International Journal of Rock Mechanics & Mining Sciences 79 (2015) 157–165

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

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

Delineation of large localized damage structures forming ahead of an active mining front by using advanced acoustic emission mapping techniques

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ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form
17 July 2015
Accepted 19 August 2015

Keywords:
Acoustic emission
Gold mine
Mining-induced fracture
Joint hypocenter determination
Double-difference hypocenter relocation

ABSTRACT

We applied advanced mapping techniques to 291 230 acoustic emission (AE) events as small as around M -4 that were recorded over 50 days by an ultra-high resolution network close to the active front of a tabular mining stope being advanced northward at 1 km depth in the Cooke 4 Gold Mine in South Africa. We first applied joint hypocenter determination (JHD) to improve absolute locations, and then applied the double-difference relative location algorithm to the JHD output. These steps resolved the seemingly continuous, dense cloud of AEs that extend about 20 m ahead of the stope front into several discrete, steeply dipping tabular clusters a few meters thick and 10–30 m in dip extent, separated by quiet intervals a few meters thick. The clusters have a strike parallel to the stope face and a dip of about 65°, resembling commonly observed large shear fractures along the plane of maximum shear (Ortlepp shears). In general, the activity of the clusters changed in similar ways as the stope face advanced, but each cluster remained stationary and the gaps between clusters were impressively quiet. This study demonstrates that high-resolution AE mapping can delineate the formation of large structures of localized damage in the highly stressed intact rock mass ahead of the stope face, a process that may culminate in hazardous seismic events.

1. Introduction

In South African gold mines, where extensive tabular mining of subhorizontal reefs at depth creates a zone of high differential stress around the mining front,[1] various types of macroscopic fractures, with dip dimensions of decimeters to several tens of meters, are observed around the stope,[2,3] posing serious hazards to mining operations (Fig. 1). The most common types of macrofractures are vertical extension fractures (type I), which form by tensile failure of rock near the stope face when confinement is removed. Together with another secondary extension fracture (type III), type I fractures degrade the integrity of the rock mass and make the stope prone to collapse. Type I and type III fractures correspond to E1 and E2 fractures in the terminology of van Aswegen and Stander.[3] Type II fractures are steeply dipping shear fractures that can be as large as several tens of meters in the dip dimension. Ortlepp[4,5] studied their distinct morphological characteristics and emphasized their close association with seismic

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http://dx.doi.org/10.1016/j.ijrmms.2015.08.018
1365-1609/

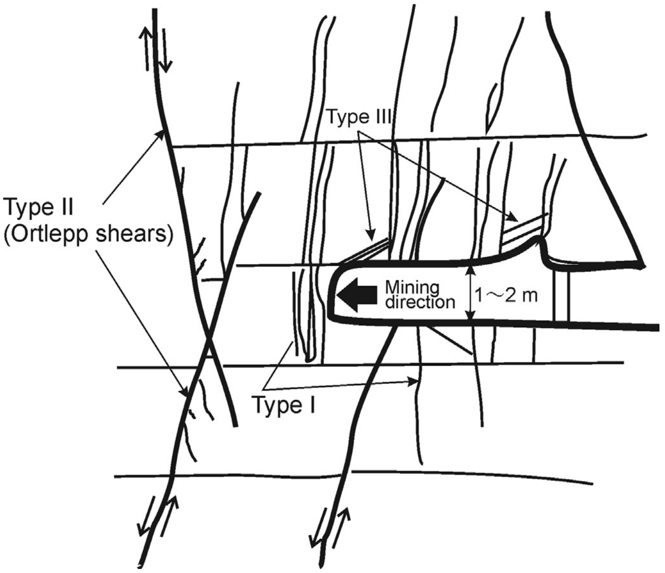

Fig. 1. Schematic diagram of the distribution and orientation of three types of fracture around a stope.[2] Modified after.[2].

events. Following van Aswegen,[6] we refer to these brittle shear structures formed in intact rock as Ortlepp shears. Ortlepp shears often are the sources of violent seismic events with magnitudes between M 1 and M 4,[4–6] which cause severe rockburst damage in the stopes and beyond. Ortlepp shears form in macroscopically intact rock as far as tens of meters ahead of the stope face,[4] where a similarly steeply dipping zone of elevated shear stress is present.[1] Because they occur near the active mining face where people are working, seismic events from Ortlepp shears pose a hazard comparable to that from larger events caused by reactivation of geological faults, which can reach M 5.[5,7] Ortlepp shears are not rare; around 20 of them were found in the East Rand Proprietary Mine (ERPM) in the wake of face advancement for about 200 m.[4] This averages one in every 10 m of face advancement.

The characteristics of these types of macrofractures are explained by the stress field induced around the stope front.[3] Indeed, almost all seismicity associated with the sub-horizontal tabular mining typical in South African gold mines is concentrated in a zone of excessive vertical compression a few tens of meters in extent along the mining front. Routine monitoring of seismicity down to $M\ -1$, as conducted in most gold mines in South Africa, commonly detects “seismic clouds” that migrate with the advancing mining front, highlighting this volume of high stress.

Very high resolution imaging of seismicity down to very small magnitudes as acoustic emissions (AE) may be able to trace the development of macrofractures in a stressed rock mass, delineating developing macrofractures as clusters of numerous, much smaller AEs. The damage structures delineated by AEs, if found and monitored, could have more specific implications for rock mass stability than the relatively featureless volumes of elevated stress implied by conventional seismic monitoring. AEs have been mapped during projects in tunnel construction, mining, and the development of geothermal and petroleum fields e.g.,[8–14]. However, active mining faces at depth have never been covered by seismic observations with a resolution suitable for this purpose. If we seek to monitor the development of macrofractures of, for example, 10 m, the minimum requirement would be a methodology with the ability to detect microfractures (AEs) smaller than a square meter (corresponding to $M\ -2$ for a 3 MPa assumed stress drop) at relative location accuracies better than a meter.

This paper presents our analysis of the seismicity around an advancing mining front using AE monitoring data in the Cooke 4 Mine (previously known as the Ezulwini Gold Mine) in South Africa. Deployed as part of the Science and Technology Research Partnership for Sustainable Development (SATREPS) program,[15–20] sensors have located AEs as small as -4 in moment magnitude (M_w) or even smaller. We applied the joint hypocenter determination (JHD) method[21] to these AE data to improve the absolute location accuracy followed by the double difference (DD) method[22] to improve the relative location accuracy. We have found that the seismic cloud around the stope front can be resolved into several discrete planar clusters 10–30 m across with orientations similar to Ortlepp shears. The planar clustering of this seismicity suggests that the AE activity represents the formation of relatively large structures of localized damage rather than pervasive microfracturing throughout the stressed rock volume ahead of the mining front.

2. Observation of AE events at the Cooke 4 mine

The Cooke 4 Mine is about 40 km southwest of Johannesburg, near the town of Westonaria in Gauteng Province, South Africa. Operations at the mine commenced more than 40 years ago. The mine is in an Archean sedimentary basin several kilometers thick that consists mainly of quartzite and shale with scattered minor volcanic units. The volume considered in this study consists entirely of quartzite, except for a lava layer near its top edge. Since 2010, ore has been mined from the upper Elsburg reef within a shaft pillar about 400 m in diameter at a depth of about 1 km. An extension of the reef outside the shaft pillar had been mined out by 2001, when the mine was temporarily closed, and was left as an extensive tabular cavity, thus the background vertical stress in the shaft pillar is high for its depth. Faces (panels) in the current mining are 20–30 m across and 1–2 m high. In the study area, the stope is sub-horizontal, gently dipping about 10 °WSW. Daily blasting advances the panels to the north by about 10 m per month.

We conducted AE monitoring during mining operations by using 6 three-component accelerometers and 24 single-component AE sensors installed in a volume measuring approximately 95 m (N–S) × 50 m (E–W) × 30 m (depth).[16] Three of the accelerometers have a flat frequency response up to 25 kHz (Wilcoxon Model 736) and the other three up to 10 kHz (Wilcoxon Model 728). The AE sensors (GMuG, Bad Nauheim, Germany) cover up to 50 kHz and are very sensitive. All of the detectors were grouted into their boreholes.

Seismic signals were transmitted to the data acquisition system through coaxial cables and recorded on a computer hard disk. Waveform data were recorded on all 42 channels whenever the amplitude of an AE event exceeded a threshold at any detector. Events were acquired as digitized waveforms of 65.5 ms duration (32 768 samples) at a sampling frequency of 500 kHz. Before recording, high-pass filters with cutoff frequencies of 50 Hz and 1 kHz were applied to the signals from the accelerometers and AE sensors, respectively.

We used travel-time detection software from Home Seismometer Corp. (Japan)[23] that automatically picks the P- and S-wave arrival times and determines the source locations. We visually inspected the travel-time readings, theoretical travel times, and observed waveforms for several hundred of these events and confirmed that obvious mistakes in readings led to erroneous hypocenter determinations in fewer than 1% of events.[16] The velocities of the P- and S-waves used in the analysis were 5700 and 3600 m/s, respectively, as estimated by transmission tests in which elastic waves from active ultrasonic sources were received by network sensors.[17]