Computers & Geosciences 37 (2011) 1413–1424

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Slope orientation assessment for open-pit mines, using GIS-based algorithms

Martin Grenon *, Amélie-Julie Laflamme

Department of Mining, Metallurgical and Materials Engineering, Université Laval, Quebec, Canada G1V 0A6

A R T I C L E I N F O

Article history:
Received 30 June 2010
Received in revised form
8 December 2010
Accepted 20 December 2010
Available online 1 February 2011

Keywords:
Open-pit mining
Interramp orientation
Bench face orientation
GIS
Integrated design
Block modeling

A B S T R A C T

Standard stability analysis in geomechanical rock slope engineering for open-pit mines relies on a simplified representation of slope geometry, which does not take full advantage of available topographical data in the early design stages of a mining project; consequently, this may lead to nonoptimal slope design. The primary objective of this paper is to present a methodology that allows for the rigorous determination of interramp and bench face slope orientations on a digital elevation model (DEM) of a designed open pit. Common GIS slope algorithms were tested to assess slope orientations on the DEM of the Meadowbank mining project's Portage pit. Planar regression algorithms based on principal component analysis provided the best results at both the interramp and the bench face levels. The optimal sampling window for interramp was 21×21 cells, while a 9×9-cell window was best at the bench level. Subsequent slope stability analysis relying on those assessed slope orientations would provide a more realistic geometry for potential slope instabilities in the design pit. The presented methodology is flexible, and can be adapted depending on a given mine's block sizes and pit geometry.

1. Introduction

The creation of rock slopes in open-pit mines results from the inputs of planning, production, and geomechanics groups. According to Hustrulid (2000), both good planning and good geomechanics are necessary for the preparation of good designs. Good production is required to ensure that the "as-built" slopes closely resemble the "as designed" slopes.

The planning group now routinely uses software tools for assessing geology, mineral resources, ultimate pit, and mine planning to provide plans and layouts to the production group. The geomechanics group's contribution is not fully integrated in the workflow of rock slope creations because of the inability to perform stability analysis with compatible software tools.

Some efforts have been made to integrate geomechanical design into commercially available mine design tools, such as the Stereonet Viewer and Terrain modules in Datamine (Datamine, 2010), and the Geotechnical Tools module in Vulcan (Maptek, 2010). However, while useful, these modules are not commonly used and they cannot perform complex stability analysis. More recently, Grenon and Hadjigeorgiou (2010) integrated a probabilistic limit equilibrium approach into a commercially available design tool, Gemcom Surpac (Gemcom, 2010). Although enabling more detailed deterministic and probabilistic limit equilibrium analysis within a mine planning software tool, this approach does not take full advantage of the three-dimensional representation of the planned pit geometry for assessing slope orientations.

A more complete representation of pit geometry should comprise the three main components of an open-pit slope design: overall slope angle, interramp angle, and bench face angle (Fig. 1). The overall pit slope angle is from crest to toe, and incorporates all ramps and benches. The interramp angle of the slope is defined as the slope lying between each ramp. The face angle of individual benches depends on the bench height, or combined multiple benches, and the width of benches required to contain minor rock falls (Wyllie and Mah, 2004). These angles may vary around the pit to accommodate geology and/or planning considerations.

In hard rock open-pit mines, the most common slope stability issues at the bench and interramp levels are structurally controlled. Typical stability analysis involves kinematic and limit equilibrium analysis for planar, wedge, and toppling failure modes (Fig. 2). The slope geometry is usually considered planar and constant over the studied area.

Currently, geologists and mining engineers use block modeling at the prefeasibility, feasibility, and full mine production stages in assessing mineral resources, mining reserves, and final pit layouts. Fig. 3 presents the topography of the final pit of a mining project. Pit topography is defined by blocks, as in Fig. 3a. The very strict rules governing reserves and resources estimation in the mining business ensure that block sizes are small enough to very

* Correspondence address: Faculté des sciences et de génie, Département de génie des mines, de la métallurgie et des matériaux, Pavillon Adrien-Pouliot 1065, avenue de la Médecine, Quebec, Canada G1V 0A6. Tel.: +1 418 656 7478; fax: +1 418 656 5343.

E-mail address: martin.grenon@gmn.ulaval.ca (M. Grenon).

0098-3004/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cageo.2010.12.006

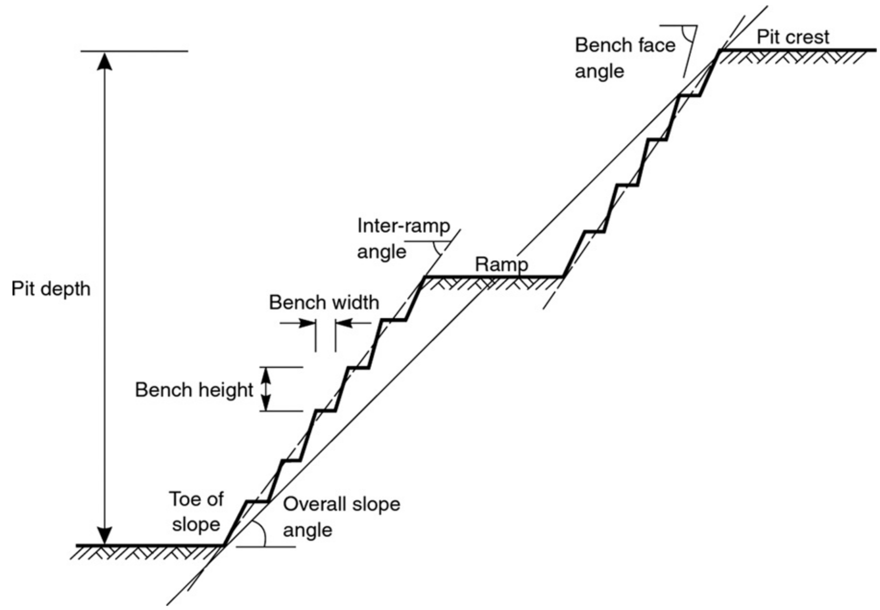

Fig. 1. Open-pit slopes after Wyllie and Mah (2004).

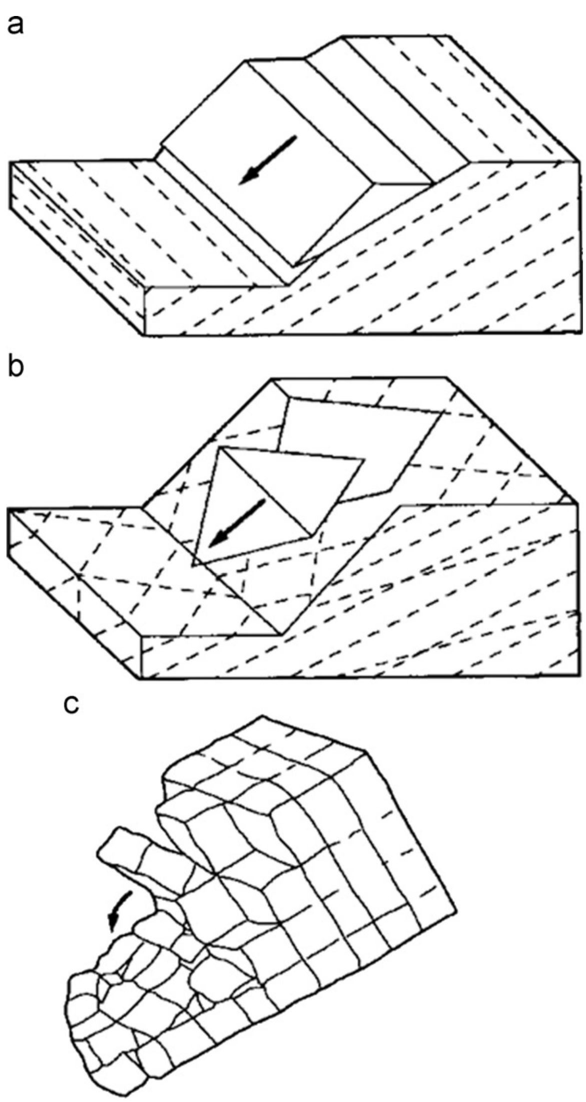

Fig. 2. Typical failure modes: (a) planar, (b) wedge and (c) toppling, modified from Hudson and Harrison (1997).

accurately define the pit topography. A plan view representation could also be used in defining the pit, as in Fig. 3b. The cells defining the ultimate pit surface can be defined by their center *x*, *y*, and *z* coordinates. This cellular representation of the pit topography is equivalent to the Digital Elevation Model (DEM), a Geographical Information System (GIS) raster layer representing elevation. Usually, cell size in GIS analyses is limited by the data acquisition method (orthophoto, laser scanning, etc.), and/or by the raster layer's intended usage. In mine block modeling, no photos or laser surveys of the final pit are available a priori. Cells or block sizes are dictated by the diamond drilling holes (DDH) pattern used in defining the mineralization within the orebody. All subsequent analyses are limited by the cell or block sizes dictated by the ore resources estimation process.

At prefeasibility and feasibility stages, the best practice lays in obtaining structural information from outcrop, drillcores and oriented drillcores mapping. This information is used to build a structural model of the pit area. At these design stages, the target levels of data confidence for structural models are 40–50 and 45–70% for prefeasability and feasibility, respectively (Read and Stacey, 2009). This structural information can be stored easily within a block model generated with a mine design tool (Read and Stacey, 2009; Grenon and Hadjigeorgiou, 2010).

Adequate slope orientation determination is necessary to better integrate the work of the geomechanical group into the slope creation process. This paper will present a formal methodology to compute slope orientation at the interramp and bench levels within mine design software tools relying on block modeling. The applicability of the most commonly available GIS algorithms for determining slope orientation will be reviewed from a mining engineering perspective. The Meadowbanks open-pit case study will be used for validating the applicability of the various algorithms and for evaluating the most appropriate methods. The slope orientations thus obtained would arguably be the best suited for assessing slope stability in subsequent stability analyses of pit slopes.

2. Slope orientation

This section presents the most common slope algorithms used to compute slope orientation as a local property of the DEM. Section 3