Evaluation of roof-pillar interface and its effect on pillar stability in mine #101

Viktor Lönnies

Civil Engineering, masters level
2017

Luleå University of Technology
Department of Civil, Environmental and Natural Resources Engineering
Evaluation of roof-pillar interface and its effect on pillar stability in mine #101

Viktor Lönnies

2017

Master Programme in Civil Engineering
Soil and Rock Engineering

Luleå University of Technology
Department of Civil, Environmental and Natural Resources Engineering
Preface

This report is part of my studies for a Master’s degree in Civil Engineering with specialization in Soil and Rock Engineering at Luleå University of Technology (LTU). This thesis work was conducted starting in September 2016 until January 2017 and is the result of collaboration between Universidade Federal do Rio Grande do Sul (UFRGS) and LTU. The work would not have been possible without the support of Professor André C. Zingano and Dr. Tristan Jones. I also wish to express my gratitude towards the Luiz Englert foundation for financial support during the project.

Since this is the final of my studies at LTU, I want to thank family, friends and staff at LTU for their support and willingness to teach during my studies.

Stockholm, January 2017

Viktor Lönnies
Summary

The company Rio Deserto is currently mining the famous Barro Branco coal seam in the state of Santa Catarina located in the south of Brazil. One of their coal mines, #101, is experiencing problems related to the pillars in one panel. The coal seam is slightly inclined and several pillars have developed damages on the down-slope side with focus in the top corner. Damage inspections revealed a thin clay layer located between the coal pillar and the overlying siltstone. The clay layer is believed to affect the pillar strength and possibly be a source for the observed damages. Aim of this report has been to evaluate different theories behind the damages, focusing on the clay interface using numerical modelling with FLAC. Using convergence data, a calibration of the model is initially done before evaluating the combination of different interface and coal strength while observing the pillar. In addition is an evaluation of influence from structures such as cleats/joints. The results clearly show that with a small shear displacement (1-4 mm) the pillar damages are almost symmetrical on the up-slope and down-slope side of the pillar. Structures can influence and contribute to non-symmetrical pillar damages although not perfectly matching the field observations. Furthermore, the results show that a forced shear movement (8-25 mm) best reproduce the observed damages. A shear movement along the interface is therefore believed to be source mechanism behind the pillar damages. The forced shearing can potentially be explained by factors not considered in the model such as horizontal stresses, disturbances by mining and presence of water within the clay.
Sammanfattning

Contents

1. Introduction ............................................................................................................. 1
   1.1. Background ......................................................................................................... 1
   1.1. Aim and purpose ................................................................................................. 1
   1.2. Delimitation ......................................................................................................... 2
   1.3. Layout of report .................................................................................................. 2

2. Site description ....................................................................................................... 3
   2.1. General ................................................................................................................. 3
   2.2. Geology ............................................................................................................... 4

3. Theory ..................................................................................................................... 5
   3.1. Room and pillar mining ..................................................................................... 5
   3.2. Pillar design ....................................................................................................... 5
   3.3. Rock and coal interface .................................................................................... 7

4. Methodology ........................................................................................................... 9
   4.1. Numerical modelling ........................................................................................ 9
       4.1.1. Model set up ................................................................................................. 9
       4.1.2. Material parameters .................................................................................. 10
       4.1.3. Interface parameters ................................................................................ 11
       4.1.4. Modelling procedure .............................................................................. 12
   4.2. Calibration with instrumentation data .............................................................. 13
   4.3. Evaluation of influence from interface on pillar ............................................. 15
   4.4. Structures in coal seam .................................................................................... 16
   4.5. Increased shearing between roof/pillar ......................................................... 17

5. Results .................................................................................................................... 19
   5.1. Evaluation of influence from interface on pillar ............................................. 19
   5.2. Structures in the coal ....................................................................................... 22
   5.3. Increased shearing between roof/pillar ......................................................... 25

6. Analysis ................................................................................................................. 26

7. Discussion .............................................................................................................. 29

8. Conclusions .......................................................................................................... 30

9. Recommendations and future research .............................................................. 31

10. References .......................................................................................................... 32

11. Appendix .......................................................................................................... 33
1. Introduction

1.1. Background

One of Rio Desertos current underground mines is called #101 because of the location under a main highway with the same name. The mine is located close to the Atlantic Ocean in the south of region Santa Catharina in Brazil and borders the region of Rio Grande do Sul. The mine has recently experienced problems with the pillars in a specific panel of the mine. After development and excavation, cracks and fractures have developed in the pillars. Most of the damages, but not all, have developed on the down-slope side of the pillar with focus in the top corner. The pillars were immediately supported with steel mesh and bolts (Figure 1). All mining activities in the area have been halted in order to ensure the safety of personnel and machinery until there is a solution to the problem. Upon damage mapping a clay interface between the pillar and the roof was discovered (Figure 1). It is believed that this thin clay layer possibly affects pillar stability.

Figure 1 Left: Pillar damages and steel mesh used for support. Right: Clay interface between pillar and roof. Photo: André Zingano

This master thesis project is the result of a collaboration between Universidade Federal do Rio Grande do Sul (UFRGS) in Porto Alegre in Brazil and Luleå University of Technology. Most of the project has been performed at UFRGS but also from a distance in Sweden.

1.1. Aim and purpose

The aim of this report is to evaluate theories regarding the pillar stability in mine #101. This will hopefully lead to an increased understanding of why the damages have occurred and can be advisory for future mining in nearby areas that may potentially experience the same pillar problems. The project will focus on evaluating the main theory regarding the source mechanism that involves a clay interface between the roof and the coal pillar. This will be done by conducting numerical modelling for the required section and calibrating the model with available instrumentation data.

The scope of this project will therefore be:

- Create a numerical model over a specific section of mine
- Calibrate model with instrumentation data
- Evaluate influence from interface
- Investigate joints/cleats as a possible source for damages
1.2. Delimitation
There is no information related to in-situ rock stress and the panel of interest is located on less than 60 meters depth. Therefore it is assumed that only gravitational stresses are acting and no tectonic stresses. The rock mass conditions are also assumed to be dry i.e. no water is present.

1.3. Layout of report
After the introduction chapter follows a general site description which covers the mine and the geology. Next is a theory chapter which gives information about room-and-pillar mining, general information about pillars and pillar design. It also gives information about research related to pillar-interfaces and numerical modelling. The fourth chapter covers the methodology used in the project. It includes how to set up the model, material and interface parameters used and the modelling procedure. This chapter also gives information about the model calibration and all the different scenarios modelled. Thereafter are the results from the project displayed prior to an analysis. Finally are the discussion, conclusion and recommendations.
2. Site description

2.1. General
The Brazilian company Rio Deserto have been active and produced coal since the beginning of the 20th century. Although focus is on mining Rio Deserto is a diverse company and active in other areas such as forestation, agronomy and metallurgy. The mining operations have mainly been localized to one of the more southern regions in Brazil called Santa Catharina. Today mining is carried out in a total of two locations using the technique of room- and- pillar mining. One of Rio Desertos current mines is called #101. The mine has been in production since 2010 and is the company’s largest underground mine with a yearly production of 600,000 tonnes. The mine is located next to the Atlantic coast close the city of Criciúma and can be seen in Figure 2.

![Figure 2 Map over southern Brazil and location of mine.](image)

The mine covers an approximate area of 1500x1000 meters as is located at a depth less than 90 meters. It is today considered an important employer in the region and roughly 200 people are employed at the mine. The mine implements the technique of room-and-piller mining and is today scheduled to be in production until 2031. Core drilling has indicated an extension of the orebody in the north-south direction and the mine is therefore planned to be extended this way which can be seen in Figure 3.
2.2. Geology

The geology in the area consists of layered sedimentary rocks. Commonly layers of coal, siltstone and sandstone are alternated and repeated with varying thicknesses. There are two wide spread coal seams in the area known as Barro Branco and Bonito Inferior. The Barro Branco seam is shallower and can be found at a depth of ~40-60 meters while the Bonito Inferior seam is located deeper approximately at 85 meters depth. Mine #101 is only mining the Barro Branco seam together with a total of three other mines. The coal in Barro Branco seam and more specifically in the panel of interest is fractured having a RQD of 29% while the siltstone is more competent having a RQD of 72% (Appendix 1). A thin layer of coal covering a layer of siltstone is displayed in Figure 4.

Many faults have been located in the area of interest. Most faults have a clear east-western direction and approximately 20-30 faults intersect the specific panel. These faults have a varying width from 0.05-0.5 meters and are almost perpendicular to the panel. The coal seam is not entirely horizontal but dipping slightly to south-east. In the section of interest the strike of the orebody is approximately 20° and the dip is 7°.
3. Theory

3.1. Room and pillar mining

One of the most popular mining methods for horizontal or nearly horizontal deposits is room-and-pillar mining. The method is a so called unsupported mining method and is widely used for soft rock deposits like limestone and coal as well as in hard rock. In a room-and-pillar mine openings are driven perpendicular to each other and when intersected square shaped pillars are created in a repetitive pattern. The final outline of room-and-pillar mine resembles a checkerboard pattern with identical sized pillars. Room-and-pillar mines can be developed with either conventional methods (drill and blast) or in soft rock deposits continuous mining. Mine #101 mainly use the technique of continuous mining. Some of the characteristics for room-and-pillar mining are shown below (Hartman & Mutmansky, 2002):

- Poor recovery without pillar extraction
- Inflexible method
- Good ventilation
- Low dilution
- Suitable for mechanization
- Production on multiple locations.

3.2. Pillar design

Pillars are defined as the remaining rock mass between excavations or openings. For room and pillar mines it is most common with vertical pillars but for other mining methods horizontal pillars are widely used. Regardless of the orientation of the pillar, its purpose is still to stabilize the remaining rock mass and it is to be considered an important construction element in the mine. There are different types of pillars depending on the orientation and location and some can be seen in Table 1 (Sjöberg, n.d.).

Table 1 Different types of pillars that can be found in a mine.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier pillar</td>
<td>Pillar dividing different mining area</td>
</tr>
<tr>
<td>Rib pillar</td>
<td>Barrier pillar with its long axis in the dip direction of the orebody</td>
</tr>
<tr>
<td>Panel pillar</td>
<td>Pillars within a mining panel (mining area)</td>
</tr>
<tr>
<td>Sill pillar</td>
<td>Horizontal pillar used in cut-and-fill and open stope mining</td>
</tr>
<tr>
<td>Crown pillar</td>
<td>Horizontal pillar at the top of an orebody or stope.</td>
</tr>
<tr>
<td>Shaft pillar</td>
<td>Pillar around a shaft</td>
</tr>
<tr>
<td>Dip pillar</td>
<td>Pillar oriented perpendicular to the sidewalls/orebody</td>
</tr>
</tbody>
</table>

In a room-and-pillar mine most of the pillars are developed well inside the orebody as mining progresses. This means that most pillars consist of the same ore as what is currently being mined. Thus do large-size pillars affect the total extraction rate for the mine and from an economical perspective the pillar size should be kept to a minimum without risking the safety (Sjöberg, n.d.).

Pillars in rock are designed with a comparison between the stress and the strength of the pillar. Empirical formulas are commonly used. The normal procedure for the design is not to analyse the maximum stress, which is custom in many engineering fields and geomechanics, but instead use the average stress in the pillar. The reason behind this procedure is that there are often difficulties in determining the in-situ strength properties of the material, as well as the complex loading conditions in pillar mining (Wagner & Eng, 1980).
One of the consequences of considering the pillar as a unit is that local failure can occur in a single point in the pillar without risking the stability of the entire pillar. When local failure occurs the stresses are just redistributed to adjacent points, thus is the bearing capacity for entire pillar not exceeded (Sjöberg, n.d.).

Assuming that the stress is shared equally through the pillar is a gross simplification. In reality, the loading situation is more complex. Wagner, (1974) showed by subjecting coal pillars to hydraulic-jack-induced stresses that the outer portions of the pillars are initially subjected to high stresses. As these areas fail first the stresses are transferred inwards the pillar to the core. The outer failed portions may not be able to take any further load, but still serve an important purpose by adding confinement to the core. This confinement allows the inner core to take further load, even though the peak strength of the overall pillar has been exceeded. This can be seen in Figure 5.

![Figure 5 Stress profiles through a coal pillar measuring 2 m in width and 1 m in height at various stages of pillar failure (Wagner & Eng, 1980)](image)

The confinement stress, also referred to as the minor principal stress, is to a large degree dependent on the shape of the pillar. Wider pillars tend to generate larger confinement for the core resulting in an increased load bearing capacity than for a slim pillar. Even the height of the pillar plays an important part for the minor principal stress within the pillar. If combined together these two geometrical measurements describe the slenderness of the pillar which is most often referred to as the width-to-height ratio (W/H).

As stated above, the minor principal stress is important for pillar strength. There are numerous criterions available to calculate the shear strength in geotechnical engineering but the Mohr-Coulomb criteria is the most common and considers the confinement. The shear strength can be calculated according to Equation 1).

$$\tau = c + \sigma_3 \tan \varphi$$  \hspace{1cm} (Eq. 1)

Where $c$ and $\varphi$ are material parameters and $\sigma_3$ is the minor principal stress. Using the above equation it can be seen that the confinement ($\sigma_3$) have a large impact on the shear strength.
3.3. Rock and coal interface

For many coalmines there is a clear distinction between the coal pillars and the host rock. The interface connecting the material layers is seldom taken into account when designing pillars although it may have a large impact on pillar stability. Research conducted by Peng (1978), Wagner (1974), Iannacchione (1990) and Lu, Ray, Morsy, & Peng (2008) have evaluated the interface effect on rock samples and pillar stability. In the 1970’s Peng conducted several experiments with cylindrical rock samples under different interface conditions. It was concluded that even though the rock material was the same, the strength of the rock could vary as much as 100% by changing the interface properties (Peng, 1978). Therefore, the strength of the rock samples depends to a large extent on the interface connecting the sample to the testing machine. Wagner conducted similar research in which he evaluated the effect from adding a softer material next to the rock sample. In the experiments he added a thin lead sheath between the rock sample and the testing machine while evaluating the strength of the sample. Wagner also compared failure modes between experiments using no sheaths, one sheath and sheaths at both ends. Unfortunately the results were never fully published but it was concluded that not only did large changes of strength occur for the samples but also different failures modes (Wagner & Eng, 1980). Looking at the result it seems as no sheath between the rock and testing machine result in hour-glass shaped damages. Lead sheaths at both ends cause a failure mode of shearing while a sheath at one end cause damages on the same side (Figure 6).

![Figure 6 Effects of end constraints on mode of failure of rock samples. Left: Interface between rock and steel platen. Centre: Thin lead sheath on both contacts. Right: Thin lead sheath on top contact only (Wagner & Eng, 1980)](image)

From Peng and Wagners research it can be stated that the strength of a rock sample can possibly be reduced if a weak interface is present. It can be explained that once slip occurs along an interface, the horizontal stress component is significantly reduced, affecting the confinement and thereby reducing the overall strength of the pillar (Iannacchione, 1990). If no interface is present, or the interface connection is glued, slip is restricted resulting in an increased minor principal stress in the pillar. Hence, low resistance to slip along the interface result in a low-strength pillar with spalling as the likely failure mode, while high resistance to slip create a triaxial stress state with the likely failure mode of shearing.

Additional research by Lu, Ray, Morsy, & Peng (2008) investigated how the confinement effect (W/H ratio) changes together with the interface strength. The study observed how these factors affected the average minimum principal stress for a coal pillar by numerical modelling. It was found that for low interface strengths the influence from increasing the W/H ratio on the minor principal stress in the pillar was significantly reduced. The research also concluded the opposite in which a high strength interface magnifies the confinement effect induced by the W/H ratio. The reasearch also indicated that the material behaviour changed from brittle plastic to strain hardening when the interface strength was increased (Figure 7).
Figure 7 Average minimum principal stresses with different W/H ratios and interface properties (Lu, Ray, Morsy, & Peng, 2008)
4. Methodology

4.1. Numerical modelling

The problems is analysed using the software FLAC7.0 developed by Itasca Consulting Group Inc. FLAC uses an explicit finite difference method to conduct geotechnical analysis of soil, rock, groundwater and ground support in two dimensions (Itasca Consulting Group Inc., 2011). Depending on the degree of fracturing within the rock mass and the jointing pattern, a rock mass is classified as either continuous or discontinuous. FLAC is designed to handle continuous rock masses. However, in the software it is possible to model a few discontinuities as interfaces. The interfaces in FLAC can account for a shear movement and displacement in the direction of the interface. Meaning it is not possible to model rotation, separation or opening of blocks. If that behaviour is sought and believed to be important, other types of software should be used. In mine #101, only shear movement is believed to be present along the clay interface, thus is FLAC believed to be suitable software to analyse the problem. It is also selected due to availability and previous experience of the author.

The numerical model in FLAC will focus on one pillar and not the entire panel. The pillar damages have occurred on a panel wide basis but a panel pillar with the width of 12 meters is selected for modelling. The pillar orientation is not perpendicular to the dip of the coal seam. In order not having to do 3D model the pillar is slightly rotated to match the inclination.

4.1.1. Model set up

The cross section is modelled looking from west to east. A start block is generated with the dimensions 100 m (width) and 100 m (depth). The upper left corner is located at the surface with the coordinate 0;0 and the bottom right corner at 100; -100. These dimensions are large enough to model the area of interest. The starting block is then split twice horizontally giving each line an inclination of 13% (or 7.4°) which corresponds to the dip of the coal seam in the area. The upper created line is to be the top of the coal seam. It is set to the depth of -56.4 meters at the up-slope pillar corner. The spacing between the two lines is set to 2.1 meters to represent the height of the coal seam. In addition the starting block is splitted four times vertically in the locations of the pillar and the drift. The panel pillar is 12 meters and the widths of the drifts are 6 meters.

Core logging in the area have indicated many alternating layers of silt- and sandstone (Appendix 1). In order to enable modelling the result from the core logging is simplified resulting in 3 layers of material. These layers are modelled by again splitting the block horizontally with the same inclination as above. The immediate superior layer is given a thickness of 5 meters. In order to allow a more unison zooning, two horizontal supporting lines are created with a distance of 15 meters above and below the coal seam.

An interface is created between the coal and the overlying siltstone and gravitational stresses are applied. The zooning is given automatic conditions of MEDIUM for the entire model. In areas above, beneath and within the drifts the mesh is densified two and four times to enable a more square and homogenous zone size. Each zone within the coal seam has a height of 0.35 m. The input information from the mine is somewhat limited. Thus would a very fine zone size not result in a better result.

Horizontal and vertical roller boundaries are applied to the side and bottom of the model while the top is set as a free surface. An additional model is created in which only the part underlying the interface is given roller boundary condition and the upper half is set free. When evaluating and comparing the results between
the two models, little to no difference is observed and therefore only the results from the first model will be presented.

An overview and close-up view of the model can be seen below in Figure 8 and Figure 9.

![Figure 8 Model overview](image)

![Figure 9 Close up view on pillar and opening.](image)

### 4.1.2. Material parameters

Evaluations of the rock material parameters for the coal and siltstone have been conducted by UFRGS, mainly through uniaxial compressive strength and triaxial testing. Due to the complexity of the orebody a wide range of values are available. However, UFRGS have not evaluated rock strength parameters such as friction angle or cohesion for the coal, only compressive strength and Young’s modulus. The strength parameters can be evaluated using GSI values together with results from the compressive strength testing. Although no GSI values are available for the coal seam, core logging has indicated an RQD of 29% (Appendix 1). The RQD value can be used to evaluate the GSI-value according to Equation 2) (Hoek, Carter, & Diederichs, 2013):
where $J_{Cond_{89}}$ is the joint condition.

Neither are values available to describe the joint condition but using the above equation together with chart in Appendix 2 it is reasonable to assume GSI will range between 15 and 35. Adding this into Rocdata together with compressive testing information (Appendix 3) results in a span of values for friction angle (20°-26.5°) and cohesion (0.48-0.79 MPa). The average values (23° and 0.6 MPa) are selected as starting values for further evaluations. Benchmarking also shows that the selected parameters match well with textbooks, which suggest coal to have friction angles between 22° and 27° and cohesion between 0.07 to 1.38 MPa (Farmer, 1983) & (Barron, 1984).

Laboratory testing has also shown large deviations regarding the Young’s modulus for the coal (0.13-8.19 GPa). After an initial testing of the model using different values, a starting value of 1.5 GPa is selected to use in the calibration of the model (Rio Deserto, 2015).

Regarding the siltstone, the Young’s modulus has been established by UFRGS to range between 1.3-5.7 GPa, friction angle to 31° and cohesion to 19 MPa, while no evaluations have been made regarding the sandstone (Appendix 3) & (Rio Deserto, 2015). The sandstone is therefore given textbook values according to the Itasca manual.

No information is available about Poisson’s ratio for any rock material but it is assumed to have a typical value of 0.3.

As stresses will deviate around the opening, tensile stresses will develop in the roof and floor in the drift. No information about damages in this location is available and this area is not in the main interest of this report. At the same time, the sand and siltstone are reported to be fairly competent. Thus are the tensile strengths here assumed to be 0.5 MPa. The coal seam is very layered and reported to be weak. It is therefore assumed to have 0 MPa in tensile strength.

The complete list of material properties used is displayed in Table 2.

### Table 2 Material parameters (Itasca Consulting Group Inc., 2011) & (Rio Deserto, 2015)

<table>
<thead>
<tr>
<th>Type</th>
<th>Density (kg/m³)</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Friction angle (°)</th>
<th>Cohesion (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>2700</td>
<td>19300</td>
<td>0.38</td>
<td>27</td>
<td>27</td>
<td>0.5</td>
</tr>
<tr>
<td>Siltstone</td>
<td>2700</td>
<td>1300-5700</td>
<td>0.3</td>
<td>31</td>
<td>19</td>
<td>0.5</td>
</tr>
<tr>
<td>Coal</td>
<td>2700</td>
<td>130-8190</td>
<td>0.3</td>
<td>20-27</td>
<td>0.48-0.79</td>
<td>0</td>
</tr>
</tbody>
</table>


#### 4.1.3. Interface parameters

The thin clay layer between the pillar and the roof is modelled by adding an interface. An interface in FLAC allows the two sides to slide and move relative to one another. However, it does not allow for separation or rotation but these mechanisms are not believed to be present in-situ. The clay layer is in reality very thin (2-3 cm), soft, and easily washed away by water, hence it was not identified during core logging. No values are available regarding the material parameters for the clay. According to the Itasca manual, a rule-of-thumb for when missing parameters for interface stiffness is to set $k_n$ and $k_s$ to ten times the equivalent stiffness of the
stiffest neighbouring zone. The stiffness is therefore calculated according to Equation 3 (Itasca Consulting Group Inc., 2011)

\[ 10 \times \max \left( \frac{k + \frac{4}{3}G}{\Delta z_{\text{min}}} \right) \]  

(Eq.3)

where \( K \) is the bulk modulus, \( G \) is the shear modulus and \( \Delta z_{\text{min}} \) is the smallest width of an adjoining zone in the normal direction. Values for the bulk and shear modulus are obtained from the overlying siltstone which is stiffer than the coal.

This results in a starting normal and shear stiffness equivalent of

\[ 10 \times \max \left( \frac{3.75 \times 10^9 + \frac{4}{3}1.73 \times 10^9}{0.35} \right) = 173 \text{ GPa} \]

The normal and shear stiffness changes, however, as the stiffness of the surrounding material is varied throughout the modelling.

Regarding discontinuity strength parameters controlling slip, no in-situ measurements have been made. The value for these parameters (\( c \) and \( \varnothing \)) are known to be depending on normal stress, water content, weathering, surface roughness and fill material. Iannacchione (1990) used a friction angle between 10° to 25° and cohesion from 0 MPa to 1.38 MPa for modelling a clay infill. The same range of values are used to represent the connection between the overlying siltstone and the coal seam. In order to simulate a discontinuity with different strengths it is divided into three sets according to Table 3. The glued discontinuity can not slip but can still undergo elastic deformations.

<table>
<thead>
<tr>
<th>Discontinuity strength</th>
<th>Friction angle ( \varnothing )</th>
<th>Cohesion ( c ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glued</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>High</td>
<td>25</td>
<td>1.38</td>
</tr>
<tr>
<td>Medium</td>
<td>17</td>
<td>0.7</td>
</tr>
<tr>
<td>Low</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

### 4.1.4. Modelling procedure

After creation, the numerical model is first solved elastically until equilibrium is reached. This simulates consolidation and initial deformation of the rock mass. The second step is excavation of the drifts which creates the pillar, meanwhile resetting displacement measurements to zero. Thereafter the model is evaluated as a so called fake-elastic material. This means that the cohesion and tensile strength is set unrealistically high making it impossible for the material to fail. The benefit of doing so is that it allow the stresses in the model to deviate around the opening without causing failure. This is normally a procedure which can shock the model and cause unrealistic damages and patterns. After solving the model the correct strength parameters are finally applied. This allows the material to develop damages after additionally solving to equilibrium. The modelling procedure is summarized in Table 4.
Table 4 Summary of modelling procedure.

<table>
<thead>
<tr>
<th>Modelling sequence</th>
<th>Objective</th>
<th>Material behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Consolidate and allow for initial deformations of the rock.</td>
<td>Elastic</td>
</tr>
<tr>
<td>2</td>
<td>Create openings without developing rock damages</td>
<td>Fake-elastic</td>
</tr>
<tr>
<td>3</td>
<td>Allow damages to develop</td>
<td>Perfectly-plastic</td>
</tr>
</tbody>
</table>

4.2. Calibration with instrumentation data

Due to the availability of a large span of material parameters and an uncertainty about their usefulness, an initial calibration of the numerical model with instrumentation data is desirable. The instrumentation data available from mine #101 is convergence measurements which mine survey obtained by installing extensometers in the area. A total of 7 extensometers were installed in the panel of interest just after the pillar damages developed with the objective of measuring the roof and floor convergence. The rate at which the convergence was developing was highest right after installation and the maximum rate for one extensometer was measured to 0.85 mm/day. After one year, the convergence rate had been significantly reduced, measuring on average 0.05 mm/day (Appendix 2).

The roof-floor convergence measured by the installed extensometers shows on varying displacements between 7-22 mm averaging 13 mm (Figure 10).

![Convergence between roof and floor](image)

Figure 10 Convergence between roof and floor (courtesy of Rio Deserto)

It is believed that the roof convergence is mainly influenced by the roof siltstone and the coal. The underlying sandstone’s contribution is believed to be very small. Calibration of the model is therefore done by reducing the elastic strength parameters (Young’s modulus and Poisons ratio) for the coal and immediate siltstone while evaluating the influence from the different interface types. The convergence is always larger in the middle of the drift compared to in the pillar. Since there is no information about where the convergence measurements where installed both the drift and pillar displacements are monitored. Both the up- and down-slope side of the pillar are observed according to Figure 11. The maximal vertical
displacement on either of the sides are used to calculate the convergence separately for the drift and the pillar.

Figure 11 Monitoring points for vertical displacement.

The modelling procedure for the calibration is such that one set of elastic parameters for the coal is combined with the different interface types (Table 3) and three different sets of siltstone stiffnesses. The combinations of elastic parameters used for calibration are therefore the following:

- Coal
  - E=1.5 GPa, v=0.3
  - E=0.3 GPa, v=0.2
- Siltstone
  - E=4.5 GPa, v=0.3
  - E=1.5 GPa, v=0.2
  - E=1 GPa, v=0.2

The resulting roof-floor convergence is displayed in Figure 12 and Figure 13. It can be seen that when the elastic parameters are reduced, the roof-floor convergence is increasing. When applying the lowest values regarding both the siltstone and the coal, the convergence for the drift and pillar results in 9.4 mm and 5.3 mm respectively. In-situ convergence measurements are also believed to be affected by compression and dislocation of the 10-30 mm thick clay layer and not only pillar and roof strain. Therefore are these values believed to satisfyingly represent the coal and siltstone rock masses and are used for further modelling.
4.3. Evaluation of influence from interface on pillar

After the initial calibration an evaluation of the interface influence of the pillar stability is done. The objective is to see how the different interfaces affect the pillar. In order to properly evaluate the influence the following factors are considered:

- Yielded elements
  - The number of yielded elements and the pattern they develop in.
  - Symmetry of pattern
- Minor horizontal stress
- Major horizontal stress
- Maximum shear displacement on interface
  - Interface slip
Once again the four different types of interfaces (glued, strong, medium and weak) from Table 3 are used. As the initial calibration only gave information about the elastic parameters, different sets of values for the coal strength are applied together with the interfaces. Previously the cohesion for the coal seam was stated to range between 0.48-0.79 MPa and friction angle between 20-27°. These values are divided in to three sets according to Table 5.

Table 5 Sets of values used for evaluating the coal strength.

<table>
<thead>
<tr>
<th>Type</th>
<th>Cohesion (MPa)</th>
<th>Friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>0.79</td>
<td>27</td>
</tr>
<tr>
<td>Medium</td>
<td>0.6</td>
<td>23</td>
</tr>
<tr>
<td>Weak</td>
<td>0.48</td>
<td>20</td>
</tr>
</tbody>
</table>

4.4. Structures in coal seam

Structures and joints that occur in systematic sets in coal seams are normally referred to as cleats. Cleats most often develop in two sets perpendicular to one another and also oriented perpendicular to the coal seam. The primary cleat (face cleat) is developed first and is considered a through-going structure. The secondary cleat is created later and ends when intersecting the primary cleat. It is therefore not considered through-going and is sometimes referred to as Butt-cleat. The presences of cleat most often have little impact on production but could potentially be of great importance when considering the safety and underground stability (Laubach, Marrett, Olson, & Scott, 1998).

There is no information about the cleat orientations at mine #101. However, its potential impact is evaluated by replacing the perfectly plastic coal material in FLAC with a material model known as ubiquitous joints. This material model accounts for weak planes embedded within a solid material. Either the solid material or the weak plane can fail by the Mohr-Coulomb criteria (Itasca Consulting Group Inc., 2011). The objective of the experiment is to see if the structures can contribute to the non-symmetrical damage pattern observed in the field.

In the experiment four different primary cleat orientations towards the coal seam are evaluated; 90° (perpendicular), 180° (parallel) and with an inclination of 135° and 225°. As stated above is the most likely primary cleat orientation perpendicular or parallel to the coal seam, thus are the 135° and 225° orientations unlikely but still evaluated because they are anticipated to generate non-symmetrical damages on the pillar. The cleat orientations are shown in Figure 14.
Figure 14 Cleat orientations used in the experiments.

For the jointed material to have any effect it needs to be weaker than the solid material, thus are two separate sets of strengths used to model the cleats in the models.

- Joint condition of 0.4 MPa and joint friction angle of 20°
- Joint condition of 0.6 MPa and joint friction angle of 23°

4.5. Increased shearing between roof/ pillar

Large shearing between the roof and the pillar and its effect on the pillar is evaluated by adding an additional horizontal velocity to the model. For the velocity to act, the roller boundaries are removed for the part of the model overlying the interface. The velocity is added to the same upper half of the model while the bottom remains fixed resulting in a dextral movement over the interface. The material above the interface is changed to only behave elastically prior to applying the velocity. The model with its new boundary conditions is visible in Figure 15.

Figure 15 X-velocities and boundary conditions for the new model.
The weak strength interfaces are evaluated together with the different coal strength and three velocities. A range of different velocities are initially used in the model. But the range is narrowed down and three velocities (0.1, 0.2 and 0.3 mm/s) are selected for a closer evaluation.
5. Results
Under this chapter the results are presented separately for each experiment apart from the calibration which was presented earlier in the report.

5.1. Evaluation of influence from interface on pillar
For each scenario modelled the number of yielded elements and the pattern they develop in is observed and plotted. The complete plots are displayed in Appendix 5. The total numbers of yielded elements in the pillar are the same regardless of using a glued, strong or medium interface type. It is only changing when applying the conditions equivalent of the weak interface. The same behaviour is observed for all the coal strength combinations but is most visible when applying the weak strength. The results also indicate that a weak coal strength generates more yielded elements compared to a medium and strong interface (Figure 16).

![Total number of yielded elements in pillar](image)

Figure 16 Total number of yielded elements in pillar

Another factor that was considered is the symmetry of which the damages develop. In reality damages have been observed on both sides of the pillar but more so on the down-slope side and thus is this behaviour sought. Unfortunately when comparing the number of yielded elements on right side of the pillar with the left side no clear distinction can be made. The difference is small, only one element or no difference can be observed. It also seems as the up-slope side develops more yielded elements than the down-slope side when applying the weak interface conditions (Figure 17).
Figure 17 Comparison between the yielded elements developed on each side of the pillar.

The minor principal stress in the pillar is plotted and compared for all the scenarios. The full plots are available in Appendix 5. Regarding the difference concerning the minor principal stress at the different scenarios, no major change is observed between the glued, strong and medium interfaces regardless of coal strength condition. However, when the weak interface condition are applied and comparing with a glued condition, there is a clear distinction especially on the pillar boundary as can be seen in Figure 18.
The major principal stress in the pillar is also monitored and no difference between a glued, strong and medium interface is observed regardless of the coal strength. Just like the minor principal stress, a difference is only observed when comparing a weak interface with a glued interface. The major principal stress for a glued interface and a weak interface on a weak coal is displayed in Figure 19. The complete plots related can be found in Appendix 5.
Figure 19 Major principal stress for a weak coal. Left: Glued interface. Right: Weak interface.

The maximal shear displacement along the interface inside the pillar is monitored during the experiment. For all of the different scenarios the shear displacement is not changing until the weak interface is applied (Figure 20).

Figure 20 Maximal shear displacement along the interface

5.2. Structures in the coal

Initially the four different joint orientations are evaluated together with a glued and weak interface. The number of yielded elements is observed on both sides of the pillar and a comparison can be seen in Figure 21. It is clear that a cleat orientation perpendicular or parallel to the coal seam is the most favourable orientation in order to reduce pillar damages. However, cleats orientated 225° to the coal seam produces 45% more damages on the down-slope side of the pillar and thus this orientation has been evaluated further.
For the cleat orientation of 225° all the different interfaces are applied together with two different coal and cleat strengths. It can be seen that the difference is small when comparing the two sides when the joint cohesion is 0.6 MPa and joint friction angle is 23° (Figure 22).

When the joint/cleat strength conditions are slightly reduced the results are more interesting. It can be seen that the jointed coal develops between 50-57% more damages on the down slope side of the pillar compared to the up slope side for a glued, strong and medium interface. However, when the weak interface conditions are applied the difference changes resulting in more damages on the up-slope side (Figure 23).
Figure 23 Yielded element when \( J_c = 0.4 \) MPa and \( J_f = 20^\circ \)

The damage pattern in the pillar for the different conditions is also observed. The yielded elements for the combination of a medium interface, medium coal, joint cohesion of 0.4 MPa and friction angle \( 20^\circ \) is displayed in Figure 24. Out of all the evaluated scenarios related to structures, this case is closest matching to the field observations.

Figure 24 Yielded elements for a medium interface, medium coal, joint cohesion 0.4 MPa and joint friction angle \( 20^\circ \)
5.3. **Increased shearing between roof/pillar**

The number of yielded elements that develop when applying a velocity to the upper half is monitored. It can be seen that for both a medium and a strong coal there are more damages on the down-slope side of the pillar than on the up-slope side regardless of the applied velocity (Figure 25). There is an insignificant change in shear displacement between the strong and weak coal. The developed shear displacement is depending on the applied velocity and is monitored to 8.8, 16.8 and 24.8 mm.

![Figure 25 Number of yielded elements when forcing shearing](image)

Focus for the damages are towards the top corner and the yielded elements for a strong coal with the applied velocity of 0.2 mm/s is displayed in Figure 26. The complete plot of yielded elements is found in Appendix 6.

![Figure 26 Yielded elements for a strong coal with velocity 0.2 mm/s](image)
6. Analysis

Regarding the difference in results when evaluating the combination of interfaces and different coal strength it is clear that an interface may have a negative impact on pillar stability. In the result, this is most visible when comparing the number of yielded elements between a glued and weak interface. No difference is observed between a glued, strong and medium type interface. It is therefore believed that the pillars in the panel are in a very early state of failure with just partial failure of the outer portions under low stress conditions. Most research available shows a large difference for interfaces when evaluating the ultimate pillar strength or post-peak strength. The peak strength of the pillar is most likely far from being exceeded, and if stresses were severely increased the glued, strong and medium interfaces would most likely show significant differences.

The effect of a adding a weak interface is increased if combined with a weak coal material. When evaluating the results it can be seen that the presence of an interface reduces the minor principal stress within the pillar. As stated in an earlier chapter, the minor principal stress is of great importance to the pillar strength as it gives to confinement to the pillar. This stress reduction is most visible on the up-slope side of the pillar but may also be observed on the down-slope side. As the effect is larger on the up-slope side and the damage pattern is more or less symmetrical the presence of the clay interface alone is not believed to be the cause of the pillar damages. Furthermore, the effect is visible when applying a weak interface. This interface is evaluated with 0 MPa in cohesion which is low and somewhat unlikely for a clay interface.

Structures such as cleats and joints can contribute to a non-symmetrical damages pattern, with a larger number of yielded elements on the down-slope side. Out of the four different orientations evaluated, cleats orientated 225° provided the damage pattern most similar to field observations. The largest variation from field observations is on the model’s down-slope side, where the centre of the pillar tends to generate hour-glass shaped damage, while the field observations indicate the primary damage zone to be in the top corner of the pillar.

The results also indicated that cleats with an orientation of 135° to the coal seam generated most total amount of damages in the pillar. This scenario was not evaluated further as the up-slope side generated more damages than the down-slope side.

It is also observed that cleats orientated 180° (parallel) or 90° (perpendicular) to the coal seam have almost no impact on the pillar damages. As the major principal stress is vertical, for cleats orientated parallel to the coal seam the joint is just clamped together. A perpendicular orientation could potentially be unfavourable if the vertical stresses were large. That could potentially generate a failure mode of buckling. But the mine is shallow, resulting in low vertical stresses and little to no influence from perpendicular joints. There is no information regarding the cleat orientations in the coal seam. However, cleats are almost always orientated perpendicular or parallel to the coal seam thus is the cleat orientation of 225° not realistic.

The final experiment provides the most satisfying damage pattern. It matches well with the field observations. The shear displacement is realistic ranging between 8-25 mm. The applied shearing has only an affect when combined with the stronger coal. This is because the weak and medium coal types have already developed a notable amount of damages on both sides of the pillar just after drift excavation. Thus are these strengths believed to be somewhat too weak and not correctly representing the in-situ rock mass.

There are 3 main reasons that could possibly explain this increased shearing and how it could develop in reality. The first reason concerns the fact that no horizontal stresses have been accounted for in the model. No in-situ rock stress measurements have been made and as the panel is fairly shallow no horizontal stresses
were added into the models. If horizontal stresses are present they would deviate around the excavation and increase the shear stress along the interface (Figure 27). This would increase the potential for a shear movement.

![Horizontal stress diagram](image)

**Figure 27 Principal sketch how horizontal stresses can deviate around opening and increase the shear stress**

Using the Mohr-Coulomb criterion, the shear strength along the interface can be calculated according to Equation 4).

\[
\tau = c + \sigma_N \tan \phi
\]

(Eq.4)

Where \(c\) is the cohesion, \(\sigma_N\) is the normal stress acting on the interface and \(\phi\) is the friction angle. The normal stress on the interface will almost have the same orientation as the major principal stress monitored in the pillar. It has been observed to range between 1.5-2 MPa. If applying this together with the conditions for the weak interface, the shear strength of the interface is calculated as:

\[
\tau = 0 + 1.75 \tan 10^\circ = 0.31 \text{ MPa}
\]

This is a fairly low strength and can be compared with the vertical in-situ stress which is 1.62 MPa.

When looking at the mine map it is also noted that many of the surrounding panels have already been mined. Hence is the current panel one of the remaining panels left to mine in the nearby area. The means that if horizontal stresses are present at this depth it is likely that for some orientations they would deviate around the nearby mined out area and concentrate in the panel of interest. This would also increase the likeliness of a shear movement (Figure 28).
Figure 28 Mine map with possible horizontal stress orientations that could result in high stress concentrations

The final possible explanation to the forced shearing could be the presence of water within the clay layer. Not only could the presence of water reduce the strength of the clay infill increasing likeliness of slip but just as important affect the normal stress on the clay. Pore water in geotechnical engineering has a negative impact on the effective stresses. The effective stress is reduced with the pore water pressure according to Equation 5).

\[ \sigma' = \sigma - u \]  

(Eq.5)

Where \( \sigma \) is the total stress and \( u \) is the pore water pressure. If applying this to the normal stress on the clay calculated above. The new shear strength along the interface would be

\[ \tau' = 0 + (1.75 - 1000 \times 60 \times 10 \times 10^{-6}) \tan 10^\circ = 0.20 \, MPa \]

That is equivalent of a shear strength reduction on 34% and that does not include the potential reduction of the friction angle induced by water.

A final possible contributing factor might be the large number of faults located within the panel. Approximately 20-30 faults with a clear east-west orientation have been observed intersecting through the panel. They have a varying width between 0.05-0.5 meters. The faults are believed to be dividing the overlying siltstone into small blocks and also enable space (8-25 mm) for shearing to take place.
7. Discussion

Cleats in coal are most often if not always developed as a primary and secondary cleat. They are both developed orthogonal to each other and together they cut the coal into smaller rectangular shaped pieces. In this report, the cleat is analysed using the material model of “Ubiquitous Joints” in FLAC. This material model allows for evaluation of structures (joints/beddings/cleats) with a given orientation and strength anywhere within a solid material. Since FLAC only analyse continuum materials, are the modelled cleats not real discontinuities. The modelled cleats cannot separate, rotate or shear. In reality the cleats, together with the opening and the clay interface, would create wedges which potentially could dislocate and contribute to the damages. This behaviour is not possible to model in FLAC but other software such as UDEC is better for this purpose. In addition, only the primary cleat is modelled in the project due to limitations in FLAC and the “Ubiquitous Joints” material model. Most certainly would the presence of the secondary cleat contribute to more pillar damages. However, the results from the models with cleats in this project do not provide a satisfying damage pattern and the damages on the up-slope side are already too large compared field observations. A contribution from the secondary cleat would not make the models match the field observations any better. Finally, the closest matching result to the field observations is for a cleat orientation of 225°. Primary cleats with this orientation are very unlikely and the addition of the secondary cleat and discontinuum modelling would not make the orientation more likely or make the result match the field observations any better.
8. Conclusions

The results clearly show that the best matching results are obtained when increasing the shearing along the interface up to between 8-25 mm. A relatively small shear movement along the clay layer is therefore believed to be the main cause behind the observed pillar damages. Other major findings of this report can be summarized as:

- An interface between pillar/roof may have a negative impact on pillar strength
  - It reduces the minor principal stress in the pillar.
  - It is most obvious on the up-slope side but can also be observed on the down-slope side.
  - The interface on its own is not believed to be the cause of the damages.
- Structures such as cleats/joints can contribute to a similar damage pattern observed in field.
  - Cleats orientated 225° result in damage pattern similar to field observations. However, the damage pattern does not match perfectly.
  - Cleats with this orientation (225°) are unlikely to find in field.
- Best results obtained when shearing is forced
  - Magnitude of shear displacement is realistic between 8-25 mm.
  - 3 potential non-investigated contributing factors may be horizontal stress, disturbance by mining and influence from water.
- Pillars are in an early state of failure where the overall peak-strength have not yet been exceeded
- Cohesion of 0.79 MPa and friction angle of 27° are representative values for the coal seam
- Young’s modulus of 0.3 GPa and Poisson’s ratio of 0.2 are representative values for the coal seam
- Young’s modulus of 1 GPa and Poisson’s ratio of 0.2 are representative for the immediate siltstone

Minor findings of this report include the following:

- No difference between glued, strong and medium interface
  - Possibly because early stage of pillar failure under low stress conditions
- Joints/cleats orientated parallel to coal seam have no effect on pillar damages
- Joints/cleats orientated perpendicular to coal seam have little effect on pillar damages
- Cleats orientated 135° towards the coal seam have a large impact on pillar damages.
- The interface strength type used in the models have no influence on convergence
9. Recommendations and future research

Before extending the operations further north and south, a final panel located in the centre of the mine is planned. The planned panel is adjacent to the panel which is of interest in this study. It is therefore possible that the clay layer located between the pillar and the roof extends and will be present in the new panel. It is recommended to take extra precaution and investigate the eventual presence of the clay layer as soon as possible. If no clay layer is present, or if the coal seam is horizontal, there is no need for additional action. However, if the clay layer exists the following might be worth considering.

The planned panel will be surrounded by mined out areas in several directions which increases the likeliness of a horizontal stress concentration. This can increase the potential for a shear movement. As mining progresses in the new panel it is also recommended to observe the amount of water in the area. As discussed in an earlier chapter, water is believed to be a contributing factor as it reduces effective stress which prevents slip.

It is also recommended to re-evaluate the sequence of mining for the new panel. Previously the sequences have been to mine from the lowest part of the panel advancing up to the highest point. It is possible that an opposite sequence, in which mining starts at the highest point, would be more beneficial. This would need to be investigated further.

As always, adding reinforcement and support to the pillar increases the confinement and pillar strength. It brings extra cost but should be considered an option for the new panel. It is believed that using steel mesh would be beneficial as it retains rocks and can take large deformation which might be induced by the shear movement. In coal mines located in the USA, a common support method is to combine steel mesh with right-angle-irons and bolt these between the pillar and roof (Figure 29). This method gives support to both the wall and roof as well as it provides a neat installation of the mesh enabling it to start acting even at low strains.

Figure 29 Recommended support method using bolts, right-angle irons and steel mesh (JENNMAR, 2016)
10. References


Sjöberg. (n.d.). *Course litterature for applied rock mechanics*. Luleå University of Technology.


11. **Appendix**

Appendix 1 – Results from core drilling.

Appendix 2 – Quantification of GSI by Joint Conditions and RQD.

Appendix 3 – Summary of uniaxial and triaxial testing by UFRGS.

Appendix 4 – Rate of convergence.

Appendix 5 – Plots for yielded element and for minor/major principal stress.

Appendix 6 – Plots of yielded elements when shearing is forced.
Appendix 1

Results from core drilling in the mine (courtesy of Rio Deserto)

<table>
<thead>
<tr>
<th>INTERVALO (m)</th>
<th>UNIDADES ESTRATIGRÁFICAS / DESCRIÇÃO LITOLÓGICA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quaternário/ Fm. Palermo/ Fm. Rio Bonito</td>
</tr>
<tr>
<td>0,00 - 17,05</td>
<td>Argila (sem recuperação).</td>
</tr>
<tr>
<td>17,05 - 28,95</td>
<td>Silítio cinza claro na base e esverdeado no topo, com raras e dispersas lâminas de arenito.</td>
</tr>
<tr>
<td>28,95 - 34,95</td>
<td>Silítio cinza claro a cinza escuro com intercalações de lâminas e leitos de arenito, forte estrutura flaser e/ou wave em todo o intervalo.</td>
</tr>
<tr>
<td>34,95 - 44,32</td>
<td>Arenito fino, cinza claro a esbranquiçado, maciço e silificado, com fraça e dispersas lâminas de silítio, mediano e poroso nos 4,00 m da base.</td>
</tr>
<tr>
<td>44,32 - 49,75</td>
<td>Silítio, cinza claro a cinza escuro, com fraça e dispersas lâminas finas de arenito, e fraça estrutura flaser e/ou wave em todo o intervalo.</td>
</tr>
<tr>
<td>49,75 - 53,12</td>
<td>Arenito fino cinza claro a esbranquiçado, maciço e silificado. <em>Teto superior RQD = 65%. Falta em 52,75 m.</em></td>
</tr>
<tr>
<td>53,12 - 53,34</td>
<td>Silítio carbonoso com raras lâminas de arenito e fraça estrutura flaser e/ou wave.</td>
</tr>
<tr>
<td>53,34 - 54,27</td>
<td>Silítito laminado.</td>
</tr>
<tr>
<td>54,27 - 56,61</td>
<td>Silítito cinza escuro, maciço. <em>Teto Imediato RQD = 72%.</em></td>
</tr>
<tr>
<td>56,61 - 58,51</td>
<td>Carvão Camada Barro Branco. RQD = 29%.</td>
</tr>
</tbody>
</table>

**Detalhe da camada**

- 0,18 Carvão Forrinho
- 0,02 Silítito
- 0,03 Carvão
Appendix 2

Figure 30 Quantification of GSI by Joint Conditions and RQD (Hoek, Carter, & Diederichs, 2013)
Appendix 3

Table 6 Summary of UCS and triaxial testing on coal by UFRGS (courtesy of Rio Deserto).

<table>
<thead>
<tr>
<th>( \sigma_1 ) (MPa)</th>
<th>( \sigma_3 ) (MPa)</th>
<th>E (GPa)</th>
<th>( \sigma_1 ) (MPa) Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.83</td>
<td>0</td>
<td>0.16</td>
<td>15.19</td>
</tr>
<tr>
<td>23.27</td>
<td>0</td>
<td>8.19</td>
<td>22.4</td>
</tr>
<tr>
<td>39.59</td>
<td>3</td>
<td>0.36</td>
<td>-</td>
</tr>
<tr>
<td>29.46</td>
<td>1.5</td>
<td>0.57</td>
<td>-</td>
</tr>
<tr>
<td>42.23</td>
<td>5</td>
<td>0.74</td>
<td>-</td>
</tr>
<tr>
<td>42.28</td>
<td>5</td>
<td>1.27</td>
<td>-</td>
</tr>
<tr>
<td>42.24</td>
<td>3</td>
<td>2.28</td>
<td>-</td>
</tr>
<tr>
<td>45.54</td>
<td>3</td>
<td>1.67</td>
<td>-</td>
</tr>
<tr>
<td>32.36</td>
<td>1.5</td>
<td>2.05</td>
<td>-</td>
</tr>
<tr>
<td>25.74</td>
<td>1.5</td>
<td>1.36</td>
<td>-</td>
</tr>
<tr>
<td>29.69</td>
<td>3</td>
<td>1.29</td>
<td>-</td>
</tr>
<tr>
<td>44.43</td>
<td>5</td>
<td>2.05</td>
<td>-</td>
</tr>
<tr>
<td>25.12</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>27.45</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18.33</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>24.3</td>
<td>0</td>
<td>0.5</td>
<td>21.44</td>
</tr>
<tr>
<td>23.61</td>
<td>0</td>
<td>0.66</td>
<td>23.13</td>
</tr>
<tr>
<td>5.84</td>
<td>0</td>
<td>0.13</td>
<td>5.63</td>
</tr>
</tbody>
</table>

Table 7 Summary of UCS and triaxial testing on siltstone by UFRGS (courtesy of Rio Deserto).

<table>
<thead>
<tr>
<th>( \sigma_1 ) (MPa)</th>
<th>( \sigma_3 ) (MPa)</th>
<th>E (GPa)</th>
<th>( \sigma_1 ) (MPa) Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>45,0</td>
<td>3,0</td>
<td>3,2</td>
<td>-</td>
</tr>
<tr>
<td>64,2</td>
<td>5,0</td>
<td>3,0</td>
<td>-</td>
</tr>
<tr>
<td>51,5</td>
<td>5,0</td>
<td>1,5</td>
<td>-</td>
</tr>
<tr>
<td>29,2</td>
<td>0,0</td>
<td>1,3</td>
<td>29,0</td>
</tr>
<tr>
<td>69,4</td>
<td>2,0</td>
<td>4,9</td>
<td>-</td>
</tr>
<tr>
<td>88,3</td>
<td>5,0</td>
<td>4,8</td>
<td>-</td>
</tr>
<tr>
<td>80,1</td>
<td>7,0</td>
<td>5,7</td>
<td>-</td>
</tr>
<tr>
<td>24,4</td>
<td>0,0</td>
<td>4,5</td>
<td>23,8</td>
</tr>
</tbody>
</table>
Figure 31 Rate of convergence (mm/day) over time (courtesy of Rio Deserto)
Appendix 5

Yielded element plots for different interfaces and a strong coal.

From top left to right bottom: Glued, strong, medium and weak interface.
Minor principal stress for different interfaces and a strong coal.

From top left to right bottom: Glued, strong, medium and weak interface.
Major principal stress for different interfaces and a strong coal.

From top left to right bottom: Glued, strong, medium and weak interface.
Yielded element plots for different interfaces and a medium coal.

From top left to right bottom: Glued, strong, medium and weak interface.
Minor principal stress plots for different interfaces and a medium coal.

From top left to right bottom: Glued, strong, medium and weak interface.
Major principal stress for different interfaces and medium coal.

From top left to right bottom: Glued, strong, medium and weak interface.
Yielded element plots for different interfaces and a weak coal.

From top left to right bottom: Glued, strong, medium and weak interface.
Minor principal stress for different interfaces and weak coal.

From top left to right bottom: Glued, strong, medium and weak interface.
Major principal stress for different interfaces and a weak coal.

From top left to right bottom: Glued, strong, medium and weak interface.
Appendix 6

Yielded elements when shearing is increased by applying a velocity.

From top to bottom: Velocity 0.3, 0.2, 0.1 mm/s. Left to Right: Strong coal, Medium coal.