Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 210–225

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Risk of shear failure and extensional failure around over-stressed excavations in brittle rock

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A R T I C L E I N F O

Article history:
Received 13 June 2016
Received in revised form
10 November 2016
Accepted 14 November 2016
Available online 30 November 2016

Keywords:
Fracture propagation
Tension
Shear
Poisson's ratio
Break-out
Rock burst
Deep tunnels
FRACOD model

A B S T R A C T

The authors investigate the failure modes surrounding over-stressed tunnels in rock. Three lines of investigation are employed: failure in over-stressed three-dimensional (3D) models of tunnels bored under 3D stress, failure modes in two-dimensional (2D) numerical simulations of 1000 m and 2000 m deep tunnels using FRACOD, both in intact rock and in rock masses with one or two joint sets, and finally, observations in TBM (tunnel boring machine) tunnels in hard and medium hard massive rocks. The reason for 'stress-induced' failure to initiate, when the assumed maximum tangential stress is approximately $(0.4-0.5)\sigma_c$ (UCS, uniaxial compressive strength) in massive rock, is now known to be due to exceedance of a critical extensional strain which is generated by a Poisson's ratio effect. However, because similar 'stress/strength' failure limits are found in mining, nuclear waste research excavations, and deep road tunnels in Norway, one is easily misled into thinking of compressive stress induced failure. Because of this, the empirical SRF (stress reduction factor in the Q-system) is set to accelerate as the estimated ratio $\sigma_{\theta\max}/\sigma_c >> 0.4$. In mining, similar 'stress/strength' ratios are used to suggest depth of break-out. The reality behind the fracture initiation stress/strength ratio of '0.4' is actually because of combinations of familiar tensile and compressive strength ratios (such as 10) with Poisson's ratio (say 0.25). We exceed the extensional strain limits and start to see acoustic emission (AE) when tangential stress $\sigma_\theta \approx 0.4\sigma_c$, due to simple arithmetic. The combination of 2D theoretical FRACOD models and actual tunnelling suggests frequent initiation of failure by 'stable' extensional strain fracturing, but propagation in 'unstable' and therefore dynamic shearing. In the case of very deep tunnels (and 3D physical simulations), compressive stresses may be too high for extensional strain fracturing, and shearing will dominate, both ahead of the face and following the face. When shallower, the concept of 'extensional strain initiation but propagation' in shear is suggested. The various failure modes are richly illustrated, and the inability of conventional continuum modelling is emphasized, unless cohesion weakening and friction mobilization at different strain levels are used to reach a pseudo state of yield, but still considering a continuum.

1. Introduction

We will start by illustrating two very different failure modes, both of them being 'physical realities' but from very different environments. The first is from petroleum well-bore simulations in sandstones. With change of scale, a small deep tunnel in a weak but brittle rock can be envisaged. Failure is dominated by (log-spiral) shearing (Fig. 1). The second is a real case involving highly-stressed granite in an underground research laboratory (URL): the URL in Canada. Crack initiation is induced by tensile/extensional fracturing, but there is shearing, buckling, and a final characteristic notch (see Fig. 2). In the following investigations, both tensile (or extensional strain) initiation and progression in shear have their important roles to play. Tensile initiation may consist of critical strain-initiated extensional fracturing, which can explain several puzzling phenomena such as tensile fracturing in entirely compressive stress fields (e.g. Fairhurst and Cook, 1966).

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2016.11.004

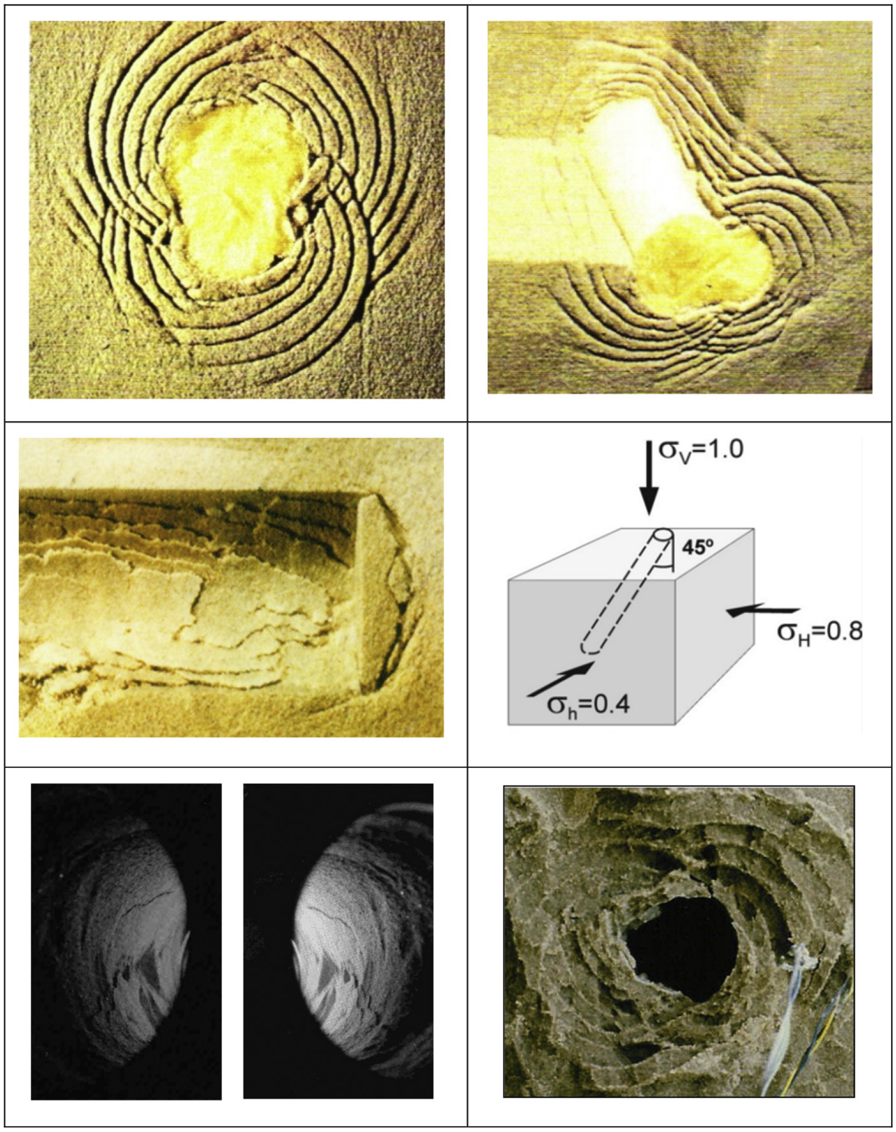

Fig. 1. Obvious log-spiral shearing in model tunnels/well-bores, which were drilled into highly-stressed blocks (measuring 0.5 m × 0.5 m × 0.5 m) of weak model sandstone. All three principal stresses could be varied independently through flat-jack loading, and drilling did not need to be parallel to any of the principal boundary stresses. (Flat-jacks could have central or off-centre holes). The upper four photographs show the results of stress anisotropy and hole deviation from the horizontal. The lower two photographs show tests in a smaller polyaxial cell in which hole drilling was parallel to the minimum horizontal stress. Miniature monitoring boreholes and pressure cells were installed before drilling under 3D stress. Coloured cemented sand in the pre-drilled boreholes (an idea from Dr. Stavros Bandis) confirmed that 'log-spiral' shearing does indeed involve discrete, repeated, log-spiral shear displacements, somewhat different from the 'zonal disintegration' phenomena described and modelled by Wu et al. (2008). Tensile/extensional modes were not evident in these physical model studies, which might be due to the level of confinement. From the first author's joint-industry petroleum-sponsored project at NGI, 1986–1988. See some of our published results in Addis et al. (1990).

2. Stress-strength ratio introduction

Forty years ago, when the Q-system of Barton et al. (1974) was developed, 'stress-induced' fracturing was assumed to initiate when the ratios of UCS/major principal stress (or σ_c/σ_1 in Table 1) became <5, or the inverse >0.2. The recommended value of SRF (stress reduction factor) was increased rapidly, so as to make tunnel support adequate, since high SRF values ensured heavier support in the case of newly fractured massive rock. As many more high-stress case records were collected between 1987 and 1993 by former NGI (Norwegian Geotechnical Institute) geologist and tunnelling colleague Eystein Grimstad, mostly from deep Norwegian road tunnels, where 'stress-fracturing' and rock bursting had been experienced, we added the second column seen in the lower table in Table 1 (σ_θ/σ_c). An appendix in Barton and Grimstad (2014) records the details of these historic (pre-1990s) case records. A number of ratios of σ_θ/σ_c were in the range 0.4–0.8, with a maximum value of 1.2 at Strynefjell. The depth range was between 600 m and 1400 m.

As can be noted from the second tabulation in Table 1, from Grimstad and Barton (1993), an acceleration of SFR values is noted when the ratio σ_θ/σ_c increases above 0.4, with sharp acceleration when 0.5 is exceeded and 'moderate slabbing', 'rock burst' and 'strain burst' are recorded, needing rapidly increasing SRF. There are additional comments on 'strain bursting,' 'rock slabbing' and 'block yielding' for given depths and Q-value ranges in Barton and Grimstad (1994), using Singh et al. (1992) suggestions for relating the Q-value to an estimate of the strength of the rock mass. This