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Considerations and observations of stress-induced and construction-induced excavation damage zone in crystalline rock

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ABSTRACT

Bsed on the recent observations from two underground laboratories, the construction-induced excavation damage zone (EDZ_{CI}) caused by explosion or by mechanical excavation and stress-induced excavation damage zone (EDZ_{SI}) are distinguished. The key location for *in situ* testing of EDZ and method development has been the TBM tunnel in Äspö Hard Rock Laboratory in Sweden since the 1990s. The research and development has been continued between 2010 and 2012 with *in situ* stress measurement campaign and in 2013 with ground penetrating radar investigations with new GPR EDZ method. The new GPR EDZ method based on frequency analysis of the reflected signal indicates mean depth for EDZ_{CI} of 120 mm. The same zone is indicated also by various other geophysical and laboratory methods, and is distinguished as construction-induced and continuous around the tunnel perimeter. Fracture mechanics modelling suggests a lowered hydraulic conductivity of 1.8×10^{-13} m/s in EDZ_{SI} and 4.0×10^{-11} m/s in EDZ_{CI}. Biaxial testing suggests a zone in which Young's modulus values are lowered, and which is not continuous around the tunnel. This zone is distinguished as an observable part of stress-induced EDZ_{SI}.

1. Introduction

In geological nuclear waste disposal, the knowledge of *in situ* stresses, excavation damage zone (EDZ), rock mass strength, hydraulic conductivity and other rock mass properties are important for long term safety assessment. Both Finnish and Swedish nuclear waste disposal projects have initiated research, method development and *in situ* experiments on these subjects during the last twenty years. Although the research related to EDZ in nuclear waste disposal concept has been thorough, the blast-induced and stress-induced excavation damage are often clumped without clear terminological definition. However this scientifically motivated article describes and discusses the EDZ in more detail than nuclear waste management industry practically needs.

One of the key places for *in situ* testing and method development has been the Äspö Hard Rock Laboratory (HRL) in Sweden. In the standpoint of the EDZ studies one of the interesting locations has been the a tunnel which was mechanically excavated using a Tunnel Boring Machine (TBM) in Äspö at −440 m depth where ZEDEX experiment was conducted in the 1990s [1,2]. The TBM tunnel is 5 m in diameter and namely TASA tunnel (T=tunnel, AS=Äspö, A=tunnel code). The TASQ tunnel at −450 m level where the Äspö Pillar Stability Experiment (APSE) *in situ* rock mass spalling strength test was conducted is located only few tens of metres from the TBM tunnel section.

The Finnish and Swedish waste management companies Posiva Oy and Swedish Nuclear Fuel and Waste Management Co. (SKB) continued the research and development between 2010 and 2012 with *in situ* stress measurement campaign [3], and in 2013 with ground penetrating radar (GPR) investigations in TBM tunnel (Fig. 1). In the stress measurement campaign cores were overcored from the tunnel and were later biaxially ($\sigma_1=\sigma_2;\ \sigma_3=0$) tested for Young's modulus and Poisson's ratio. The cores were obtained from both deep (from 0.5 m to 1.0 m depth) in the rock mass and near the excavation surface. Young's modulus and Poisson's ratio were also tested in TASS tunnel excavated with drill-and-blast (D&B) method. The elastic rock properties acquired during the stress measurement campaigns and results from GPR measurements are used in this article when assessing the stress-induced and construction-induced excavation damage zone. Also data from EDZ investigations by Posiva Oy in underground rock characterization facility ONKALO in Western Finland is used to describe the stress-induced damage.

2. Background

Considering deep mines or a TBM tunnel at great depth in hard crystalline rock, the stress-induced damage will cause majority of

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the relevant geohazards. In the nuclear waste disposal concept, at reasonably low depths (400–500 m), the stress-induced damage is not able to neither cause significant physical damage nor increase the hydraulic conductivity significantly, whereas the blast (construction-induced) damage can cause significant hydraulic flow paths. In the hard rocks of Fennoscandia and Canadian Shield these two processes are distinguishable with thorough investigations, but in softer rock masses the distinction between the processes may be even more difficult.

2.1. *Terminology of damage surrounding tunnel*

The terminology for damage surrounding a man-made opening varies significantly between sources mostly depending on if TBM method or D&B method is used in excavation. There are several meanings for the used terminology of damage and multiple terms with same meaning. The acronyms used in the literature are: BIDZ, BID, DRZ, HDZ, EFZ, CDZ, EDZ and EdZ. All damage zones except EdZ host irreversible changes of rock mass properties.

The rock and fracture properties change more significantly near the excavation [4,5]. According to Tsang et al. [6] D&B method significantly and irreversible change the rock properties “from 0.1 m to as much as 1.5 m into the rock, increasing permeability by two or three orders of magnitude” however TBM only changes from 1 to 3 cm by one order of magnitude [1,6]. Because of its significance the damage caused by the explosions are often simplified to be the only source of excavation damage in D&B method context.

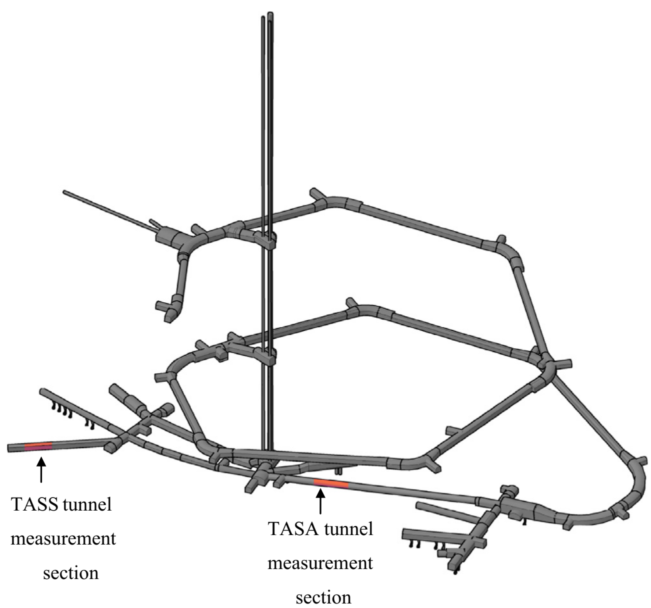

Fig. 1. Hard Rock Laboratory from SE direction where the measurement locations in D&B tunnel (TASS tunnel) and TBM tunnels (TASA tunnel) are marked.

Dinis da Gama and Torres [7] defined the blast hole near-field from near to far: “(1) zone of crushing, (2) zone of radial cracking, (3) zone of extension and expansion of fractures and (4) elastic Zone, where no cracks are formed”. The near-field of blast hole has also been researched for example by Saiang [8] defining it as blast-induced damage zone (BIDZ), but abbreviations BID [9] and DRZ [10] have also been used. In larger perspective zones from 1 to 3 and BIDZ [7] belong to highly damaged zone (HDZ) defined for example in [5] as a zone containing macro-scale fracturing that is caused either by explosion or high stresses (*e.g.* spalling). HDZ is also referred as excavation fracture zone (EFZ) [11].

Considering the deepening mines and nuclear waste disposal projects that reach several hundreds of metres where spalling and other stress-induced failures occur, the stress-induced damage zone must be separated from blast-induced damage zone to distinct the two different processes and property areas. Harrison and Hudson [12] divided the disturbance to the initial *inevitable* excavation consequences and to the *additional* effects induced by the construction method. The inevitable effects are: (1) Displacements due to unloading, where the excavated rock mass is unable to provide support pressure to the remaining rock mass. This leads to block falls and deformations (almost strictly meaning shrinking of excavation area). (2) Change and rotation of stresses, leading to number of locations with significant stress peaks and lows. (3) Water inflow due to lowering of fluid pressure to atmospheric pressure near opening, causing water flow towards the excavation.

The need for dividing the effects is also noted by The Swedish Radiation Safety Authority noted in their “Review of Engineering Geology and Rock Engineering aspects of the construction of a KBS-3 repository at the Forsmark site”. In the review Eberhardt and Diederichs [11] point out and define that the construction damage zone (CDZ), that only contains damage that is caused by construction method, should be separated from stress-induced excavation damage zone (EDZ_{SI}). EDZ is the most often used and researched damage zone (see for example [4,6,13–17]). In EDZ for tunnel stability and reinforcement analysis the stress-induced damage zone EDZ_{SI} and construction-induced damage zone EDZ_{CI} are the most significant damage zones, since they significantly and irreversible change the rock properties in with significant depth.

Excavation disturbed zone (EdZ) is usually used to distinguish furthest zone around opening where reversible changes caused by

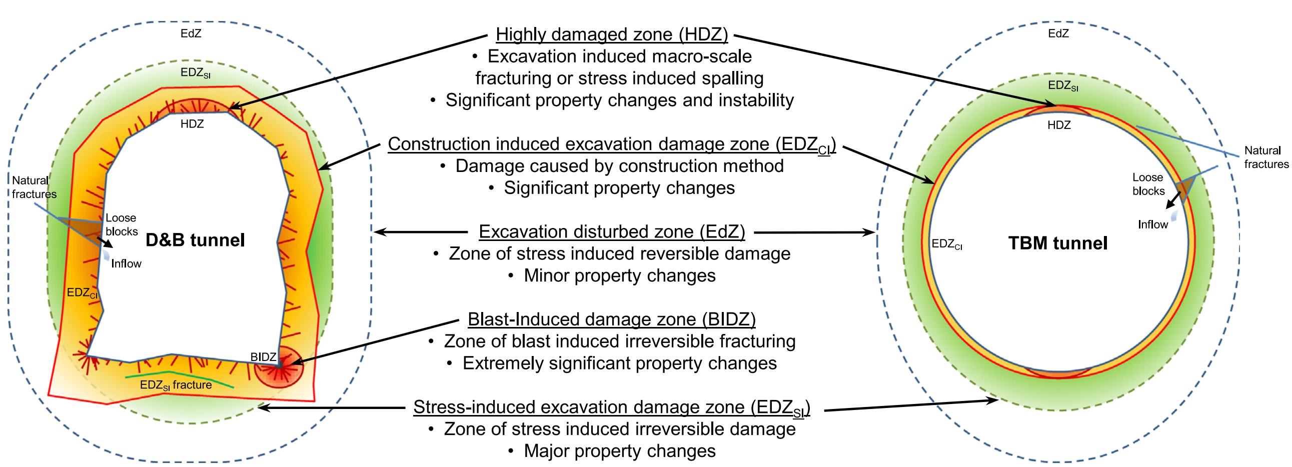

Fig. 2. Overview of the different damage zones.