# Long-range terrestrial digital photogrammetry for discontinuity characterization at Palabora open-pit mine

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ABSTRACT: This paper documents a field survey using long-range terrestrial digital photogrammetry at the Palabora open-pit mine, South Africa, for multi-scale characterization of rock mass discontinuities. Stereomodels covering the entire mine were generated based on photographs taken from a distance of 1600m across the pit, using a series of f=20-400mm lenses. Details on the methodology used and its accuracy are discussed. Preliminary results on discontinuity orientation, persistence and intensity are presented, highlighting the effect of observation scale. The potential uses of long-range terrestrial digital photogrammetry in open-pit mine and large natural rock slope environments is emphasized. The use of an f=400mm lens from distances larger than 1.5km may represent an important step forward in the geotechnical characterization of inaccessible remote rock faces.

## 1 INTRODUCTION

Terrestrial digital photogrammetry (TDP) is now routinely applied in rock mass discontinuity characterization of both natural and engineered rock slopes. Discontinuity mapping on photogrammetric stereomodels allows measurement of discontinuity geometric properties, which include discontinuity position, orientation, persistence, roughness, frequency and block size. Several authors, including Krosley et al. (2006), Martin et al. (2007), Coggan et al. (2007), Haneberg (2006 and 2007) and Sturzenegger and Stead (2009a), have highlighted the accuracy and potential of photogrammetric techniques. Software allowing both stereomodel generation and discontinuity characterization are available (Gaich et al., 2006; Birch, 2006; Poropat, 2006) and are designed to be used by non-photogrammetrists, i.e. geologists and geotechnical engineers.

Until now, TDP has been applied predominantly on individual benches or roadcuts, at closerange. Characterizing larger rock slopes at medium- to long-range represents a logical development (Sturzenegger and Stead, 2009b). Large rock slopes may be represented by entire mountain cliffs or open-pit slopes at scales ranging from the multibench to entire pit wall. Using TDP on large rock slopes can solve obvious issues related to accessibility and hazard. In addition, it allows accurate assessment of the properties of large structures that may potentially affect slope stability.

The current paper summarizes the challenges faced and presents preliminary results in the application of long-range TDP for discontinuity characterization at the Palabora open-pit mine, South Africa. Photographs were taken across the diameter of the pit from a distance of 1600m. Complete sets of photographs, covering the entire pit, were obtained using f=20mm, 55mm, 100mm and 200mm lenses and partial coverage of the walls were achieved using a f=50mm and 400mm lens. Multi-scale discontinuity characterization is being achieved on these stereomodels and the results at selected locations are presented. This data highlights the need to consider the effect of observation scale in the planning phase of a long-range photogrammetric field survey.

## 2 THE PALABORA MINE

Located approximately 390km North East of Johannesburg, the Palabora copper mine began open pit operations in 1964. Surface excavations ceased in 2003, and since then the mine has been operating as an underground block cave operation. Following the inception of the underground activities beneath the north wall of the open pit, cracking was observed in the northern pit wall during 2003. As caving progressed, so the wall disturbance increased, ultimately leading to the development of an approximately 800m high failure of the north wall.

The Palabora Igneous Complex consists of a succession of subvertical pipe-like bodies of alkaline and ultramafic rocks that have intruded the surrounding Archean granite (Piteau Ass., 2005). The copper orebody occurs in the Loolekop pipe emplaced in pyroxenite host rock and contains successive intrusions of micaceous pyroxenite, foskorite and banded carbonatite. Subvertical, northeasterly trending dolerite dykes cut across the complex. Four large scale faults, striking WSW, WNW and S, cross the open pit. Three dominant discontinuity sets are ubiquitous within the mine.

# 3 TERRESTRIAL DIGITAL PHOTOGRAMMETRY

Photogrammetry was carried out using a Canon 30D and a Canon XTI digital SLR cameras, with f=20-400 mm lenses. All images have been processed using the software 3DM Calibcam and 3DM Analyst (Adam Technology, 2007). In addition, models have been imported into Maptek Vulcan (2008) for further analysis and presentation. Photogrammetric models of the entire pit were made using f=20mm, 55mm, 100mm and 200mm photographs (Fig. 1), while f=50mm and 400mm models were generated at specific locations to provide more details of the topography.



Figure 1. *F*=20mm stereomodel of the entire open pit, providing a general view of the mine. The diameter of the pit is approximately 1600m.

# 3.1 Network setting

All stereomodels were generated within the mine grid, using control stations set out by the mine survey department. A few additional control points and the camera positions were added to the network and surveyed for the photogrammetric survey (Fig. 2). A baseline approximately equal to 1/6 of the distance between the camera and the imaged rock face was used and in some cases, three camera stations per photogrammetric model were used. The images were captured using an image fan model layout (Adam Technology, 2007).

The north, east, south and west walls of the pit were covered by four different sets of photographs, in order to locate the camera stations sub-perpendicular to each wall. For the f=200mm and 400mm models, where a large number of photographs were required to cover entire walls, the sets of photographs were split in two or three sub-sets in order to create two or three stereomodels with a manageable amount of images (in terms of digital photomodel size).



Figure 2. Network of surveyed points, including control targets (red filled circles) and camera locations (white circles) (after Beveridge et al., 2008).

# 3.2 Accuracy

Because of the limited number of available mine control points (15 over the entire pit), these could only be used in the registration of the low resolution models (f=20-55mm). Some inaccuracy in the model registration can be expected because of the non-optimal sizes/shapes of the control points. Prisms located at the top of permanent survey rods are sub-optimal, because the poles are too thin to be represented on stereomodels. The prisms located on top of massive concrete monuments were usually adequate; the best control points being provided by large targets painted directly on the rock walls.

As mentioned in section 3.1, at higher resolution, the sets of photographs had to be split into sub-sets, which individually did not contain enough control points for registration. Consequently, f=100 to 400mm models were registered by transfer of control from selected recognizable features in the 55mm model. Since this model had been registered, any point could potentially be used as a control point. It must be noted that absolute errors in the 55mm model are consequently transmitted to the higher resolution models. Maximum inaccuracy of -3.7, 4.2 and 0.6m

in the x, y and z coordinates, respectively and maximum imprecision of 5.0, 6.5 and 1.5m in the x, y and z coordinates, respectively have been measured on the f=55mm model. As the predominant use of models is in the measurement of relative dimensions/orientations (not absolute coordinate), the obtained accuracy and precision are considered adequate for rock mass characterization.

Based on a comparison of discontinuities mapped on a specific bench of the north wall both from a 1600m distance using f=400mm lens (long-range) and at a 30m distance with the f=50mm lens (close-range), Fig. 3 shows that there is a good consistency between stereonets. This suggests that the methodology provides accurate discontinuity orientation measurements for rock engineering purposes.



Figure 3. Equal angle, lower hemisphere stereonets with poles of discontinuities mapped using f=50 and 400mm lenses on a selected bench in the north wall. f=50mm mapping was carried out at a 30m distance and f=400mm at a 1600m distance (after Beveridge et al., 2008).

## 3.3 Ground resolution

Table 1 summarizes ground point spacing for each focal length used. Ground point spacing is the distance between spatial points in the stereomodels and represents the product of the ground pixel size and the step size (number of pixels, both horizontally and vertically, used to generate one spatial point).

Focal length	Distance	Ground point spacing	Observation scale
[mm]	[m]	[cm]	
20	1600	365	Wall
50	30	3	Bench
55	1600	133	Wall
100	1600	82	Wall
200	1600	41	Wall
400	1600	21	Wall/Bench

Table 1. Ground point spacing and observation scale for the various stereomodels (after Beveridge et al., 2008).

## 3.4 Specific issues to be addressed in photogrammetric pit wall survey

To ensure the quality of stereomodels, pairs of photographs should be taken within a short period of time to avoid changes in lighting of the walls. This condition was sometimes difficult to adhere to, because of the distance between successive camera positions (several hundreds of meters and on different benches). Consequently, when the weather is characterized by an alternation of sun and clouds, the conditions can be sub-optimal. In addition, field work must be carefully planned so that the walls illuminated by the sun at a certain time of the day are surveyed at the appropriate time.

Another fieldwork component, where difficulties may be encountered, is in the calibration of long focal length f=200 and 400mm lenses. Calibration is an important step in the photogrammetric process, necessary to calculate the exact focal length of a lens and to quantify internal camera parameters. With large focal lengths, the network of successive camera locations used for calibration (see AdamTech, 2007), involves large distances. Consequently, for the same reasons as highlighted in the previous paragraph, optimal weather conditions may be difficult to attain. In addition, at such large ranges, it may be difficult to survey a rock slope with relatively sufficient relief, a requirement for good calibration. Calibration may however be conducted after the field survey at a location optimal for maximizing success.

# 4 DISCONTINUITY CHARACTERIZATION

To date, a total of 2808 discontinuities have been manually mapped on the various focal length stereomodels. At this stage, characterization on the f=55 and 100mm models covers both the north and west walls, while on the f=50, 200 and 400mm models, it is concentrated predominantly in specific areas of the north walls. Characterization using various resolution stereomodels must be applied with care because of the potential for observation scale effects. Sturzenegger and Stead (2009b) summarized the effects of observation scale on discontinuity orientation and persistence. While high resolution stereomodels usually allow the most detailed characterization, lower resolution can be useful in the recognition of highly persistent features, which can be critical for wall stability.

The numerous images required to cover the pit walls at f=100 mm, 200 mm and 400 mm resolutions has presented some issues for simultaneously displaying a large number of stereomodels on computer screens. This was particularly problematic for the characterization of large features, which cross several stereomodels, and where censoring issue must be considered. As this limitation is a function of computing processing/memory facilities and not a limitation of high focal length imagery, it is considered that future censoring problems will be more easily addressed.

#### 4.1 Discontinuity orientation

Fig. 3b and Table 2 show the orientation of discontinuities mapped on the north wall, using the f=400mm stereomodels. Four sets have been recognized, three of which are approximately orthogonal to each other. Discontinuity sets 1 to 3 agree well with those described by Piteau Ass. (2005) as present throughout the open pit.

Discontinuity set	Dip	Dip direction	Piteau (2005) discontinuity set
	[°]	[°]	Dip/DipDir [°]
1	70	235	80/225
2	90	351	80/320
3	74	276	82/270
4	03	063	n/a

Table 2. Discontinuity orientation on the north wall using the f=400mm stereomodels.

## 4.2 Discontinuity persistence

Persistence is expressed as the diameter of the mapped discontinuities, which is termed "equivalent trace length" for comparison with field surveys. Fig. 4 shows the "equivalent trace length" distribution of discontinuities mapped on the north wall using both f=100 and 400mm stereomodels. It is notable that there is a shift of the distribution to the left, i.e. towards shorter persistence, when the ground resolution increases. This effect of observation scale has been studied by Sturzenegger and Stead (2009b) and suggested regression equations were proposed as a planning tool to evaluate the required focal length for mapping specific discontinuity persistence.



Figure 4. Equivalent trace length distributions of discontinuities mapped on the north wall on both f=100 mm and f=400 mm stereomodels.

# 4.3 Fracture intensity

A preliminary attempt to estimate fracture intensity have been undertaken. Areal fracture intensity represents the total length of all fractures intersecting a sampling window, divided by the window area. It is termed " $P_{21}$ " in the FracMan code (Golder Associates Inc., 2008). A 10m diameter virtual window with average slope orientation has been delineated on stereomodels of a specific bench of the north wall. Trace maps have been created as illustrated in Fig. 5 and areal fracture intensity directly calculated. This process has been repeated using the various focal length stereomodels.

It is important to highlight that the delineation of a sampling window with an averaged rock slope orientation can be expected to bias fracture intensity estimation. Indeed, small discontinuities, having a size smaller that the magnitude of the irregular rock face relief, will be omitted. Research on appropriate photogrammetric windows for estimation of fracture intensity is ongoing. Notwithstanding, the preliminary results obtained from this study of fracture intensity provide an interesting observation concerning the effect of observation scale. Fig. 6 shows the variation in areal fracture intensity ( $P_{21}$ ) with respect to ground point spacing.



Figure 5. Areal fracture intensity estimation. (a) 10m diameter circular sampling window, (b) mapped discontinuities, (c) discontinuities intersecting the window, (d) traces of these discontinuities (after Beveridge et al., 2008).



Figure 6. Graph illustrating a decrease in  $P_{21}$  value as ground pixel spacing increases.

## 5 DISCUSSION

The authors successfully applied long-range terrestrial digital photogrammetry in a large open-pit mine, at Palabora. At this mine, it is no longer possible to obtain access to pit walls for conventional mapping due to safety concerns. Previous data were obtained during the life of the open pit. As the orebody contains magnetic rock types, this is also a factor in conventional mapping. Further data on the fracture networks is required to allow the application of state-of-the-art modeling codes with increased confidence (Vyazmensky et al., 2009; Sainsbury et al., 2008). This paper presents an extension of conventional rock engineering photogrammetry to long range high focal length applications. During the fieldwork and subsequent stereomodel generation, practical difficulties encountered included:

- i. Registration of stereomodels with a limited number of control points, due to the lack of optimal and accessible targets,
- ii. Lighting issues, non-optimal weather conditions necessitating careful planning of fieldwork according to the position of the sun,
- iii. Management of large sets of photographs, providing difficulties to achieve resection and successful bundle adjustment.

The experience gained in solving these problems will allow improvements in future applications of the technique. Long-range TDP has significant potential in large open-pit mine environment and on large natural slopes, where limited accessibility and rockfall hazard exist.

Concerning discontinuity characterization, the following observations are noted based on the preliminary results of this research:

- i. Characterization at the pit wall scale using the f=55mm lens has proven useful, since it has enabled mapping to be conducted relatively quickly at reasonable detail, providing an initial view of the structure. Clearly defined, persistent structures have been mapped at this resolution and compare well to structures mapped on other focal length stereomodels. The intention is to extend the use of f=400mm imagery to map key areas in an attempt to improve the detail of the structure captured (Fig. 7).
- ii. A current limitation of the photogrammetry-specific software for f = 400m mapping is the number of models that can be stored on screen at any one time. On high resolution stereo-models, this increases the potential for censoring of persistent planes, making it harder to establish a true trace length. Some initial work using the Maptek Vulcan code has been carried out to overcome this issue, the use of this code allowing more images to be loaded on-screen at any one time while the operator continues delineating persistent planar structures. (This limitation is considered transient and related to hardware/software issues, which will undoubtedly be alleviated in the near future.)
- iii. The results of this research show that long-range TDP is able to accurately quantify discontinuity orientation, persistence and intensity. These three parameters are the main input required for the generation of discrete fracture network (DFN) models. In this preliminary application at the Palabora site, it is shown that discontinuity persistence and fracture intensity are highly dependent on the photogrammetric observation scale. Further work on the effect of observation scale on both fracture intensity and block size is ongoing.

Work to date emphasizes that it is critical that geologists and geological engineers decide at the planning stage on appropriate resolutions for the specific purposes of their application. If only large structures need to be characterized, low ground resolution stereomodels may be sufficient, while if a more detailed characterization of rock mass fracturing is required, higher ground resolution must be achieved.



Figure 7. Long-range *f*=400mm TDP model imaged from 1600m and illustrating the detailed structure within a section of the North Wall (the model contains 4 images).

# 6 CONCLUSION

A significant number of stereomodels were obtained by terrestrial digital photogrammetry during approximately one full week at Palabora open pit. Preliminary results are presented but the volume of existing data still requires considerable processing time for both stereomodel generation and geotechnical analysis of areas of interest. The data is also available for other TLS applications, including rock fall/bench deterioration monitoring. Indeed, subsequent surveys would provide the opportunity to quantify/record (multi)bench deformation mechanism that might be related to underground mining. Deformation monitoring using long-range TDP would be possible but would require appropriate improvements in survey control points. This would be particularly useful to track continuing underground activities related movements and to guarantee the security of the mine personal at specific locations of the pit.

### 7 ACKNOWLEDGMENTS

All salaries, equipment and travel involved in this work were funded through an Endowment to Professor Stead, NSERC CRD and NSERC Operating Grants, an NSERC Undergraduate research scholarship (Sung Lee) and an SFU Ph.D. scholarship (Andy Beveridge). We are grateful to Palabora Mine and the geotechnical/geological staff for providing food and accommodation and the generous field support while undertaking the field work.

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