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Determination of volumetric changes at an underground stone mine: a photogrammetry case study

Slaker Brent [a,*], Westman Erik [a], Ellenberger John [b], Murphy Michael [b]

[a] Virginia Polytechnic Institute and State University, Blacksburg 24060, USA
[b] Office of Mine Safety and Health Research, NIOSH, Pittsburgh, PA 15236, USA

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ABSTRACT

Photogrammetry, as a tool for monitoring underground mine deformation, is an alternative to traditional point measurement devices, and may be capable of accurate measurements in situations where technologies such as laser scanning are unsuited, undesired, or cost-prohibitive. An underground limestone mine in Ohio is used as a test case for monitoring of structurally unstable pillars. Seven pillars were photographed over in a 63 day period, punctuated by four visits. Using photogrammetry, point clouds of the mine geometry were obtained and triangulation surfaces were generated to determine volumes of change over time. Pillar spalling in the range of 0.29–4.03 m^3 of rock on individual rib faces was detected. Isolated incidents of rock expansion prior to failure, and the isolated failure of a weak shale band were also observed. Much of the pillars remained unchanged during the monitoring period, which is indicative of proper alignment in the triangulated surfaces. The photographs of some ribs were of either too poor quality or had insufficient overlap, and were not included. However, photogrammetry was successfully applied to multiple ribs in quantifying the pillar geometry change over time.

1. Introduction

Adequately measuring underground rock mass movements is integral to understanding how rock masses behave and how to interact with them safely and efficiently. Many modern measurement techniques employed in underground mining environments rely on point measurements, such as through extensometers or borehole relief methods [1]. These techniques, while commonplace, do not provide a comprehensive view of how the rock mass is behaving. The dynamic changes in stress states underground, coupled with the mechanical uncertainty of rock masses, near active excavations, creates a need for measurement systems which better capture the true behavior of the rock mass. Laser scanning and photogrammetry are two such measurement technologies that provide wide-area monitoring capabilities.

Digital photogrammetry will be tested in this study, not because of its superiority, but due to its more probable adoption in hazardous mining environments. Digital photogrammetry is a means of obtaining three-dimensional point clouds from digital photographs. Close range digital photogrammetry (CRDP) is photogrammetry applied to measuring objects or scenes less than 100 m away, and is used for various functions in underground mining environments [2]. These uses include, but are not limited to mapping fracture networks, characterizing fractures, and measuring volumes of blast rock [3–6].

One additional application to underground mining environments is monitoring geometric change in support structures, such as pillars. Using time-lapse observations, three-dimensional point clouds or surfaces can be compared to observe temporal change. The ability to measure or observe object displacements in an underground mining setting, using photogrammetry, differs in practice and obstacles from a surface setting. This study explores the viability of applying photogrammetry to monitoring temporal geometric change in pillar structures.

1.1. Site description

The setting for this study is an underground limestone mine in eastern Ohio. The mine follows the Vanport Limestone seam, with a mining depth that ranges from 60 to 75 m, while maintaining a near-horizontal inclination. The mine plan consists of varying pillar sizes and orientations, with many pillars reduced from their planned size due to over mining and scaling or sloughing. The predominant planned pillar dimension was 7.6 m wide and 18.2 m long, on 30 m crosscut centers and 19.8 m drift centers. This results

* Corresponding author. Tel.: +1 757 8803050.
E-mail address: slakerba@gmail.com (B. Slaker).

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in the north–south crosscuts that are 12 m wide with the east–west crosscuts also being 12 m wide.

The mine has experienced significant structural instabilities. A collapse on May 27th, 2014 encompassed 10 pillars in a 61 m by 107 m region, and an additional collapse, involving 10 pillars, occurred on June 24th, 2014. Spalling and scaling of pillars occurred throughout the mine, and when coupled with over mining, resulted in pillar dimensions likely in the range of 6.4 m by 17.0 m, instead of the planned 7.6 m by 18.2 m.

The instability is believed to be due to the presence of weak 20–30 cm shale bands within the pillar and a weak 1 m thick moisture-sensitive fireclay beneath the pillar. The weak bands can create tension in the surrounding strata through extrusion, and if the pillars punch into the weak floor strata, it can create floor heave and reduce the support provided to the roof. Further detail of site characterization and mechanisms of the pillar failures are discussed by Murphy et al. [7]. The collapse of roof structures is beyond the scope of this study, but the sloughing and scaling associated with this instability provides an excellent subject for photogrammetry.

2. Methods

Seven pillars were photographed across four different visits: August 26th, September 16th, September 26th, and October 28th 2014. The photographs were taken with a Digital Single-Lens Reflex (DSLR) Nikon D70S camera. Camera settings, shown in Table 1, were kept consistent during visits, but slight changes were made between them. The lighting was provided by a source external to the camera, which was moved as needed to provide sufficient light on the subject. The photographs were taken by hand, without the aid of a tripod. Several photographs were of poor quality, but were still used for reconstruction if clearer photographs were unavailable. Fog is believed to be partially responsible for blur in some photographs, as well as a lower *f*-number causing spherical aberration in the lens.

Table 1
Photograph EXIF data from each visit.

Date	Resolution	*f*-number	Shutter speed (s)	Focal length (mm)
Aug. 26th	3008 × 2000	*f*/2.8	1/80	20
Sep. 16th	3008 × 2000	*f*/2.8	1/80	20
Sep. 26th	3008 × 2000	*f*/2.8	1/60	20
Oct. 28th	3008 × 2000	*f*/4.5	1/60	20

A map of the pillars that were photographed is shown in Fig. 1. The pillars are on the boundary of a collapsed area. The number of photographs taken of each pillar is listed in Table 2. With the need to move the light sources, the pictures were not taken continuously surrounding the pillar, but rather in distinct segments, fragmenting the pillar into "sides" instead of one contiguous object. Further displacement of material, through spalling, on these pillars was expected, but the magnitude of material being displaced was unknown.

The photographs were processed through a combination of Agisoft Photoscan, CloudCompare, and Maptek iSite. Photoscan was used to obtain the point clouds and triangulation surfaces from the photographs. Next, CloudCompare was used to orient and scale the time-lapse photos. Several 30 cm squares were placed in each scene to provide a reference for scaling the resultant triangulation surfaces. The squares were not placed in the same location during subsequent visits, and as a result, would create the appearance of movement on the rib face at the locations they were placed.

Orienting the photos was performed by locating the same points on the rib or roof between visits. Exposed rock faces have a significant number of visual features that can be located across the photographs from different visits and assigned the same three-dimensional coordinate. Four of these features were chosen in each point cloud to align with a point cloud of the same region at the next visit. If reference points moved between scenes, such as in the expansion of a rib, this would cause a systematic error clearly visible when aligning the triangulation surfaces.

Lastly, iSite was used to determine the distances between the triangulation surfaces at different time periods. The volumes reported are the volumes enclosed by two triangulation surfaces. The older surface will always be the reference. Negative volumes correspond to the removal of material from the rib, while positive volumes correspond to an expansion of the rib or accumulation of material that did not previously exist. The same process was applied previously, in an underground limestone mine, using laser scanning as the point cloud collection method [8].

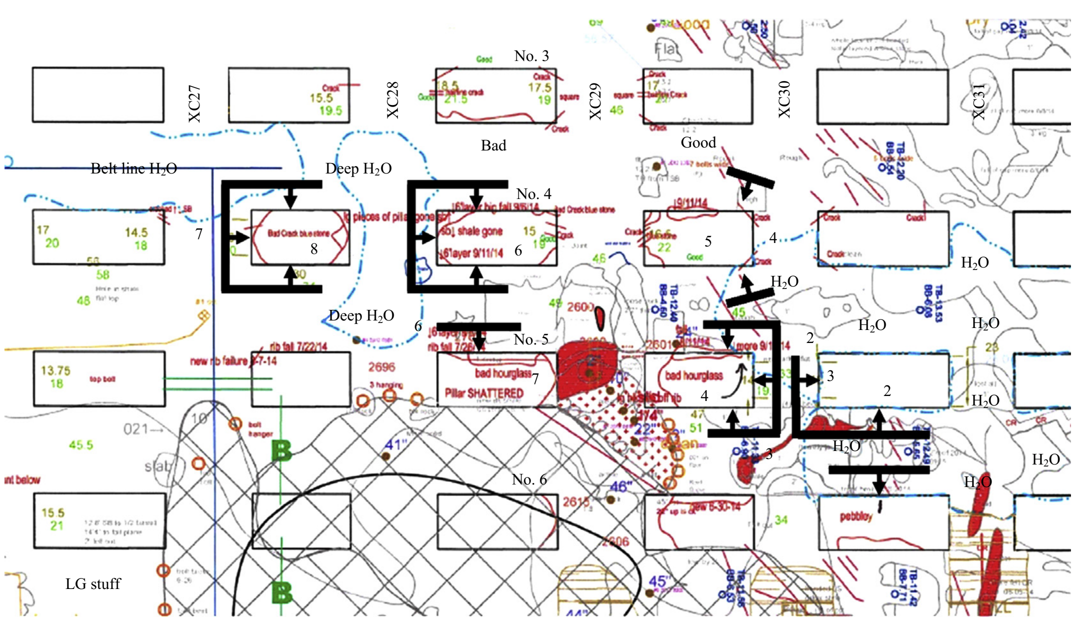

Fig. 1. Map of the photographed areas of the mine with pillars numbered.