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Drone photogrammetry: a structural data gathering tool for open pit mining geotechnics

J Dey *SRK Mining Services (India) Pvt Ltd, India*

S Roy *SRK Mining Services (India) Pvt Ltd, India*

A Matin *University of Calcutta, India*

Abstract

Structural elements, such as folds, faults, shear zones (major structures) and closely spaced structural defects (structural fabric) determine the stability of open pit slopes. As a result, a site-specific structural model is required for reliable slope design, its implementation and management. However, attaining a robust fabric model is often difficult for lack of adequate and reliable data, and therefore, uncertainty is introduced in the resulting pit designs.

To overcome data inadequacy and uncertainty, drone flights were used to develop a photogrammetry-based model of an operating limestone pit. The deposit occurs in a structurally complex terrain with varied orientation of strata and joint systems typical of a folded sequence. An automated mission plan was devised with the drone flying at a constant speed in a predefined path, maintaining a constant distance from the pit benches. Images were captured automatically with vertical, inclined, and horizontal camera angles. The high resolution, 3D photogrammetric model was processed by Datamine Sirovision package. Different lithologies, their contacts, and the fabric systems were captured through the process and were used for structural interpretation and modelling.

At project scale, the deposit showed signatures of three phases of deformation: 1) a bench to sub-bench-scale isoclinal folding; 2) mine-scale upright, open folding with ~east–west trending axial plane; and 3) mine-scale cross folding with ~north–south trending axial planes. Orientation of bedding planes were largely controlled by the first order second generation folding. Sub-vertical, persistent, axial planes associated with the two major folding episodes (2 and 3) formed the most prominent structural fabric that strikes ~east–west and ~north–south, respectively. In addition, sub-horizontal, small-scale, axial planes associated with the first phase of folding were found locally alongside partially developed joint sets. Structural domains were outlined based on rock mass conditions and structural fabric.

Resulting structural model helped to develop a reliable geotechnical model, established opportunities of slope steepening, and finally to develop a slope management program.

Keywords: *drone application technology, unmanned aerial vehicle, photogrammetry, structural data processing, structural model, pit slope design, design uncertainty*

1 Introduction

The dimensions of open pit mines are ever increasing with large surface footprint and depths in the order of thousands of metres. Economics and safety of these operations rely largely on the stability of the pit slopes. While an increase in the pit slope angle may reduce waste stripping and enhance recovery of ore, steepened pit slopes will increase the likelihood of slope failures. Therefore, a careful design is necessary that optimises the pit slope angles considering the geological, structural, and geotechnical conditions of the ground.

The fundamental unit that defines the overall pit slope angle is the bench-berm geometry that consists of bench height, bench width and the bench face angle (Hustrulid et al. 2013). While major structures, such as folds, faults and shear zones influence the inter-ramp to overall slope angles, design parameters at bench-scale rely primarily on the disposition of close spaced structural defects that occur mostly in the form of rock joints, fractures, bedding planes, etc. (Read & Stacey 2009). This signifies the importance of a structural model for optimal pit slope designs, and later for design implementation and for managing the pit slopes.

Traditionally, structural geological data for pit slope designs were acquired by handheld compass. The advent of technology added digital compasses and terrestrial digital photogrammetry techniques (Haneberg 2008). However, all these techniques rely on walk over surveys and therefore, are restricted by accessibility and risks associated with fieldwork within an operating mine. Walk over surveys generally produce limited volume of structural data and may contain some form of orientation bias. Such limited data may help conceptualise the major structures, however, they are often inadequate for statistical evaluation of structural fabric. For example, defining optimal bench face angle and bench width requires detailed fabric data that include the number of joint sets, their orientation, spacing, persistence, and surface conditions. Further information, such as the position of these discontinuities with respect to the pit slopes helps to define the design sector specific parameters. Such multi-parameter mapping of the structural fabric is not practical by walk over surveys. Moreover, orientation bias inherent within the field mapping dataset may lead to incorrect structural interpretation (Watkins et al. 2015). Therefore, pit slope designs based on walkover surveys contain some degree of uncertainty that may impact a mine from the safety perspective.

In order to overcome the limitations of inadequate structural data, we used drone flights in an operating open pit mine. The objective was to assess the stability conditions of the current pit walls and assess opportunities for steepening the pit slopes. In general, automated mission planning software for drone flight allows horizontal fly paths suitable for imaging the topographic surface. We planned a specialised mission to capture structural data from the steeply dipping bench faces. The resulting photogrammetry-based model was robust and allowed collection of significant volumes of structural data from the bench faces. We used Sirovision for picking the structures from the photogrammetry-based model. A conceptual structural model was developed that identified the different deformation episodes within the deposit and the associated structures. Based on this understanding, a 3D large-sale structure model and a structural fabric model was developed. The resulting structural model formed the basis of a geotechnical model and helped optimise the bench designs and the overall pit slope angles. Later, a monitoring program was also devised considering the structural conditions at site.

2 Structural data for open pit mine design

Structural data are routinely collected for greenfield and brownfield mining projects. While greenfield projects are evaluated by outcrop mapping and borehole logging, exposed mining faces form an additional data source for the brownfield projects. As a result, field mapping is widely practised to provide structural inputs to operating mines (Read & Stacey 2009). While classical field techniques are used to interpret major structures, specialised techniques are used to collect structural fabric data, such as scanline mapping, window mapping, terrestrial digital photogrammetry, etc. These techniques are very useful for operating open pits, where additional structural data and improved structural understanding may help optimise the pit designs. Following is a brief discussion on the methodologies and the limitations of currently practised field mapping techniques.

Scanline mapping in the open pits: Scanline mapping technique is useful to map the structural fabric and to record geotechnical characteristics of the discontinuities. A measuring tape is placed on the bench face (considered as the scanline) and each structure intersecting the scanline is characterised by measuring its orientation, spacing, persistence, intensity, aperture, infill, discontinuity surface conditions, etc. (Priest & Hudson 1981; Priest 1993). Usually, the length of the scanlines ranges between 30 and 50 m and scanline data are collected from multiple locations across a pit.

Window (cell) mapping: Window or cell mapping considers an imaginary rectangle on the pit wall and examines the structural fabric that occurs within the rectangle (Priest 1993; Read & Stacy 2009; Watkins et al. 2015). Usually, the vertical dimension of the window matches the bench height and as a practice window, mapping data is collected from various locations within the pit.

Terrestrial digital photogrammetry: With the advent of technology, field measurements are complimented by terrestrial digital photogrammetry, allowing 3D rock face modelling and virtual mapping, even in areas without access or safety. Stereopair photographs are captured with currently available off-the-shelf digital cameras. Commercially available software packages facilitate development of stereo models suitable for mapping of the structural elements. A virtual mapping platform helps to identify, map, and quickly calculate the orientation of modelled discontinuities using the experience-based logical process as used by traditional fieldworkers. A structural dataset can be developed quickly with discontinuity characteristics, orientation, persistence, frequency, and block size (Haneberg 2008). Comparison of field measurements and photogrammetry-based discontinuity mapping shows close agreement between the datasets (Coggan et al. 2007; Grobler et al. 2003; Haneberg et al. 2006; Krosley et al. 2006; Sturzenegger & Stead 2009; Salvini et al. 2016). Cronin (2008) proposed that orientations determined from 3D photogrammetric models are more representative as they take into account, and indeed quantify, the variability of irregular joint surfaces in a way that manual measurements rarely can.

However, all these techniques are human intensive, require extensive fieldwork, and produce limited volumes of data with some form of orientation bias. As a result, structural data from traditional field mapping may be found inadequate, especially for modelling of structurally complex deposits.

3 Drone photogrammetry-based structural data

A conventional structural data gathering program can be replaced by unmanned aerial vehicles (UAVs), commonly known as drones. Drone technology has evolved significantly in the last few years. Consumer-grade unmanned aircraft systems, particularly small unmanned aircraft systems, are generally used for photogrammetric image capture (Toth & Jóźków 2016).

The Structure-from-Motion (SfM) processing emerged parallel to the growth of drone technology. In SfM, static, 2D, overlapping images from a moving sensor (such as a drone) are subjected to an automated feature matching algorithm. Camera position, orientation and scene geometry are reconstructed simultaneously by automatic identification of matching features in successive images. The processing finally results in a dense point cloud, a digital elevation model, orthophotos and a 3D photogrammetry-based model from multiple overlapping (70–80%) 2D images. Ground control points (GCPs) from the area of interest are used to scale and orient the model in an actual space coordinate system (Westoby et al. 2012).

However, it is important to note that the quality of drone imaging depends on a number of factors such as lighting conditions, position of the shadow, presence of dust particles in the air, etc.

Drone photogrammetry provides many advantages over the field-based structural assessment. It allows quick data collection in a much safer way and with limited involvement of human resources. A drone photogrammetry derived dataset helps multi-disciplinary evaluation of an open pit, including:

- Mapping of various lithologies exposed in the pit walls.
- Mapping of large-scale structures and structural fabric.
- Mapping of the weathering profile.
- Acquiring fabric data for structural modelling.
- Assessment of pit slope performance with identification of areas having higher risk of slope instability.
- Identification and mapping of areas with groundwater seepage.
- Assessment of likely links between the pervasive structures and nearby water bodies (if any), and so on.

Drone photogrammetry may also help to develop a large structural dataset with reduced uncertainties. A photogrammetry-based model offers the opportunity to measure structures anywhere in the pit, without a concern of safety or accessibility. Virtual scanlines may be constructed in locations having a perpendicular relation between a particular joint set and the plane of measurement, and thereby orientation bias may be minimised. However, it is better to avoid drone flights for an extended period of time as any mining activity such as a blasting event may change the geometry of the pit walls during the period and may therefore pose difficulty during SfM modelling.

Despite its immense potential, the use of drone-based photogrammetry is relatively uncommon in structural data gathering and evaluating 3D structure of open pit mines. This may be attributed to the difficulties associated with drone data capture in an open pit where the majority of structural elements are exposed in sub-vertical bench faces. On the other hand, commercially available flight (mission) planning programs generally offer flight paths suitable for imaging topographic surfaces. Vertically looking down (nadir) camera angles (gimbal pitch) are useful for the vast majority of applications, however, are not suitable for capturing structural data from vertical and sub-vertical bench faces. This problem may be resolved with horizontal camera angles ‘looking’ at the bench faces, however, irregular geometry of an open pit mine poses further difficulties to automate drone flights. Manual flights are not appropriate to maintain a constant distance between the camera and the object (i.e. the bench faces).

3.1 Drone fly paths tailored to open pit mine geometry

To overcome these limitations, we evaluated various fly path options for drone photogrammetry mapping programs. A DJI Phantom 4 aircraft was used to capture images of an operating pit. This series of UAV products are used by many researchers and found to deliver a trade-off between cost, sensor quality, functionality, and portability (Peppa et al. 2019). Commercially available mission planning packages (i.e. software for flying drones) either offer horizontal fly paths, such as single or double grid with nadir photography suitable for topographic surveying, or 3D fly paths orbiting an object with convergent photography, suitable for surveying building-like structures. Common mission planning packages also offer a free flight option where the drone flight is managed manually by the pilot. Figure 1a shows a summary of commonly available flight options and Figure 1b shows available camera angles with DJI Phantom 4 that range from +30° to -90° (DJI Technology Company Limited 2017).

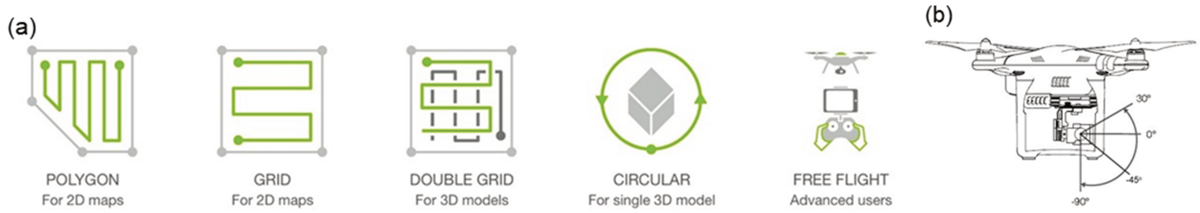


Figure 1 (a) Common mission planning options for flying drones; (b) Camera angles (pitch) available with DJI Phantom 4

None of the automated flight controls are suitable for photogrammetry-based modelling of an open pit as the mission plans are not tailored to capture images of sub-vertical bench faces. As an example, Figure 2a shows a photogrammetry-based model of an open pit where the drone flew with a horizontal, automated double grid, at about 60 m above the pit crest. The camera was set to automatically capture images from a nadir position (-90°) with 80% overlap and side-lap. The 3D photogrammetry-based model developed from this dataset shows that the structures exposed in the pit benches are not visible and therefore, the model is not useful for structural evaluation purposes.

To improve the quality of the photogrammetry-based model, double grid nadir (-90°) images were added with another set of images captured with a double grid flight with -45° camera angles. An automated mission planning was used to capture these images. The resulting photogrammetry-based model shows improvements, and the pit benches are better seen in the photogrammetry-based model. However, the dataset is still not appropriate for picking structural features (Figure 2b).

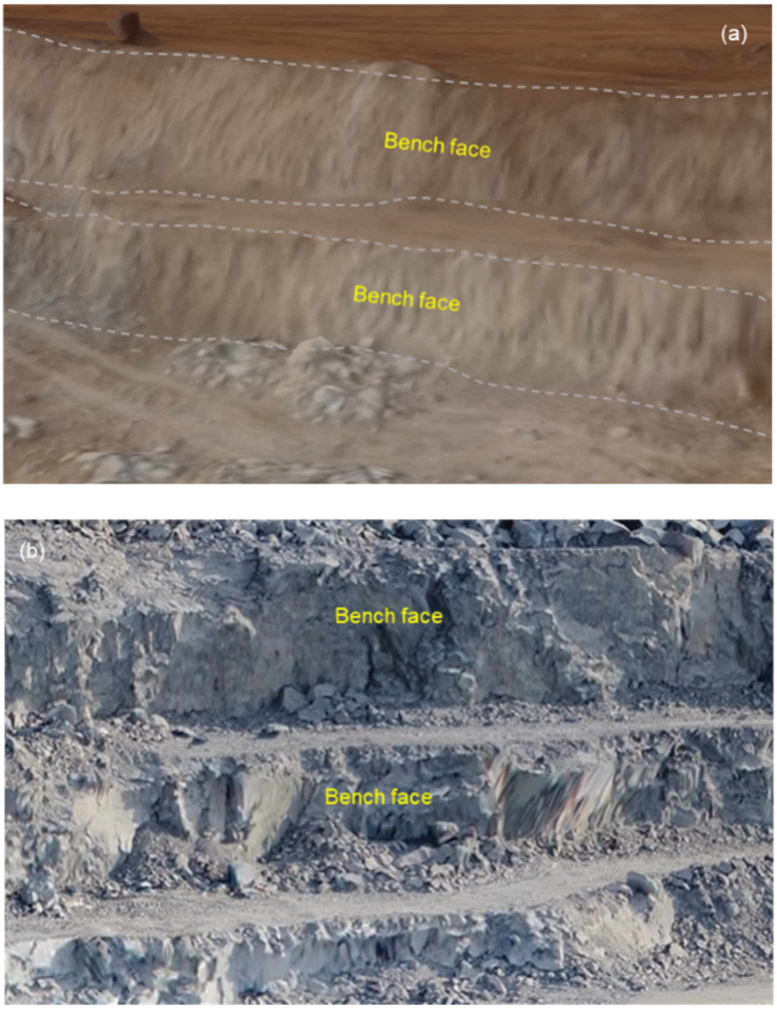


Figure 2 **Snapshots from drone photogrammetry-based model of an open pit with (a) double grid flight with nadir camera and (b) double grid flight with nadir camera and another double grid flight with -45° camera. Bench height ~6 m**

To further improve the quality of a photogrammetry-based model, it was planned to capture another set of images with horizontal camera angle (0°) with the camera 'looking' at the bench faces. However, this flight is not possible to execute with an automated mission plan. For an accurate photogrammetry-based model, the camera should always be equidistant from the target and therefore, the flight path should honour the irregular geometry of a mine face. This can theoretically be achieved with manual flight, however, maintaining a constant distance between the camera position and the bench face is practically impossible with human control.

In order to overcome this limitation, we used the latest 3D pit survey model and constructed equidistant 3D polylines by using Leapfrog software (Figure 3a). These 3D polylines were converted to .kml files and exported to mission planning packages as fly paths for automated drone flight. Images were captured automatically with 80% overlap and side-lap. After some trial and errors, an optimal distance between the camera position and the pit benches were arrived at. It was noted that high resolution images can be captured when the camera takes a snap of each bench separately (Figure 3b).

The resulting photogrammetric model consists of high-resolution images of the open pit benches, appropriate for structural and geotechnical assessment. GCPs across the pit helped georeferencing the dense point cloud and derived products. This high resolution, geocoded, 3D photogrammetry-based model is useful to develop a comprehensive structural model of the mine. Since the model captures images of the entire pit, a comprehensive pit scale structural assessment was possible (Figure 3c and 4a).

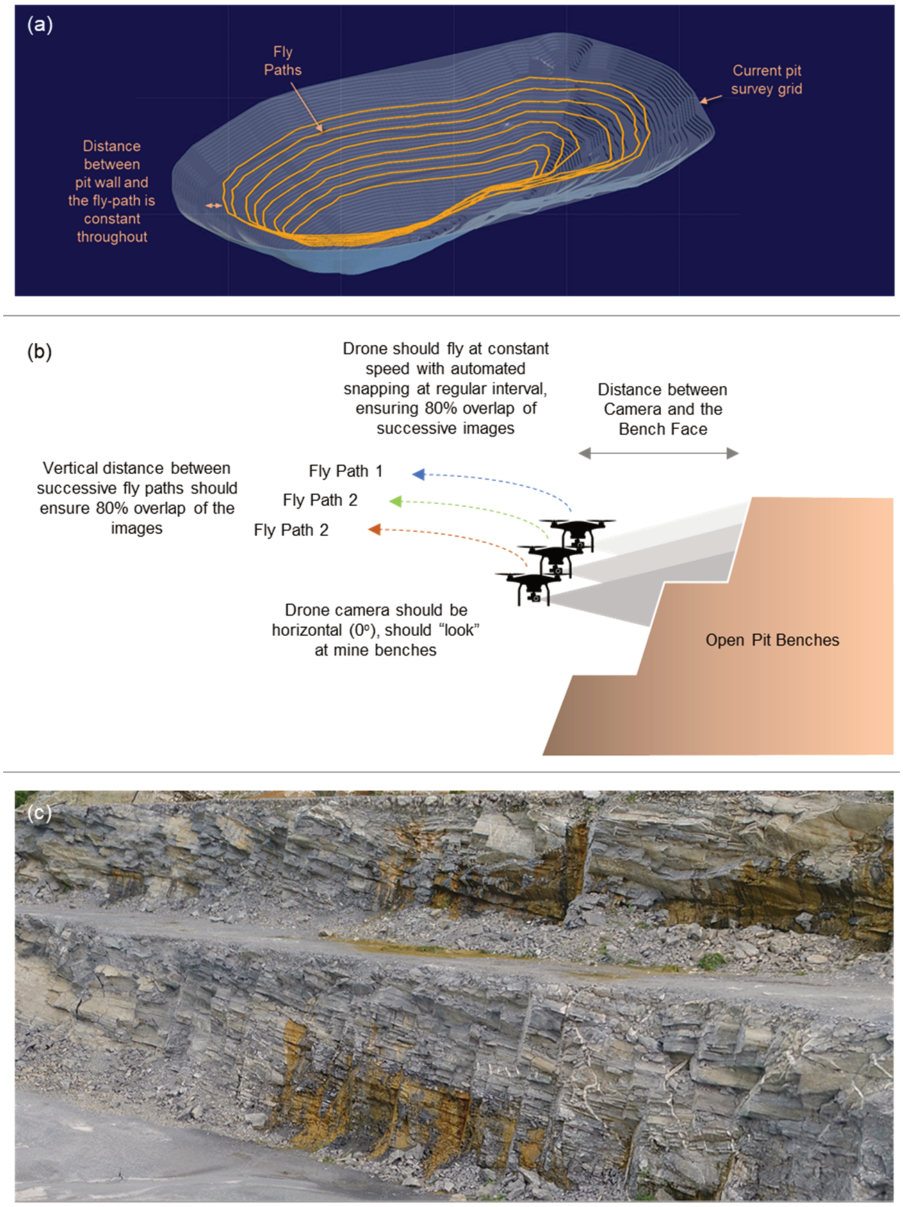


Figure 3 **(a) Defining fly path for open pit photogrammetry; (b) Drone fly paths adopted; (c) High resolution open pit photogrammetry, showing image of a bench face**

3.2 Structural data capture and modelling in Sirovision

Commercially available Sirovision Open Pit (SOP) software package (Datamine 2018) is useful to interpret the high-resolution photogrammetric model. SOP is a photogrammetric remote data acquisition system for geological mapping and interpreting structural and geotechnical features exposed in mining faces. The system can utilise both stereo photographs from off-the-shelf digital SLR cameras and 3D imagery from drones or laser scanners and is able to generate accurate 3D models using the latest image processing technology suitable to extract unbiased and accurate geological, structural, and geotechnical data. Various 3D import formats are supported by SOP, including .LAS, .OBJ and .PLY files.

The software is able to manage 3D models that cover an entire pit. Structural features can be mapped with instant structural and geotechnical interpretations. Discontinuity orientation data can be visualised using spherical projections, rose plots and statistical analysis tools alongside their numerical attributes. SOP also captures the real-world physical characteristics such as persistence and location in a 3D georeferenced space.

The software offers high accuracy for structural measurements with better than +/- 0.5° for dip angle and dip directions (Datamine 2019).

The drone photogrammetry-based model and the SOP was used in an operating limestone mine to pick the structural elements, like bedding planes, joints, axial planar cleavages, and fractures from the photogrammetric model. Field mapping experience along with computational and data visualisation facilities of SOP was used to classify the structural fabric and characterise the features from a structural and geotechnical point of view.

4 Structural model of an operating limestone mine: a case study

4.1 General geology

The limestone mine is located in the Precambrian terrain of eastern India. Currently the mine pushbacks are restricted by lease boundary in north and south, and approved overall slope angles are also achieved. As a result, steeper slope angles are required to unlock deeper seated limestone resources.

We undertook a reconnaissance site visit to assess the structural geology of the deposit. Hard, compact limestone and thin beds of dolomite forms the depositional sequence. Signatures of multi-phase deformation are identified which shows development of three phases of folding followed by later joints that occur sparsely across the pit. As a consequence, stability at bench and inter-ramp scale are governed by the relative orientation between the pit face and the penetrative structural elements associated with folds and later fractures.

Preliminary field mapping helped conceptualise a structural model. At project scale, the deposit shows signatures of three phases of deformation:

1. Bench to sub-bench-scale isoclinal folds with sub-horizontal axial planes (named AP1), mostly reoriented due to the effect of later generations of folding.
2. Mine-scale upright, open fold with ~east–west trending sub-vertical axial plane (named AP2) and fold axis (FA) gently plunging towards east.
3. Sub-mine-scale cross folds with ~north–south trending sub-vertical axial planes (named AP3).

In addition, fracture sets developed intermittently across the limestone pits with a significant degree of scatter.

This conceptual structural model is based on reconnaissance mapping and limited structural data. Although this model provides an understanding of the overall structural setting and different discontinuity surfaces, it is not adequate to help redesigning the slopes of the operating pit. Detailed mapping of the current pit was restricted due to accessibility and safety issues. In order to fulfil the requirement of a robust structural model, we planned to undertake a drone-based data gathering program. The program utilised multi-level drone flights with:

1. Horizontal, double grid flights with nadir camera view.
2. Horizontal double grid flights with -45° camera view.
3. A series of horizontal flights within the pits, with horizontal camera looking at the benches.

For this mission, the fly paths were derived considering the current pit geometries, and a constant distance was maintained from the pit benches. GCPs positioned across the pits were used to convert the photogrammetry-based model in real-time coordinates. Resulting photogrammetry-based model formed the basis of a detailed structural interpretation (Figure 4a). The model was interpreted by using Datamine SOP package (Figure 4b and c).

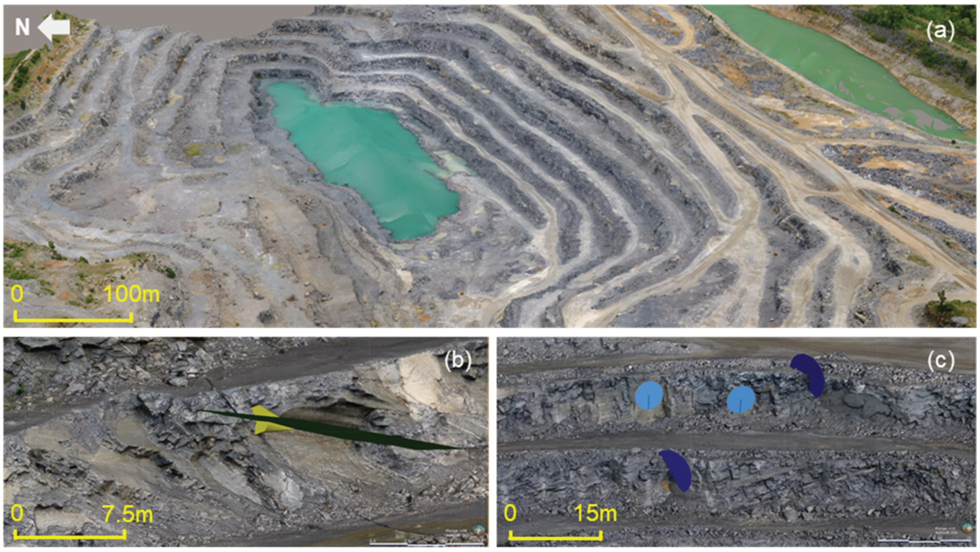


Figure 4 (a) A comprehensive, high-resolution, geocoded, 3D photogrammetric model of the pit utilised for picking structures; (b) First generation isoclinal fold hinge exposed in the pit bench, fold axis and AP1 are picked from the model; (c) Picking AP2 and AP3 from the model

4.2 Interpretation of structures

The photogrammetry-based model helped measure the orientation of all major structural elements such as the bedding planes, axial plane cleavages, and the fracture sets (Figure 5). A robust dataset was developed that helped evaluate these structures including a measurement of orientation variability. In addition, persistence (trace lengths) and the spacing between the discontinuities and their variability were also assessed. The structural map developed from the photogrammetry-based model also outlined areas showing better development of some of these structural elements. The drone photogrammetry derived dataset helped validate the conceptual structural model and also improved mine-scale structural geological understanding.

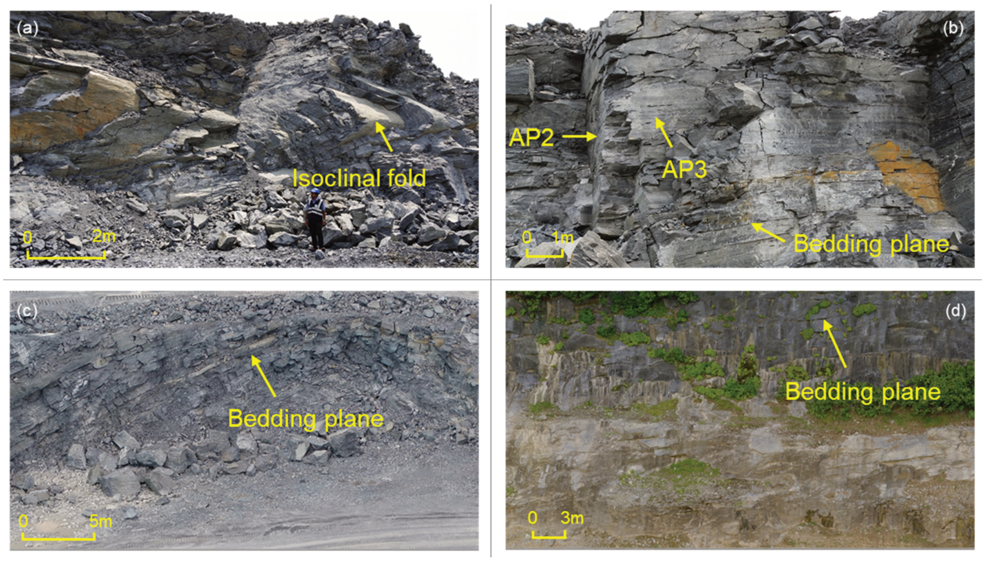
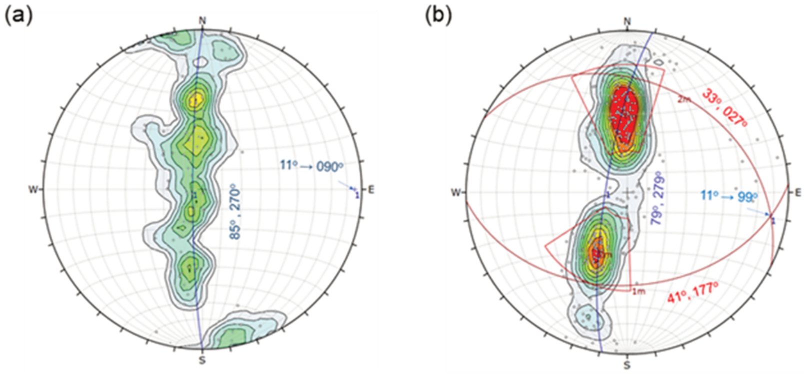


Figure 5 Interpreted structural elements. (a) First generation tight to near isoclinal folds having sub-horizontal axial planes; (b) Sub-vertical AP2 and AP3 exposed in the benches; (c) Exposed hinge zone associated with third generation of folding. Note thinly laminated bedding planes and development of close spaced AP3 in the hinge zone; (d) Massive to thickly bedded limestone exposed in the southern pit walls. Note poor development of axial planar cleavage in this limestone unit

4.2.1 *Bedding planes*

Bedding planes are the primary depositional surface (S0) that are deformed (folded) during three major phases of deformation. Out of these, the second phase of deformation largely controlled the orientation of the bedding plane and defined an upright open fold with ~east–west trending axial plane. Local variation of orientation of the bedding plane is observed and that relates to first and third generations of folding that are present at a smaller scale than the second generation fold (Figures 5a and 5c). In addition to direct field measurements, more than 300 bedding plane orientation data was acquired from the photogrammetry-based model. Orientation of different structural elements were assessed by stereoplots using Dips software package (Rocscience 2016). Figure 6 shows a comparison of bedding plane orientation data obtained from field mapping (Figure 6a) and drone photogrammetry (Figure 6b). These two datasets and the information after processing the data show good agreement, indicating the reliability of the drone photogrammetry derived data.

The pole to bedding in both the cases are distributed along a more or less well-defined great circle (Figures 6a and 6b), suggesting the cylindrical nature of the first order second generation fold structure. Two clusters of poles along the great circle indicate the general orientations of the northern and southern limb of the second generation upright fold (mean orientation of northern limb is 33°, 027°, and southern limb is 41°, 177°, Figure 6b). The FA plunges easterly (towards 090° and 099°, as shown in Figures 6a and 6b) at an angle of 11°. Some degree of scatter in the pole plots is due to the influence of first and third generation of folding on the bedding planes (Figures 6a and 6b).



Bedding plane - based on field mapping data (n=88)

Bedding plane - based on drone photogrammetry data (n=373)

Figure 6 Pole plots of bedding planes based on data collected during (a) field mapping and (b) from drone photogrammetry-based model. 'n' is the number of structural data

Since the orientation of the bedding plane varies across the deposit, it is important to assess this variability through a 3D model considering the structural data and its interpretation. Leapfrog Geo (LF) software package (Seequent 2021a) was used to develop this model. Following is a brief discussion on the modelling workflow.

Bedding plane measurements were imported as planar structural data under the structural model workflow in LF (Figure 7a). This allowed evaluating the variability of bedding plane orientation data and assessing its regional trend. Subsequently, form interpolants were developed based on the bedding plane orientation data (Figure 7b). A form interpolant is a radial basis function (RBF) interpolant that uses planar structural data to control the RBF gradient. The RBF gradient resembles the geological orientation that develops form interpolants useful for visualising structural data and identifying broad trends in 3D (Seequent 2021b). These isosurfaces or interpolant meshes are then used in the geological model workflow. Individual surfaces are introduced as depositional layers arranged chronologically based on their RBF gradients to develop a 3D model of the deposit. Upper extent of the model is clipped to the topographic surface in order to depict the current conditions.

Layers seen in LF view (Figure 7c) are the bedding planes showing a prominent folded sequence. The resulting LF structural model honours the following field observations:

- F2 folding with ~east–west striking, sub-vertical axial plane.
- F3 folding with ~north–south striking, sub-vertical axial plane.
- Easterly dipping F2 FA.

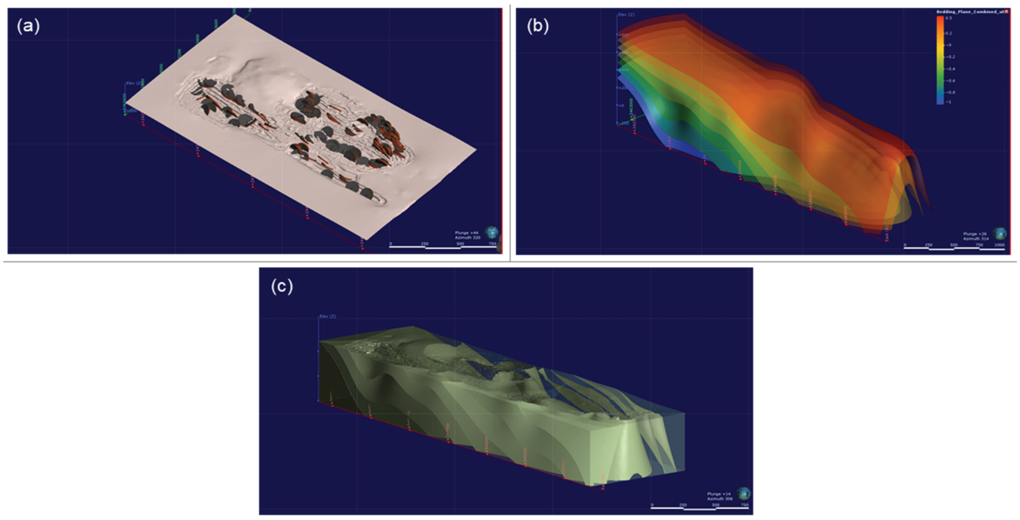
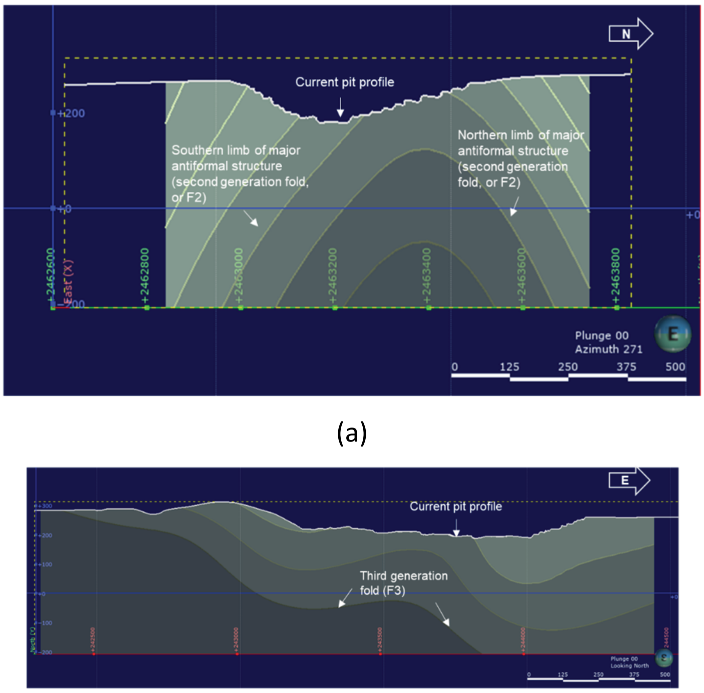


Figure 7 **Modelling the bedding planes and construction of the second generation folded structure. (a) Structural discs of bedding planes are plotted across the mine; (b) Form interpolant surfaces generated from bedding plane orientation data; (c) 3D Leapfrog model of the deposit showing the form surfaces**

Figure 8 shows cross-sections of the LF model, depicting large-scale F2 and F3 folds defined by the bedding planes.



(a)

(b)

Figure 8 **Cross-section of LF model showing the large-scale folded geometry. (a) North–south section showing second generation fold geometry having ~east–west trending sub-vertical axial plane; (b) East–west section showing third generation of fold geometry having ~north–south trending axial planes**

Further interrogation of the drone photogrammetry-based model showed that the thickness of limestone beds is variable, ranging from 0.2 m to a few metres. It was noted that the limestone beds are relatively thick in the upper pit benches in both north and south, with relatively thinner beds towards the bottom of the pit. Limestone in the south pit wall is generally massive with poor development of bedding planes. Possibly the limestone sequence is characterised by an upward increase in bed thickness, however, this needs to be proved with additional drillhole data.

4.2.2 *Structural fabric*

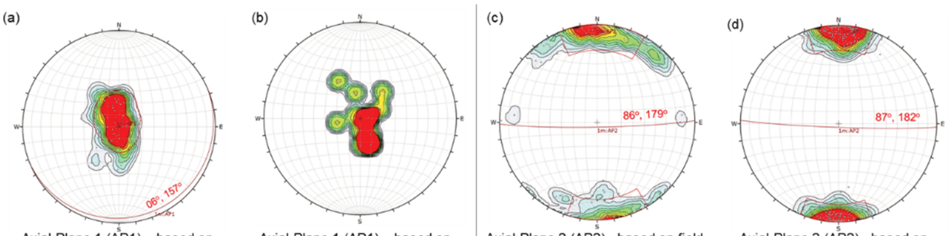
Axial planes, named AP1, AP2 and AP3 associated with the three folding events are the most prominent and persistent structural fabric found across the pit. In addition, late stage fracture sets were also developed intermittently with a significant degree of scatter. Structural fabrics were mapped and conceptually modelled during reconnaissance pit mapping, however, a detailed evaluation of these structures was only possible by interrogating the drone photogrammetry-based model.

The first phase of folds are present as metre-scale isolated folds found at places in the limbs of the large-scale second phase fold. These tight to near isoclinal first phase folds show sub-horizontal axial planes (named AP1, Figure 5a). These axial planes are discrete, impersistent, and could not be adequately modelled with the limited orientation data. Majority of the orientation data were measured from field and a stereoplot of poles is presented in Figure 9a. AP1 is not distinct in the photogrammetry-based model and only a small volume of orientation data was captured from the model (Figure 9b).

Second generation of folding is the most distinct deformation episode, forming an upright fold in the scale of hundreds of metres. The axial plane (named AP2, Figure 5b) trends approximately ~ with near vertical dip. AP2 is the most prominent structural fabric present throughout the area. The orientation of this plane was determined by field mapping (mean plane 86°, 179°, Figure 9c) and was corroborated with the volume of data captured from the drone photogrammetry-based model (mean plane 87°, 182°, Figure 9d).

Third generation folding is overprinted on the earlier folds. The axial plane associated with this folding, named AP3, was conceptualised from field data (mean plane 83°, 280°, Figure 9e), and was corroborated with the data from the drone photogrammetry-based model (mean plane 83°, 261°, Figure 9f). Close spaced AP3 was noted near the hinge of the third generation fold (Figure 5c), however, the trace length was found relatively less in these areas. AP3 is not developed in the massive limestone exposed in the southern pit wall (Figure 5d), indicating control of lithology over the development of the third generation folds.

The joint planes are sparsely developed across the pit and show a significant degree of scatter.

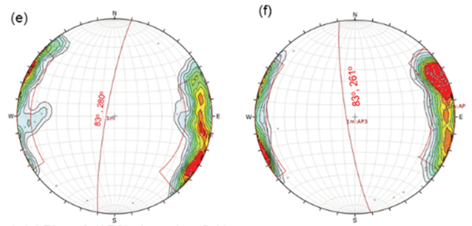


Axial Plane 1 (AP1) – based on field mapping data (n=70)

Axial Plane 1 (AP1) – based on drone photogrammetry data (n=13)

Axial Plane 2 (AP2) - based on field mapping data (n=98)

Axial Plane 2 (AP2) - based on drone photogrammetry data (n=244)



Axial Plane 3 (AP3) - based on field mapping data (n=72)

Axial Plane 3 (AP3) - based on drone photogrammetry data (n=272)

Figure 9 Pole plots of different structural elements based on structural data collected during field mapping and from drone photogrammetry-based model. 'n' indicates the number of structural measurements. Note that data from both the sources show similar orientation

5 Conclusion

This paper emphasises the importance of a structural geological model for geotechnical evaluation of an open pit mine. Considering the limited volume of structural data that can be collected from field mapping, drone-based data collection and modelling is proposed. A specialised mission planning is devised that is ideal for capturing images of open pit benches and to produce a high-resolution 3D photogrammetry-based model. Finally, a limestone open pit case study is presented where a detailed structural model is developed based on reconnaissance field mapping and a drone photogrammetry-based model. The work shows that structural data collected from the drone photogrammetry-based model are in good agreement with the field data. This provides confidence on the specialised flight planning we adopted, and the photogrammetry-based model we used for the purpose. The data acquisition and processing technique helps to gather a significant volume of structural data and its interpretation, and therefore may reduce uncertainties in open pit slope designs.

Although very advantageous for structural data acquisition and modelling purposes, drone photogrammetry-based models are not useful to assess the surface conditions of the discontinuities. It requires careful field investigation to assess the characteristics of the discontinuities after a structural model has been established from a drone photogrammetry-based model.

Our study with drone photogrammetry along with selective field mapping establishes the usefulness of a drone photogrammetry-based model in open pit mine planning, designing and production. We suggest the method may be applied in open pit mining projects in future.

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