MODELLING THE SHORT-TERM BEHAVIOUR OF OPALINUS CLAY AROUND A CIRCULAR EXCAVATION

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ABSTRACT
A mine-by test of a 3.6 m diameter circular tunnel, known as the ED-B tunnel, was conducted at the Mont Terri rock laboratory, Switzerland. The instrumented tunnel was excavated through a relatively weak, middle Jurassic claystone with low porosity and water content, known as Opalinus Clay. The ED-B tunnel was instrumented prior to tunnel driving, allowing for detailed monitoring of the rockmass response with tunnel advance. Excavation induced stresses resulted in an excavation disturbed zone (EDZ) around the ED-B tunnel where the dominant damage mechanism observed consisted of extensional fracturing. As a result of this mode of yielding, the instrumentation records contained fairly unique deformation signatures. Two-dimensional, hydromechanically uncoupled finite element method (FEM) analyses, using the recommended stress tensor and material properties, were used to identify the major issues associated with excavation in the Opalinus Clay for more sophisticated future analyses. Although modelling was unable to accurately capture the mode of yielding, the simplified total stress analysis showed reasonable agreement with the field measurements. In addition, insight into the larger issue of tunnel interaction of the Mont Terri tunnel system was predicted by the model and verified by physical observations.

RÉSUMÉ
Un test de mine-par d'un 3.6 m diamètre tunnel circulaire, connu comme le tunnel d'ED-B, a été dirigé aux Mont Terri balance le laboratoire, la Suisse. Le tunnel de instrumented a été creusé par un relativement faible, le milieu claystone Jurassique avec la porosité basse et le contenu d'eau, connu comme Opalinus Clay. Le tunnel d'ED-B a été instrumented avant la conduite de tunnel, tenant le compte de l'interception détaillée de la réponse de rockmass avec l'avance de tunnel. L'excavation a persuadé des tensions ont eu pour résultat une excavation une zone dérangée (EDZ) autour du tunnel d'ED-B où le mécanisme de dommages dominant a observé a consisté en fracturer de extensional. A la suite de ce mode de produire, l'instrumentation enregistre les signatures de déformation assez uniques contenues. A deux dimensions, hydromechanically a découplé la méthode d'élément finie (FEM) analyse, utilisant le tensor de tension recommandé et les propriétés matérielles, ont été utilisé pour identifier les problèmes majeurs associés avec l'excavation dans Opalinus Clay pour l'avenir plus sophistiqué analysent. Bien que le modelage était incapable précisément de capturer le mode de produire, l'analyse de tension de total simplifiée accord raisonnable montrée avec les mesures de champ. En plus, la perspicacité dans le plus grand problème d'interaction de tunnel du système de tunnel de Mont Terri a été prédite par le modèle et vérifié par les observations physiques.

1. INTRODUCTION

The behaviour of the Opalinus Clay claystone around deep underground excavations is of great interest to many organizations currently studying argillaceous rocks for potential geological disposal of nuclear waste. Argillaceous rocks are often describes as the transition material between soil and soft rock and are well known for presenting challenges to civil engineers from identification of basic laboratory parameters to difficult tunnel construction. The research discussed in this paper is a portion of the larger research project underway on the behaviour of Opalinus Clay around deep underground openings.

A mine-by test tunnel was excavated through Opalinus Clay at the Mont Terri rock laboratory in 1997-98. Modelling this class of material is particularly challenging. The 3.6 m diameter circular excavation, known as the ED-B tunnel, was modelled using a simplified finite element method (FEM) analysis. The construction sequence, problem geometry, *in situ* stresses, constitutive model, material properties and behaviour were the main issues investigated. A plane strain, two-dimensional, isotropic, elasto-plastic FEM analysis was carried out using Phase2[1]. Pore pressures were not directly considered in the hydromechanically uncoupled analyses, but because of the low permeability and relatively rapid rate of excavation, undrained conditions are believed to control the short-term behaviour.

2. OVERVIEW OF OPALINUS CLAY

The Opalinus Clay, found mainly in Germany and North-western Switzerland, is a relatively weak argillaceous rock classified as a claystone. Named for the ammonite *Leioceras Opalinum*, it is a Lower Aalenian (middle Jurassic aged) marine deposit with past overburden estimated to have been at least 1000 m thick (Marschall *et al.* 2002). Based on the observed intensity of slaking when immersed in water, it appears to be lightly or

[1] Information available at www.rocscience.com

uncemented. Like most argillaceous rocks, the laboratory properties are transversely isotropic in nature, with bedding on the centimetre scale. It has a pronounced microstructure that consists of clay plates, or particles that are tabular shaped and highly oriented approximately parallel to bedding. This microstructure is thought to have a significant impact on the macro-behaviour of the material (Bock 2000).

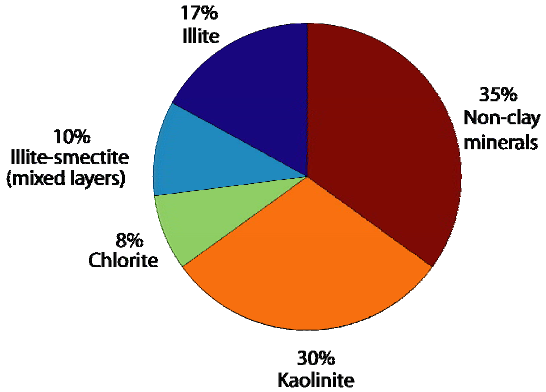

Figure 1: Typical composition of Opalinus Clay.

Table 1: Index properties of Opalinus Clay (Bock 2000).

Property	*Value*	*Property*	*Value*
Bulk Density (ρ)	2450 kg/m^3	Liquid limit (w_L)	38 %
Porosity (n)	13.7 %	Plastic limit (w_P)	23 %
Unconfined strength (UCS)	13 MPa	Plastic index (PI)	15 %
Hydraulic conductivity (k)	5e^{-13} m/s	Water content (wc)	6.1 %

Typically, Opalinus Clay is composed of about 50-65 % clay particles, with the clay mineralogy consisting mostly of fairly low activity kaolinite and illite. It has significant swelling potential due to its high clay content, regardless of the low activity mineralogy. Figure 1 shows the typical mineral composition of Opalinus Clay and a summary of the basic index properties is tabulated in Table 1. The most notable mechanical properties are the very low water content and porosity as well as the highly anisotropic nature. There have been a number of studies conducted on the shear strength of Opalinus Clay showing that the material is fairly linearly elastic, followed by the onset of dilatant behaviour at or near peak strength. It is very brittle with a significant reduction in post-peak strength. This behaviour is typical of a large range of geomaterials from stiff over consolidated clay, such as London clay, to hard rocks, such as Lac du Bonnet granite.

3. MONT TERRI ROCK LABORATORY

The Reconnaissance Gallery, also referred to as the Security Gallery, was originally constructed as part of the original motorway tunnel of the A16 Transjurane motorway near the town of St. Ursanne, Switzerland. The rock laboratory began in 1995 with the excavation of a number of Niche's within the Reconnaissance Gallery to carry out various experiments in the Opalinus Clay. Over the last decade additional experiments and expansion of the rock laboratory have been carried out. A layout of the rock laboratory and the ED-B tunnel, which is the focus of this paper, can be seen in Figure 2.

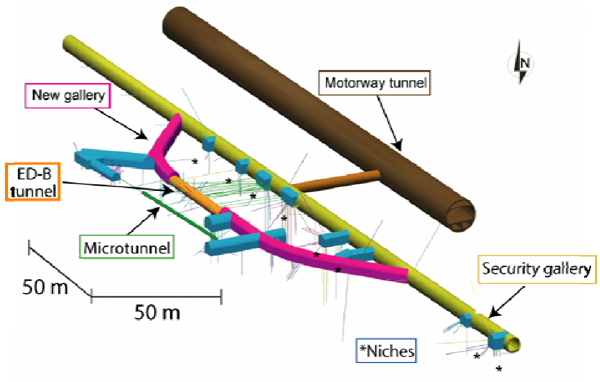

Figure 2: Layout of Mont Terri rock laboratory (from www.mont-terri.ch). Notice the ED-B tunnel within the New Gallery section.

3.1 Geological Setting

Located in the Jura Mountains of north western Switzerland, Mont Terri is an asymmetrical anticline which was folded during the Late Miocene to Pliocene period. Stratigraphy consists of competent limestones and incompetent marly/shaly formations, dipping about 45˚ to the southeast in the area of interest (Thury and Bossard 1996). Where it intersects the rock laboratory, the Opalinus Clay is about 250 m thick. Figure 3 shows a geological section along the motorway tunnel. As a result of differing sedimentation, the Opalinus Clay can be grouped into three facies consisting of a shaly facies, a sandy facies and a carbonate-rich facies. The ED-B tunnel is located entirely within the shaly facies. One major fault runs through the rock laboratory south of the ED-B tunnel and a number of discrete minor faults have been observed throughout the rock laboratory. Structurally controlled instability is not believed to play a significant role in the ED-B tunnel.

3.2 *In situ* Stresses

The *in situ* stress conditions were measured during a number of campaigns utilizing an assortment of techniques such as undercoring, slotter and hydrofracture. However, the results were somewhat unclear as some of the findings were not in agreement, and occasionally appear to conflict. Martin and Lanyon (2003a) have investigated the various stress measurement programs and pertinent observations and have recommended the stress tensor known as the *Rosas 1* tensor, obtained using the undercoring method. The magnitude and orientation of this stress tensor is shown in Figure 4. The maximum principal stress (6.5 MPa) is sub-vertical and agrees well with the estimated vertical stress due to overburden ($\sigma_v = \gamma z =$ 6.6 MPa). The orientation of σ_2 is approximately parallel to the ED-B tunnel axis, while σ_3 is nearly perpendicular.

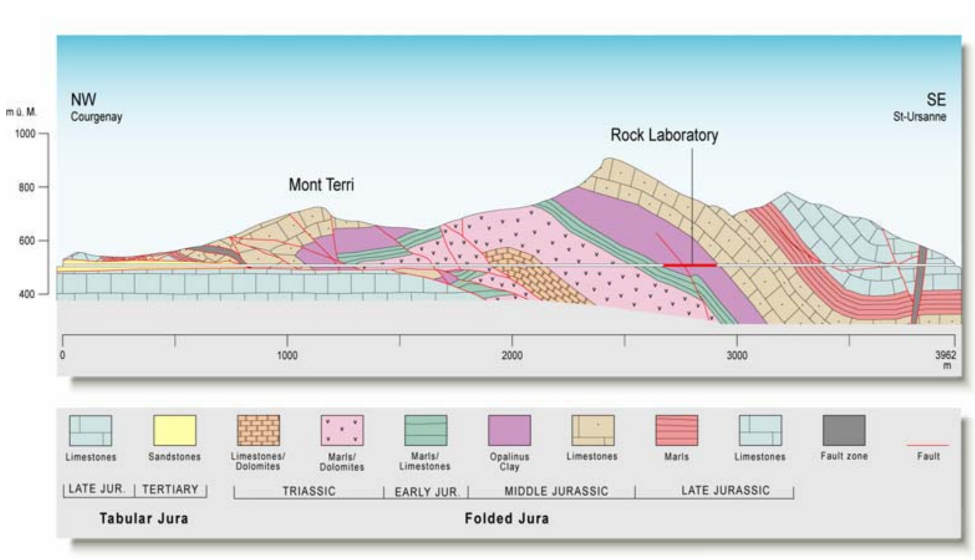

Figure 3: Geological profile along Mont Terri motorway tunnel (from www.mont-terri.ch).

The magnitude of σ_3 is very low and results in an extreme horizontal to vertical stress ratio (k) of 0.09 in the plane perpendicular to the tunnel (i.e. plane stain orientation). It should be noted that there is some uncertainty associated with the magnitude of σ_3.

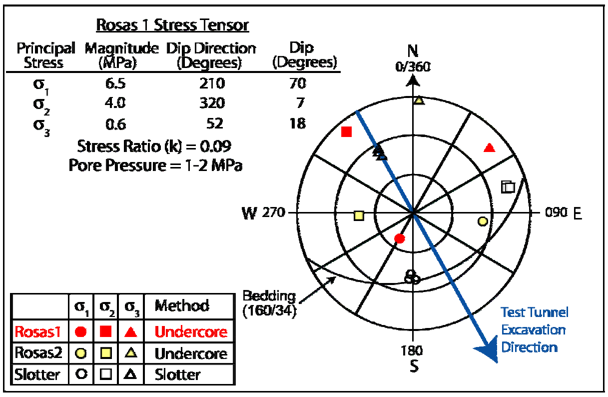

Figure 4: *Rosas 1* is the recommended *in situ* stress tensor at Mont Terri (from Martin and Lanyon 2003a).

4. MINE-BY EXPERIMENT

In addition to the many other field tests carried out at Mont Terri, a mine-by experiment was conducted during excavation of the 3.6 m diameter ED-B tunnel in 1997-98. This experiment has provided deformation data from a number of instruments, such as inclinometers, extensometers and convergence arrays, with time as the excavation advanced (Fierz 1999). Most of the instrumentation was installed from the Security Gallery located approximately 24 m away from the ED-B tunnel *prior* to excavation (see Figure 5). One multipoint extensometer was installed in Borehole BED-B5 as well as 3 instrumentation casings capable of acting as both sliding micrometers and horizontal inclinometers were installed in Borehole BED-B6 through –B8. Three sets of five point convergence arrays were installed in the ED-B tunnel just behind the excavation face as it advanced. The instrumentation layout is shown in plan and section in Figures 5 and 6, respectively. The deformation instruments were measured 19 times between September 1997 and June 1999.

A number of piezometers were installed as part of the mine-by experiment. Unfortunately, it appears that mechanical effects, such as squeezing and fracture initiation, dominate measurements near the tunnel, thus greatly reducing their applicability.

Following instrumentation, the ED-B tunnel was excavated full face using mechanical methods with a roadheader. Excavation was carried out from a northwest to southeast direction. The tunnel was stable during excavation and about 200 mm thick steel fibre reinforced shotcrete support was installed. The excavation was generally stable and shotcrete was installed approximately 7 m behind the excavation face.

Instruments such as micrometers and inclinometers measure the incremental displacement at discrete intervals along the instrument. These are integrated along the instrument length to get the cumulative displacements that represent (after appropriate corrections) the total displacement of the instrument in the ground. A major assumption is that there is at least one known fixed point along the instrument to act as a datum. In the case of the inclinometers and sliding micrometers for the mine-by test, it was assumed that the collars, located greater than 24 m from the new excavation, would be the fixed points. However, the instrumentation data clearly shows that large deformations were recorded at these points as the ED-B excavation advanced.

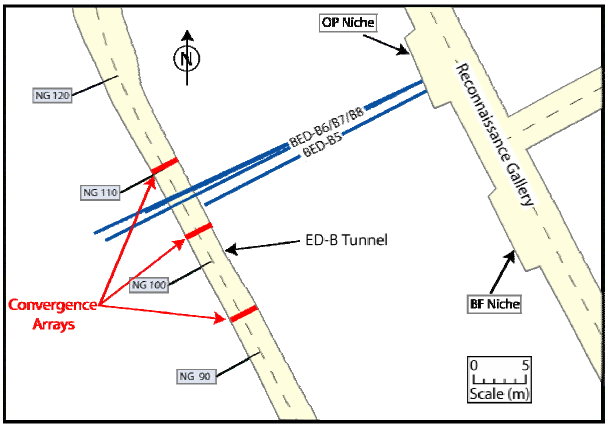

Figure 5: Layout of instrumentation for ED-B mine-by test showing inclinometers/extensometers and convergence arrays.

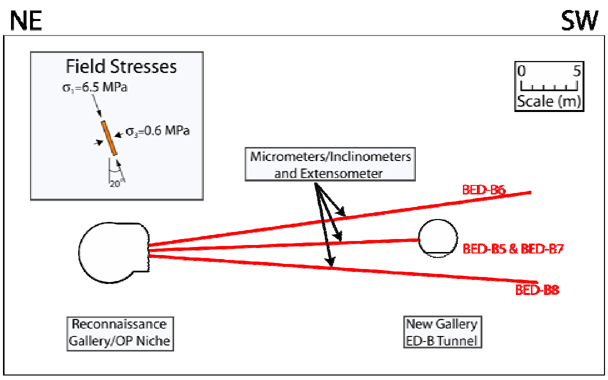

Figure 6: Elevation view looking southeast in the direction of excavation advance.

Upon careful observation of the instrumentation data, a point approximately 8 m from the Security Gallery showed the least amount of relative movement. The amount of movement that did occur at this point is unknown, but FEM modelling indicated it would be negligible in comparison with the magnitude of movement typically measured along the instruments. As such, the 8 m point was used as the new datum assuming zero movement here. The deformation data was readjusted with the new datum using the following convention when looking towards the southeast (direction of excavation): positive movement is upward and negative is downward for inclinometers; and positive is to the right and negative is to the left for micrometers. This removes the more difficult concept of instrument "extension" and "contraction" for the micrometers and presents a more intuitive meaning to the inclinometer and micrometer data.

5. NUMERICAL MODELLING

A two-dimensional, isotropic, elasto-plastic analysis using the FEM code Phase2 was used for the analysis. A total stress (undrained) analysis was used to model the Opalinus Clay. According to Anagnostou and Kovari (1996), tunnelling in materials of this permeability and rate of advancement are considered undrained conditions. An effective stress (drained) analysis was also carried out for comparison because the extent of applicability of effective stress concepts to some argillaceous materials like the Opalinus Clay may be questionable (Martin and Lanyon 2003a). Purely elastic, elastic perfectly-plastic and elastic brittle-plastic constitutive models were used for both total and effective stress analyses.

5.1 Modelling Methodology

A simplified methodology was adopted to simulate the known physical conditions and construction sequence of the ED-B mine-by test as closely as possible. A three-noded graded mesh was automatically generated by Phase2 around the user defined excavation, stage and exterior boundaries of the problem. The nodal spacing for the mesh was approximately 0.1 m in the vicinity of the ED-B tunnel and decreased with distance. The boundary nodes were fixed (zero displacement) in both "x" and "y" and constant far-field stresses corresponding to the *Rosas 1* tensor were initiated throughout the model. The chronology of events associated with the mine-by experiment was simulated using a six-staged model. These stages consisted of:

Stage 1: The initial stage where far-field stresses (*Rosas 1*) and boundary conditions were applied.

Stage 2: In order to simulate installation of the shotcrete liner *prior* to full convergence of the Reconnaissance Gallery, the modulus softening method was used (Curran *et al.* 2003). This consisted of reducing the elastic Young's modulus by 50 %, then installing the 200 mm shotcrete liner.

Stage 3: Excavation of the Reconnaissance Gallery allowing the liner and ground to come into equilibrium.

Stage 4: The OP niche was excavated and lined with shotcrete. This point corresponded in real time to installation of instrumentation.

Stage 5: Excavation of ED-B tunnel, leaving it temporarily unsupported. The invert was left in place at this stage.

Stage 6: Installation of the shotcrete support and cutting through of the invert (later replaced by a concrete invert).

As mentioned previously, during excavation shotcrete support was not required at the tunnel face and lagged excavation by up to 7 m. By this time the majority of the deformation had occurred. Therefore, most of the deformation measured by instrumentation occurred between Stages 4 and 5 in the model. It is these deformations that are compared to the measured instrumentation data.

5.2 Model Parameters

Model parameters are based on a summary of rock mechanics data compiled by Helmut Bock (2000) for the Opalinus Clay at Mont Terri. As mentioned previously, the Opalinus Clay is highly anisotropic and averaged properties were used for the isotropic model discussed here. Table 2 below shows the parameters used for the Opalinus Clay in the elastic brittle-plastic models. The constitutive model used was characterized by cohesion dominated peak strength and frictional residual properties, as suggested for weak rock by Hoek *et al.* (2004).

Table 2: Elastic brittle-plastic modelling parameters.

Analysis	*Peak strength*		*Post-peak strength*	
	ϕ Deg.	c MPa	ϕ_r Deg.	c_r MPa
Total stress	0	6.5	23	0
Effective stress	25	1	23	0

6. RESULTS AND COMPARISON

The data obtained from the ED-B mine-by test provided a very comprehensive set of measurements and observations for comparison with the FEM model. The deformation measured around the ED-B tunnel by the instrumentation show fairly unique signatures with all deformations tending inwards towards the tunnel. However, as already discussed it presented some challenges in interpretation.

To gage the results of various constitutive models, elastic and perfectly-plastic models have been conducted in addition to the brittle-plastic analysis. The deformation magnitudes from the elastic and perfectly-plastic analyses do not approach those observed in the field. For clarity of comparison, only the results of the brittle-plastic analysis are shown in the various plots in this section.

Convergence arrays provide a relatively simple and reliable form of directly measuring tunnel wall deformations, with the sign convention that positive convergence is *inward* tunnel deformation. Because the convergence arrays were installed behind the excavation face, approximately 1/3 to 1/2 of deformations occurred before their installation and were not included in the measurements. This means total convergence from tunnel excavation is significantly discounted. The deformation magnitudes and trends were very similar for all three sets of convergence arrays and average convergence from the three arrays is shown on Figure 7 with the results from the FEM modelling. Due to the nature of the two-dimensional staged model, the data from the model includes all of the deformation associated with the ED-B tunnel excavation.

Figure 7 also shows the layout of a typical convergence array looking in the direction of excavation advance (southeast). By far the largest deformations occur along convergence line 2-5 which are roughly in the direction of σ_1. Apart from convergence line 2-5, the trends of convergence show a reasonable match although the magnitudes from the model are not achieved, especially considering that the field measurements only pick up a portion of total deformation.

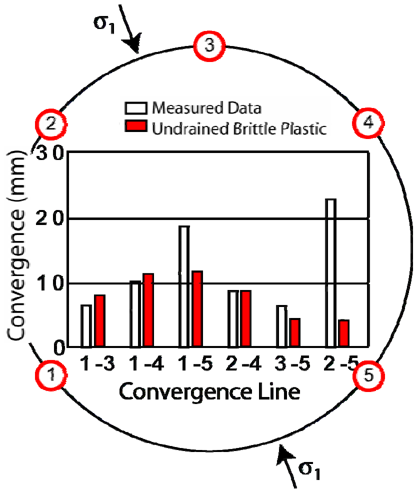

Figure 7: FEM data and average measured convergence data. Note that significant portions of the deformations are not picked up by the instrumentation.

The instrumentation installed from the OP niche provides excellent data over a large extent of the rockmass around the ED-B tunnel. 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 same sign convention discussed previously. The cumulative deformations for sliding micrometers and inclinometers in Boreholes BED-B6 through –B8, along with the corresponding model data, are shown in Figure 8. The inclinometers above and below the tunnel show a maximum of about 8 mm of inward movement with the maximum deformation approximately in line with the direction of σ_1. Similarly, the micrometers show a maximum of about 3 mm of horizontal movement towards the tunnel with a transition between positive and negative movement approximately in the direction of σ_1.

Inclinometer data generally show a good fit to the model data for all instruments throughout their length except BED-B7. The modelling data for inclinometer BED-B7 shows good agreement with the measured data near the collar, but has the opposite orientation near the ED-B tunnel. This is understandable because it occurs along the neutral axis of the tunnel in a zone of transition between positive and negative vertical displacement. In general micrometers show a good fit near the collar, but the most notable deficiency is the poor fit of the micrometer data above and below the ED-B tunnel (BED-B6 and –B8). A multipoint extensometer was installed in Borehole BED-B5 from the OP niche to the ED-B tunnel in the same orientation as BED-B7. Both instruments show a good fit to the model data throughout their length. Data from this extensometer show similar deformation magnitudes and trends as micrometer BED-B7, except the deformations occur over a more discrete zone closer to the tunnel.

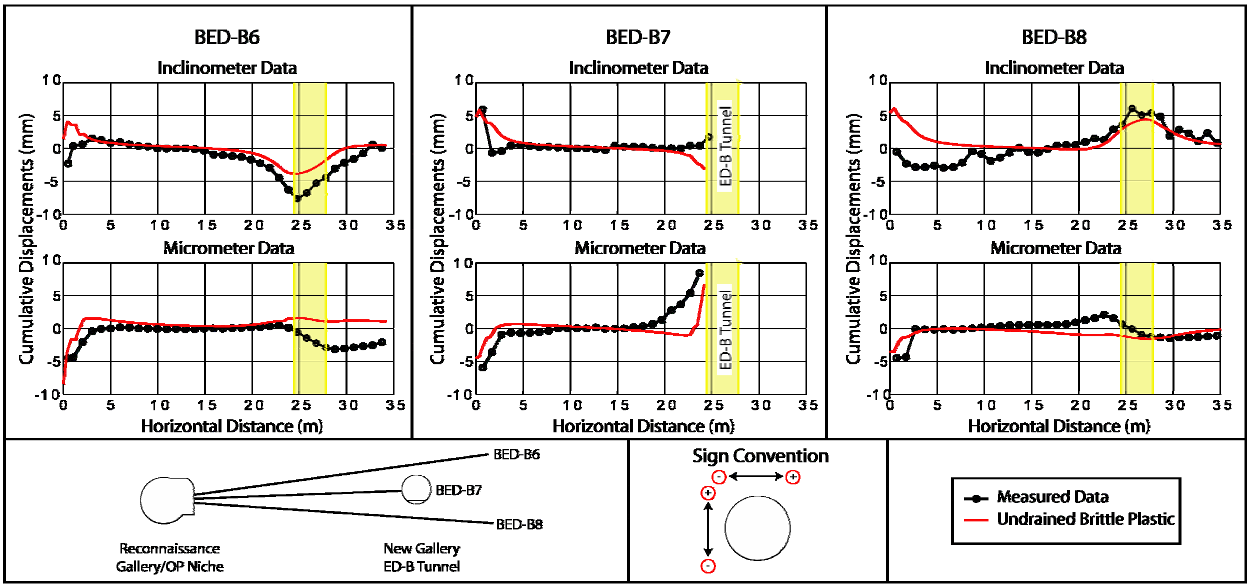

Figure 8: Results of FEM analysis compared with measured data for cumulative inclinometers and sliding micrometers.

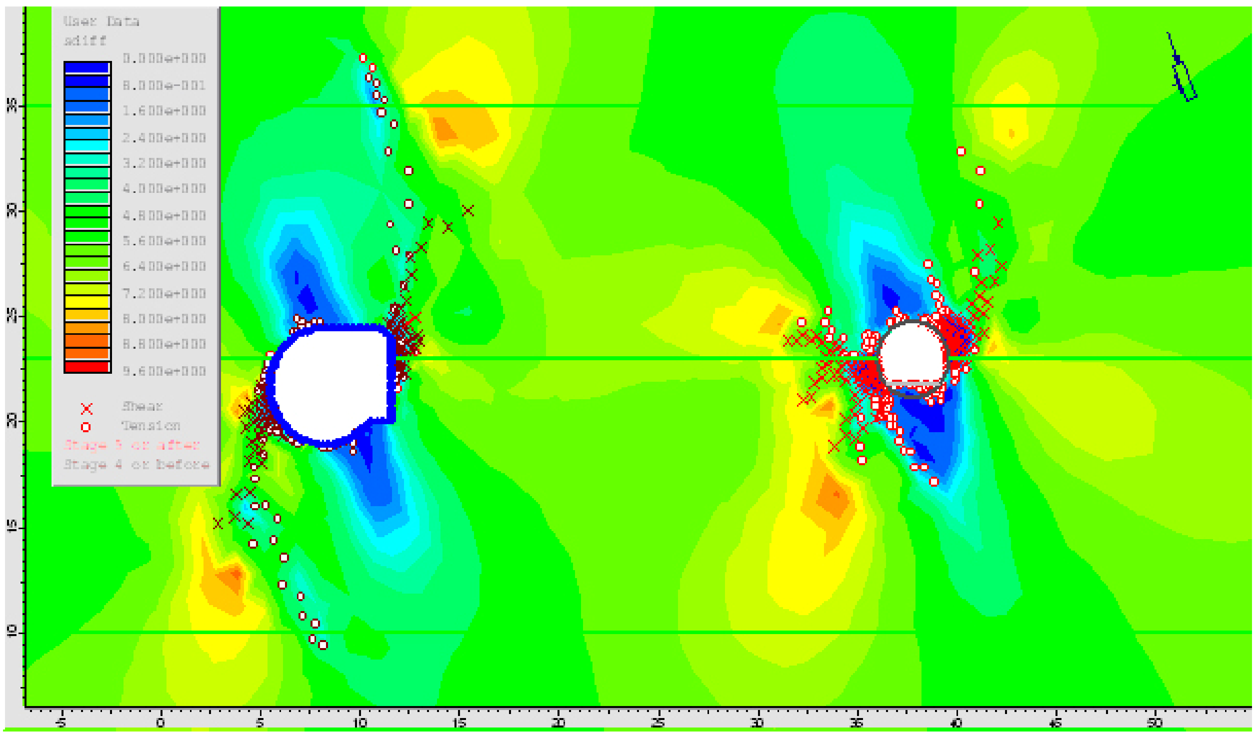

Figure 9: Phase2 model looking southeast showing yielded elements and contours of deviatoric stress (MPa).

Deformations in Figure 8 demonstrate that a good match of the deformation signatures was achieved by the simple brittle-plastic model. Inclinometer data appears to be modelled better than micrometer data. This could be due to anisotropy in the material that was not captured by the purely isotropic FEM model. Interestingly, the best match occurred near the collar of the boreholes around the OP niche, as opposed to the ED-B tunnel itself. These indicate outward movement of the OP niche wall with excavation of the ED-B tunnel. This movement was predicted by the model, measured by the instrumentation and observed by severe damage to the shotcrete in the OP niche (Corkum 2004). According to the instrumentation and modelling, the zone of damage is isolated within the first 3 m of the borehole collars/niche wall.

The pattern of yielded elements observed around the ED-B tunnel from the FEM analysis is shown in Figure 9. It consists mainly of shear failure mode near the tunnel wall and develops into tensile yielding away from the tunnel. These yielded elements are concentrated along the sidewalls of the tunnel in the direction of the minimum principal stress where the maximum deviatoric stress occurs. The failure pattern extends greater than a tunnel diameter in a diagonal direction before trending towards a more vertical orientation away from the tunnel wall. The pattern of yielded elements is unsymmetrical, probably because of the affects of the invert in the floor of the ED-B tunnel.

7. DISCUSSION

The goal of the analysis presented in this paper has been to identify the major issues contributing to the behaviour of Opalinus Clay around a circular excavation. The main limitations were that the following were not given direct consideration:

- Hydromechanical coupling.
- Material anisotropy.
- Time dependant behaviour.
- Three-dimensional geometry.
- Excavation advance.

There is some debate regarding the *in situ* stress tensor at Mont Terri, in particular the low value of σ_3. The recommended value of 0.6 MPa is lower than the measure value of pore pressure (2 MPa). A parametric study varying the value of σ_3 between 0.6 and 2.2 MPa was conducted as part of this programme. This study found that as the value of σ_3 increased (increased k), the magnitudes of deformation decrease, but the deformation trends remained fairly constant for the range of *in situ* stresses considered. Unfortunately, this study was unable to further constrain the stress tensor at Mont Terri.

For most soft rocks, the *in situ* stress ratio is often close to one. With these stress ratios, a typical elastic deformation pattern has inward movement all around the circular excavation with maximum deformation in the direction of the maximum principal stress. However, with stress ratios below 0.3, such as that measured at Mont Terri (k=0.09), the stress pattern again has maximum inward deformation in the direction of the maximum principal stress, but in the direction of the minimum principal stress deformations move *away* from the excavation. As mentioned, all measured data shows inward movement all around the tunnel.

A field study called the Fracture Propagation (FP) study (Möri and Bossard 1999) was carried out to investigate the extent of the EDZ around the ED-B tunnel. Resin was injected into the formation under controlled pressure and then core samples were taken. This allowed for careful observation of the frequency, orientation and mode of failure. The results show that the EDZ extended around the ED-B tunnel approximately 0.5-1 m from the tunnel boundary. The dominant mode of yielding identified consisted of open extensional fractures. These fractures have also been observed on excavation walls where the EDZ has been intersected. Interestingly, these extensional features have not been identified in the excavation face.

The location, if not the correct mode, of yielded elements within the first 1 m of the tunnel wall has been adequately matched by the model. However, a significant disagreement between field conditions and model results was the difference in the failure pattern and mode of yielding away from the tunnel wall. There has been much speculation on the physical processes that result in the failure pattern observed in the field. Deformations were more accurately matched away from the tunnel wall, but the magnitudes of deformation were not achieved in the near-field. These observations indicate that near-field deformations were dominated by non-elastic behaviour associated with the failure mode identified in the FP study.

Deformations observed at the instrumentation borehole collars (see Figure 8) indicated inward movement of the OP niche. This observation has been further verified by significant shotcrete damage in this area. During cementation of the instruments in the OP niche, water was released into the network of EDZ fractures around the niche (Peter Blümling, pers. comm.). A short time after this, (also corresponding to the excavation of the ED-B tunnel) significant deformations of up to 0.5 m were observed in the OP niche. This was accompanied by extensive shotcrete damage. Water continues to be observed slowly dripping out of the formation along cementation lines. A sampling programme conducted in this area showed only slightly increased *in situ* water content. This indicates that swelling alone would probably not be sufficient to explain the large deformations.

The neighbouring BF and PP niche's have not experience shotcrete damage to the same extent as the OP niche, indicating that the phenomenon is somewhat isolated. Whether it is the inherently less competent rockmass, degradation of the rockmass properties due to ingress of water, or formation water travelling along the borehole, is not apparent. From elastic analysis alone, no movement of these borehole collars would be predicted, but based on the instrumentation, it appears that the trigger mechanism for this displacement was indeed excavation of the ED-B tunnel. The observations regarding the impact of the ED-B tunnel on the OP niche show that three-dimensional geometry is an issue at Mont Terri even at significant distances. During tunnel driving there are other geometrical features involved, such as corners and intersections and face advancement itself is a three-dimensional problem. Finally, the recommended stress tensor is not in exact alignment with the tunnel direction adding another three-dimensional component to the problem.

8. SUMMAY AND CONCLUSIONS

This paper has presented preliminary results of modelling the behaviour of Opalinus Clay (claystone) around a circular excavation at the Mont Terri rock laboratory, Switzerland. Field data from a mine-by test of the ED-B tunnel has provided a fairly comprehensive set of data with time and excavation advance. The analysis presented in this paper has demonstrated that a simplified total stress model, using the recommended stress tensor and material properties, was able to achieve a reasonable match to field measurements. This provided insight into the major issues that require further consideration to accurately capture the behaviour of Opalinus Clay around underground openings.

Three-dimensionality is a strong issue in this problem for a number of reasons and must be given consideration in any future modelling of the ED-B tunnel. Modelling and field observations from the ED-B mine-by test have shown that tunnel interaction at Mont Terri can occur over distances much greater than would be expected based on elastic solutions. The analysis described in this paper was able to predict this interaction. The continually increasing frequency of openings at Mont Terri may require interpretation of the system-wide response for future analyses.

The fracture propagation study has shown that the EDZ was dominated by frequent open extensional fractures within the first 1 m of the tunnel wall. Near-field deformations were dominated by non-elastic behaviour. Although reasonably successful in modelling the instrumentation response, the FEM model was unable to accurately capture this mode of failure.

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