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Predicting excavation damage zone depths in brittle rocks

Matthew A. Perras [a,b,*], Mark S. Diederichs [a]

[a] *Queen's University, Miller Hall, 36 Union Street, Kingston, Ontario, K7L 3N6, Canada*
[b] *Swiss Federal Institute of Technology, Sonneggstrasse 5, Zurich, CH-8092, Switzerland*

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ABSTRACT

During the construction of an underground excavation, damage occurs in the surrounding rock mass due in large part to stress changes. While the predicted damage extent impacts profile selection and support design, the depth of damage is a critical aspect for the design of permeability sensitive excavations, such as a deep geological repository (DGR) for nuclear waste. Review of literature regarding the depth of excavation damage zones (EDZs) indicates three zones are common and typically related to stress induced damage. Based on past developments related to brittle damage prediction using continuum modelling, the depth of the EDZs has been examined numerically. One method to capture stress induced damage in conventional engineering software is the damage initiation and spalling limit (DISL) approach. The variability of depths predicted using the DISL approach has been evaluated and guidelines are suggested for determining the depth of the EDZs around circular excavations in brittle rock masses. Of the inputs evaluated, it was found that the tensile strength produces the greatest variation in the depth of the EDZs. The results were evaluated statistically to determine the best fit relation between the model inputs and the depth of the EDZs. The best correlation and least variation were found for the outer EDZ and the highly damaged zone (HDZ) showed the greatest variation. Predictive equations for different EDZs have been suggested and the maximum numerical EDZ depths, represented by the 68% prediction interval, agreed well with the empirical evidence. This suggests that the numerical limits can be used for preliminary depth prediction of the EDZs in brittle rock for circular excavations.

1. Introduction

The depth of excavation induced damage is required for the design process of deep geological repositories (DGRs) for nuclear waste or other underground containment facilities. It is well known that the damage caused by the excavation process increases the permeability from the undamaged rock mass and represents a potential contaminate transport or leakage pathway. To date predicting the depth of excavation related damage induced by high stress concentrations in brittle rock masses has relied on empirical methods (for example, Martin et al., 1999; Diederichs, 2007) or case specific numerical modelling (for example, Hou, 2003; Hudson et al., 2009; Rutqvist et al., 2009; Lisjak et al., 2015a,b).

Numerical back analysis of brittle rock damage and spalling notch development has been shown to be best captured using methods which employ a cohesion weakening frictional strengthening or similar approach (for example, Martin, 1997; Hajiabdolmajid, 2001; Hajiabdolmajid et al., 2002; Diederichs, 2001, 2003, 2007; Diederichs et al., 2004; Perras and Diederichs, 2014; Walton et al., 2014). This paper examines the suitability and sensitivity of the damage initiation and spalling limit (DISL) approach of Diederichs (2007) for the prediction of excavation damage zone (EDZ) depths around circular excavations in brittle rocks.

2. Excavation damage zones

The concept of excavation induced damage and EDZs has been studied since the early 1980s in relation to nuclear waste disposal (Kelsall et al., 1984). Determining the depth of damage is important and is required for design of excavation geometry and cut-off structures to reduce flow along the damage zone, parallel to the excavation axes, which can act as a transport pathway for contaminants or leakage of the stored commodity for permeability sensitive underground excavations. This is particularly important for DGRs for nuclear waste storage which are concerned about radionuclide transport along the EDZ escaping from the geological barrier used for isolation.

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[*] Corresponding author. Tel.: +1 41 44 633 3865.
E-mail address: mperras@ethz.ch (M.A. Perras).

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2.1. Excavation damage zone terminology

The terminology related to damage zones has changed from the early investigations because of the improved understanding of how the damage is induced and how it changes the permeability around the excavations. Various acronyms are used in the literature to describe the damage zones. Siren et al. (2015) provided a brief and up-to-date description of these zones. Tsang et al. (2005) provided a more thorough description and their terminology is used herein with one exception discussed below.

The damage zones are traditionally referred to collectively as the EDZs and various zones therein are depicted in Fig. 1. The density of excavation induced fractures decreases moving away from the excavation surface. Harrison and Hudson (2000) divided the excavation response into two: initial inevitable excavation consequences and additional effects induced by the construction method. The latter form of damage, also known as the construction damage zone (CDZ), can be reduced or nearly eliminated by adjusting or changing the excavation method (Martino et al., 2007; Jonsson et al., 2009). In contrast, the inevitable damage can be purely the result of geometry, structure, and/or induced stress changes (independent of excavation method). This type of damage, which is typically observed as interconnected macro-fractures, is referred to as the highly damaged zone (HDZ). Moving outwards, the inner EDZ (EDZ_{i}), with connected damage, makes a gradual transition to the outer EDZ (EDZ_{o}), with only partially connected to isolated damage (Bossart et al., 2002). The EDZ_{i} and EDZ_{o} contain irreversible micro-damaged rock with (inner) and without (outer) significant dilation. Beyond the EDZs is a stress and/or strain influence zone that involves only elastic change, the excavation influence zone (EIZ) (Siren et al., 2015). This has been called the excavation disturbed zone (EdZ) (for example, Tsang et al., 2005; Martino and Chandler, 2004); however, the authors of this work feel that the lowercase “d” is too easily confused with the uppercase “D”. In addition the term “disturbed” is used in geotechnical engineering to describe a material with a substantial reduction in competency and is not appropriate to describe this zone of elastic change. The outer limit of the EIZ is typically of minimal interest for a single excavation, as it occurs at a large distance from the excavation surface. The interaction of EIZ (and EDZ) with adjacent excavations is important and should be considered. In nature, the transition between these zones is gradational and distinguishing between them from in-situ measurements can be difficult.

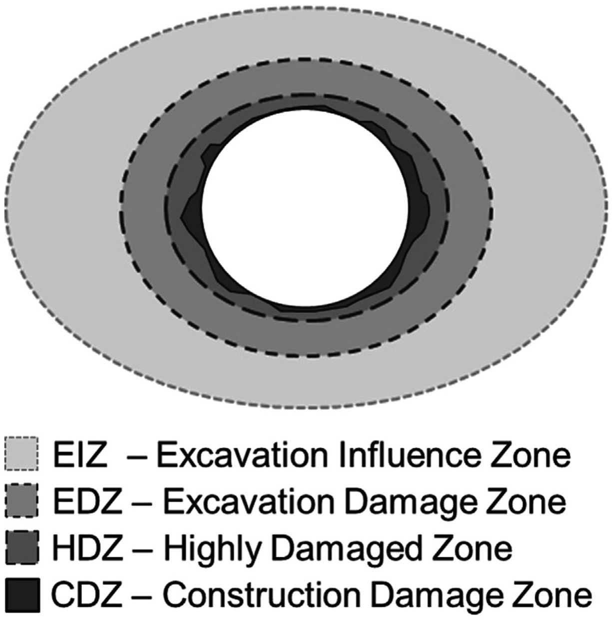

Fig. 1. The excavation damage zones (HDZ, EDZ, EIZ) and the construction damage zone (CDZ). Note that the EIZ was referred to as the excavation disturbed zone (EdZ) by Tsang et al. (2005) and was re-named due to potential confusion with the lowercase “d” and the uppercase “D” of the EdZ and EDZ, respectively.

2.2. Excavation damage zone studies

Many studies have been conducted on EDZs with focuses on: formation and long-term processes (e.g. Blümling et al., 2007), depth of damage (e.g. Bäckblom, 2008), and changes in permeability (e.g. Jakubick and Franz, 1993; Ababou et al., 2011). These studies have focused on crystalline (e.g. a review by Bäckblom (2008)), argillaceous (e.g. a review by Lanyon (2011)) and salt rocks (Hou, 2003). These are the most commonly considered rock types for nuclear waste storage (Tsang et al., 2005).

Relevant in-situ observations and measurements of the EDZ depth have been gathered and are presented in Fig. 2. In Fig. 2, the depth of damage has been normalised to the tunnel radius for circular excavations only and plotted against the maximum tangential stress normalised by the unconfined compressive strength (UCS), similar to the work by Martin et al. (1999). The empirical depth of failure line of Martin et al. (1999), which was later adapted to a normalisation by crack initiation (CI) and included additional case studies by Diederichs (2007), has been shown to successfully predict the depth of brittle spalling around tunnels (Carter et al., 2008; Martin and Christiansson, 2009; Perras et al., 2015). Diederichs (2007) discussed the theoretical basis for which failure in hard rocks, such as granite (Martin, 1993), quartzite (Ortlepp and Gay, 1984), andesite (Kaiser et al., 1995), and dense sandstone (Pestman and Van Munster, 1996) initiates at approximately (0.3–0.5)*UCS*.

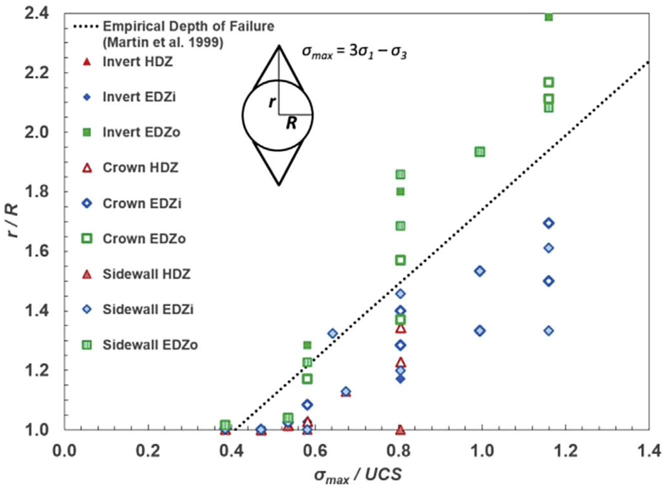

Fig. 2. In-situ measurements of the EDZ depths from the literature compared with the empirical depth of spalling failure by Martin et al. (1999), where EDZ_{o} represents the detectable extent of rock mass properties, EDZ_{i} represents visible damage (connected micro-fractures), and HDZ represents failed material. The data sources are associated with various underground research laboratory (URL) sites as follows: general reviews of EDZ for various sites (Bäckblom, 2008; Lanyon, 2011), AECL’s URL, Canada (Ohta and Chandler, 1997; Chandler et al., 1998; Martin et al., 1999; Everitt, 2001; Martino and Chandler, 2004; Read, 2004; Martino et al., 2007), Stripa Mine, Sweden (Pusch et al., 1987; Börgesson et al., 1992), Äspö URL, Sweden (Bäckblom and Martin, 1999; Olsson et al., 2004), Grimsel Test Site, Switzerland (Keusen et al., 1989; Frieg and Blaser, 1998; Sabet et al., 2003), Mont Terri URL, Switzerland (Bossart et al., 2002; Amann et al., 2011), Yucca Mountain, USA (Sobolik and Bartel, 2010), Olkiluoto, Finland (Autio and Kirkkomaki, 1996; Autio et al., 1998).