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Volumetric measurement of rock movement using photogrammetry

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ABSTRACT

NIOSH ground control safety research program at Spokane, Washington, is exploring applications of photogrammetry to rock mass and support monitoring. This paper describes two ways photogrammetric techniques are being used. First, photogrammetric data of laboratory testing is being used to correlate energy input and support deformation. This information can be used to infer remaining support toughness after ground deformation events. This technique is also demonstrated in a field application. Second, field photogrammetric data is compared to crackmeter data from a deep underground mine. Accuracies were found to average 8 mm, but have produced results within 0.2 mm of true displacement, as measured by crackmeters. Application of these techniques consists of monitoring overall fault activity by monitoring multiple points around the crackmeter. A case study is provided in which a crackmeter is clearly shown to have provided insufficient information regarding overall fault ground deformation. Photogrammetry is proving to be a useful ground monitoring tool due to its unobtrusiveness and ease of use.

1. Introduction

1.1. NIOSH mine safety research

Photogrammetry systems have been implemented by the National Institute for Occupational Safety and Health (NIOSH) as part of its ground control research to improve mine safety. Conventional monitoring of ground movement has typically focused on movement of a few discrete points that are marked or anchored to instruments. Loss of a designated point or anchor, or the ability to identify a stable point in an unstable area, has often frustrated monitoring efforts. NIOSH researchers are using photogrammetry to conduct full-field measurements of rock surfaces underground. Periodic measurements of the entire surface of a ramp allow patterns of displacement to be observed. Full-field measurements provide much more insight into ground behavior than point measurements.

1.2. Background

Previous work by Benton, et al. discussed laboratory calibration and verification testing of two photogrammetry systems being used by NIOSH researchers [1]. Both systems utilize stereoscopic image pairing techniques for photogrammetric reconstruction. This paper discusses how a laboratory system was used to conduct volumetric analyses of testing of shotcrete panels with varying types of reinforcement. The laboratory system was found to be accurate to within 2 mm. Additionally, a field photogrammetry system was found to produce linear measurements within 1 mm of known lengths in laboratory conditions. This system is currently being used at a deep underground mine to observe ground support conditions and deformations that have occurred. This paper discusses comparison of preliminary volumetric measurements of rib deformation to laboratory tests, as well as comparison of the field system against a crackmeter installed across a fault surface where it intersects the ramp.

2. Photogrammetric volume calculations

2.1. High energy, high deformation testing

Ground control safety often depends on supporting, or at least containing, the ground between rock bolts. Shotcrete and mesh, in various combinations and with other components, are often called upon to do this, as shown in Fig. 1.

Applications are especially common in mines with squeezing ground or seismic loading. The combination of mesh and shotcrete forms a panel, or plate, that is typically bent by ground extruding between restraining rock bolts. The resistance of these panels to bending across large ground deformations is important for maintaining ground support safety. Combinations of shotcrete,

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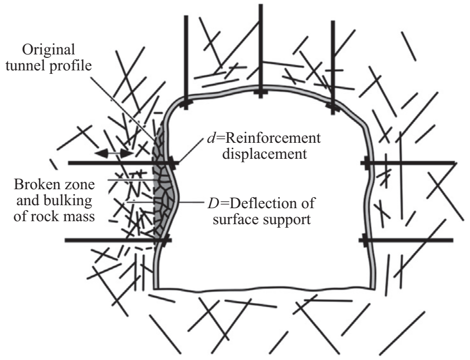

Fig. 1. Diagram of the reinforced shotcrete system [2].

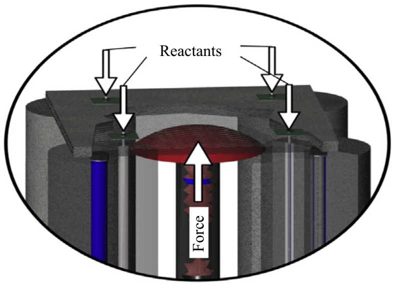

Fig. 2. Diagram of the force during the high-energy displacement panel test and tester.

mesh and other components that can maintain significant support pressure are desired, a characteristic described as the "toughness" of support. Toughness can be quantified as the work done during deformation (e.g., force *x* displacement). However, the toughness of a design is difficult to estimate. NIOSH researchers have responded to this deficiency by designing a full-scale test device.

Previous testing of total system toughness has been completed by Kirsten and Tannant and Kaiser [3–5]. However, the test "stroke" or maximum displacement fell far short of displacement magnitudes observed in-situ. As such, a test device was needed to measure high resistance energies (toughness) over high displacements. A combination dubbed high-energy high-displacement (HEHD) incorporated these alterations [6]. First, a stroke of 25 cm was specified, roughly doubling the test stroke of previous systems. Second, the scale of testing was expanded somewhat to accommodate a 1.2 m bolt pattern while minimizing edge effects. Finally, better information on deformation volume changes and crack geometry was desired for comparison with test observations.

2.2. Photogrammetry application to shotcrete panel testing

Photogrammetric observation of HEHD panel testing was conducted to track deformation volume changes. This information could then be used to delineate the relationship between reinforced shotcrete "bulge" deformation between rock bolts and residual toughness of the intact support. This can be done by correlating volumetric displacements of shotcrete panels with known displacements and loads obtained during panel tests. This technique may also be applied to mesh or reinforced shotcrete installed in a mine to infer remaining support toughness from observed volumetric changes. This is particularly important knowledge where seismic loading may impart significant energy to the support system; thus, photogrammetric methods can aid in designing a safe work site.

A laboratory photogrammetry system developed by NIOSH researchers allows for documentation of tests [1]. This system has been used during HEHD shotcrete panel tests. The laboratory photogrammetric system consists of two Nikon® D800 digital SLR cameras, each mounted with a Sigma 20 mm prime wide angle lens. 3DM CalibCam camera calibration software and 3DM analyst photogrammetry software from Adam Technology® were used to complete the 3D reconstructions of laboratory testing [7]. Each test included capturing left and right images at one-second intervals. Camera clock times were synchronized with the data acquisition system clock times immediately prior to each test.

The HEHD testing process begins as aspherically-shaped hydraulic ram head is pushed through the test panel while being restrained by paddle anchor D-Bolts® embedded in the four columns of the test frame, as shown in Fig. 2.

D-Bolts are designed specifically to absorb energy in dynamically loaded rock masses [8]. Load and displacement data are collected during the test using an advanced data acquisition system. Once the ram reached 25 cm displacement, the system was de-energized and photogrammetric monitoring ended.

2.3. Photogrammetry data analysis

Photographic image pairs were selected at 5 cm ram displacement intervals. These pairs were reconstructed in 3D for volumetric analysis. The top corners of the shotcrete panels were used as control points for scale and orientation. Camera calibrations, images and control points were input into the software. The reconstruction process was conducted in four steps for each test:

(a) Locate the control points on the first image pair.
(b) Find relative points between image pairs.
(c) Run the bundle adjustment with control points for the first image pair with known camera locations for subsequent image pairs.
(d) Construct the digital terrain models for each interval.

The models were then trimmed to remove extraneous points prior to comparing volumes. The Adam Technology software has a built-in volume calculation function that determines maximum height and volume calculations from a defined base plane, which in this case was set to the plane defined by the four control points and the zero elevation.

2.4. Volume-energy relationship analysis

Volume-energy relationship analyses were conducted for three types of shotcrete panels. A weakest-to-strongest spectrum for analysis was created by using a panel made of a standard shotcrete mix (no reinforcement), one made of poly-fiber shotcrete mix (fiber reinforced), and a third made with cyclone fencing enclosed in a fiber shotcrete mix (mesh and fiber reinforced). An additional test using only a 1.8 m × 1.8 m cyclone fence piece with no shotcrete was conducted as a baseline. This test used a piece of burlap underneath the fencing to provide an adequate background for photogrammetric reconstruction. The burlap's influence on fence performance was judged to be negligible. The cyclone fence test also used a 1.2 m bolt spacing to replicate mine application. Synchronized clock times were established prior to each test between the cameras and data logger. The load and displacement data for each test were used to calculate energy, which was then matched with digitally recorded time stamps for each photograph pair. These data were used to match photogrammetric data with the calculated energy data at 5 cm ram displacement intervals. Corresponding deformation volumes acquired through photogrammetric measurement were then compared to energy calculations for each interval.