International Journal of Rock Mechanics & Mining Sciences 60 (2013) 301–311

Contents lists available at SciVerse ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

Rock mass response ahead of an advancing face in faulted shale

Salina Yong [a,*], Peter K. Kaiser [b], Simon Loew [a]

[a] Department of Earth Sciences, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland
[b] Centre for Excellence in Mining Innovation, 935 Ramsey Lake Road, Sudbury, Ontario, Canada P3E 2C6

ARTICLE INFO

Article history:
Received 15 March 2012
Received in revised form
22 November 2012
Accepted 2 January 2013
Available online 1 March 2013

Keywords:
Tunnelling
Nuclear waste disposal
EDZ
Opalinus clay

ABSTRACT

In this study, the rock mass response ahead of an advancing test tunnel in the Opalinus Clay at the Mont Terri Rock Laboratory (Switzerland) was investigated. Characterisation of the excavation-induced damage zone at Mont Terri is a challenging task due to the anisotropic and heterogeneous nature of the shale: pronounced bedding leads to intact rock anisotropy and prevalent small-scale tectonic shears lead to rock mass heterogeneity. Rock mass damage ahead of an experimental tunnel or niche was characterised through single-hole seismic wave velocity logging, borehole digital optical televiewer imaging, and geological drillcore mapping. Three-dimensional elastic stress analyses were completed and showed that rock mass degradation can be correlated to changes in the maximum to minimum principal stress ratio (i.e., spalling limit). Numerical results showed that close to the niche boundary, unloading lowers stress ratios, which correspond with decreasing seismic wave amplitudes and velocities; thus, indicating that strength degradation resulted from increasing crack-induced damage. Considerations of tectonic shears and distance from a previously stressed volume of rock were necessary in understanding both the damage state and extent ahead of the face. By integrating field and numerical data, the investigation showed that geological structures (i.e., bedding and bedding-parallel tectonic shears) were most influential near the entrance but played a lesser role as the niche deepened. Additionally, a portion of the niche is located in the perturbed zone of the intersecting Gallery04.

1. Introduction

Tunnel construction damages the surrounding rock mass, which can lead to the alteration of rock mass transport properties and/or tunnel instability. Safety assessment of geological nuclear waste repositories necessitates understanding the processes that lead to rock mass perturbations induced by tunnel excavation. While many previous studies have investigated perturbations around tunnels in shale, few have considered the development of perturbations ahead of an advancing tunnel. However, degradation of the rock mass ahead of the advancing face may influence development of the perturbed zone around the tunnel away from the face: e.g., possibly leading to asymmetric tunnel breakouts [1].

Abel and Lee [2] demonstrated that changes in the stress state can be detected several tunnel diameters ahead of the face in both laboratory and field studies. The laboratory studies involved tunnelling in models built from acrylic (ideally elastic), concrete (heterogeneous elastic), and granite (approximately elastic brittle). The onset of stress changes were detected two to four diameters ahead of tunnels drilled into the laboratory models. Compressive stress peaks, one to two diameters ahead of the tunnel, were also measured in these models. In the field study, two probes were installed about 15 m ahead of a proposed crosscut in jointed and closely foliated gneiss and gneissic granite. Changes in stress associated with the advancing tunnel were measured more than seven tunnel diameters ahead of the face with a compressive stress peak about six tunnel diameters away from the advancing face. This was followed by a much larger decrease in compressive stress. Stress-change trajectories were also determined from the field measurements and demonstrated that local structural variations in the foliated and faulted metamorphic rocks controlled the rock mass response. The crosscut was driven orthogonal to the strike of the major geological weakness in the rock mass, or the foliation in this case. Because the foliation and associated jointing provided a ready avenue for tensile strain relief, the rock mass was postulated to have expanded preferentially perpendicular to the foliation and towards the advancing face. In this case, strain relief was provided parallel with the crosscut axis and normal to the strike of foliation. Overall, the tunnel advance resulted in decompression of the rock mass ahead of the face and to the side of the tunnel.

Read et al. [1] and Martin [3] investigated the development of v-shaped notches around a test tunnel that was excavated in the Lac du Bonnet granite, and concluded that notch development

* Corresponding author. Present address: MIRARCO, 935 Ramsey Lake Road, Sudbury, Ontario, Canada P3E 2C6. Tel.: +1 7056751151x5097; fax: +1 7056754838.
E-mail address: syong@mirarco.org (S. Yong).

1365-1609/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijrmms.2013.01.002

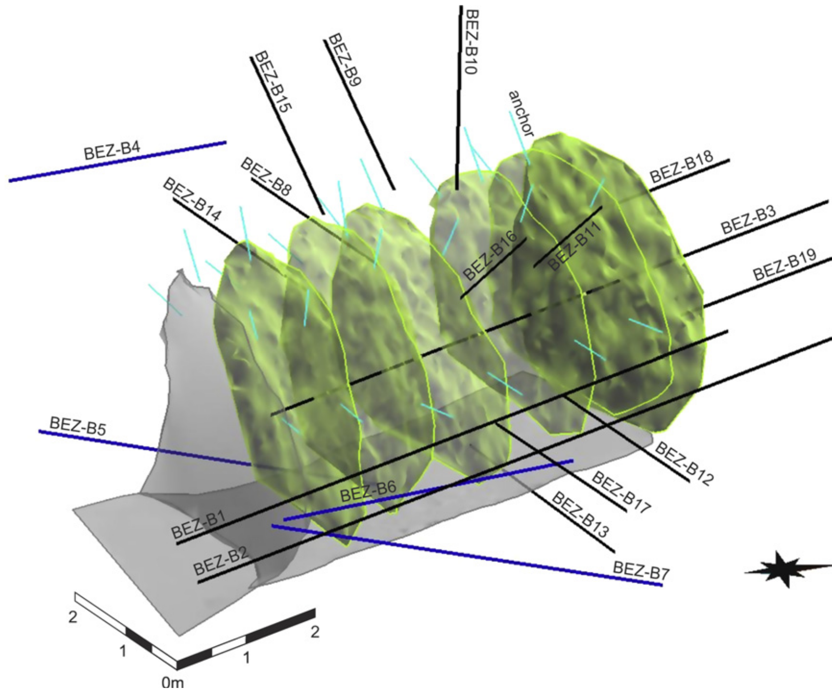

Fig. 1. Isometric view of the various EZ-B niche faces, boreholes, and roof anchors.

depended on changes in the stress state ahead of the face. The Mine-by Experiment tunnel was aligned roughly with the intermediate principal stress (σ_2) axis while the minimum principal stress (σ_3) axis was sub-vertical. The maximum principal stress (σ_1) was nearly orthogonal to the tunnel axis. V-shaped notches formed in the roof and floor of the tunnel about 0.6 m behind the face. The notches were not diametrically opposed due to non-symmetric stress concentrations caused by a 10° offset of the tunnel axis with the intermediate principal stress direction [1]. Stress path analyses indicated that well ahead of the advancing face in regions where the notches formed, the crack initiation threshold [4] was exceeded and thus, damage was in the form of micro-fracturing. Additionally, principal stress rotations, when stress levels exceeded crack initiation, also initiated ahead of the face with the maximum rotation in σ_3 occurring in the roof. Consequently, rock mass degradation near the tunnel perimeter may be further exacerbated. Through a numerical study, Eberhardt [5] found magnitude and directional changes in the redistributed stress field near the face differed depending on the tunnel alignment with the far-field principal stress axes. It was postulated that magnitude and directional changes in the redistributed stress field would lead to progressive accumulation of damage.

Investigations relating to nuclear waste storage in argillaceous media have also shown rock mass perturbations initiating ahead of the face. Induced fracturing has been mapped in tunnel faces at the Meuse/Haute-Marne Underground Research Laboratory in France [6] and at the HADES Underground Research Facility in Belgium [7]. In both cases, fracturing formed an open "v" with a horizontal axis of symmetry near the tunnel springline. Fracturing was also found to be more pronounced when the tunnel axis was aligned parallel with the maximum horizontal stress at Meuse/Haute-Marne.

The Opalinus Clay in Switzerland is under consideration as a potential host rock for the storage of nuclear waste [8]. At the Mont Terri Rock Laboratory, the typical zone of perturbation around the tunnel cross-section consists of sub-vertical extension fracturing in the sidewalls and bedding-parallel fracturing above the crown and below the invert [8]. The rock mass response several metres ahead of the face has been examined in the EDB section of Gallery98 [9], HG-A niche in Gallery04 [10], and the MB section of Gallery08 (unpublished reports are currently under review, CD Martin, pers. comm.). This paper examines the rock mass response immediately ahead of an advancing face before and during the excavation of a short test tunnel, the EZ-B niche (Fig. 1), at the Mont Terri research facility.

2. The Mont Terri Rock Laboratory

The EZ-B niche is located in Gallery04 (Fig. 2) at the Mont Terri Rock Laboratory in northern Switzerland. Mont Terri is the northernmost in a series of anticlines in the Jura Mountains and the research facility is located in the southern limb, which is weakly deformed and less tectonically disturbed [11]. The anticline was formed by fault-bend and fault-propagation folding [12]. At the laboratory scale, tectonic features consist of networks of thin (i.e., in the order of millimetres) shear zones and a larger thrust fault zone [11,12].

Three sets of tectonic shears have been mapped in Gallery04 [12] but only two intersect the EZ-B niche [13]. The most frequently occurring is sub-parallel with bedding and dips south-southeast. On average, the bedding-parallel shears in the niche dip 46° towards an azimuth of 146° [13], resulting in a strike that is roughly perpendicular to the niche axis (Fig. 2). The bedding-parallel shears are closed and sealed with calcite and clay minerals. The second set are minor sub-horizontal shears that dip south to southwest and are found in isolated regions in the niche [13]. The sub-horizontal shears dip from 0° to 20° towards azimuths of 132° to186° [13]. In the niche, sub-horizontal shears are bound by the bedding-parallel shears. Surfaces of both sets are slickensided and indicate thrusting towards the northwest [12].

The in situ stress field (Fig. 2) consists of sub-vertical maximum (σ_1) inclined towards the south–southwest and sub-horizontal minimum (σ_3) inclined towards the northeast