Study of the stability of barricades. Neves Corvo (Somincor) case study.

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ABSTRACT: The main purpose of this work is to develop a practical model design based on finite element methods that can simulate the dimensions and layout of bulkheads, using data from the Somincor mine. Bidimensional and tridimensional finite element models were developed, and comparing the results on this models with analytic and empiric hypotheses it was possible to determinate the security factor of these bulkheads.

The results allow validating the security of the bulkhead to sliding, falling and ruptures, as well as identifying the more solicited areas in the bulkheads and quantifying the security factors.

Keywords: Bulkhead filling, design, backfill, finite elements

1. INTRODUCTION

Barricades or bulkheads are structures use to retain backfill, these are fundamental to guaranty the security of stopes where backfill is used. The defective design of those structures as lead to several working hazards. Those hazards are mainly due to, the using of empiric methods of design. In Mount Isa Mines between 1980 and 1997 there were reports of 11 ruptures of barricades containing backfill (Sivakugan et al., 2006).

Finite elements software have showed grate versatility and application to several areas, allowing the quantification and acquisition of concrete values were those data acquisitions were difficult or very expensive to obtain.

The purpose of this work is to study the design of barricades using finite elements software, assuring that those structures are secure and using the materials and methods of construction of the Neves Corvo Mines.

2. BACKGROUND

The essence of the mining industry is the extraction of minerals from earth’s crust, which creates voids that altered the preexistence tension field and contributes to the instability. The use of backfill offers a wide flexibility because it increases the strategic approach to the exploitation process.

The use of different types of backfill is linked to technical requirements, function, mining method and mining plan. The need to use backfill is worldwide. Just in Australia there are generate, ten millions of cubic meters of voids each year, that explains the increasing interest in mine fill (Grice, 2001).

The main mining methods that generally resort to backfill, as a technic or as a combination with other technics, are Cut and Fill and there several variations and Open Stope. With the deeper Mines exploitation, the need for backfill increased, as the critical span is turning smaller.

2.1. Mining Methods

What usually defines the mining method is the geometry of the ore body. Mining methods that use backfill as a component support system are generally: Open Stope, Cut & Fill and Bench & Drift and Fill (Figure 1 and 2). The use of backfill as a support technic offers support to the stope walls, decreasing the displacement of those walls; it normally decreases the environment impacts and also can prevent the ore dilution due to the self-support capability of having a surface exposed without “contaminating” adjacent ore bodies (M.Yumlu, 2001).

Another aspect that can lead to the Cut and Fill mining method is the quality of the rocks massive; these methods can prevent or minimize both internal and surface subsidence and pillars ruptures (Brackebusch, 1992). It is also possible to control the tension on exposed walls and avoid rockburst since the rock massive compresses the backfill filling the void (Figure 3) With a smaller amount of voids, the need for ventilation may be less than the parameters established theoretically. Cut and Fill mining method is more expensive than other methods, nevertheless and due to these facts, it can become more viable than other methods.

2.2. Backfill

The fill of the mining voids is as old as mining itself. At the beginning, it occurs as a natural process due the accumulation of sterile rocks or mining tailing. The first reports of backfill application go back to the end of the XIX century (McLeod, 1992).

The use of backfill allows an increase of the stability of the rock massive in two distinct ways: firstly, limiting the opening of cracks and discontinuing on rock masses; secondly, the use of fill limits the convergence of the openings increasing the regional stability. If the backfill is confine by the rocks massive,
then its mechanical characteristics are not that relevant, but it can lead to the chemical contaminations or quick conditioning phenomenon.

With the increasing social economic and environmental pressure felt on the mining industry, the use of backfill is a good solution to accommodate the tailings, becoming a good alternative to tailing dams.

The backfill systems are planned according to the material and functions required and each application is controlled by the geotechnical characteristics of the fill, the mechanical properties of the rock masses and the exploitations objectives.

The main types of backfill are the hydraulic, paste, and rock mining fills.

The hydraulic fill is generally made of fine tailing, transported by tubes in a solid percentage and imposes a turbulent flux. The solid percentage varies between 50 and 70%, if there is an expose surface it is then necessary to add some sort of binder in order to guaranty the self-support capability.

Other type of fill is the paste; this one is also made of fine tailings, however it presents less water content and a higher solid percentage 78 to 87%. The real paste does not segregate (even if the flux is interrupted for several hours), if the paste reveals exudation phenomenon it is appropriated to name the fill as Hydraulic of high density. Paste presents Bingham fluid characteristics (Sivakugan, 2006), and generally cures quicker and does not apply such high pressures in the barracades as Hydraulic fill does; this is because it has less water content. The transport system is more expensive than the Hydraulic, although the operation costs may be smaller (Potvin, 2005).

Finally, we have the rock fill. Transportation and production of the fill requires more labor, sometimes it is more expensive, especially when there is a target strength that requires adding more binder to this fill.

2.3. Backfill Composition

At first, when mine fill started to be use, its properties were neglected. As the span of the stopes increased, so did the complexity of the fill, especially with the addition of binders. The need to know about the technical features of the fill emerged from the necessity to predict its behavior, knowing if it is suitable for the end required and to minimized the costs of production while maintaining the performance.

The main components of backfill are the tailings, sterile rocks, water and binders. The source of these constituents are variable but they mainly result from the processing mining-central unit.

The tailings are particles that can range from fine sands to clay, the grainsize distribution influences directly the void volume, density and strength. It also dictates flux properties such as the permeability and percolation (Henderson & Revell, 2005).

The mineralogy of the particles influences some characteristics of the fill, such as water retention and chemical reactions that can weaken the fill (Henderson & Revell, 2005).

The waters may also influence the total strength of the fill, in particular in what concerns the adding of salt water (Wang & Villaescusa, 2000).

The binder also contributes to the strength and time of cure of the fill.

2.4. Backfill Properties

Mining fill is a complex theme. This area of study ranges from soil mechanics, fluid mechanics, to mineral processing and others subjects. It is fundamental to comprehend the behavior of the fill in order to guaranty that this one is safe to use.

The most relevant properties to study the mechanical behavior of the fill are its weight volume, friction angle, grainsize distribution, void ratio, permeability, cohesion, etc.

Generally we consider particles with caliber smaller than a 20 µm as fine particles, although hard to forecast precisely. For instance, Hydraulic fill should not have a solid weight of particles smaller than 10 µm greater than 10%, to achieve the required permeability, yet in the Paste fill it is common to consider that the weight of particles that are smaller than 20 µm must be greater than 15% (Kuganathan, 2005).

The Coefficient of uniformity (Cu) illustrates the distribution of the particles. The (Cu) value of Paste fills range from 10 to 20, while in Hydraulic fill it range from 5 to 10 (Kuganathan, 2005). The greater the Cu, the well-grained material is. The increasing of fine particles aggravates the viscosity of the fill. In order to prevent piping and quick conditioning phenomenon, it is important to know the relative compactness of the fill.

Depending on the quantity of water, the fill can be in several states: solid, semi-solid, liquid or plastic. This change of behavior is knnown as the Atterberg limits and while using this analogy from the soil mechanics; it is possible to have a general idea of the tangential stress in the fill (Kuganathan, 2005).

The shear stress is important when there is a free surface in the exposed backfill. Shear strength has two components: sliding and interlock of particles; both are frictional, and depend on the normal stress. The interlock is influenced by the density and compactness of the fill. The sliding is govern by the tangential stress.

The permeability is define according to the Darcy law and general depends on the compactness. When there is underground water flux its necessary to take that in account when design the barricades, because that flux while exerted pressure on them. If the vertical water flux is to high liquefaction may occur, due to the vertical impulse of the flux being greater than the gravity and nullify that component making the fill behaving like a liquid (Bell, 2007), when the fill is subject to suddenly pressure change it can change state becoming plastic or liquid again (Kuganathan, 2005).

The consolidation of the fill is the process where the particles agglomerate, due to gravity, expelling water from its pores. The consolidation of Paste fill can take some times, in the interior of a stope it can take several months, on Hydraulic fill its almost instant (Brummer, 1996).

The effective stress (Equation 1) is the stress that provokes displacements and movement of the fill, is the stress on the solid part of the fill. The total stress is (σ) and (u) is the pore pressure.

\[ \sigma' = \sigma - u \] (Equation 1)

The tangential stress in a fill can be govern by the equation of Mohr-Coulomb, it’s important to know the cohesion, friction angle and principle stress (Kuganathan, 2005).

The lateral pressure it is the main solicitation mechanism on barricades. The lateral pressure it is relate to the vertical stress (weight of the fill) and the earth lateral coefficient(\(k\)) (Figure 4). When the barricade is solicited the stress state is rearrange in order to find equilibrium, in case of raise of solicitation, the structure may start moving or break. When designing bulkheads it’s important to allow extra pressures or install a drainage system (Kuganathan, 2005).

![Figure 4 – Schematic illustration of the lateral pressure. (Adapted from Helwany, S., 2007)](image)

During the filling process of a stope, gravity pulls the fill down, increasing the vertical stress (\(\sigma_v\)) and consequently increasing the lateral stress (\(\sigma_h\)). With the increasing stress, particles try to rearrange to accommodate the next fill. This rearrange contradicts partially the down movement of the particles, increasing the tangential stress near the walls of the stopes. This process is known as the arch effect, and in it, the fill transfers some self-weight to the walls of the stope. Terzaghi, in 1943 studied the arch effects in soils and rocks while developing the support for tunnels.

2.5. Bulkhead Design Methods

After finishing the load and cleaning operations in the stopes, a drainage system should be installed, so that the fill operation may begin. Bulkheads or
barricades are described as permeable structures that allow drainage, and that are used to sustain the fill in the stopes (Grice, 1989).

Different types of backfill or filling procedures require bulkheads with different functions, although the approach in the design should always be to maintain the security and efficiency of these structures. The great challenge here is to identify the solicitations on bulkheads, the type of material in use, and the size and position of the barricade. It is of great importance to know the tension state in the fill in order to control the stability of the barricades and avoid ruptures. The ruptures of barricades can lead to great impacts in the exploitation.

The distance of the barricades to the stope can influence the loads on the structures. The closer to the stope the bigger the loads (Mitchell et al., 1975).

The materials that constitute barricades contribute directly to the performance. Those materials can be: wood, concrete, masonry, etc. For the bulkhead design, it is necessary to determine the moment of flexion, tyrant loads, the external loads and the properties of the materials. It is important to determine the mechanical behavior of the surrounding rock mass, the roughness of the walls, as well as the convergence of the stopes.

The traditional design methods use the codes of construction from the American Concrete Institute (ACI), the Yield Line Theory and specific applications of this theory.

According to the ACI, the barricade design is based on the moments, the normal stress and the shear stress. An analytic method proposal by Smith and Mitchell (1982) utilize the tension stress and the flexion moments to determine the thickness of the barricade.

The design according to the Yield Line Theory estimates that the ultimate pressure of a slab is determinate by the lines of flexion. With that being said, it is possible to relate the ultimate pressure by using the virtual work principle, and assuming a rupture by flexion. The equation that governs this mechanism is:

\[ M = \frac{1}{2} \sigma I \]  

Where \( M \) is the maximum moment supported by the structure, \( l \) is the thickness of the barricade and \( \sigma \) is the tension strength. Based on Equation 2, it is possible to calculate the ultimate load on bulkheads based on several types of contact between the bulkhead and the walls. On Table 1 those equations are presented, \( W \) is the ultimate load and \( l \) is the structure width.

<table>
<thead>
<tr>
<th>Foundation or support of the barricade sides</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sides in contact</td>
<td>( W = 24M/l^2 )</td>
</tr>
<tr>
<td>All sides fixed</td>
<td>( W = 48M/l^2 )</td>
</tr>
<tr>
<td>Upper and down sides fixed, lateral sides in contact</td>
<td>( W = 35.44M/l^2 )</td>
</tr>
<tr>
<td>Down side in contact, other sides fixed</td>
<td>( W = 41.36M/l^2 )</td>
</tr>
<tr>
<td>Down side fixed, other sides in contact</td>
<td>( W = 29.9M/l^2 )</td>
</tr>
</tbody>
</table>

The structural engineer experience indicates that the yield line method doesn’t determine with precision the rupture load, mostly in cases where the slab is solicited by lateral pressures. Famiyesin et al. (2001) suggested that the numerical modeling might be an assertive tool to determinate the strength of the slabs.

The method used in Australia is a variant of the yield line method; formulated by Beer 1986, it suggests mainly to estimate the resistance of masonry barricades. Some investigators suggest the lack of support of this approach (Martini, 1997).

The formulation of Beer (Equation 3 and 4) is similar to the Equation 2, but it uses the compression strength \( (\sigma_c) \) rather than the tension.

\[ M = \frac{1}{2} \sigma_c I \]  

\[ W = \frac{2A}{I^2} \]  

Bulkheads build to sustain hydraulic fill need to be strong and permeable, as hydraulic fill has a great content of water. There are several ways to build these barricades: using masonry blocks, wood, steel beams copulated with steel mesh with a layer of shotcrete. In order to control the excess of water, there may be a need to install water pumps. These structures are normally subject to a lateral pressure of 100 to 200 kPa, and have a typical thickness of 40 to 50 cm. The lateral pressure is around 1/3 of the vertical pressure due to the arch effect (Helinski et al., 2011) (Figure 5). Due to the arching effects, the self-support of the fill increase. A backfill can have a surface exposed with a height of 100 m, with 500 kPa of strength, and if there weren’t any arching effects, there would be a need of the fill to have 2 MPa of strength (Kuganathan, 2005).

The filling process is generally made in layers in order to control the pressure on the barricade. The first layer has the height of the barricade and after the backfill consolidation; it is possible to continue the filling process.

Theoretical paste fill does not have excess of water, though when designing the barricades, there should be taken in account the possibility of an excess water.

![Figure 5 – Schematic illustration of the arch effect. (Adapted from Belem & Benzaazoua, 2008)](image)

When designing bulkheads for sustaining paste fill, one should determinate the hydraulic loads, the weight of the fill and the drainage. A simple building technic consists on building a wall of boulder rocks and after that, spraying a layer of shotcrete on that boulder (Villaescusa, 2014). To control the pressure, piezometers are installed.

2.6. Numerical Modelling

The finite element method (FEM) is a numerical technic that tries to find proximal solutions to partial differential equations, by dividing the domain of the problem in small parcels, named finite elements; by summing all solutions of each finite element, we get the estimated value of the domain.

The principle objective is to try to identify the basic physic actions that are involved in the domain and try to transform that information in a mathematical model.

The FEM calculations can also be attained using differential finite methods; in this case, the elements present an orthogonal mesh, while the finite element method uses a single division for each element. The finite elements can be triangular or quadrilateral in 2D, tetrahedrons, or hexahedrons in 3D, in each element the variables can be describe as a linear or high order equation.

Using FEM to design a barricade can be very useful to prevent errors associated with the analytic or empiric methods (Sheshpari, 2015) (Figure 6).

![Figure 6 – FEM analysis of a Square bulkhead. (Revell et al., 2007)](image)

Before the filling process, bulkheads are built at the base of the stope or close to it, in order to contain the mine fill. It is important to secure the stability of the structures during the first stages of the fill (Seshpari, 2015). The rupture of these
structures happens during the early stages of filling, mainly due to quick conditions phenomenon and deficient drainage systems.

Li & Aubertin observed, using FEM, that the horizontal pressure on the bulkheads diminish with the distance between the barricade and the stope, and also that pressure diminish with the increasing of the friction angle (Figure 7). The normal stress is bigger that the effective stress due to the distance of the bulkhead and the stope and the water pressure.

**Figure 7 – Total Stress on a bulkhead, using different drifts heights, and friction angles. (Li e Aubertin, 2009)**

Li & Aubertin compared their results with physical test of Mitchell (1992). The bulkheads where placed in different positions on the drift, and the fill had no cohesion, 30° of friction angle, weight volume of 18 kN/m³ and a Young model of 300 MPa. In this simulation, it was also assumed that the convergence ends before the placing of the fill. The filling process was made in four steps. A good relation between the analytical, physical and numerical tests suggests that the solution was representative.

An analytic analysis may not be enough to prevent ruptures, and the numerical modelling can identify the ruptures, their mechanism and extension (Dirige et al., 2009).

Bulkheads ruptures are a geotechnics risk of the mining methods that use fill. In 2005/2006, Revell & Sainsbury used FEM to design six bulkheads of concrete. To validate the results, there where some physic tests using the date of two wood barricades. In both tests, the rupture happened in the base of the barricade, with a pressure of 124 kPa and 165 kPa.

In 2006 in Australia, the rupture of a barricade happened after 2.5 hours of the filling process. It is estimated that the height of the fill was around 7 m witch points to a lateral pressure of 132 kPa, Revell & Sainsbury model estimated that the maximum load would be 130 kPa (Figure 8).

**Figure 8 – Photo and simulation of a rupture in a bulkhead. (Revell et al., 2007)**

Revell & Sainsbury studies showed that barricades with a curve, increases the resistance and that barricades with a slab layout are best studied with the yield line theory.

3. CASE STUDY

The objective of the study is to contribute to the design of barricades used in Somincor Mines (Neves Corvo), using FEM software. This report focuses essentially on the barricades used in the top drift of the stopes. This kind of barricades sustain both paste and hydraulic fill. In this work, the barricades will sustain paste fill.

3.1. Neves-Corvo Mines

The orebody of Neves-Corvo was discovered in 1977. Neves-Corvo is located in the west part of the Iberian pyrite belt that goes from the south of Spain to Portugal; the reserves occur in a Volcano-Sedimentary Complex (Figure 9) and the predominate extract metals are copper, tin and zinc. It is the biggest mine in Portugal and a World-class mine due to the abnormal high grades of ore (Oliveira et al., 2015).

In 1980 the Portuguese company Somincor was created to begin the exploitation. Corvo, Graça, Neves and Zambujal ore body were partial defined, covering 1.5x2 km². In 1985, Rio Tinto venture in the project with the EDM.

**Figure 9 – Iberian pyrite belt. (Oliveira et al., 2015).**

Production started in the end of 1988 with the exploitation of Graça and the superior area of Corvo. During the development of the mine, a great concentration of tin was discovered associated with the copper ores. That led to the construction of a tin treatment plant at 1990.

The mining method use in the mines is essential: Bench and Fill, Drift and Fill, Mini Bench and Fill e Sill Pillar. Bench and Fill is responsible for 55% of the production, while the remaining 45% is mainly produced with Drift and Fill (Somincor brochure, Communication and Public Relations, 2010).

Somincor stopes have dynamic dimensions, which vary with the necessary management. The drift dimensions are generally 5 m per 5 m, while the height of the stopes vary between 20 to 30 m. The length of the stope is a maximum of 30 m and the width of the stope is approximately 12 m (Figure 10).

**Figure 10 – Scheme with a longitudinal cut and a transversal cut of a norm stope.**

There are two types of barricades used in Somincor stopes: Bottom structures are reinforced concrete barricades, with a robust construction capable of sustaining bigger solicitations. The top structures are essentially made of wood, with phased construction, adapted to the local site and phased filling process.

3.2. Barricade construction

The object of study are the wood doors (Figure 11), these are quick and easy structures to assemble, which use materials like steel mesh, a rock damn and jute.

Afterwards, it will be presented a resume procedure of the construction of this structures based on in-situ observations of the construction and the internal procedure of construction.

The building place of the barricade is chosen by the management team, and given the technical aspects of the place and after an inspection to the construction site, in order to guaranty the security and stability of the place. The place to build the barricade is clearly marked in the drift walls.
Teams of miners arrive at the construction site and remain responsible for building the first phase of the barricade. Their efficiency depends essentially on the barricade dimensions.

At around 1 m of distance, a loader truck places a rock embankment with a height of 1 to 2 m. The embankment is compacted by the loader truck and appears to be a trapezoidal prism. This embankment has two functions: during the early stages of the filling processes and construction, it retain the excess fill and water, and it works as a support for the flood beam. After that and due to the development of strength and self-support of the fill retained in the embankment, it will work as a foundation of the barricades.

The materials used are eucalyptus beams, with a variable diameter and a length of 4 to 6 m; pine lath with a thickness of around 5 cm; steel mesh, typically used with shotcrete; steel chains that link the barricade to a stanchion, retaining backfill, and eucalyptus beams. Before the filling process starts, steel chains and eucalyptus beams are connected to the barricade (identified as (6) in Figure 12), where the steel chains will be attached. The stanchion is around 5 m inside the drift with a shape similar to a football goal (Figure 11). After that, the steel mesh and jute is attached to the pine lath and eucalyptus beams, and the barricade is ready, and is around 2 m height. The paste fill as a Mohr-Coulomb behavior (Li & Aubertin, 2009), and is an isotropic material. Table 3 represents the properties of the paste fill based on Carvalho, J. (2014) and Manaras, S. (2009). The tailing has a volume weight of 3600 kg/m³.

3.3. Materials used in the models

The observation of the barricades construction was indispensable to the models design. An important fact to the models design is the mechanics of the materials. Some of those properties were already determine in previews works. The wood properties of the eucalyptus and pine were studied by Santos, J in 2007. The fill properties by Carvalho, J. in 2014. Based on those studies, the materials in the models were characterized. Other material properties were determined with catalogs, norms and sellers information.

The woods have elastic behavior and are considered orthotropic materials. In Table 2, the wood properties are numerated, based on Santos, J. (2007), although there isn’t a pattern determinate values it is possible to build the models based on these values.

<table>
<thead>
<tr>
<th>Material</th>
<th>Eucalyptus</th>
<th>Pine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average weight volume</td>
<td>800 kg/m³</td>
<td>470 kg/m³</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>18.2 GPa</td>
<td>13.2 GPa</td>
</tr>
<tr>
<td>Poisson coefficient</td>
<td>0.47</td>
<td>0.46</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>13.6 MPa</td>
<td>6.6 MPa</td>
</tr>
<tr>
<td>Tension Strength</td>
<td>6.7 MPa</td>
<td>3.9 MPa</td>
</tr>
</tbody>
</table>

The paste fill properties are specified in Table 3, which represents the properties of the paste fill based on Carvalho, J. (2014) and Manaras, S. (2009). The tailing has a volume weight of 3600 kg/m³.

<table>
<thead>
<tr>
<th>Material</th>
<th>Paste fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average weight volume</td>
<td>2300 kg/m³</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>150 MPa</td>
</tr>
<tr>
<td>Poisson coefficient</td>
<td>0.12</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>281.25 kPa</td>
</tr>
<tr>
<td>Cohesion</td>
<td>164 kPa</td>
</tr>
<tr>
<td>Friction angle</td>
<td>20 °</td>
</tr>
</tbody>
</table>

The observation of the barricades construction was indispensable to the models design. An important fact to the models design is the mechanics properties of the materials. Some of those properties were already determined in previews works. The wood properties of the eucalyptus and pine were studied by Santos, J in 2007. The fill properties by Carvalho, J. in 2014. Based on those studies, the materials in the models were characterized. Other material properties were determined with catalogs, norms and sellers information.

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In table 4 are specified the properties used for schist formations with a Mohr-Coulomb behavior, typical to simulate landfill, and is considered an isotropic material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Embankment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average weight Volume</td>
<td>3500 kg/m³</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>20 GPa</td>
</tr>
<tr>
<td>Poisson coefficient</td>
<td>0.2</td>
</tr>
<tr>
<td>Cohesion</td>
<td>0</td>
</tr>
<tr>
<td>Friction angle</td>
<td>40 °</td>
</tr>
</tbody>
</table>
The steel chains have elastic-plastic behavior and are considered a isotropic material. In table 5 it’s presented the chain properties based on Scana Ramnas (1990 & 1995) catalogs

<table>
<thead>
<tr>
<th>Material</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average weight volume</td>
<td>7800 kg/m³</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>54.4 GPa</td>
</tr>
<tr>
<td>Poisson coefficient</td>
<td>0.2</td>
</tr>
<tr>
<td>Tension Strength</td>
<td>1250 kg</td>
</tr>
</tbody>
</table>

### Table 5 – Chain properties. (Scana Ramnas)

4. BULKHEAD MODELLING

The used FEM software are Plaxis, from Plaxis, and Abaqus from Dassault systems Corp.

Plaxis was develop to do real geotechnical simulations. The backfill is represented as a soil. The results are always approximation to the reality, and some errors are inevitable (Plaxis manual, 2016). The model is a representation of the understanding of the problem.

Abaqus is a FEM tool for linear and nonlinear solutions; it has a vast spectrum of analysis that range from structural to electromagnetic. It is possible to import models or parts of models from computer-aided design (CAD) software (Abaqus Unified FEA).

With the purpose of quantify and compare the results of the models, bidimensional models were created in Plaxis and Abaqus and tridimensional models were also created in Abaqus.

#### 4.1. Models

The models were created at scale, and mainly represent a bulkhead built in a drift of 5 per 5 m in with 30 m of length, with vertical structures that represent the door and a trapezoid that represents the embankment. In the bi-dimensional models, the two vertical structures near the embankment represent the eucalyptus layer, with 0.15 m of thickness, and the other layer represents mainly the pine wood put also the steel mesh and jute, with a 0.05 m of thickness. This type of models are identify as Compounds (Figure 14).

Tridimensional models are more complex. The door is made of vertical and horizontal beams where lath is attached. This part of the door is linked to the stanchion zone with beam and chains, inside of the drift.

Figure 14 represents a bi-dimensional drift model in the initial state when the door was concluded. The horizontal lines represent the different layers of fill, to simulate the filling process. On Figure 15 is presented the tridimensional models simulated.

#### Figure 14 – Bi-dimensional model, in Plaxis

![Bi-dimensional model, in Plaxis](image)

#### Figure 15 – Tridimensional model, in Abaqus.

The materials used in the models elaboration are the ones referred previously, with specific alterations that are necessary on each software. The permeability of the fill is 0.00036 m/h (Godbout, J et al., 2007) and for the embankment 1.8 m/h (Swiss Standard). The void ratio is 0.7 to the fill (Belem, T. et al. 2002) and 0.28 to the embankment (Swiss Standard).

The simulation process occurs during eleven stages of static calculation where only the self-weight of the backfill acts on the barricade. In the first stage, it is established the initial state of the problem with only the barricade construction, the next ten stages simulate the filling process and, at each stage, the static equilibrium is reached. To simplify the process of simulation, we assume that the convergence process has finished. The worst-case scenario is simulated admitting that there were no dissipation of the neutral stress, and the backfill is completely saturated and there is still exudation water.

Similar to Li & Aubertin models, models with “L” shape stopes were tested, considering a height above the drift of 15 m. The object of this analysis was to determine the importance of the overweight of the backfill on barricades. Other types of models include the presence or absence of the steel chains, and to simulate the barricade structure, there were used two types of models, beyond the Compound model; in Plaxis it was used a Plate type, and in Abaqus it was used the Beam type.

In Plaxis the model was constructed directly in the software, while in Abaqus it was possible to import the model from CAD. The models try to represent in the most accurate possible way, the barricades. This is notorious in the tridimensional models. In order to get better results, isotropic behavior was adapted to the wood, even though that in reality, they are orthotropic. It was also adapted the weight of the tailing particles to maximize the deformations and stress in the simulations.

#### 4.2. Results

These evaluations have the purpose to calculate in an analytic form, the forces and solicitations that barricades are subjected to. Considering the bulkheads as earth supporting structures, where the use of Coulomb and Rankine theory have several applications and allowed to determinate this solicitations.

Taking in account the self-weight of the backfill we can consider:

- Vertical stress: $σ_y = \gamma h$
- Horizontal stress: $σ_x = k \cdot \gamma h$

$\gamma$ is the weight volume, $h$ is the height and $k$ is the lateral coefficient. There are several possibilities for the state of the lateral coefficient. There are three base types of lateral coefficient for purely frictional soils: coefficient of active earth pressure at rest ($k_a = 1 - \sin \phi$); coefficient of active earth pressure ($k_a = (1 - \sin \phi)/(1 + \sin \phi)$); and coefficient of passive earth pressure ($k_p = (1 + \sin \phi)/(1 - \sin \phi)$).

Considering the backfill as a coherent “soil”, cohesion ($c$) is taken in account to calculate the earth pressure (at rest, active and passive) on the barricade, according the Mohr-Coulomb:

$$Force = \frac{1}{2}k_a\gamma h^2 \quad (Equation \ 5)$$
$$Force = \frac{1}{2}k_a\gamma h^2 - 2ch\sqrt{k_a} \quad (Equation \ 6)$$
$$Force = \frac{1}{2}k_p\gamma h^2 + 2ch\sqrt{k_p} \quad (Equation \ 7)$$

Using the data from table 3 to calculate the three coefficients of the backfill. Coefficient of active earth pressure at rest ($k_a$)is 0.65; coefficient of active earth pressure ($k_a$) is 0.49, finally for the coefficient of passive earth pressure ($k_p$) is 2.04.

The backfill inside the drift exerted on the barricade a load that will be contraposed by the load of the backfill and embankment after the barricade. The problem can be simply schematized as presented in Figure 16, with these it is easy to proceed to the calculation of the stress and loads on the barricade, establishing three possible hypotheses.
In the three hypotheses, the lateral earth coefficient is changed in order to maximize and minimize the loads on the barricades. On the first hypotheses, it is considered $k_0$ on the drift and on the backfill and embankment outside the barricade. On the second hypotheses, the backfill in the drift has a $k_0$ and the fill and embankment outside the barricade has $k_0$. Finally, on the third hypotheses, the backfill inside the drift has a $k_0$, and outside the barricade it is considered to have $k_p$. In the active situation ($k_p$) there is a relief of the horizontal stress in the vicinities of the barricade. On the passive situation ($k_p$) there is an increase of the horizontal stress, and in the at rest situation ($k_0$) it is assumed a stabilization or equilibrium of the backfill. Assuming that there was no dissipation of the neutral stress and using the values of the materials, we get the following stress and load values presented in Tables 6 to 9.

**Table 6 – Vertical stress.**

<table>
<thead>
<tr>
<th></th>
<th>Drift</th>
<th>Fill</th>
<th>Embankment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypotheses 1</td>
<td>112.70</td>
<td>22.54</td>
<td>34.30</td>
</tr>
<tr>
<td>Hypotheses 2</td>
<td>112.70</td>
<td>22.54</td>
<td>34.30</td>
</tr>
<tr>
<td>Hypotheses 3</td>
<td>112.70</td>
<td>22.54</td>
<td>34.30</td>
</tr>
</tbody>
</table>

**Table 7 – Horizontal stress (kPa).**

<table>
<thead>
<tr>
<th></th>
<th>Drift</th>
<th>Fill</th>
<th>Embankment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypotheses 1</td>
<td>73.26</td>
<td>14.65</td>
<td>12.01</td>
</tr>
<tr>
<td>Hypotheses 2</td>
<td>73.26</td>
<td>45.76</td>
<td>157.44</td>
</tr>
<tr>
<td>Hypotheses 3</td>
<td>55.22</td>
<td>45.76</td>
<td>157.44</td>
</tr>
</tbody>
</table>

**Table 8 – Horizontal load (kN).**

<table>
<thead>
<tr>
<th></th>
<th>Drift</th>
<th>Fill</th>
<th>Embankment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypotheses 1</td>
<td>183.14</td>
<td>5.33</td>
<td>6.00</td>
</tr>
<tr>
<td>Hypotheses 2</td>
<td>183.14</td>
<td>490.20</td>
<td>78.72</td>
</tr>
<tr>
<td>Hypotheses 3</td>
<td>-1009.94</td>
<td>490.20</td>
<td>78.72</td>
</tr>
</tbody>
</table>

**Table 9 – Application point (m).**

<table>
<thead>
<tr>
<th></th>
<th>Drift</th>
<th>Fill</th>
<th>Embankment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypotheses 1</td>
<td>1.67</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Hypotheses 2</td>
<td>1.67</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Hypotheses 3</td>
<td>1.67</td>
<td>0.33</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Figure 16 – Schematic simplification of the stress application on barricades.

Figure 17 – Distribution of the displacement and its direction. With 0.5 m of backfill, 6 m of backfill and 20 m of backfill, in Abaqus.

In these models, even not considering the friction between the walls and the fill, the arch effect can be seen. This effect is mainly due to the internal friction of the backfill. It also shows the accumulation of stress in the corner of the stope and the drift (Figure 18).

Figure 18 – Distribution of the vertical stress ($\sigma_y$), in Plaxis.
displacement of the barricade, even with the overfilling of more than 15 m. as
the backfill movements become predominantly vertical.

4.2.1.2. Bidimensional Drift Models

As referred before, the steel chains concede to the barricades more rigidity,
moving the center of gravity inside the drift. In the models with chains, there is a
raise of loads on the barricade, that small raise (compared with models without
chains) is accompanied by smaller displacements of the barricade. The effects of
the chains are observed up to 3 m inside the drift, the anchorage zone of the
chains after which the values in all the models stabilize. The use of chains
decreases the tension on the barricade in 200 kPa, in Plaxis, and 10 kPa, in
Abaqus.

The results of the models that replace the Compound barricade for a plate, in
Plaxis, or beam barricades, in Abaqus, had similar results to those of the
compound barricades, with the downside of not allowing extracting values from
those structures.

In Figures 19 to 22 are presented some results from the models. The
maximum displacement of the barricades in Plaxis is around 26 mm and in
Abaqus is around 67 mm. The horizontal stress on the doors has values between
53.5 kPa, in Plaxis, and 60 kPa, in Abaqus.

4.2.1.3. Tridimensional Drift Models

Tridimensional models are more complex and closest to reality. They
simulate the barricade and the stanchion, inside the drift.

In these models, it was possible to identify the most solicited zones of the
barricade. These zones are: the beams that connect the barricade to the
stanchion, which suffer tension solicitations; and the base of the barricade, with
a lot of compression accumulated (Figure 23).

The displacements, as in the bi-dimensional model, is more expressive in the
early stages of the filling process, with the difference that the stanchion tries to
follow that movement. There is a lot of tension accumulated in the chains during
the first stages of the fill, and the results suggest that the chains cause more
stress in the horizontal beams of the stanchion.

Figure 24 presents the result of the horizontal stress distribution on the
model.

5. Results Analysis

With the results quantify in the previews chapter, it is now possible to do a
stability analysis of the bulkheads. Assuming that the instability of bulkheads
results from sliding or falling phenomenon, we try to estimate the security factor
to those mechanisms as well as to flexion.

The sliding movement is in the embankment direction, and is the relation
between the stability loads and the instability loads. The stability loads are the
weight of the bulkhead, the weight of the backfills and embankment, and the
loads of the embankment and backfill between the barricade and the
embankment (Figure 25).

In these models, it was possible to identify the most solicited zones of the
barricade. These zones are: the beams that connect the barricade to the
stanchion, which suffer tension solicitations; and the base of the barricade, with
a lot of compression accumulated (Figure 23).

Figure 23 – Distribution of the minimal principal stress, in Abaqus.

The displacements, as in the bi-dimensional model, is more expressive in the
early stages of the filling process, with the difference that the stanchion tries to
follow that movement. There is a lot of tension accumulated in the chains during
the first stages of the fill, and the results suggest that the chains cause more
stress in the horizontal beams of the stanchion.

Figure 24 – Distribution of the horizontal stress, in Abaqus.

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loads of the embankment and backfill between the barricade and the
embankment (Figure 25).

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follow that movement. There is a lot of tension accumulated in the chains during
the first stages of the fill, and the results suggest that the chains cause more
stress in the horizontal beams of the stanchion.

Figure 24 presents the result of the horizontal stress distribution on the
model.

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stability analysis of the bulkheads. Assuming that the instability of bulkheads
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to those mechanisms as well as to flexion.

The sliding movement is in the embankment direction, and is the relation
between the stability loads and the instability loads. The stability loads are the
weight of the bulkhead, the weight of the backfills and embankment, and the
loads of the embankment and backfill between the barricade and the
embankment (Figure 25).
Moments are calculated with the force and the distance ($d_{xy}$) between the application point of that force, and the falling point of the barricade. As the third analytic hypotheses favors stability, it was decided not to present those calculations.

5.1. Verification of Security Based on Analytic Results

The security to the sliding can be determinate using the previews Equations (8 to 10): We will have the following relation:

$$\frac{\sum \text{Stability Moments}}{\sum \text{Instability Moments}} = \text{Security}$$

$$\text{Moment} = \text{Force} \times d \quad \text{(Equation 12)}$$

Moments are calculated with the force and the distance ($d_{xy}$) between the application point of that force, and the falling point of the barricade. As the third analytic hypotheses favors stability, it was decided not to present those calculations.

The main risk zones are: the base of the barricade, that accumulates relatively small (20 a 25 mm, in Plaxis, and 60 a 75 mm, in ABAQUS) a small increase of those slidings in an magnitude of 100 mm would still be a small sliding, almost undetected to the naked eye, while allowing some stress relief on the barricades.

### Table 10 – Sliding security values.

<table>
<thead>
<tr>
<th>Friction Angle ($\varphi$)</th>
<th>15</th>
<th>25</th>
<th>35</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypotheses 1</td>
<td>0.16</td>
<td>0.22</td>
<td>0.29</td>
<td>0.38</td>
</tr>
<tr>
<td>Hypotheses 2</td>
<td>3.41</td>
<td>3.63</td>
<td>3.90</td>
<td>4.23</td>
</tr>
</tbody>
</table>

Applying Equations (11 and 12) to the problem we get the following relation:

$$\frac{\sum \text{Moments}_{\text{fill}} + \text{Moments}_{\text{drift}}}{\sum \text{Moments}_{\text{fill}} + \text{Moments}_{\text{drift}} + \text{Moments}_{\text{embankment}}} = \text{Security}$$

The perpendicular distance to the falling point multiplies by the orthogonal loads. The results are presented in Table 11.

### Table 11 – Falling security values.

<table>
<thead>
<tr>
<th>Security</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypotheses 1</td>
<td>2.17</td>
</tr>
<tr>
<td>Hypotheses 2</td>
<td>3.27</td>
</tr>
</tbody>
</table>

5.2. Verification of Security Based on Models Results

These values ensure the security to falling: A fact in the design of these barricades that influence the security to falling is the height of the embankment; this height will raise the application point of the horizontal load component, which will rise and stabilize that orthogonal moment.

Using the results, it is possible to evaluate the security of the materials on the barricades to compression, tension and flexion, in the models. According to table 2, the strength of the materials is: Compression of pine 6.6 MPa, of eucalyptus 13.6 MPa; tension of pine 3.9 MPa, of eucalyptus is 6.7 MPa. With these values as reference, it is possible to verify if there are any ruptures.

The maximum values on the models are 1.8 MPa tension stress on the eucalyptus beams, on the 3D model pine have a maximum of 460 kPA of tension stress due to the self weight of the backfill, although due to the tight fill, these contacts happen in all the drifts walls. In Table 13 are presented the security values based on the models and varying the friction angles.

### Table 13 – Sliding security values.

<table>
<thead>
<tr>
<th>Friction angle ($\varphi$)</th>
<th>15</th>
<th>25</th>
<th>35</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaxis with chains</td>
<td>0.76</td>
<td>0.87</td>
<td>0.99</td>
<td>1.14</td>
</tr>
<tr>
<td>Plaxis without chains</td>
<td>0.87</td>
<td>0.98</td>
<td>1.12</td>
<td>1.29</td>
</tr>
<tr>
<td>Plaxis Plate with chains</td>
<td>0.75</td>
<td>0.85</td>
<td>0.97</td>
<td>1.13</td>
</tr>
<tr>
<td>Plaxis Plate without chains</td>
<td>0.87</td>
<td>0.99</td>
<td>1.12</td>
<td>1.29</td>
</tr>
<tr>
<td>ABAQUS 2D with chains</td>
<td>0.87</td>
<td>0.98</td>
<td>1.11</td>
<td>1.28</td>
</tr>
<tr>
<td>ABAQUS 2D without chains</td>
<td>0.97</td>
<td>1.08</td>
<td>1.22</td>
<td>1.40</td>
</tr>
<tr>
<td>ABAQUS 2D Beam with chains</td>
<td>0.86</td>
<td>0.97</td>
<td>1.10</td>
<td>1.26</td>
</tr>
<tr>
<td>ABAQUS 2D Beam without chains</td>
<td>0.94</td>
<td>1.06</td>
<td>1.19</td>
<td>1.37</td>
</tr>
<tr>
<td>ABAQUS 3D with chains</td>
<td>0.61</td>
<td>0.71</td>
<td>0.84</td>
<td>1.01</td>
</tr>
<tr>
<td>ABAQUS 3D without chains</td>
<td>0.64</td>
<td>0.75</td>
<td>0.89</td>
<td>1.06</td>
</tr>
</tbody>
</table>

With these results, it is possible to verify that even with a conservative approach the security to sliding is partially guarantied. The values of the models are more favorable than hypotheses 1, but less favorable then hypotheses 2.

Using the ($d_{xy}$) values determinate in the simulations, and applying them to equation 14, we have the falling security of the barricade, based on the models (Table 14).

### Table 14 – Falling security values.

<table>
<thead>
<tr>
<th>Security</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypotheses 1</td>
</tr>
<tr>
<td>Hypotheses 2</td>
</tr>
<tr>
<td>Hypotheses 3</td>
</tr>
<tr>
<td>Hypotheses 4</td>
</tr>
<tr>
<td>Hypotheses 5</td>
</tr>
<tr>
<td>Hypotheses 6</td>
</tr>
<tr>
<td>Hypotheses 7</td>
</tr>
<tr>
<td>Hypotheses 8</td>
</tr>
<tr>
<td>Hypotheses 9</td>
</tr>
<tr>
<td>Hypotheses 10</td>
</tr>
</tbody>
</table>

These values ensure the security to falling: A fact in the design of these barricades that influence the security to falling is the height of the embankment; this height will raise the application point of the horizontal load component, which will rise and stabilize that orthogonal moment.

Using the results, it is possible to evaluate the security of the materials on the barricades to compression, tension and flexion, in the models. According to table 2, the strength of the materials is: Compression of pine 6.6 MPa, of eucalyptus 13.6 MPa; tension of pine 3.9 MPa, of eucalyptus is 6.7 MPa. With these values as reference, it is possible to verify if there are any ruptures.

The maximum values on the models are 1.8 MPa compression stress and 1.5 MPa tension stress on the eucalyptus beams, on the 3D model pine have a maximum of 1.6 MPa, and a maximum of 460 kPA of tension. These values are far away from the strength of the materials. Although the risk of material failing seems far away, it is possible to identify the most solicited zones on the barricades, this point is quite explicit in the 3D models.

The main risk zones are: the base of the barricade, that accumulates compression stress due to the self-weight of the backfill; the linking beams between the barricade and the stanchion inside the drift and the zone of the barricade above the embankment height where the tension is accumulated.

The security of flexion is given in Table 15, using Equations 15 and 16 and the model values.

### Table 15 – Flexion security values.

<table>
<thead>
<tr>
<th>Security</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypotheses 1</td>
</tr>
<tr>
<td>Hypotheses 2</td>
</tr>
<tr>
<td>Hypotheses 3</td>
</tr>
<tr>
<td>Hypotheses 4</td>
</tr>
<tr>
<td>Hypotheses 5</td>
</tr>
<tr>
<td>Hypotheses 6</td>
</tr>
<tr>
<td>Hypotheses 7</td>
</tr>
<tr>
<td>Hypotheses 8</td>
</tr>
<tr>
<td>Hypotheses 9</td>
</tr>
<tr>
<td>Hypotheses 10</td>
</tr>
</tbody>
</table>
5.3. Classics Design Methods

Using the classic design methods, based on yield line theory and other variants, it is possible to have access to useful information about the security of the barricades, even knowing that these methods are applied to concrete plate barricades.

With the yield line theory, from equation 2 and table 1, and knowing the tension strength of the materials, it is possible to know the maximum momentum supported by the barricades, depending if its pine or eucalyptus: 39 kN/m, 67 kN/m. Assuming the best scenario and the worst (Equation 1 and 2 on table 1), we get the ultimate pressure for pine (37.44 kPa a 64.32 kPa) and for eucalyptus (74.88 kPa e 128.64 kPa). Comparing these values with the results observed in the models we get the security factor (Table 16).

Table 16 – Security factors

<table>
<thead>
<tr>
<th>Security factor</th>
<th>Worst</th>
<th>Best Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytic</td>
<td>0.51</td>
<td>0.88</td>
</tr>
<tr>
<td>Plaxis with chains</td>
<td>0.70</td>
<td>1.20</td>
</tr>
<tr>
<td>Plaxis without chains</td>
<td>0.75</td>
<td>1.29</td>
</tr>
<tr>
<td>Plaxis Plate with chains</td>
<td>0.75</td>
<td>1.29</td>
</tr>
<tr>
<td>Plaxis Plate without chains</td>
<td>0.75</td>
<td>1.29</td>
</tr>
<tr>
<td>Abaqus 2D with chains</td>
<td>0.62</td>
<td>0.99</td>
</tr>
<tr>
<td>Abaqus 2D without chains</td>
<td>0.65</td>
<td>1.12</td>
</tr>
<tr>
<td>Abaqus 2D Beam with chains</td>
<td>0.58</td>
<td>1.03</td>
</tr>
<tr>
<td>Abaqus 2D Beam without chains</td>
<td>0.60</td>
<td>1.17</td>
</tr>
<tr>
<td>Abaqus 3D with chains</td>
<td>0.69</td>
<td>1.19</td>
</tr>
<tr>
<td>Abaqus 3D without chains</td>
<td>0.68</td>
<td>1.17</td>
</tr>
</tbody>
</table>

With this method we can partially confirm the security (values superior to 1). Yet, the wood barricades design is more closed to the best scenario because the embankment works as a foundation and during the building process the workers always try to confine the door the maximum possible.

With the Beer formulation (1986) of the yield line test, according to Equation 3 and 4, the moments will range from 33 kNm/m to 68 kNm/m, with a ultimate pressure of 31.68 kPa (pine) 65.28 kPa (eucalyptus). In table 17 is presented the security values based on this formulation.

Table 17 – Beer security factors

<table>
<thead>
<tr>
<th>Security factor</th>
<th>Worst</th>
<th>Best Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytic</td>
<td>0.43</td>
<td>0.89</td>
</tr>
<tr>
<td>Plaxis with chains</td>
<td>0.59</td>
<td>1.22</td>
</tr>
<tr>
<td>Plaxis without chains</td>
<td>0.63</td>
<td>1.31</td>
</tr>
<tr>
<td>Plaxis Plate with chains</td>
<td>0.63</td>
<td>1.31</td>
</tr>
<tr>
<td>Plaxis Plate without chains</td>
<td>0.63</td>
<td>1.31</td>
</tr>
<tr>
<td>Abaqus 2D with chains</td>
<td>0.52</td>
<td>1.08</td>
</tr>
<tr>
<td>Abaqus 2D without chains</td>
<td>0.55</td>
<td>1.13</td>
</tr>
<tr>
<td>Abaqus 2D Beam with chains</td>
<td>0.49</td>
<td>1.00</td>
</tr>
<tr>
<td>Abaqus 2D Beam without chains</td>
<td>0.51</td>
<td>1.05</td>
</tr>
<tr>
<td>Abaqus 3D with chains</td>
<td>0.57</td>
<td>1.18</td>
</tr>
<tr>
<td>Abaqus 3D without chains</td>
<td>0.59</td>
<td>1.21</td>
</tr>
</tbody>
</table>

These results are less satisfying; both scenarios have smaller factors that the yield line theory, the scenario closer to reality is the best scenario where all sides of the barricade are fixated. According to in situ test done in Mount Isa Mines, in Australia, the values of this analysis are 1.7 times smaller than the observed in reality (Revell & Sainsbury, 2007).

According to the Hassani formulation the maximum pressure on the barricade is: \( \text{Stress}_{\text{maximum}} = FS \times \sigma_v \) (Equation 17)

This formulation admits that stress is the maximum stress supported by the barricade, \( FS \) is the factor of security, to Hassani it should vary from 3 to 5, and \( \sigma_v \) is the vertical stress, due to the weight of the backfill. In this formulation, Hassani admits a relation between \( \sigma_v/\sigma_h \) of 1. The maximum stress in the barricades is present in table 18, their determinate by using \( \sigma_v \) of the models near the barricade.

Table 18 - Maximum stress in the barricades

<table>
<thead>
<tr>
<th>Security factor</th>
<th>FS</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytic</td>
<td>225.4</td>
<td>338.1</td>
<td>450.8</td>
<td>563.5</td>
<td></td>
</tr>
<tr>
<td>Plaxis with chains</td>
<td>170.4</td>
<td>255.6</td>
<td>340.8</td>
<td>426.0</td>
<td></td>
</tr>
<tr>
<td>Plaxis without chains</td>
<td>240.0</td>
<td>360.0</td>
<td>480.0</td>
<td>600.0</td>
<td></td>
</tr>
<tr>
<td>Plaxis Plate with chains</td>
<td>245.4</td>
<td>368.1</td>
<td>490.8</td>
<td>613.5</td>
<td></td>
</tr>
<tr>
<td>Plaxis Plate without chains</td>
<td>293.0</td>
<td>439.5</td>
<td>586.0</td>
<td>732.5</td>
<td></td>
</tr>
<tr>
<td>Abaqus 2D with chains</td>
<td>262.8</td>
<td>394.2</td>
<td>525.6</td>
<td>657.0</td>
<td></td>
</tr>
<tr>
<td>Abaqus 2D without chains</td>
<td>2608</td>
<td>391.2</td>
<td>521.6</td>
<td>652.0</td>
<td></td>
</tr>
<tr>
<td>Abaqus 2D Beam with chains</td>
<td>360.0</td>
<td>540.0</td>
<td>720.0</td>
<td>900.0</td>
<td></td>
</tr>
<tr>
<td>Abaqus 2D Beam without chains</td>
<td>355.6</td>
<td>533.4</td>
<td>711.2</td>
<td>889.0</td>
<td></td>
</tr>
<tr>
<td>Abaqus 3D with chains</td>
<td>264.2</td>
<td>396.3</td>
<td>528.4</td>
<td>660.5</td>
<td></td>
</tr>
<tr>
<td>Abaqus 3D without chains</td>
<td>263.2</td>
<td>394.8</td>
<td>526.4</td>
<td>658.0</td>
<td></td>
</tr>
</tbody>
</table>

According with this evaluation, these values are inferior the strength of the materials used, we can admit the security of the barricades.

5.4. Results Discussion

Comparing the several results obtain in this work, we can verify that:

The models allow the determination of the stress state in the barricade, verifying their security. The security factors obtained for the compression and tension stress, remove the rupture scenario. On the other hand, models allow to verify which are the most solicited areas, for instance, the eucalypt beams that link the barricade do the stanchion, and the development of flexion on the barricade.

A critical security value is the flexion. The results of this value are around 2, both in the analytic and models analysis.

The sliding and falling security depends on the barricade weight and the friction angle of the structures and the contacts. In this case, the friction angle is equal for all materials. The sliding values (1) are reasonable for a friction angle of 25, although we can acknowledge that these values are a bit conservative because it only admits contact with the drifts bottom. The falling values are acceptable and show that the structure is stable.

The classic design methods reveal a wide range of security values; these methods are more appropriated to concrete, plate barricades. With the confinement of the barricade to the drift walls the situation referred in classic methods, that more approximate to this scenario is the one that admits fixation of the barricade to the walls. Hassani formulation gave the pressure the barricade are subject, those values are far away from the materials strength. According to the classic methods, we can admit the security of the barricades.

Analyzing the relation between \( \sigma_v/\sigma_h \) in the models its possible to determine the k value, and with this values we can demonstrate which of the hypotheses is more probable. We verify that close to the barricade, the lateral earth coefficient is 0.65, at rest coefficient, further in the drift the values decrease suggesting stress relief and getting closer to 0.49, active earth pressure. Has for the values in the embankment and backfill between the embankment and the barricade, there is a raise of the k values, suggesting an increasing of the stress, although it never reaches the values of 2.03, passive earth pressure. These results validate the second hypotheses, that underling an active earth pressure in the backfill inside the drift, and a passive earth pressure outside the barricade.

Another possible observation is the calculations the programs do, both programs suggest the relief of stress inside the drift backfill. But in Plaxis the horizontal stress at the top of the drift is around 0 kPa, will in Abaqus there's development of tension, with values around 17 kPa, that suggest the activation of the cohesive parcel. These effects are internal to each programs calculations, because in each program the backfill behavior is define as Mohr Coulomb.

6. CONCLUSIONS

6.1. Conclusions

Based on the results of the models, and comparing those with the results of the analytic analysis and the classic design methods, we can conclude that Somincor wooden barricades guaranty safety.
It is possible to verify that there is not a great increase of stress in the “L” models, although there is an obvious increase of the load on the barricades. This model is, of course, a limit scenario and it is not a common practice in Somincor. The models allow the verification and confirmation of the safety in the barricade materials as the stress developed is far from the material strengths. It is still possible to identify the most brittle or solicited zones. Although the rupture of the materials does not seem to happen, there is still that possibility due to the complex microstructure of the woods and its entropic nature.

Flexion is the most critical safety factor of the materials, but the results seem reassuring, with values bigger than 2. We can still observe the displacements that the barricade suffers, suggesting a flexion just above the embankment height.

The sliding and falling safety is partially guaranteed and just as expected, the safety factors depend essentially on the barricade weight. Therefore, the embankment placement and the fact that backfill will occupy the space between the barricade and embankment, will increase the safety of the barricade, making those structures work as a part of the barricade itself. In the models, the movements seem stabilized, although some safety factors may suggest a need for the barricade to slide. With this sliding, the loads on the barricades will drop and, because the maximum sliding value is relatively small (73 mm), a small increase of that movement should be accepted.

A downside of the steel chain use is the increase of the local stress, where the chains are attached, yet the use of chains decreases the tension that the barricade suffers. Another fact from the use of chains is that the displacement is smaller in those that are attached, yet the use of chains decreases the tension that the barricade suffers, suggesting a flexion just above the embankment height.


Although this study is not an exhaustive one of all possibilities and combinations of solicitations, it allows us to conclude that with this design, building techniques and materials, the safety of Somincor barricades is ensured, and the confidence in these structures can continue as it has been up until now.

6.2. Future Developments

As a future development, it should be consider the monitoring of the barricades using, for instance, vibrant string gages in the steel chains, strain gages in the eucalyptus beams, and a hydraulic jack to allow to determine the load on an area perpendicular to the barricade. It would be useful a complete mechanic characterization of all materials used in the barricade design, which would allow more complex models to be simulated.

It would be interesting to make a construction of a scale physical model and, in abandoned mine areas, an in situ ultimate load test could be done.

Another relevant study would be the use of FEM models to study the shockwave felt in the backfill, due to exploitation of near stopes.

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