Drone Photogrammetry Structural Mapping & Geotechnical Optimization Design – A Case Study from Penhorwood Mine, Toronto Canada

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**ABSTRACT:** The Penhorwood Tale Mine slope design optimization is based on data collection from drone photogrammetry with resolution capabilities allowing for mapping of major structure and rock fabric (joints). The rock mass at Penhorwood is massive and the slope heights are limited; therefore, the slope design is controlled by major structure and rock fabric which control the interramp slopes and bench catchment. Call & Nicholas Inc. (CNI) developed a drone flight plan program that maximizes resolution with enough precision to map major structural features and rock fabric (joint patterns) in bedrock. Initial mapping of this project focuses on major structures defining structural domain boundaries followed by rock fabric mapping. The rock fabric mapping data confirms the distinct patterns of joints within structural domains and is used for interramp slope catchment design analyses. The design analyses are probabilistic and calibrated to measured bench geometries. Initial analyses show the interramp design can be steepened by approximately two degrees, which would reduce the stripping ratio at Penhorwood. This study demonstrates the potential for utilizing advanced open pit mine-specific drone flight planning and high-resolution point cloud mapping as a means to optimize interramp and catchment designs when pit access is limited or unavailable.

1. **INTRODUCTION**

Recent advancements in drone technology have created opportunities for geotechnical analyses using remote sensing in open pit mines. With inexpensive drone hardware and photogrammetry software, high-resolution point clouds of mine highwalls can be generated for geotechnical and geological mapping. Call & Nicholas, Inc. (CNI) created the drone flight planning software, DronePlan3D, because no commercially available software existed that allowed for (1) terrain following using current topography, and (2) optimized gimbal angles over varying terrain (Barkley et al., 2020). Drone surveys conducted using DronePlan3D flight plans provide optimal coverage of mine highwalls, especially on the bench faces where critical geologic and rock fabric data is acquired.

High-resolution point clouds are generated from these drone surveys using the Pix4D photogrammetry software, and are well suited for geotechnical and geologic mapping to augment or, in some cases, to replace field-based mapping. While field-based mapping is most often preferred, there are several advantages to drone-based data collection, such as the ability to map inaccessible areas, the high precision and accuracy of measurements on a georeferenced survey, and the ability to review, revisit, and revise measurements and interpretations.

This study describes a geotechnical slope design analysis conducted by CNI based solely on drone survey data for the Imerys Tale Penhorwood Mine. The objective of this study was to utilize point cloud derived rock fabric and major structure data to determine the maximum interramp slope angle (ISA) benched slope design which maintains stability and provides adequate catchment for operational safety at Penhorwood.

2. **BACKGROUND**

In 2018, CNI began conducting drone surveys for clients in order to generate high-resolution point clouds for geotechnical mapping and analysis. These surveys were planned using CNI’s proprietary software DronePlan3D, which achieves uniform ground sampling due to its unique terrain following and optimized gimbal angle features as shown in Figure 1 (Barkley et al., 2020). Point clouds generated from these scans have a typical ground
sampling distance of 2.5 cm/pixel, retain true-color information, and are georeferenced using on-site RTK GPS surveyed ground control points, which results in a highly accurate representation of the terrain.

Figure 1. Typical methodologies of drone flight paths over changing terrain.

At first, these high-resolution point clouds were primarily used to map major highwall structures, geologic contacts, water seeps, and other important large-scale geotechnically important features. In late 2019, CNI began experimenting with bench-scale rock fabric mapping on point clouds, and it was determined that this form of mapping yielded good results relative to traditional field-based mapping.

In 2020, CNI was commissioned for a study of the Imerys Penhorwood Talc Mine to determine the maximum ISA benched slope design which maintains stability and provides adequate catchment for operational safety. These types of analyses rely primarily on rock fabric and major structure mapping, though due to travel restrictions, scheduled site visits to the Penhorwood Mine by CNI geologists were not possible. Drone surveying and point cloud mapping remained the only viable solution for collecting the data required to conduct the study.

3. METHODS

Flight plans were created by CNI using DronePlan3D and sent to the geotechnical staff at Imerys Penhorwood. The plans covered the entire Penhorwood open pit, which encompasses roughly 47 acres, and included six individual flights, with a total of 321 photos, in five sectors, as shown in Figure 2. Surveys are planned with flight path azimuths perpendicular to the overall wall orientation, and sectors were created in order to accommodate the varying aspect of the pit walls.

A contractor conducted the flight using a DJI Phantom 4 Pro V2 drone, and the survey photographs and ground control point coordinates were sent to CNI for photogrammetric processing using the Pix4D software package. After processing, virtual point cloud mapping was performed using CloudCompare (CloudCompare, 2020).

Figure 2. Flight sectors for the different major wall orientations of the Penhorwood Mine.

3.1. Point Cloud Mapping

The processed and georeferenced point cloud was loaded into CloudCompare for major structure and rock fabric mapping. CloudCompare is an open source software that allows for manipulation and measurement of point clouds in a 3D interface. Mapping was conducted using the Compass plugin tool within CloudCompare, which contains tools for digitizing linear features such as fault traces and geologic contacts, and planar features such as exposed joint faces. Rock fabric mapping locations and major structures are shown in Figure 3.
3.1.1 Major Structure Mapping

Major structures are defined as geotechnically significant features (faults, dikes, joints, etc.) that encompass at least two bench heights in size. Identification of major structures starts with high-level scanning of the highwall, noting any large throughgoing features. Prior geologic mapping was made available to CNI from the Penhorwood geotechnical staff to aid in identifying the locations and type of structures. Once identified, the structures are traced using the CloudCompare Compass plugin, which digitizes a best-fit line through the point cloud between selected points (Fig. 4). Confidence in the mapping is gained by observing the structure at different orientations. Most structures possess characteristics that aid in their identification, such as color differences both within and on either side of the structure, preferential erosion, alignment with tension cracks on benches, and water seepage. Once the trace of the structure has been digitized, a best-fit plane is applied to the structure trace. The orientation of the plane (dip, dip direction), and thus the structure, is calculated by CloudCompare.

3.1.2 Domain Boundary Mapping

Initial analysis of major structure mapping reveals an East and West Domain boundary in the Penhorwood Mine (Fig. 3). Distinct structural patterns are observed within the rock fabric data and major structure mapping that define each domain. The East Domain is further subdivided by a highly altered and fault-bounded zone which includes an area of instability. The West Domain consists of long faults and faulted contacts trending north to northeast (Fig. 3). Generally, the West Domain is very blocky and massive and komatiite/talc contacts are easily distinguished. The East Domain is blocky with large joints and wedge forming major structures. Several long low to medium angle faults dip to the east to northeast (Fig. 3).

3.1.3 Rock Fabric Mapping

Rock fabric is mapped using a mapping technique for defining structural sets within a defined window, known as a cell, approximately 15 meters wide and 12 meters high. Cell mapping locations for this study are shown in Figure 3. CNI uses the cell mapping method to acquire the orientation, length, and spacing on structure sets to be used in the stability analysis (Nicholas & Sims, 2000).

Utilizing the cell mapping method in CloudCompare consists of measuring and cutting out each cell from the greater point cloud, and a mesh of the cell is created to aid in visualizing the structure sets within the cell (Fig. 5a). A plane is fit to the cell point cloud and adjusted to measure the minimum bench face angle (Fig. 5b). Next, structures within the cell are measured using planes (Fig. 5c). Structure sets are counted along imaginary vertical or horizontal lines across the cell to get spacing data, or the spacing is measured directly.
Figure 5. Cell mapped in CloudCompare with the A) raw point cloud mesh, B) minimum bench face angle plane, and C) planes representing structures measured on the bench face.

Stereonets are created from the raw cell mapping data, which provide a visual aid for grouping structures into sets with similar orientations. To reduce the data for analysis, the representative orientation, length, and spacing statistics for each set is calculated along with their standard deviations. Figure 6 shows an example of cell mapping data from the West Domain of Penhorwood.

Figure 6. Example equal area stereonet of point cloud mapping rock fabric orientations with a summary table of statistics for each rock fabric set mapped on the west wall

Rock fabric data from 13 cells were mapped on the west wall for a total of 61 rock fabric sets. The West Domain rock fabric generally has a strong northeast trend, with lower angle sets dipping pitward. Spacing is relatively wider and lengths are shorter, which is generally favorable for pit design. Eleven cells were mapped on the east wall for a total of 55 rock fabric sets. A zone of weathered rock occurs in the southern portions of the east wall as a fault-bounded block of ground which has an area of instability. The East Domain rock fabric generally has a strong northeast trend with very shallow angle sets dipping pitward. The spacing is lower and lengths are longer compared to the west wall domain, which is less favorable for pit design in comparison to the West Domain fabric.

3.1.4 Probabilistic Bench Scale Stability Analysis

Using the data collected in the point cloud mapping, a probabilistic bench scale stability analysis was conducted on the eastern and western walls of the pit. The probabilistic bench scale stability analysis is based on the measured variability of geologic structural parameters, including orientation, length, spacing, and probability of occurrence in any given location of the exposed rock. These structural parameters are the primary inputs into Backbreak, a proprietary CNI software package that
simulates the potential wedge and plane shear failure mechanisms bound by the probability functions of the structural parameters (Ryan & Pryor, 2000). The results of the program are the expected amount of back break with associated probabilities at the crest of freshly mined benches. An example of the probability function is presented in Figure 7. The back break and probability can be used to calculate effective ISAs for design purposes that have a certain percent chance of maintaining adequate rockfall catchment.

Figure 7. Example Backbreak results

4. RESULTS

Outputs from the Backbreak analysis are presented in Table 1, which shows the predicted ISAs, bench face angles (BFA), and catch bench widths for 15-meter-tall single benches that are required to maintain a minimum operationally required catch bench width of 15 meters with about 80% reliability. Due to the varying structural rock fabric revealed in the point cloud cell mapping, the backbreak results for the East and West Domains are different. The West Domain is more amenable to higher ISAs due to the more favorable structural orientations than the East, and both can be steepened by approximately 2 degrees from the design if careful pre-split blasting is implemented.

Table 1. Results from Backbreak

<table>
<thead>
<tr>
<th>Domain</th>
<th>Analysis</th>
<th>ISA (deg)</th>
<th>BFA Height (m)</th>
<th>BFA Catch Width Design (m)</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>Predicted BFA (Single)</td>
<td>27</td>
<td>12</td>
<td>66</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>Predicted BFA (Single Pre-Split)</td>
<td>29</td>
<td>12</td>
<td>68</td>
<td>16.8</td>
</tr>
<tr>
<td>East</td>
<td>Predicted BFA (Single)</td>
<td>27</td>
<td>12</td>
<td>61</td>
<td>19.1</td>
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<tr>
<td></td>
<td>Predicted BFA (Single Pre-Split)</td>
<td>29</td>
<td>12</td>
<td>63</td>
<td>17.4</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

CNI’s slope stability analysis of the Imerys Talc Penhorwood Mine proves the utility of drone-derived high resolution point clouds for conducting geotechnical analyses. Importantly, careful flight planning using CNI’s DronePlan3D was paramount in acquiring imagery that yields uniform ground sampling, especially on the bench faces where the majority of mapping takes place. The potential of drone imagery for mapping is broad for geotechnical professionals. Until now, field mapping of major structure and rock fabric was limited to accessible benches where precise measurements on bench faces can be difficult. Drones allow for data collection where field mapping is limited, dangerous, or entirely inaccessible, which opens the door to geotechnical studies that might otherwise be deemed infeasible.

Structural measurements taken from a properly georeferenced point cloud are very precise, and allow the mapper to view the structures at any orientation. Moreover, the ability to revisit, review, and revise measurements and interpretations with colleagues and clients is a significant advantage over traditional field mapping. While field mapping has a number of benefits such as easier rock type and very small-scale rock fabric identification (i.e., foliation), drone data has the ability to cover large areas with high accuracy and precision. An ideal scenario involves a drone survey that encompasses both a field mapping area and additional areas of the highwall, allowing for significant augmentation of the field mapping data. In this case, the field mapping serves as a ground truth for the drone data, and the benefits of both methods are enjoyed.

REFERENCES


