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Author(s):
Perras, Matthew A.; Loew, Simon; Diederichs, Mark S.; Lam, Tom; Jensen, Mark

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Excavation damage zone cut-off dimension assessment using continuum mechanics

Matthew A Perras
Swiss Federal Institute of Technology, Zurich, Switzerland (ETHZ)

Simon Loew
Swiss Federal Institute of Technology, Zurich, Switzerland (ETHZ)

Mark S Diederichs
Queen's University, Kingston, Canada

Tom Lam
Nuclear Waste Management Organization, Toronto, Canada

Mark Jensen
Nuclear Waste Management Organization, Toronto, Canada

ABSTRACT: A critical component of a nuclear waste repository is the cut-off seal, which will mitigate flow and gas migration along the excavation surface and damage zone. This paper examines a thin to wide slot cut-off geometry under fixed stress (an upper bound) and sedimentary rock properties. Volumetric extensile strain was used as an indicator of the extent of excavation damage prior to and after the construction of the cut-off. Using the volumetric extensile strain to plastic yield zone area ratio the cut-off performance for thickness to depth ratios between 0.05 and 0.7 were examined. It was found that for a cut-off with a thickness to depth ratio of less than 0.13 a complete disconnect could be established across the cut-off slot, indicating that a slender slot is optimum under the conditions modelled. Further modelling with different stresses and properties will establish if these results are applicable for a wider range of possible repository settings.

1 INTRODUCTION

1.1 Excavation Damage Zones

A nuclear waste repository requires a system of barriers, natural and man-made, acting together to isolate the waste from the surrounding hydrosphere and biosphere. The conceptual components of a repository include access and ventilation shafts or ramps, horizontal adits, and placement drifts, caverns or boreholes. The access and ventilation shafts or ramps pass from surface, through the isolating rock mass, and end in the host rock. The horizontal adits are long tunnels for access and from which large-diameter boreholes are drilled or caverns can be excavated to provide the waste canister receptacles. The canister itself is an isolating component, designed to withstand high compressive stresses and to minimize the rate of corrosion of the canister. For the case of high level waste storage; the canister will typically be surrounded by a highly compact bentonite, which will act as the first barrier in the event the canister is breached. The interface between the bentonite and the rock mass, as well as the excavation damage zone (EDZ) represent a potential pathway for radionuclide migration if the canister is breached.

The excavation process damages the rock mass, producing zones of damage. This concept has been studied since the early 1980s in relation to nuclear waste disposal since it changes the rock mass permeability due to stress re-distribution and subsequent yielding and damage (Kelsall et al. 1984). Determining the depth of damage is important and is required to design cut-off structures to reduce flow along the EDZ. The terminology related to damage zones has changed because of the improved understanding of how the damage is induced around the excavations. The terminology used herein is only slightly modified from past literature (e.g. Tsang et al. 2005) to make a clear distinction between where the rock mass is damaged and where elastic changes are occurring. The damage zones are traditionally referred to collectively as the excavation damage zones (EDZs). The density and size of excavation induced fractures decrease moving away from the excavation surface. The inner most zone is termed the highly damaged zone (HDZ). It comprises macroscopic interconnected fractures. Moving outwards, the inner EDZ (EDZi) makes a gradual transition to the outer EDZ (EDZo). These zones contain micro-damaged rock with (inner) and without (outer) significant dilation and transitioning from interconnect (inner) to isolated microcracks (outer). Beyond the EDZs is a stress and/or elastic strain influence zone, the Excavation Influence Zone (EIZ) or also called the Excavation disturbed Zone (EdZ) by Tsang et al. (2005). In nature, the transition between these zones is gradational, and distinguishing between them can be difficult without in situ measurements to validate the numerical results, which is beyond the scope of this paper.

Another important distinction is between the HDZ and the Construction Damage Zone (CDZ). Construction damage is purely a result of construction methods (blasting, for example). This form of damage can be reduced or nearly eliminated through precision rotary or line boring (controlled drill and blast), road header or tunnel boring machine excavation. In contrast, the HDZ can be purely the result of geometry and induced stress change (independent of excavation method) and in some cases can never be eliminated or significantly reduced. Close to the excavation surface an increase in porosity and permeability is caused by interconnected fractures within both the CDZ and the HDZ. The depth of damage is a function of the excavation method, stress regime, and rock mass properties. If the degree of fracturing in the HDZ is severe enough to cause post-peak weakening or softening and associated stress shedding, it is within the EDZi that the stresses are able to concentrate as the induced fractures become less inter-connected and the rock mass begins carrying the stress load. This zone gradually transitions into the EDZo, where fractures begin to occur under enough confinement such that fracture propagation is inhibited. Damage within the EDZo has minimal affects on the bulk hydraulic properties within this zone due to the isolated nature of micro-cracks which may form in this zone.

1.2 Cut-off strategy

The purpose of a cut-off seal is to impede the flow of radionuclides along the periphery of the excavation, either along the bentonite-rock mass contact or along the EDZ. As such it must be constructed to bisect damage induced in the surrounding rock mass from the excavation process. A variety of cut-off construction methods are available, for example, saw cuts, precision line drilling, or road header (Perras 2014). Cut-off seals will be constructed at various key locations along the adits, ramps, emplacement caverns, drifts or shafts and will be site dependent. Conceptually, cut-offs will be purposefully placed at locations to reduce flow and mass transport in the host rock. Along the access ramp or shaft cut-off seals are likely to be constructed in key geological formations to minimize flow and migration across formational contacts. The cut-off must intersect the EDZ and be constructed in manner which does not further extend the EDZ beyond the cut-off.

2 NUMERICAL CRITERIA FOR CUT-OFF PERFORMANCE ASSESSMENT

Conceptually, the different EDZs were mapped to the constitutive Damage Initiation and Spalling Limit (Diederichs 2007) failure envelopes, damage threshold and spalling limit in Figure 1, to understand the expected model behaviour. When the stress path of an element around the simulated tunnel changes in response to the excavation, this element can be considered part of the EIZ, as long as the stress path remains below the damage threshold envelope. When the stress path crosses the damage threshold envelope, the element yields plastically and the spalling limit envelope becomes the governing stress envelope, dictating the maximum allowable stress that an element can carry. If the stress path crosses the damage threshold envelope in tension or in the spalling region, then this zone is considered to be part of the HDZ, and the element can be considered to undergo strain-weakening. Otherwise, under confinement, the element undergoes strain-hardening, when the stress path cross the damage threshold envelop and the spalling limit envelope allows higher σ1 stresses to be carried. Perras (2014) examined various numerical indicators (using Phase2 and FLAC3D) and found that yielded elements, volumetric strain, and principal stress concentrations were the best indicators for determining the dimensions of different EDZs. Perras (2014) also found that it was possible to differentiate numerically between an inner and outer EDZ using volumetric strain. These were differentiated using the reversal point in the volumetric strain (contraction to extension). This finding indicates the transition between a confined micro-damaged state (EDZo) and a potentially dilated EDZi. The outer boundary of the highly damaged zone, HDZ, is related to volumetric strain and a reduction in minor stress confinement.

The concept of using volumetric strain as an indicator between EDZi and EDZo is illustrated in Figure 1. The values in the graphs were measured along a line which passed from the centre of the excavation through the deepest yield zone away from the excavation surface (parallel to σ3). This modelling was for circular excavations only and so the cut-off modelling presented herein is also for a circular shaft. The different points in Figure 1 represent different stages of the model used to simulate three-dimensional excavation advance in two dimensions, using a gradually decreasing a distributed load around the excavation surface in Phase2, by Rocscience.

Three plastic stress paths are shown with respect to the DISL stress envelopes, one taken to represent the HDZ, the EDZ_i, and the EDZ_o, at distances from the excavation surface of 0.0 m, 0.6 m, and 1.4 m, respectively. The stress path analysis was used to validate and update the conceptual model by demonstrating that the volumetric strain reversal, from contraction to extension, is an important indicator of the behaviour of the rock around the tunnel model. This transition occurs when the stress path crosses the intersection of the damage threshold and spalling limit envelopes (Figure1a. This point has been called, σ_{3crt}. In the modelling presented in this paper all stress paths cross the damage threshold envelope to the right of σ_{3crt}. For the stress path at the excavation surface, stresses exceed the damage threshold envelope, causing the stresses to follow the spalling limit envelope (higher strength when to the right of σ_{3crt}). When the stresses at the surface pass σ_{3crt}, there is a deviation in the linear stress path at 0.6 m from the excavation surface.

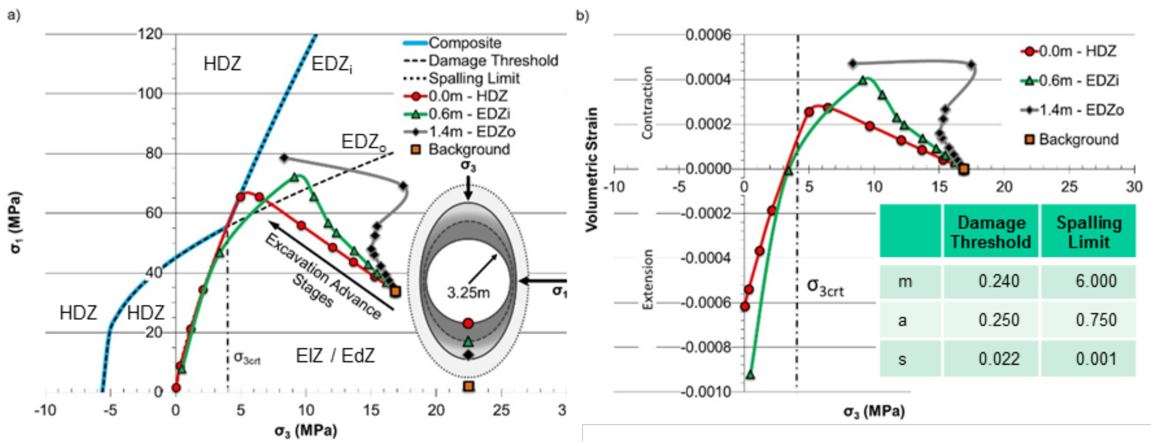

Figure 1ab. Numerical model results from Perras (2014) showing the stress and volumetric strain behaviour of elements within the different excavation damage zones. Inset table of Phase2 input properties to describe the DISL envelops, following method described by Diederichs (2007).

The comparison of Figure 1a and 1b shows that this point in the stress evolution corresponds to the extensile strain at the excavation surface, resulting in stress shedding to the surrounding elements.

This shedding also occurs when the stresses at 0.6 m away from the excavation surface fall below σ_{3crt}. At 1.4 m from the excavation surface, the stress shedding to 0.6 m is also evident by a deviation from the linear stress path. The EDZ_i is associated with the extensile strain, which occurs when the minimum principal stress falls below σ_{3crt}. However; for the limestone case, at 1.4 m (near the start of the EDZ_o), the stresses remain above σ_{3crt} and the strains remain in contraction. Realistically, this confinement would inhibit fracture propagation; therefore, the damage in the EDZ_o is considered to be distributed and unconnected.

The following specific criteria (guidelines) were used to determine the dimensions of the EDZs for the shaft excavation prior to cut-off construction:

- The HDZ–EDZi transition was taken as the first point where σ3 increases from the value at the excavation surface and either maximum or rapidly decreasing extensile or shear strain moving away from the excavation surface.
- The EDZi–EDZo transition was taken as the start of extensile volumetric strain.
- The EDZo–EIZ transition was taken as the start of plastic yielding.

Although discontinuum methods are gaining ground for damage analysis, it is still reasonable in many cases to use simpler continuum analysis methods for EDZ prediction, as such, FLAC3D is used in this paper to generate the results of Figure 2.

3 CUT-OFF MODELLING

The construction of a cut-off has been investigated numerically and in-situ by a number of authors (e.g. Damaj 2007, Li et al. 2010, Martino et al. 2007, Souley et al. 1999) and is also currently the subject of many research programs related to nuclear waste management (e.g. White et al. 2014 - DOPAS). The different methods, mentioned above, of constructing the cut-off can achieve different shapes more efficiently and consideration for the stress regime, rock mass properties, rock mass anisotropy, structure and construction induced damage must be taken into account on a site-by-site basis. In this paper a thin to wide slot of various depths has been examined numerically using a single stress field and rock mass properties, examples of the thinnest and widest are shown in Figure 2. The slot, of various dimensions in different models, has been constructed for a circular shaft at a depth of 500 m in the finite difference program FLAC3D. The vertical stress was calculated based on 0.026 MPa/m with a vertical stress ratio of 1.6 and a horizontal stress ratio of 3.2. The rock mass was assumed to behave in a brittle fashion and was that used by the authors to predict the depth of EDZs around a circle shaft in a strongly over consolidated argillaceous formation (Perras et al. 2014), with a UCS of 53 MPa and a modulus of 17500 MPa (other input values are listed in Figure 1).

The analysis was conducted to progressively increase the thickness of the slot cut-off, which was constructed to key into the EDZo created by the shaft excavation. The depth of the slot away from the excavation surface was also progressively increased. Thickness to depth ratios of 0.05 to 0.6 were investigated. In order to assess the cut-off functionality, the ratio of volumetric extensile strained area to plastic yielded area on the face of the slot tip was determined for each slot. The assumption being that if within the plastic yield zone volumetric extensile strain occurred that this would be representative of connected fractures. Therefore, when the entire plastic yield zone is in volumetric extension (i.e. ratio equal to 1.0) then there is a flow pathway around the cut-off tip parallel to the shaft axis throughout the entire plastic yield zone area. With a ratio of less then 1.0, each model results was examined to determine if a connection across the cut-off was established (i.e. volumetric extensile area from top to bottom on the slot face within the plastic yield area). In the numerical results plotted in Figure 2, a disconnected area of volumetric extension across the cut-off was found when the thickness to depth ratio was less than 0.13. This suggests that a thin slot cut-off is optimum given the extreme stress to strength scenario modelling in this preliminary work.

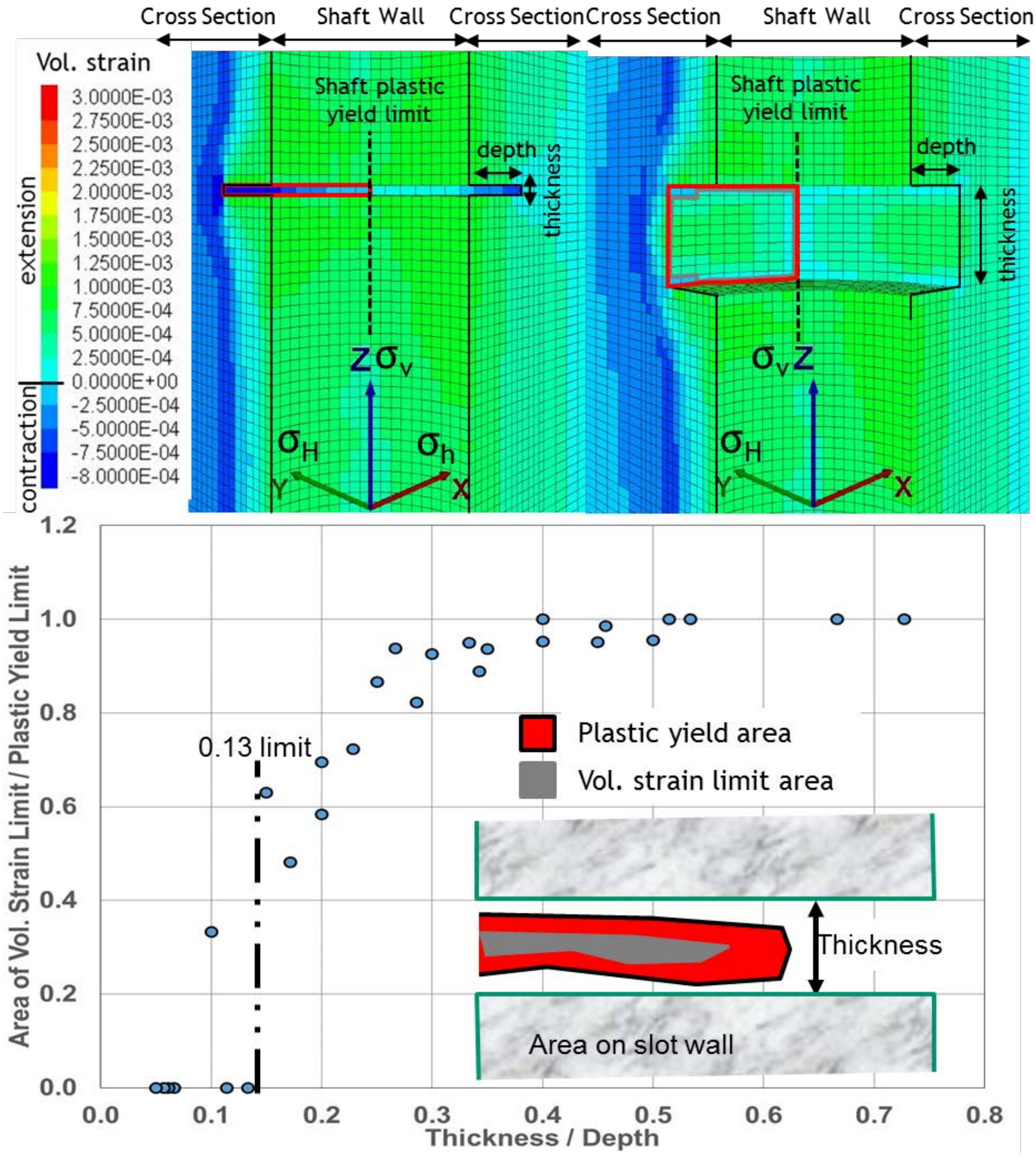

Figure 2. Numerical modelling results from FLAC3D showing relationship between thickness to depth ratio and the area ratio (volumetric extensile strain area to plastic yield area) for slot cut-offs excavated radial from a circular shaft of radius 2.5 m.

4 DISCUSSION AND CONCLUSIONS

This numerical analysis does not consider the long-term rock mass behaviour aspects of the construction cycle for cut-offs (100 years after shaft excavation). These include the anisotropic and heterogeneous nature of sedimentary rocks, the temperature effects, or effective stresses. These influences will affect both the EDZ around the excavation and the cut-off structure. Some, such as time dependent behaviours such as swelling or the anisotropy, can act to reduce the expansion of the damage zone due to the cut-off slot construction at the point of repository closure. The long-term rock mass behaviour should reduce the stress (i.e. from creep, relaxation, swelling) such that when the cut-off is constructed the new crack propagation energy is absorbed by the rock mass without forming a connected fracture network. Similarly, for a vertical shaft in horizontally bedded sedimentary rocks the stress concentration at the slot tip will clamp the bedding due to increased normal stress and thereby reduce inward convergence and damage by absorbing the strain energy on the bedding. Other factors, such as temperature effects or effective stresses, will be rock type dependent. For example, a granitic host rock is far less influenced by temperature or effective stresses than an argillaceous host rock.

The work presented in this paper demonstrates that even under extreme stress to strength conditions a cut-off can be constructed which disconnects the flow pathway (within the EDZi) along a circular shaft excavation. Given the limitations of the modelling presented here, a thin cut-off compared to the depth (thickness : depth < 0.13) is required to make the disconnection. Future modelling will investigate other influencing factors of the rock mass, different shapes, and loading conditions, with a key consideration for the constructability of the cut-off geometry.

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