ANALYSIS OF TUNNEL DEFORMATIONS IN OPALINUS CLAY USING A STRESS-DEPENDENT MODULUS MODEL

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ABSTRACT
A mine-by test was conducted at the Mont Terri rock laboratory, Switzerland, in 1997-98 to assess the rockmass response to tunnel excavation in a middle Jurassic claystone (Opalinus Clay). Prior to tunnel driving, the 3.6 m diameter circular tunnel, known as the ED-B tunnel, was instrumented to allow detailed monitoring of the rockmass response with tunnel advance. Excavation induced stresses resulted in unusually large deformations and the development of an excavation disturbed zone (EDZ) around the tunnel where the dominant mode of yielding consisted of extensional fracturing. This response cannot be accounted for by conventional elasto-plastic numerical analysis. From field and laboratory observations, it has been observed that Opalinus Clay exhibits responses that often are not represented adequately by linear-elastic or elasto-plastic models. In particular, strong non-linear elastic behaviour at low stresses was observed in laboratory tests. This behaviour has been captured by a phenomenological-based model, known as the stress-dependent modulus (SDM) model. The behaviour model was implemented into a finite difference numerical code (FLAC3D) and used to simulate the short-term deformations measured during the ED-B mine-by test.

RÉSUMÉ
Un test mine-by a été effectué au laboratoire de mécanique des roches de Mont Terri en Suisse courant 1997-98 afin d’évaluer la réponse de la masse rocheuse autour d’un tunnel excavé dans une pierre argileuse provenant de la période jurassique. Avant la perforation du tunnel, un tunnel circulaire de 3.6 m de diamètre, appelé tunnel ED-B a été instrumenté afin de permettre la surveillance de la réponse de la masse rocheuse à l’avancement du tunnel. Les contraintes provoquées par l’excavation du tunnel ont causé de grandes déformations anormales et ont provoqué le développement d’une zone de perturbation due à l’excavation (EDZ) autour du tunnel où la forme dominante de fléchir était la fracture en traction. On ne peut pas expliquer ce comportement par une modélisation numérique élasto-plastique conventionnelle. Les observations relevées sur le terrain et au laboratoire montrent que l’argile opalinus présente un comportement qui ne peut être expliqué de manière satisfaisante par des modèles élastiques linéaires ou élasto-plastiques. En particulier, des tests au laboratoire ont montré un comportement très non-linéaire et élastique aux faibles contraintes. Ce comportement a pu être expliqué par un modèle phénoménologique appelé modèle Stress-Dependent Modulus (SDM). Le modèle de comportement a été implanté dans le logiciel numérique de différence finie FLAC3D, et a été utilisé pour simuler les déformations à court-terme observées au cours du test ED-B mine-by.

1. INTRODUCTION

In 1997-98, a mine-by test tunnel was excavated at the Mont Terri rock laboratory, Switzerland (see Figure 1) to assess the issues associated with tunnel excavation in Opalinus Clay. The 35 m long, 3.6 m diameter circular excavation, known as the ED-B tunnel, was excavated at a depth of approximately 270 m. The rockmass was instrumented prior to tunnel driving, allowing for monitoring of the rockmass response with tunnel advance. The measured large near-field deformations and EDZ fractures have been attributed to plasticity (Corkum 2004). However, only limited plasticity is anticipated around the ED-B tunnel based on new information regarding the stress field at Mont Terri (Corkum 2006).

Corkum and Martin (2006) have demonstrated that the mechanical response of Opalinus Clay is unique and reflective of a micro-structure that is dominated by diageneric bonding and stored latent strain energy. They showed that the low stress, low stiffness non-linear stress-strain response of laboratory samples, typically attributed to sample disturbance, is due to the formation/opening of micro-cracks. This is a real material behaviour that can have significant impact on the rockmass response to excavation.

Figure 1 Map showing Mont Terri rock laboratory near the town of St. Ursanne in northwestern Switzerland (modified from www.mont-terri.ch).
For deep boreholes in the petroleum industry this issue has been addressed by Ewy and Cook (1990) and Santarelli (1986) using a pressure-dependent modulus (PDM) model. A stress-dependent modulus (SDM) phenomenological model for the Opalinus Clay has been developed based on a rational interpretation of the physical properties and geological history of the Opalinus Clay as described by Corkum (2006). This model has been implemented into the finite difference method (FDM) code FLAC3D and used to model the ED-B mine-by test.

2. BACKGROUND

The A16 Transjurane motorway tunnel traverses Mont Terri near the town of St. Ursanne in the Jura mountains of northwestern Switzerland. The Reconnaissance Gallery (or Security Gallery) was originally constructed as part of the motorway tunnel. The Mont Terri rock laboratory traces its origin to the excavation of a number of niches within the Reconnaissance Gallery in 1995, created to conduct various experiments in the Opalinus Clay formation. Over the last decade expansion of the rock laboratory and additional experiments have been carried out.

Mont Terri is an asymmetrical anticline folded during the late Miocene to Pliocene period. The stratigraphy of Mont Terri consists of competent limestones and incompetent marly/shaly formations. The rock laboratory is located within the south-eastern limb of the anticline where the stratigraphy generally dips about 45° to the southeast (Thury and Bossart 1999). The Opalinus Clay is immediately overlain by a limestone layer and underlain by marly units. Where it intersects the rock laboratory, the Opalinus Clay is about 250 m thick along the length of the tunnel. As a result of differing sedimentation, the Opalinus Clay can be grouped into three facies: a sandy facies, a carbonate-rich sandy facies and a shaly facies, the latter being of most interest for repository construction. The ED-B tunnel is located entirely within the shaly facies. One major fault zone runs through the rock laboratory south of the ED-B tunnel and a number of discrete minor faults and joint sets have been observed throughout the tunnel system. Structurally controlled instability does not generally play a significant role at the rock laboratory.

The Opalinus Clay is a weak argillaceous rock, classified as a claystone, found mainly in Germany and northwestern Switzerland. Named for the ammonite Leioceras Opalinum, it is a Lower Aalenian (middle Jurassic age) marine deposit with past overburden estimated to have been at least 1000 m thick (Marschall et al. 2002). The claystone is a competent soft rock with an average unconfined compressive strength of about 15 MPa. Typically, Opalinus Clay is composed of 50-65% clay particles, with the clay mineralogy consisting mostly of low activity kaolinite and illite which results in medium plasticity. It is very dry with low water content and porosity and, like most argillaceous rocks, many of the mechanical properties are sensitive to changing water content.

The ED-B mine-by experiment was conducted at Mont Terri in 1997-98. Consisting of a 36 m long, 3.6 m diameter circular excavation, this experiment has provided measurements from a number of instruments such as piezometers, inclinometers, extensometers and convergence arrays, with excavation advanced (Fierz 1999). Most of the instrumentation was installed prior to excavation from the OP Niche in the Reconnaissance Gallery, located approximately 24 m away from the ED-B tunnel. The instrumentation layout is shown in plan and section in Figure 2 and Figure 3, respectively. Borehole deformation instrumentation consisted of one multipoint extensometer, installed in Borehole BED-B5, and three sliding micrometers/horizontal inclinometers installed in Borehole BED-B6 through -B8. The borehole deformation instruments were measured 19 times between September 1997 and June 1999. Near-field deformations were measured using three sets of five-point convergence arrays installed in the ED-B tunnel approximately 1 to 2 m behind the excavation face.

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1 For details see www.itascacg.com
Following the installation of instrumentation, the ED-B tunnel was excavated full face using a road-header from a northwest to southeast direction. The tunnel was stable during excavation and 200 mm thick steel fibre reinforced shotcrete support was installed approximately 7 m behind the excavation face. The lack of instability indicates that yielding of the rockmass was not significant.

3. MODELLING THE MINE-BY TEST

The goal of the analysis was to use the SDM phenomenological-based model, described by Corkum (2006), to simulate the short-term rockmass deformation around a circular excavation in the Opalinus Clay. The results are compared to linear-elastic and elasto-plastic conventional analyses.

3.1 Modelling Methodology

A three-dimensional model was selected because of such geometrical issues associated with tunnel modelling as potential tunnel interaction, orientation of the stress tensor relative to the tunnel, and the nature of tunnel advancement. The well-established FDM code FLAC3D was used because of the flexibility it offers in programming constitutive models and other user defined modifications, in addition to its native ability to conduct plasticity analyses.

It was not known how far behind the excavation face the shotcrete support was installed in the Reconnaissance Gallery, but it was most likely installed prior to full convergence. Elastically, full convergence occurs approximately three tunnel diameters behind the excavation face. For the numerical simulation, it was assumed that 50% of convergence occurred prior to installation of shotcrete. A pilot-tunnel was excavated with a diameter suitable to allow 50% of elastic displacement of the tunnel boundary to occur (5.6 m diameter tunnel with 3.6 m diameter pilot-tunnel). Then the Reconnaissance Gallery was fully excavated, 200 mm of shotcrete support installed, and the rockmass and support were allowed to come to equilibrium together. A five-staged methodology was adopted to simulate the construction sequence of the mine-by test.

Stage 1. Generation of the geometry in modular form providing adequate distance between excavations and boundaries.

Stage 2. Application of boundary conditions and far-field stresses.

Stage 3. Excavation of Reconnaissance Gallery pilot-tunnel (to simulate three-dimensional tunnel advance).

Stage 4. Full excavation of the Reconnaissance Gallery and niches allowing the liner and ground to come into equilibrium. In real time this point corresponded to installation of instrumentation.

Stage 5. Excavation of the ED-B tunnel, leaving it temporarily unsupported. The invert was unexcavated at this stage.

3.2 Model Geometry

As with most geomechanical models, some simplifications of the problem geometry were required to model the ED-B mine-by test. These simplifications were selected to minimize their impact on the areas of interest in the model while limiting the number of model elements to a reasonable size. The model geometry consisted of the two main tunnels, the 3.6 m diameter ED-B tunnel and 5.6 m diameter Reconnaissance Gallery, and the two niches (OP and BF) closest to the instrumented section of the mine-by test. Neither the Highway tunnel, located 33 m northeast of the Reconnaissance Gallery, nor the Highway-Reconnaissance connector tunnel were included in the model. Preliminary finite element modelling indicated that inclusion of these two tunnels would have minor influence on the rockmass near the ED-B tunnel while increasing run times to impractical levels.

3.3 In-Situ Stresses and Boundary Conditions

An understanding of the in-situ stress conditions is essential for the analysis of underground excavations. The in-situ stress conditions at Mont Terri were measured during a number of campaigns utilizing an assortment of techniques such as undercoring, slotter and hydro-fracturing methods. The measured maximum principal stress ($\sigma_1 = 6.5$ MPa) was sub-vertical and agreed well with the estimated vertical stress due to overburden ($\sigma_v = \gamma_z = 6.6$ MPa). The intermediate principal stress ($\sigma_2 = 4.0$ MPa) was oriented sub-parallel, while the minimum principal stress ($\sigma_3 = 2.2$ MPa) was sub-perpendicular to the ED-B tunnel axis. The minimum principal stress has been upgraded from the measured value of 0.6 MPa based on the findings described by Corkum (2006). The orientation and magnitudes of the stress tensor are shown in Table 1. The measured in-situ pore pressure at Mont Terri was between 1.5 and 2 MPa.

<table>
<thead>
<tr>
<th>Principal stress</th>
<th>Magnitude (MPa)</th>
<th>Dip direction</th>
<th>Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_1)</td>
<td>6 - 7 (6.5)</td>
<td>210</td>
<td>70</td>
</tr>
<tr>
<td>(\sigma_2)</td>
<td>4 - 5 (4.0)</td>
<td>52</td>
<td>18</td>
</tr>
<tr>
<td>(\sigma_3)</td>
<td>2 - 3 (2.2)</td>
<td>320</td>
<td>7</td>
</tr>
</tbody>
</table>

3.4 Material Properties

At Mont Terri, the rockmass bedding planes dip approximately 45° in the direction of tunnel advance striking perpendicular to the tunnel axis. As a result, given the stress field discussed previously, any shear yielding would be expected in the tunnel sidewall (highest deviatoric stress) and tensile yielding would be expected in the roof and floor. Both of these modes of failure and locations correspond to the stronger parallel-to-bedding orientation. Therefore, the higher parallel-to-bedding strength values would be appropriate for the isotropic model.
Figure 4 For model implementation, the geometry of the Mont Terri rock laboratory was simplified as two parallel tunnels (ED-B and Reconnaissance Gallery) with two instrumentation niches. The 34 x 56 x 85 m FLAC3D model contained 540,000 zones and five modelling stages were used to simulate the excavation sequence.

According to Anagnostou and Kovari (1996), a total stress undrained analysis is appropriate for tunnel advancement in materials of this permeability (about $5 \times 10^{-13}$ m/s). Only effective stress parameters were available for bedding planes. As a result, effective stress shear strength parameters were used for bedding planes for the ubiquitous joint model analysis.

The recommended intact Young’s moduli were 10 and 4 GPa parallel and perpendicular to bedding, respectively (Bock 2000). Geophysical measurements reported by Schuster (pers. comm.) indicate an average isotropic Young’s modulus of 4 GPa for the rockmass. The mechanical properties used in the numerical model are summarized in Table 2, below.

### Table 2: Average isotropic mechanical properties of Opalinus Clay used in the numerical model (Bock 2000).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density ($\rho$)</td>
<td>2450 kg/m$^3$</td>
</tr>
<tr>
<td>Poisson’s ratio ($\nu$)</td>
<td>0.3</td>
</tr>
<tr>
<td>Young’s modulus (E)</td>
<td>4 GPa</td>
</tr>
<tr>
<td>Cohesion ($c_u$)</td>
<td>8 MPa</td>
</tr>
<tr>
<td>Friction ($\phi$)</td>
<td>0</td>
</tr>
<tr>
<td>Tension (t)</td>
<td>1.5 MPa</td>
</tr>
<tr>
<td>Bedding cohesion ($c_{u}^{b}$)</td>
<td>1 MPa</td>
</tr>
<tr>
<td>Bedding friction ($\phi_{u}^{b}$)</td>
<td>23°</td>
</tr>
</tbody>
</table>

3.5 Constitutive Models

Laboratory testing indicated that the stress-strain behaviour of Opalinus Clay is highly non-linear with low stiffness at low stress levels. There has been significant evidence that this response is inherent to the material itself and not a result of testing equipment or procedures. A phenomenological-based model has been developed to capture this response from observations of field and laboratory studies, along with the geological history of the Opalinus Clay. The development and implementation of this phenomenological model into FLAC3D is described by Corkum (2006). Some background is provided here to orientate the reader.

The incremental secant modulus at low axial stress levels ($\sigma_1$) is shown by circles for an unconfined compression test (Sample 2-22-2p) in Figure 5. Confining stress ($\sigma_3$) and Young’s modulus (E) at 0.2 % strain from triaxial data are shown as diamonds (original data provided by Rummel (2004)). The use of this combined data gives stiffness properties for a large spectrum of stresses, particularly low stress levels. From this plot it can be seen that a relationship exists between E and $\sigma$. A curve can be fitted to the combined data with an equation of the same form used by Santarelli (1986) for carboniferous sandstone. The fitted curve has an $r^2=0.89$ with the equation:

$$E(\sigma) = -0.7 + 2.2(\sigma)^{0.48} \quad [1]$$
Figure 5 Non-linear elastic Young’s modulus related to stress levels ($\sigma_1$, $\sigma_3$) that forms the basis for the SDM model (Corkum 2006).

Although the Opalinus Clay is bedded and strongly anisotropic, the effects of non-linearity on the stiffness properties is more dominant than that of its natural anisotropy alone. As a result, a simplified isotropic constitutive model was used in the analyses. A total of four constitutive models were used to simulate the ED-B mine-by test:

- Linear-elastic model.
- Elasto-perfectly plastic model.
- Ubiquitous joint anisotropic elasto-plastic model.
- SDM phenomenological model.

4. MODELLING RESULTS AND COMPARISON

The ubiquitous joint perfectly-plastic model, showing yielded elements and the location of the borehole instruments, is shown in Figure 6. There was some yielding along joints, but very little yielding of rockmass elements. The instrumentation deformations for the elasto-plastic and ubiquitous joint elasto-plastic analyses were similar (within about 10 %) to the linear-elastic results. Therefore, only elastic model results are shown in the deformations plots for comparison.

The data obtained from the ED-B mine-by test provided a comprehensive set of measurements and observations for comparison with the numerical model. In general, the deformations measured around the ED-B tunnel show unique signatures with all deformations trending inwards towards the tunnel. The deformations away from the tunnel boundary, measured using borehole instrumentation, will be discussed first, followed by the convergence measurements that capture deformations in the near field at the tunnel boundary.

4.1 Borehole Deformation Instruments

In order to directly compare the results of modelling data to actual instrumentation data, the model data was transposed into deformation components that correspond to the instrumentation orientations. This was done using the sign convention that deformations to the right (away from Reconnaissance Gallery) and upward are positive displacements.

The cumulative deformations for sliding micrometers and inclinometers in Boreholes BED-B6 through -B8, along with the linear-elastic and SDM model predictions, are shown in Figure 7. The inclinometers above and below the tunnel recorded a maximum of about 8 mm of inward movement with the maximum deformation approximately in line with the direction of $\sigma_1$ as it passes through the tunnel centre. Similarly, the micrometers show a maximum of about 3 mm of horizontal movement towards the tunnel, with a transition between positive and negative movement again in line with the direction of $\sigma_1$. The proximity of the flat invert near BED-B8 explains the asymmetrical response of the borehole instruments above and below the tunnel.

The linear-elastic analysis was unable to capture the magnitude of deformations, while the SDM model was able to match both the trend and magnitude of the inclinometer data well. In general, the micrometer field measurements were not matched particularly well by any of the constitutive models. The shape of the curves in the immediate tunnel vicinity was adequately matched, particularly the change from positive to negatively sloping deformations, but the horizontal deformations to the left of the tunnel were over-predicted by the SDM model in BED-B6 and under-predicted in BED-B8.
Figure 7  Results of FLAC3D analyses compared with measured field data for cumulative inclinometers and sliding micrometers. The stress-dependent modulus model shows a good match of inclinometer data and a lesser fit to the micrometer data.
Due to deformations at the borehole collar, there is greater uncertainty with the quality of the micrometer data compared to the inclinometer data. There are clear discrepancies between the model and measured micrometer data. Martin and Lanyon (2004) showed that the sidewall was subjected to deviatoric stresses capable of inducing extensional fractures. This was also confirmed by the field mapping (Bossart et al. 2002). The SDM model used a non-linear stiffness response to capture strains in the zones not subjected to these deviatoric stresses. An additional inconsistency between the model and measured data was the significant field deformations measured near the borehole collars (shown in Figure 6).

4.2 Convergence Arrays

Convergence arrays provide a relatively simple and reliable means of directly measuring tunnel wall deformations, with the sign convention that inward rockmass deformation is positive convergence. The convergence arrays were installed approximately 1 to 2 m behind the excavation face. The numerical model was used to estimate that 50% of maximum convergence had occurred before the convergence arrays were installed (at X=1 m or X/D=0.3). Initially, the calculated convergence measurements included all deformation and were therefore reduced by 50% for direct comparison with field measurements.

A total of three convergence arrays were installed during the mine-by test, as shown in Figure 2. Figure 8 shows measured convergence with excavation advance for Array CP-3 and model convergence along a vertical line. The deformation magnitudes and trends were similar for all three sets of convergence arrays. Typically, elastic deformations stabilize approximately three tunnel diameters behind the excavation face (X/D=-3). Deformations beyond this are controlled mainly by time-dependent processes. Figure 8 illustrates that time-dependent deformations are significant for tunnels in Opalinus Clay.

Average measured convergence from the three arrays and modelled convergence, excluding the time-dependent component (at X/D=-3), is plotted in Figure 9. Deformations from the elastic analysis do not match in magnitude, but have somewhat similar trends to the measured values. This supports non-linear elasticity, as opposed to plasticity, as the source of the large deformation magnitudes. The SDM model shows greater overall deformation magnitudes than linear-elasticity. Line 5-2 and 5-3 were over-predicted, while Line 1-4 and 1-5 were under-predicted by the models. This indicates that the modelling deficiency is associated with under-predicting deformations mainly with Pin 1. Pin 1 is located near the sharp corner of the invert in a zone of high deviatoric stress and it is understandable that the effects of EDZ fractures associated with high deviatoric stresses should result in larger than predicted inward deformations in this area. This agrees with the distribution of yielded elements shown in Figure 6.

Figure 8 Measured convergence with excavation advance (Array CP-3) compared to the SDM model along a vertical convergence line.

Figure 9 A comparison of the average convergence measurements from three arrays to the numerical model results shows a reasonable fit with the SDM model. Measurements associated with Pin 1 are under-predicted due to local yielding (see Figure 6).

The calculated vertical convergence line in Figure 8 is nearly aligned with the maximum principal stress and therefore agrees well with the diagonal convergence line, Line 5-2 in Figure 9. The SDM model generally over-predicts deformations in zones of low stresses (aligned
with the maximum principal stress) and under-predicts deformations in zones of high deviatoric stresses. This indicates that deviatoric stresses induce increased dilation in the rockmass by opening EDZ fractures. Although this is not accounted for adequately by the SDM model, it is in agreement with the concepts of the microstructure model.

5. CONCLUSIONS

From field and laboratory observations it has been observed that Opalinus Clay exhibits stress-strain responses that are often not adequately represented by simple linear-elastic or elasto-plastic models. A stress-dependent modulus (SDM) model has been formulated to capture the highly non-linear response as the Opalinus Clay is unloaded. The SDM model was implemented into FLAC3D in order to analyze the ED-B mine-by test case study.

Four constitutive models were used to analyze the ED-B tunnel response. The construction of the ED-B test tunnel produced relatively large displacements for the size of the opening, yet the construction experience suggested essentially an elastic response (i.e., no support was required near the face). The response from elastic and elastic ubiquitous joint analyses (used to simulate bedding), significantly under-predicted the measured displacements. A traditional plasticity model was also used and gave deformations similar to the elastic model (minimal yielding). A non-linear elastic model (SDM) was formulated that captured the highly non-linear response of the Opalinus Clay measured in laboratory samples at low confining stresses. This SDM approach provided better agreement with the measured response. However, the model was unable to match the micrometer and convergence data correctly. Both of these are likely due to the same predictive shortcoming: the inability to include the effects of dilation associated with deviatoric loading.

The goal of this work was to assess if the short-term development and behaviour of the excavation damaged zone around underground openings in Opalinus Clay could be approximated using non-linear elastic modelling. This approach is in keeping with the understanding of the geological history of the Opalinus Clay and its unloading behaviour. Observations regarding the behaviour of Opalinus Clay around underground openings are mutually supportive and present a compelling argument for the non-linear elastic model incorporated in the SDM model. While the mine-by test was heavily instrumented, the authors are aware that this is only one case study and that further refinement and validation of the proposed model is required. Nonetheless, these findings suggest that while an excavation damaged zone will develop around underground openings in the Opalinus Clay, the damaged zone need not be analyzed using complex constitutive models.

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References