Geotechnical observations from the Niagara Tunnel Project: Numerical back analysis for application to shaft damage dimension prediction

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During the excavation of the Niagara Tunnel Project challenges in Queenston Formation, a mudstone, were encountered which slowed the excavation advance. As the tunnel reached 140m below ground, large overbreak in the order of 3-4m began to occur due to stress induced spalling, which created a notch shaped geometry. The failure mechanism is the result of increased lateral strain around the excavation due to the anisotropic nature of the mudstone and the high stress concentration at the excavation boundary. Back analysis was conducted and determined at a $K_o$ ratio of 4 a plastic yield zone of roughly 4m resulted using the Damage Initiation and Spalling Limit approach. Forward numerical prediction of damage in a shaft that will pass through the Queenston Formation at a different site was conducted to estimate the maximum depth of plastic yielding, which was found to be 1.9m.

1. INTRODUCTION

The newly constructed Niagara Tunnel, for water diversion, went into service in March 2013 after an extended construction period. Difficult tunnelling conditions were encountered in the Queenston Formation, which originally was to be almost 80% of the tunnel length [1]. The 14.4m diameter Tunnel Boring Machine (TBM) began excavating the 10.2km long tunnel in September 2006 and excavation was completed in May 2011. Final lining and grouting was completed in early February 2013.

The tunnel was constructed to divert water from above Niagara Falls to an existing power station, the Sir Adam Beck Generating Station (SAB-GS). The major benefit of the project is that it reduces the percentage of time, from 60% to 15%, for which the allowable water diversion exceeds the capacity of the SAB-GS. This paper is intended to discuss the geotechnical challenges faced during the tunnel excavation and explore through numerical back analysis the conditions leading to maximum observed overbreak.

1.1. Geotechnical Properties for Numerical Analysis

The tunnel passes through eleven formations of the Appalachian sedimentary basin in North America. The formations within the basin lie relatively flat, dipping 6m/km [2]. Southern Ontario is relatively flat, with the exception of several topographic features including the Niagara Escarpment, the Niagara River Gorge and the buried St Davids Gorge. Perras et al. [2] determined that there is a large increase in the horizontal stress magnitude, from 10 to 24MPa ($\sigma_H$ in the Queenston) at the nominal elevation of the bottom of the Niagara River Gorge, roughly 40masl. This corresponds to a stress ratio change from approximately 2.5 to 6 at a similar elevation, as shown in Figure 1a, and is in agreement with previous studies by Yuen et al. [2].

The sedimentary formations which the tunnel was excavated through ranged from limestones, shales, sandstones, mixed sandstone and shale, and mudstone (Queenston) formations. There is a wide spectrum of Unconfined Compressive Strengths (UCS) as indicated in Figure 1b, particularly for the formations above the Queenston. The Queenston strength lies between 20 and 50MPa within the elevations which were tunnelled through. The UCS of the Queenston is anisotropic, but crack initiation (CI) is isotopic. The average UCS (39MPa) and CI (15MPa) values [2] were used as a starting point for the analysis.

2. OBSERVATIONS FROM THE NTP

Observations of the overbreak indicated four behaviour zones, Figure 1c, three within the Queenston [2]. Zone 1 is all the formations above the Queenston. Zone 2 lies at the contact between the Whirlpool and Queenston formations, which is a disconformity. The reduction in stress due to a stress shadow and jointing created large blocks failing from the crown. The overbreak was observed to break back to the overlying
Whirlpool Formation to a maximum depth of 1.4m, at which time forward spiling was used to advance the tunnel. When the tunnel reached maximum depths, 140m deep, stress induced failure was observed. However; the behavior was influenced by the buried St Davids Gorge which the tunnel had to pass under.

On reaching the structural influence of the buried gorge, Zone 3, overbreak was in the order of 2.0m. It should be noted that through most of this zone, forward spiling was used. Vertical jointing, spaced 2-3m, and horizontal and inclined shear surfaces were observed. Jointing remained clamped due to the stress concentration and had minor influence on the overbreak geometry. The shear surfaces likely affected the overbreak, although was not observed. The overbreak geometry remained asymmetric throughout this zone, however; it was generally inconsistent in size and shape, due to the influence of the buried gorge.

Stress induced fracturing became more prominent, as the tunnel passed away from the influence of the buried gorge, marking the transition to stress induced overbreak, zone 4. The crown overbreak formed an arch 7-8m wide with a consistent notch shape, skewed to the left, likely indicating a high stress ratio with the major principal stress orientation slightly inclined from horizontal (Figure 2a). Overbreak reach maximum depths up to 6 m. Failure in the invert continued with induced spall planes, which were marked with plumose and conchoidal surfaces. Minor sidewall spalling occurred in the sidewall area (Figure 2b).

![Figure 1: The measured a) stress ratios ($K_o = \sigma_H / \sigma_v$) and b) unconfined compressive strengths (UCS) for the formations and groups c) encountered in the Niagara Tunnel Project.](image-url)
3. NUMERICAL BACK ANALYSIS

The ubiquitous joint double yield (UBJ DY) model in FLAC3D, by Itasca, allows for two Mohr Coulomb segments to be used to define the failure envelop, as well as a tension cutoff. This model was chosen due to the simplicity in the input parameters, which only require cohesion, friction and tension values. The model also considers ubiquitous joints to capture the anisotropic strength. The UBJDY envelopes were selected to approximate the Damage Initiation and Spalling Limit [3] peak and residual envelopes. This method can capture the curvature of the DISL peak yield surface for both the NTP and the DGR [4]. The UBJDY model allows for peak and residual properties to be captured with a strain soften/hardening approach, utilizing plastic shear strain as an indicator to reduce/increase the properties.

Since the notch was fully formed prior to installation of rock support, when spiles were not installed, numerical simulation of the rock support has been neglected. Thus the numerical results should yield maximum notch geometries. The observed depth of overbreak (Figure 2a) was used as a target to determine the likely stress conditions. For the stress ratio ranges discussed previously the modeled maximum depth of plastic yielding ranged between 2.0 and 5.0m (Figure 3a). At a depth of ~4m the stress ratio (Ko) was found to be 4, which is in agreement with the measured values (Figure 1a).

4. IMPLICATIONS FOR CANADA’S DGR

Canada is in the final stages of licensing for a Deep Geological Repository (DGR) to store low and intermediate level nuclear waste (L&ILW). The project will include an access shaft with a radius of approximately 4m and a slightly smaller ventilation shaft. The shaft will pass through a 200m thick shale sequence, including the Queenston, overlying the Cobourg host Formation. For a detailed review of the
project and the geological setting the reader is referred to the Descriptive Geosphere Site Model [5].
Understanding the damage potential is key to designing cutoffs to restrict flow along the shaft damage zone.
Utilizing the understanding from the back analysis of the NTP, modelling was conducted to determine the
potential range of the Excavation Damage Zone (EDZ) dimensions at the DGR.

Using the average strength and stiffness values for the Queenston at the DGR site [4] and varying the stress
field the range of potential EDZ dimensions were determined using the same UBJDY model approach
utilized for the NTP back analysis. The results of the DGR modeling are presented in Figure 3b. The
maximum depth of damage for the 4 m shaft model is 1.9m, with an average depth of damage of 1.3m. At a
maximum stress to CI value between 1.2 and 1.4 there is little to no damage in the numerical models. It
should be noted that at the upper end of the possible stress scenarios, for maximum stress to average CI
values greater than 2.2, the empirical limits would over predict the depth of damage.

5. CONCLUSIONS
In conclusion the NTP brittle models capture the range of observed notch geometry using the average
strength and stiffness properties. Shear based failure criteria was unable to capture the notch shaped
geometry. The target notch depth of 3.8m (Figure 2a) closely corresponds to the model with $K_o=4.0$ and
$K_{th}=1.4$, with a modelled notch of 3.9m. A similar methodology was implemented to predict the depth of
damage around the DGR shaft in the Queenston Formation. The models predict maximum depths of 1.9m.
These models represent a preliminary back analysis of the tunnel and forward prediction for the DGR shaft.

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