UNIVERSIDAD DE CHILE
FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS
DEPARTAMENTO DE INGENIERIA DE MINAS

GEOTECHNICAL CHARACTERIZATION AND METHODOLOGY FOR A RISK EVALUATION OF ORE RELATED TO MUD RUSHES IN BLOCK/PANEL CAVING MINING

TESIS PARA OPTAR AL GRADO DE MAGISTER EN MINERIA

KENJI ANDRÉS BASAURE MATSUMOTO

PROFESOR GUÍA:
JAVIER VALLEJOS MASSA

PROFESOR CO-GUIA:
RAÚL CASTRO RUIZ

MIEMBROS DE LA COMISIÓN:
KIMIE SUZUKI MORALES
JAVIER CORNEJO GONZÁLEZ

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RESUMEN

Los bombeos de barro son un ingreso repentino de mineral barro dentro de instalaciones mineras subterráneas. Pueden causar daños a personas y equipos, retrasos de producción, dilución, y cierre de minas. El objetivo de este trabajo es caracterizar a través de ensayos geotécnicos de laboratorio el barro de una mina de block/panel caving para proporcionar razones mecánicas para la falla fluida de este material mientras es extraído. Además se busca desarrollar un método para establecer pautas de decisión y aplicarlas a muestras de barro. Se ha utilizado muestras de mineral proveniente de puntos de extracción cerrados por potencial riesgo de bombeos de barro en la mina Diablo Regimiento, El Teniente, las muestras representan tres tipos de mineral barro presentes en la mina. De la caracterización se obtiene que las muestras tienen tamaños de partícula correspondientes a grava, arena, limo y arcilla, en donde las partículas finas se clasifican como limo y arcilla de baja plasticidad. Las muestras presentan leves diferencias una de otra en cuanto a contenido de finos, densidad y empaquetamiento. La resistencia del mineral a condiciones no confinadas es evaluada variando la densidad y el grado de saturación, esto permite observar que la densidad relativa es la variable más importante que gobierna la resistencia no confinada. Ensayos triaxiales consolidados saturados muestran una relación lineal entre la resistencia deviatórica y el esfuerzo confinante efectivo, esta relación es encontrada para las muestras evaluadas. La resistencia deviatórica se relaciona con la capacidad de fluir ante condiciones triaxiales, en consecuencia podría estar relacionado con los bombeos de barro. Ensayos triaxiales no consolidados saturados muestran una baja resistencia deviatórica máxima muy baja, seguida de licuación estática, lo que resulta en valores de resistencia residual cercanos a cero. Llevados a la minería estos resultados se relacionan con la tasa de extracción y las condiciones de saturación: Una alta tasa de extracción puede generar condiciones no consolidadas, haciendo que la resistencia del mineral tenga valores cercanos a cero, mientras que una baja tasa de extracción generaría condiciones consolidadas, en donde el mineral puede expulsar la presión de poros y tener mayor resistencia. Si el mineral se encuentra en condiciones no saturadas presenta un riesgo menor, ya que desarrolla incluso resistencia uniaxial. El cono de Abrams se utiliza para desarrollar ensayos de asentamiento a muestras de barro y caracterizar la consistencia del mineral ante distintas condiciones de saturación y densidad. La resistencia no confinada también se evalúa para distintas condiciones de saturación y densidad. Estos resultados permiten establecer una relación entre la consistencia y la resistencia no confinada: las condiciones para una consistencia fluida en el cono de Abrams son las mismas que generan una baja resistencia no confinada. También se encontró el contenido de humedad al cual cada muestra cambia su consistencia de plástica a suave de acuerdo a los ensayos de asentamiento. Estos valores fluctúan de 12.2% a 16.9% de humedad dependiendo de la muestra. Finalmente se define un factor de seguridad a la fluidez para diseñar una pauta de extracción basada en humedad a las muestras evaluadas. Se concluye que un mineral altamente compactado no tiende a fluir, además las propiedades fluidas del mineral dependen fuertemente de las propiedades específicas de cada tipo de mineral, en consecuencia un criterio específico debe ser desarrollado para cada tipo de mineral en una misma mina.

ABSTRACT

Mud rushes are sudden inflow of mud ore into underground mining facilities. They may cause harm to people and equipment, production delays, dilution and mine closure. The aim of this work is to characterize by geotechnical laboratory tests, mud from a block cave, to derive mechanical reasons to the failure of this material while is being drawn and finally to develop a method to establish decision patterns and apply them to mud samples. We have used ore samples from closed extraction points due to mud rush potential from Diablo Regimiento at El Teniente, which represents the three types of mud ore. Characterization shows that samples have gravel and sand with silt and clay grain sizes, where fine particles are classified as low plasticity silt and clay. We found that samples have small differences from one to another in fine content, density and packing. Ore strength to unconfined conditions is evaluated varying the density and saturation degree, this allows to observe that relative density is the most relevant variable that governs the unconfined strength. Triaxial consolidated tests show a linear relation between deviatoric strength and effective confining stress, and it has been found for the samples tested. Deviatoric strength is related to the capacity to flow under triaxial conditions, consequently it could be related to mud rushes. Unconsolidated, saturated tests exhibit a very low deviatoric maximum strength followed by static liquefaction, resulting in residual strength values near to zero. In terms of mining the geotechnical tests were related to the draw rate and the saturated conditions: a high rate of drawing could cause unconsolidated conditions as the strength of the mud decreases to near zero while a low extraction rate could be related to consolidated conditions where the ore is allowed to release the pore pressure. If the ore is under unsaturated conditions it presents a lower risk as it will develop uniaxial strength. The Abrams's Cone has been used to perform slump tests to mud samples and characterize their consistency by setting the saturation degree and packing. The unconfined strength for different saturation degrees and packing is then evaluated. The results show that conditions for fluid response in slump tests correspond to conditions for low strength in unconfined compression tests. We also found the water content value in which each sample changes the flowing consistency from plastic to soft behaviour according to slump tests classification. These values fluctuate from a content of 12.2% and 16.9% of water content depending on the sample tested. Finally, we defined a fluid security factor in order to design an extraction pattern for the samples tested, based on the water content value. We conclude that a very dense packed ore is not prone to flow, also flow properties strongly depend on the specific properties of ore tested, consequently a specific criterion should be developed for different types of ore in the same mine.

CONTENTS

INTRODUCTION

INTRODUCTION

Block/Panel caving is an underground mining method which is based on gravity for mineral breakage and transportation to drawpoints. It can involve several hazards as rock bursts, air blasts and mud rushes (Heslop, 2000). One of those hazards is mud rush, which consists in sudden income of fine material with water into the underground facilities (Butcher, 2005). They can cause injuries, fatalities, production delays and damage to equipment, in consequence mud rushes are an inadmissible risk. However block/Panel caving mining operations are inherently prone to suffer mud rushes because they frequently have all the conditions for their occurrence: Mud forming material, water, discharge point and disturbances (Butcher, 2000). Mud forming material is fine mineral from caving process and surface, water from surface and underground sources, discharge points are the drawpoints and finally extraction and blasting can do as disturbances.

Mud forming material are described by different authors as fine particles and water (Becerra, 2011; Hubert, 2000; Jakubec, 2012; Lacy, 1992; Samosir, 2008). In one hand, fine particles come from dilution from surface or milled ore by caving process. In the other hand, water sources are rain and snow infiltrated from surface or underground water.

Different mechanisms in which an initial stable material can flow in a mud rush event have been theorized given the characteristic of very low shear strength that fluids have. One of them is the increase of water content that produces a loss in shear strength (Butcher, 2005; Jakubec 2012). The other one is the increase of pore pressure induced by stress that can cause a sudden weakening in shear strength in a phenomena called flow failure (Yoshemine, 1998) or static liquefaction (Yamamuro, 1998).

Classification systems based on grain size and water content measured in drawpoints have been used in order to control the risk of mud rush in block/panel caving operations. El Teniente mine classification system was established using historical data, and includes water content measured in laboratory and the proportion of sizes less than 25cm observed in drawpoints.

OBJECTIVES

The main objective of this research is to characterize in laboratory the material prone to suffer mud rushes in order to understand its mechanical behaviour under different conditions. Also we aim to provide the mechanical reasons of material failure while is being drawn that could generate mud rushes. Finally we aim to develop recommendations to classify risk for tested material.

METHODOLOGY

In order to accomplish the objectives a list of objectives were performed:

1. Determine the variables to be evaluated in laboratory testing by performing a literature review of known characteristics and behaviour of mud forming material.
2. Set the list of tests to be performed and variables to evaluate in order to characterize the material and behaviour under different conditions.
3. Select and obtain material classified as critical from Diablo Regimiento, El Teniente, Codelco.

4. Perform the laboratory tests and give an interpretation of the results. Provide a detailed geotechnical and mechanical characterization of the obtained material.
5. Provide the mechanical reasons of material failure related with extraction conditions operation condition of the mine.
6. Develop a method to classify the material based on its flowing behaviour and apply it to the obtained material.

THESIS CONTENTS

This research resulted in the following articles:

- **Article 1: "Towards an understanding of mud rush behaviour in block-panel caving mines"**, presented in Caving 2014. This paper describes the first approach to propose the fundamentals of mud rushes. Furthermore, it will elaborate a geotechnical model that includes a quantitative component. This will be done through developing a force diagram. A geotechnical characterization will be done to know the determinant variables in the failure of saturated fine material
- **Article 2: "Geotechnical characterization of ore related to mud rushes in block caving mining"**, elaborated and sent to Journal of the Southern African Institute of Mining and Metallurgy. The aim of this work is to characterize by geotechnical laboratory tests mud from a block cave and to derive mechanical reasons to the failure of this material while is being drawn.
- **Article 3: "Methodology for a risk evaluation of mud rushes in block caving mining"** sent for Journal of the Southern African Institute of Mining and Metallurgy. The aim of this study is to develop a method to establish decision patterns for control of drawpoints conditions.

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1. TOWARDS AN UNDERSTANDING OF MUD RUSH BEHAVIOUR IN BLOCK-PANEL CAVING MINES

M. Elena Valencia[a,b], Kenji Basaure[a,b], Raúl Castro[a,b], and Javier Vallejos[a,b]

[a] Advanced Mining Technology Center, University of Chile, Santiago, Chile
[b] Block Caving Laboratory, Department of Mining Engineering, University of Chile, Santiago, Chile

1.1. ABSTRACT

One of the most serious caving mine risks are mud rushes. Mud rushes are sudden inflows of saturated material from drawpoints. This paper will describe the first approach to propose the fundamentals of mud rushes. Furthermore, it will elaborate a geotechnical model that includes a quantitative component. This will be done through developing a force diagram. A geotechnical characterization will be done to know the determinant variables in the failure of saturated fine material. The main objective of this work is understand the behaviour of mud under block caving mining conditions. In addition to get a measurable model and the main geotechnical indexes to establish relations between compactation of mud, water content and behaviour.

1.2. INTRODUCTION

Block/panel caving operations can involve numerous hazards, one of those are mud rushes. Mud rushes are sudden inflows of saturated fines from drawpoints or other underground openings (Butcher et al 2000). The quick response of this phenomenon has terrible consequences for safety. Mud rushes are responsible of numerous fatalities and severe damage to infrastructure.

Caving operations are inherently susceptible to mud rushes (Jakubec, 2012). Due to the nature of caving it has the potential of accumulating water from subsidence field as well as generating fines (comminution process) during the extraction process. Persistence of both water and fine material will cause mud rush.

El Teniente mine (CODELCO Chile) is not immune to the problem of mud rushes. According to Becerra (2011), El Teniente history is replete with examples. One of the last mud rushes was occurred in October of 2007, killed an operator. The incident inflicted an extensive restructure of the control and extraction in saturated drawpoints. After this event, the operations policies have been set to limit the extraction rate and close areas when drawpoints has presence of mud (Ferrada, 2011). The strategy of restrict extraction has not only had a severe impact on ore reserves but it is also unable to resolve the progressive appearance of mud in drawpoints (Castro, 2014).

This paper aims to understand the behaviour of mud in development of a mud rush. The main objective is to elaborate a geotechnical model that includes a quantitative component. It has been achieved discussing and proposing the failure mechanism for mud rushes in a single drawpoint. Then, find the determinant variables in the process following a geotechnical characterization of mud according to soil mechanics testing, by the samples was collected from El Teniente mine. This is the first stage of a project. The obtained results are supposed to propose an early warning system that will enable to detect mud rush risk based on operational variables.

1.2.1. THE CURRENT KNOWLEDGE OF MUD RUSHES

There are four conditions necessary for a mud rush; water, mud forming material, a disturbance and a discharge point. Operational experience shows these four are mandatory elements for the occurrence of a mud rush (Butcher et al., 2000). According to published literature, There are several triggering mechanisms of mud rushes which are classified based on the source of mud forming material and water. Table 1-1 resumes the mud rushes classification proposed by Butcher et al. (2005).

Table 1-1 Mud rushes classification and proposed mechanism (Butcher et al., 2005)

Classification	Mechanism
External	Inflow of tailings. The material flows through a shaft, adit or open bench.
	Failure of backfill in stopes. Material can flow through a barricade due to the poor quality backfill.
	Open pit slope failures. Mud flows due to the failure of a open cut slope.
Internal/Mix	Formation of mud pockets in ore column with comminuted shale and rainwater. Rapid muckpile compactation. Responsible of mud pocket discharge.

Today mine operations with mud rush risk deals with the problem of mitigation practices through:

- Drawpoint categorization according to the percentage of fines and moist (Call and Nicholas et al., 1998).
- Draw control to ensure uniform draw (Butcher et al., 2000).
- Limitation of ore reserves by height for specific drawpoints (Butcher et al., 2000).
- Drainage to reduce the potential for mud rushes (Call and Nicholas et al., 1998).
- Limitation of extraction rate and closure of areas with drawpoints containing mud (Ferrada, 2011).
- Mud rush score system (Holder, 2013).

This knowledge has been built up over practice and operation on caving mines. However, the models and mitigation practices are conceptual and qualitative proposals. There is no single model to explain the behaviour.

Geotechnical characterization was carried out by Call & Nicholas (1998) for IOZ mine (Freeport McMoRan Indonesia). On the other hand, Jakubec (1998) fulfil experiments about mudflow behaviour. Both were conducted to know the material properties and size the flow potential. Likewise, they have established failure mechanism for fine granular materials; mudflow and liquefaction. Nevertheless, they have not suggested a model that explains a mechanism for mud rushes.

1.3. GEOTECHNICAL MODEL: A FIRST APPROACH

Experiments mentioned above state that mud rushes, it is often because a stability problem. Variations in water content and stress conditions can increase of pore pressure. Then, the granular material behave as a fluid by decreasing the shear stress resistance. Besides, they specify three kinds of mechanisms that make the granular material fluid:

- Static mechanisms: Related with the extraction of mud. Increase of pore pressure, sudden increase of stress because collapse of arcs or drawbell walls.
- Dynamic mechanisms: Related with perturbations like blasting vibrations. These cause induced liquefaction by seismic movement.
- Water as a movement force: Related with the increase of water content. This can change the mud properties, making the material fluid or drag along due the excess of pressure.

From another point of view, there are similar circumstances in mining with backfill, particularly stopes with hydraulic and paste backfill. Hydraulic backfill are characterized by include fine granular material and high water content from tails.

An analogy can be drawn between the geotechnical analysis of filled stopes and an isolated drawpoint. Both are made in rock (drawbell and stope) filled with saturated fine material. Stope stability analyses allow calculating the resistance of a bulkhead to seal off the extraction point. For block caving application stress analysis is alike, except for the bulkhead. Extraction point for the block caving is dynamic and the calculated resistance should be done on the pile of ore in the drawpoint.

From this perspective, an analytical solution is proposed. This model represents an instant before a mud rush. The purpose of this is to simplify to a static model by reducing the dynamic variables. A single drawbell filled with mud is proposed as a force diagram in Figure 1-1. For the new approach, the objective is estimate the possible ore column, saturated mineral and water pressures on the pile of material in the extraction point. In this case, the pile of material works as a bulkhead.

On the system presented in Figure 1-1 the acting forces are from the weight of the material that fill the drawpoint (F_m + F_c) and water (F_w). Filling material has two parts: broken ore and mud (Heights of this material are H_b and H_m respectively). The horizontal component of this forces (F_H) act against an ore pile in extraction point. Shear resistance of this material (F_B) will define the occurrence of mud rush.

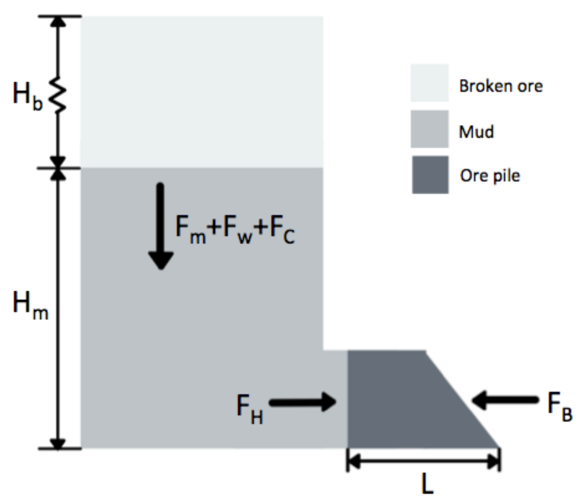

Figure 1-1 Analytical model of a single extraction point

The equation of equilibrium can be proposed in extraction point, equating horizontal forces. The idea is represented in equation (1), taking into account that horizontal force for filling material is $F_{F(h)} = K_h \cdot (F_m + F_C)$ and water forces are the same for the horizontal or vertical component.

$$F_B = K_h(F_m + F_c) + F_w \tag{1}$$

A limit equilibrium analysis can be developed according methods to design barricades for backfilled stopes under submerged conditions (Smith and Roettger, 1984). To understand how the mud pressure acts it is necessary to acknowledge two components of total pressure: effective fill pressure and water pressure. According to Smith and Mitchell (1982) the total bulkhead pressure for a fully saturated fill can be estimated as equation (2). The first component represents the horizontal effective fill pressure on the pile of material in drawpoint. On the other hand, the second component represents the water pressure on the drawpoint.

$$\sigma_h = 0.4 \cdot H \cdot \gamma_m \left(1 - 0.6\frac{l}{w}\right) + \frac{s \cdot \gamma_w}{R\left(1+\frac{l}{H}\right)} \tag{2}$$

R is referred as a drainage ratio and is calculated according equation (3).

$$R = \frac{P \cdot A}{P_1 \cdot A_1} \tag{3}$$

Where:

H = Fill height of mud in column (m)

γ_m = Unit weight of the mud (kN/m^3)

l = Pile of material length (m)

w = Pile of material width (m)

γ_w = Unit weight of water (kN/m^3)

P = Percolation rate in the drawpoint

P_1 = Percolation rate in ore column

A = Total area of drawpoint (m2)

A_1 = Ore column cross-sectional area (m2)

This model is useful for the first part of ore column, filled with mud. According several incidents, this height should not exceed the height of the drawbell.

For this new analysis the overload is considered. This additional variable is incorporated using the Janssen (2004) solution showed in equation (4).

$$\sigma_j = \frac{\gamma_{cr} \cdot R_h}{\mu}\left(1 - \exp\left(\frac{-z \cdot k \cdot \mu}{R_h}\right)\right) \tag{4}$$

Where:

γ_{cr} = Unit weight of caved rock (kN/m^3)

ϕ = Internal friction angle (º)

R_h = Hydraulic radius

μ = Friction coefficient ($\tan(\phi)$)

k = $1 - sen^2(\phi) \big/ 1 + sen^2(\phi)$

z = Depth (m)

Then, the total stress on the pile of material in drawpoint it can be estimated as equation (5).

$$\sigma_T = 0.4 \cdot H \cdot \gamma_{mud}\left(1 - 0.6\frac{l}{w}\right) + \frac{s \cdot \gamma_w}{R\left(1+\frac{l}{H}\right)} + \frac{\gamma_{cr} \cdot R_h}{\mu}\left(1 - \exp\left(\frac{-z \cdot k \cdot \mu}{R_h}\right)\right) \tag{5}$$

1.4. CASE STUDY

The use of the stress equation is illustrated with a sample application. The following parameters are showed in Table 1-2. The analysis is conducted for illustrative purposes. It is only an attempt to incorporate the water effect on the pile of material.

Table 1-2 Parameters for illustrative case

Parameter	Unit	Value
Depth (z)	m	100
Unit weight of caved rock (γ_{cr})	kN/m^3	19
Pile of material length (l)	m	2
Pile of material width (w)	m	4
Hydraulic radious (R_h)	-	2.25
Internal friction angle (φ)	º	45
Unit weight of the mud (γ_m)	kN/m^3	27

Figure 1-2 shows the variation of the total stress on the pile of material as a function of drainage ratio through the ore column. It is calculated for three heights of mud in a drawbell. It can be seen that stresses increases when there is no drainage through the ore column. The stress of water only matters when it is accumulating in the drawbell. When there are hardly drainage conditions (R = 0.1) more than a half of the stress belongs to water pressure.

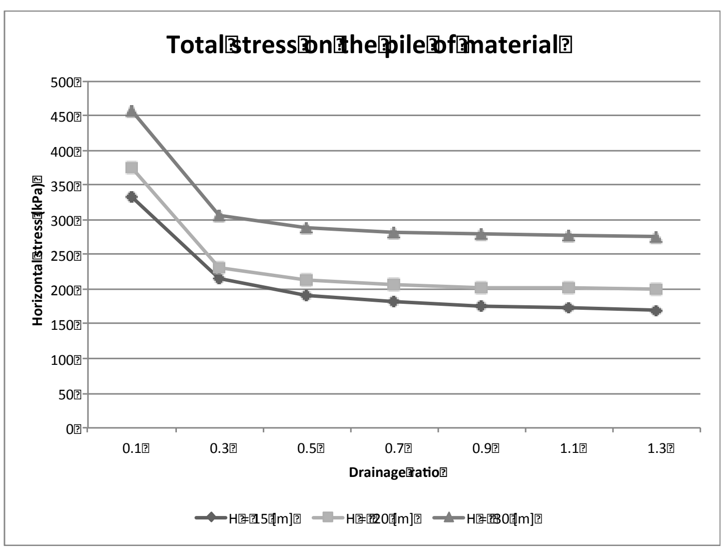

Figure 1-2 Total stress on the pile of material according drainage ratio

Once, stresses on drawpoint have been estimated, it is necessary to know the resistance of the pile of material. This ore could be under different conditions of moisture and granulometry. In order to get the correct parameters to estimate this resistance, a geotechnical characterization is performed. Furthermore, relations among compaction of mud, water content and behaviour have been also established to understand failure process and the response of material to operational variables.

1.5. GEOTECHNICAL CHARACTERIZATION

Samples of saturated fine material are collected from drawpoints classified as “Critical” in El Teniente mine which have been closed days before sampling due to the risk classification as “Critical”. The risk classification was implemented in the mine according to the fine material and water content (Becerra, 2011).

Following the standard procedure for representative sampling in El Teniente, three samples was collected. This samples represent three different “mud color” in mine: Grey (Sample 1), Yellow (Sample 2) and Mixture (Sample 3).

Two different test are implemented in this study:

1. Tests to define the index properties of material: Grain Size Distribution, Atterberg Limits, Specific Gravity, Maximum and Minimum Void Ratio.
2. Tests to evaluate the relations between water content and compaction: Set of unconfined compression and set of slump tests.

The outcomes of the first test are used to achieve the second test. Full size distribution curve of samples was used to perform slump test and unconfined compression test. These tests are both carried out with different saturation and relative density values.

Saturation, Void Ratio and Relative Density are defined using (6), (7) and (8) equations respectively.

$$S = \frac{V_w}{V_v} \tag{6}$$

$$e = \frac{V_v}{V_s} \tag{7}$$

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \cdot 100 \tag{8}$$

Where:

V_w = Volume of water

V_v = Volume of voids

V_s = Volume of solids

Water content is a relation between mass of water and mass of solids. These measure are used to determine the degree of saturation and mobility of the material. The Atterberg limits are a measure of critical water content of fine soil. Those limits classify behaviour of fine grain soil from solid to plastic (LP) and plastic to liquid (LL). Density of the mud material is important in determining how much water and air can fill the voids between particles, which effects the flow potential of the material. The void ratio is an important material property in assessing strength permeability, and collapse potential.

Tests are accomplished accord ASTM standard and are described in Table 1-3.

Table 1-3 Performed tests for geotechnical characterization

Parameter	Method
Water Content	Oven Dry (ASTM)
Grain size distribution	Sieve Analysis (ASTM)
Atterberg limits	Method of Casagrande (ASTM)
Specific Gravity	Picnometer, Submerged Mass (ASTM)
Void Ratio Maximum	Minimum Density (ASTM)
Void Ratio Minimum	Modified Proctor (ASTM)

1.6. ANALYSIS OF RESULTS

Geotechnical indexes are used to understand the behaviour of saturated fine material. Table 1-4 synthetise the main results.

According to the results of laboratory test, the material is well graded granular aggregate. It contains gravel, sand, lime and clay in different proportions. Sample 2 seems to be the one with the most portion of fines (22% limes and clays) and less gravel. While, sample 1 has the less portion of fines (11% lime and clay) and most gravel (60%), moisture contents range from 9.5 to 13.4 percent. The water content and fine material portion corresponds to the closing conditions for drawpoints in El Teniente.

Atterberg limits produced a liquid limit range between 21.7 and 26.1 percent. The plastic limits are between 16.9 and 21 percent. These values indicate that the fines are classified as low plasticity silt and clay (ASTM D2487-00).

Table 1-4 Outcomes from geotechnical characterization

	Sample 1	**Sample 2**	**Sample 3**
Water Content	9.50%	13.40%	12.50%
Grain size distribution	D_{60}=11.35 mm	D_{60}=3.907 mm	D_{60}=12.288 mm
	D_{30}=2.385 mm	D_{30}=2.43 mm	D_{30}=1.045 mm
	D_{10}=0.043 mm	D_{10}=0.006 mm	D_{10}=0.018 mm
Atterberg limits	LL=21.7%	LL=25.7%	LL=26.1%
	LP=16.9%	LP=21%	LP=19.1%
Specific Gravity (G_s)	2.76	2.68	2.72
Maximum Void Ratio (e_{max})	0.9	1.00	0.92
Minimum Void Ratio (e_{min})	0.26	0.28	0.22

For unconfined compression test, the results indicate that resistance increases with the decrease of relative density. It seems that all samples have similar unconfined behaviour. The mud whit low relative density and hight saturation shows no resistance. The water content for this case is over plastic limit. Figure 1-3 shows the average behaviour of material for the three samples at different saturations and relative densities.

Slump test indicate that in conditions of high relative density, there is no settling (no deformation). For a relative density lower than 65%, the possibility of flow or plastic behaviours is depending on saturation. In particular, when fluid behaviour appears, water content is over or near plastic limit. Sample 1, including the most cases on fluid state, has the lowest limit.

The outcomes of the geotechnical characterization suggest that the resistance of the pile of material will be overcome depending mostly on relative density. Plastic deformations could explain mud rushes for abrupt changes of load or moist.

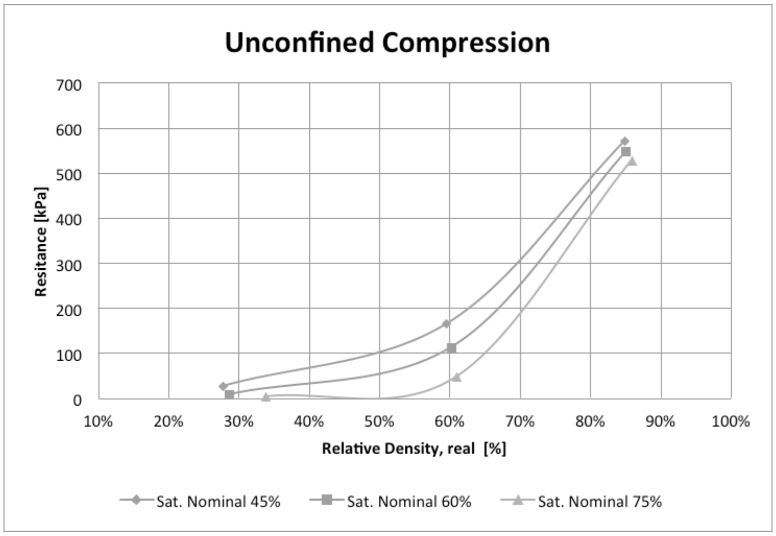

Figure 1-3 Unconfined compression test results (average between three samples)

1.7. CONCLUSIONS

This paper outlines the procedure to propose a model that quantifies the amount of pressure applied in a single extraction point with a drawbell filled with saturated fine materials. The new model represents an instant before a mud rush. The objective of this is to simplify to a static model by reducing the dynamic variables. This model takes account three components: the weight of the mud in drawbell, the pressure of water that is accumulated in the column and the overload of the broken material.

The simplified model is consistent with some mitigation practices like drainage. Drainage ratio is one of the most important variables. When there are hardly drainage conditions (R = 0.1) more than a half of the stress belongs to water pressure.

Once the amount of load was estimated, a geotechnical characterization was performed regarding the resistance of the pile of material. Saturated fine material was tested to know the behaviour of mud under different conditions. Results indicate that plastic deformations could explain mud rushes for abrupt changes of load or moist. Furthermore, relative density has an important role in the resistance of material.

Incorporate the extraction of material is the next step to understand the behaviour of mud under block caving mining. This will be developing a numerical model and experiments in a physical model.

1.8. ACKNOWLEDGEMENT

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1.9. REFERENCES

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2. GEOTECHNICAL CHARACTERIZATION OF ORE RELATED TO MUD RUSHES IN BLOCK CAVING MINING

Raúl L. Castro[a,b], Kenji Basaure[a,b], Sergio Palma[a,b] and Javier Vallejos[a,b]

[a] Advanced Mining Technology Center, University of Chile, Santiago, Chile
[b] Block Caving Laboratory, Department of Mining Engineering, University of Chile, Santiago, Chile

2.1. ABSTRACT

Mud rushes are sudden inflow of mud ore into underground mining facilities. They may cause harm to people and equipment, production delays, dilution and mine closure. The aim of this work is to characterize by geotechnical laboratory tests mud from a block cave and to derive mechanical reasons to the failure of this material while is being drawn. We have used ore samples from closed extraction points due to mud rush potential from Diablo Regimiento at El Teniente, which represents the three types of mud ore. Characterization shows that samples have gravel and sand with silt and clay grain sizes, where fine particles are classified as low plasticity silt and clay. We found that samples have small differences from one to another in fine content, density and packing. Ore strength to unconfined conditions is evaluated varying the density and saturation degree, this allows to observe that relative density is the most relevant variable that governs the unconfined strength. Triaxial consolidated tests show a linear relation between deviatoric strength and effective confining stress, and it has been found for the samples tested. Deviatoric strength is related to the capacity to flow under triaxial conditions, consequently it could be related to mud rushes. Unconsolidated, saturated tests exhibit a very low deviatoric maximum strength followed by static liquefaction, resulting in residual strength values near to zero. In terms of mining the geotechnical tests were related to the draw rate and the saturated conditions: a high rate of drawing could cause unconsolidated conditions as the strength of the mud decreases to near zero while a low extraction rate could be related to consolidated conditions where the ore is allowed to release the pore pressure. If the ore is under unsaturated conditions it presents a lower risk as it will develop uniaxial strength.

Keywords: Mud rushes, underground mine, block caving, geotechnical characterization

2.2. INTRODUCTION

Mining is the process of extraction of minerals from the earth. Different mining methods have been developed in the history (Lacy, 1992). Block/Panel Caving is an underground mining method based on the action of gravity for ore breakage and transport. Also, it has the lowest cost and has the highest production rates for underground methods (Douglas, 1992 and Heslop, 2000). In addition, Block/Panel Caving is the safest underground mining method used in the industry. However it has associated operational risks as rock bursts, air blasts and mud rushes (Heslop, 2000). Mud rush is an operational hazard of Block/Panel Caving method, which is defined as a sudden inflow of mud from drawpoints or other underground openings inside the mine (Butcher, 2005). Mud rushes can cause damage to equipment, dilution, production delays, injuries and fatalities. In Block/Panel Caving mines, an undercut level is developed in the base of orebody and a production level is constructed some distance below. An arrangement of openings called drawbells is built up between undercut and production level where drawpoints are placed on the bases of drawbells. A horizontal ore layer is extracted from undercut level in order to collapse the ore body above, broken ore falls into drawbells and is managed in production level, as broken ore is removed from drawpoints the ore above continues to break and cave (Douglas, 1992). This method is inherently susceptible to mud rushes, owing to the fact that it has all elements that are necessary: mud forming material, disturbances, discharge points and water (Butcher, 2000). On the other hand, mud is formed by fine granular particles and water (Becerra, 2011; Hubert, 2000; Jakubec, 2012; Lacy, 1992; Samosir, 2008). Water comes from the surface or underground sources and fine granular particles sources come from surface or from milled ore by caving. Discharge points are drawpoints in production level. Disturbances are the triggers of mud rush phenomena, and they can be in one hand dynamic as blasting, equipment moving or earthquakes (Call and Nicholas, 1998; Jakubec, 2012), and on the other hand, static as stable arch collapse above drawbells (Butcher, 2000; Butcher, 2005; Jakubec, 2010) and ore drawing (Butcher, 2000; Butcher, 2005; Call and Nicholas, 1998; Jakubec, 2012). Previous authors have postulated two mechanisms for the occurrence of mud rushes in which the ore loses shear strength: increase of water content in mud can change its properties (Butcher, 2005; Jakubec, 2012) decreasing its shear strength, and also a high pressure of water in mud pores induced by stress (Call and Nicholas, 1998; Hubert, 2000) can cause a sudden weakening of the shear strength in a phenomena called static liquefaction (Yamamuro, 1998) or flow failure (Yoshimine, 1998) by different authors. The proposed mechanisms had not been proven and quantified to date. Ore from 6 samples involved in mud rushes has been characterized geotechnically in IOZ mine, Freeport, Indonesia (Call and Nicholas, 1998). They founded that ore involved in mud rushes had more than 20% of grain sizes less than 2 mm, and it is classified as “well graded fine gravel with coarse to fine sand”, “poorly gravel to silty fine gravel” and “poorly graded fine gravel to silty fine gravel” depending on each sample. They also compared the samples with other sandy gravel materials to conclude that with a saturation value greater than 80% the material is prone to develop liquefaction due to the excess of pore pressure. They performed five unsaturated, consolidated, undrained triaxial tests on a composite from two of the samples using initial conditions of confining stresses from 50 kPa to 200 kPa, loose compaction and water contents from 1% to 9%. Results showed that all samples reached 100% of saturation degree after consolidation, and three of them developed liquefaction: instability with an increase of pore pressure (Yamamuro, 1998). Nevertheless they did not establish the specific conditions in which liquefaction occur, because of the low number of triaxial tests and their unspecific initial set of conditions.

In the present paper we study geotechnical properties of mud type ore at Diablo Regimiento mine (DR), El Teniente, Codelco. The aim is to obtain geotechnical parameters to describe the ore, characterize the strength and behaviour at different conditions, and use it to evaluate and quantify the mechanisms for occurrence of mud rushes presented on this section. In Section 2.2.1 we describe concepts to understand the results and interpretation of experimentation. Section 2.3 has a description of material samples and experimental methods. Finally, in Section 2.4 we discuss the results and the proposed mechanisms for mud rushes based on experimental results.

2.2.1. Framework

Mud ore is known to be a moist fine sized granular material, where its void ratio and porosity are uncertain because of the density changes caused by the ore flowing through column and drawbells until it reaches drawpoints where the material is extracted, as was shown through experiments by Kvapil (1992). Water content is also a variable of mud ore in mine conditions, depending on permeability of ore and water sources (Call and Nicholas, 1998). In this Section we show physical relations between water, void and solid phases on a granular assemblage in order to describe compaction and water content in mud ores. Also, we present concepts to understand the behaviour of granular materials in relation with stress and pore pressure. Minimum and maximum densities of packing are properties of granular materials that can be measured in a laboratory but their values also depend on the procedure used (Lambe, 1969). Eq. [1] represents the relative density, an index designed for the purpose of compare packing of different materials depending on their own packing properties (Lambe, 1969), e_{max} and e_{min} are maximum and minimum possible void ratio for a granular material, respectively; e is the current void ratio, where void ratio is the ratio of void volume to solid volume (Lambe, 1969). If relative density is 0%, the material is on its loosest possible packing state, and if it is 100% this indicates that material is on the densest possible state

$$RD[\%] = \frac{e_{max} - e}{e_{max} - e_{min}} \cdot 100 \quad [1]$$

Wet presence on a granular material is to hold inside voids between particles, for this reason the quantity of water that a granular material can hold depends on available voids. Saturations is presented on Eq. [2] in order to quantify water inside a granular material in relation with voids available (Lambe, 1969). V_W is the volume of water on a granular material, and V_V is the volume of voids between solid particles.

$$S = \frac{V_w}{V_v} \quad [2]$$

On the other hand, Eq. [3] shows the relation between void ratio and saturation with water content and specific gravity, where specific gravity is unit weight of solid divided by the unit weight of water and the water content is the ratio of water weight to solid weight (Lambe, 1969). This equation is used for relations between volume and mass indexes.

$$G_s \cdot \omega = S \cdot e \quad [3]$$

Pore pressure concept mentioned related to mud rush mechanisms in Section 2.2 refers to the pressure of water inside pores or voids of a saturated granular material as soil or other aggregates. It depends on the water level over the point where the pore pressure is evaluated, also on stresses acting on the saturated granular material. Pore pressure is related with the concept of effective stress that is presented on Eq. [4], where effective stress σ’ is calculated subtracting pore pressure (u) from total stress (σ), and it symbolizes stresses supported only by the solid structure of the granular material.

$$\sigma' = \sigma - u \quad [4]$$

For granular materials, there are available three types of triaxial tests depending on the conditions of drainage and initial consolidation: Unconsolidated-undrained (UU), consolidated undrained (CU) and consolidated-drained (CD), (Das, 2002). Drainage condition depends on rate of shear stress and permeability conditions in the field: drained test for low rate loads or high permeability aggregates in which pore pressure can dissipate when the sample is under stress. On the other side, undrained test is for high rate loads or low permeability in which pore pressure cannot be dissipated and changed during the application of stress. On the other hand, consolidation is the process in which water content decreases with consequent reduction in volume due to confining stress acting on a saturated granular material (Lambe, 1969). Consolidation finishes when all pore pressure has been dissipated from the inside of the material, and consequently water content and volume stays stable. In order to understand the mechanical behaviour, stresses developed in triaxial tests of this work are interpreted using deviatoric (q) and mean stress (p), both depending of principal stresses. Mean stress is the isotropic (spherical) component of stress and deviatoric stress is the component that causes the shearing (Schofield, 1968). Triaxial tests have well defined principal stresses, with vertical compression (σ_v) as the major principal stress and confining stress (σ_c) as the minor and intermediate principal stresses (Lambe, 1969). Mean stress (p) can also be expressed as effective mean stress (p'). Eqs. [5] and [6] show the mean effective stress and the deviatoric stress for triaxial test conditions (Schofield, 1968), respectively

$$p' = \frac{\sigma_v + 2 \cdot \sigma_c}{3} - u \quad [5]$$

$$q = \sigma_v - \sigma_c \quad [6]$$

Granular materials as silty sands can develop different behaviours of deformation depending on the initial density and confining stress. Dilative and contractive behaviours indicate increasing or decreasing rate of volume changes respectively. In undrained conditions dilative and contractive behaviour can be identified by the decrement or increment of pore pressure respectively. Consequently according to Eq. [4] dilative and contractive behaviours are indicated by the increment or decrement of mean effective stress respectively. Loose sand tends to contract until mean effective stress reaches a minimum and changes from contractive to dilative behaviour in a point called phase transformation (Yoshimine, 1998). Flow failure or static liquefaction occurs when a confined loose granular with contractive behaviour exhibits instability or loss of shear strength before the phase transformation (Yamamuro, 1998).

2.3. METHODS AND MATERIAL

2.3.1. SAMPLES

Samples for this study were obtained at Diablo Regimiento sector at El Teniente which is the largest underground copper mine in the world. It is located 50 km east from Rancagua city in Chile between 2100 and 2800 meters above sea level. The mining method is mechanized Block/Panel Caving using load, haul, dump machines (LHD). Mud has appeared in several drawpoints in El Teniente and there have been seven mud rush events since 1989 (Becerra, 2011). In Diablo Regimiento, three kinds of mud ore have been found according to visual characterization by personnel of the mine: Grey mud associated with sulphide ores, yellow mud associated with oxide ores and mixture mud between yellow and grey. Three samples of mud ore were collected from different drawpoints classified as critical risk in DR (classification in Becerra, 2011). Each sample is representative of one type of mud ore according to mine personnel as shown in Table 2-1.

Table 2-1 : Samples and visual description.

Sample	Description	Composition
1	Grey color	Sulphides
2	Yellow color	Oxides
3	Mixed color	Mixture

Sampling was carried out by mine personnel in charge of water content sampling. They were extracted using a hand shovel to take increments of mud on an imaginary horizontal line across the drawpoint 1.5 m from the floor, this method was developed by El Teniente in order to take samples that are representative of ore in drawpoints. Samples were transported in plastic sealed bags until they reached the laboratory where they were dried and prepared for testing.

2.3.2. TESTS

Samples were tested in the Solids Laboratory facilities of Civil Engineering Department of Universidad of Chile. Tests were carried out in order to obtain a geotechnical characterization and geomechanical behaviour of mud type ore. Given the known characteristics of mud ore listed on previous Section, ASTM standard tests for soils were selected for geotechnical characterization, one for each Sample. Table 2-2 lists a summary of tests.

Table 2-2: ASTM standards for geotechnical characterization.

Parameter	Test	ASTM standard	Number of tests for each Sample	Total Number of tests
Grain size distribution	Sieve Analysis	D6913	1	3
Specific gravity	Water pycnometer	D854	1	3
	Water immersion	C127	1	3
Liquid Limit	Casagrandes's spoon	D4318	1	3
Plastic limit	Rolling	D4318	1	3
Minimum density	Pouring in known volume cylinder.	D4254	1	3
Maximum density	Modified proctor	D1557	1	3
Permeability Coefficient	Constant head permeability	D 2434	3	9
Unconfined strength	Unconfined compression	D2166	9	27
UU confined behaviour	UU triaxial	D2850	4	12
CU confined behaviour	CU triaxial	D4767	9	27

Tests listed in Table 2-2 have different objectives, on one hand grain size distribution, specific gravity, liquid and plastic limits, maximum and minimum density are carried out to perform characterization and classification of mud type ore, and also to obtain index geotechnical parameters for using in the geomechanical tests. On the other hand, unconfined compression tests are carried out to determine unconfined and partial saturation strength of mud ore, and how it changes with different grades of saturation and compaction. Finally, triaxial tests were performed in order to obtain geomechanical behaviour in saturated confined condition of mud type ore, and how it changes with different initial compaction grade, initial consolidation and confining stress.

Grain size distributions were obtained using sieve analysis method to 32 kg subsamples separated by quartering. Material was cleaned with water to separate fines using 200-mesh sieve (75 μm) as filter. Finally, material was placed on the superior sieve to proceed with vibration. Weights of fine from cleaning and grains retained on sieves were obtained in order to develop the grain size distribution of the samples.

Specific gravity is carried out with two different methods depending on the grain size. For particle sizes smaller than 4.75 mm we used the water pycnometer method which consists in weight a volume of water and then fill the same volume with a known mass of solid material submerged in water, finally using the difference we obtained the soil density, which divided by water density is the specific gravity of the solid. For particle sizes over 4.75 mm the method is to weigh a dry portion of material, then submerge the same portion and obtain its weight under water, finally the dry weight is divided by the difference between dry and submerged weights to obtain the specific gravity. Liquid limit was performed to fine fraction of samples (less than 0.425 mm), the method consists in adding a wet layer of material over a specially designed standard spoon, and then cut a groove in the middle, finally repeatedly dropping the spoon from a high standard until the groove is closed. The aim of this procedure is to obtain water content of two subsamples that require from 15 to 25 drops, two from 25 to 35 drops and one near to 25 drops, then plot drops versus water content and adjust a straight line between plotted points, liquid limit is the interception of 25 drops and the straight line. In regards to the minimum density test method, it consists in filling a known volume and weight container with material using a pouring device to place it as loosely as possible, and then weigh the container with the loose material inside and obtain the density. This procedure is repeated at least 3 times and the lowest density is selected as the minimum density.

Maximum density is carried out using the modified proctor test in which a wet portion of material is compacted in layers in a known volume container, this procedure is repeated with different water contents to get the maximum wet density. Finally, dry density is calculated from maximum wet density and water content to obtain the maximum density. On the other hand, maximum and minimum void ratios are calculated using minimum and maximum density respectively with specific density for each sample. The plastic limit was also performed only to fine fraction of samples (less than 0.425 mm). This method consists in form an ellipsoidal mass with 1.5 to 2 gr of wet material and roll it with the hand against a ground-glass plate until it has an uniform diameter of 3.2 mm, then break it down in several pieces and squeeze it together to repeat the procedure. The mass of material slowly dries with each cycle, when the mass crumbles after obtaining a 3.2 mm diameter it is put on a container to obtain water content which is the plastic limit of the sample.

A set of three constant head permeability tests were performed on each sample in order to determine the permeability coefficient for different relative densities. Samples were compacted to RD values of 30%, 60% and 70%. The test consists in measure the time (in seconds) in which a volume (in mm) of water passes through a cylindrical permeameter filled with saturated sample. Water temperature is also measured in order to normalize water viscosity to 20°C. This procedure is repeated at least three times for each test in which final result is the average. Eqs. [1], [2] and [3] in combination with index parameters are used to set different conditions of saturation degree and compaction for unconfined and triaxial compression tests. Unconfined compression test consist in the axial compression of a cylindrical specimen in a strain controlled compression device until failure. It means that the test ends when there is a decrease in stress or more than 20% of axial strain. The maximum stress reached during testing is called unconfined compressive strength. Force and axial strain are measured during testing with precision of 0.001 kN and 0.001 mm. The initial cross Sectional area of the specimen is calculated as the average of 9 diameter measures with precision of 0.1 mm on the specimen in order to calculate the stress. Cross Sectional area changes during test, and is corrected depending of the axial strain using Eq. [7] given by the test procedure, in which A is the cross Sectional area and A_0 is the initial cross sectional area and ε is axial strain.

$$A = \frac{A_0}{1-\varepsilon} \quad [7]$$

A set of 9 combinations of relative density and saturation degree in Table 2-3 are used to perform unconfined compression tests. Ranges for the relative densities and saturation degrees were selected in order to allow the correct confection of cylindrical specimens for testing in unconfined conditions. Specimens were moulded using the known characteristics of each sample to calculate, using Eqs. [1] and [3], the pertinent water content and then apply it to a sub-Sample. Finally, the moist sub-Sample is compacted in 5 layers using a metal mold in order to accomplish with the density and saturation set previously. The Triaxial test consists within an axial compression of a saturated cylindrical specimen with constant iso tropic, Confining stress given by the water pressure until 20% of axial strain is reached. The specimen is separated from the confining water with a rubber membrane. In the base and top of the specimen porous discs are disposed that allows water drainage from the inside of the specimen. Drainage is connected to a valve in order to allow or close water drainage. For a consolidated test there is an initial consolidation stage in which the drainage valve is open and water outflow is measured with precision of 1mL. In compression test stage, the drainage valve is closed for undrained triaxial, and the pore pressure is measured with precision of 0.1 kPa. Triaxial tests were carried out using three controlled variables: confining stress, initial relative density and consolidation. Samples are fully saturated for all cases. For consolidated tests three confining stresses and three initial relative densities were selected. For unconsolidated tests, pore pressure equals confining stress and initial effective stress is zero for any confining stress, consequently, behaviour should not change for different confining stresses, only two of them are tested in order to verify phenomena. On the other hand, compaction of 40% relative density shows a very low strength (near zero kPa), this is why 0% relative density tests were not performed and there are only four unconsolidated tests for each Sample. Table 2-4 summaries the conditions for the thirteen triaxial tests performed for each sample.

Table 2-3: Relative density and saturation degree combinations for unconfined compression test on each Sample.

Relative density [%]	Saturation degree [%]
20	45
20	60
20	75
60	45
60	60
60	75
90	45
90	60
90	75

Table 2-4: Conditions of consolidation, relative density and confining stress for triaxial tests.

Consolidation	Initial relative density [%]	Confining stress [kPa]
Yes	0	196
Yes	0	392
Yes	0	588
Yes	40	196
Yes	40	392
Yes	40	588
No	40	196
No	40	588
Yes	80	196
Yes	80	392
Yes	80	588
No	80	196
No	80	588

2.4. RESULTS AND DISCUSSION

2.4.1. GEOTECHNICAL CHARACTERIZATION

Geotechnical characterization is summarized using index values from the test results. In Table 2-5 there are indexes of ore from the three samples for each test. Grain size distribution results are presented as percentage of weight passing each size in Figure 2-1, we can see that all samples have similar distribution: well graded with coarse sizes mostly under 50 mm and fines with sizes less than 75 µm are over 10% of the weight of the samples. Sample 2 has more fines (under 75 µm) than others (over 20% in weight) in contrast with Sample 1 which has the lowest percentage of fines. On the other hand, Sample 3 has the biggest maximum size particle between 150 mm and 75 mm in spite of the other samples whose maximum size particle is between 75 mm and 50 mm. Specific gravity results from Table 2-5 show small differences for the three samples, with Sample 2 showing the smallest specific gravity. We calculated the specific gravity as the average between coarse and fine method results, with attention to the minimal differences between measured values of coarse and fine specific gravity (less than 2%) for all samples, therefore specific gravity does not depend on grain size for analyzed material. Plastic and Liquid limits are similar for all samples, and they all are classified in the same group according to ASTM (D2487-00) standard: Low plasticity silt and clay. However, liquid limit of Samples 2 and 3 are 4% and 4.4% higher than liquid limit of Sample 1, respectively, and plastic limit of Samples 2 and 3 are 4.1% and 2.2% higher than plastic limit of Sample 1. These differences mean that fines from Sample 1 are more prone to flow with the same water content than the rest of samples. Minimum and maximum void ratios are very similar for the 3 samples. Values are between silty sand (from e_{max} = 0.9 to e_{min} = 0.3) and fine to coarse sand (from e_{max} = 0.95 to e_{min}=0.2) according to typical values (Douglas, 1992). Sample 2 has the highest minimum and maximum void ratios of all samples: Maximum void ratio of Sample 2 is 12% and 8% higher than Sample 1 and Sample 3 maximum void ratios, respectively, moreover minimum void ratio of Sample 2 is 6% and 25% higher than Sample 1 and Sample 3 minimum void ratios, respectively. It means that Sample 2 is prone to have looser densities states than other samples, because its density is lower than the others in both cases, maximum and minimum density. It must be noted that the above indexes could not be related to the strength of the granular mass. In the next sections the strength of the media was quantified using uniaxial and triaxial tests for a range of densities, confining stresses and saturation degrees.

Table 2-5: Summary of geotechnical characterization.

Parameter	Test	ASTM standard	Results		
			Sample 1	Sample 2	Sample3
Grain size [mm]	Sieve Analysis	D6913	Percentages in weight passing		
150			100%	100%	100%
75			100%	100%	98.0%
50			98.0%	99.5%	93.0%
37.5			94.0%	97.7%	85.7%
25			82.8%	94.0%	75.5%
19			74.0%	90.0%	69.8%
9.5			55.0%	74.6%	54.2%
4.75			39.8%	62.8%	44.8%
2.36			29.8%	52.7%	36.7%
0.6			19.1%	37.6%	25.7%
0.3			15.9%	31.5%	21.6%
0.15			13.5%	26.6%	18.0%
0.075			11.5%	22.5%	14,8%
Specific gravity	Water pycnometer, water immersion	D854, C127	2.76	2.68	2.72
Liquid Limit	Casagrandes's spoon	D4318	21.7%	25.7%	26.1%
Plastic limit	Rolling	D4318	16.9%	21.%	19.1%
Minimum void ratio	Pouring in known volume cylinder.	D4254	0.27	0.28	0.22
Maximum void ratio	Modified proctor	D1557	0.90	1.00	0.93

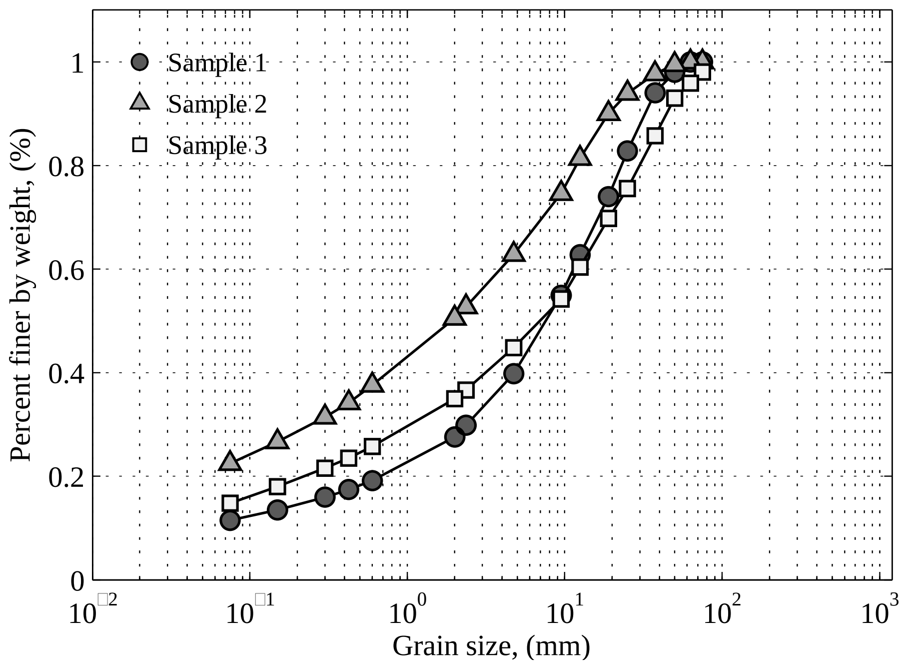

Figure 2-1: Grain size distribution curve on all samples.

Permeability results are presented on Figure 2-2, coefficient is greater with as lower is RD. Sample 1 has the lowest values for all RD conditions, it means water can flow faster trough Sample 1 than the others at the same compaction condition.

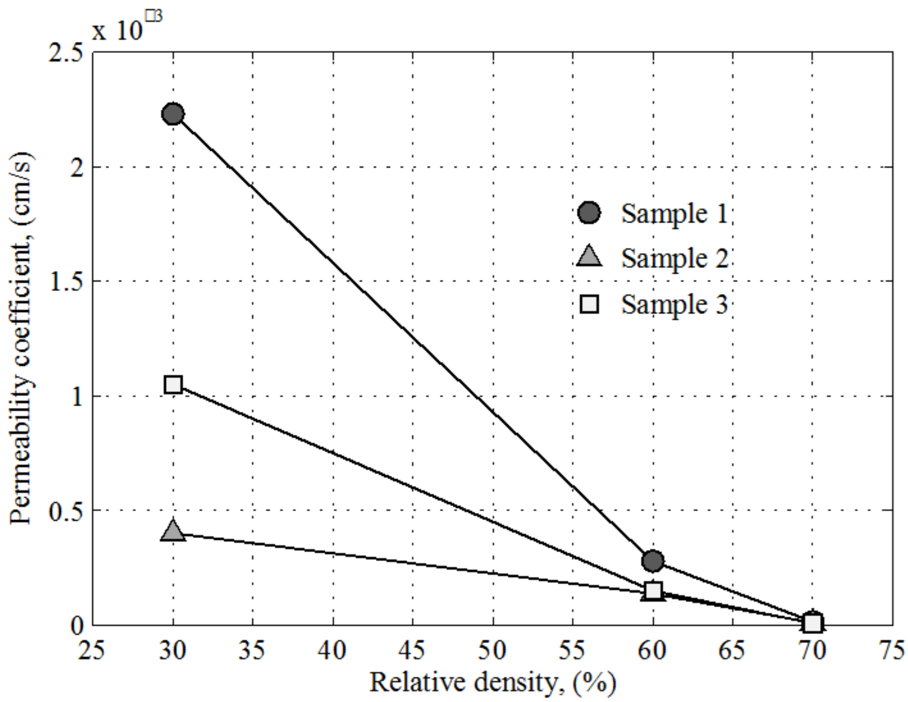

Figure 2-2: Permeability coefficient as a function of the relative density for all samples. The solid lines are for visual aid purposes.

2.4.2. GEOMECHANICAL BEHAVIOUR

Unconfined compression tests were carried out varying relative density and saturation as explained in Section 2.3.2. Results show small strength changes with saturation variation (in the range from 45% to 75% of saturation degree) and large strength changes with relative density variations. Consequently, unconfined strength values for each sample and relative density (RD) but different saturation degrees are averaged and plotted in Figure 2-3, where vertical error bars exhibit standard deviations of averaged values. In all samples strength increases with compaction, and the exponential model of Eq. (8) is fitted to each Sample, where S_u is unconfined strength, α and β are model constants and RD is the relative density. Sample 2 has less strength than the others at high relative densities. For example, using the exponential models we can see differences in strength in which Sample 1 and Sample 3 have strengths 30% and 49% higher than Sample 2 at 95% of relative density. Table 2-6 contains the detail of the parameters fitted using Eq. [8] to unconfined strength values for each sample

$$S_u = \alpha e^{\beta RD} \quad [8]$$

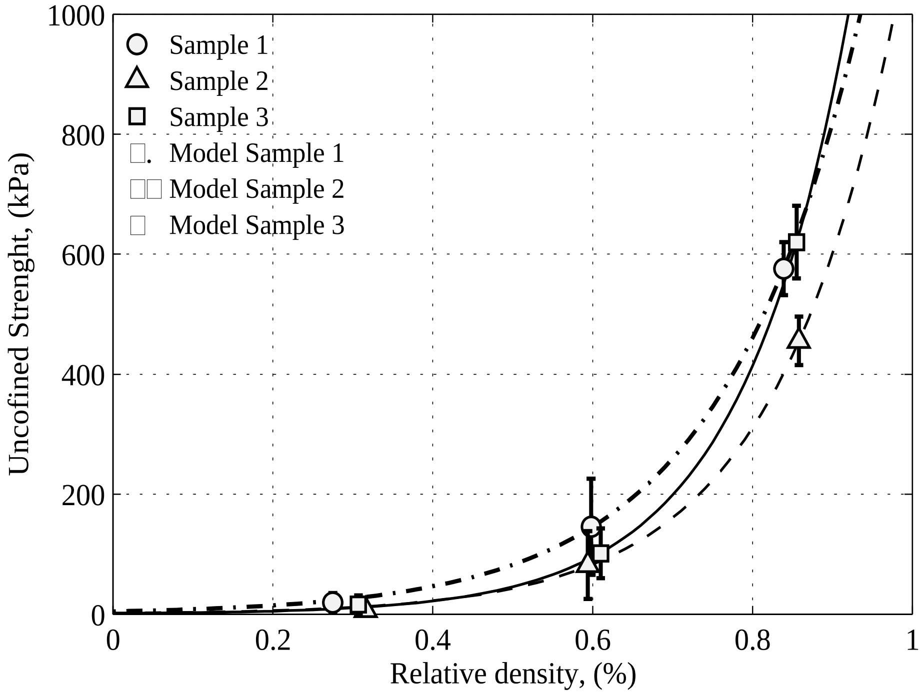

Figure 2-3: Unconfined compression results for all samples. Each point represents the averaged value of strength for 3 saturations at the same compaction state and, error bars represent the standard deviation for the averaged values on each point.

Table 2-6: Parameters of exponential model for unconfined strength.

Sample	α	β	R^2
1	4.660	5.742	0.999
2	1.587	6.596	0.999
3	1.163	7.344	0.999

Table 2-7: Nominal and real values for Relative density in triaxial tests.

Initial Consolidation	Nominal initial Relative Density	Confining Stress [kPa]	Sample 1		Sample 2		Sample 3	
			Real Initial Relative Density	Final Relative Density	Real Initial Relative Density	Final Relative Density	Real Initial Relative Density	Final Relative Density
Yes	0%	196	31.0%	69.0%	24.8%	71.7%	35.5%	70.2%
Yes	0%	392	27.8%	74.6%	32.4%	76.5%	29.6%	72.9%
Yes	0%	588	28.0%	80.3%	30.4%	78.7%	31.1%	73.9%
Yes	40%	196	40.5%	71.5%	47.2%	73.6%	41.9%	71.8%
Yes	40%	392	42.0%	77.8%	40.6%	78.2%	38.8%	74.9%
Yes	40%	588	45.3%	80.9%	43.3%	80.4%	40.0%	77.5%
Yes	80%	196	58.7%	72.7%	62.8%	74.7%	66.1%	76.3%
Yes	80%	392	68.3%	77.9%	60.5%	79.1%	64.5%	77.6%
Yes	80%	588	63.0%	83.0%	59.9%	81.2%	67.9%	78.9%
No	40%	196	41.4%	41.4%	42.5%	42.5%	40.1%	40.1%
No	40%	588	41.0%	41.0%	42.6%	42.6%	42.3%	42.3%
No	80%	196	65.5%	65.5%	62.5%	62.5%	61.9%	61.9%
No	80%	588	67.0%	67.0%	60.3%	60.3%	60.4%	60.4%

For triaxial testing compaction conditions of Table 2-4 were set, nevertheless after saturation compaction changes, and real initial relative density of tests are listed in Table 2-7, where we also show the final relative density after consolidation for all samples. Triaxial test results show the same behaviour for all samples. In order to explain material behaviour, only Sample 2 results are presented. In Figure 2-4(a) we observe fast initial increase of deviatoric stress for all consolidated tests, and then deviatoric stress stabilizes before passing 5% of axial strain followed by low rate increase. In some cases deviatoric stress reaches a maximum value and then it slowly decreases less than 8% of the maximum. Figure 2-4(b) shows deviatoric stress against mean effective stress, we can see a contractive behaviour with an initial fast increase of deviatoric stress that stabilizes when mean effective stress reaches the minimum at phase transformation for each test. After phase transformation, a contractive behaviour is achieved with small increases in deviatoric stress. According to Figure 2-4(a) and 2-4(b), consolidated saturated triaxial strength at phase transformation and maximum strength, depends on mean effective stress, and also it is possible to see a relation between relative density and strength. Final relative density after consolidation depends more on confining stress than initial relative density as seen in Table 2-8, where we observe that values of initial relative density standard deviation are 5 to 12 times greater than values of final relative density standard deviation for the same confining stress. Consequently the strength at phase transformation and maximum strength only depend on effective confining stress for consolidated undrained conditions. We can use Eq. [9] to fit the strength at phase transformation and maximum strength separately for each sample in a linear relation depending only on mean effective stress

$$q = M \cdot p' \quad [9]$$

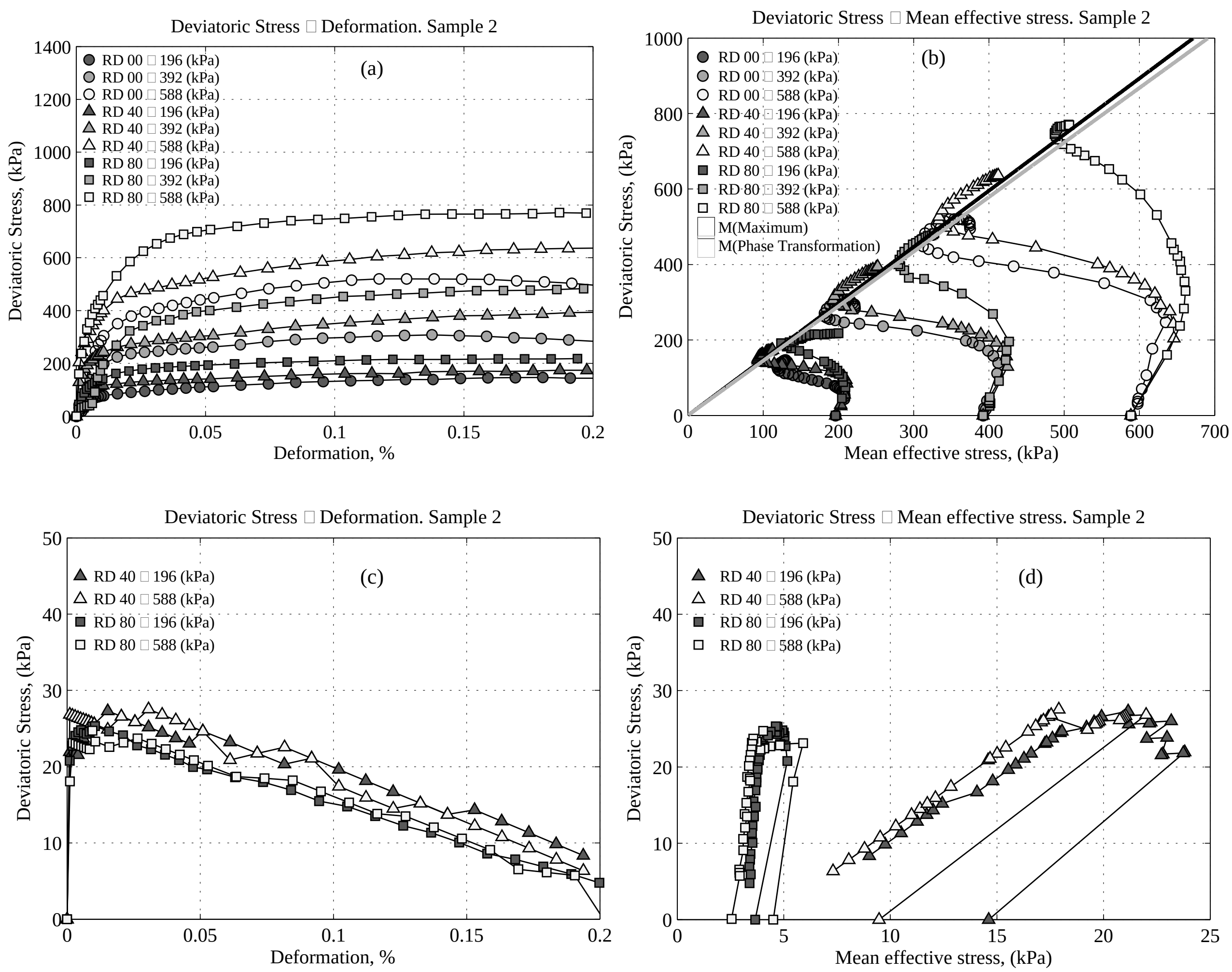

Figure 2-4: Triaxial results for Sample 2. Consolidated and unconsolidated tests were plotted separately in order to improve the clarity of results. Panel (a) and (b) depict the consolidated tests results and panel (c) and (d) represent the unconsolidated tests results. Panels (a) and (c) show the deviator stress as a function of the deformation curves. Panel (b) and (d) show the deviator stress as a function of the mean effective stress curves.

Table 2-8: Analysis of average and standard deviation of initial and final relative density for triaxial tests.

Confining Stress [kPa]	Statistic Measure	Sample 1		Sample 2		Sample 3	
		Real Initial Relative Density	Final Relative Density	Real Initial Relative Density	Final Relative Density	Real Initial Relative Density	Final Relative Density
196	Average	43.4%	71.0%	44.9%	73.3%	47.8%	72.8%
	Standard Deviation	14.1%	1.9%	19.1%	1.5%	16.1%	3.2%
392	Average	46.0%	76.8%	76.8%	44.5%	44.3%	75.1%
	Standard Deviation	20.5%	1.9%	14.4%	1.3%	18.1%	2.4%
588	Average	45.4%	81.4%	44.5%	80.1%	46.3%	76.8%
	Standard Deviation	17.5%	1.4%	14.8%	1.3%	19.2%	2.6%

Fitted parameters of the model for all samples are presented in Table 2-9, they indicate that all samples have similar failure envelopment for strength at phase transformation and maximum strength. M parameter is obtained by the best fit of Eq. [9] to results. M is 4% higher in Sample 1 and Sample 3 than in Sample 2 for maximum strength. On the other hand for residual strength, M factor is 3% higher in Sample 1 than in Sample 2 and Sample 3. Unconsolidated tests for Sample 2 are plotted in Figure 2-4(c) and Figure 2-4(d). Deviatoric stress of unconsolidated mud exhibits a fast increase to a maximum value and then decreases in constant rate until it reaches almost no strength, with maximum values around 30 kPa and residual values between 0.1 kPa to 10 kPa for all samples. These results exhibit loss of strength after phase transformation, consequently monotonic liquefaction or flow failure is developed, given by high pore pressures developed. Nerveless, maximum and residual deviatoric strengths of unconsolidated tests are minimal compared with consolidated results, and does not depend on initial compaction or confining stress. Samples with dense compaction shows a higher variation in pore pressure during tests, but mean effective stress is very low for all tests, due to the similar pore pressure and confining stress values that is applied in the experiments. Given these points, we concluded that mud type ore in saturated condition is more prone to flow under low mean effective stress condition than under high effective stress. Low mean effective stress condition is possible in the case of low confining stress and also when pore pressure is high according to Eq. [4]. In unconsolidated triaxials and unconfined compressions, effective confining stress is zero (or near zero for triaxials), nevertheless strength for unconsolidated is only comparable with lowest values for unconfined tests even when packing for unconsolidated tests is medium to high. Values of unconsolidated strength are closer to loose unconfined tests, this can be explained because of the partial saturation of unconfined tests. When saturation is not full, capillarity forces are developed inside the granular structure, giving to the ore an apparent cohesion, on the other hand unconsolidated tests are fully saturated, consequently there are no capillary forces acting on the ore, also high pore pressures are developed and flow failure or static liquefaction is present on this condition.

Table 2-9: Phase Transformation and maximum Strength models for saturated triaxial tests.

Constant	Sample 1	Sample 2	Sample 3
M (Maximum)	1.547	1.489	1.544
M (Phase Transformation)	1.493	1.447	1.448

2.4.3. MUD RUSH MECHANISMS

In Section 2.2 we collect different triggers and mechanisms for mud rushes from different authors, now considering the experiments conducted so far, we analyze the geomechanical behaviour in order to determine the feasibility of different mechanisms and triggers. In Section 2.2.1 we describe deviatoric stress as the stress that generates shear in a material, therefore a material flows or deforms when the shear stresses acting on it exceeds shear strength of the material. Consequently we assume that deviatoric strength of the ore is directly related to its capacity to flow. In section 2.2 we presented two mechanisms in which mud can lose shear strength to flow: Liquefaction and increase in water content. Additionally, in section 2.4.2 we established that DR mud is affected by static liquefaction or flow failure phenomena only in unconsolidated condition, which means low mean effective stress. Also, we have showed that strength variations with saturation were minimal compared with compaction (RD) changes, nevertheless saturation depends not only in water content, but also in void ratio as can be seen in Eq. [3]. At constant saturation, the more is the volume of voids, the more is the water content, it means that results from Figure 2-3 also shows indirectly an exponential increase in strength with a decrease in water content.

The shear strength of the mud could be modeled with Eq. [9] for saturated condition and Eq. [9] for partial saturation. They depend on effective confining stress and compaction (packing), respectively. Consequently ore can only lose shear strength if it loses confining effective stress for saturated condition or gets looser for unsaturated condition. Extraction from drawpoints involves loosening of the flowing ore as demonstrated by scale models of Kvapil (1992). This also means a distribution of vertical stresses where zones under draw would reach low vertical stresses or low confined conditions. The higher the mass drawn in a cycle the less the vertical load to be expected. This also means that the zones that are not extracted will achieve higher vertical loads which implies compaction (for partial saturation) or consolidation (for full saturation). As mentioned in Section 2.2.3, UU and CU conditions for triaxial test are representing extreme cases of consolidation before shearing. We hypothesize that on the field a very high rate of drawing means no full consolidation of ore, and a low rate of drawing gives a stabilization amount of time enough for full consolidation. As we have seen in Section 2.4.2, no consolidation means zero (or very low) effective confining stress. It is important to note that the process of consolidation is always occurring, and a true non-consolidated mud on the field is improbable, we can have the cases that are more close to non-consolidated condition given by the extraction and low permeability of the mud. Given these points, high rates of drawing can be an important trigger mechanism for mud rush phenomena occurrences. To summarize, if ore is saturated and drawing is too fast to allow consolidation, it is then more susceptible to flow than a consolidated ore. On the other hand, if ore is not saturated, it also loses strength with drawing by obtaining a looser packing, nevertheless saturated strengths are lower than partial saturation strength, and a saturated condition is always more prone to flow than an unsaturated condition. In saturated condition, mean effective stress can also decrease by increasing pore pressure; this is possible if the water level is increased inside or over the drawbell, given by limited drainage of the water from the granular mass. A very compacted mud in the base of drawbells is a very low permeability media which favors the water accumulation. It is important to realize that mud ore can always flow if it is exposed to a disturbance that exceeds its shear strength, nevertheless, ore fully consolidated or with high compaction can be hundreds of times stronger than the same ore under unconsolidated or loose states.

2.5. CONCLUSIONS AND DISCUSSION

Geotechnical parameters have been obtained, mud type ore in Diablo Regimiento shows to be sand and gravel with silt and clay. There are differences between samples in the finest portion of sizes (under 1 mm size). Oxide Sample is finer than the other two, and its liquid and plastic Atterberg limits are higher, which means that it is less susceptible to change its state from solid to plastic and from plastic to liquid by increasing water content than other two. It means that given the differences on the samples, water content should not be considered as a flow parameter directly, because its influence can change depending of the characteristics of each kind of mud. Unconfined compression tests shows no important variation in strength with an intermediate variation of saturation degree (from 45% to 75%) but a very important increase in strength related to an increase in packing density is developed for all samples, this is modeled using an exponential function for each sample. Triaxial tests show a clear correlation between deviatoric strength and effective confining stress. Unconsolidated tests have almost non deviatoric strength compared with consolidated condition, and this condition is the only prone to suffer static liquefaction or flow failure. For a mud rush it is necessary to exceed ore strength under a given stress state. If there is a high rate of drawing from drawpoint, consolidation is not full and stresses are also low. Therefore ore strength is lower than in the case of fully consolidation ore. For this it's easier for a mud rush to occur with a high drawing rate. Water accumulations inside pores of ore inside and over drawbells can increase pore pressure inside the ore lowering the effective confining stress and consequently is also easier to exceed its strength and generate a mud rush with a high level of water over the drawbell. Research on mud rush phenomenon is in an incipient state and would require from a geomechanical point of view an understanding of stresses acting on the granular media during flow.

2.6. ACKNOWLEDGEMENTS

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3. METHODOLOGY FOR A RISK EVALUATION OF MUD RUSHES IN BLOCK CAVING MINING

Javier Vallejos[a,b] , Kenji Basaure[a,b], Raúl L. Castro[a,b] and Sergio Palma[a,b]

[a] Advanced Mining Technology Center, University of Chile, Santiago, Chile
[b] Block Caving Laboratory, Department of Mining Engineering, University of Chile, Santiago, Chile

Keywords: Mud rushes, block caving, risk evaluation

3.1. ABSTRACT

Mud rushes are a sudden income of wet fine ore into facilities in underground mines; they can harm people and equipment, and cause production delays. Block and Panel Caving mines are prone to develop mud rushes in their production level, with mud flowing from drawpoints. Different mines have developed methods to control drawpoint conditions and decided how to perform a safe ore extraction. The aim of this study is to develop a method to establish decision patterns and apply them to samples from drawpoints for the Diablo Regimiento mine, Codelco, El Teniente Division (Chile). The Abrams's Cone has been used to perform slump tests to mud samples and characterize their consistency by setting the saturation degree and packing. The unconfined strength for different saturation degrees and packing is then evaluated. The results show that conditions for fluid response in slump tests correspond to conditions for low strength in unconfined compression tests. We also found the water content value in which each sample changes the flowing consistency from plastic to soft behaviour according to slump tests classification. These values fluctuate from a content of 12.2% and 16.9% of water content depending on the sample tested. Finally, we defined a fluid security factor in order to design an extraction pattern for the samples tested, based on the water content value. We conclude that a very dense packed ore is not prone to flow, also flow properties strongly depend on the specific properties of ore tested, consequently a specific criterion should be developed for different types of ore in the same mine. Criterion developed for Diablo Regimiento ore provides critical water content values from 11% to 15% depending on the ore type.

3.2. INTRODUCTION

Block/Panel Caving is an underground mining method. It has the lowest cost and the highest production rates for underground methods (Heslop, 2000; Hubert et al., 2000). A good management for the risks are important to ensure the security of the people and infrastructure, operational risks of the method include: rock bursts, air blasts and mud rushes (Hubert et al. 2000). Mud rushes are defined as a sudden inflow of mud from drawpoint or other underground openings to the mine (Butcher et al., 2000, 2005). They can cause dilution, production delays and damage to equipment as well as injuries and fatalities. Elements necessary for mud rushes are: mud forming material, disturbances, discharge point and water (Butcher et al., 2000). All these elements are present in block/panel caving mines: mud-forming material comes from milled ore by caving process; water comes from underground and surface sources. Drawpoints in production level are discharge points for the mud when a mud rush takes place. Finally there is a list of disturbances that could trigger the mud rush phenomena: blasting, earthquakes, equipment operation (Call & Nicholas et al., 1998; Jakubec et al., 2012), arch collapse above drawbells (Butcher et al., 2000, 2005; Jakubec et al. 2012) and ore drawing (Butcher et al., 2000, 2005; Call &

Nicholas et al., 1998; Jakubec et al., 2012). Shear strength loss is considered in two mechanisms of mud rushes postulated by different authors: on one hand the increase of water content that changes mud properties thus decreasing the shear strength (Butcher et al., 2005; Jakubec et al. 2012). On the other hand induced pore pressure that causes sudden strength loss (Call & Nicholas et al., 1998; Jakubec et al., 2012). In the present paper we study the impact of the variation of the water content, which lead to a modification of the mechanical properties of mud ore. Samples were taken from Diablo Regimiento sector (DR), El Teniente Mine, Codelco, Chile, located in the Andes Mountains, 80 km south east from Santiago, where the mining method employed is panel caving. The aim is to present a method for risk classification of ore in drawpoints in order to prevent the uncontrolled flow of ore into the mine.

3.3. BACKGROUND

3.3.1. RELEVANT RISK CLASSIFICATION

Mud ore from IOZ mine, Freeport, Indonesia has been characterized geo-technically (Call & Nicholas et al., 1998). They concluded that ore involved in mud rushes had more than 20% of grain sizes less than 2 mm. Additionally, with saturation degrees greater than 80% the material is prone to develop liquefaction due to the excess of pore pressure. They also measured the density of the ore pile in drawpoints in order to establish the water content in which ore reaches 80% of saturation degree. Finally, they proposed a classification system, which recommends a draw procedure depending on grain size and water content from ore in drawpoints. They defined 6 classes for mud ore associated with a recommendation of how it should be drawn. In Table 3-1 we summarize the classes defined for IOZ mine. Classes A and B are recommended to be drawn with any loader with even draw and twice a week checking for changes. C and D are recommended to be drawn with a closed cabin loader with supervision, even draw, dry ore blend and twice a week checking for changes. E and F classes are recommended to be drawn with remote loader, supervision, check for changes every shift and at least 6 buckets per shift drawing. Water content of this classification system was established specifically for IOZ ore, a different ore material requires a new water content evaluation. Also, the density measured in ore pile could be different than density in ore column, and as the saturation degree depends on density. This method could be inaccurate to predict the risk of mud rushes that involves the ore column, because they used only the density of the ore pile for water content recommendations. Finally, drawing recommendations are fitted to IOZ specific shovels and mine conditions, a different mine will require specific recommendations.

Table 3-1: Mud ore classes proposed for IOZ mine (Call & Nicholas et al., 1998).

W: Water Content [%]	G: Grain size less than 50mm	
	G < 30%	G > 30%
W < 8.5%	A: Coarse Dry	B: Fine Dry
W >8.5% and W < 11%	C: Coarse wet	E: Fine wet
W > 11%	D: Coarse very wet	F: Fine very wet

El Teniente mine uses criterion based in historical data of ore grain size and water content of 7 drawpoints in which a mud rush took place. A risk classification (Becerra, 2011) with three classes is defined: Normal condition (NC), in observation (IO) and critical risk (CR). Table 3-2 summarizes the grain size and moisture content conditions for risk classification in El Teniente. The use of seven cases from historical data from different sectors of El Teniente can be inaccurate to predict the risk in particular zones and different types of ore.

Both criteria use grain size and water content to classify ore in drawpoints. Criterion for IOZ (Table 3-1) is based in geotechnical characterization of six samples (Call & Nicholas et al., 1998), meanwhile for El Teniente criteria's historical data from 7 events is used (Becerra 2011). One difference of these criteria is the grain size: IOZ uses 5 cm as the relevant grain size and El Teniente uses 25 cm. The other difference is that El Teniente classification takes coarse grain size as a critical risk if moisture content is more than 10%, while IOZ only recommends closed cabin loader for the same condition.

Type of clays available in ore from different drawpoints can play an essential role in water absorbing properties and consequently in flowing risk evaluation (Call & Nicholas et al., 1998). Also, the influence of density must be considered in the ore mechanical characterization. In order to develop an improved classification system it's necessary to characterize the behaviour of specific ores, using not only the water content and saturation degree, but also relate those parameters with a variable density. We propose a new method to develop classification systems for specific ores, based on a simple characterization of ore with different density and saturation degree values.

Table 3-2: Mud risk classification for drawpoint in El Teniente mine (Becerra, 2011).

Moisture content	Grain size (G) ≤ 25cm		
	G < 30% (Mostly thick granulometry)	30% ≤ G ≤ 70%	G ≥ 70% (Mostly fine granulometry)
<4%	NC	NC	NC
4% - 7%	IO	IO	IO
7% - 10%	IO	IO	CR
≥10%	CR	CR	CR

3.3.2. DENSITY AND WATER CONTENT PARAMETERS

In the last section we presented relevant criteria for ore evaluation, depending on the water content, which is easy to obtain in the laboratory. The water content value is calculated by obtaining only water and solid weights. Also, as mentioned in the introduction one of the mud rush mechanisms are the increase of water content. In granular materials the water content is mostly held in the voids between the solid particles. A granular material with high density has fewer voids than the same material with a low density; consequently a material with high density can hold less water content than a low density material. This is why we emphasized the importance of density as parameter when water content is involved. Density of mud in ore column is uncertain because of the changes caused by the ore flow in which density changes as material is extracted from drawpoints, this phenomenon was demonstrated by Kvapil (1992) experiments. Nevertheless, the range of density in which a certain granular material can develop, is a measurable value given by its minimum and maximum void ratios representing the maximum and minimum density, respectively. Ratio between void volume and solid volume in a granular material is called void ratio. Range of maximum and minimum void ratio is used to define relative density parameter (RD), which assigns a 0% value to the maximum void ratio (e_{max}) and 100% value to the minimum void ratio (e_{min}). Eq. [1] shows the RD parameter defined by maximum and minimum void ratio values.

Saturation is the ratio between the volume of water and volume of voids. Consequently it depends on the void ratio and water content and therefore is an important parameter for mud rush risk evaluation. Furthermore, previous studies have directly related saturation with mud rush risk (Becerra, 2011; Call & Nicholas et al., 1998). Eq. [2] shows the relation between void ratio (e) and saturation (S) with water content (ω) and specific gravity (Gs), where specific gravity is unit weight of solid divided by the unit weight of water and the water content is the ratio of water weight to solid weight (Lambe & Whitman, 1969). In the next section we will use all these parameters as an input for testing the mud samples.

$$RD[\%] = \frac{e_{max} - e}{e_{max} - e_{min}} \cdot 100 \quad [1]$$

$$G_s \cdot \omega = S \cdot e \quad [2]$$

3.4. MATERIALS AND METHODS

3.4.1. SAMPLES

This study is based on test results performed on three samples obtained from the El Teniente mine, Diablo Regimiento sector. In this sector, three kinds of mud ore have been identified by visual characterization according to personnel from the mine: (1) Grey mud, (2) yellow mud and (3) mixture mud, which are associated with sulphide, oxide and mixture minerals respectively. Three samples were collected from different drawpoints, each one representative of one different type of mud according to mine personnel. Drawpoints chosen for sample extraction are classified in critical risk category according to risk classification used in El Teniente (Becerra, 2011). Table 3-3 lists the samples with their description and composition. Mine personnel in charge of water content control performed the process of sampling. It was carried out using a hand shovel to extract increments across the drawpoint, on a horizontal line 1.5 m away from the floor. This method is regularly used in El Teniente for the representative sampling of mud ore for water content control. Samples were packed and transported in sealed plastic bags to the laboratory.

Table 3-3 Samples and visual description.

Sample	Description	Composition
1	Grey color	Sulphides
2	Yellow color	Oxides
3	Mixed color	Mixture

3.4.2. EXPERIMENTAL METHOD

3.4.2.1. TESTS

Samples were tested in the Solids Laboratory facilities of Civil Engineering Department of Universidad of Chile. Slump tests are carried out in order to classify the behaviour of mud ore based on the slump results for different conditions. Samples grain size is 95% under 5cm. Slump tests are performed using a standard metal mold (according to ASTM C143 standard) shaped as the surface of a frustum cone with base of 200 mm diameter, top is 100 mm diameter and the height 300 mm called Abram's cone (Figure 1). The mold is filled with material through the top while the base is placed on a flat surface, and then is removed in vertical direction. The result of the test is the slump, it's measured with 1mm precision immediately after the mold removal. Slump is different between the height of the mold and the height of the material.

Figure 3-1: Abram's cone, mold used for slump tests.

We also conducted unconfined compression tests, in order to compare the slump behaviour results with unconfined strength in kPa units. Unconfined compression consists in axial loading to a cylindrical specimen in a strain-controlled device until failure (according to ASTM D2166 standard). Force and strain are measured with 0.001kN and 0.001mm precision respectively. The test ends when force decreases or vertical strain reaches 20%. Initial cross-sectional area (A0) is measured from the average of nine diameter measures; it is corrected during the test depending on vertical strain (ε) according to Eq. [3].

$$A = \frac{A_0}{1 - \varepsilon} \qquad [3]$$

In this study, two variables are controlled for slump tests and unconfined compressions: Saturation degree and relative density. The Table 3-4 contains the values of the variables set for each slump test and Table 3-5 contains the values for each unconfined compression: three different relative densities and saturations for each sample, which means nine tests each sample. Variables are carefully set when the mold is filled, by calculating the water content and mass necessary for each combination. For slump tests mold is filled in three layers in order to obtain uniform density inside. For unconfined compression mold it's filled with five layers in order to make each specimen be tested.

Table 3-4: Relative density and saturation degree combinations for slump test on each sample.

Relative density [%]	Saturation degree [%]
45	60
45	80
45	100
65	60
65	80
65	100
85	60
85	80
85	100

Table 3-5: Relative density and saturation degree combinations for unconfined compression test on each Sample.

Relative density [%]	Saturation degree [%]
20	45
20	60
20	75
60	45
60	60
60	75
90	45
90	60
90	75

Geotechnical indexes of specific gravity, maximum and minimum void ratios must be obtained in order to set variables from Tables 3-4 and V according to Eqs. [1] and [2]. Specific gravity is obtained using two different methods depending on the grain size. On one hand for particle sizes smaller than 4.75 mm we used the water pycnometer method. On the other hand for particle sizes greater than 4.75 mm the method is to weigh a dry portion of material, then submerge the same portion and obtain its weight under water, finally the dry weight is divided by the difference between dry and submerged weights to obtain the specific gravity. Maximum void ratio is obtained by pouring the material in a known volume cylindrical mold with to obtain minimal density (according to ASTM D4254 standard). Minimum void ratio is obtained by modified proctor test in which material is compacted in layers in a known volume container (according to ASTM D1557 standard).

3.4.2.2. CLASSIFICATION RISK

In order to develop a risk classification pattern we use the classification system for concretes presented in Table 3-6. Each consistency represents one type of behaviour of the ore. We use the slump corresponding to dry and plastic consistency as not flowing behaviour, and slump soft or greater as a flowing behaviour. The aim is to find the minimal water content in each sample in which the slump passes from plastic to soft behaviour; we named that value “fluid limit” (FL). In order to find FL we plot slump versus water content, drawing curves for slump results with the same saturation degree. Then we find the water content values, which are the interception between the plastic-soft limit (9,5 cm of slump) and each saturation curve. Finally we select the minimum water content as FL for each sample.

Table 3-6: Consistency classification based in Slump from BS-8500 standard.

Consistency	Slump range [cm]
Dry	0 – 5
Plastic	4 – 10
Soft	9 – 16
Fluid	15 - 30

3.5. RESULTS

3.5.1. TESTS

Obtained geotechnical indexes are presented in Table 3-7. These indexes are necessary to set the unconfined compressions and slump tests conditions according to Eq. [1] and Eq. [2]. Three samples have similar specific gravity and maximum and minimum void ratios, nevertheless sample 2 is prone to have higher void ratios.

Table 3-7: Relative density and saturation degree combinations for unconfined compression test on each Sample.

Parameter	Test	ASTM standard	Results		
			Sample 1	Sample 2	Sample3
Specific gravity	Water pycnometer, water immersion	D854, C127	2.76	2.68	2.72
Minimum void ratio	Pouring in known volume cylinder.	D4254	0.27	0.28	0.22
Maximum void ratio	Modified proctor	D1557	0.90	1.00	0.93

Results for unconfined compression strength are shown in Figure 2. Strength increases with RD and decreases with saturation degree. The parameters were obtained while fitting the Eq. [4] in order to generalize the strength depending on RD and saturation. It has six experimental adjustment parameters (p,q,r,a,b,c), Table 3-8 shows the values obtained for the constants for the three samples. Here, Us is the unconfined strength for a given RD and saturation degree (S). Figure 2 also shows the 80% and 100% saturation degree curves according to Eq. [4] and parameters in Table 3-8.

$$U_s = (pS^2 + qS + r)RD^{(aS^2+bS+c)} \qquad [4]$$

Table 3-8: Parameters for Eq. [4].

Constant	Sample 1	Sample 2	Sample 3
P [kPa]	12,882	11,439	11,993
Q [kPa]	-12,288	-11,416	-12,132
R [kPa]	3,810	3,656	4,276
a	45	80	39
b	-39	-78	-36
c	11	22	12

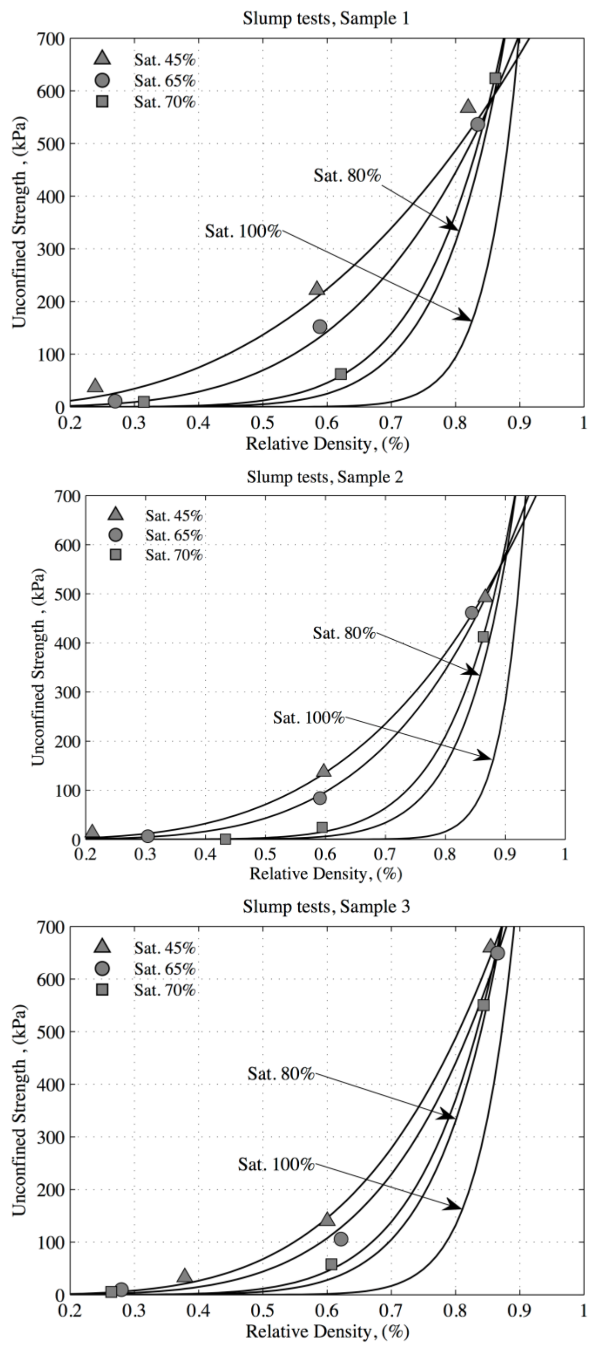

Figure 3-2: Slump tests results for three samples, consistency classification and LL determination.

Figure 3 shows the results of slump tests, vertical axis has the slump measures and horizontal axis has the water content, each curve shows a different saturation degree so there are also three states of compaction represented on each curve. Horizontal divisions show different classes of consistency depending on slump according to Table 3-6. Figure 3 reveals that slump increases with the increase of saturation, but decreases with relative density. Also, RD of 85% means a dry consistency for all cases. Oxide Sample requires 100% of saturation to reach fluid consistency, mixed sample requires 80% of saturation and sulphide sample requires only 60% of saturation. Vertical dashed lines show the value of Fluid Limit (FL) defined in section 3.3. On the other hand, water content values obtained from this interception indicate that Sample 1 (sulphide) is prone to flow with less water content than the other samples, thus with a water content of 12.2% versus 16.9% and 15.6% of Sample 2 (oxide) and Sample 3 (mix) respectively.

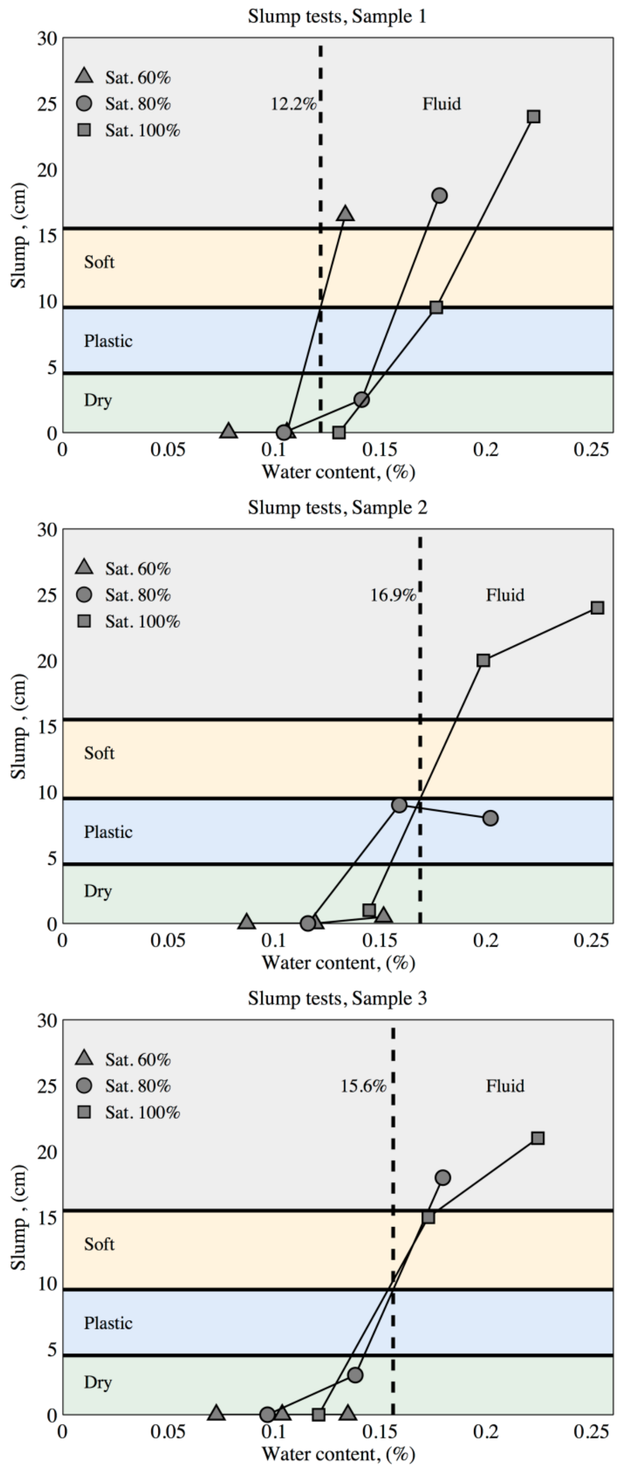

Figure 3-3: Slump tests results for three samples, consistency classification and FL determination. The solid lines are for visual aid purposes.

We used Eq. [4] to calculate unconfined strength using the conditions given to slump tests (Table 3-4). In Table 3-9 we summarized all the results for slump, consistency category and unconfined strength using Eq. [4] for all samples. Fluid and Liquid states are achieved with less than 46 kPa of Us. Nerveless, there are some cases, which the Us is very low with dry consistency (RD 45% and 60% of Saturation degree). These cases imply that Eq. [4] it's not entirely valid to explain slump and should be used only as reference values, because the range of saturation was different for slump tests and unconfined compression.

Table 3-9: Results for slump tests, consistency classification and equivalent unconfined strength.

DR	S	Sample 1			Sample 2			Sample 3		
		Slump [mm]	Consistency	U_s [kPa]	Slump [mm]	Consistency	U_s [kPa]	Slump [mm]	Consistency	U_s [kPa]
45%	60%	165	Liquid	46	5	Dry	27	0	Dry	26
45%	80%	180	Liquid	2	80	Soft	0	18	Liquid	2
45%	100%	240	Liquid	0	240	Liquid	0	21	Liquid	0
65%	60%	0	Dry	196	0	Dry	137	0	Dry	159
65%	80%	25	Dry - Plastic	51	90	Soft	15	3	Dry	55
65%	100%	95	Soft - Fluid	3	200	Liquid	0	15	Fluid	5
85%	60%	0	Dry	566	0	Dry	450	0	Dry	593
85%	80%	0	Dry	534	0	Dry	299	0	Dry	556
85%	100%	0	Dry	267	10	Dry	70	0	Dry	336

3.5.2. RISK CLASSIFICATION

With FL results from slump tests we developed the risk classification pattern for each sample and different SFf values, we calculate different water content ranges related with a specific risk level. We calculate water content using Eq. [5], consequently water content ranges depends on FL value.

$$SF_f = \frac{FL}{\omega} \qquad [5]$$

Water content Classification of risk classification for DR drawpoints are in Tables 3-10, 3-11 and 3-12 for samples 1, 2 and 3 respectively. Each pattern is specific for each mud type. Sample 1 has lower water content values for the same risk level than the other samples. The last row contains the critical water content value, in which the drawpoint is classified as critical risk regardless of the grain size.

Table 3-10: Risk classification for DR, sample 1.

FS_f	w	Grain size (G) ≤ 25cm	
		G < 70%	G > 70%
<1.5	< 8%	NC	NC
1.5 - 1.2	8% - 10%	IO	IO
1.2 - 1.1	10% - 11%	IO	CR
>1.1	> 11%	CR	CR

Table 3-11: Risk classification for DR, sample 2.

FS_f	w	Grain size (G) ≤ 25cm	
		G < 70%	G > 70%
<1.5	< 11%	NC	NC
1.5 - 1.2	11% - 14%	IO	IO
1.2 - 1.1	14% - 15%	IO	CR
>1.1	> 15%	CR	CR

Table 3-12: Risk classification for DR, sample 3.

FS_f	w	Grain size (G) ≤ 25cm	
		G < 70%	G > 70%
<1.5	< 10%	NC	NC
1.5 - 1.2	10% - 13%	IO	IO
1.2 - 1.1	13% - 14%	IO	CR
>1.1	> 14%	CR	CR

3.6. DISCUSSION AND CONCLUSIONS

Different risk and operation criteria have been developed in the past, all based on grain size and water content. On one hand El Teniente criterion does not contemplate different behaviour of ore depending on its composition. On the other hand, IOZ criterion assumed constant density. The method presented within this study is specific for a type of ore and also contemplates a density analysis. On one hand, highly compacted ore is not able to flow, on the other hand, medium and loose ore can flow depending on saturation values, the higher is the saturation, and the higher is the flowing. We determined flowing water content values: 12.2% for sulphide ore, 16.9% for oxide ore and 15.6% for mixed ore. Consequently, different samples have different abilities to flow with the same water content; sulphide ore is more prone to flow than oxide and mixed ore. The application of the developed criterion for drawpoint-ore-classification provides different water content critical values: 11% for sulphide ore, 15% for oxide ore and 14% for mixed ore. In order to improve the mine's production a criterion for each ore type must be developed, in order to operate the drawpoint until the ore reaches its specific water content critical value. If a general mine criterion is developed, the criterion with the minimal water content values should be selected. In this case, sample 1 (sulphide) has the lowest values of water content, with 11% of critical water content.

3.7. REFERENCES

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GENERAL CONCLUSIONS

Geotechnical parameters have been obtained, mud type ore in Diablo Regimiento shows to be sand and gravel with silt and clay. There are differences between samples in the finest portion of sizes (under 1 mm size). Oxide Sample is finer than the other two, and its liquid and plastic Atterberg limits are higher, which means that it is less susceptible to change its state from solid to plastic and from plastic to liquid by increasing water content than other two. It means that given the differences on the samples, water content should not be considered as a flow parameter directly, because its influence can change depending of the characteristics of each kind of mud. Unconfined compression tests shows no important variation in strength with an intermediate variation of saturation degree (from 45% to 75%) but a very important increase in strength related to an increase in packing density is developed for all samples, this is modeled using an exponential function for each sample. Triaxial tests show a clear correlation between deviatoric strength and effective confining stress. Unconsolidated tests have almost non deviatoric strength compared with consolidated condition, and this condition is the only prone to suffer static liquefaction or flow failure. For a mud rush it is necessary to exceed ore strength under a given stress state. If there is a high rate of drawing from drawpoint, consolidation is not full and stresses are also low. Therefore ore strength is lower than in the case of fully consolidation ore. For this it's easier for a mud rush to occur with a high drawing rate. Water accumulations inside pores of ore inside and over drawbells can increase pore pressure inside the ore lowering the effective confining stress and consequently is also easier to exceed its strength and generate a mud rush with a high level of water over the drawbell. Research on mud rush phenomenon is in an incipient state and would require from a geomechanical point of view an understanding of stresses acting on the granular media during flow.

Different risk and operation criteria have been developed in the past, all based on grain size and water content. On one hand El Teniente criterion does not contemplate different behaviour of ore depending on its composition. On the other hand, IOZ criterion assumed constant density. The method presented within this study is specific for a type of ore and also contemplates a density analysis. On one hand, highly compacted ore is not able to flow, on the other hand, medium and loose ore can flow depending on saturation values, the higher is the saturation, and the higher is the flowing. We determined flowing water content values: 12.2% for sulphide ore, 16.9% for oxide ore and 15.6% for mixed ore. Consequently, different samples have different abilities to flow with the same water content; sulphide ore is more prone to flow than oxide and mixed ore. The application of the developed criterion for drawpoint-ore-classification provides different water content critical values: 11% for sulphide ore, 15% for oxide ore and 14% for mixed ore. In order to improve the mine's production a criterion for each ore type must be developed, in order to operate the drawpoint until the ore reaches its specific water content critical value. If a general mine criterion is developed, the criterion with the minimal water content values should be selected. In this case, sample 1 (sulphide) has the lowest values of water content, with 11% of critical water content value.