International Journal of Rock Mechanics & Mining Sciences 65 (2014) 96–115

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

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

Continuum–discontinuum analysis of failure mechanisms around unsupported circular excavations in anisotropic clay shales

A. Lisjak [a], G. Grasselli [a,*], T. Vietor [b]

[a] *Department of Civil Engineering, University of Toronto, 35 St. George Street, Toronto (ON), Canada M5S 1A4*
[b] *National Cooperative for the Disposal of Radioactive Waste (NAGRA), Hardstrasse 73, 5430 Wettingen, Switzerland*

ARTICLE INFO

Article history:
Received 20 February 2013
Received in revised form
19 July 2013
Accepted 18 October 2013
Available online 11 November 2013

Keywords:
Clay shales
Excavation Damaged Zone
Mechanical anisotropy
Numerical modelling
FEM/DEM
Brittle failure

ABSTRACT

The stability of circular excavations in clay shales is a key issue in the drilling and tunnelling industries as well as in the field of deep geological waste storage. A large body of experimental evidence indicates that the damaged zone around these cavities is influenced by strong mechanical anisotropy induced by the layered material structure. The vast majority of numerical models adopted to date to analyse the stability of openings in layered rocks have been based on continuum mechanics principles using classic shear failure theory for elasto-plastic materials. However, a number of experimental observations demonstrate that clay shales may fail in a brittle manner under low-confinement conditions such as those characterizing the near-field of the excavation. Therefore, an alternative numerical approach based on non-linear fracture mechanics principles and the discrete element method is adopted to gain new insight into the failure process of this class of geomaterials. In order to account for the influence of clay shale microstructure on its mechanical behaviour a newly developed approach to capture the anisotropy of strength is proposed. With this numerical approach, the cohesive strength parameters of the fracture model are assumed to be a function of the relative orientation between the element bonds and the layering orientation. The effectiveness of the numerical technique is quantitatively demonstrated by simulating standard rock mechanics tests on an indurated claystone, namely Opalinus Clay. Emergent strength and deformation properties, together with the simulated fracture mechanisms, are shown to be in good agreement with experimental observations. The modelling technique is then applied to the simulation of the Excavation Damaged Zone (EDZ) around a circular tunnel in horizontally bedded Opalinus Clay. The simulated fracturing process is mainly discussed in the context of the damage mechanisms observed at the Mont Terri URL. Furthermore, the influence of *in situ* stress on resulting EDZ geometry is analysed together with possible implications for ground support and tunnel constructability. Modelling results highlight the importance of shear strength mobilization along bedding planes in controlling the EDZ formation process. In particular, slippage of bedding planes is shown to cause rock mass deconfinement which in turn promotes brittle failure processes in the form of spalling. The numerical technique is currently limited to two-dimensional analyses without any thermo-hydro-mechanical coupling.

1. Introduction

The stability of underground openings in clay shales is an issue of particular interest for a number of geo-engineering applications, including the geological disposal of nuclear waste, the drilling industry, and the construction of tunnels at depth. Shale formations are currently being assessed as host rocks for the underground storage of solid radioactive waste as they present favourable long-term isolation properties [1]. These properties include: low permeability, good radionuclide retention properties, geological stability over long time periods, and self-sealing capacity. However, one main concern is that these isolation properties may be negatively affected by the rock mass damage associated with the excavations comprising the underground repository, namely the Excavation Damaged Zone (EDZ). In the oil and gas industry, the stability of boreholes is a long-standing problem which results in substantial yearly expenditure [2]. In the presence of instabilities, drilling and production are impacted by several additional costs in the form of time and equipment losses, washouts, problematic logging, and sidetracking [3]. Depending on the depth and well trajectory, these problems are generally further aggravated when drilling through shales due to their particular geomechanical properties. Finally, construction and ground support difficulties have been reported when excavating road or hydroelectric tunnels in shale formations [4].

The mechanical behaviour of shales is heavily influenced by strong deformation and strength anisotropy which arises at different spatial scales within the rock. At the mineral scale, textural anisotropy is due to the laminated material microstructure, which consists of

---

* Corresponding author. Tel.: +1 416 978 0125.
E-mail address: giovanni.grasselli@utoronto.ca (G. Grasselli).

1365-1609/$ - see front matter
http://dx.doi.org/10.1016/j.ijrmms.2013.10.006

preferably oriented platy clay minerals resulting from the rock formation process [5]. At a slightly larger scale, the presence of schistosity, foliation or bedding planes marking the limits of strata further contribute to induce directionality in the rock mechanical response. At the rock mass level, anisotropy can be related to the presence of physical discontinuities such as joints, fractures and tectonic structures.

The mechanical anisotropy of shale specimens has been widely documented by several laboratory studies [6–8], which typically report a distinctive variation of elastic response, strength characteristics and failure mechanisms with sample layering orientation. At a larger scale, this particular behaviour directly affects the stability of underground structures and the observed failure behaviour. Field observations from the Mont Terri URL situated in an indurated, overconsolidated clay shale, namely Opalinus Clay, indicate that the shape and extent of the EDZ around tunnels are dependent upon the relative orientation between bedding planes and the excavation axis [9]. The most unfavourable conditions are encountered when excavating in the direction parallel to the bedding plane strike due to the development of delamination mechanisms (e.g., shearing, bending and buckling of layers) in response to the excavation-induced stress redistribution [10,11] (Fig. 1). Similarly, several examples of premature borehole collapse have been reported in extended reach and horizontal wells in shale formations with pronounced bedding [3,13,14]. Due to the low strength properties of the bedding planes, enhanced instabilities have been observed with failure patterns far more extensive than those predictable under isotropic material conditions [15].

Furthermore, several experimental observations clearly indicate that shales may fail in a brittle manner under low-confinement conditions such as those characterizing the near-field of underground openings. For example, a recent laboratory study indicated that the mechanical behaviour of Opalinus Clay under unconfined compression exhibits several features of the failure process of brittle rocks such as staged stress–strain response, strong strain localization and acoustic activity [16]. These laboratory findings are corroborated by numerous field observations relative to macroscopic extensional fractures (i.e., spalling) in the EDZ of tunnels in argillaceous rocks [9,10,17,18]. Therefore, an alternative numerical approach based on non-linear fracture mechanics principles, namely the combined finite–discrete element method (FEM/DEM) [19,20], was adopted in this study to gain new insight into the failure process around excavations in shales. The technique is, at present, limited to purely mechanical two-dimensional analyses.

The paper is organized as follows. A brief overview of the main modelling techniques for anisotropic rocks is initially provided (Section 2). The fundamental principles of FEM/DEM are then illustrated with special emphasis on the assumptions inherent to the material failure modelling approach (Section 3). In Section 4, the simulation of mechanical anisotropy is discussed within the context of FEM/DEM; a newly developed technique to capture strength anisotropy is illustrated in detail. The effectiveness of the numerical approach is then demonstrated by quantitatively reproducing the short-term response of Opalinus Clay observed during standard rock mechanics tests (Section 5). The mesh sensitivity of the FEM/DEM model is discussed in Section 6. Finally, the failure process of a circular excavation in Opalinus Clay is simulated and qualitatively analysed in the context of the EDZ formation mechanisms observed at the Mont Terri URL and other sites (Section 7). A quantitative comparison of the simulated EDZs and associated deformation fields with actual *in situ* observations is, however, outside the scope of this work.

2. Overview of modelling techniques for layered rocks

The numerical approaches for modelling the mechanical behaviour of layered rocks can be classified according to the type of material representation, as (i) equivalent continuum methods and (ii) discrete element methods (DEM).

With the continuum method, the presence of layers is smeared to produce a fictitious continuous material that exhibits mechanical characteristics that are similar to the original discontinuous medium. While the layering-induced directionality of deformation properties is commonly captured using the theory of elasticity for transversely isotropic materials [21], the treatment of strength anisotropy is sensibly more complex. To evaluate the slip zones around excavations in layered rock masses, a technique often adopted in practice involves calculating a strength factor using an elastic stress–strain analysis together with a ubiquitous distribution of joints characterized by reduced frictional properties [22,23]. Although this simplified approach can give a good indication of failure development, slippage along bedding planes leads in reality to a stress redistribution which is not accounted for by the elastic model [24]. This limitation can be overcome by introducing a failure criterion for anisotropic rocks within elasto-plastic models. Among these failure criteria, the most common is arguably the discontinuous plane of weakness model [25–28], which assumes that shearing along bedding planes and failure of the intact rock matrix are independently characterized. To fully capture the main features of the progressive breakdown of anisotropic rocks, including mechanical degradation, dilatancy, stiffness non-linearity and post-peak softening or hardening, more advanced models have been developed by directly assuming a continuous variation of strength within the continuum mathematical formulation of plasticity for anisotropic solids [29–32]. Finally, to overcome some of the limitations of standard continuum formulations when simulating strain localization of brittle materials (e.g., mesh-dependency, ill-posed problems), enriched continuum formulations with microstructural effects [33–35] or statistical damage models [36] have been proposed.

With the DEM approach, layers or joints are explicitly represented in the numerical model. The medium is modelled as an assembly of rigid or deformable blocks or particles with interaction laws governing the emergent behaviour of the rock. Numerical

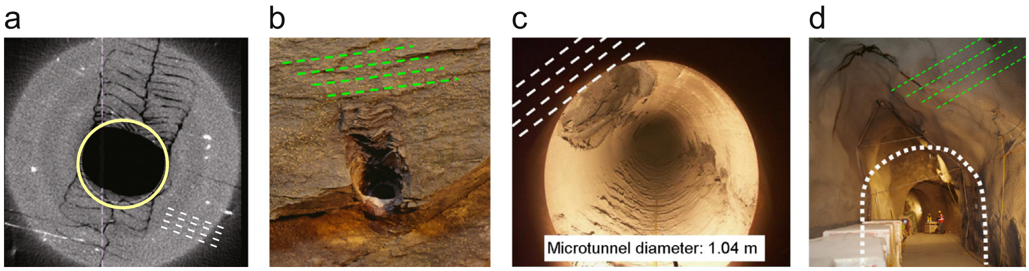

Fig. 1. Examples of damaged zones around openings in Opalinus Clay (Mont Terri) having excavation axis parallel to the strike of layering. The trace of bedding planes is indicated by a dashed line. (a) Hollow-cylinder experiment (source: Labiouse and Vietor [12]), (b) small borehole (source: Blümling et al. [10]), (c) micro-tunnel (source: Marschall et al. [11]), (d) horseshoe-shaped access drift (source: Blümling et al. [10]).