Tunnelling and Underground Space Technology 60 (2016) 30–40

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Mechanical behaviour of scaled-down unsupported tunnel walls in hard rock under high stress

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ARTICLE INFO

Article history:
Received 20 October 2015
Accepted 19 July 2016
Available online xxxx

Keywords:
Underground tunnels
Rock strength
Rock failure
Rock spalling
Violent failure

ABSTRACT

A large number of scaled-down tunnel experiments were undertaken to investigate the response of unsupported walls to an increased stress field. The experiments were undertaken in 200 mm diameter tunnels that were drilled into intact rock blocks of sandstone and granite ranging in strength from moderately strong to very strong. The tunnels were loaded by a servo-controlled, 450 tonne capacity INSTRON compression testing machine. As the ratio of intact rock strength to induced stress decreased, the unsupported tunnel walls became increasingly unstable. Critical ratios of compressive strength to induced stress were determined for critical instability stages such as tunnel spalling and also pillar crushing adjacent to the tunnels. The physical models have been simulated using three-dimensional finite element modelling. The values of the critical ratios correlate well with underground observations of full scale tunnels with similar Uniaxial Compressive Strength materials. Dynamic ejection velocities similar to those calculated from back analysis of actual failures have been determined. In addition, the seismic responses prior and during key failure stages have been established as a function of the increased loadings.

1. Introduction

As underground mining proceeds to depths below surface approaching or exceeding 1000 m, the ratio of intact rock strength to induced stresses around conventional development excavations is such that failure of the rock mass adjacent to the excavations can occur very soon after construction. At the present time, such conditions have led to the abandonment of mining operations that have reached these depths, resulting in losses of hundreds of millions of dollars. In addition, over the next two decades or so, when the moderate depth resources are likely to be depleted, those conditions are likely to be faced routinely. Hence over the last three years the WA School of Mines (WASM) has undertaken a large number of laboratory experiments in order to understand the fundamentals of violent tunnel failure as a function of an increased induced stress.

The stability and behaviour of the rock masses surrounding an excavation are dependent upon several factors including the rock mass strength, the geometry of the excavation, the induced stresses surrounding the opening, the blasting or construction practices and the amount of water and weathering process (Hoek and Brown, 1980). In particular, the rock mass strength is a function of the intact rock properties and the geological discontinuities intersecting the rock mass near the boundaries of an excavation. Furthermore, as mining progresses to greater depths, the induced stresses increase relative to the rock mass strength, such that excavation instability becomes increasingly apparent. Violent failures where the seismic source is located within the immediate vicinity of the excavation are often experienced (Fig. 1).

Historically, the ratio of intact rock Uniaxial Compressive Strength (σ_c) to the induced compressive stress tangential to the wall of an excavation (σ_{max}) has been long recognized as a critical factor controlling excavation stability (Barton et al., 1974; Mathews et al., 1980). As the ratio of σ_c/σ_{max} reduces, excavation instability increases as shown in Fig. 2. Data from many years of numerical modelling and observations of open stoping at Mount Isa Mines (Villaescusa, 2014) have shown that as the ratio decreases below the value of 5, the instability increases markedly. Large deformations are experienced in tunnels driven within low strength rock while sudden, violent failure occurs in tunnels excavated in high strength rock (Barla, 2014; Bhasin and Grimstad, 1996).

2. Testing of unsupported scaled-down tunnels

In order to investigate stress-driven fracturing around underground excavations, a large number of scaled-down tunnels have

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http://dx.doi.org/10.1016/j.tust.2016.07.012
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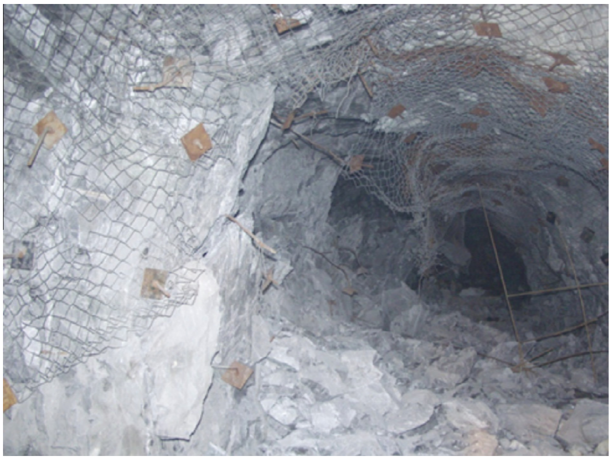

Fig. 1. Stress-driven failure near the boundary of an excavation.

been constructed and tested at the WASM Rock Mechanics Laboratory.

2.1. Tunnel models

The tunnels were constructed by drilling into 400 W × 400 H × 200 D mm blocks of intact rock ranging in strength from moderately strong to very strong (20–200 MPa). The material consisted of soft and hard sandstone and also granite. The sandstone materials consisted of fine and coarse sand particles densely packed to form slightly coloured layers. The granite material consisted of quartz, feldspar and biotite. In all cases, the intact rock blocks were inspected and arranged such that the subsequent loading was undertaken perpendicular to any bedding or obvious geological weaknesses.

The size of the scaled down tunnels was in most cases 200 mm in diameter, leaving 100 mm wide pillars both sides of the unsupported openings. However, in some experiments, 50 mm and 100 mm diameter tunnels were also constructed to compare the effects due to wider pillars adjacent to the simulated tunnels. Mechanical drilling of the miniature tunnels into the rock blocks minimised damage to the rock to ensure that any failure was predominantly stress-driven.

2.2. Test configuration

The blocks of rock were constrained horizontally by two mild steel plates (16 mm thick) which were held by 4 threaded bars. This allowed the post-peak strength and behaviour to be determined during the tests. Prior to testing, the bolts were tightened with a known torque to apply small initial horizontal stresses on the side of the rock block.

The blocks of rock were loaded vertically using a 450 tonne capacity stiff INSTRON compression testing machine. The rate of loading was 0.5 mm/min.

Fig. 3 shows a typical experimental set-up before and after testing. The depth of failure was largely controlled by the presence of geological discontinuities or potential planes of weakness.

2.3. Monitoring

Vertical load and vertical displacement were monitored during tests. Two acoustic emission sensors were installed to monitor the seismic response from initial loading to wall spalling and pillar crushing.

A high speed Canon EOS 650D video camera was used to monitor the tunnel walls during the progressive loading. This digital single-lens reflex camera, was set up in front of the sample and the tunnel behaviour was recorded through a special window within the INSTRON protective door. The camera is capable of capturing up to 50 frames per second. A set of special lights and a suitably placed background grid were used to estimate the displacement versus time motion of the failed particles that were ejected.

3. Computer simulations

In order to better understand the failure processes and to check the three-dimensional calculations, computational modelling was undertaken using the program Abaqus. A finite element mesh used for 3D modelling of the test geometry is shown in Fig. 4.

3.1. Model material properties

For each block tested the 200 mm diameter core that resulted from drilling the tunnels was subsequently re-drilled to determine the intact rock strength and elastic constants. Uniaxial Compressive Strength, σ_c and the Modulus of Elasticity E_i, were determined

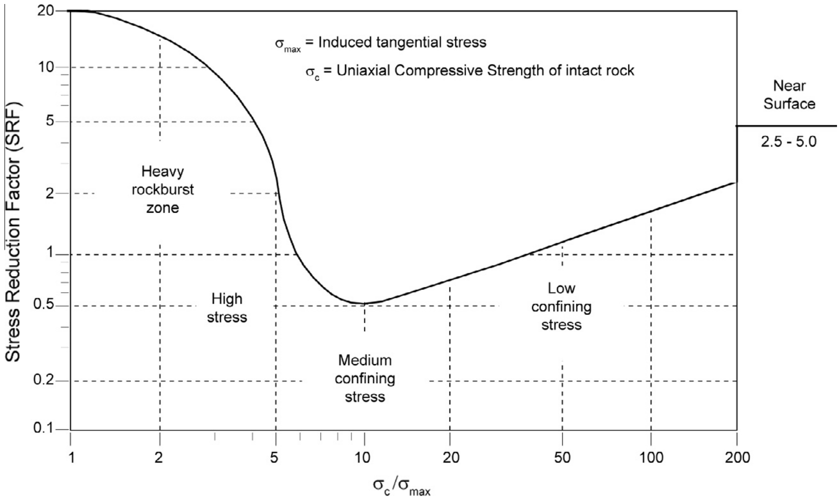

Fig. 2. Excavation behaviour as a function of the ratio of compressive strength to the induced stress (after Barton et al., 1974; Hutchinson and Diederichs, 1996).