strategies to improve mine safety and operational reliability.

Keywords

UAV photogrammetry, Structural geologic mapping, Kinematic analysis, Wedge failure, Block failure.

1 Introduction

Structurally controlled rock mass instabilities such as wedge and planar sliding failures, block topples and rockfalls represent significant hazards in both natural and engineered environments due to their sudden occurrence and the limited warning time available prior to failure. In mining environments, where steep rock slopes are commonly developed to optimize ore recovery, the impacts of such failures can be substantial, including damage to infrastructure, interruption of production, and risks to personnel safety.

Back-analysis of documented failure cases and a realistic determination of shear strength of discontinuities are utmost importance for predictive block stability analysis and safer slope designs.

With its ability to provide contact-free access to steep, inaccessible and hazardous rock slopes, and enabling high-quality data collection even in areas where conventional field mapping would be impractical or unsafe, UAV-based photogrammetry has emerged as a powerful and practical method for high-resolution surface characterization in geotechnical engineering applications (Zekkos et. al 2018). Various studies have demonstrated the applicability of UAV-based photogrammetry for slope characterization, hazard assessment and management, emphasizing its growing importance in modern geotechnical practice (Giordan et al. 2018; Kallimogiannis et al. 2019; Watman et al. 2025).

This study explores a case study involving detailed investigation of rock slope stability and wedge failure hazards in an open pit mine by integrating UAV-based photogrammetry and limit equilibrium based back analysis.

2 Geological Setting and Site Characterization

2.1 Geological Setting and 3D Model

This study presents a detailed assessment of rock slope stability and wedge failures in an open pit mine, utilizing a high-resolution three-dimensional (3D) model generated from UAV-based photogrammetry. A dataset comprising 959 overlapping aerial images was processed in ShapeMetriX (3GSM GmbH) to reconstruct a section of the south-facing pit wall, which is primarily composed of limestone and sandstone units. The reconstructed 3D model contains six benches, a haul road, and an access tunnel located at the base of the slope, as illustrated in Figure 1. This 3D model provides a detailed spatial framework for structural mapping and slope hazard evaluation. Based on the 3D model, the average bench face orientation within the modelled area was estimated to be approximately 73°/188° (dip/dip direction).

2.2 Structural Geological Mapping

Detailed structural geological mapping was carried out directly on the reconstructed 3D model, allowing for the identification of joint traces and wedge-shaped block geometries. Two past wedge failures (called Wedge Failure 1 - WF1 and Wedge Failure 2 – WF2) were also identified on the slope surface. Displaced rock fragments of WF1 were observed on the lower benches, with some blocks reaching areas close to the access tunnel entrance. WF2 was recognized directly above the haul road, as presented in Figure 1. These findings present an operational safety concern for both the haul road and the tunnel.

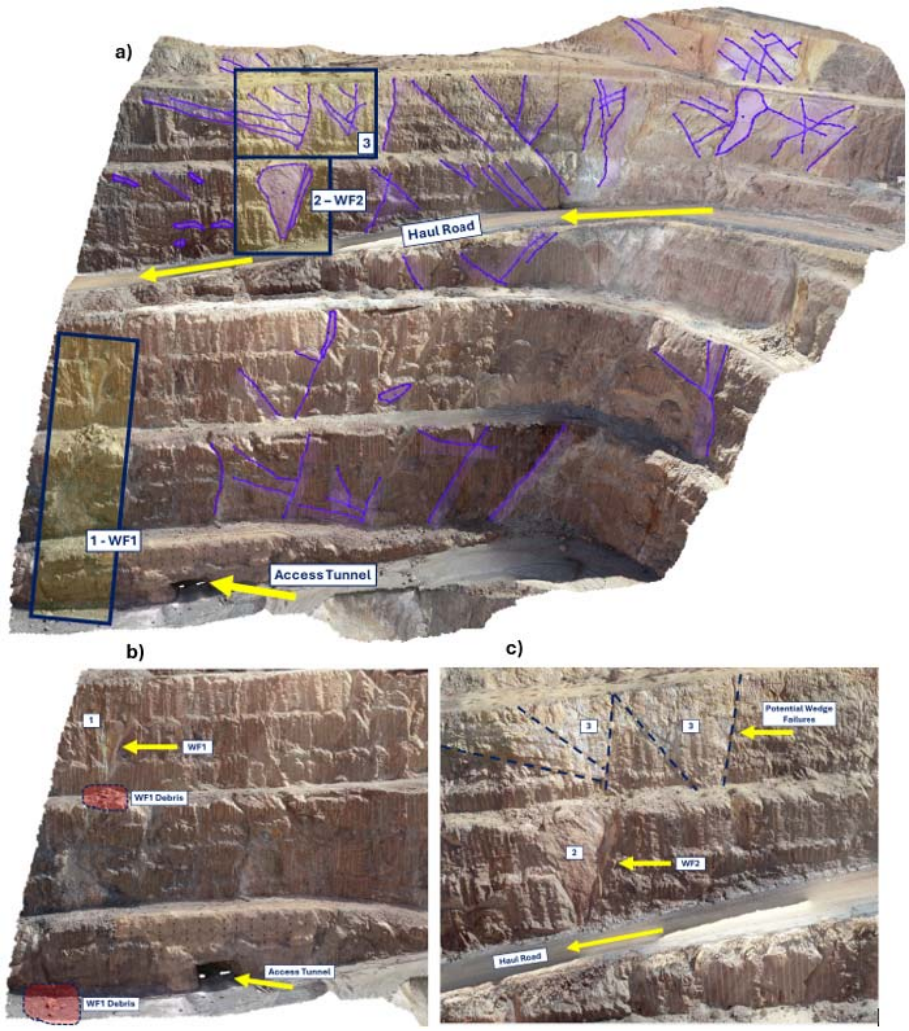


Fig. 1a) Reconstructed 3D model and mapped structures (blue), b) WF1 and rock deposition locations, c) WF2 and potential wedge failures.

2.3 Quantifying Past Wedge Failures

Detailed block size, block volume and joint orientation measurements were carried out on the 3D model as shown in Figure 2, to quantify the geometry, size, and failure characteristics of the past wedge failures identified as WF1 and WF2. Block volume, total block weight (for an assumed unit weight of 26 kN/m^3) and joint orientations for WF1 and WF2 were provided in Table 1.These measurements provided critical inputs for both kinematic analysis and LE based back analysis.

Table 1. Geometrical measurements for WF1 and WF2.

Block ID	Block Volume (m3)	Block Weight (kN)	Joint Orientations (Dip/Dip Dir.)	J1 – J2 Line of Intersection (Trend/Plunge)
WF1	21.4	556.8	J1=67.3°/158.3° J2=59.3°/215.8°	205.2°/58.5°
WF2	79.3	2062.6	J1=64.1°/170.5° J2=54.9°/212.8°	216.9°/54.8°



Fig. 2a) WF1 block size, block volume and joint orientation measurements, b) WF2 block size, block volume and joint orientation measurements.

2.4 Kinematic Analysis

The mapped structural data was subsequently exported from ShapeMetriX to Dips (Rocscience Inc.) for stereonet and kinematic analysis. Interpretation of the stereonet plots identified two dominant joint sets, identified as JS1 with a mean orientation of 72°/182° (dip/dip direction) and JS2 with a mean orientation of 55°/220°. Kinematic analysis carried out in Dips, using the previously determined average slope orientation, indicated that WF1, WF2 and multiple other wedges formed by the intersection of JS1 and JS2 satisfy the kinematic conditions for wedge sliding. WF1, WF2 and these potentially unstable wedge configurations are illustrated in Figure 3.

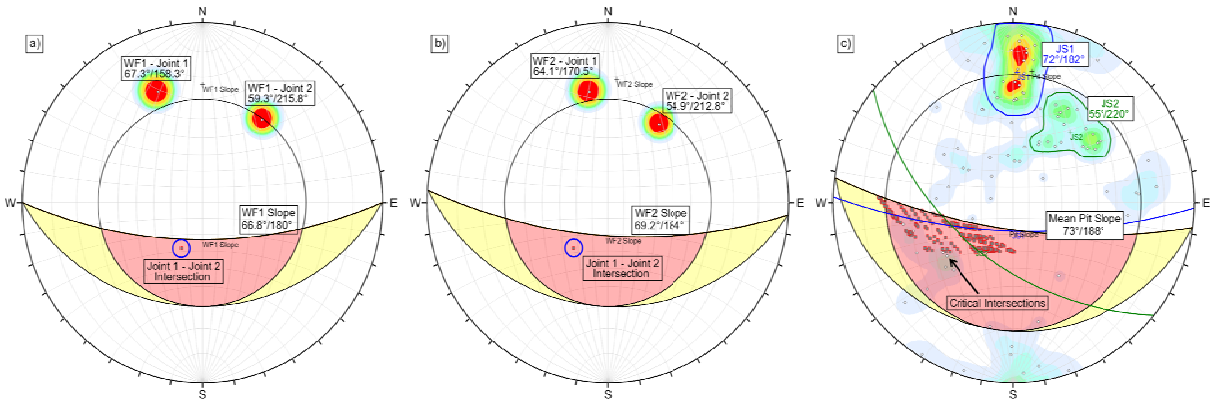


Fig. 3Wedge sliding kinematic analysis a) WF1, b) WF2 and c) mapped structural data.

3 Wedge Failure Back Analysis

Back analysis is an inverse method used to determine unknown material properties, mostly shear strength parameters, from an observed or documented failure. In wedge failure back analysis, this procedure usually involves carrying out aLE based stability analysis utilizing available information such as slope geometry, joint orientations, material unit weight, etc. to calculate unknows parameter like shear strength properties by setting Factor of Safety (FS) at 1.0 (limit equilibrium state). Back analysis is particularly valuable because the obtained parameters typically demonstrate higher

reliability than other means of data estimations (i.e laboratory tests, empirical equations, etc.), especially for large-scale in-situ conditions (Wyllie 2017).

In this study, RocSlope2 (Rocscience Inc.) was used to perform wedge failure back analysis. RocSlope2 is a state-of-art software package to analyse 3D wedge, planar and toppling blocks with structurally controlled failure. The objective of the back analysis was to obtain joint shear strength parameters that led to observed and documented wedge failures. A single variable approach was employed in back analysis, where cohesion (c) was assumed to be zero (0) and the analysis was solved for friction angle (φ) (assuming Mohr-Coulomb failure criterion for joint shear strength)that produces FS ≈ 1.0. Remaining model inputs were known or assumed to be well constrained. Failed wedge creation for WF1 in RocSlope2 was illustrated in Figure 4, for reference. RocSlope2 back analysis model input parameters for WF1 and WF2 were presented in Table 2.

Joint friction angle (φ) values that produces FS ≈ 1.0 for WF1 and WF2 were determined as 56.9° and 54.8°, respectively. These estimated joint friction angle values were assumed to be almost identical considering uncertainties in rock joint shear strength arise from natural geological variability.

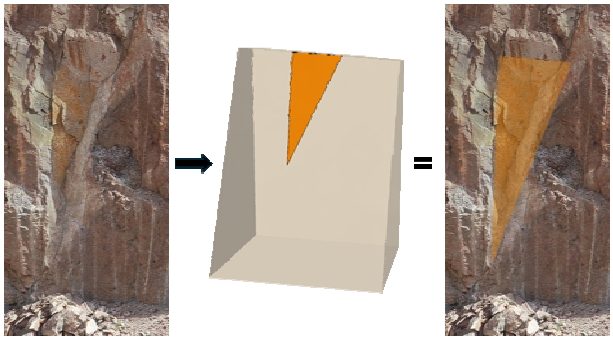


Fig. 4 Failed wedge creation for WF1 in RocSlope2.

Table 2. RocSlope2 back analysis model input parameters for WF1 and WF2.

Input Parameter	**WF1**	**WF2**
Slope Face Dip/Dip Dir. (°)	66.8°/180°	69.2°/184°
Upper Face Dip/Dip Dir. (°)	4°/180°	3°/184°
Slope Height (m)	15.9	12.5
Slope Length (m)	25	25
Bench Width (m)	6.32	6.4
Tension Crack Dip/Dip Dir. (°)	88.6°/173°	-
Rock Unit Weight (kN/m^3)	26	26
Groundwater Conditions	Dry	Dry

4 Forward Block Stability Analysis

Following the calibration of site-specific joint shear strength parameters, these parameters were utilized in limit equilibrium based forward block stability analyses to assess the potential future instabilities of blocks that were identified on the 3D model, which might significantly threat the mine safety and mining operations.

RocSlope3, a comprehensive software package for assessing 3D block stability risk for rock slopes, was used to perform LE block stability analysis. Program also enables to identify key blocks which controls the stability of the overall slope, and to simulate unravelling blocks (referred as 'domino effect' of rock slope failure) where the failure of one key block triggers the failure of adjacent, previously stable blocks (successive failure). The 3D model reconstructed in ShapeMetriX was imported into RocSlope3 to generate 3D slope geometry for stability analysis. Joints mapped in ShapeMetriX were also imported into RocSlope3 with their locations, sizes and orientations (Figure 5). Considering relative uniformity of the slope lithology, a single material was applied to the entire slope geometry. Where applicable, same input parameters presented in Table 2 were utilized. Joint friction angle was set to 55.9° (assuming c=0) considering average friction angle obtained for WF1 and WF2 through back analysis. Successive failure analysis was carried out to identify key blocks and unravelling blocks. A total of 14 blocks were estimated to be marginally stable where FS between 1.0 and 1.3, as illustrated in Figure 5. 7 of these blocks were determined to be key blocks while the other 7

blocks were found out to be failing in second or third iteration after the failure of a key block. These marginally stable blocks can be assumed to be in a state of limiting equilibrium, where resisting forces barely exceed driving forces. These blocks have little to no buffer against changing environmental or loading conditions and carries a high risk of failure with a small increase in driving forces, i.e. increasing pore pressure due to rain or reduction in joint shear strength. Therefore, these blocks were determined to require engineering intervention in order to prevent any future failures.

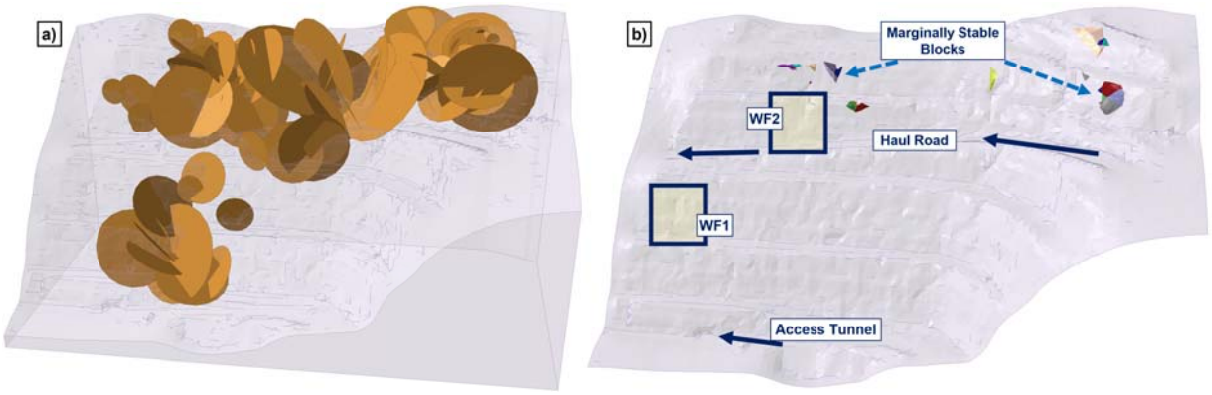


Fig. 5a) 3D geometry and mapped joints in RocSlope3, b) RocSlope3 analysis results and marginally stable blocks.

5 Conclusions

In this research case study, the practical applicability and efficacy of integrating UAV-based photogrammetry, 3D contact-free structural geologic mapping, LE based back analysis for parameter calibration and validation, and LE based block stability analysis for rock slope hazard assessment in open pit mines were demonstrated.

Kinematic analysis was performed using the mapped structural data, confirming kinematically admissible wedge blocks. Geometric measurements were also performed on identified past wedge failures. Quantified data for these failed wedge blocks were used in back analysis to calibrate and validate joint shear strength parameters. Finally, these parameters were utilized in block stability analyses to assess the potential future instabilities of blocks that were identified on the 3D model. These predictive simulations of this case study revealed possible impacts on the haul road and the access tunnel, emphasizing the importance of proactive hazard management.

This workflow not only delivers detailed, high-resolution documentation of slope conditions and associated failure mechanisms, but also enables the development of calibrated predictive tools that support effective risk management and safer mining operations.

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