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Using drone photogrammetry to optimise geotechnical analysis through efficient data collection

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Abstract

This paper presents the application of drone photogrammetry to acquire high-resolution data to conduct geotechnical analysis. The application of this technology enables the collection of data with significant time and cost savings when compared to conventional methods.

The employment of drones in mapping and pit inspection services yields many advantages. Whether through manual flight or pre-planned flight paths, efficient data collection becomes possible; covering areas that are inaccessible for visual inspection by personnel. Furthermore, the acquisition of high-resolution data through drone photogrammetry enhances the quality and quantity of gathered information.

By leveraging the collected photogrammetric data, 3D textured meshes of pit walls can be generated, facilitating the identification and mapping of defects as well as significant large-scale structures.

Drone photogrammetry ensures operator safety by enabling geotechnical data collection from secure locations. Operators can remotely gather data without the need for physical mapping, thereby eliminating exposure to potential hazards. Additionally, drones can operate at altitudes that do not interfere with ongoing pit operations, minimising disruptions and sustaining productivity.

The methodology employed in drone photogrammetry for open pit mines can be extended to other large-scale excavations with restricted access. Inactive quarries, road cuttings and cliff faces are prime examples of scenarios where drone-based geotechnical analysis can prove invaluable, providing detailed information that could not otherwise be obtained.

Keywords*: drone photogrammetry, open pit, quarry*

1 Introduction

Drone photogrammetry presents a viable alternative to traditional mapping methods and conventional approaches to gathering structural data. By utilising this technology, operators can remotely collect data without the need for physical mapping, effectively mitigating exposure to potential geotechnical hazards.

With the capability to cover flight paths of 40 to 50 km a day, drone photogrammetry significantly reduces costs and time requirements while concurrently improving the quality and quantity of remotely acquired information.

This advanced technique encompasses the utilisation of 3D textured meshes, enabling the precise identification and mapping of defects and large-scale structures. This comprehensive structural interpretation facilitates the analysis of faults, shears and highly fractured zones. It also enables valuable insights into back-analyses of structural failures and the identification of unfavourable structures within open pit mines and disused quarries.

The availability of detailed structural information supports in-depth analysis, including structural analysis, kinematic analysis, back-analysis of previous failures and limit equilibrium analysis.

This paper highlights the process shown in Figure 1, accompanied by relevant case studies and demonstrating the potential of drone photogrammetry in geotechnical analysis.

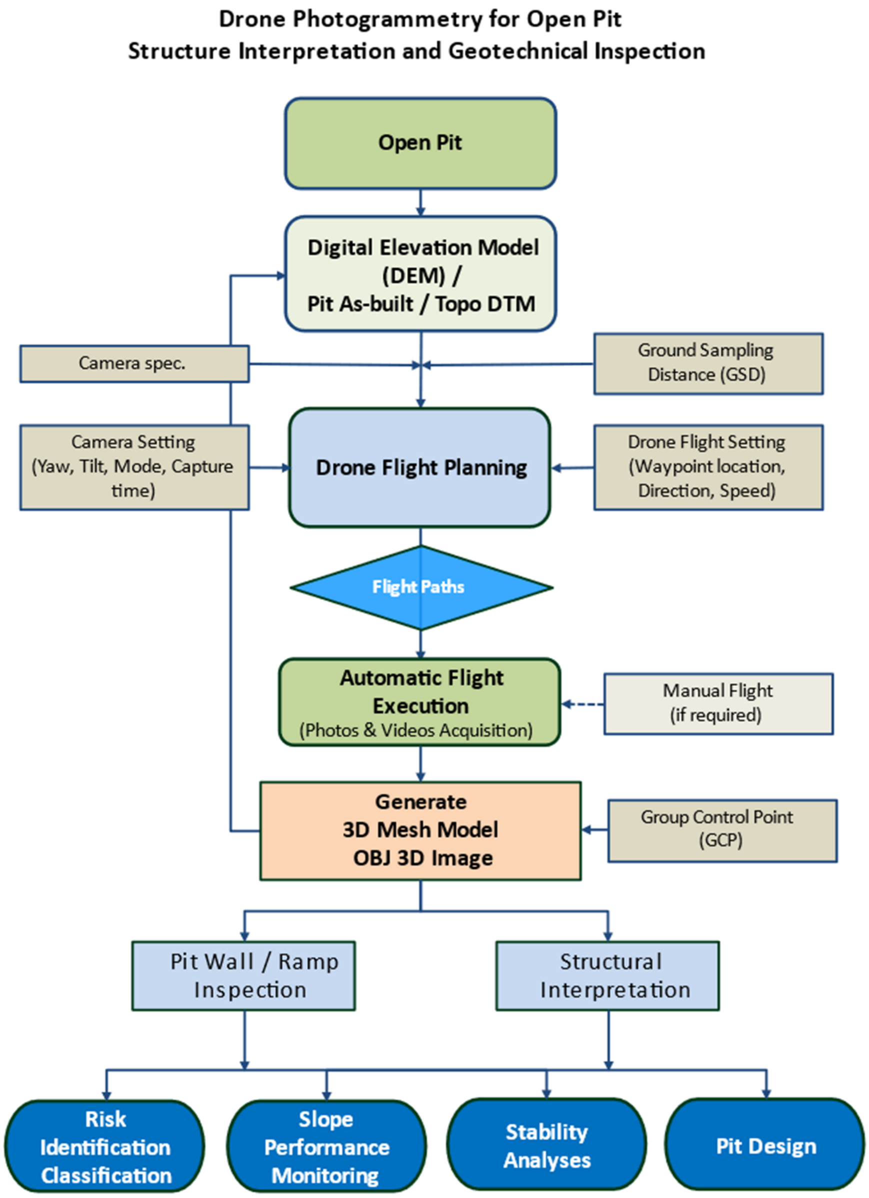


Figure 1 Drone photogrammetry flow sheet

2 Drone photogrammetry planning and data acquisition

To generate 3D images or mesh models using photogrammetric technology it is necessary to capture multiple photographs from different angles with a minimum of 66% overlap, ensuring acceptable image quality and resolution. Manual drone flight and photography require skilled operators who must focus on capturing each image while dealing with uncertain overlapping areas and variable flight distances.

Automatic flight with pre-planned flight paths offers a solution that precisely adheres to design parameters such as image coverage, overlapping percentage, quality, and resolution. This approach saves time and mitigates uncertainties associated with manual flight.

During automatic flight, the positions of the drone, camera yaw and angle for each photograph are calculated and pre-planned based on the specifications of the camera mounted on the drone and the desired ground sampling distance (GSD) or image resolution. The choice of GSD or image resolution depends on survey objectives, with a GSD of 2 cm/pixel suitable for target feature thickness greater than 1 cm. Higher resolutions with smaller GSDs are acceptable for geotechnical pit inspections and structural interpretation. GSD can be calculated using the following formula (Pix4D n.d.):

$$\text{Ground sampling distance (GSD)} = \frac{\text{Camera sensor width (mm)} * \text{Flight height (m)} * 100}{\text{Focal length of the camera (mm)} * \text{Image width (pixels)}} \tag{1}$$

For example, the Mavic 2 Zoom drone, equipped with a built-in camera with a 12 MP 1/2’’ sensor and capable of capturing images with dimensions of 4,000 width x 3,000 height pixels (DJI n.d.), can cover an area of 80 m width x 60 m height with a GSD of 2 cm/pixel when flown at a height of 52 m. Conversely, the required flight height can be calculated based on the desired GSD value and the camera specifications.

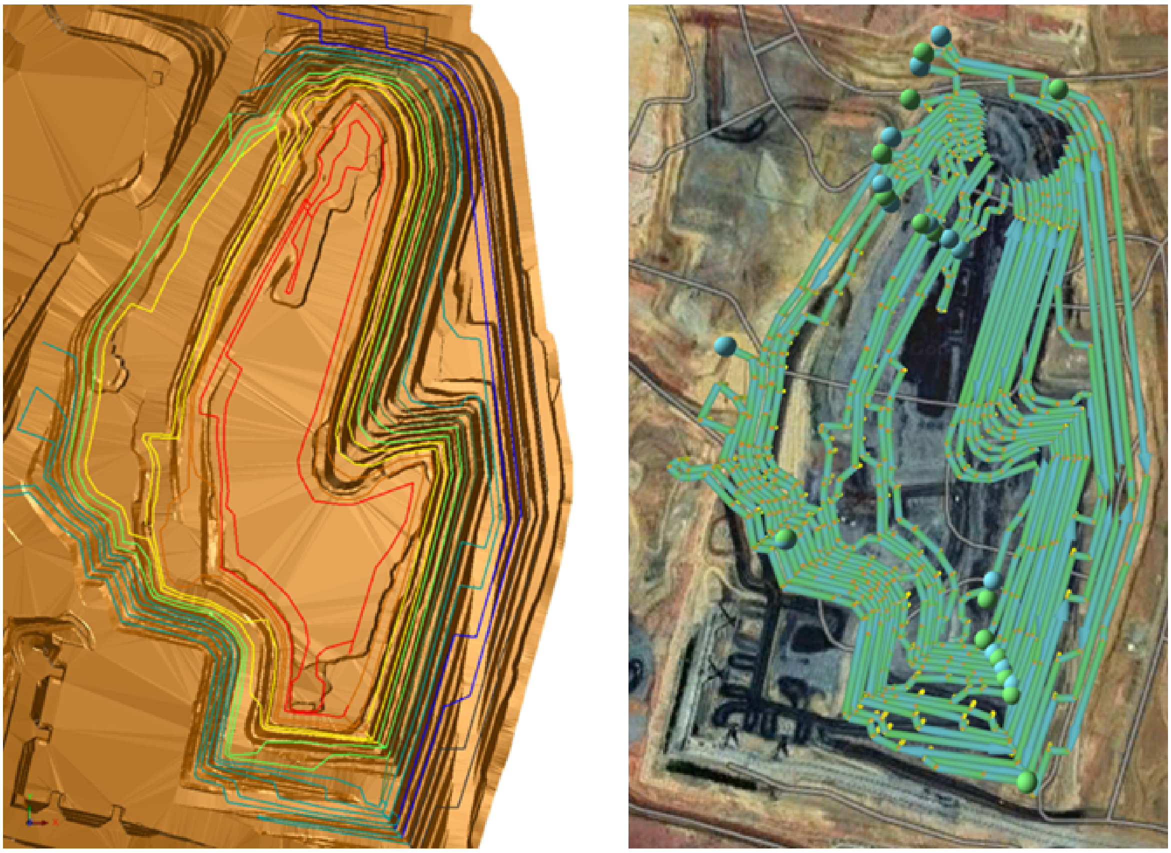
In 3D software (for example Surpac, Datamine, Vulcan etc.), terrain models or pit as-built wireframes are employed to create pre-flight paths with consistent flight height or distance, specifically for inspecting pit walls or conducting structural interpretation. The slope angles or pit wall angles, along with the orientation of each bench, are measured from the terrain model or pit as-built wireframe and used to project flight paths using the calculated flight distance. The camera angle is set perpendicular to the bench face to enhance image quality. Terrain models or pit as-built wireframes are also used to create digital elevation models, improving the accuracy of the elevation model in drone flight planning software to input planned flight parameters.

Once the pre-flight paths have been created in 3D software they are imported into the drone flight software (for example UgCS, Litchi, DJIFlightPlanner etc.) for flight planning, including input of flight information and photograph parameters, and execution of the drone flight. The pre-flight paths are imported as line string segments with waypoint locations which control the operations of the drone flight and camera. Depending on the drone and camera types, various parameters may be required for drone flight planning, such as:

- Flight direction – set orientation of the drone flight between the waypoints.
- Flight speed (recommended at 5 m/s or lower for photography).
- Camera yaw, roll and tilt – to set the camera direction and angle relative to the flight direction (between the waypoints) or the actual magnetic north direction. It is preferred that the camera direction and angle should be pointed perpendicular to the slope face or the pit wall bench face.
- Camera mode (photograph or video).
- Photo shooting interval based on time or distance. The shooting period can be calculated based on the required overlapping images (minimum of 66%), flight height or image covering area, and drone flight speed. For instance, using the above-mentioned GSD example with an image covering an area of 80 m width and a required overlap of 70%, the photograph shooting distance required would be every 24 m (30% × 80 m). With a flight speed of 5 m/s, the shooting time should be every 4.8 seconds (24 m ÷ 5 m/s).

Once the operational parameters for the drone and camera have been set, the flight paths can be simulated on a desktop computer or the flight controller to verify the accuracy of the input information before executing the flight in the field.

An example of pre-planned flight paths designed with consistent distance from the pit wall using 3D software and imported into drone flight software is shown in Figure 2.



(a) (b)

Figure 2 Example of pre-planned flight paths. (a) Designed in 3D software (Surpac); (b) Flight planning software (UgCS)

Subsequent to the data acquisition phase, the collected data is then processed using specialised photogrammetry software. This process yields a textured mesh model with true colour image and point cloud, in which each individual point encapsulates precise (x, y, z) positional data as shown in Figure 3.

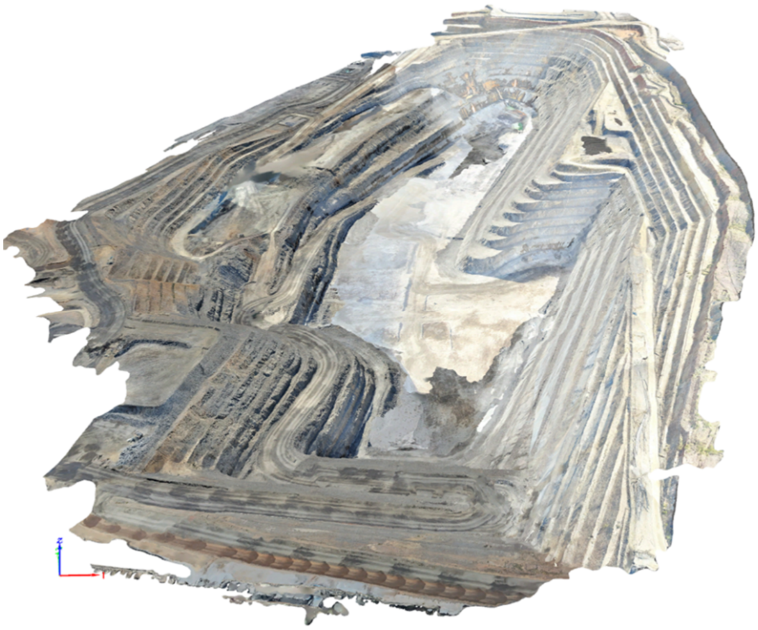


Figure 3 Example of generated 3D textured mesh with true colour image

The generated model enables the determination of structural orientation, precise location and continuous features. This utilisation of the model significantly enhances both the quality and quantity of the structural dataset, leading to a more comprehensive and accurate interpretation.

To facilitate structure interpretation and risk identification, Pix4D software is employed to generate a high-resolution 3D mesh model and OBJ file. This is achieved by combining the photos and videos captured by the drone, with the added benefit of using ground control points (GCPs) for image transfer and correction. Furthermore, BasRock GEM4D software is utilised for the interpretation of structure orientation and classification.

3 Case studies

3.1 Introduction

Case studies involving photogrammetry surveys for structural evaluation in mining and quarrying operations are presented. The objective of these surveys was to capture structural data and utilise it to provide input data for design and stability analyses. The photogrammetry surveys successfully generated textured meshes and point clouds, providing precise (x, y, z) coordinates and colour information for structural interpretation. This paper highlights the parameters employed for accurate data acquisition, the subsequent structural evaluations conducted, and the resulting design and support measures implemented based on the survey findings. The case studies showcase the effectiveness and importance of utilising photogrammetry surveys in assessing structural regimes and mitigating potential risks in mining operations.

3.2 Case study 1: portal face assessment

An assessment was conducted for a portal and decline to access a proposed underground operation from the base of an open pit mine. The photogrammetry survey captured structural data at the locations of the proposed decline, ventilation drive and the opposite pit wall. Figure 4 shows the pit wall before the excavation of the decline and ventilation drive.

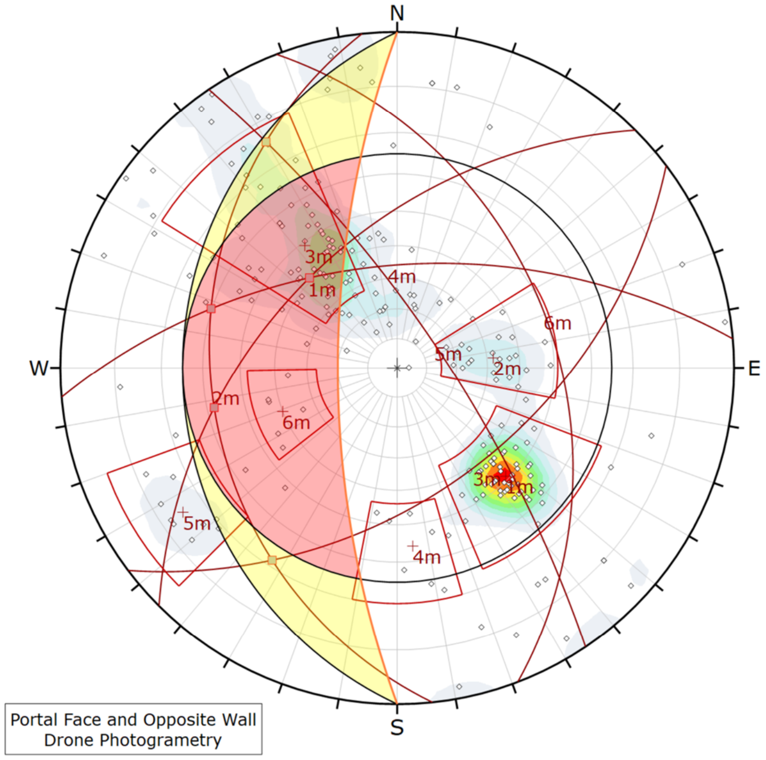
Figure 4 Decline and ventilation portal locations

To ensure the accurate creation of a photogrammetric model with a GSD of less than 3 pixels/cm, the following parameters were employed:

- Flight distance from the wall was limited to less than 60 m.
- Photos were captured with an 80% overlap and 80% side lap, while the camera remained perpendicular to the face.
- GCPs were strategically utilised to position the south wall within a tolerance of +/- 20 cm.
- The camera used had a 12 MP resolution, a 6.17 mm sensor, a 4.2 mm focal length and image dimensions of 4,000 x 3,000 pixels.

Following the acquisition of data, specialised photogrammetry software was utilised to process the information. This resulted in the generation of a textured mesh with true colour image and point cloud, where each point contained precise (x, y, z) coordinates. This data was crucial for determining the structural regime used for the design of the portals and initial drive excavation.

The structural evaluation involved analysing the photogrammetry data obtained from the pit wall of the proposed portals and the opposite face. Notably, the photogrammetry surveys revealed the presence of large planar surfaces on the face of the proposed portal wall. Utilising the structural information from these surveys, potentially unstable wedges requiring support for the decline and ventilation drive portal faces were identified, as shown in Figure 5.



Symbol	Feature
◇	Pole Vectors
■	Critical Intersection

Color	Density Concentrations
	0.00 - 1.40
	1.40 - 2.80
	2.80 - 4.20
	4.20 - 5.60
	5.60 - 7.00
	7.00 - 8.40
	8.40 - 9.80
	9.80 - 11.20
	11.20 - 12.60
	12.60 - 14.00

Contour Data	Pole Vectors
Maximum Density	13.85%
Contour Distribution	Fisher
Counting Circle Size	1.0%

Kinematic Analysis	Wedge Sliding		
Slope Dip	70		
Slope Dip Direction	270		
Friction Angle	25°		
	Critical	**Total**	**%**
Wedge Sliding	5	15	33.33%

	Color	Dip	Dip Direction	Label
Mean Set Planes				
1m	■	49	315	
2m	■	32	264	
3m	■	49	143	
4m	■	56	355	
5m	■	75	56	
6m	■	40	69	

Plot Mode	Pole Vectors
Vector Count	234 (234 Entries)
Intersection Mode	Mean Set Planes
Intersections Count	15
Hemisphere	Lower
Projection	Equal Angle

Figure 5 Joint sets and wedge analysis determined from drone photogrammetry

Comprehensive analyses were performed on all valid wedges in each face area, and support regimes were investigated to ensure the stability of these wedges. The resulting design, incorporating appropriate ground support measures, is illustrated in Figure 6.

Figure 6 Completed ground support

Effective and optimum ground support design for the portal face could not have been completed to the same level of accuracy via traditional methods.

3.3 Case study 2: haul ramp assessment

At a large open pit mine in Western Australia, significant damage to the haul ramp occurred due to blast damage related to major geological structures intersecting the haul ramp, as shown in Figure 7.

Figure 7 Blast damage from intersecting major structures

To investigate these structures and proactively identify them prior to mining activities, a high-resolution drone photogrammetry survey was conducted on the pit wall. The goal was to identify structures associated with the blast damage. The structures identified through the photogrammetry survey were then projected onto the pit ramp. Two prominent structures were found to be related to the blast damage: a horizontal structure dipping at 13°/213° and a sub-vertical structure dipping at 71°/317°, as illustrated in Figure 8.

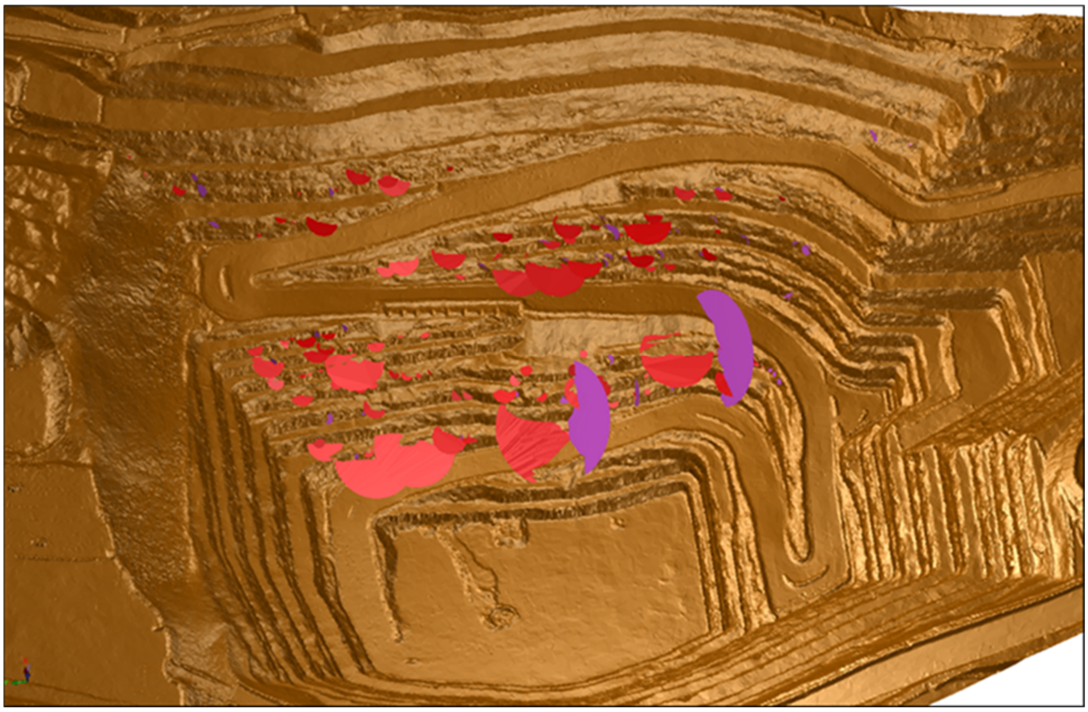


Figure 8 Structures identified through drone photogrammetry

As a result of these identified structures, the pit haul ramp was reduced to a single lane in the affected section and buttressing of the ramp wall was necessary. Furthermore, these structures continued to induce significant displacement on the batter and ramp crests, which further highlighted their significance and the need for continued identification and monitoring.

Risk mitigation and successful planning of haul ramp design would not have been effective without the application of drone surveys.

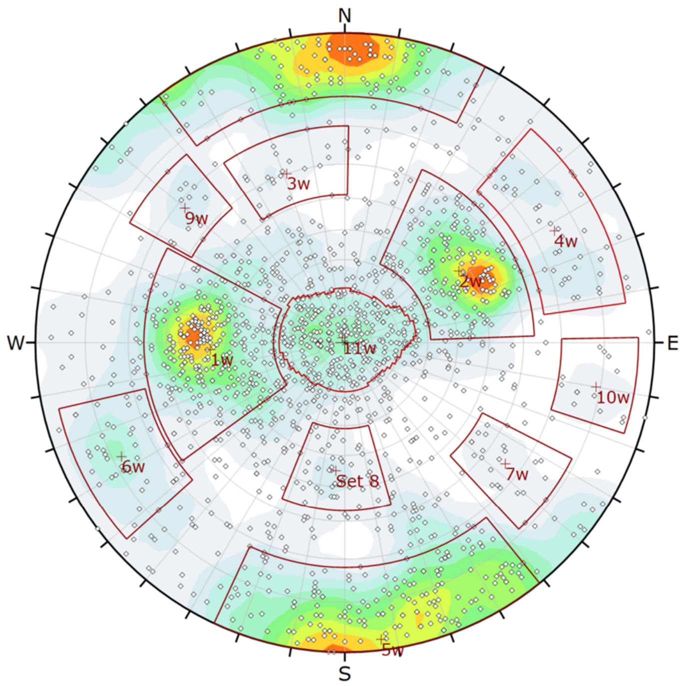
3.4 Case study 3: pit cutback

Teleview surveys and interpretation were conducted for the expansion of an open pit. As further expansion was planned, drone photogrammetry was utilised to determine the structural regime and compare it with the results from teleview surveys, thereby facilitating the design process.

A photogrammetry survey was carried out over the existing pit with the objective of creating a precise 3D reconstruction of these pits for structural interpretation. To ensure the accurate generation of this photogrammetric model with a GSD of less than 1.7 cm/pixel, the following parameters were employed:

- The drone was positioned 45 m away from the wall.
- Photos were captured with a 75% overlap, while the camera remained perpendicular to the face.
- The camera used had a 12 MP resolution, a 6.17 mm sensor, a 4.2 mm focal length and image dimensions of 4,000 x 3,000 pixels.

Following the data acquisition, dedicated photogrammetry software was employed to process the collected data. Structural data was evaluated by comparing downhole televiewer surveys with the drone photogrammetry data obtained from the existing open pits. The comparison revealed a strong correlation between the two datasets, as demonstrated in stereographic plots in Figures 9 and 10.



Symbol	Feature
◇	Pole Vectors

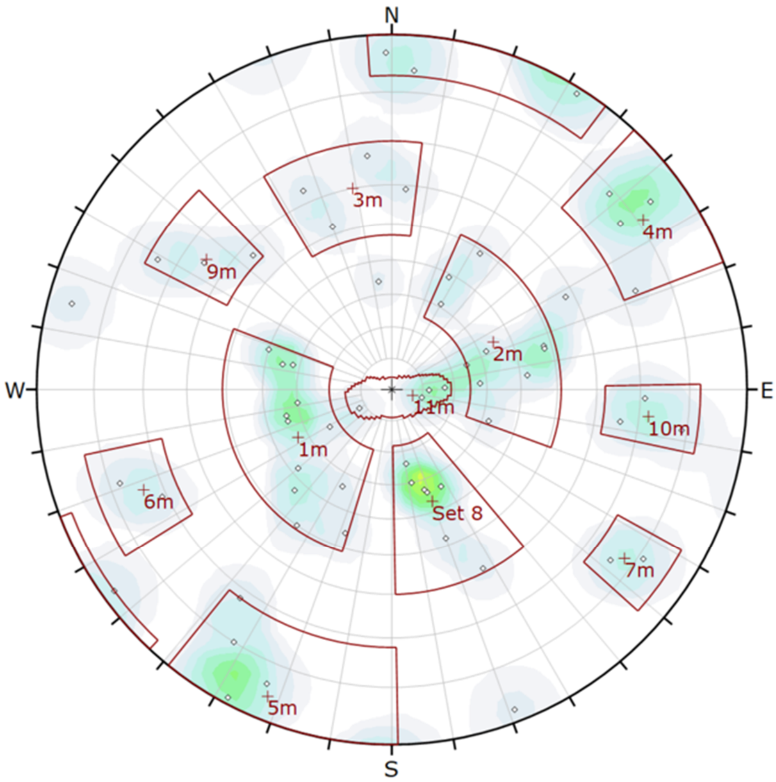
Color	Density Concentrations
	< 0.45
	0.45 - 0.81
	0.81 - 1.16
	1.16 - 1.52
	1.52 - 1.87
	1.87 - 2.23
	2.23 - 2.58
	2.58 - 2.94
	2.94 - 3.29
	3.29 - 3.65
	3.65 <

Contour Data	Pole Vectors
Maximum Density	3.68%
Contour Distribution	Fisher
Counting Circle Size	1.0%

	Color	Dip	Dip Direction	Label
		Mean Set Planes		
1w		47	87	Set 1
2w		47	238	Set 2
3w		60	161	Set 3
4w		75	242	Set 4
5w		88	353	Set 5
6w		78	63	Set 6
7w		66	307	Set 7
8w		45	4	Set 8
9w		68	130	Set 9
10w		79	280	Set 10
11w		2	151	Set 11

Plot Mode	Pole Vectors
Vector Count (Weighted)	2882 (1557 Entries)
Terzaghi Weighting	Minimum Bias Angle 15°
Hemisphere	Lower
Projection	Equal Angle

Figure 9 Stereographic projection – televiewer data



Symbol	Feature
◇	Pole Vectors

Color	Density Concentrations
	< 0.81
	0.81 - 1.51
	1.51 - 2.22
	2.22 - 2.93
	2.93 - 3.64
	3.64 - 4.34
	4.34 - 5.05
	5.05 - 5.76
	5.76 - 6.46
	6.46 - 7.17
	7.17 - 7.88
	7.88 - 8.59
	8.59 - 9.29
	9.29 <
Contour Data	Pole Vectors
Maximum Density	6.71%
Contour Distribution	Fisher
Counting Circle Size	1.0%

	Color	Dip	Dip Direction	Label
Mean Set Planes				
1m		33	63	Set 1
2m		35	245	Set 2
3m		60	169	Set 3
4m		81	236	Set 4
5m		86	22	Set 5
6m		74	68	Set 6
7m		78	306	Set 7
8m		37	340	Set 8
9m		65	125	Set 9
10m		72	276	Set 10
11m		7	286	Set 11

Plot Mode	Pole Vectors
Vector Count	63 (63 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure 10 Stereographic projection – drone photogrammetry

Confidence and the level of accuracy achieved in identifying the structural regime that will be encountered in the planned pit cutback would not have been achieved without the use of drone photogrammetry.

3.5 Case study 4: disused quarry

A drone photogrammetry survey was conducted for an entire disused quarry. The primary objective of the survey was to examine the old quarry and generate a 3D textured mesh for structural interpretation and subsequent structural analyses, as depicted in Figure 11 using GEM4D software (BasRock n.d.).

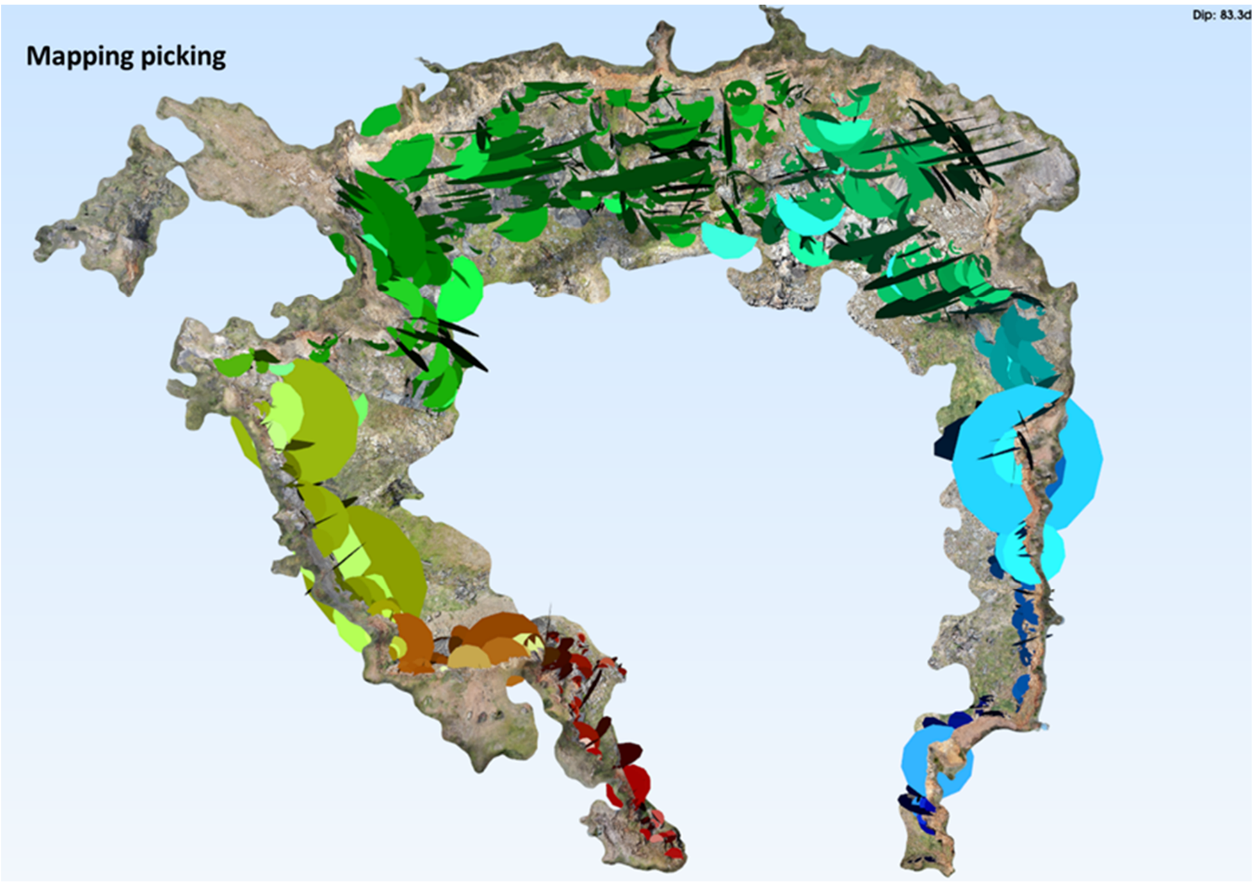


Figure 11 Drone photogrammetry in a disused quarry

To ensure accurate data acquisition, automatic flight paths were designed using existing elevation data obtained from the Shuttle Radar Topography Mission elevation datasets and Google imagery. The aim was to create a photogrammetric model with a GSD of 1.2 cm/pixel. The flight distance was planned to maintain a 30 m distance from the quarry wall. During the flight, photos were captured with a 75% overlap, ensuring comprehensive coverage, while the camera remained perpendicular to the face. The camera employed for this survey had a 12 MP resolution, a 6.17 mm sensor, a 4.2 mm focal length and image dimensions of 4,000 × 3,000 pixels.

Upon completion of the survey, thorough back-analyses of failed wedges were conducted, focusing on structures exhibiting potential failure characteristics. Probability of Failure (PoF) analyses were performed, and the resulting assessment was visually depicted on the quarry surface, accompanied by a table highlighting the identified PoFs and their respective locations, as illustrated in Figure 12 using GEM4D software (BasRock n.d.).

Figure 12 Drone photogrammetry showing wall locations for Probability of Failure analyses

Table 1 Joint sets with potential failure by different walls

Walls	Type of risk	Probability of Failure	Walls	Type of risk	Probability of Failure
	Planar sliding 1	34%		Planar sliding 1	46%
Wall 3	Planar sliding 2	66%		Planar sliding 2	55%
	Wedge sliding	66%	Wall 10	Planar sliding 3	52%
Wall 5	Wedge sliding	34%		Planar sliding 4	33%
	Planar sliding 1	45%		Planar sliding 5	36%
Wall 6	Planar sliding 2	49%		Wedge sliding	35%
	Planar sliding 3	39%		Planar sliding 1	55%
Wall 7	Planar sliding	33%	Wall 11	Planar sliding 2	36%
Wall 8	Planar sliding	39%		Planar sliding 3	28%
	Planar sliding 1	36%		Planar sliding 4	57%
Wall 9	Planar sliding 2	36%	Wall 15	Planar sliding	52%
	Planar sliding 3	29%		Wedge sliding	39%
	Wedge sliding	57%	Wall 16	Planar sliding	47%

The time taken to map the disused quarry and the amount of data collected would be limited without drone photogrammetry. Data quality and back-analyses of existing failures would not be possible using traditional mapping methods.

4 Data quality and reliability

There are five pillars associated with geotechnical mapping and data collection as follows:

1. Completeness.
2. Timeliness.
3. Safety risk.
4. Precision.
5. Accuracy.

A rating system has been developed for data quality and reliability: a score of 20 being the desired standard and a score of 5 the worst, as shown in Table 2.

Table 2 Data quality and reliability rating system

Completeness	**Complete**	**Partially complete**	**Partially incomplete**	**Incomplete**
Score	4	3	2	1
Timeliness	<5 hr	<1 day	<2 days	<4 days
Score	4	3	2	1
Safety risk	Low	Medium	High	Extreme
Score	4	3	2	1
Precision	High	Medium	Low	Very low
Score	4	3	2	1
Accuracy	High	Medium	Low	Very low
Score	4	3	2	1

Table 3 and Figure 13 show data quality from drone surveys and traditional methods, highlighting the advantages of drone photogrammetry versus traditional mapping for the case studies.

Table 3 Drone photogrammetry versus traditional mapping

	Case study 1: portal face design		**Case study 2: haul ramp assessment**		**Case study 3: pit cutback**		**Case study 4: disused quarry**	
	Drone	**Traditional**	**Drone**	**Traditional**	**Drone**	**Traditional**	**Drone**	**Traditional**
Completeness	Complete	Partially complete	Complete	Partially complete	Complete	Partially complete	Complete	Incomplete
Timeliness (per 1 km^2)	<2 Hours	1 Day	<3 Hours	1 Day	<2 Hours	4 Days	<2 Hours	4 Days
Safety risk	Low	Medium	Low	High	Low	Medium	Medium	Extreme
Precision	High	Medium	High	High	High	Low	High	Very low
Accuracy	High	High	High	High	High	High	High	High
Score	20	16	20	16	20	13	19	8

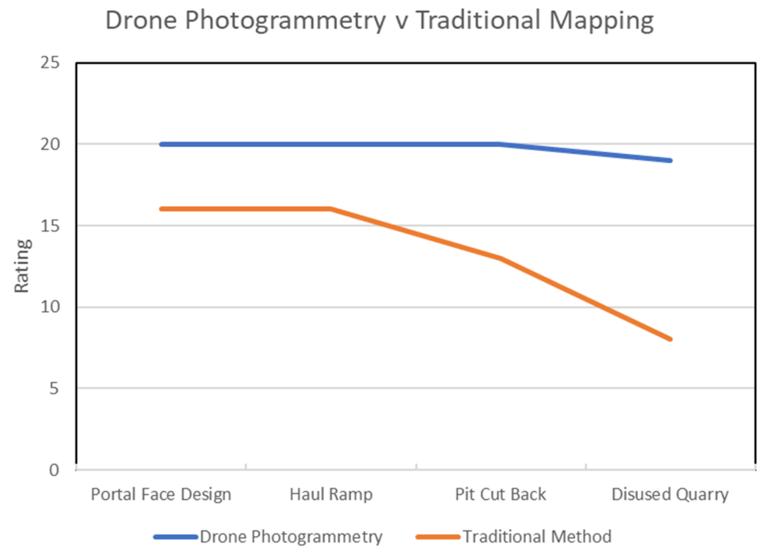


Figure 13 Drone photogrammetry compared to traditional mapping for the case studies

5 Conclusion

Drone photogrammetry offers an efficient and cost-effective solution for high-resolution data collection, surpassing traditional methods in terms of data quality and quantity, time taken to complete mapping, safety, precision and accuracy.

The methodology enables the precise identification and mapping of defects and significant large-scale structures. The implementation of drone photogrammetry improves the safety of personnel by reducing human exposure to hazardous environments while minimising the impact on production activities. The availability of detailed structural information further facilitates in-depth analysis, including structural analysis, kinematic analysis and back-analysis of previous failures. Data quality and quantity is improved, enabling informed decision-making and effective risk management.

Drone photogrammetry can also be extended to other large-scale excavation sites. Inactive quarries, which are accessed by the general public for leisure activities, road cuttings and cliff faces are among the scenarios where drone-based geotechnical data capture and analysis proves invaluable; providing detailed information in areas with limited or no access and improving levels of safety by quantifying structural risks.

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