International Journal of Rock Mechanics & Mining Sciences 47 (2010) 894–907

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

Influence of tectonic shears on tunnel-induced fracturing

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

[a] Department of Earth Sciences, ETH Zurich, Wolfgang-Pauli-Strasse 15, 8093 Zurich, Switzerland
[b] Centre for Excellence in Mining Innovation, 935 Ramsey Lake Road, Sudbury, Ontario, Canada P3E 2C6

ARTICLE INFO

Article history:
Received 18 July 2009
Received in revised form
7 May 2010
Accepted 30 May 2010
Available online 15 June 2010

Keywords:
Tectonic structure
Induced fracture
EDZ
Tunnelling
Failure mechanism
Opalinus Clay

ABSTRACT

The Opalinus Clay is currently under investigation as a potential host rock for deep geological disposal of nuclear waste at the Mont Terri Rock Laboratory in Switzerland. Bedding in the Opalinus Clay at Mont Terri is ubiquitous and highly persistent leading to mechanical transverse isotropy. Adding to the complexity at the Rock Laboratory is the frequent occurrence of small-scale tectonic shears.

This paper explores the influences of millimetre-thick tectonic shears and bedding on the development of induced fractures mapped in the EZ-B field experiment at the research facility. A series of numerical analyses were carried out by increasing the geological complexity of the host rock and comparing the redistributed stress field with geological maps of the induced fractures. The analyses show that if tectonic shears are not kinematically constrained, mobilisation of the shears can play a key role in the development of the induced fracture network and therefore, be a primary factor in the development of the excavation damaged zone. This illustrates that under certain conditions rock mass heterogeneity (in this case, resulting from the tectonic shears) may dominate over rock matrix anisotropy (in this case, resulting from bedding) and must be considered when predicting the induced fracture network of the excavation damaged zone.

1. Introduction

At the Mont Terri Rock Laboratory in Switzerland (Fig. 1), research is currently underway to investigate the potential use of the Opalinus Clay as a host rock for deep geological disposal of high-level nuclear waste. The performance of a geological repository may be affected by the excavation damaged and/or disturbed zone (EDZ/EdZ) [1] that is inevitably created when an underground opening is constructed. Hydromechanical and geochemical modifications occur in the EDZ and result in significant changes to flow and transport properties whereas no major changes in flow and transport properties occur in the EdZ [1]. In many geological materials, fractures are the conduits through which preferential groundwater flow and contaminant transport occur. Consequently, understanding the conditions and mechanisms under which fracturing is induced by excavation are important to performance assessment.

The mechanical response of a rock mass to the construction of an underground opening depends on the orientation(s) of existing geological structures and the path of the ensuing stress redistribution. Structurally controlled failure is gravity driven and depends on the intersection of the opening with existing geological discontinuities. Stress-driven failure depends mainly on the rock mass strength and on the magnitudes and orientations of the in-situ stress field relative to the opening axis. In both cases, confinement (i.e., σ_3) plays an important role in dictating the mode of failure and the orientation of macroscopic fracturing.

Indurated argillaceous materials, such as the Opalinus Clay (with an in-situ water content of 6%, liquid limit of 38%, and plasticity index of 15% [2,3]), exhibit both rock-like (brittle) and soil-like (ductile) behaviour; thus, complex mechanisms are involved in the development and evolution of the EDZ/EdZ in such materials. Additionally, inherent to most shale is the added complexity of depositional and tectonic structures. As a result, understanding induced fracturing in indurated argillaceous media requires considerations of both stress redistribution and the influence of significant geological structures. Examples of this can be found at the Tournemire Underground Research Laboratory [4] and the Mont Terri Rock Laboratory [5].

Bedding in the Opalinus Clay at Mont Terri is the most prominent geological feature consisting of persistent ubiquitous planes spaced in the millimetre range. This is consequently reflected in the transverse-isotropic nature of the mechanical properties; Young's modulus ranges from 4 GPa perpendicular to bedding to 10 GPa parallel with bedding [2,3]. An additional complexity at the Rock Laboratory is the consistent occurrence of three sets of tectonic shears [6]. In this paper, "shear" is used in place of the facility-established term, "fault," as the former better describes the fabric and thickness of the structures mapped at the location of this study. Much of the analyses at the research facility

* Correspondence to: Exponent Failure Analysis Associates, Inc., 149 Commonwealth Drive, Menlo Park, CA 94025, USA. Tel.: +1 650 353 6319; fax: +1 650 328 3094.
E-mail address: syong@exponent.com (S. Yong).

1365-1609/$ - see front matter
doi:10.1016/j.ijrmms.2010.05.009

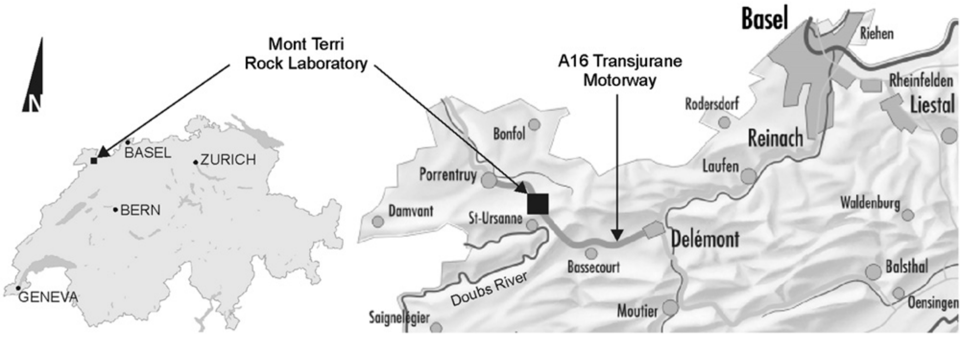

Fig. 1. Location of the Mont Terri Rock Laboratory in northern Switzerland (modified from www.swisstopo.ch).

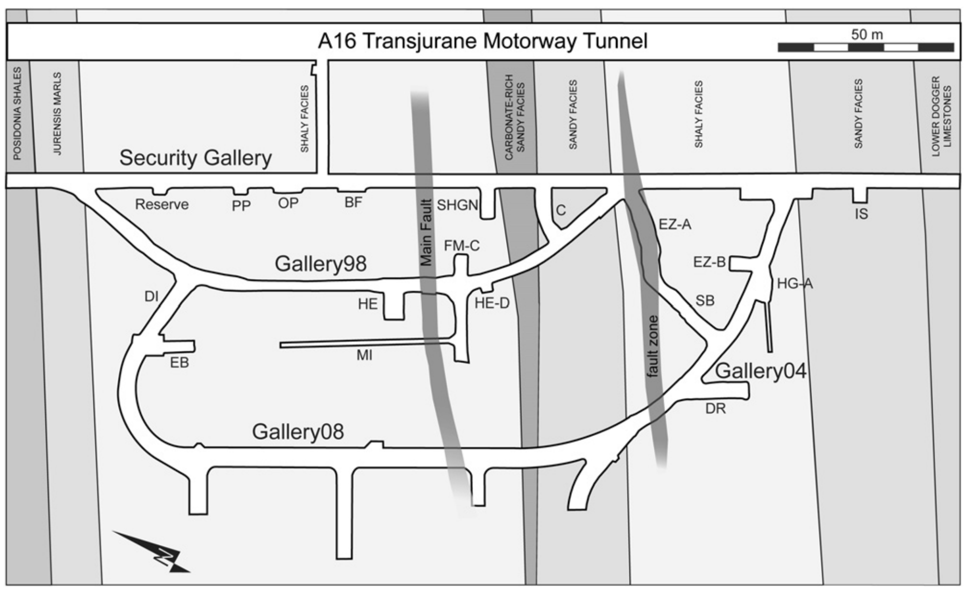

Fig. 2. Plan of the Rock Laboratory (modified from www.mont-terri.ch).

have focused on the bedding anisotropy owing to its prominent nature in affecting both the mechanical properties and the development of the EDZ/EdZ [5,7]. Consequently, little is known regarding the impact of the tectonic shears on the EDZ/EdZ. Observations made during expansions of the laboratory in 2004 and 2008 indicate that the shears play a predominant role in the development of excavation-induced fractures. A new 80-m-long gallery (Gallery04) was excavated in 2004 with four adjoining niches that facilitated mapping of damage caused by the gallery construction. This paper examines the influence of these tectonic shears on the fracturing induced by the excavation of Gallery04 at the location of the EZ-B Niche entrance. The observations made during the excavation of the EZ-B Niche itself are described in Yong [8] and companion papers.

2. Site description

Located northwest of Saint-Ursanne (Fig. 1), the Mont Terri Rock Laboratory (Fig. 2) consists of three galleries and a series of niches excavated adjacent to the A16 Transjurane Motorway tunnel. The Rock Laboratory was initiated in 1996 as an international research facility (and is not under consideration as a repository site) with the excavation of eight niches in the southwest wall of the Security Gallery. In 1998, Gallery98, with a nominal length of 175 m, was excavated southwest of the Security Gallery. In 2004, the laboratory was expanded southeast of Gallery98 with the excavation of the 80-m-long Gallery04. Gallery04 trends at a nominal azimuth of 262° for the first 30 m then curves northwestwards to a final azimuth of about 300°. In 2008, Gallery04 was extended northwestwards to create Gallery08. The site of interest in this paper is Gallery04 in the vicinity of the EZ-B Niche or between tunnel metres (TM) 20 and 25 (Fig. 3).

2.1. Geological setting

The Mont Terri Rock Laboratory is situated in the Opalinus Clay formation in the southern limb of the northeast/southwest trending Mont Terri Anticline, which is weakly deformed and less tectonically disturbed [9]. The Opalinus Clay is shale that was deposited in a basinal marine environment during the Middle Jurassic. The present overburden at the laboratory site is between 250 and 320 m [10].

Mont Terri is the northernmost in a series of anticlines that constitute the Folded Jura in the Jura Mountains. The Jura Mountains formed during late Miocene-to-early Pliocene in response to late alpine folding and thrusting, which resulted in the Folded Jura being thrusted more than 1 km northwestwards over the Tabular Jura [11]. The Mont Terri anticline (Fig. 4) was formed by fault bend folding and fault propagation folding that have resulted in a number of thrust faults [12,6].