THE APPLICATION OF DIGITAL PHOTOGRAMMETRY TO ASSESS LONG-TERM STABILITY OF MINESITE WASTE ROCK DUMPS

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Abstract

Terrestrial close range digital photogrammetric methods were used to obtain three-dimensional data on erosion gullies associated with waste rock dumps at Newmont Australia's Jundee gold mining operations. Digital stereo pairs of photographs were taken at each site and three-dimensional images produced using the CSIRO software package SIRO3D. Difficulties associated with producing accurate three-dimensional images included: aspect; complex gully morphology; and excessive vegetation in and around gullies. Data from each image were then imported into the GIS program ArcView, where gully volumes were calculated and gully morphology (profile shape and length) was documented. The gully data were then used to develop parameters for the landform evolution model SIBERIA. The three main parameters of the model were adjusted until the simulated gullies were of similar morphology and volume to those measured in the field. The model was then used to predict the evolution of the waste rock dumps through periods of up to several hundred years using the derived parameters. The SIBERIA parameters derived were comparable with parameters developed during previous erosion studies performed at the site. Predicted long-term erosion rates were comparable with current estimated erosion rates.

Additional Keywords: gullies, erosion modeling, SIBERIA, SIRO3D

Introduction

The Newmont Jundee Gold Operation (NJO) near Wiluna in central Western Australia has a number of waste rock dumps that are visibly affected by gullying. In at least some instances, that gullying has been triggered by tunnel erosion of berms, with the failed berm directing concentrated flows onto lower batter slopes. The situation is exacerbated by the potential for such failures to cascade downslope when 40 m high slopes are constructed as a series of lifts and berms.

Landloch staff visited NJO from 16-18 July 2003 to carry out an initial assessment of erosion gullies located on its waste rock dumps via digital photogrammetric methods. The data collected are to be used for ongoing monitoring of erosion rates experienced by the gullies and also for derivation of input parameters for the landform evolution model SIBERIA to model the long-term erosion and landform stability of the older waste rock dumps.

This paper describes the method employed in both the acquisition and processing of photogrammetry data and the subsequent use of that data to derive SIBERIA parameters based for waste rock dump w12wn3. Erosion rates predicted by the SIBERIA model using those derived parameters are presented and recommendations for future work in this area suggested.

Materials and Methods

Data acquisition

Photogrammetry is defined as: "The science, and art, of determining the size and shape of objects as a consequence of analysing images recorded on film or electronic media" (Fryer in Atkinson, 2001). Photogrammetry can either be terrestrial or aerial; long or close range. "Close range" is defined as images taken at a distance less than 100 m from the object or surface of interest. Close range terrestrial photogrammetry was employed for the acquisition of site data at Jundee.

Gullies on three of the existing mine waste rock dumps at NJO were photographed in July 2003, using a Kodak Pro 14n camera fitted with a Nikkor 60 mm lens. This lens/camera combination can provide accuracy of up to 1 mm, when images are taken from a distance of 10 m or less and up to 8 mm when taken from a distance of less than 100 m. Stereo digital pairs of photographs were taken with known camera locations at close range (<100 m) from the surface of interest. At least one control point was positioned to appear within each image. Survey support provided the exact locations of both the camera positions and the control points. Tilt was minimised via the use of a spirit level positioned on top of the camera. Convergence angles were maintained at approximately 8-10 degrees, where possible, to enhance the accuracy of data obtained from the images. Three digital stereo pairs of images were obtained from each site, employing slightly different views and different aperture settings and shutter speeds.

This was done to ensure suitable images were obtained for processing. Large gullies, which could not be captured in an image set, were divided into sections. The largest gully had a total of four sets of images taken in an attempt to achieve complete coverage of the gully. Data acquisition was efficient with a total of 14 gullies photographed within two days in the field.

Data processing and analysis

The resulting stereo digital pairs of images were processed using the SIRO3D (Mapper3D) software developed by CSIRO's Division of Mining and Exploration. SIRO3D produces a three-dimensional model of the object or surface of interest. The software requires the position of both camera locations and a control point in the photo. Combined with image data, the software uses triangulation to determine a mass of 3D points (CSIRO, 2000). This model is presented in SIRO3D as a point 'cloud' of X, Y and Z values. To create this 'cloud', pixel-by-pixel matching between the two images needs to be performed. The greater the matching, the more accurate the final 3D data. Difficulties were encountered during data processing in achieving high level matching between the stereo pairs of images.

Vegetation and rocky spoil in images significantly reduced the level of matching achieved due to occlusion. Complex gully morphology also led to occlusion of large portions of gullies behind gully walls, as well-developed gullies had evolved distinctly sinuous morphologies. Occlusion was by far the greatest difficulty encountered when producing accurate three-dimensional images.

SIRO3D was originally developed for production of 3D images of pit walls, with close to a 90-degree angle between the camera line of site and the wall. Low slope gradients (<30%) therefore also reduced matching levels achieved. In addition, unless large aperture numbers are used (creating a greater depth of field), then only a section of the photograph will be focused adequately for successful matching. Images taken from a short distance (1-2 m) from the gully of interest led to high convergence angles between the camera lines of sight. SIRO3D has difficulty matching images with extreme changes in perspective created when the images are taken from a short distance or with the camera positioned on a berm, which was unavoidable in some situations due to limited available space.

A number of processing techniques were used to minimise the effects of these factors, including:

- sectioning images into segments in which high levels of matching could be achieved (low vegetation cover and uniform planes present in both images) using the SIRO3D software's irregular area feature and then 'mosaicking' the image back together. 'Mosaicking' was by far the most common processing technique employed; and
- processing data to remove outliers.

Although these practices were effective in improving the quality of the data obtained, they also significantly increased processing time. In response to these difficulties, CSIRO's Division of Mining and Exploration developed a new matching algorithm designed to cope with low slope angles and extreme geometry. This new algorithm significantly improved the gully representations.

Once data of a sufficiently high quality were obtained for each of the sites, volumes of spoil lost due to erosion were determined for the derivation of SIBERIA parameters. Data analysis capabilities in SIRO3D are limited, so data were exported as XYZ files into ArcView GIS for analysis. ArcView created 3D representations of the data 'cloud', interpolating areas without data through a Triangulated Irregular Network (TIN). Volumes for each of the sections of gullies were determined using the cut and fill feature contained in the ArcView Spatial Analyst extension. Gully profiles were extracted using the PE 6.0 for 3D Analyst extension.

SIBERIA parameter derivation

The SIBERIA model simulates runoff and erosion from a landform that evolves in response to predicted erosion and deposition. It is a 3-dimensional topographic evolution model that predicts the long-term evolution of channels and hillslopes in a catchment on the basis of runoff and erosion and has been successfully applied to explain aspects of geomorphology of natural landforms (Willgoose, 1994).

SIBERIA predicts the long-term average change in elevation of a point by predicting the volume of sediment lost from a node. Fluvial sediment transport rate through a point (q_s) is determined by the equation:

$$q_s = \beta_1 q^{m1} S^{n1} \qquad (m^3 yr^{-1}) \qquad (1)$$

where S = slope (m m^{-1}), q = discharge (m^3 y^{-1}), and n_1, m_1 and β_1 are fitted parameters.

While the SIBERIA model has a large number of input parameters, m_1, β_1 and n_1 have been shown to have the most significant influence on the final output from the model. The method used to determine the n_1, m_1 and β_1 parameters required SIBERIA simulations to be run on an 'ideal slope', based on the design specifications of the dump. These were 10 m lifts at a 30% gradient and 5 m berm structures at the base of each lift.

Most gully formation at Jundee appears to occur through failure of the berms and subsequent concentration of flows. SIBERIA cannot simulate berm failures. Therefore, to simulate this condition; the 'ideal slope' file was adjusted to incorporate breaks at intervals representative of gully spacing on an actual slope observed at Jundee. Gullies chosen were selected based on their origin from a berm failure and running the complete length of the lift, 48 m in length. Based on these criteria, the breaks were spaced 30 m apart on the bottom berm, 50 m apart on the second berm and 80 m apart on the third berm. An assumption was made for the simulations that all erosion experienced on the slope was in the form of gully erosion.

A general investigation of the effect of each of the parameters on gully size and morphology was then performed using this "ideal" test slope. Approximately 130 simulations were performed on the "ideal slope" with various combinations of the three parameters. Resultant gully morphologies were documented after a 10-year period (ie. a typical dump age). From this investigation the general effect of each of the parameters on gully morphology was determined. Due to the interrelatedness of the parameters (refer to Equation 1), it was difficult to determine the precise effect of each parameter. Certain patterns were evident however. Gully length was clearly maximised by reduction of the n_1 parameter, whilst adjusting the β_1 parameter and m_1 parameter had notable effects on gully width and depth respectively. Reduction of the n_1 parameter below 1 led to erroneous results in the output from the model for long-term simulations and as such was avoided. The m_1 parameter increased the incision experienced by the slope and led to significant rilling on the slope in areas other than below a forced berm break. As an assumption for the modeling had been made that all erosion was gully erosion due to berm failure, the m_1 value was maintained at a level where excessive rilling was avoided.

Parameter values were then developed for each of the waste rock dumps. All simulations to determine parameters were performed using SIBERIA version 8.18 with a 0.5 m grid and a 0.005 time-step. An n_1 value of 1.01 was set to maximise gully lengths whilst avoiding the problems associated with n_1 values less than 1. An iterative approach was then used to establish β_1 and m_1 values, these parameters being adjusted until comparable gully volumes and similar gully morphology was obtained for gullies present on each dump (standard gully width of 1 m, standard gully depth of 0.5 m and standard gully volume of 25 m^3). As gully length of 48 m could not be achieved with n_1 set at above 1, depth and gully width were allowed to increase slightly to ensure gully volumes were preserved.

The rainfall experienced at the Jundee site since the beginning of 1995 was significantly higher than the long-term average at the site. In the 8-year period from 1995 to 2003, average annual rainfall at the nearby Wiluna site was 380 mm. In comparison, long-term average annual rainfall at Wiluna was 260 mm (information acquired from the Bureau of Meteorology website). This raised concern as to the accuracy of long-term erosion predictions based on the gully erosion experienced at Jundee during this period. An investigation of the rainfall patterns revealed that the occurrence of Cyclone Bobby in February 1995, prior to construction of w12wn3 dump, contributed to the higher than average rainfall experienced at the site. An assessment of rainfall events excluding the influence of Cyclone Bobby in the 8-year period from 1995 to 2003 indicated that the rainfall erosivity over this period closely resembled the long-term annual average rainfall erosivity. Due to this, no adjustments to the modeling method were necessary to account for the increased rainfall over this period.

SIBERIA landform evolution modeling

For this study the SIBERIA landform evolution model was run through an ArcView extension, ArcEvolve 1.3. The use of the ArcView environment allows for the correction of Digital Elevation Model (DEM) files; the definition of boundary and region files; and hydrological analysis to be performed on the DEM before processing (Boggs, et al. 2001). ArcEvolve also allows for resultant DEM files produced to be imported back into ArcView for subsequent analysis and display of the erosion predicted by the SIBERIA model.

The SIBERIA Landform Evolution Model requires accurate DEMs of the waste rock dumps as input into the model. A DEM created via photogrammetric methods performed on an aerial shot of the Jundee site was supplied to Landloch for the purposes of analysis. The DEM was of insufficient quality for input into the SIBERIA model and was therefore corrected based on observations from an aerial shot of the site. As a consequence, the resulting DEM of the waste rock dumps can only be considered an approximate representation.

The model was run, using the derived parameters, for a period of 500 years and output requested for 100, 200 and 500 years. These simulations were performed with a grid size of 10 m, using SIBERIA version 8.18 and a 0.05 time-step. Analyses to determine total spoil losses and average annual erosion rates for the whole of each dump were performed. Additional analyses excluding the dump tops and areas of deposition at the base of the slope were also performed to estimate erosion solely occurring from the waste rock dump batter slopes.

Results and Discussion

Photogrammetry

Due to specific difficulties associated with the application of photogrammetry to the surveying of gullies discussed in the previous section, the results achieved from the photogrammetry method were variable. Gullies with simple morphology and clear of vegetation produced reasonable results. However, the results obtained from sites with larger, more complex geometries or sites with excessive vegetation could not be used for the purposes of analysis. Despite these difficulties, enough sites with a sufficient representation of the gullies were achieved for derivation of SIBERIA parameters.

The difficulties associated with complex gully morphology could potentially be avoided by taking a greater variety of images at these sites to ensure complete coverage of the gullies. While this does lead to a large number of images being acquired, the capacity of modern digital cameras allows for this with no additional expense being incurred.

SIBERIA parameters

At present the method for determining SIBERIA parameters β_1 and m_1, is somewhat subjective. Further work is required to determine the precise effect of each parameter on gully morphology. The constraints applied to the modelling (n_1 set to 1.01, conservation of gully volumes and the assumption of no sheet or rill erosion) do however constrain the β_1 and m_1 parameters, thus ensuring the uniqueness of a parameter set for a given site.

The final parameter estimations (gully morphology method) are presented in Table 1 along with parameters developed for SIBERIA during a previous study (laboratory method) of the site (Landloch, 2001). The topsoil/rock combination studied in the laboratory had WEPP parameters similar to those measured for oxidised spoil in the field (though a slightly lower erosion rate overall). The parameters predicted by the gully morphology method employed in this study are comparable with those developed from previous studies.

Table 1. Comparison of gully morphology method and laboratory method SIBERIA parameters

Parameter	Gully volume and morphology fitting method	Derived from rainfall simulator data
n_1	1.01	1.5
m_1	1.11	1.08 (Topsoil/rock (2:1))
β_1 (1m)	0.039	0.032

SIBERIA landform evolution modelling

The accuracy of the final landform morphology is dependent upon the detail of the original DEM provided. The use of a simplified DEM in this study resulted in the landform for this site consisting of fewer, larger gullies than would have occurred had a more detailed DEM, that included berm failures, been used.

The long-term erosion rates for 2 dumps were calculated based on the predicted total soil loss for the 500-year SIBERIA simulation (Table 2). As the majority of erosion on these sites was driven by erosion on the batter slopes, long-term erosion rates were also calculated by assuming that all erosion from the site occurred on the batter slope, excluding both the waste rock dump top and the area of deposition at the bottom of the dumps from the calculations. This was done to enable comparison with erosion rates estimated for a period of 43-years by the WEPP model in previous erosion studies (Landloch, 2001).

The WEPP model was used to predict the annual average erosion rates for: topsoil, spoil, and spoil of lowest hydraulic conductivity. The predicted erosion rates for these materials were 6.9, 15.2 and 20 (t ha^{-1} yr^{-1})

respectively. It should be noted that the WEPP model erosion predictions were based on 5 m rill spacing and a slope length of approximately 33 m compared with the 195 m slope length and much wider gully spacing of the waste rock dump. As such, it is not surprising that in this study, predicted erosion rates are higher.

Table 2. Long term erosion rates for both waste rock dumps

Waste Rock Dump	Dump Area (ha)	Batter Slope Area (ha)	Simulation Period (years)	Erosion Rates for Whole Dump ($t\ ha^{-1}\ yr^{-1}$)	Erosion Rates for Batter Slopes Only ($t\ ha^{-1}\ yr^{-1}$)
w12wn3	193	101	100	12.69	24.25
			200	13.08	25.00
			500	13.92	26.60
wn16	75	28	100	11.17	29.91
			200	11.46	30.71
			500	11.24	30.11

The estimated erosion rate for the Jundee site for the last 8-years is 18.9 t ha^{-1} yr^{-1} (based upon observed gully spacing and gully volumes established from photogrammetric data). The long-term erosion rates predicted in this study are therefore considered reasonable. Ongoing monitoring of the Jundee site will enable the verification of the erosion rates predicted and subsequent calibration of the method outlined.

Conclusions

Acquisition of photogrammetric data was highly efficient. Some difficulties were encountered in processing the data to produce the final 3D gully representations (data matching difficulties by extreme changes in aspect and occlusions due to vegetation, rocks and complex gully morphology). Advances in field acquisition methods and the SIRO3D software will reduce these difficulties and hence increase the accuracy of the gully representations. With improved available information on gully morphology and volumes, the accuracy of determined SIBERIA parameters should increase.

The constraints applied to the derivation of SIBERIA parameters from the gully data (n_1 set to 1.01, conservation of gully volumes and the assumption of no sheet or rill erosion) produced a unique set of parameters for the site (β_1 of 0.039 and m_1 of 1.11). The resulting parameters generated by this method compared favourably with parameters derived in previous erosion studies at the site.

Long-term erosion rates predicted by the SIBERIA model, for waste rock dump w12wn3, using those derived parameters ranged between 12.7 t ha^{-1} yr^{-1} (over the entire waste rock dump) and 26.6 t ha^{-1} yr^{-1} (on batter slopes only). The estimated erosion rate for the Jundee site for the last 8-years, based on current gully volumes and spacings, is 18.9 t ha^{-1} yr^{-1}. As such, the predicted long-term erosion rates in this study are considered reasonable.

The accuracy of final landform morphology predicted using the SIBERIA model is dependent upon the detail of the original DEM input. However, a simplified DEM still appears to provide reasonable predictions of erosion rates using the method outlined in this paper. Utilising an improved DEM for simulations should improve the accuracy of both predicted erosion rates and final landform morphology.

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