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GUIDELINES FOR PORE WATER PRESSURE MONITORING PROGRAMS DESIGN AND INTEGRATION TO OPEN PIT MINE PLANS

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GUIDELINES FOR PORE WATER PRESSURE MONITORING PROGRAM DESIGN AND INTEGRATION TO OPEN PIT MINE PLANS

El diseño de taludes es una tarea crítica en proyectos de minería a cielo abierto. Generalmente, planificadores y diseñadores buscan operar en paredes tan empinadas como sea posible para optimizar la cantidad de mineral extraído y reducir el lastre. Sin embargo, esto conlleva una disminución en la estabilidad del talud. De este modo, se requiere una gestión adecuada del talud para permitir a los planificadores y operadores realizar su trabajo con seguridad.

Una de las principales variables que debe ser manejada adecuadamente en minas a cielo abierto es la presión de poros que se genera detrás de los taludes ya que esta presión disminuye la resistencia al corte del suelo. Para controlar la influencia de la presión de poros se han desarrollado distintos tipos de instrumentos para monitorear presión de agua en minas y usar los datos obtenidos como input en la toma de decisiones.

Entre los instrumentos desarrollados para monitorear presión de agua subterránea están los piezómetros, que se han convertido en tecnologías establecidas en proyectos civiles y mineros. Existen distintos tipos de piezómetros y entre ellos la tecnología más aceptada para realizar monitoreo de agua en minas es la de Vibrating Wire Piezometer (VWP).

En esta tesis se desarrollaron lineamientos para seleccionar instrumentación basada en las características de una mina. Utilizando estos lineamientos se seleccionaros dos tecnologías para ser comparadas, los VWP y los Networked Smart Markers (NSM). Esta comparación involucra el desarrollo de un proyecto minero teórico que incluye empinar una pared potencialmente inestable de la mina como contexto para el uso de los instrumentos. Posteriormente, se desarrollaron lineamientos para integrar un programa de monitoreo al plan minero.

Para comparar dichas tecnologías, se proponen dos programas de monitoreo equivalentes y se consideran los costos de los equipos para ser instalados en los años 3 y 13 del plan minero. Un análisis de pits anidados reveló que el VAN del proyecto aumenta a medida que la pared se empina, de este modo, el parámetro de control en la comparación es cuál programa es más barato al tomar en cuenta el ingreso extra y una tasa de descuento del 8% para calcular el VAN.

Los resultados de esta comparación mostraron que el uso de VWP es más barato que el uso de NSM (600,015.5[US$] versus 766,142.5[US$]). Sin embargo, esta diferencia en costo es pequeña considerando la escala del proyecto (0.39% de la inversión), además empinar la pared generó 42,420,000[US$] extra al VAN original del proyecto, lo que hace que ambas alternativas sean factibles para llevar a cabo el monitoreo propuesto. Los NSM sin embargo poseen una ventaja para realizar mediciones multipunto ya que permiten un mayor número de puntos de muestreo en un mismo pozo.

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GUIDELINES FOR PORE WATER PRESSURE MONITORING PROGRAM DESIGN AND INTEGRATION TO OPEN PIT MINE PLANS

Slope design is one of the most critical tasks in open pit mine projects. Generally, mine planners and slope designers aim to operate on walls as steep as possible to optimize the amount of ore retrieved from the mine while reducing the extracted waste. However, this approach also involves a reduction in overall slope stability. Consequently, a proper management of slope stability is required to assist mine planners and operators to perform their work safely.

One of the main variables that need to be properly managed in open pit mines is the pore water pressure generated behind the slopes, as this pressure decreases the ground's shear strength. To manage the influence of pore water pressure, several geotechnical instruments have been developed over the years to monitor pore water pressure and to use the data to make proper decisions.

Piezometers are devices developed to monitor groundwater pressure that have become established technologies to measure pore water pressure in civil and mining projects. There are different types of piezometers with varying characteristics. The most accepted sensing technology for pore pressure monitoring in mines is the Vibrating Wire Piezometers (VWP).

This thesis developed guidelines for the selection of instrumentation given the characteristics of a mine site. Using those guidelines, Vibrating Wire Piezometers and the emergent technology of Networked Smart Markers (NSM) were selected to be compared. For this comparison, a theoretical mine project, that included the steepening of a potentially unstable wall, was developed as context for instrumentation use. Subsequently, guidelines for the integration of a pore water pressure monitoring program into the mine plan were developed.

To compare the selected technologies, two equivalent monitoring programs were proposed considering the current installation costs of the devices and installations in years 3 and 13 of the mine life. A nested pit analysis revealed that the NPV of the project increases when the wall gets steeper, therefore, the parameter of interest is which program is less expensive compared to the extra income, considering a discount rate of 8% to calculate the NPV of the project.

The results of this comparison showed that the use of Vibrating Wire Piezometers was less expensive than the NSMs (600,015.5[US$] against 766,142.5[US$]). However, this difference in cost is small in terms of the scale of this project (0.39% of the investment) and the steepening of the wall generated 42,420,000[US$] extra to the NPV of the original project, thus, making both alternatives feasible to perform the proposed monitoring. NSMs are, however, more suitable to perform multi-point readings as they allow a higher number of measurement points in a single borehole.

I believe that in this life, nothing is impossible,
not a single thing.

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CHAPTER 1: INTRODUCTION

1.1. Introduction

The thesis entitled “Guidelines for Pore Water Pressure Monitoring Programs Design and Integration to Open Pit Mine Plans” to obtain the degree of Master in Mining Engineering at Universidad de Chile presents the development of guidelines for the application of geotechnical instrumentation to measure pore water pressure in open pit mines towards better understanding of the rock mass behavior and safe slope management.

The development of these guidelines for pore water pressure monitoring in mining slopes is of high importance due to the characteristics of the currently operating and future large open pit mining operations.

The knowledge of geotechnical instrumentation can be applied to establish a monitoring campaign that better suits the needs of the monitoring site; the developed guidelines can be used to determine sections of the slope where pore pressure variation rates are critical and drainage campaigns or other methods of slope control are needed.

1.2. Hypothesis

Current monitoring programs are generally developed in a qualitative manner. The mining industry would have better tools to manage variables in slope stability as mining progresses if: (1) this qualitative selection of instruments is supported by the development of guidelines and (2) the monitoring program, based on guidelines, is integrated within the mine plan.

1.3. Objectives

The main objective of this research is the development of guidelines for the application of pore water pressure monitoring instrumentation in open pit mines focusing on the integration of the monitoring program into the mine schedule.

To accomplish this objective the research focused on devices currently used to measure groundwater pore pressure in hard rock environments and, on the emergent technology of Networked Smart Markers. The developed guidelines were applied to a theoretical mine site created using the DeepMine software.

The following sub-objectives list the steps taken in reaching the main objective of this thesis, which was accomplished by:

- Carrying out a thorough review of established geotechnical instruments and assessing their measurement technique for physical changes in rock and their application range.

- Establishing guidelines for the application of established pore pressure monitoring instruments in open pit mines.

- Describing the experience of the installation of Networked Smart Markers and how the enhancement of that technology can be used to monitor pore pressure in open pit mines.

- Developing a mine plan from a standard block model, establishing the geometry of pushbacks and final pit. Defining a theoretical scenario that required groundwater control through pore pressure monitoring.

- Integrating the pore pressure monitoring program with the mine schedule. Considering the cases of established technologies and Enhanced Networked Smart Markers to develop new guidelines.

1.4. Context of the Research

For open pit operations, the design of slope geometry is a critical stage of the overall mine operational design as it must ensure the prevention of rock fall and slides and minimize the risks related to the safety of personnel and equipment. At the same time, slope design must address economic concerns of the investors and maximize the ore recovery while keeping waste stripping at minimum.

After the design requirements are met, it is vital to ensure the stability of the slope. This aspect of the design cannot be underestimated as evidenced by the events that occurred in April, 2013 at Bingham Canyon Mine, Utah, USA, where, according to Pankow, K. L. et al. (2014), a massive landslide sent 165 million tons of rock into the pit burying 3 shovels and 14 haul trucks and forcing the closure of the pit's main access ramp. It is important to point out that this incident comprised two events: the first one was the failure of a supporting passive block followed by the release of the body of the active block as the support given by the passive block was removed. Both failure phases were identified by available surface monitoring near the site, but their extent was not predicted. This entire incident revealed the importance of an effective coordination between subsurface ground movements monitoring and surface monitoring instrumentation.

Geotechnical instrumentation is the key to address slope stability since it allows to assess whether the rock mass is moving. Generally, slopes are instrumented to measure deformations and monitor the rate at which the wall face is moving. Latest developments in sensing technology have contributed to more reliable and accurate devices used to monitor surface deformations. However, subsurface deformations and variations in pore pressure inside the rock mass must also be taken into consideration.

In particularly, groundwater monitoring is vital in open pit slopes as, unlike deformations, pore pressure inside a rock mass can be addressed and reduced via draining campaigns, which minimizes the effects of slope failure. This is the only way that mine personnel can intervene with the rock mass' properties to improve the competence of the rock, since reducing pore pressure diminishes the effective stress in the rock mass and thus increases its shear strength.

The development of guidelines to install pore pressure sensors in open pit mines is the main subject of this thesis. The work undertaken was part of a joint project between CSIRO Chile and Universidad of Chile to develop and implement sensors to measure subsurface deformation and other relevant variables for the rock mass monitoring in real time.

The new sensors, called Networked Smart Markers or NSM, are based on a novel technology developed by Elexon Electronic, a company specialized in providing electronic solutions with base in Brisbane, Australia. The initial application of this technology was in underground caving operations. For open pit applications, the NSMs are installed in the rock mass behind the wall of the pit. The NSMs contain on-board radio transmitters that allow the sensor's movement to be recorded and to be reported in real time, as the signal is transferred from one marker to another until it reaches the surface data acquisition system.

This thesis relates the first implementation (two field installations) of the NSM technology. The objectives of the field trials were to: (1) confirm the functionality and wireless communication capabilities of the NSM technology in the open pit environment and (2) assess the NSM's potential to integrate several sensors in a single device.

1.5. Scope of the work

1.5.1. Geotechnical Instrumentation

The scope of the research in terms of geotechnical instrumentation will be limited to the instruments currently available on the market, identified by surveying different instrument's manufacturers based on the list presented by Dunnicliff, J. (2013) and the instruments that have potential to be applied in mining operations.

Given the way geotechnical instruments have been developed and the problem of assessing slope stability, the research conducted as part of the Master's degree thesis was focused on instruments that have been accepted as established practices at mine sites to measure water levels and pore pressure. Together with deformation records, these are the most relevant parameters to assess stability of open pit mine slopes. The most commonly used instruments used for this purpose, as defined by Marr, W.A. (2013) are presented in Table 1.1.

Table 1.1: Types of instruments to be reviewed, based in Common Instruments chart by W. A. Marr (2013)

Groundwater Instrumentation
Observation Well
Standpipe Piezometer
VW Piezometer
Pneumatic Piezometer
Twin-Tube Piezometer
Flushable Piezometer

The research focused on the instruments and their application range as there have been multiple works trying to establish the need of geotechnical instrumentation for slope stability (e.g. Marr, W. A., 2013; Villarroel, C., 2014).

Finally, case studies were reviewed to establish a connection between site characteristics and deployment of monitoring instrumentation.

1.5.2. Chapter Overview

The thesis include the following chapters:

Chapter 1: Introduction. In the context of open pit mining operations and slope design, the motivation behind this research is explained. Afterwards, the objectives of this work are listed and the scope of this thesis is established.

Chapter 2: Literature Review. This chapter includes the literature review relevant to the subject explored in this thesis. The review commenced by analyzing basic notions of slope design and how those designs can be improved to maximize profit, but jeopardizing the safety of the operation. Then, the subject moved towards slope stability, how it is assessed and controlled, to later expand on the effects of groundwater on mining slopes. Afterwards, the issue of how to manage and control the effects of groundwater is analyzed leading to a thorough review of available groundwater monitoring technologies or instruments. Finally, a review of the main considerations when implementing geotechnical instruments for pore pressure monitoring in open pit mines was performed.

Chapter 3: Instrumentation Trial. This chapter describes the activities undertaken in the installation of Networked Smart Markers at a mine site in Chile. It also provides information related to the new developments of this technology which allows the devices to house pore pressure sensors and take measurements at several points inside a single borehole.

Chapter 4: Development of a Mine Plan. This chapter focused on establishing a context in which the posterior analyses took place. A theoretical mine plan was developed under the assumption that it would guarantee the stability of the slopes. Afterwards, this design was modified as it was reasoned that the VPN of the project could be maximized by steepening a slope, thus creating a scenario where groundwater control was required.

Chapter 5: Development of Groundwater Monitoring Programs. In this chapter, a number of guidelines and recommendations for groundwater monitoring were presented as they were developed from the research made in the literature review. Those guidelines were later used to propose two monitoring campaigns for the previously defined pit, based on established (Vibrating Wire Piezometer) and emergent (Networked Smart Markers) technologies. Both programs were later integrated into the mine schedule and the cash flow of the project was updated to compare which of the technologies fare better.

Chapter 6: Results & Analyses. This chapter presents the results of the research and critically reviews them. The main focus of this section is to establish a method to successfully integrate monitoring campaigns into the mine schedule.

Chapter 7: Conclusions & Future Work. The conclusions provide a summary of the analyses made in Chapters 4, 5 and 6 with respect to the thesis' objectives presented in Chapter 1. Subsequently, all the subjects of interest for this research that were not addressed in this thesis are discussed and recommendations are made for future works in this area of investigation

1.6. Methodology

A brief summary of the main activities that were undertaken is presented in this Section.

The study conducted to establish recommendations and application ranges for different types of Geotechnical Instruments considered several steps:

- Assessment of which physical processes are the most relevant and should be considered in a monitoring campaign of a slope.
    - Determination of the influence of the pore pressure generation in rocks.
- Determination of the most effective control measures currently adopted by the industry to manage the effects of pore water pressure on mining slopes.
- Identification of which devices are established technologies for groundwater monitoring in the mining industry.
- Survey of different types of instruments based on the information made available by the providers.
- Identification of the technologies available for every relevant groundwater variable to be measured.
- Establishment of the technical and economic characteristics of each instrument.
- Comparison of different technologies able to perform the same type of measurement, identifying their strengths and limitations.
- Survey of study cases to relate site's geological properties and mine geometry to deployment of instruments.
- Development of guidelines for slope monitoring based on the acquired knowledge.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

In open pit mines, slope design is one of the most challenging stages of design and planning (Stacey, 2009). Slope movement is a common occurrence in open pit mines, and many mines accept it as part of their operating conditions while endeavoring to operate safely and profitably for several years with carefully monitored moving slopes (Wyllie & Mah, 2004). When some slopes undergo long-term movements and the displacement reaches the level where safe operation is no longer possible, the slope is considered to have failed (Stacey, 2009).

Landslides are one of nature's most destructive geological forces causing damages that may result in numerous fatalities. During a period of just eight (8) years (2004-2011) more than 32000 fatalities related to landslides were reported (Pankow et al., 2014). This type of geological events also result in huge economic losses; just in the United States annual losses average 2 to 4 billion dollars (US Geological Survey, 2015).

When referring only to slopes present in surface mining operations, landslides are one of the principal causes of fatalities in open pit mines in the US. Retrospectively, between 1995 and 2001 deaths caused by landslides represented 15% of all fatalities registered in surface mining operations (Girard, 2001).

To reduce the inherent hazards of slope instability both preventive and remedial actions can be taken. The principal measure used to prevent adverse situations is to develop safe designs based on geotechnical characteristics of the site, install support or rock catchment systems, implement thorough monitoring campaigns and perform regular examination of slopes to give warning signs on impending slides, thus protecting both lives and equipment (Girard, 2001).

2.2. Slope Design

An appropriate slope design is a critical step for an open pit mining project. An inadequate slope design may produce instabilities that might have serious repercussions if failure occurs. The effects of a landslide are not limited only to potentially endanger lives, but also affect the operation by destroying equipment and properties, may endanger the environment surrounding the mine and often results in a partial or total mine closure for an extended period of time.

As slope failure has a detrimental effect on both the operation and the environment, therefore, geological, geotechnical, operational, safety, social, economic, environmental and even legal factors play important roles in slope design. The number of factor to be considered gives a notion of the extent of ramifications that any type of failure can have and why it is imperative to prevent them.

Nowadays, the process of pit slope design formulation is relatively standard after many years of development in different mining operations around the globe. The fundamental basis for all slopes designs is the generation of a geotechnical model (Stacey, 2009) which is built from the development of the four sub models: Geological model, Structural model, Rock Mass model and Hydrogeological model.

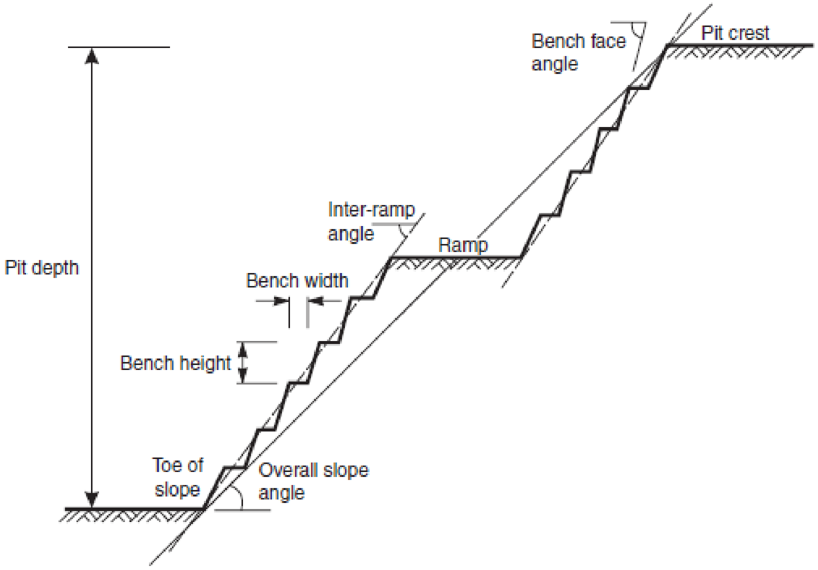


Figure 2.1: Typical open pit slope geometry (Wyllie & Mah, 2004).

The standard nature of open pit slope geometry allows the use of the results of surveys of stable and unstable slopes around the globe to develop guidelines for stable pit slope angles, relating them to the slope height and geology (Wyllie & Mah, 2004). This experience-based design allows for the first approach and should be used carefully since geological conditions vary from one mining operation to another.

2.2.1. Geotechnical Model

To construct the previously mentioned models it is important to define the geologic domains, the outcropping lithology and debris and the interactions that exist between them. Other geological characteristics that need to be accounted for are: the presence and direction of seepage, the structural sets on the slope, structures and deformations caused by gravity and the jointing conditions for the rock mass (Maffei et al., 2005).

One of the most important components of the geotechnical model is the structural model since its primary function is to deliver information about the orientation and distribution of the structures that have an influence on reducing the stability of pit slopes. This model includes descriptions of the major structures such as folds, faults and metamorphic structures as well of the fabric of the rock, considering minor folds and joints (Read, 2009).

The structural models have been studied using different tools: generally, at most mine sites Autocad^{TM} is used to map the structural geology of the rock mass, then the data DXF file is imported to software packages like Vulcan^{TM}, DataMine^{TM}, Gemcom^{TM} or MineSite^{TM} (Read, 2009). The main issue with this practice is that the resulting model does not take into account the geological, geotechnical or hydrogeological characteristics of the rock mass.

In recent years, new techniques, such as, Discrete Fracture Network modeling have been used to account for geological structures in rock mass numerical models which allows a better representation of the deformations and failure modes, as well as size distributions for fragmentation analyses. In hard rock mining, this approach is relevant since the main structures within the rock mass are one of the inputs needed to analyze the response of the rock mass in terms of deformations to different slope design parameters.

Another model, which acts as a critical input for the rock slope design, is the hydrogeological model. The most important parameter to be measured in this model is the in situ water pressure (Kliche, 2011). The importance of the presence of water in joints and pore spaces within a rock mass is that the pressure induced by the water reduces the effective stress and, consequently, reduces the shear strength of the rock mass (Read et al., 2013).

The seepage inside the rock mass can also be investigated to better estimate the stress-strain interactions (Maffei et al., 2005). However, the most preferred approach is the determination of the water pressure using piezometers on representative sites inside the rock mass (Kliche, 2011).

Once the geotechnical model has been constructed considering all the previous models described, the rock slope design can begin. In order to establish a proper design it is necessary to define sectors for the design, analyze the bench design to define the optimum inter-ramp slope and, subsequently, apply an economic analysis to this slope to determine the slope angle and evaluate the resulting overall slope to ensure its stability, modifying the design if necessary (Kliche, 2011).

2.2.2. Experience Based Design

There are many aspects that need to be considered to develop a geotechnical model for designing a slope. However, through experience many standard solutions have been provided over the years for the early stages (conceptual and pre-feasibility) of a mining slope design project (Lorig et al., 2009).

Among those preliminary solutions, the Design Charts can provide simple and practical guidelines for slope construction. For instance, the chart in Figure 2.2 defines the angle of the slope based on the rock mass quality and slope height (Haines & Terbrugge, 1991) while the chart in Figure 2.3 helps determining the slope angle given a certain height and Factor of Safety based on previous experience of different mining slopes (Hoek, 1970).

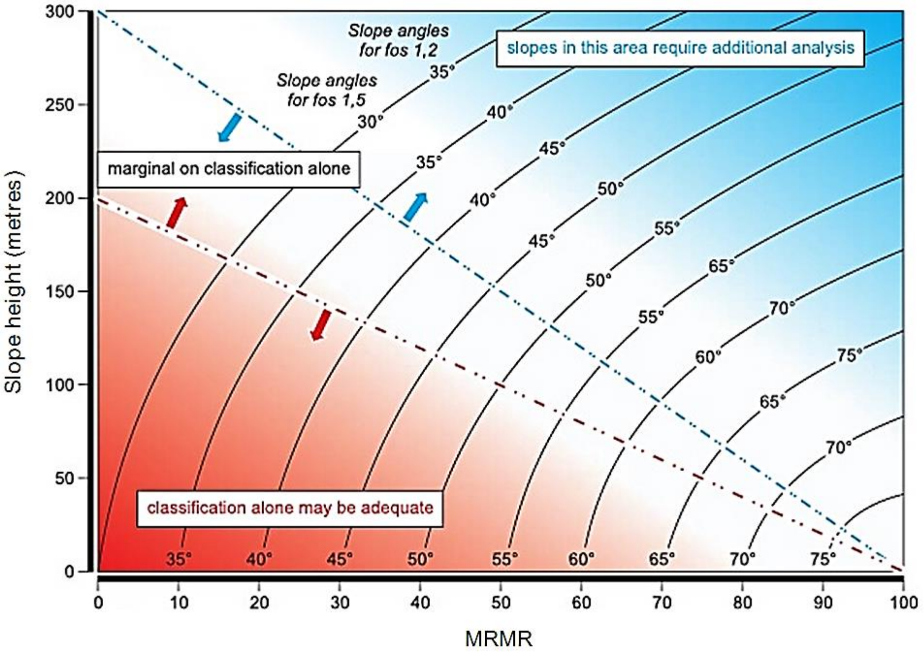


Figure 2.2: Chart for slope angle and slope height (Haines & Terbrugge, 1991)

The main drawback of the Empirical Design Charts is that, in most cases, the characteristics of a certain mine do not necessarily relate to those studied in the past and used to develop charts, which might prevent their use, as there is no correlation between the slope angle and its height. However, for similar rock types and strength, a reasonable correlation can be reached allowing the use of these design tools (Wyllie & Mah, 2004).

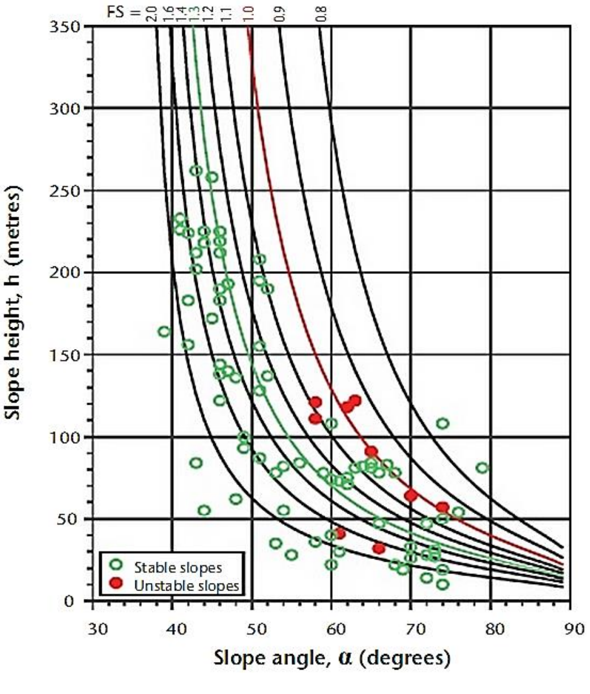


Figure 2.3: Chart of rock slope vs slope height for stable and unstable cases (Hoek, 1970)

2.2.3. Optimized Designs

According to Schellman et al. (2006), slope design can be optimized by steepening the slopes in zones where it is possible to do so. This is possible because, in an open pit mine, steepening of the walls can have a major impact on the economics of the project since such change in the geometry of the slopes allows for an increase in ore recovery and minimization of waste extraction (Stacey, 2009; Calderon & Tapia, 2006; Bye & Bell, 2001; Jefferies et al., 2008).

A steeper angle of the slopes is usually achieved by excavating double benches which exposes more ore to be extracted at a much lower cost than the stripping (Figure 2.4). Commonly, this steepening of the walls takes place during the last years of the project (Calderon & Tapia, 2006) or in walls that are near to reach their final pit state (Schellman et al., 2006).

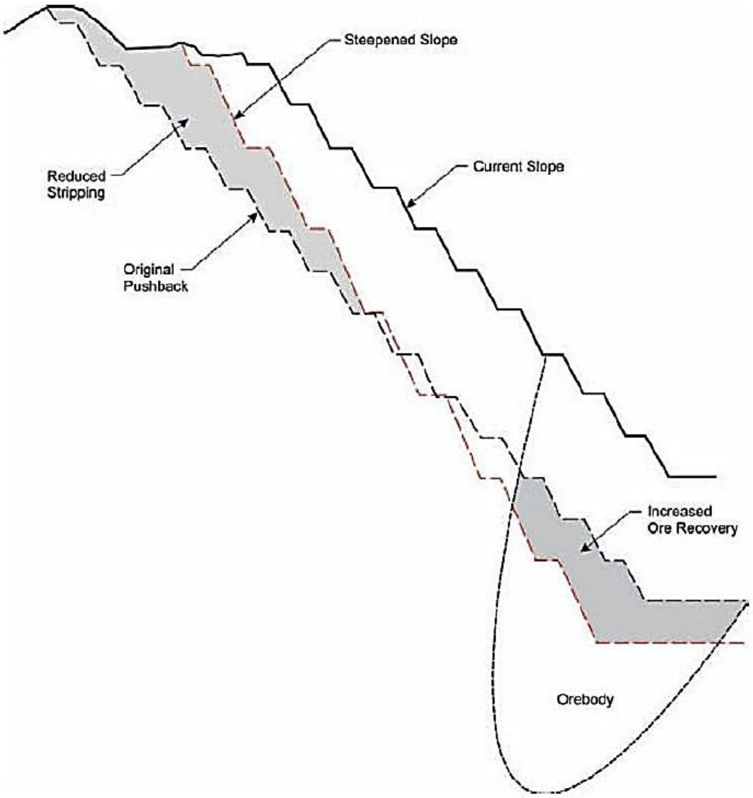


Figure 2.4: Potential impact of steeper slopes in open pit mines (Stacey, 2009)

However, those economic benefits are not the only consequences of steepening the slopes in an open pit mine. The modification of the wall's design reduces the stability of the slopes and, thus, increases the likelihood of a major slope failure (Steffen et al., 2008; Mphathiwa & Cawood, 2014).

To prevent slope failures, a balance between the economic gain and loss of stability due to steeper slopes need to be reached for which a continuous evaluation of the stability of the slopes is necessary to determine an acceptable slope angle (Jefferies et al., 2008) and to ensure that the critical geotechnical variables do not exceed the thresholds defined by the acceptance criteria for the design.

2.3. Slope Stability

The main concern of slope designers is whether the open pit walls will remain stable for the entire duration of the mine project. As rock masses are created by random geological processes, engineers find themselves facing anisotropic and highly variable construction conditions (Kliche, 2011). This variability makes it difficult to precisely assess the stability of slopes, which has led to a reliance on stability criteria that provide relations of the driving forces acting on the rock mass and its capacity to withstand them.

2.3.1. Acceptance Criteria

For a proposed slope design that has been established, stability evaluation is undertaken based on several criteria. The most used acceptance criteria in the industry is the Factor of Safety (FoS) defined as the ratio between the resisting strength of the rock mass (Capacity) and the loading or driving stresses of the system (Demand) (Wesseloo & Read, 2009).

$$\boldsymbol{FoS = \frac{Capacity}{Demand}} \tag{2.1}$$

In terms of mining operations, FoS in the range of 1.2–1.4 are generally considered as acceptable, meaning that the slope movement and even partial slope failures may occur during the life of the mine (Wyllie & Mah, 2004).

The FoS is a deterministic criterion and, therefore, to assess the inherent variability of the system other criteria has been established, for example, the Probability of Failure (PoF). This criterion is defined as the probability of the FoS being equal or less than 1, but that means that, as withj the previous criterion, the PoF only takes into account the resisting forces and the driving forces to assess the stability of a structure on rock.

$$\boldsymbol{PoF = P[FoS \leq 1]} \tag{2.2}$$

Over the years, other criteria, such as the Risk Model, have been formulated, but its focus is not to ensure the stability of the slope but rather to optimize the economic impact while ensuring safety in case of failure (Wesseloo & Read, 2009).

The previously mentioned criteria rely on deterministic values for the stresses and strength of the rock mass. Therefore, there exist a need for other acceptance and design criteria to be developed that take into account the inherent variability of the rock mass' properties (Kliche, 2011). New criteria are being developed for their use in the industry based on slope displacements estimated by numerical models (Jefferies et al., 2008).

The aforementioned models require updated information of the variables of the rock mass to successfully manage the uncertainty generated by the variability of the rock mass' properties. To acquire that type of information it is necessary to monitor variables, such as, displacement, crack development, stress and pore water pressure in a rock slope, to ensure the slope's stability for the duration of the open pit mining project.

2.3.2. Geotechnical Instrumentation

Generally, mining projects have anisotropic and highly variable construction conditions when structures have to be built in the rock mass, but as rock masses are created by random geological processes this variability is to be expected and it needs to be controlled. One of the solutions proposed to the problem of uncertainty is to assess the characteristics of rock masses by the use of geotechnical instruments.

Some observations permit to conclude that, nowadays, in the Chilean mining industry, geotechnical instrumentation in open pit slope projects is generally used for operational control of activated sectors and for monitoring of aggressive designs (Villarroel, 2014). However, in recent years there have been multiple works that attempt to encourage the use of geotechnical instrumentation in slope's construction projects, e.g. as a way to develop risk management models (Marr, 2013) or by reviewing study cases that were benefited by the instrumentation usage (Villarroel, 2014).

In terms of the applications, slope's behavior can be monitored by installing geotechnical instruments able to measure the physical changes in the soil and/or rock mass. A geotechnical instrument consists of a transducer, a data acquisition system or readout unit and a communication system between them (Dunnicliff, 1993; Eberhardt & Stead, 2011; Hawley et al., 2009). The transducer is the sensor that measures the physical change in the material and converts it into an output variable that can be used for analysis. This transformation can be carried out by different means depending on the type of transducer used.

Since slope failure involves large deformations of the rock mass, the most common type of tools and techniques used to monitor a mining slope are designed to account for the displacements. However, before this monitoring can take place, it's important to conduct a characterization of the ground, which can be done using techniques, suich as, Light Detection and Raging (LiDAR), digital photometry and surface geophysics, in order to identify the most relevant characteristic of the ground at the site of interest (Eberhardt & Stead, 2011).

The sensing technology developed to measure and monitor both surface and subsurface deformations is out of the scope of this research. However, a table summarizing several types of instruments and their applications is provided in Appendix E. For this thesis, the variable of interest is ground water, more accurately, pore water pressure in the rock mass. Therefore, the focus is on the pore water pressure influence on and importance to the slope's stability.

2.3.3. Groundwater effect on Slope Stability

The presence of water in open pit mines is a critical issue as it has the potential of creating adverse conditions for the operations. The main effect that the presence of groundwater has on open pit mines is that pore pressure in rock reduces the shear strength of the materials that make up the mine, thus having a negative effect on slope stability.

Shear strength (S) is generally expressed by the Coulomb equation where it is defined as a function of the normal stress in the surface of contact (σ), the pore water pressure in the rock mass (u), the friction angle of the material (ø) and the cohesion of the rock (c) (Brawner, 1982).

$$\boldsymbol{S} = (\boldsymbol{\sigma} - \boldsymbol{u}) \times \mathbf{tan}\, ø + \boldsymbol{c} \tag{ 2.3}$$

Equation (2.3) illustrates the reduction in strength in the rock mass as a direct result of the reduction of effective stress (σ') and/or the reduction in cohesion (Brawner, 1982). However, soil mechanics theory states that the behavior of the soil is controlled by the effective stress, which is generally expressed by the Terzaghi equation (Preene, 2012):

$$\boldsymbol{\sigma'} = \boldsymbol{\sigma} - \boldsymbol{u} \tag{ 2.4}$$

Therefore, from equation (2.4) it can be noted that pore water pressure has a direct influence on the shear strength of the rock mass. Reductions in groundwater pressure at constant normal stress increase the effective stress in the rock mass and, consequently, enhance the ability of the rock mass to resist shear, thus improving the slope's stability (Preene, 2012; Beale et al., 2013).

In addition, water can flow into the working area when mining is occurring below the water level, which will further reduce the overall efficiency of the operation by inundating accesses, wetting drill and blast holes and accelerating the wear of equipment (Beale, 2009). Consequently, seepage can increase mine costs in the areas of pit drainage, drilling and blasting, tire wear and equipment maintenance (Brawner, 1982).

2.4. Groundwater Control

Control measures are needed to keep the effects of groundwater to a minimum by dissipating pore water pressure in the slopes as part of the mining process (Beale et al., 2013) and, thus, maintaining stable working conditions. Preene (2012) defines groundwater control as a set of activities performed that allow the operation to continue when the works are being performed below groundwater level. Generally, in open pit mines groundwater level is expected to be found below 50 to 150 meters (Brawner, 1982).

A mine water management program should consider continuous evaluation of groundwater conditions and, if that evaluation shows excessive inflow into the pit or pore pressure behind slopes, then several measures to control water should be implemented. Dewatering programs such as (sub) horizontal drains, drainage tunnels, pumping wells and groundwater cut off systems (Beale et al., 2013; Brawner, 1982; Sperling et al., 1992) are the preferred propositions to successfully manage pore pressure as they are the most effective ways to manage the influx of water into open pit mines (Figure 2.5).

It is important to mention that the ground water pressure is the only parameter in the rock mass that can be readily modified to improve slope stability without changing the design (Read et al., 2013). In other words, drainage of the slope is the most effective method for stabilization of rock slopes (Wyllie & Mah, 2004).

However, an appropriate groundwater management will also allow an increase in the overall slope angle. For example, in a slope that was designed taking the Factor of Safety as its acceptance criterion a reduction of pore pressures by 6 to 10 meters allows an increase by 3 to 6 degrees in the slope angle while maintaining the same value of safety factor (Brawner, 1982).

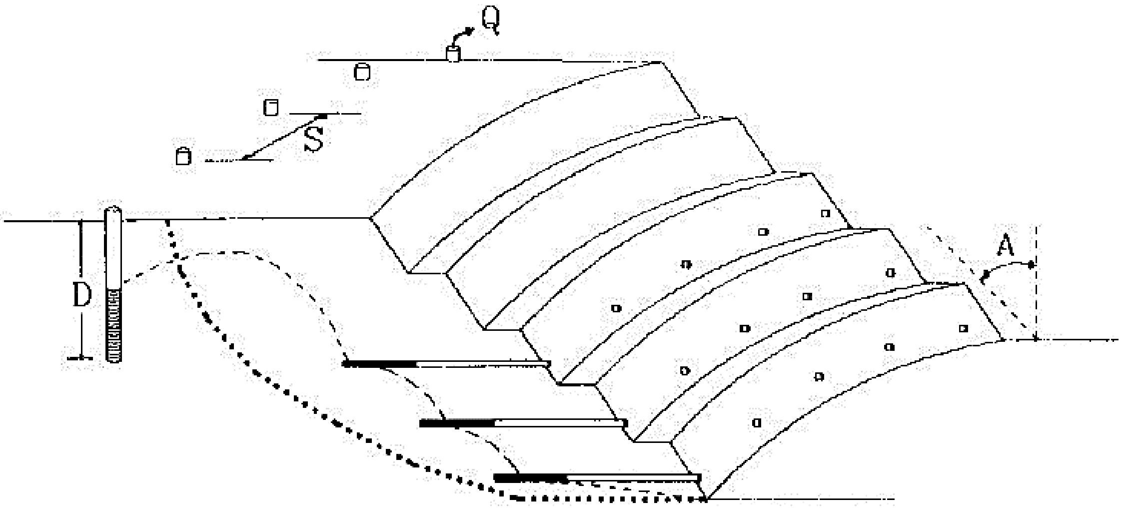


Figure 2.5: Horizontal drains and pumping wells in open pit mines (Sperling et al., 1992)

Considering all the potential benefits that an adequate management of pore water pressure can bring to the mining operation, groundwater monitoring becomes a highly important task to perform to evaluate the effectiveness of the drainage.

2.5. Applications of Groundwater Monitoring

Groundwater monitoring is essential to assess the performance of the slope design and the depressurization programs adopted by the geotechnical office. However, the need to continuously monitor pore water pressure is also important to cater for the uncertainty inherent in the construction of projects in rock (Dunnicliff et al., 2012).

Figure 2.6 illustrates how seepage of water into the open pit can produce forces that act in the direction of water. It is important to keep slopes monitored even when they appear to be dry, as for rock masses of low permeability the rate of evaporation may be higher than the rate of seepage, causing high stresses and pore pressure to develop because of seepage forces (Brawner, 1982).

Another important application of pore pressure measurement instruments consists of monitoring seasonal pressure gradients. During summer, water flows normally through the cracks of the rock mass; however, depending on the environmental conditions, it can freeze during the winter reducing the permeability of the medium. This can lead to a high build-up of pore water pressure behind the face of the slope which, in turn, would lead to a diminishing shear strength (Brawner, 1982).

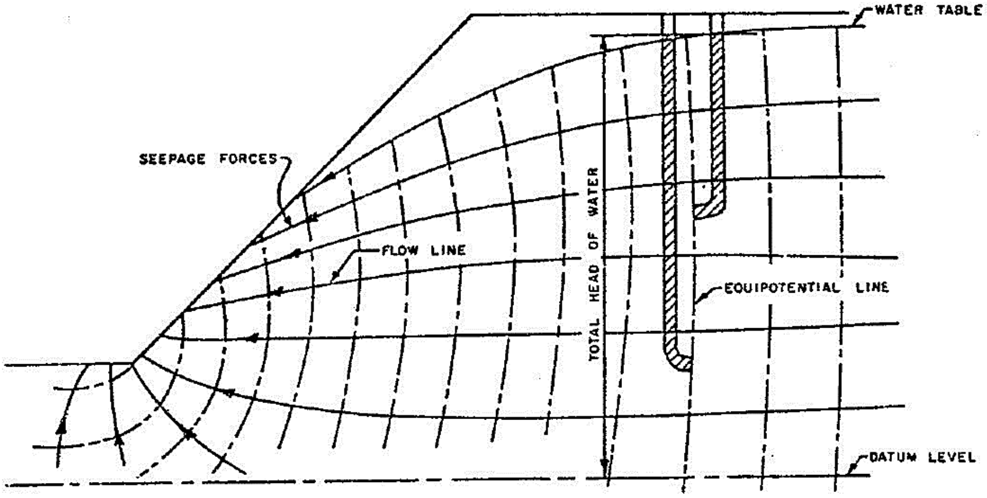


Figure 2.6: Flow net illustrating seepage forces in a slope (Brawner, 1982)

For groundwater control by dewatering to be effective, a thorough knowledge of the site's hydrogeological properties is required. In addition to the rock's permeability, porosity and density, charge and discharge rates of water within the rock mass as well as the location of the water table need to be characterized. This groundwater characterization can be performed using piezometers and groundwater flow testing (Eberhardt & Stead, 2011).

2.6. Instrumentation for Groundwater Monitoring

There are two main activities that should be undertaken to successfully monitor groundwater behavior in open pit mines. The first requires determining the elevation of the water table at the site to later check the variation in water level, especially after rain or thaw seasons (Brawner, 1982) while the second is the monitoring of pore water pressure behind the face of the slopes.

2.6.1. Water Table Monitoring

To define the characteristics of the groundwater, it is necessary to assess the location of the water table and then measure and monitor pore pressure. This will allow to monitor in-ground water flow patterns, water pressure and determine effective stresses to have an assessment of material strength and, finally, if measurements are made at different elevations, construct a site's piezometric profile (Dunnicliff, 2012).

2.6.1.1. Observation Wells

Observation wells are perforated pipes, typically 25-50[mm] diameter, installed in a filled borehole (diameter 70-250[mm]). The boreholes are usually filled with coarse sand or fine gravel. Sometimes a cement mortar surface seal is required to prevent overland flow to enter the borehole (Dunnicliff, 2012).

As any other geotechnical instrument, observation wells require a transducer able to assess the elevation of the water table. Generally, a probe is introduced through the pipe that sends an audible and visual sign to the surface when it comes into contact with the surface of the water.

Observations wells have very limited applications as they tend to create vertical connections between strata. This is a consequence that should be avoided and thus the use of observation wells is only recommended in continuous permeable ground where water pressure increases uniformly with depth (Dunnicliff, 2012). This type of instruments are rarely used to monitor groundwater pressure in hard rock environments (Wyllie & Mah, 2004).

Electric Dipmeter.

The most common transducer used in probes for identification of the water surface is the Electric Dipmeter. This type of transducer is made of stainless steel and consists of two electrodes with an insulating gap between them. The probe used to send the Electric Dipmeter into the hole is connected to a measuring tape that allows pinpointing the probe's position inside the borehole.

Inside the probe, there are conductors connected to an electronic circuit: when the tip of the probe comes in contact with the water inside the borehole, the circuit is completed and a signal is sent to the surface triggering a sound and light alarm in a high volume buzzer. Then, the depth of the water level is measured on the tape and registered (Encardio-rite Electronics, 2014).

2.6.1.2. Water Level monitoring techniques

There are different types of instruments that focus on monitoring variations in water level. These devices allow for continuous verification of the water table's location and identify interfaces between two types of fluids. The availability and operation ranges of these technologies depend on the alternatives in instruments offered by manufacturers (Dunnicliff, 2013).

Water level logger.

Water level loggers have been designed for remote environmental monitoring. They are used for long-term monitoring since, at regular intervals, a silicon sensor is used to measure pressure at the input and the result is written in the memory, thus recording changes in water level over time. The logger is housed in a tubular case of stainless steel vented to compensate for barometric pressure variation. The case can be lowered into 50[mm] diameter boreholes (Geotechnical Systems Australia, 2014).

Vibrating Wire Water Level Indicator.

This indicator measures changes in water level. It consists of a chamber, where a weight is suspended from a vibrating wire transducer. The weight hangs partially in the water and any changes in the water level of the chamber modify the buoyancy force acting on the weight and, thus, modify the tension and the resonant frequency of the vibrating wire (Roctest Group, 2014).

Ultrasound Level Meter

This type of instruments are designed to measure water level based on the response time of a sound wave. The working principle is divided in two phases: in the first, a series of sound waves are released into the well and, in the second phase, the echo is recorded, and the distance to the water is calculated by relating the speed of sound and the time that passes since the sound wave was sent until the echo was received.

There are several considerations to be aware of when implementing this technology. First, the speed of sound changes as the temperature varies (for variations of ±10°C in an environment of 20°C average, there is a speed of sound variation of 0.5%). Second, the pipe's diameter needs to be large enough to allow the wave's reflection preventing false echoes. Third, the distance between the reader and the water surface has to be short enough to allow the wave to reach the water and come back and to have sufficient measuring resolution (Enamorado et al., 2006).

Infrared Light Detector

These instruments possess an infrared light emitter, which sends a beam through a lens to a detector, which is able to differentiate between conductive and non-conductive fluids, for example, water and oil. Different tones are used for every liquid allowing the identification of the water level and the interface between different fluids.

Conductivity Meter

There are some instruments that measure conductivity to identify the water table. A probe that uses a four-electrode system that includes two arrays of a single electrode within a concentric electrode, reversing its polarity 2,000 times/second is used to detect the water level when the probe passes from a non-conductive medium (air) to a conductive medium (water).

2.6.2. Pore Pressure Monitoring

As stated in Section 2.2.3, the most important parameter of the groundwater within the rock mass is the pressure generated by its presence in discontinuities and pores as it is the water pressure and not the rate of flow that is responsible for the stability of slopes (Wyllie & Mah, 2004).

There are two possible methods to assess groundwater pressure in a rock mass using instrumentation. The first requires to deduct the water flow pattern from the conductivity of the ground and water sources while the second involves direct measurements of pore pressure using piezometers. With respect to the former, as the hydraulic conductivity for a determined type of rock can vary within 4 orders of magnitude as the spacing and aperture of joints changes, this method becomes highly unreliable compared to a direct piezometric measurement of water pressure (Wyllie & Mah, 2004).

Currently, while different types of instruments are used to measure pore pressure; the most common of them are known as piezometers, which are all the devices that, when sealed in a borehole, respond only to the groundwater pressure in the vicinity of the instruments and not to water pressure due to water from higher elevations (Dunnicliff, 2012). Piezometers are usually classified based on the type of transducer employed to register the variations in water pressure (Lomberg et al., 2013).

2.6.2.1. Piezometers

There are different types of piezometers that can be used for different applications e.g. open standpipe, pneumatic and vibrating wire piezometers can be used to register positive pore pressures in soil and hard rock applications while twin-tube and flushable piezometers are mostly used to instrument structures built in soil as they were designed to register pressure in embankment dams and negative pore pressures such as the ones that are developed by soils in dilatational behavior. In addition, multipoint piezometers can be used to measure groundwater pressure at several points in a drill hole to assess how pore pressure can change with depth and in different strata.

The type of piezometer to be used is not only determined by the type of measurement to be obtained but also the environmental conditions of the site. The type of piezometer influences its installation in the ground to ensure its optimal performance.

Standpipe Piezometers

An Open Standpipe Piezometer system is recognized by its simplicity and reliability. The most common configuration utilized for this type of piezometers consists of a plastic pipe installed in a borehole. The pipe has a perforated lower section that allows the water to enter the tube from within a filter element. When the flow of water ceases to enter the pipe, the height of the water column in the pipe is measured.

The filter element surrounding the end of the piezometer within the soil (called the “intake”) consists of a clean medium-coarse sand (Hanschke & Baird, 2001). This layer of filter material within the borehole is isolated from the rest of the excavation by a seal composed of compact pellets of bentonite located above the sand pack (Figure 2.7 (a)).

This method measures the elevation of the water surface in the standpipe above the piezometer’s tip, which corresponds to the piezometric head or water pressure in the column. In some cases, Standpipe piezometers can also incorporate pressure transducers in the filter zone to become remote-reading instruments to monitor groundwater pressure (Dunnicliff, 2012).

It is common to install several standpipe piezometers in a single borehole to measure groundwater pressure at different depths; this is a system known as a Multipoint Standpipe Piezometer. However, given the complex nature of the installation and, to achieve a robust design, many users prefer to install piezometers in different boreholes located on the same platform; this configuration normally guarantees a better resolution of vertical pressure heads than the installation on a single borehole (Read et al., 2013).

Because Open Standpipe Piezometers register the average pressure and do not allow for measurements at a single point, they are not widely used in the mining environments.

Diaphragm Piezometers

Instruments that register pressure by measuring the deformation of a diaphragm caused by the water entering the sensor are called diaphragm piezometers. Subsequently, the changes in the diaphragm position are captured by a transducer and are related to pressure values that indicate pore water pressure. These sensors vary in their construction depending on the type of technology used to make the measurements. This section discusses the different alternative diaphragm piezometers available in the market.

Pneumatic Piezometers

A pneumatic piezometer consists of a valve assembly with a flexible diaphragm attached to a pressure transducer and a pair of lines that connect the valve to the surface. Measurements are taken by pumping air into the valve by the inlet tube (supply line) until the air pressure exceeds the groundwater pressure acting on the diaphragm (Wyllie & Mah, 2004).

When the diaphragm is deformed and the valve opens causing the air to circulate into the outlet tube (return tube), the excess of air exits the system and, at the same time, the gas supply is shut off allowing the diaphragm to return to its original position. Finally, the pressure that is required to open the valve is measured by a Bourdon Tube or another Pressure Gauge (Dunnicliff, 2012).

Vibrating Wire Piezometers

Vibrating Wire (VW) Piezometers are highly accurate instruments, which are used to measure changes in groundwater pressure. This type of instrument comprises a metallic diaphragm that separates the measuring system of the instrument from the groundwater in the measuring point. A vibrating wire piezometer uses its transducer to convert groundwater pressure into a frequency signal that can be measured and analyzed.

The measuring system consists of a tensioned wire attached to the diaphragm and an electromagnetic coil located next to the wire. The operating principle of this transducer is based on the excitation of the wire by the coil, which forces the wire to vibrate at its natural frequency. Afterwards, any amount of deviation in the diaphragm caused by groundwater pressure will change the wire’s tension and, thus, change its natural vibration frequency.

The vibration of the wire generates a signal that is transmitted to a data logging device, where the signal of natural frequencies is processed and a calibration, usually based on a constant supplied by the manufacturer of the measuring instrument, takes place to determine and to display a reading of groundwater pressure.

Twin-Tube Hydraulic Piezometers

A twin-tube piezometer consists of a porous filter element buried in the soil that is connected to two plastic tubes with a pressure transducer located at the end of each tube. These pressure transducers can be Bourdon pressure gauges, U-tube manometers or electrical transducers.

The tubes are filled with de-aired water and are used to acquire pressure readings; the piezometric elevation can be determined by adding the pressure measurements in the gauge to the gauge elevation. If both tubes are completely filled with water then the readings in both gauges will be the same; however, if some air enters the system, it must be removed by flushing (Dunnicliff, 1993).

Twin-tube piezometers were developed for their installation in the foundations and fill of embankment damn as they are constructed for their long-term monitoring. Therefore, this technology is not considered further in this study as it is not currently used at the mine site, even though, there are some potential mining applications for this type of piezometers, e.g. monitoring pore pressure in tailing dams.

Advantages of this system are that the buried system does not have any moving or electrical components that could malfunction and that the sensors and circulation system are located on the surface allowing the system to be checked in an easy manner. However, this separation between the porous filter and the pressure transducer can have negative implications when measuring negative pore pressures since every meter of elevation between them reduces the range of pressures that can be measured by 10[kPa] (Ridley, 2003). The main issues presented by these devices are the presence of air within the piezometer and the reduction of range caused by the separation between the filter and the pressure sensor.

Suction Probes

Suction probes are piezometers preconditioned by applying a vacuum and then a high positive pressure inside the probe to drive out any air. This technique has major limitations for its use outside the laboratory since the preconditioning of the piezometers is impracticable in situ and the application of high water pressure can cause fracturing in the ground (Ridley, 2003).

Flushable Piezometers

Flushable piezometers appear as an alternative to the limitations of twin-tube piezometers and suction probes. Flushable piezometers work allowing the water to be extracted from inside the piezometer through the porous filter until the stress holding the water in the reservoir equals the suction of water in the soil. The porous filter has a blow-through of 1[bar] (100[kPa]), meaning that it can withstand up to that pressure before air enters the piezometer via diffusion, also the pressure sensor is located in a removable socket above the porous filter reducing the distance between the filter and the sensor. Finally, the socket have a system of tubes to flush water into the piezometer and remove air (Ridley et al., 2003).

Twin-tube piezometers, suction probes and flushable piezometers have been designed for their application in soil since their main objective is the measurement of negative pore pressures. Consequently, there will not be a further analysis of their characteristics in this thesis since they have limited applications in hard rock mining.

Fiber Optic Piezometers

Fiber optic piezometers are a recently developed technology and, as they are not a common practice within the industry, are beyond the scope of this research. However, the potential for this technology to be used regularly in mining applications in the future makes it relevant to be mentioned.

This type of piezometer consists of a capillary glass tube containing two partially mirrored optical fibers with a few microns of air gap between them. Light is emitted and confined to one of the fibers and propagates along it obtaining a back-reflected signal. Any disturbance in the filter alters the light, then the variations in the signal can be related to the changes in pore pressure.

Semiconductor Piezometers

Semiconductor Piezometers are manufactured with a semiconductor pressure sensor that use the 4-20 [mA] output method. Inside the piezometer, the water acts on a diaphragm where the semiconductor strain gauges bonded to the inside of the diaphragm sense the pressure and output a signal that is proportional to the pressure on the diaphragm. This type of pressure transducers use high output strain gauges that are fitted with Application-Specific Integrated Circuits (ASIC) to provide an output signal which is transmitted to the data-logger or readout device via a 4-20 [mA] loop circuit.

Semiconductor piezometers are highly reliable devices especially useful for low pore pressure measurements, e.g. 1-2 [kgf/cm^2] (98-196[kPa]). They are also used to measure static pore pressure where the readout system is incompatible with vibrating wire type transducers.

Piezoresistive Piezometers

A piezoresistive sensor is made of semiconductor materials whose resistivity depends on the density of charge carriers, applying some stress on the material changes the number and mobility of the charge carriers thus inducing great changes in the sensor's resistance (Dally et al., 1993).

The application of this technology in piezometers is possible by using resistors located in a ceramic diaphragm to form strain gauge arrays where a fixed excitation voltage is applied. The water pressure induces strain on the diaphragm that result in resistance changes in the array, different values of the resistors will cause an output signal proportional to the stress applied on the diaphragm i.e. the pore pressure.

There are some piezometers that measure pore pressure using the piezoelectric effect as opposed to the piezoresistive effect. In a piezoelectric material an applied strain creates a difference in electrical potential or voltage that is used as a signal to measure the magnitude of the pressure acting on the material. However, this type of piezometers are less common than piezometers that use piezoresistive materials (Dally et al., 1993).

2.7. Considerations for Piezometer Installation

2.7.1. Hydrodynamic Time-lag

Open standpipe piezometers are simple instruments and generally considered more reliable than other types of piezometers. The biggest advantage of their use is their ability to physically measure water level and allowing hydraulic testing and water chemistry sampling to take place (Read et al., 2013). However, their major limitation is the slow response to changes of piezometric head (Dunnicliff, 1993), which is known as hydrodynamic time-lag and is defined as the volume of water required by an instrument to register changes in pressure. In the case of standpipe piezometers, this time-lag is much greater than in diaphragm piezometers since a larger amount of water is required to acquire a measurement (Wyllie & Mah, 2004).

When a monitoring campaign has the objective to measure groundwater pressure, but the fluctuations in pressure are not expected to be significant, a technology with a short time-lag is preferred. In these cases, diaphragm piezometers should be used to monitor the response of the ground to a drainage campaign since the changes are too subtle to be measured by an open standpipe piezometer (Wyllie & Mah, 2004).

For various diaphragm piezometers, the time-lag ranges from seconds to several minutes before the device stabilizes after a pressure change occurs.

Electrical piezometers have a significantly smaller time-lag than pneumatic, hydraulic and flushable sensors as the volume of water required to actually obtain a measurement by an electric piezometer is extremely small. Therefore, electrical sensors have a time advantage over pneumatic sensors in terms of their ability to measure subtle pressure changes that occur in the ground (Mikkelsen & Green, 2003).

2.7.2. Grouting

Diaphragm piezometers require a small volume of water to activate the sensor's diaphragm. This characteristic allows for these devices to be installed with a fully grouted method that uses a cement-bentonite grout to backfill the entire hole (Figure 2.7 (b)) instead of using a sand pack around the piezometer tip and a bentonite seal layer above (Figure 2.7 (a)) which is much more complex and time-consuming (Mikkelsen & Green, 2003).

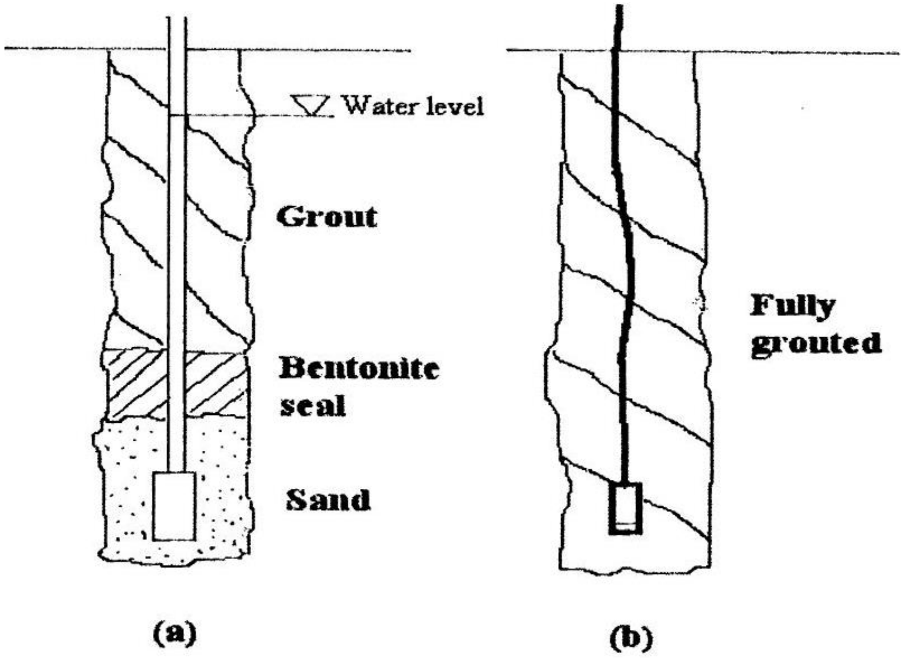


Figure 2.7: Installation diagram: (a) Standpipe piezometer (b) diaphragm piezometer (Mikkelsen & Green, 2003)

The biggest concern related to the fully grouted method is the permeability of the grouting mix. A low permeability can cause the tip to be completely isolated preventing the instrument from taking measurements, while a high permeability can create vertical connection between strata altering the readings. Several studies have been conducted to determine the proper permeability of the grouting mix; some authors recommend that it should have a permeability 2 to 3 orders of magnitude greater than the ground (Vaughan, 1969; Contreras et al., 2008) while others recommend the use of a grout with lower permeability (Gray & Neels, 2015).

They all concur, however, that the grout must have the same stress-strain behavior than the ground and a similar permeability. Mikkelsen & Green (2003) developed a chart, widely accepted in the industry to determine the ratio of grout mix (see Figure 5.3).

Experience has shown that an appropriate formulation of the cement-bentonite grout used for the fully grouted method ensures a high void ratio and a low permeability allowing transmission of low volumes of water to the instrument in a short radial distance while preventing vertical flow (Wyllie & Mah, 2004). That behavior within the grouting is because radial pressure gradients are usually of the order of magnitude greater than vertical pressure gradients, thus controlling piezometer response (Mikkelsen & Green, 2003).

2.7.3. Multi-point Measurements

Aside from the issue of grouting, one of the main concerns in using electrical piezometer systems is the low number of measurement points that can be attained when implementing a multi-point measurement campaign. Since it is common to find perched water tables in bedrock it is recommended to install more than one device per hole, at least two or three (Brawner, 1982). However, to develop an accurate piezometric profile a higher number of data points is required.

A string of VW piezometers can be installed in a single borehole; however, generally, only two to five sensors can be installed in the same hole, with up to six or more instruments in HQ sized (96 mm) or Reverse Circulation (RC) boreholes. This limitation is due to technical issues as the infrastructure required for installation (cables, tremie pipes, and other matters) covers much of the available area of the borehole (Read et al., 2013). To overcome this limitation, emergent technologies are being developed as an alternative to enable multi-point measurements of pore water pressure.

In recent years, Networked Smart Markers (NSMs), devices based on the Smart Marker technology developed to monitor mineral flow and ore recovery in caving mines, were introduced to the market. These devices are equipped with an antenna for data transmission via radio frequency, which allows them to communicate wirelessly between sensors by transferring the signal through rock for a distance of up to 5 meters (Steffen & Kuiper, 2014).

In 2015, the NSMs were installed at an open pit mine to determine their applicability to monitor subsurface deformations behind the slope’s wall (Widzyk-Capehart et al., 2015). They have been proven successful in transmitting data wirelessly through the rock mass. Currently, electronic pore pressure sensors are being implemented within the Networked Smart Markers. The device is being designed to be covered by a mesh screening to act as a porous filter and a piezoelectric transducer to perform the actual measurements (Widzyk-Capehart et al., 2016).

This emergent technology is studied at depth in Chapter 3. The advances in the development of these devices represent a step forward to perform multi-point pore water pressure measurements as; theoretically, there are no technical limitations to the number of measuring points that can be provided in a single hole, aside from the limit given by the depth of the borehole and the length of the instruments.

2.7.4. Design of an Instrumentation Program

Geotechnical monitoring is much more than merely selecting the adequate instrument to perform a specific type of measurement. As McKenna (2006) states: “Purchasing and installing an instrument is just the start”. Designing an instrumentation campaign is a thorough and comprehensive engineering process that defines the objectives behind the monitoring and the integration of the instrumentation process with the mining project (Dunnicliff et al., 2012).

To design a program, it is necessary to consider and understand the life cycle of the instruments. It should be noted that the cost of instrumentation is not limited to the devices themselves but it should also consider installation, datalogging, data acquisition throughout the life of the instruments and, eventually, a replacement, as approximately 20% of the instruments need to be replaced every 10 years (McKenna, 2006).

Chapters 3, 4 and 5 focus on the emergent monitoring technologies, e.g. the Networked Smart Markers, and how the new and the already established sensing devices can be applied in an integral fashion within the mine plan.

CHAPTER 3: INSTRUMENTATION TRIAL

3.1. Networked Smart Marker Technology

Networked Smart Markers (NSM) are novel electronic devices consisting of battery-operated radio transceivers developed by Elexon Electronics. The electronic components of these instruments are housed by a plastic casing 34.5[cm] long and 6.35[cm] diameter in their widest section (Figure 3.1).

Figure 3.1: Networked Smart Marker

These NSMs are instruments developed from the original Smart Markers which were conceived for their application in underground caving mines as a tool to track ore flow and ore recovery. Smart Markers have been installed in the ore body with their original locations registered and then retrieved in the draw points by LHDs. Subsequently, several Reader stations placed alongside the hauling path identified the Markers in the LHD's bucket allowing to infer rock flow in the mine.

The main difference between the Networked Smart Markers compared to the Smart Markers is the formers ability to use a radiofrequency signal to establish communication between two neighboring NSMs at a distance not exceeding 5 meters. This improvement provided a possibility to apply this technology in open pit mines for geotechnical monitoring. At this stage of development, the radio signal strength between Markers can be registered regularly; variations in the measured signal strength indicate movement of the NSMs, which can be related to rock mass subsurface deformation.

The wireless communication achieved between Markers can be used to transmit any type of data and is not limited only to radio signal strength. This feature will allow for new sensors to be integrated inside the NSMs. Particularly, the next stage of development considers the installation of pore pressure sensors within the Markers, which will allow multipoint measurements in a single borehole without the restriction that are inherent to other available technologies, as discussed in Section 2.7.3.

The first trial installation of a Networked Smart Marker system in an open pit mine environment was carried out to assess the communication capabilities of these instruments, proving they can be applied to monitor movement of rock mass.

3.2. Trial Setup

The instrumentation trial for the NSM system and associated infrastructure was conducted in a mine site with an instrumented slope. The selected site was Mina Sur mine, property of Codelco, located in the Antofagasta Region in Chile. The installation of NSMs in the slope was part of the construction of a 52[m] high and nearly 90° angle gravel slope to be excavated in four stages.

Every stage of the construction involved the extraction of a 13[m] high bench, the novelty of the process was in the excavation of the last two benches using remotely controlled equipment as a safety measure. The high vertical slope was instrumented using established technology: inclinometers, geophones, prisms, and radars. Subsequently, the NSMs were installed, as shown in Figure 3.2.

The trial was performed to: (1) determine if it is feasible to construct this type of slopes in the cemented gravel material present on top of the open pit mines' slopes in the area, as an inquiry of the mine personnel, and (2) assess the communication capabilities and performance of the NSM system in an open pit operational mining environment.

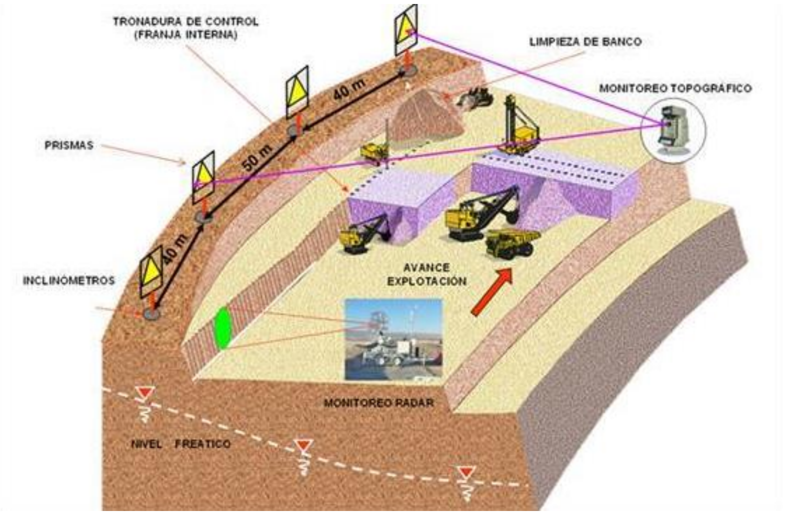


Figure 3.2: Mina Sur's slope monitoring early trial's diagram

3.3. Characteristics of the Trial Site

The predominant geological unit at the site where the trial installation was carried out corresponds to a consolidated gravel with no mayor structures that cut the zone where the slope is being constructed. Studies at the zone showed that the phreatic level is located below the maximum depth of the slope; groundwater was not a variable to be measured during this trial.

The characteristics of the site simplified the installation and testing of the NSM system, allowing the trial to focus exclusively on the communication capabilities of the devices through the rock without the interference of other variables.

3.4. NSM's Trial Installation in Open Pit

The NSM system and associated infrastructure's installation in an open pit mine under operation was intended to demonstrate that this technology can be applied in open pit environment and that wireless signal transmission through the rock mass is possible using NSMs.

3.4.1. Preparation

For the trial at Mina Sur, first generation prototype NSMs were used, which required testing aside from the ones performed during their manufacturing process, those tests were performed at the Advanced Mining Technology Centre (AMTC) facilities at the University of Chile, Santiago.

Communication tests confirmed that the NSMs shipped to AMTC were activated and functioning. Prior to the field trial, the NSMs were arranged in sequence and tied together with two ropes on diametrically opposed sides of each marker to build the arrays that would be lowered inside the boreholes to test the strength of the rope and the stability of the assembly (Figure 3.3).

Figure 3.3: NSM array hanging from the stairs to test rope's resistance

Since the maximum communication distance for two neighbouring NSMs was assumed 5 meters, the Markers in the arrays were placed two meters apart from each other to ensure communication redundancy. The ropes used were chosen based on their capacity to withstand 1.5 times the weight of 22 NSMs in one array for a 53[m] deep borehole. Cotton ropes were used to ensure that, once the NSMs were placed within the borehole, the ropes could be cut due to the roughness of the medium, allowing the Markers to move along with the rock mass.

3.4.2. Installation

The trial site had two boreholes of 53[m] depth drilled to be instrumented using the NSM technology. Those holes were located five meters behind the crest of the slope and 47 meter away from each other. The site was also instrumented with boreholes for Probe Inclinometer 5 meters away from each NSM hole and a Geophone drill hole (Figure 3.4).

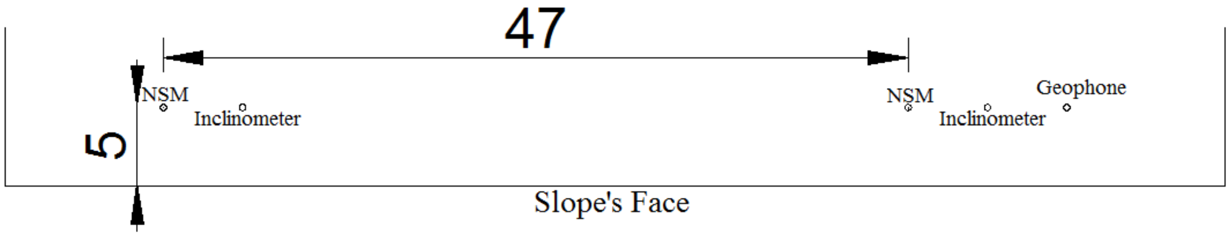


Figure 3.4: Floor Plan of the Instrumented Slope

The NSM arrays were lowered into the boreholes using a trestle system to keep the ropes from tangling (Figure 3.5). After the instruments were in place, a mix of sand and cement was poured from the surface to seal the holes (Figure 3.6). Once the grouting was completed, a NSM antenna was placed two meters above the uppermost Marker in each borehole and one meter below the ground surface.

Figure 3.5: Networked Smart Marker installation

Figure 3.6: Grouting process

NSM antennas were modified markers (Figure 3.7) that have a cable connecting them directly to the data acquisition system i.e. Reader station. The trial setup had an antenna placed in each sealed borehole and both holes were connected to a Splitter-Box located 50 meters away from the closest borehole. The Splitter-Box was used to provide a link between the data acquisition system and both arrays simultaneously.

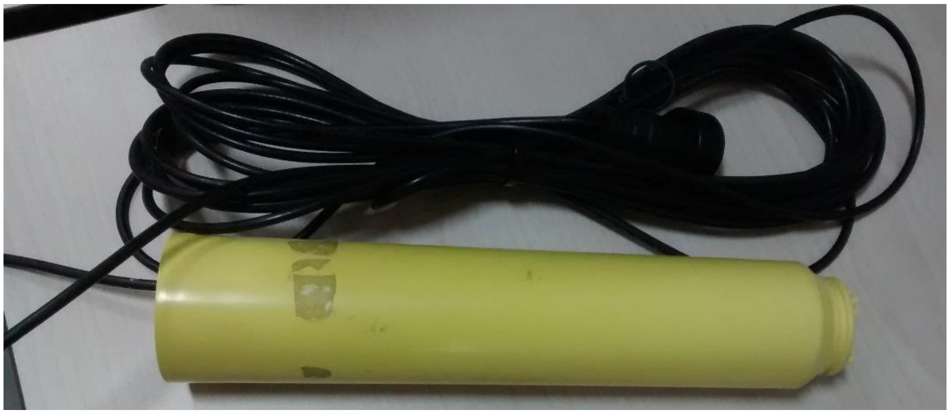


Figure 3.7: NSM Antenna

The Reader Station was a solar-powered autonomous equipment, installed on a trolley and placed approximately 100 meters away from the Splitter-Box (Figure 3.8). It was used to issue commands to the NSMs and gather all data that the arrays transmitted. The station was located in an accessible, safe, and stable zone of the mine since remote access to the Reader Station was not a feature in this version of the system, all data from NSMs was gathered at a set frequency and stored on the Reader until manually retrieved.

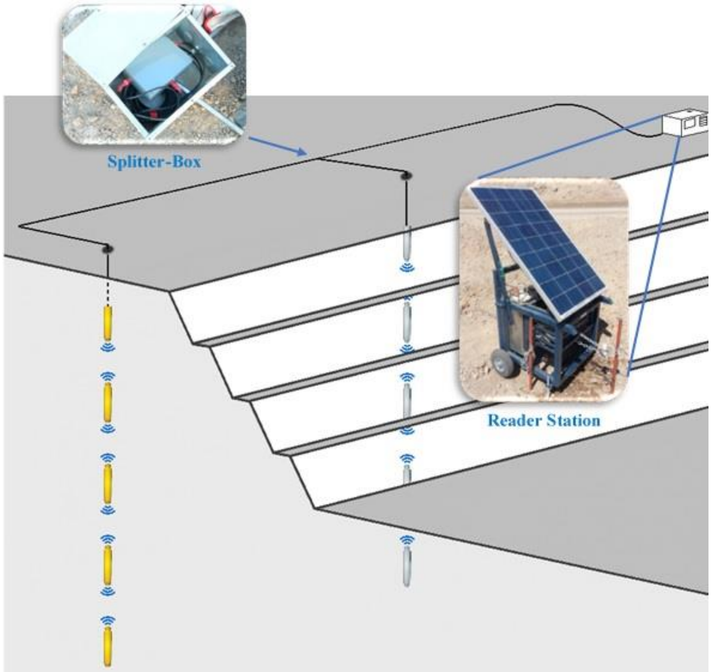


Figure 3.8: NSM Installation diagram

In summary, NSM installation involved using a trestle to lower arrays of Markers into two 53[m] deep boreholes and to hold them in position until the holes were grouted. Subsequently, the boreholes were sealed using a cement-sand-water mix poured from the surface. Before the grout became dry, the antennas were placed at the top of each borehole, one meter below the collar. The antennas had cables that were connected to a Splitter-Box, which connected to the Reader station. The cable section between the Splitter-Box and the Reader was buried in a shallow ditch for protection.

3.5. Performance of the System in Operation

The NSM system and associated infrastructure performed well for about 6 weeks. During that time, several log files containing data concerning signal strength between Markers were acquired periodically. Figure 3.9 shows a measurement of signal strength and connectivity between NSMs in one of the instrumented boreholes.

In Figure 3.9, the white boxes marked with the numbers 2.2 to 2.23 represent the 22 NSMs installed inside the drill hole from the surface to the bottom; the marker 2.1 is not listed as it is the representation of the Reader Station in the system. The coloured boxes indicate the measured signal strength between the Markers; some NSMs demonstrated the ability to detect signals up to the fourth NSM in each direction (up and down). Coloured boxes also represent signal strength based on the colour: green boxes indicate high signal strength links, yellow boxes an average signal strength, and orange boxes low signal strength.

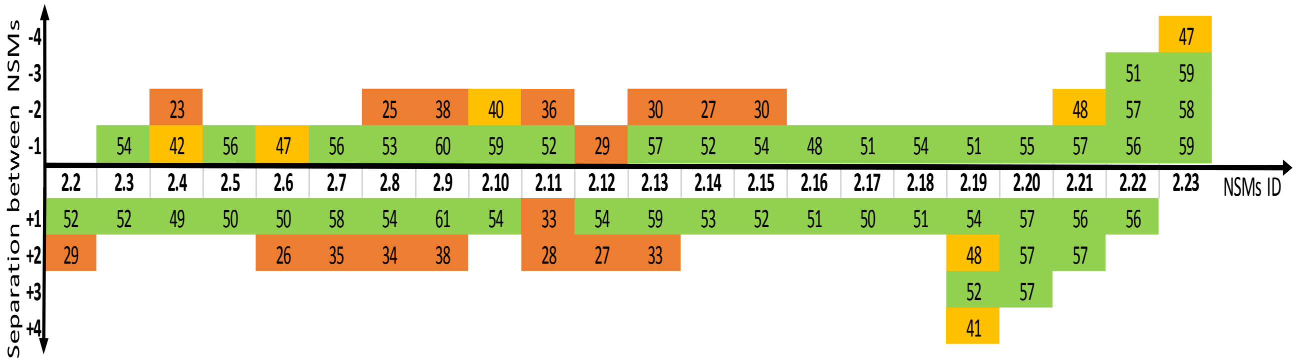


Figure 3.9: NSM's connectivity

From the data displayed in Figure 3.9, it is clear that several NSMs were unable to detect more than one other marker in any direction, which showed that communication redundancy was not always achieved. In addition, the devices located at the bottom of the borehole had higher signal strength readings than those at the topmost section of the borehole and were more likely to establish connections with more than one NSM.

After 6 weeks of continuous operation, the Reader suddenly stopped receiving new data. Several visits to the trial site were made during the following two months to assess the system and attempts were made to restore communication between the Reader and the boreholes.

3.5.1. System Evaluation

During the visits to the trial site, several experiments were conducted to determine why the system stopped communicating. Through visual inspections and conductivity tests, it was discovered that the main feed line between the Reader Station and the Splitter-Box had been cut, being one of the causes for the loss of communication.

Therefore, several cables were disconnected and re-installed inside galvanized conduit ducts, the Splitter Box was protected inside a metal box and the motherboard inside the Reader was replaced by an updated version. With those improvements, communication in the system was restored.

However, after the improvements were made, communication was again lost to both boreholes; the issues of poor signal strength between Markers at a distance over 2 meters and Markers losing communication were addressed. Through laboratory testing using spare NSMs from the same production batch, a number of possible causes for lost communications were identified, including the following:

3.5.1.1. Poor 2-Marker distance communication

- Poor Marker Communication Range.
    - Difference in performance was observed between individual Markers.

    - It was noted that the performance of the Marker's antennas is randomly distributed, which may had caused that some NSMs had a shorter communication range.
    - Out-of-spec antenna tuning produced by a faulty production process.
    - This is a likely possibility and would have a strong contribution on the overall performance of the markers.
- Atmospheric noise penetrating the bench.
    - The NSMs located at the bottom of the boreholes may had been more successful in communicating with more than one marker since they receive less background radiofrequency atmospheric noise.
    - Markers receiving higher background noise would have reduced range compared to others.
    - However, this was thought to be unlikely since Markers were tested on the surface without showing significant reductions in range; this factor would have only a medium contribution to the reduced communication.
- Poor Radiofrequency transmission properties of the earth/ground.
    - The ground and/or grout composition might have changed significantly over the length of the borehole.
    - This was thought to be highly unlikely since it was known that the ground properties did not change drastically over the length of the instrumented slope.

3.5.1.2. Markers becoming non-contactable

- Marker's Software Issues.
    - A firmware fault was discovered that could have possibly cause a Marker to stay in an un-contactable state.
    - Since the fault in the firmware was discovered this is factor was considered a strong contributor to the loss of communication between Markers.
- Marker's Battery Issues.
    - It was possible, however unlikely, for NSM's batteries to have drained during shipment since they were shipped in a "pre-activated" state to simplify the installation procedure.

    - It might have been a strong contributor, but there were no NSMs that showed drained batteries.

- Failed/Locked-up Markers.

    - Some Markers may have failed after shipment.

    - This factor may have possibly contributed since a bug in the software was identified that could have caused failure.

- Broken installation rope.

    - Possibly the rope broke during the installation of the Markers causing some NSMs to be left out of range.

    - This was deemed possible but unlikely since the rope breaking during installation would have been noticed by the work team during grouting.

- Elongated installation rope.

    - Rope stretch may have caused that the planned distance spacing of the markers had increased. That way, the distance from one Marker to the next NSM in the chain would have exceeded the maximum communication range.

    - This is very likely and would have a strong contribution in the communication capabilities of the system.

3.5.2. System Upgrades

After the main issues in the system's performance were identified several improvements were made to all the components to avoid these problems to arise in future implementations. The upgrades made to the system consisted of installing protection on cables and the Splitter-Box to avoid any damage that could be caused by the surrounding mining operation and improvements on each component of the system itself to achieve a better performance.

The experience acquired during the first implementation of the NSMs and associated infrastructure led to several upgrades made to improve the overall performance of the system. Table 3.1 summarizes the most important improvements made to the system considering those issues that were deemed of high importance after the evaluation.

It was also concluded that the grouting process was one of the critical tasks in the installation of Markers and it must be performed carefully to ensure its success. During this installation, the grouting started by filling the hole from the bottom using a pipe, but the weight of the grout mix prevented the pipe to be lifted from the bottom to continue the process, which forced the grouting to be completed by pouring the mix from the top of the hole. The installation procedure was then modified to ensure that proper tools and equipment were used to pump the grout to the holes.

Table 3.1: System Improvements

Identified Issues	**Improvements**
NSM's inner antenna tuning Out-Of-Specification that may result in poor communication range.	Manufacturing process included automatic testing for NSM´s antenna tuning.
Software's bug causing locked-up individual Markers.	Second-generation software resolved bugs improving reliability.
Manual access to Reader required personnel on the trial site, which placed additional workload and security issues.	Remote access to Reader capabilities using a GSM modem was installed enabling continuous remote data acquisition.
Main feed line being damaged. Antenna cabling and Splitter-Box susceptible to physical impact damages.	All cables were protected using galvanized conduits. Splitter-box was protected using a metal box.
NSM's communication testing prior to grouting.	NSMs tested on the surface. Marker's communication ranges tested inside the borehole before grouting it.

3.6. Second NSM's Trial Installation in Open Pit

A second mine site trial was prepared to: (1) test the improvements made to the installation procedures, the devices and the overall NSM system and (2) fulfil the objectives of the original trial. For the second trial two boreholes were instrumented using NSMs. However, unlike the previous trial where both holes were of the same depth, for this installation the first borehole was 10[m] deep while the second was 40[m] deep.

The boreholes were drilled in the same slope as the previous ones, but this time they were drilled 10 meters behind the crest of the slope. The 10-meter hole was located behind the 53[m] borehole that was closer to the Splitter Box in the first installation while the 40-meter hole was placed 10 meters away from the 10-meter drill hole (Figure 3.10).

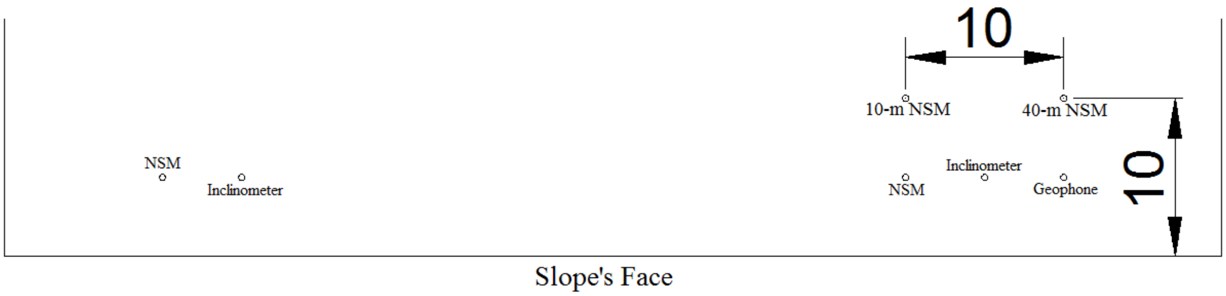


Figure 3.10: Floor Plan of the second trial installation

Two different depths of boreholes allowed performing specific tests. The 10-meter borehole was equipped with five NSMs and was used to test the installation, before the deeper hole was instrumented, and assess the effect of the grouting in the final setup of the Markers. The 40-meter hole had 35 NSMs and was only grouted after confirming that the installation in the 10-meter hole was successful.

3.6.1. Updated Installation Procedure

Several changes were made from the first trial for NSM installation; the most important were as follows:

- The Markers in a single array were placed 1-meter apart from each other to ensure that the communication capabilities to more than one NSM in each direction were not lost.
- The NSMs were tied together using a climbing kernmantle rope instead of a cotton rope.
    - This type of rope was capable of holding 3.5 time the weight of 35 connected NSMs.
    - It was used to prevent an excessive elongation of the rope due to weight of the Markers.
- The cables that came from both boreholes to the Splitter Box and the main feed line to the Reader Station were protected with galvanized conduit ducts.
- The NSMs were left hanging inside the boreholes for one week before applying the grout.
    - Tests on signal strength were performed to detect any possible communication loss and top make changes to the installation before the borehole was sealed.
- An improved grouting procedure was used, the sand-cement mix was pumped into the hole filling it from the bottom to the top. This grouting process was used to:
    - Avoid additional weight on the NSMs and the rope.
    - Minimise disturbances to the NSMs fixed positions.
    - Ensure an even filling of the boreholes avoiding leaving any air gaps.

After the installation in both boreholes was completed, the communication between NSMs inside the holes was tested from the Reader Station showing that wireless links were successfully established with both boreholes.

New data was gathered for the duration of the trial until December 2015 at fixed time intervals showing high quality signal strength between all NSMs in both holes. This proved that the shortcomings of the first installation were successfully addressed and that wireless data transmission through rock using the NSM technology in open pits was possible.

3.7. Development of Pore Pressure Measurement Capabilities

Current stages of development include a new version of the NSM technology, called ENSM (Enhanced Networked Smart Markers) where electronic pore pressure sensors and accelerometers are being implemented inside the Networked Smart Markers assembly.

The exterior of the pore pressure sensor is being designed considering a mesh screening that will cover the sensor, protecting it from getting clogged up by grout or other fines but allowing the water to pass through it.

The pore pressure sensor to be implemented inside the Marker is a piezoelectric transducer with an accuracy of 0.1% of full scale. This piezoelectric transducer can be used in ranges up to 30 bar and can stand an overpressure of at least 300%. For ranges above 30 bar the transducer to be installed is a thin-film Wheatstone measuring bridge with an accuracy between 0.15-0.2 percent of full scale and can stand an overpressure of at least 200%.

The incorporation of pore pressure monitoring capabilities into the Networked Smart Markers opens new possibilities to perform extensive multi-point measurements. Currently, the application of multi-level Vibrating Wire piezometers has been pioneered by the mining industry. However, technical constraints and the diameter of the instrumented boreholes limit the number of sensors that can be installed in a single borehole; two to five sensors are typically placed inside a hole but more than six can be installed in HQ or RC holes.

In contrast, the Enhanced NSMs will open up a possibility for the installation of a large number of pore pressure sensors in a single borehole since the wireless data transmission capabilities of those devices allow for any number of NSMs to be installed as long as the maximum communication distance is not surpassed. This new capabilities may provide better understanding of the development of vertical pore pressures gradients to define piezometric profiles around the open pit walls.

Based on the up-to-date developments, it is reasonable to assume that the Enhanced NSMs may be implemented in open pit mines in the near future to perform measurements on subsurface deformation and pore water pressure behind slopes, simultaneously. The validation trial of the ENSM against the traditional pore pressure monitoring instruments such as piezometers would have to underpin any field trial in the near future and further development and application of the ENSM in open pit mines.

CHAPTER 4: DEVELOPMENT OF A MINE PLAN

4.1. Introduction

The work described in this chapter had as its primary objective, the development of a mine plan for a standard open pit project to be used as a base to study the incorporation of groundwater monitoring in the early development stages of an open pit mine. To achieve this objective, several tools were used including mine planning and mine design softwares.

The work undertaken involved developing a mine plan for a theoretical open pit mine that took into account economic and processing issues as well as establishment of pushback or phase's geometries and their extraction rates to ensure stability. Subsequently, the proposed mine plan and geometry were optimized, changing the original slope angles to increase the revenue of the project yet, at the same time, creating some uncertainty regarding the stability of the slopes.

4.2. Mine Planning

The first step in the process of coupling instrumentation campaigns with the design of the mine is to establish a mine plan for the life of the mine. A theoretical mine was developed, since the actual focus of the research is the inclusion of instrumentation as an integral part of the mine design and not its application to the actual conditions. Therefore, the mine plan and design was not considered in details. For this reason the theoretical mine operation defined was constructed almost exclusively from the results obtained using the software DeepMine, developed by BOAMine.

The main reason behind the selection of DeepMine as the software used to perform the analyses in this research is that it has a powerful calculation engine, based on dynamic programing, which allows the software to quickly generate different mine plans based on the block model of an ore deposit (BOAMine SpA, 2015). DeepMine's high calculation speed allows the planner to determine the optimum plan for a mine by performing successive iterations in the software as the operational and economic constraints of the model change.

DeepMine is a software used to help develop strategic mine plans by evaluating and finding the best strategy to extract a mineral deposit, starting from the block model, without the need of pre-designed phases. The program creates a plan based on the information provided in five separate elements that encapsulate all the characteristics of the mine plan. These elements are:

- A GeoModel that provides Block Model characteristics,
- A Mining Environment with the characteristics of the mine and plants operation,
- A Pit Collection where the nested pits are calculated,
- An Economic Environment where the market conditions are listed, and
- A Mine Plan solver that defines the characteristics of the extraction sequence.

There are no Mining Environments in this project...

There are no Pit Collections in this project...

There are no Economic Environments in this project

To create a Mine Plan, it is required to have a GeoModel, a Mining Enviornment, a Pit Collection and an Economic Environment.

Figure 4.1: DeepMine's initial screen with its five elements to create a mine plan

The following sections describe the parameters considered and values given to every element used to construct the mine plan for the theoretical mine.

4.2.1. Block Model Characteristics

To develop the plan, the default block model loaded in DeepMine. The most important characteristics of this model were:

- The model consisted of 69,984 blocks,
- The dimension of each block were 30x30x15[m],
- The entire model was 1,620[m] long, 1,620[m] wide with 360[m] of elevation,
- The average Copper grade was 0.14%,
- The maximum Copper grade was 1.72% and
- The blocks were classified by their ore type into Oxide Ore, Transition Ore, Sulfide Ore or Waste.

The default block model included in the software could not be modified to include rock mass strength variables. However, the steepness of the final pit wall at each side of the pit was assumed to change in response to a difference in the rock mass quality. The north and east walls were considered to be built on a high-competence region with a steep global angle of 50°, while the South and West Walls were embedded in a poor quality zone of the rock mass which was represented by a lower angle of 40°.

4.2.2. Mining Environment

DeepMine recognizes as a Mining Environment a set of parameters related to mining and operational conditions under which the mine plans are created. It is in this section where all the relevant information about extraction restrictions and ore processing in the operation are defined.

The main assumptions made for defining the Mining Environment were:

- The model must ensure that the mine plan lasts at least 15 years,
- Most of the material extracted from the mine is sent to a processing plant as its primary destination,
- The re-handled material in the plant must be at a maximum the 20% of its total capacity.

To determine the maximum mine capacity for every year of operation required to fulfill the assumption of a minimum life of mine, an entire mine plan was constructed and several scenarios were run to finally set the mine capacity to 18,000,000[t] per year, which allows the mine to be operated for 17 years.

To determine the costs related to the mine and processing plants operation and expected investment related to the mine, empirical tables were used to identify relations between the mine capacity and the operational and capital costs (OPEX and CAPEX). The Tables are presented in Appendix A. Subsequently, the mine cost was fixed for the whole life of the mine at 2.7[US$/t] and the capital expenses amounted to approximately 68,780,000[US$].

As the deposit contained different types of ore, different mineral processing plants needed to be implemented. In DeepMine, a Plant represents the chain of a process that converts mineral ore into refined metal; for the analysis, two Plants were defined: the Leaching Plant, which considered processes of crushing, heap leaching and SX-EW, and the Concentrator Plant, which considered crushing, grinding and froth flotation. This project was conceived as a brownfield or expansion project that would make use of preexistent processing plants, which eliminated capital costs from consideration; the operational costs, however, were determined in the same manner as the mine costs (Appendix B). The main characteristics of the Plants are listed in Table 4.1.

Table 4.1: Processing Plant Characteristics

	Leaching Plant	**Concentrator Plant**
Feeding	Oxide and Transition Ore	Sulfide Ore
Investment [US$]	0	0
Capacity [t/year]	4,500,000	4,000,000
Plant Cost [US$/t]	5.7	10.2
Recuperation	Oxide Ore: 75% Transition Ore: 65%	Sulfide Ore: 90%

DeepMine also considers the creation of stockpiles, where material from the mine is stored until it can be processed in a plant at a later period. As the software is not limited to a single stockpile, for this project, two stockpiles were constructed to store enough material of each type of ore to feed their respective processing plants for two days (Table 4.2).

Table 4.2: Stockpile Characteristics

	Leaching Stockpile	Concentrator Stockpile
Feeding	Oxide and Transition Ore	Sulfide Ore
Capacity [t/year]	9,000,000	8,000,000
Re-handling Cost [US$/t]	1.25	1.25

The scenarios considered by the software for the stockpiles options showed that sending the ore from the mine to the stockpile and then to the processing plant was the optimum alternative to minimize all costs (Figure 4.2).

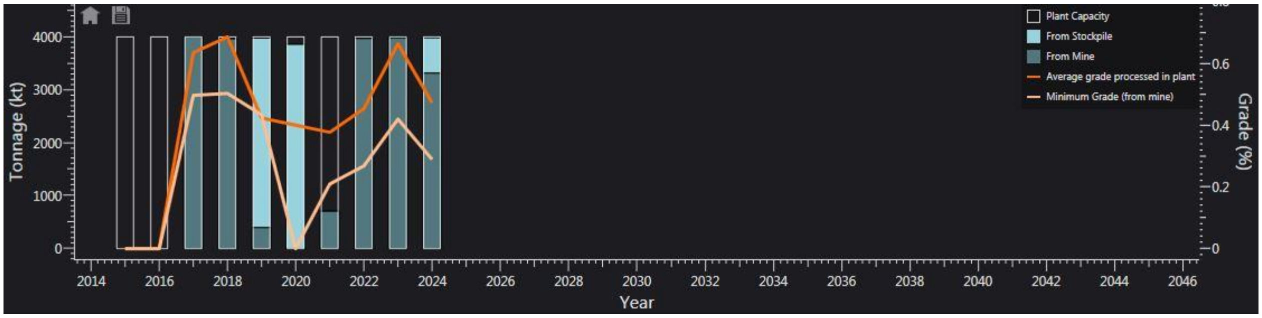


Figure 4.2: First results on concentrator plant's life

This type of scenario does not represent what occurs in a real operation since a processing plant should be the run of mine material's primary destination. To correct this situation a feature called *Surplus Limit* was used in both plants for every period of the mine plan.

The ore surplus represents the total tonnage of blocks that cannot be processed in a particular Plant since there is no capacity left in the Plant. This means that all blocks that cannot go to the processing plant that provides the highest value will go to an alternative destination, in this case an ore stockpile. This feature enabled the control of the amount of material that was sent to the stockpiles in any given period (Figure 4.3 and Figure 4.4).

Ore Mining

☑ Surplus Limit (kt)

+	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
-	2,000	2,000	2,000	2,000	4,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	4,000

Figure 4.3: Surplus Limit for Concentrator Plant per year

Ore Mining

☑ Surplus Limit (kt)

+	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
-	3,000	3,000	3,000	3,000	3,000	5,000	5,000	5,000	5,000	5,000	5,000	3,000

Figure 4.4: Surplus Limit for Leaching Plant per year

In addition to the *Surplus Limit*, a feature for stockpiles that limits the re-handling capacities of each stockpile in every period was used to control the destination of the material in each stage of the process (Figure 4.5 and Figure 4.6).


Capacities

☑ Limited Total Capacity (kt) 8000

☑ Limited Rehandling Capacity (kt)

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	4,000

Figure 4.5: Re-handling capacity for Concentrator Stockpile per year


Capacities

☑ Limited Total Capacity (kt) 9000

☑ Limited Rehandling Capacity (kt)

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
900	900	900	900	900	900	900	900	900	900	900	1,350	900	450	900	0

Figure 4.6: Re-handling capacity for Leaching Stockpile per year

Those two tools were used to ensure that the assumptions made at the beginning of this section were achieved. These constraints in the programming of the mine plan resulted in extending the life of the plants and ensured a continuous material feed (Figure 4.7 and Figure 4.8).

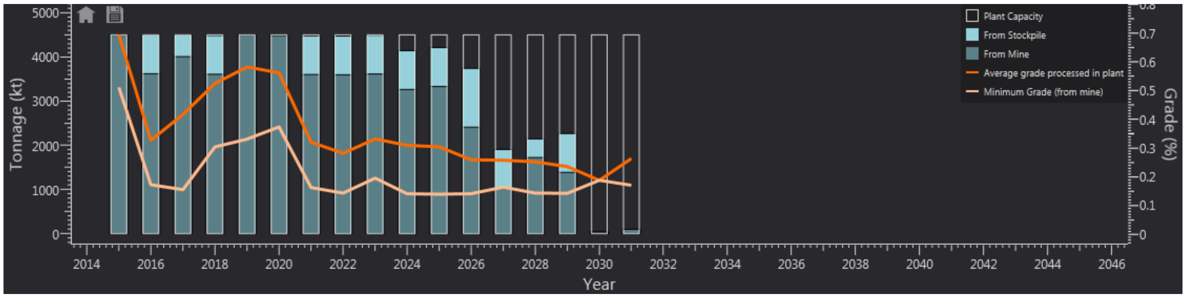


Figure 4.7: Leaching Plant Operation

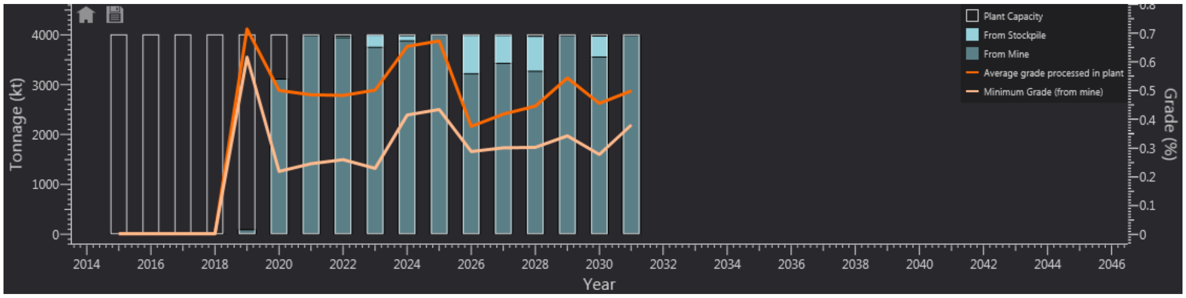


Figure 4.8: Concentrator Plant Operation

For the waste material, a dump can be represented in the program. A block is considered a waste when there is no economic incentive to process it in a plant, regardless of its rock type or the time of its extraction. Considering the scale of this project, there was a single dump constructed for the entire operation.

4.2.3. Pit Collections

DeepMine uses the Lerchs-Grossman algorithm (Lerchs & Grossman, 1964) to develop a pit collection (Figure 4.9) consisting of a series of nested topographies that represent different solutions to the ultimate pit limit problem for an open pit mine. Afterwards, these nested pits are used to calculate the dimensions of the final pit and pushbacks based on the economic environment considered for the planning.

The software associates a block model to the mining parameters through a series of commodity prices to build the nested pits. A vector of prices was provided considering 20 prices for Copper ranging from 0 [US$/lb] to 2.4[US$/lb], which was the Copper price at the time this analysis was performed.

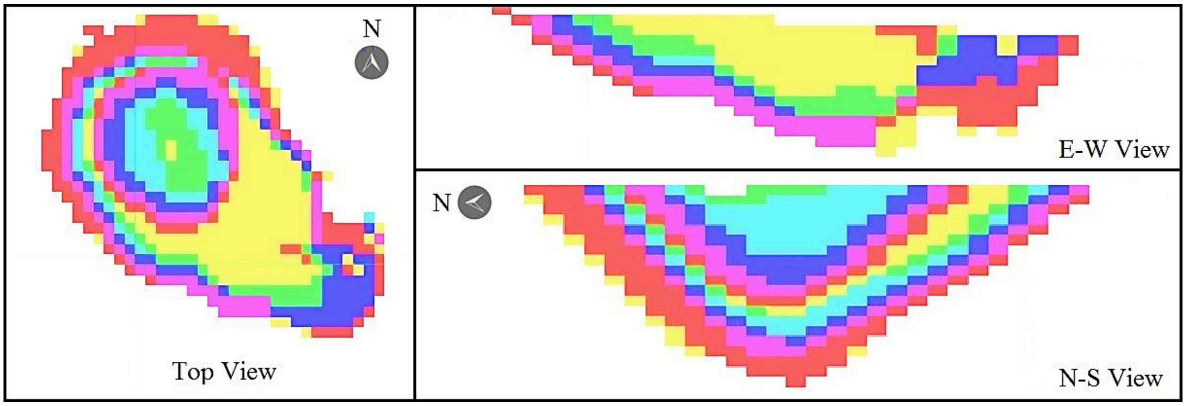


Figure 4.9: Visualization for calculated nested pits

4.2.4. Economic Environment

In DeepMine, an Economic Environment encloses all the market conditions that are relevant for the development of the mine plan. The software allows establishing commodity prices in a deterministic or stochastic manner. Since introducing uncertainty into the planning to develop a flexible plan is not the focus of this work, all the parameter taken into account for the economic environment are deterministic in their nature.

- The commodity price for the Copper products was fixed for all the years of the plan.
- The price of Copper was set at 3[US$/lb], slightly higher than the estimation made by the Central Bank of Chile during August 2015 when the commodity price for Copper was foretold to average 2.9[US$/lb] in 2016.
- Commodity sales cost was fixed at 0.5[US$/lb] for all the periods.
- A tax rate of 8% was considered for the plan, and

- A discount rate of 8% was used to calculate the NPV.

The mine plan was built based on all the parameters and assumptions made under various part of the mine planning software.

4.2.5. Mine Plan

The final considerations of the design of the pit were taken into account to solve the problem of the optimum mine plan through the design constraints:

- Maximum life of mine was up to 30 years,
- The maximum number of simultaneously active phases was 4,
- The maximum number of benches that could have been extracted in a single period (sinking rate) was 5,
- A single phase could have a maximum length of 1,000[m], but it needed to have a minimum width of 200[m] (Figure 4.10), and
- The minimum weight of a single phase was 75,000[t].

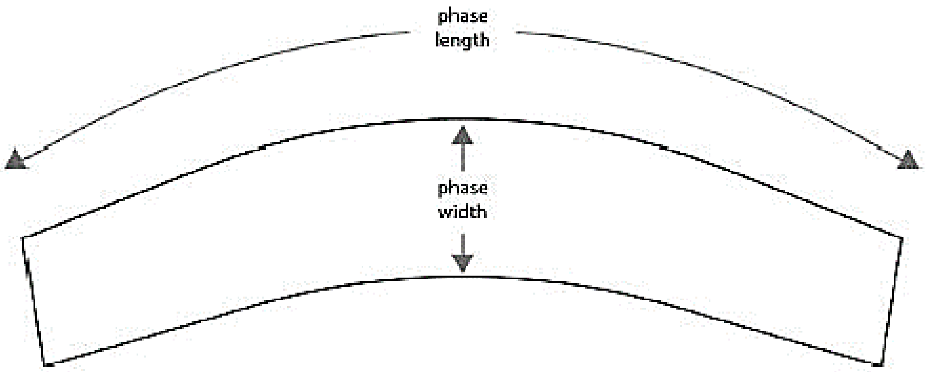


Figure 4.10: Phase dimensions (DeepMine 2.2 User Manual)

Three different solving modes for the creation of the mine plan can be selected to calculate the optimum plan. These solver modes differ in the number of evaluated alternatives, giving better results as more time is spent solving the problem, which translates to more resources spent on running the solving algorithm:

- The *quick mode* focuses on maximizing processing speed and generating a mine plan as fast as possible;
- The *balanced mode* tries to find the middle point between speed and quality for the final result, and

- The *deep mode* maximizes the NPV generating the best possible plan using all the available resources.

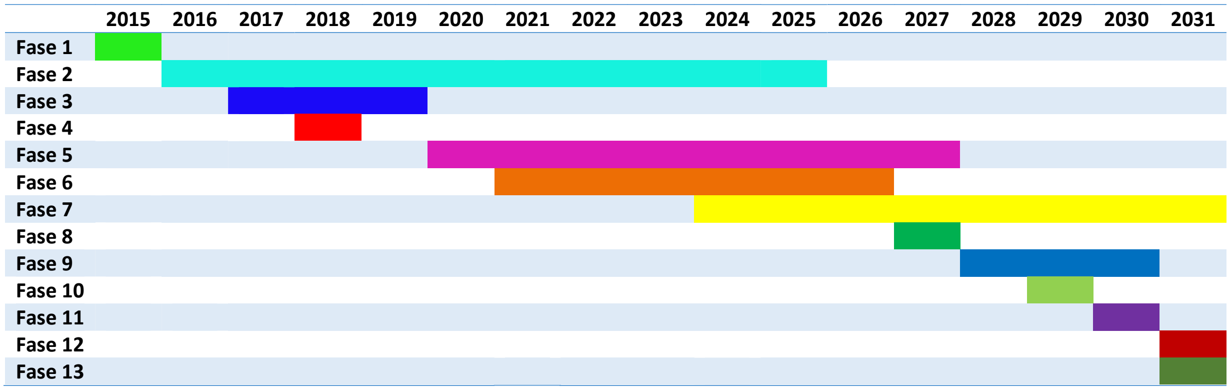
Every scenario evaluated during this research was calculated using DeepMine's *deep mode*.

4.2.6. Results

Several iterations of the solver were performed to obtain an optimum result for the mine plan. This final plan calculated an average medium scale open pit mining project, which could be used to incorporate groundwater monitoring into the mine's design. The final results are listed in this section, since they represent the best scenario calculated based on the assumptions and parameters set within the DeepMine software.

The resulting mine has an operational life of 17 years (Table 4.3). During those years a total of 252,521,020[t] (252,210.02 [kt]) of ore are to be extracted. However, based on the pushback's geometries generated by DeepMine (see Appendix C), it is clear that there were some non-operative phases that needed to be extracted as part of another phase. Section 4.3 describes the work undertaken to assess the feasibility of extracting every phase and how some of them are combined to optimize the extraction schedule.

Table 4.3: DeepMine's optimum mine plan



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Fase 1	■																
Fase 2		■	■	■	■	■	■	■	■	■	■						
Fase 3			■	■	■												
Fase 4				■													
Fase 5						■	■	■	■	■	■	■	■				
Fase 6							■	■	■	■	■	■					
Fase 7										■	■	■	■	■	■	■	■
Fase 8													■				
Fase 9														■	■	■	
Fase 10															■		
Fase 11																■	
Fase 12																	■
Fase 13																	■

While analyzing the movement of material from the mine operation (Figure 4.11) some irregularities, such as a high stripping ratio as well as abrupt changes in the total amount of extracted material in two following periods were detected during the ramp-up stage (first 5 years) of the project.

This anomalous behavior was expected as the software does not include a pre-stripping stage in the plan prior to the mine operation. This irregular result represent the attempt of the software to perform stripping and ore processing, simultaneously, in the first years. Once the mine operation entered full production stage, there were no anomalies detected and the plan was considered robust enough to allow further analyses.

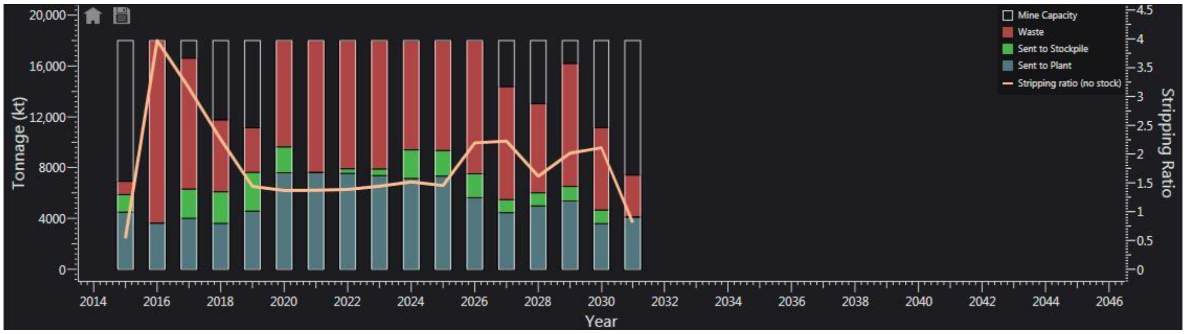


Figure 4.11: Ore movement from the Mine Operation

Processing plants were analyzed to identify any issues in their operation during the life of mine and it was noted that the largest portion of processed material in each period was re-handled ore. This scenario was not realistic and thus, needed to be changed as the origin of the material that arrives to the processing plants have direct repercussions on the mine plan.

As mentioned in Section 4.2.2, the tools of *Surplus Limit* and *Re-handling Capacity Limit* were used to ensure that the plants received enough material directly from the mine. An adequate plan that has both plants operating most of the time at their full capacity and with minimum re-handled ore was generated after the model run different scenarios (Figure 4.7 and Figure 4.8).

The final plans obtained for both plants resemble the real mine conditions considering that different types of ore were extracted during different periods. A summary of operative characteristics of the plants are shown in Table 4.4.

Table 4.4: Processing Plants operation summary

	Leaching Plant	**Concentrator Plant**
Years of operation	17	13
Total processed material [t]	58,949,000	47,038,000
Average copper grade	0.39%	0.51%
Average ore recuperation	66%	90%

The cash flow for the project (Figure 4.12) was analyzed showing that, in the second year of operation, the plan presented a negative cash flow as this year coincided with the period when the stripping ratio was at its highest. Afterwards, the cash flow experienced a recuperation that was interrupted in the year 2026, when the cash flow experienced another fall, this time caused by a drop in metal recuperation. Recovered metal diminished because of the decline of the amount of processed oxide ore in the leaching plant since this type of minerals become scarce in the mine by that time.

The cash flow was consistent with the observed behavior of the mine and its plants throughout the entire mine life. The resulting NPV for this project was 246,690,000[US$] (177,910,000[US] considering capital expenses), which was indicative of a viable mining project that would be considered for construction in a real situation.

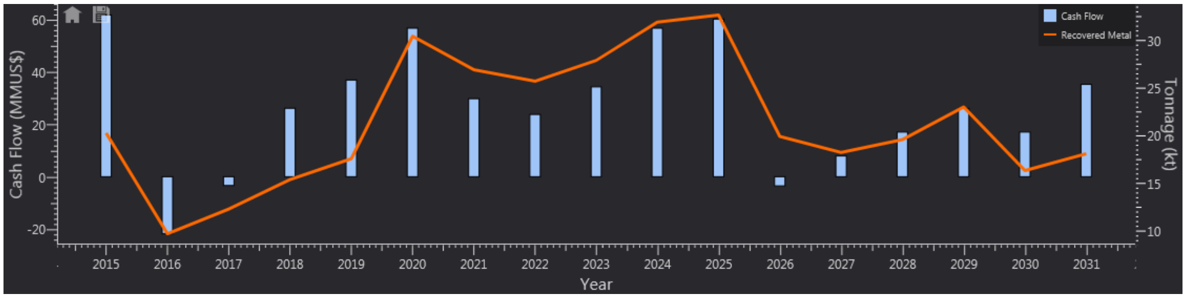


Figure 4.12: Mine Plan's Cash Flow

4.3. Pushback Design

4.3.1. Export/Import Mine Plan

All the calculations and results from DeepMine can be exported from the software in the form of a “Flagged Block Model”. This file contains all the basic information of the block model such as the block’s coordinates, density, total content of copper and soluble copper and the geological unit each block belongs to. In addition, this file also contains all the results from the mine plan giving each block in the model a numeric value for the period when they should be extracted, the phase they belong to, the part of the topography they belong to and their economic value based on the calculated cash flow.

The Flagged Block Model was imported to the software Vulcan, where all the major modifications to the geometry were made (Figure 4.13). Each phase was analyzed individually to determine if it was feasible to extract them in the order that DeepMine proposed or if it there were operational constraints that were not taken into consideration.

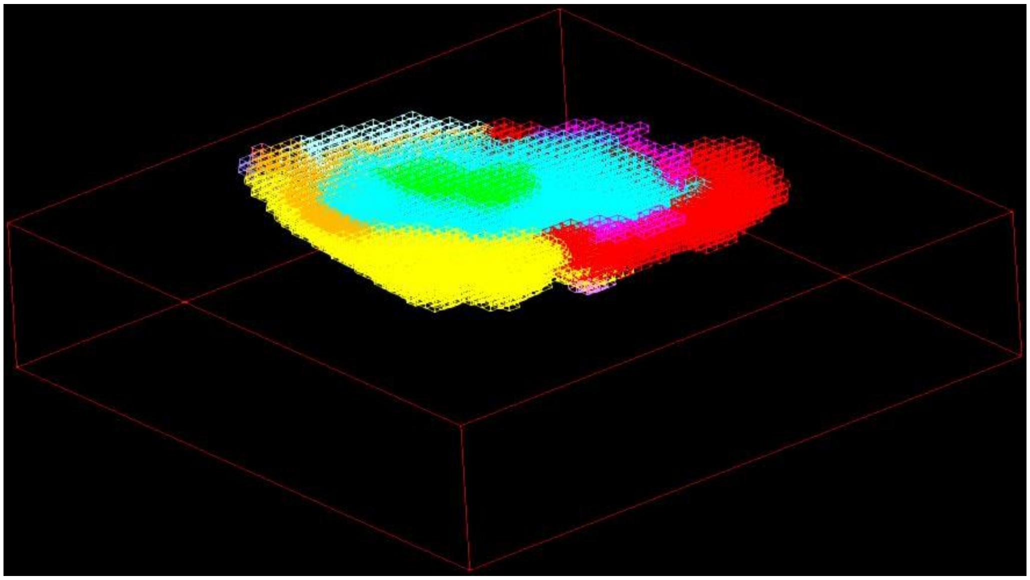


Figure 4.13: Block model's visualization per phase

4.3.2. Pushback Limitations

The main concern related to the phases created by DeepMine is their size since the operation of the mine will require trucks circulating in each pushback. To determine the minimum width for a phase, the Komatsu's Specifications & Application handbook (30th edition, 2009) was used to calculate a tentative truck fleet, since the model and width of the truck would be the basis to assess the minimum ramp width in the mine.

The daily extraction rate of rocks in the mine site was determined, based on the assumptions that the plan considered the extraction of 18,000,000[t] of rock per year and rounding the year to 360 working days, resulting in the extraction rate of 50,000[tpd].

To be able to move that amount of material from the mine every day a fleet of trucks with a capacity higher than 100[t] must be used. The chosen truck was the Komatsu model HD1500-7 with a bucket capacity of 144[t]. The fleet was determined based on the transport speed for this model of truck (Figure 4.14) and the approximate transport distance which was calculated with an inclination of 10% in a 300[m] deep pit, adding appropriate distance to reach the destination (1[km]). The average hauling distance was calculated to be 4[km].

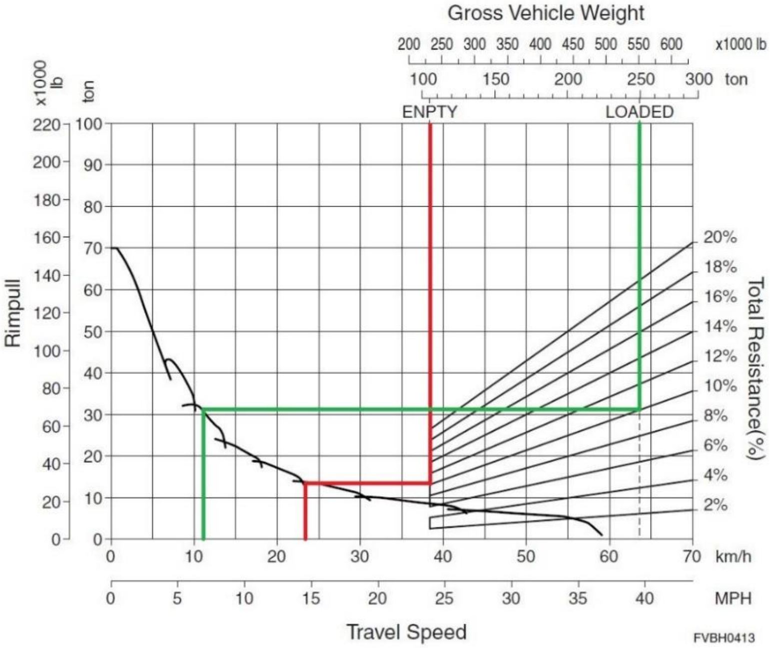


Figure 4.14: Komatsu HD1500-7 speed chart

To be conservative in the calculations, additional operational factors such as the working hours per day were taken into account and are listed in Table 4.5. The resulting fleet consisted of 17 trucks, which was deemed as appropriate for a project of this size.

Table 4.5: Truck fleet calculation

	Value	Unit
Empty truck speed	11	km/h
Loaded truck speed	24	km/h
Average hauling distance	4	km
Time to complete a round trip	31,8	min
Loading positioning time	0,2	min
Loading time	2	min
Dumping positioning time	0,2	min
Dumping time	0,35	min
Total rock hauling cycle	35	min
Hauled rocks per hour	247	t/h
Operational Factor	0,6	-
Effective working hours per day	20	h/day
Hauled rocks per day	2962	tpd
Number of trucks	17	-

The chosen truck model, Komatsu HD1500-7, is a 6.89[m] wide equipment in its widest section (Figure 4.15). A ramp must have a minimum width to allow a two-way transit for the trucks, a safety distance to the wall of the mine, a safe distance between trucks and a berm width.

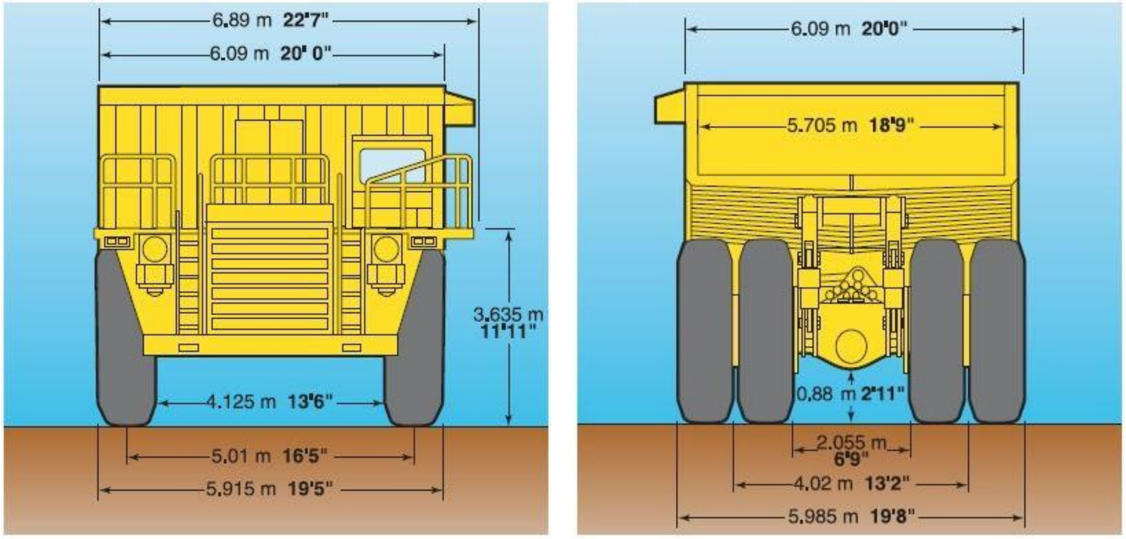


Figure 4.15: Komatsu HD1500-7 section views

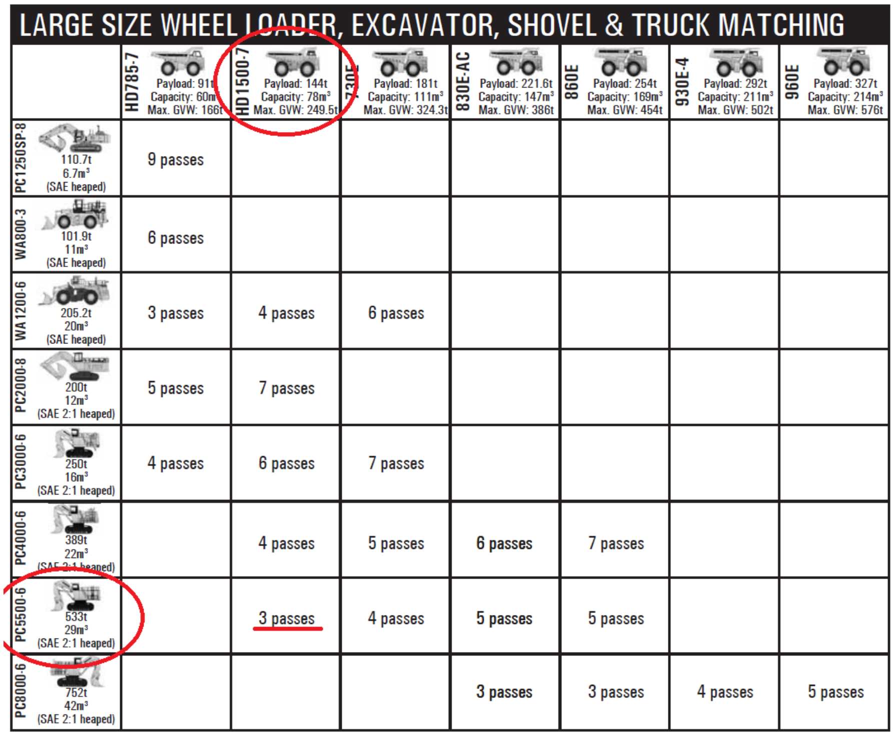
According to Tannant, D. & Regensburg, B. (2001), the minimum width of the straight sections of hauling road with more than one lane can be determined using the following empirical equation, where W represents the width of the road, L the number of lanes and X the width of the trucks. Rounding up the vehicle width to 7[m] the minimum width of the road must be at least 25[m].

$$\boldsymbol{W = (1.5 \times L + 0.5) \times X = (1.5 \times 2 + 0.5) \times 7 = 24.5 \approx 25[m]} \tag{4.1}$$

The use of a fleet of 2 Komatsu shovels model PC5500-6 (Table 4.6) was considered for the previous calculations for the truck cycle. This model of shovel was selected as an appropriate match for the trucks based on the information available in the Komatsu Product Line-up from 2015 (Figure 4.16).

Table 4.6: Shovel fleet calculation

	Value	**Unit**
Bucket cycle time	40	s
Bucket size	29	m3
Specific Gravity of the material	1,8	t/m3
Loose material Specific Gravity	1,4	t/m3
Bucket fill factor	0,95	-
Loaded rocks per bucket	38,15	t
Loaded rocks per hour	3433,15	t/h
Operational Factor	0,6	-
Effective working hours per day	20	h/day
Loaded rocks per day	41198	tpd
Number of shovels	2	-



LARGE SIZE WHEEL LOADER, EXCAVATOR, SHOVEL & TRUCK MATCHING

	HD785-7 Payload: 91t Capacity: 60m³ Max. GVW: 166t	HD1500-7 Payload: 144t Capacity: 78m³ Max. GVW: 249.5t	730E Payload: 181t Capacity: 111m³ Max. GVW: 324.3t	830E-AC Payload: 221.6t Capacity: 147m³ Max. GVW: 386t	860E Payload: 254t Capacity: 169m³ Max. GVW: 454t	930E-4 Payload: 292t Capacity: 211m³ Max. GVW: 502t	960E Payload: 327t Capacity: 214m³ Max. GVW: 576t
PC1250SP-8 110.7t 6.7m³ (SAE heaped)	9 passes						
WA800-3 101.9t 11m³ (SAE heaped)	6 passes						
WA1200-6 205.2t 20m³ (SAE heaped)	3 passes	4 passes	6 passes				
PC2000-8 200t 12m³ (SAE 2:1 heaped)	5 passes	7 passes					
PC3000-6 250t 16m³ (SAE 2:1 heaped)	4 passes	6 passes	7 passes				
PC4000-6 389t 22m³ (SAE 2:1 heaped)		4 passes	5 passes	6 passes	7 passes		
PC5500-6 533t 29m³ (SAE 2:1 heaped)		3 passes	4 passes	5 passes	5 passes		
PC8000-6 752t 42m³ (SAE 2:1 heaped)				3 passes	3 passes	4 passes	5 passes

Note: The above is based on SG of 1.8 t/m³ and a bucket fill factor of 95%

The heaped capacity is rated at 2:1 SAE

Figure 4.16: Shovel-Truck Matching

The selected shovels require a minimum working area to load the material into the trucks, to determine this distance it is necessary to calculate the radius of gyration of the shovel (Figure 4.17). From Figure 4.17, it is possible to deduce that the maximum reach of the shovel can be rounded up to 17[m].

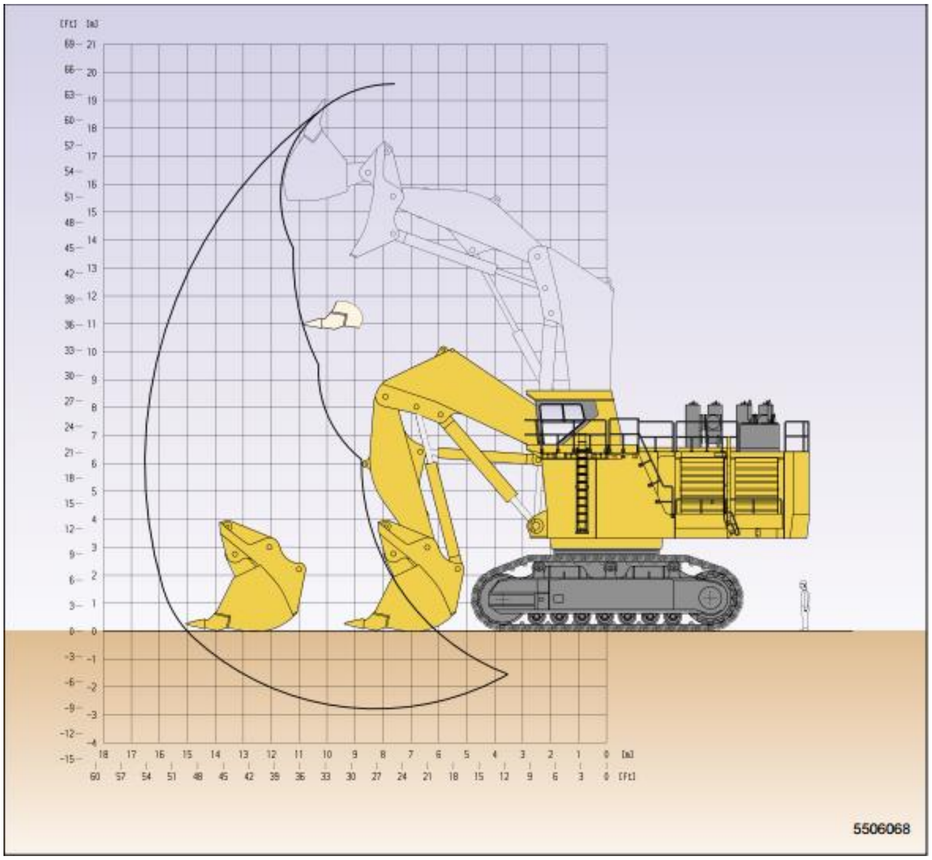


Figure 4.17: Komatsu PC5500-6 radius of gyration

Considering a case where a single shovel is located in a position where it can load trucks from both sides (Figure 4.18), which is the scenario that would require the grater working area, it is possible to determine the minimum loading distance.

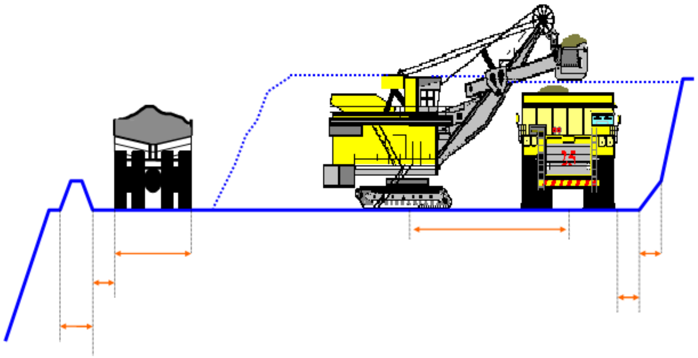


Figure 4.18: Proposed configuration for truck loading

The minimum width of the loading area can be determined using the empirical equation (4.2), where SB represents the width of the Safety Berm, SD the Safety Distance, TW the Width of the Truck, RG the Radius of Gyration of the shovel and RF the rock falling distance. Rounding up the truck width to 7[m], the safety berm to 3.5[m], the rock falling distance to 3.5[m] and the safety distance to 2[m] the minimum width of the road must be at least 52[m].

$$W = SB + SD + (0.5 \times TW) + (2 \times RG) + (0.5 \times TW) + SD + RF = 52[m] \quad (4.2)$$

Consequently, all the phases or pushbacks in the plan that were made from only one block in any given direction were combined into neighboring phases that were scheduled to be extracted during the same period to create new phases that considered the minimum loading distance.

4.3.3. Pushbacks Design

The mine plan generated by DeepMine for the mining of the open pit consisted of 13 phases to be extracted in a span of 17 years. However, as it was established in Section 4.2.6, some of these phases were combined after taking into account operational constraints to have a more realistic set of pushbacks.

To combine different phases, the *Grade Shells* tool of Vulcan was used to create solid triangulations of each separate phase and then joining the blocks to create a new triangulation that represented the new pushback (Figure 4.19).

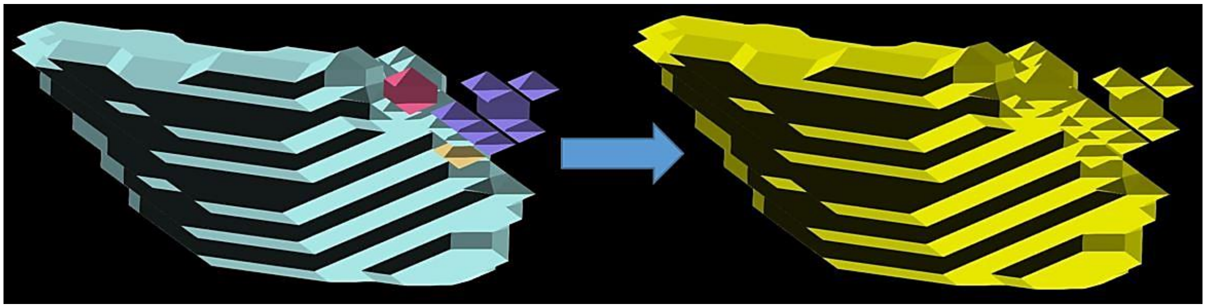


Figure 4.19: Combination of several phases into one

Once the new phases were determined, the created triangulations were superimposed on the block model viewing to identify all blocks that were part of each of the new phases.

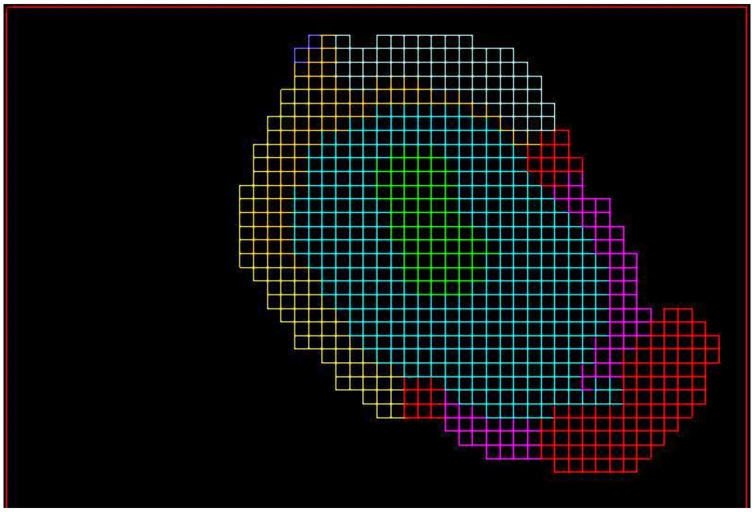


Figure 4.20: Section view of the block model

Subsequently, plan section views were created (Figure 4.20) at the bottom of each block that was part of a particular phase to draw the lines that comprised the correspondent excavation. The outlines of these pushbacks were drawn in the form of cones that represented the evolution of the open pit as the phases were extracted (Figure 4.21).

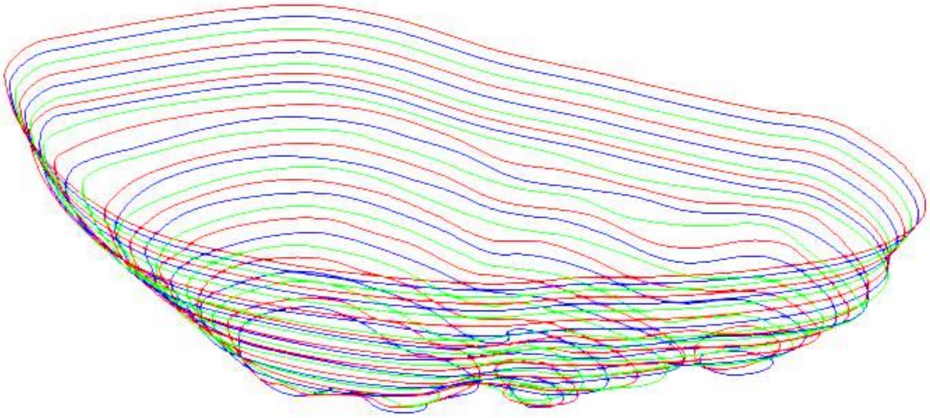


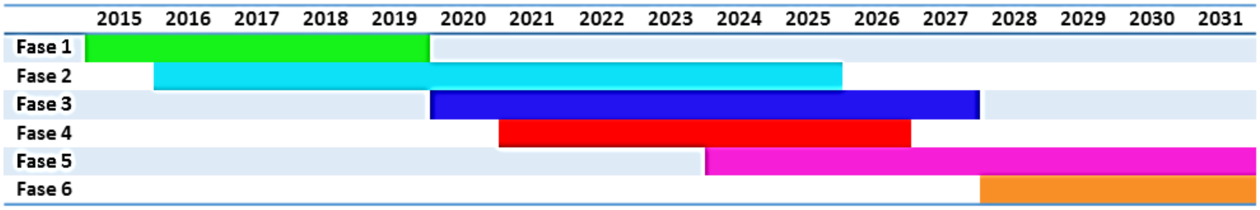
Figure 4.21: Outline of the final pit

Once the outlines of the pit were built for each particular stage, they were used to create triangulation surfaces of the excavation. Those objects were intersected with the block model's topography to generate a new triangulation that showed how the ground changes as the mine progresses when new phases are extracted (see Appendix D).

From the resulting geometries, it was possible to arrive at the following conclusions:

- The South-East Wall was the first to reach the final pit wall status.
- The progress of the mine in the first years of operation occurred in the direction of the high strength rock.
- The poor quality rock, with the exception of the South Wall, was mined in the last years of operation, being exposed for the shortest amount of time.
- The combination of pushbacks to create operative surfaces within the pit changed the extraction schedule, maintaining the life of mine in 17 years but diminishing the number of pushbacks in the pit from 13 to 6 (Table 4.7).

Table 4.7: Optimized operative mine plan



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Fase 1	🟩	🟩	🟩	🟩	🟩												
Fase 2		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦						
Fase 3						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦				
Fase 4							🟥	🟥	🟥	🟥	🟥	🟥					
Fase 5										🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
Fase 6														🟧	🟧	🟧	🟧

4.4. Optimization of the Existing Design

The optimization of the existing mine design is based on the premise of increasing the revenue of the project by making minimum modifications to the plan through steepening of the angle of the pit's walls. This notion was presented in Section 2.2.3.

Steepening a wall in an open pit mine is generally related to an increase of the ore reserves as well as a reduction in the amount of waste required to be removed to reach the ore. These changes affect the project in terms of the stripping ratio and the total tonnage of metal commodity that can be recovered and sold.

It is expected that steepening the angle of the South Wall, which is the first slope to reach the final pit wall state and in that zone is located the contact between poor quality and high quality rock, increase the revenues and the NPV of the project. To better estimate this economic benefit, the mine plan will be recalculated from the beginning incorporating the new geometry of the pit.

Following the same procedure as used for the original development of the mine plan, the modified mine plan was calculated using the software DeepMine. All the conditions detailed in Section 4.2 remain the same and the only variable changed was the angle of the South Wall, which was set to 50°, i.e. 10° steeper than in the original model.

The change in the slope's angle can be easily noted by comparing the nested pits generated for each plan. Figure 4.9 shows the pit collection for the original configuration and Figure 4.22 presents the pits generated by the Lerchs-Grossman algorithm for the current configuration of the software. By examining the North-South cut, it is clear that in the present iteration both walls have the same inclination.

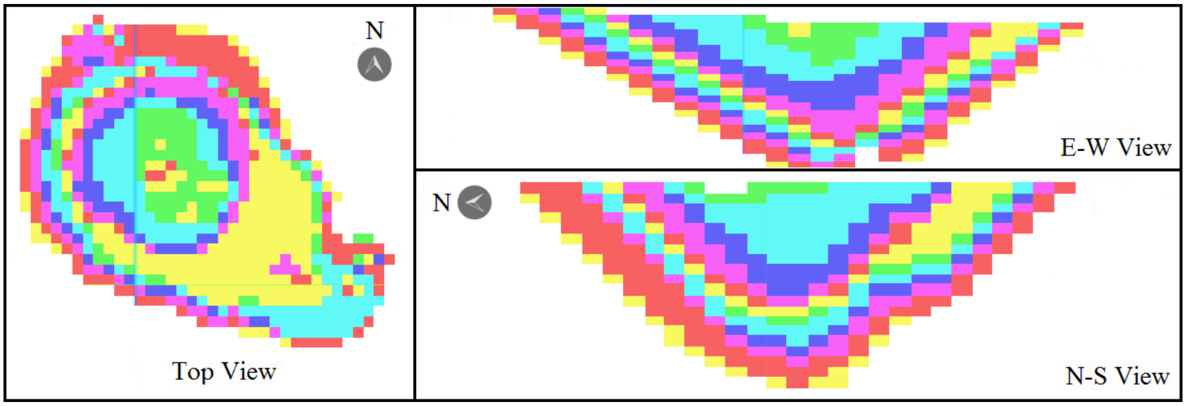


Figure 4.22: Visualization for re-calculated nested pits

Even though the new estimations for Copper commodities prices have been made over the course of the year, setting an expected price much lower than the price used for the original plan, this variable was not modified as it would force changes to the definitions of the project's economic environment and the approach would have to be considered in terms of multi-variable investigation, which is beyond the scope of this project.

4.4.1. Effects of steepening slope angle

The main focus of this new formulation for the mine plan is to identify the impact that the steepening of a single wall has over the mine project while maintaining every other variable constant. Therefore, the mine's operation, basic design and extraction sequence remain the same and the potential benefit that incorporating new ore reserves and diminishing the waste extraction can bring to the overall project is measured.

The resulting mine still has an operational life of 17 years which is the same as the previous plan, but with some slight differences. During those years a total of 253,335,120[t] of ore are to be extracted and Table 4.8 along with Figure 4.23 illustrate that the steepening of the South Wall increases the extraction of the material without major modifications to the pit's geometry.

Table 4.8: Increase on extracted material with improved mine plan

	Original Plan	**Improved Plan**	**Increase [%]**
Total Material [t]	252,521,020	253,335,120	0.32
Total Metal of Cu Commodity [t]	468,760	477,000	1.76
Total Recovered Metal [t]	366,030	373,070	1.92

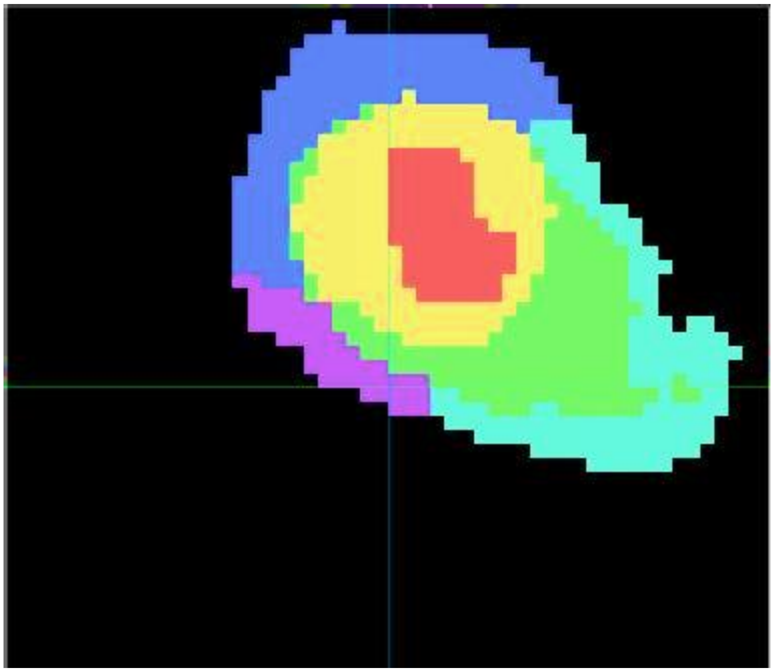


Figure 4.23: Outline of the improved pit

However, the marginal changes in the amount of extracted and recovered material have a significant impact on the profitability of the project. The resulting NPV for this new project was 289,110,000[US$], which was 42,420,000[US$] higher than the original plan. This represents an increase of 17.2% with respect to the original NPV while maintaining the same truck fleet without altering the mine and plants capacities or the geometry of the pit; this is indicative of a viable mining project that should be studied for its implementation, if it had been a real situation.

Noting that a 10° increase in the overall angle can be perceived as an aggressive approach to the problem, it is valuable to perform a sensitivity analysis to determine whether a similar behavior concerning the value of the project can be achieved by steepening the south wall of the mine.

To perform that analysis, the DeepMine software was used to calculate pit collections for different scenarios, considering increases of 1° on the south wall of the open pit, ranging between 40° and 50°. For each angle, a collection of 19 nested pits was created and for every pit in a single collection, the economic value of the pit was an output of the program.

The economic value of the nested pits was the variable used to measure the impact that steepening the south wall has on the project. This decision was made after analyzing the behavior of other variables such as the amount of ore and waste extracted for each pit. When those variables were analyzed, it was clear that the algorithm in some cases increases the overall material extracted and in others diminishes waste extraction, thus making it difficult to find clear tendencies for the behavior of those variables (Appendix E).

To create a cash flow from the nested pits and analyze the progress of the project plan as the angle of the south wall increases, it was necessary to include a notion of temporality to the extraction of the nested pits. The mine’s annual extraction rate was used to calculate the period in which every pit was to be extracted, some pits could be mined in a single year while others took several years to be completely extracted.

This affected the way the cash flow of the project was calculated since material coming from different pits with different economic values could be extracted in the same year. Once the cash flow for every scenario was constructed, the NPV was calculated to provide an indication of how the value of the project is affected by the steepening angle (Figure 4.24).

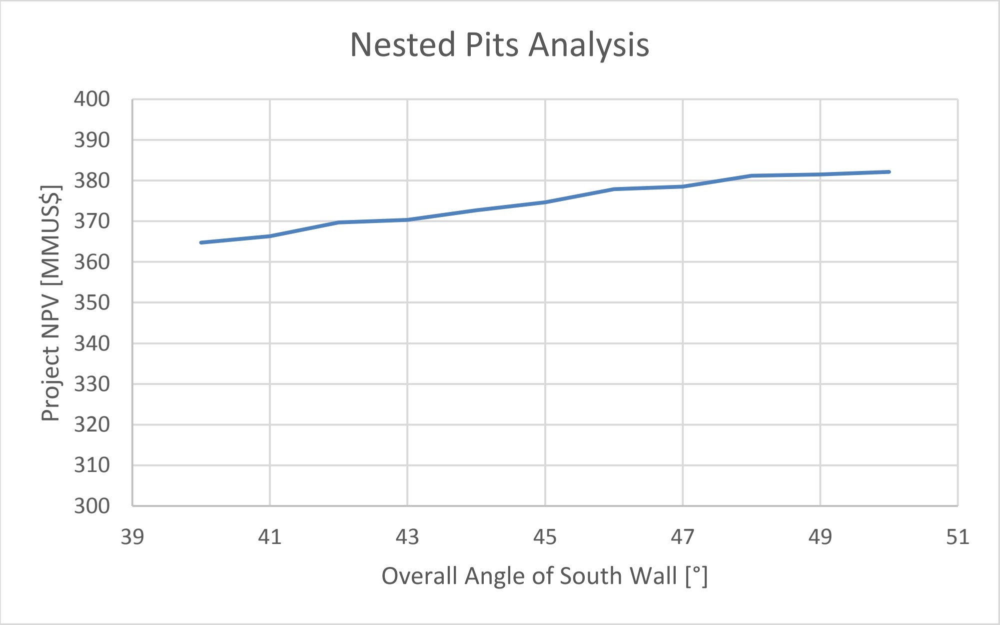


Figure 4.24: Nested Pit Analysis

The results of the nested pit analysis presented in Figure 4.24 showed that, as the angle of the south wall gets steeper, the overall value of the project increases. This is consistent with the rise of the NPV observed for project plan when the angle of the slope was steepened from 40° to 50°.

A steeper southern wall, however, is expected to generate higher pore water pressure behind the slope, which would reduce the rock's ability to withstand the effects of differential stress. Water pressure increases in the rock's pores can also change the mode in which the rock deforms as different states of fluid pressure in the rock can change the behavior of the material from ductile to brittle. In addition, the pressure generated in the interstices opposes the compression stress in the rock mass thus diminishing the effective stress, which is responsible for the deformation of any granular mass.

To counter these negative effects in the stability of the rock, mine operators have adopted the practice of performing dewatering or drainage campaigns in open pit mines. To determine whether these campaigns are effective or not, a thorough understanding of the fluid pressure state (groundwater) behind the mine's walls is required and in particularly, the understanding of pore pressure is essential. Thus, there is a need for ground water pressure monitoring, which is discussed in Chapter 5.

CHAPTER 5: DEVELOPMENT OF GROUNDWATER MONITORING PROGRAMS

5.1. Effects of Steepening of South Wall

In this section, the issue of incorporating groundwater monitoring into a mine plan for an open pit mine is discussed. The objective is to implement instrumentation campaigns to monitor pore water pressure in rock slopes taking into account the progress of different pushbacks and excavations until they reach the final pit wall state.

The main question to answer when considering geotechnical instrumentation is: *What are the objectives of the monitoring campaign?*

Or, in simpler terms: *What are we measuring and why?*

In the particular case of the mine plan developed in Chapter 4, the open pit was designed with different slope angles for different walls to ensure their stability given the difference in quality of the rock in two separate sectors of the mine. Thus, the scenario, whereas the inclination of a particular wall in the pit is increased due to a more aggressive design to increase revenue, may potentially affect the stability of the slopes, which would require a higher level of monitoring.

The decision of steepening the angle of the South-East Wall was made because, in that sector of the mine, the contact between poor quality and high quality rock was located. It was expected that pore water pressure change rates would increase with the steepening of the wall as the stresses would be re-distributed and might have potentially influence the rates of water seepage inside the rock mass.

Monitoring pore water pressure would provide: (1) information on the variation rates of liquid pressure inside the rock mass, and (2) alerts if the variation value reached levels that might have compromised the slope's stability.

In summary, geotechnical instrumentation campaigns for the South-East Wall of the open pit had, as their main objective, to monitor pore pressure in a new configuration of the mine that was designed to increase profits but not necessarily to, simultaneously, ensure stability of slopes.

5.2. Selection of pore water pressure monitoring instruments

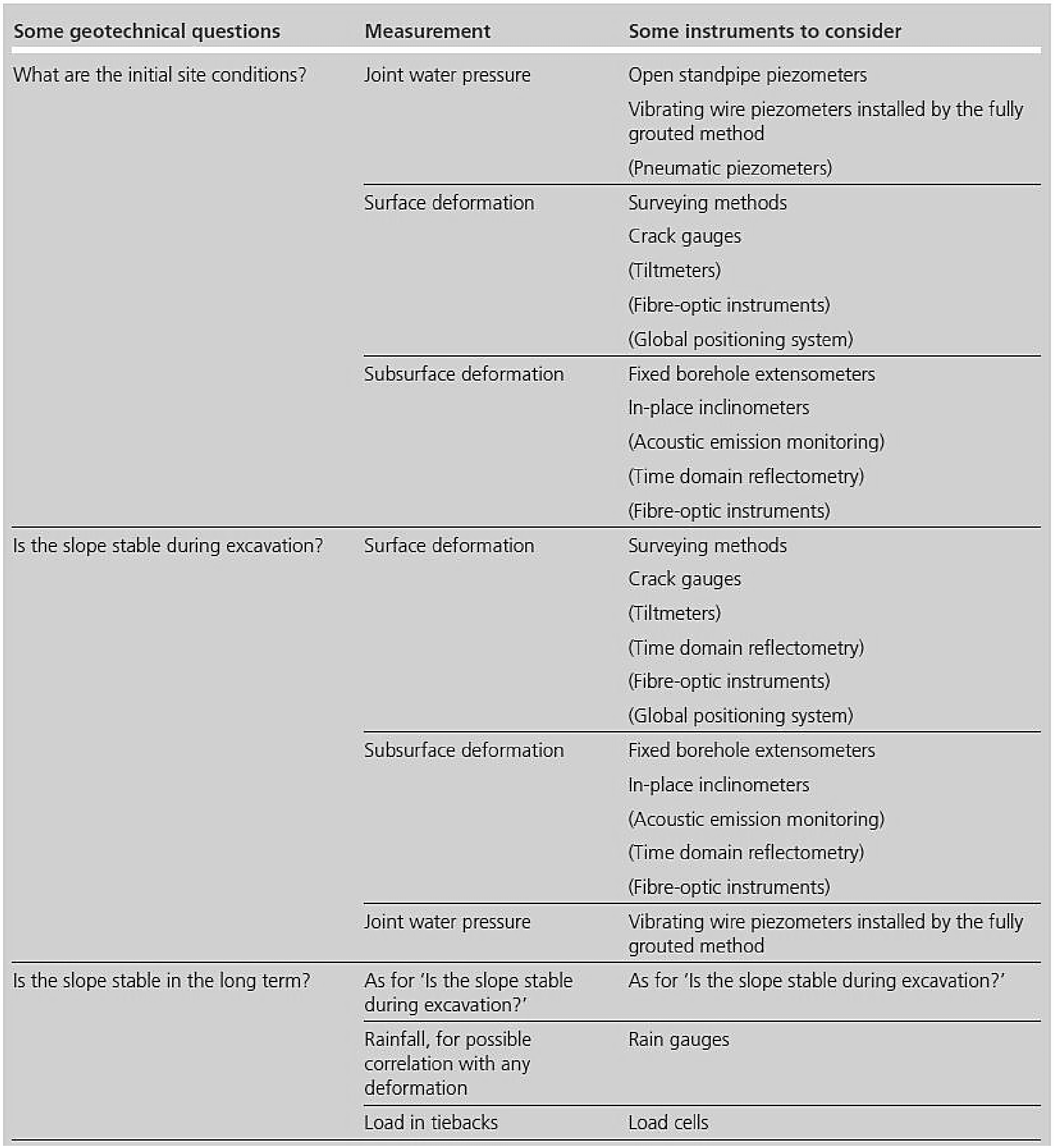
This section discusses existing guidelines for equipment selection and implementation to perform pore water pressure monitoring and, subsequently, proposes two equivalent instrumentation campaigns and compare them from an economic and technical standpoint.

5.2.1. Guidelines for Instrument Selection

To determine the type of device that should be installed in the mine site, it is necessary to determine the technologies that adjust better to the site's requirements. Several guidelines have been developed to assist geotechnical engineers in the selection of geotechnical instrumentation, but they are generally directed to civil engineering applications in soils.

For hard rock mining applications, a good approach is the use of research performed by experts and their recommendations (Dunnicliff, 2012) who listed instruments to monitor cut slopes in rock (Table 5.1).

Table 5.1: Instruments to consider for monitoring cut slopes in rock (Dunnicliff, 2012)



Some geotechnical questions	Measurement	Some instruments to consider
What are the initial site conditions?	Joint water pressure	Open standpipe piezometers Vibrating wire piezometers installed by the fully grouted method (Pneumatic piezometers)
	Surface deformation	Surveying methods Crack gauges (Tiltmeters) (Fibre-optic instruments) (Global positioning system)
	Subsurface deformation	Fixed borehole extensometers In-place inclinometers (Acoustic emission monitoring) (Time domain reflectometry) (Fibre-optic instruments)
Is the slope stable during excavation?	Surface deformation	Surveying methods Crack gauges (Tiltmeters) (Time domain reflectometry) (Fibre-optic instruments) (Global positioning system)
	Subsurface deformation	Fixed borehole extensometers In-place inclinometers (Acoustic emission monitoring) (Time domain reflectometry) (Fibre-optic instruments)
	Joint water pressure	Vibrating wire piezometers installed by the fully grouted method
Is the slope stable in the long term?	As for 'Is the slope stable during excavation?'	As for 'Is the slope stable during excavation?'
	Rainfall, for possible correlation with any deformation	Rain gauges
	Load in tiebacks	Load cells

From Table 5.1, the sections regarding joint water pressure were identified and expanded (Table 5.2) using collected information of piezometer types to be used as a primary guide to select the devices for subsequent analyses.

Table 5.2: Instruments to consider for monitoring joint water pressure in cut slopes, both in rock and soil

Some geotechnical questions	Some site characteristics	Type of measurement	Some instruments to consider
What are the initial site conditions?	Is the slope cut in rock?	High permeability materials. Pressure fluctuations not significant.	Open standpipe piezometers.
		In response to drainage and precipitation. High accuracy.	Vibrating wire piezometers. Semiconductor piezometers. Piezoresistive piezometers.
		Low conductivity rock installations.	Pneumatic piezometers.
	Is the slope cut in soil?	High permeability materials. Pressure fluctuations not significant.	Open standpipe piezometers.
		In response to drainage and precipitation. High accuracy.	Vibrating wire piezometers. Semiconductor piezometers. Piezoresistive piezometers.
		Low conductivity soil installations.	Pneumatic piezometers.
		Suction effects on unsaturated soils.	Flushable piezometers.
Is the slope stable during excavation?	Is the slope cut in rock?	In response to drainage and precipitation. High accuracy.	Vibrating wire piezometers. Semiconductor piezometers. Piezoresistive piezometers.
		Vertical pressure gradients.	Multipoint piezometers.
	Is the slope cut in soil?	In response to drainage and precipitation. High accuracy.	Vibrating wire piezometers. Semiconductor piezometers. Piezoresistive piezometers.
		Vertical pressure gradients.	Multipoint piezometers.
		Suction effects on unsaturated soils.	Flushable piezometers.
Is the slope stable in the long term?	Is the slope cut in rock?	In response to drainage and precipitation. High accuracy.	Vibrating wire piezometers. Semiconductor piezometers. Piezoresistive piezometers.
		Vertical pressure gradients.	Multipoint piezometers.
	Is the slope cut in soil?	In response to drainage and precipitation. High accuracy.	Vibrating wire piezometers. Semiconductor piezometers. Piezoresistive piezometers.
		Vertical pressure gradients.	Multipoint piezometers.
		Suction effects on unsaturated soils.	Flushable piezometers.

A thorough review of the technical characteristics and application ranges of geotechnical instruments, that are currently available in the market, was performed and a summary can be found in Table 5.3 and Table 5.4.

The full scale of the review includes a differentiation by model and manufacturer of each device and is available for examination in Appendix G of this document.

Table 5.3: Summary of Instruments for Measuring Groundwater Pressure

	Standpipe	***Pneumatic***	***Vibrating Wire***	***Semiconductor***
Range (max)	Standpipe Depth	0-14,000[kPa]	−100[kPa] to 150[MPa]	100[kPa] to 6[MPa]
Response Time	Slow	Medium	Fast	Fast
Reading Time	Minutes	5 minutes in a 60[m] (200') tubing	Seconds	Seconds
Accuracy (min)	ISO first grade	± 0.25% F.S.	± 0.1% F.S.	0.02% F.S.
Resolution (min)	1[mm] water column	1[kPa] (0.1[kPa] w/ readout)	0.025% F.S.	0.004% F.S.
Min Outer Diameter	19 [mm]	15.9 [mm]	11 [mm]	15.9 [mm] (0.625")
Max Outer Diameter	76.2 [mm]	40.6 [cm]	100-150 [mm]	32 [mm]
Lightning Protection Required	No	No	Yes	Yes
Multipoint Readings	Yes	-	Yes	Yes
Max Reading Points	Up to 4	-	<10	-
Remote Reading	No	Yes	Yes	Yes
Automated Reading	No	No	Yes	Yes
Advantages	Reliable. Allows sampling and permeability measurements.	Easy access to calibrated parts. Min. construction interference. No freezing problems.	Easy to read. Min. construction interference. Negative pore pressure readings. No freezing problems.	Easy to read. Min. construction interference. Used when VW is not compatible. No freezing problems.
Limitations	Can be damaged by construction. Repeated inflow and outflow.	Requires technique for accurate readings.	Can cause interference with radiofrequency & electromagnetic fields.	Low electrical input. Errors caused by moisture of electrical components.

Table 5.4: Summary of Instruments for Measuring Groundwater Pressure (Continued)

	Piezoresistive	***Twin-Tube***	***Flushable***	***Enhanced NSM***
Range (max)	From 0 to 20[MPa]	From −5[kPa] to 2[MPa]	From −5[kPa]	From 0 to 3[MPa]
Response Time	Fast	Medium	Medium	Fast
Reading Time	Seconds	Few Minutes	Few Minutes	Seconds
Accuracy (min)	< 0.02% F.S.	± 0.1% F.S.	-	0.1% F.S.
Resolution (min)	0.01% F.S.	-	-	-
Min Outer Diameter	25 [mm]	6 [mm]	-	-
Max Outer Diameter	30 [mm]	18 [mm]	-	63.5 [mm]
Lightning Protection Required	Yes	No	No	No
Multipoint Readings	Yes	No	No	Yes
Max Reading Points	-	1	1	Unlimited
Remote Reading	Yes	No	No	Yes
Automated Reading	Yes	No	No	Yes
Advantages	Easy to read. Minimum construction interference. Negative pore pressure readings. No freezing problems.	Reliable. Cavity can be flushed. No moving parts. Negative pore pressure readings.	Reliable. Cavity can be flushed. Negative pore pressure readings.	Wireless communication. No casing required. Blasting resistant.
Limitations	Low electrical input. Errors caused by moisture of electrical components.	Applications limited to long-term embankment dams.	Periodic flushing may be required. Not suitable for hard rock.	Not tested on mine sites yet. It can only be installed as a system of several devices.

As shown in Table 5.3 and Table 5.4, the review not only took into account the application range of the devices, but also their response time, accuracy, resolution, ability to perform multipoint readings (essential to define piezometric profiles) and other parameters related to their installation and use.

It is important to mention that all of the types of transducers that were reviewed were compared taking into account that the desired application considers an installation in a hard rock environment. This critical analysis is useful to quickly identify some technologies that might not be applicable to mining environments as they were designed to be solely used in soils and civil structures; for example, the Twin-Tube and Flushable piezometers.

However, even though some technologies have been discarded for their application in an rock slopes, Standpipe piezometers and Diaphragm piezometers, both the pneumatic and electric types, are still viable alternatives to perform pore water pressure monitoring in mining environments. Section 5.2.2 defines the most suitable device or devices for the current application.

5.2.2. Instrument Selection for the Mine Plan

For this particular situation, the slope is constructed on rock, subsequently, an instrumentation campaign needs to be designed using Standpipe, VW, Semiconductors, Piezoresistive or Pneumatic piezometers as Twin-Tube and Flushable piezometers have been discarded.

The open standpipe piezometer is a simple device and generally considered more reliable than other types of piezometers. However, its main limitation is a high hydrodynamic time-lag, which is the volume of water that is necessary for an instrument to register changes in pressure or head fluctuation.

The present monitoring campaign has the objective to measure groundwater pressure considering that steeper walls may require drainage to ensure stability. Since the fluctuations in pressure are expected to be high due to a drainage campaign or precipitation, a technology with a short time-lag is preferred. Therefore, diaphragm piezometers should be used to monitor the response of the ground to the changes in pressure, as they might be too subtle to be measured by an open standpipe piezometer.

Diaphragm piezometers, stabilize after a pressure change occurs within seconds to several minutes. However, electrical piezometers have a significantly smaller time-lag than Pneumatic sensors and, also, pneumatic piezometers are unable to measure negative pore pressures while it has been noted that VW piezometers are able to sense pressures of 50 [kPa] below atmospheric pressure. These characteristics make electrical sensors more suitable for the application than pneumatic sensors.

In addition to the favorable characteristics of the instrumentation, the VW technology has a stronger presence in the market than Semiconductor or Piezoresistive piezometers, which results in lower cost of the campaign and availability of more technical support for the devices prior and during the implementation at the mine site.

Therefore, based on the review of currently available instrumentation, a multi-point instrumentation campaign based on Vibrating Wire piezometers was decided to be the best alternative for the studied application for pore pressure measurements.

The monitoring campaign using VW piezometer was supplemented with an equivalent campaign using the Enhanced NSMs with the objective of establishing how well an emergent technology performs in terms of logistic and price to a well-established technology.

5.2.3. Guidelines for Instrument Deployment

There are several considerations to be addressed with respect to the proper implementation of the monitoring instrumentation in the mine including:

- The position of the boreholes with respect the slope’s face and their number, and

- The position of the boreholes with respect to each other.

The former serves to establish the total number of holes that need to be drilled based on the lithology that will be exposed (at least one hole in each different lithology) and, subsequently, the number of devices to be installed in a single hole and the manner in which the boreholes will be sealed once the devices have been placed inside them. In addition, with respect to surface coverage, the boreholes should be located as close to the crest of the slope as possible and no farther than 100 to 200 meters behind the slope wall. The latter enables determination of the spacing of the boreholes: the holes should be drilled every 100 to 150 meters if the length of the exposed lithology is greater than 200 meters.

Based on those requirements, there must be at least one hole placed in the South Wall and another in the east wall of the proposed mine operation.

A standard monitoring campaign is proposed considering 6 boreholes to install pore water pressure monitoring sensors with the location of the holes as determined previously: the boreholes are drilled 5 meters behind the crest of the slope and are separated 200[m] from each other in each instrumented wall (Figure 5.1). This monitoring campaign is designed for both type of sensors; both technologies monitor the same area with the same setup but differentiated by the number of devices that are installed inside a single borehole.

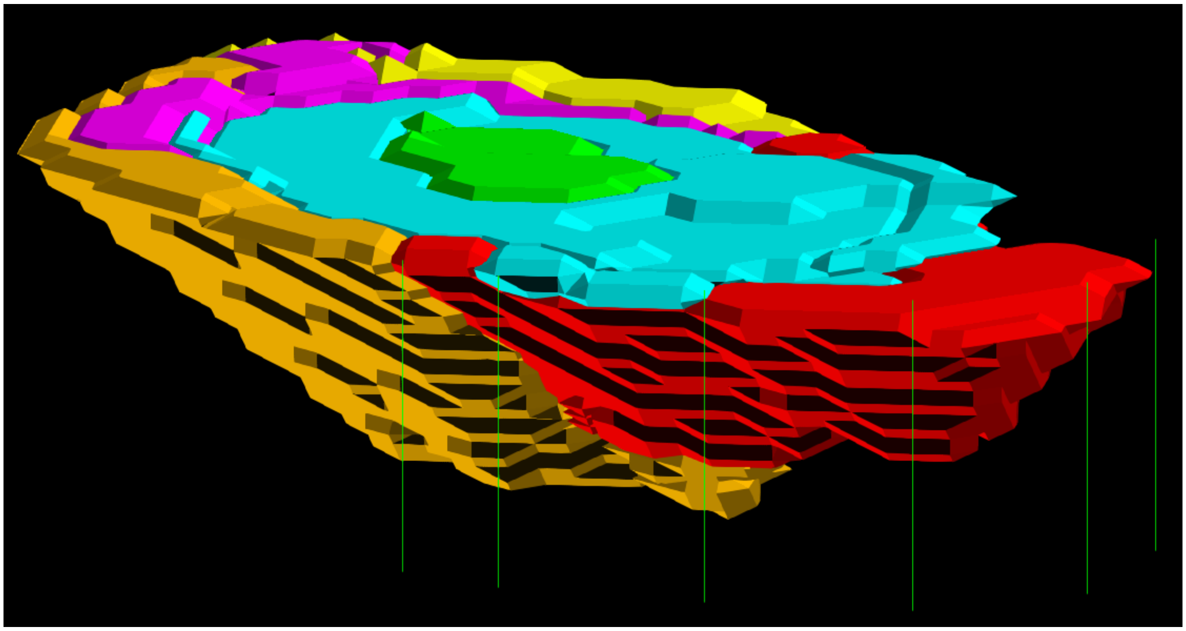


Figure 5.1: Initial setup for instrumentation campaign in the South-East walls of the open pit

An important consideration to be made when designing any geotechnical instrumentation campaign is the effect of the environment on the devices and their capacity to perform and obtain measurements over time. As a rule of thumb, it is expected that about 20% of all the installed instruments shall be replaced every 10 years due to deterioration. Therefore, the present monitoring campaign considers a second stage whereas four (4) additional boreholes are to be drilled as some of the original devices may have stopped working. The final setup considers 10 boreholes separated every 100[m] (Figure 5.2).

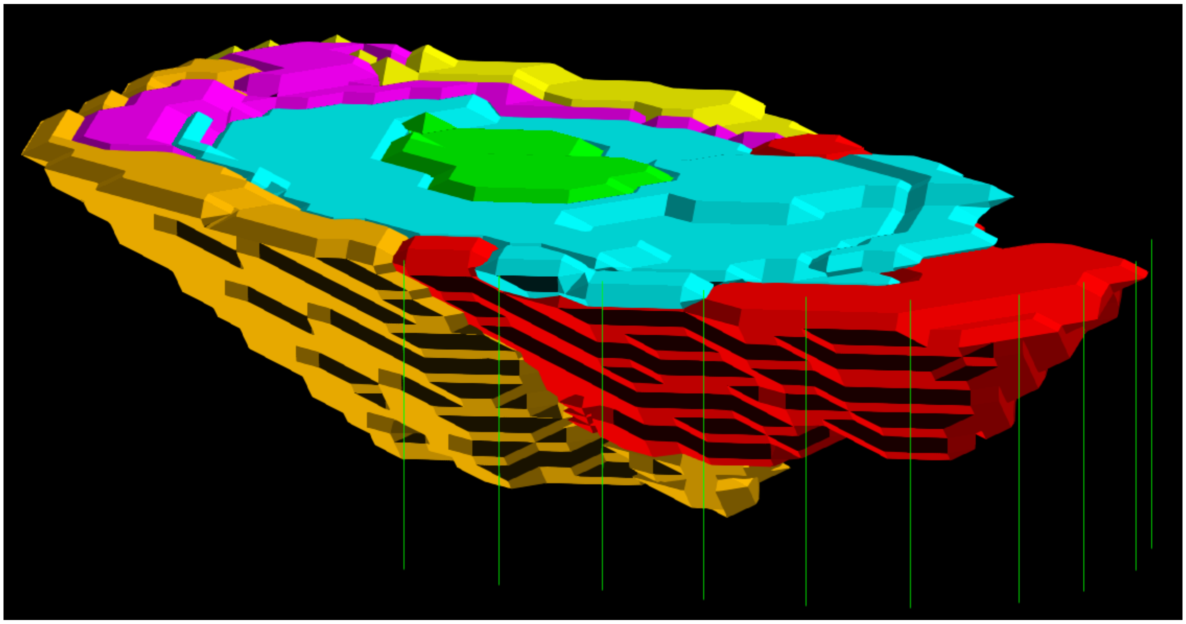


Figure 5.2: Final setup for instrumentation campaign in the South-East walls of the open pit

For the VW piezometer campaign it is known that, typically, two (2) to five (5) sensors can be placed inside a hole but for HQ or RC holes this number may be greater than six (6). On the other hand, for boreholes with Enhanced NSMs there is no limitation on the number of devices to be placed inside them as long as the communication range between sensors is not exceeded. The issue of defining the number of instruments in each borehole is discussed in detail in Section 5.3.

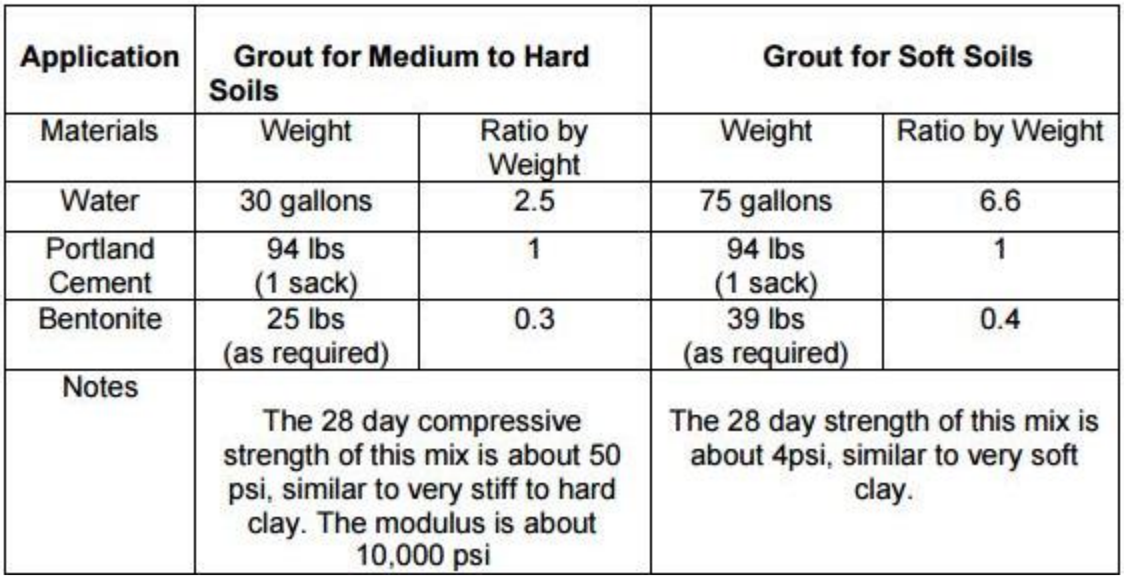
When installing piezometers in boreholes, the type of grout that is used to seal the drill holes is a critical matter that needs to be dealt with accordingly. This is due to the fact that different types of grout have different effects on the performance of piezometers: if the grout has a low permeability, it can cause the tip to be completely isolated preventing the instrument from taking any measurements while, if the grouting is too permeable, it can cause a vertical connection between strata altering the readings in the measurement zone.

As VW piezometers have a faster response time than standpipe piezometers, it allows this type of instruments to be installed with a fully grouted method that involves the exclusive use of a cement-bentonite grout to backfill the entire borehole instead of the more complex and time consuming procedure of leaving a sand pack around the piezometer tip and a bentonite seal layer above the filter zone before grouting, which is preferred for standpipe piezometer installations.

For a scenario where multiple pressure transducers are to be installed in a single borehole, a procedure that requires the installation of sand packs, bentonite seals and then backfill should be avoided because of operational impracticality; the fully grouted method should be the preferred method.

The instruments selected for the instrumentation campaign were those provided by Geokon; this company is a leader in Vibrating Wire technology manufacturing. Geokon has established guidelines for piezometer installation in boreholes in which they recommend that the Mikkelsen

& Green’s table to determine the ratios of grout mix be used. To apply this information in hard rock instead of soil, it is recommended to take as a base the Cement/Bentonite/Water ratios used for hard soils (Figure 5.3).



Application	Grout for Medium to Hard Soils		Grout for Soft Soils	
Materials	Weight	Ratio by Weight	Weight	Ratio by Weight
Water	30 gallons	2.5	75 gallons	6.6
Portland Cement	94 lbs (1 sack)	1	94 lbs (1 sack)	1
Bentonite	25 lbs (as required)	0.3	39 lbs (as required)	0.4
Notes	The 28 day compressive strength of this mix is about 50 psi, similar to very stiff to hard clay. The modulus is about 10,000 psi		The 28 day strength of this mix is about 4psi, similar to very soft clay.	

Figure 5.3: Cement/Bentonite/Water ratios for two grout mixes (Mikkelsen & Green, 2003)

5.3. Design of Pore Water Pressure Monitoring Programs

5.3.1. Groundwater Monitoring Campaigns

Two instrumentation campaigns were designed: the first considered the use of established sensing technologies e.g. the Vibrating Wire Piezometer while the second considered the use of the emergent technology of Enhanced Networked Smart Markers (ENSM).

The objective of the research described in this Section is to establish, which of the two technologies was more suitable to measure developing pressures caused by the expansion of a mine in a cost-effective way. To compare the technologies, similar implementation setups were used. The Mine Plan developed in Chapter 4 was used for this analysis.

5.3.2. Monitoring Campaign based on Vibrating Wire Piezometers

The number of devices that can be placed inside a borehole depends on the diameter of the borehole as well as the type of instrument installed. The assumption for the development of the monitoring campaign was the use of eight (8) Geokon Standard Vibrating Wire Piezometers (model 4500S) installed inside a HQ borehole.

Considering that different boreholes have different depths as they intersect the topography at different heights, the spacing between the devices inside the holes varies slightly, as shown in Table 5.5.

Table 5.5: Number and spacing of piezometers in boreholes for the first monitoring stage

	Depth [m]	Number of Piezometers	Piezometer spacing [m]
Borehole 1	292.5	8	36
Borehole 2	292.5	8	36
Borehole 3	277.5	8	34
Borehole 4	268.25	8	33
Borehole 5	262.5	8	32
Borehole 6	277.5	8	34

The data-logging system consisted of a single 16-channel data-logger (model LC-2x16) set to be used to gather the data from two neighboring boreholes. Therefore, a total of 3 data-loggers were required for the initial stage of the monitoring. Each of the 3 data-loggers was installed at a safe distance of 100[m] behind the crest of the slope. Each piezometer was connected directly to its correspondent data-logger device using a cable, which was protected by a galvanized conduit between the borehole and the data-logger.

For the second stage of the monitoring, four (4) new boreholes were drilled intersecting the topography of the model at different points resulting in the holes having different depths and thus housing different number of devices. The characteristics of these four new boreholes are presented in Table 5.6.

Table 5.6: Number and spacing of piezometers in boreholes for the second monitoring stage

	Depth [m]	Number of Piezometers	Piezometer spacing [m]
Borehole 7	292.5	8	36
Borehole 8	277.5	8	34
Borehole 9	262.5	8	32
Borehole 10	262.5	8	32

The new boreholes were connected to the data-logging system consisting of 16-channel data-loggers (one every two boreholes), i.e. two (2) new data-loggers were required for this stage of monitoring. As during the first stage of the installation, the new data-loggers were installed at a safe distance of 100[m] behind the crest of the slope and were connected directly to their correspondent piezometers using a cable protected by a galvanized conduit.

5.3.3. Monitoring Campaign based on Enhanced NSMs

For the Enhanced Networked Smart Markers, the spacing between the devices was fixed ensuring adequate communication range between the Markers. As the maximum distance at which the signal can successfully be transmitted between two consecutive markers was 5[m], the ENSMs where installed down the hole every 4[m].

For ENSMs the data transmission was wireless and only the antenna installed at the top of each borehole required a cable. Table 5.7 summarizes the quantity of NSMs that needed to be installed in a single borehole and their respective antennas.

Table 5.7: Number and spacing of Enhanced NSMs in the initial boreholes

	Depth [m]	Spacing [m]	Number of NSMs	Number of Antennas
Borehole 1	292.5	4	72	1
Borehole 2	292.5	4	72	1
Borehole 3	277.5	4	68	1
Borehole 4	268.25	4	66	1
Borehole 5	262.5	4	64	1
Borehole 6	277.5	4	68	1

The data-logging system consisted of a single Reader station capable of receiving and storing data from and sending commands to the six (6) antennas simultaneously. Thus, for the initial installation only one (1) Reader station was required.

The antenna cables coming out of the boreholes were all connected to a Splitter-box; the Splitter-box was connected to the Reader by a single cable. All the cables on the surface were protected by galvanized conduits.

For the second stage of the monitoring campaign, four (4) new boreholes were drilled, each of them located in a different section of the wall hence their difference in depth. The characteristics of these holes and the number of Enhanced NSMs installed inside them are summarized in Table 5.8.

Table 5.8: Number and spacing of Enhanced NSMs in the additional boreholes

	Depth [m]	Spacing [m]	Number of NSMs	Number of Antennas
Borehole 7	292.5	4	72	1
Borehole 8	277.5	4	68	1
Borehole 9	262.5	4	64	1
Borehole 10	262.5	4	64	1

5.4. Cost of Geotechnical Instrumentation Programs

The defined campaigns were evaluated from an economic perspective to determine which technology, Vibrating Wire Piezometers or Enhanced Networked Smart Markers, represented better alternative (economically) to perform the required monitoring.

5.4.1. Vibrating Wire Piezometer-based Monitoring Program

To determine the costs of a Vibrating Wire Piezometer campaign, a leader manufacturing company of these type of devices, Geokon, was consulted about the cost of their products and materials (Table 5.9).

Additional costs that have to be taken into account for the piezometers' installation were related to drilling, grouting and auxiliary equipment.

The drilling of the boreholes is the most expensive item of the installation. To determine the price of drilling, mine personnel was consulted regarding the cost of an HQ drilling, but without considering core-logging, since that activity was not considered for the installation itself (it is recommended to acquire a better understanding of the structures and lithology of the site prior to installation).

Table 5.9: Costs of Vibrating Wire Piezometers and related equipment

Product	Cost
Standard VW Piezometer model 4500S	400 [US$]
Communication cable	2.6 [US$/m]
16-channel Data-logger model CL-2x16	1,850 [US$]

The grouting of the boreholes to seal the devices inside depends on the ratio per weight of the mix components that was detailed in Figure 5.3. The weight of every component was converted to units of the International System (Table 5.10). This ratio was used in later calculations to determine the amount of water, cement and bentonite required to fill all of the boreholes drilled for this campaign.

Table 5.10: Ratio of materials for grout mix

Materials	Weight	Unit
Water	0.11	m^3
Cement	42.64	kg
Bentonite	11.34	kg

To calculate the cost of grouting, the cost of desalinated water in Chile, the cost of a pallet of 40 bags of standard Portland Cement and the cost of a pallet of 40 bags of Cement Stable CSR Bentonite (a cement stable powder bentonite specially developed for cement-bentonite grout) were used. In addition, the cost of the galvanized conduit to protect the cables was added. The summary of the materials' cost is presented in Table 5.11.

Table 5.11: Cost of materials used for piezometer installation

Product	Cost
Galvanized conduit	2 [US$/m]
Average cost of drilling	300 [US$/m]
40 bags of cement (42.5 kg each)	280 [US$]
40 bags of bentonite (25 kg each)	490 [US$]
Desalinated water	5 [US$/$m^3$]

The first stage of monitoring, where six (6) boreholes needed to be instrumented with eight (8) piezometers each, required a considerable amount of materials to perform the installation. The total cost of Vibrating Wire Piezometer installation was calculated to be **581,856[US$]**, Table 5.12 summarizes the materials required and their costs.

Table 5.12: Summary of costs for first VW Piezometer installation

Item	Amount	Cost [US$]
Drilling	6 boreholes	501,225
Piezometers	48 devices	19,200
Data-loggers	3 devices	5,550
Cable	14,948 m	38,864.8
Conduit	7,568 m	15,136
Water	12.09 m3	60.46
Cement	4,539.8 kg (3 pallet)	840
Bentonite	1,207.4 kg (2 pallet)	980

The second stage of monitoring considered four (4) new boreholes for pore water pressure measurement, with a total cost of **375,632[US$]**. The items used for this installation and their costs are summarized in Table 5.13.

Table 5.13: Summary of costs for second VW Piezometer installation

Item	Amount	Cost [US$]
Drilling	4 boreholes	328,500
Piezometers	32 devices	12,800
Data-loggers	2 devices	3,700
Cable	7,655 m	22,198.8
Conduit	2,789 m	7,344
Water	7.92 m3	39.62
Cement	2,975.4 kg (2 pallet)	560
Bentonite	791.3 kg (1 pallet)	490

5.4.2. Enhanced NSM-based Monitoring Program

To determine the costs of the Enhanced Networked Smart Markers campaign, the manufacturing company, Elexon, was asked to provide the price of their instruments. Table 5.14 summarizes the tentative costs of the products used for pore pressure monitoring.

Table 5.14: Costs of Enhanced NSMs and related equipment

Product	Cost
Enhanced Networked Smart Marker	540 [US$]
Coaxial cable	1 [US$/m]
Reader Station	7,026 [US$]

As the installation of these devices considered the same type of grouting and protection for the cables, the materials listed in Table 5.11 were also used in the Enhanced NSM monitoring campaign. The first installation, considering six (6) boreholes and a spacing of 4[m] between Markers, had a total cost of **740,490[US$]**. The detail of the materials used for this particular installation are presented in Table 5.15.

Table 5.15: Summary of costs for first Enhanced NSM installation

Item	Amount	Cost [US$]
Drilling	6 boreholes	501,225
Enhanced NSMs	410 devices	221,400
Antennas	6 devices	3,030
Reader Station	1 device	7,026
Cable	1,997 m	1,997
Conduit	1,967 m	3,934
Water	11.73 m3	58.66
Cement	4,404.7 kg (3 pallet)	840
Bentonite	1,171.5 kg (2 pallet)	980

The second stage of monitoring, the installation of Enhanced NSMs and their associated equipment had a total cost of **484,955[US$]**. The materials used for this campaign and their respective costs are detailed in Table 5.16.

Table 5.16: Summary of costs for second Enhanced NSM installation

Item	Amount	Cost [US$]
Drilling	4 boreholes	328,500
Enhanced NSMs	268 devices	144,720
Antennas	4 devices	2,020
Reader Station	1 device	7,026
Cable	547 m	547
Conduit	527 m	1,054
Water	7.69 m3	38.44
Cement	2,886.8 kg (2 pallet)	560
Bentonite	767.8 kg (1 pallet)	490

5.5. Cost of Geotechnical Instrumentation Programs

Both pore water pressure monitoring campaigns were compared from an economic perspective to determine the best alternative for pore water pressure measurements.

Section 5.4 showed that a monitoring campaign using Vibrating Wire Piezometers has a total cost of **957,488[US$]**, making it less expensive than the campaign based on the Enhanced Networked Smart Markers, which costs **1,225,446[US$]**. However, these costs do not take into consideration the period in which installation occurs and how the investment required for the monitoring campaign affects the value of the whole project.

Therefore, an analysis of the cost of these instrumentation campaigns was made to identify how they affect the final outcome of the project in terms of the Net Present Value. The mine plan was studied to determine the most appropriate period of the project during which the instrumentation should be installed.

After analyzing the mine plan, it was noted that the South Wall would have become the final pit wall in the fourth year of mining and thus, the first stage of the instrumentation campaign needs to commence at the beginning of the fourth year. Therefore, the capital cost of the instruments and the associated infrastructure had to be expended in the previous period.

The NPV of the project had to be recalculated for the new scenarios that included groundwater monitoring, thus differing from what was presented in Chapter 4. The first three (3) years of the project now considered the cash flow of the original plan that was the base for the extraction of the ore body since the first pushback was fully extracted before the South Wall started to be excavated. From the fourth year onwards, the cash flow of the project took the values of the optimized scenario since it considered the steepening of the final South Wall.

5.5.1. Vibrating Wire Piezometers-based Program

When an instrumentation campaign based on the use of Vibrating Wire Piezometers was implemented, the cost of installation of the devices was divided into two periods. During the third year of the project, an extra capital cost was considered in the cash flow to account for the first stage of the instrumentation that took place in year four. Subsequently, in the thirteenth year of the project, the costs of installation for the second stage of the campaign were added to the cash flow.

The NVP of the project, considering the instrumentation costs, was calculated to be 276,441,504[US$], which was less than the optimized mine plan that considered the steepening of the wall without instrumentation (289,110,000[US$]). However, the optimized plan did not account for the potential loss of stability in the southern slopes as the new plan did. On the other hand, this project, that considers the VW Piezometer campaign, has a NPV that is 29,755,592[US$] higher that the NPV of the original mine plan (246,690,000[US$]).

5.5.2. Enhanced Networked Smart Markers-based Program

The same cost analysis was undertaken for the instrumentation campaign based on the use of Enhanced Networked Smart Markers. The implementation cost was divided into two periods, where the cost for the first stage was added to the cash flow of the third year of the project while the cost for the second stage was taken into consideration in the thirteen year.

The NPV of this new project was calculated to be 276,275,377[US$] with the value of the project being less than the optimized plan but allowing a better management of the potential instabilities of the southern slopes. The project considering ENSMs generated 29,589,465[US$] more in profits than the original plan that did not considered a steeper South Wall that required monitoring.

5.5.3. Final Observations

The Net Present Value for the original plan, the optimized plan, the plan for the project that considered the use of VW Piezometers and the plan for the project that used ENSMs are listed in Table 5.17.

Table 5.17: NPV for different configurations of the project

Mine Plan	NPV [MMUS$]
Original Project	246.69
Optimized Project	289.11
Project with VWP	276.44
Project with ENSM	276.28

Based on the values shown in Table 5.17, several observations can be made:

- The optimized mine plan, which considered a steeper South Wall from the beginning of the mine extraction, had the highest NPV. However, this aggressive design did not consider any measures to manage the potential instabilities that might have been generated in the southern slopes.

- Both plans that considered the implementation of an instrumentation campaign to monitor the pore water pressure generated behind a wall that was progressively steepened from the third year of extraction onwards resulted in a more profitable operation than the original plan.

- The difference in cost between both technologies in terms of the project as a whole was small for a mining project of this scale, thus both alternatives are feasible to perform monitoring.

CHAPTER 6: RESULTS & DISCUSSION

In this Chapter the results of the work detailed in Chapters 3, 4, 5 and 6 are discussed and analyzed in depth to draw conclusions from them.

6.1. Geotechnical Instrumentation Technologies

For this thesis, several technologies used to measure and monitor pore water pressure in soil and rock were identified, studied and reviewed. Most of the devices mentioned in previous chapters rely on transducers and techniques that have been applied and perfected over a long period of years to measure pressure and transmit data. However, one type of device relies on the use of a different approach to manage and transmit the measured data, this type of device is the Networked Smart Marker.

Chapter 3 summarized the implementation of the current version of the NSM technology in a mining environment thus proving that these devices can be successfully installed and used to transmit data wirelessly through rock. In that same chapter, new developments on the devices were presented, these upgrades consist of the implementation of new sensors within the NSMs, once the integration is completed a new model of these instruments will be released called Enhanced Networked Smart Marker. The ENSMs will then have capabilities to perform direct and quantitative measurements of pore water pressure as well as inclination inside a borehole.

Subsequently, the work in Chapter 4 was focused on developing a mine plan for the extraction of a theoretical ore body while maintaining stability on the walls. Said design was optimized to increase profit at the expense of stability in the slopes, this new scenario was analyzed and it was concluded that some form of monitoring was required in the potentially unstable slope since a higher stress concentration was expected behind the wall.

Chapter 5 then dealt with that issue by providing guidelines for pore water pressure monitoring and then incorporating instrumentation campaigns of Vibrating Wire Piezometers and Enhanced NSMs to the mine’s schedule as part of the extraction plan. The guidelines developed were presented as a result of a thorough research on available technologies and recommendations made by other authors.

6.2. Guidelines for Geotechnical Instrumentation

In Chapter 5, Table 5.2 shows new guidelines developed to select the appropriate instrument required to perform measurements on pore water pressure in a specific site with its own set of particular characteristics. This guide is useful to determine the type of device that should be used in a site, but it does little to give a notion on how an instrumentation campaign can be integrated to the mine extraction schedule.

A list of several tasks (Table 6.1) has been developed that may assist in incorporating geotechnical monitoring with the mine plan. It is important to note that these guidelines were developed from the methodology that was used in this thesis, but it can be applied to instruments that measure other variables than pore water pressure.

Table 6.1: Guidelines to integrate geotechnical instrumentation to the mine plan

Analyze the Characteristics of the Mine

- Slope design is critical in the development of open pit mines. To detect any potential instability, the mechanisms of failure need to be understood.

Identify all potential risks

- Determine and prioritize all relevant geotechnical information about the rock mass and structures interactions that require instrumentation to be obtained.
- Identify which variables can and need to be measured and monitored.
- It is important to keep in mind that if there are not relevant questions nor specific reasons for monitoring, then instrumenration should not be considered.

Establish areas of interest

- Areas where stability might be compromised as a result of aggressive design or poor geotechnical properties need to be individualized.
- Identify areas where new developments that deviate from the original plan might produce high kisk conditions leading to a loss of stability in the slopes.

Perform Numerical Modeling of the slope (*)

- Run models trying to recreate the response of the slope in the areas of interest. Determine the variables which variation may be significant for the stability of the slopes and predict the magnitude of these changes.
- (*) This task was not performed in this thesis, but the author considers that an interesting conclusion might have been made if some form of numerical modeling was performed to determine the change of expected pore water pressure values behind the slope when the design is optimized (south wall steepened).

Select appropriate instruments for monitoring

- Use the previously defined guidelines to choose the adequate instrument for the specific measurement (Table 5.2).
- Take into account range, resolution, accuracy, precision, conformance, rebustness and reliability of the devices (Tables 5.3 and 5.4) as well as the technical and economic feasibility.

Establish the optimal installation set-up

- Study how the studied parameters vary spatially in the zone to be monitored. Follow guidelines to determine spacing and number of devices required.

Determine the optimal period for installation

- Take notice of the schedule of the mining to determine the period on which the mining progress starts to have an influece in the area of interest.
- Determine the best period to purchase the devices and when to perform the installation. Take into account the wear of the devices and program their replacement or the installation of new instruments when possible.

Update cash flow

- Prepare the budget for the acquisition of instruments and materials and update the cash flow of the project considering the new expenses.

Table 6.1 summarizes good practices that should be considered when trying to include geotechnical instrumentation as part of the mine planning. Most of the steps were performed for the research presented in this thesis but since the model analyzed was theoretical, there was a lack of geotechnical information available and thus the numerical model analysis of the slopes was not performed. The author considers that a numerical model might have helped to quantify the impact of steepening the South Wall on the stability of the slopes.

The results obtained from this work reveal that the monitoring of geotechnical variables in the mine site is not a task that necessarily has to be perform individually and can be planned to be performed in periods defined in the mine's extraction schedule as part of the mine plan of the project. This approach would allow to have a global view of the mine operation and further establish that mine planning and geotechnical areas are related and that both departments in a mine site should collaborate and give feedback to each other to improve the overall performance of the mine.

During this research, aside from the guidelines developed, several instruments were analyzed, mainly the Networked Smart Markers and their Enhanced version which has pore water pressure measurement capabilities. In that regard, Section 6.3 presents the results of the comparison made between instruments and particularly describes how well the ENSMs might perform when compared to established sensing technologies.

6.3. Comparison between Sensing Technologies

A technical and economic comparison between sensing technologies to perform pore water pressure monitoring was carried out during this research.

6.3.1. Technical Comparison

Table 5.3 and Table 5.4 display a thorough comparison of different sensing technologies based on their technical characteristics, their advantages for their application in open pit mines and their limitations.

From Table 5.3 and Table 5.4 it is clear that the shorter response times, wider range of application and higher accuracy are met when piezometers with electric diaphragm sensors are used. Among that type of devices, Vibrating Wire Piezometers are widely regarded by the industry as a reliable tool for pore water pressure monitoring which has caused to be accepted as an established technology in the mining industry.

However, there are not general rules for selecting an instrument to perform different types of measurement that can be applied at every site. As it has been previously mentioned, Table 5.2 can be used to determine the types of instruments that are more suitable to perform a specific type of measurement in a certain environment. As for the device that should be finally installed in the site to get the better results, that instrument has to be determined by taking into consideration the specific requirements for the particular area of study and which instruments possess the technical characteristics that better suit the monitored site's needs. Therefore, both types of guidelines developed in this thesis complement each other and neither of them is able to provide an answer to the problem of which instrument should be installed in a mine on its own.

From Table 5.3 and Table 5.4 it can also be noted that multipoint readings are difficult to accomplish with current technologies and even though ENSMs may be a good alternative to perform that type of measurements, more research and trial applications are still required before that technology can be widely applied.

Since the Enhanced NSMs show good prospects on becoming a reliable alternative to perform multi-point reading of pore water pressure it was selected as one of the alternatives to be considered for the theoretical instrumentation campaigns that were proposed and analyzed, the other one being the Vibrating Wire Piezometer. Besides their technical capabilities, which are similar in terms of their range and accuracy, another aspect of importance was taken into account: their cost.

6.3.2. Economic Comparison

From Chapter 5 it is noticeable that VW Piezometers are less expensive than Enhanced NSMs in terms of the cost of a single device and data-logger and in the global cost of the whole campaign. However, the difference between their costs is 267,957[US$] and gets reduced to 166,126[US$] when considering the discount rate and the periods on which the expenses are made, this difference in cost is clearly not significant in the scope of a large open pit project that considers investments of millions of dollars and thus it should not be the decisive factor to opt for one technology over the other one.

Therefore, this research demonstrated that Enhanced NSMs are a viable alternative to perform multi-point pore water pressure measurements as their higher installation cost, which is 1,225,446[US$] (766,142[US$] considering discount rate), is not all that relevant when compared to an established and widely used technology such as the VW Piezometer.

To determine which of these two analyzed technologies is better suited for the monitoring program in the mine site, the amount of data and observation points required by the geotechnical team are the criteria that should determine what type of instruments should be used for this particular scenario. The scope of this research did not consider making that distinction or explicitly stating which type of device was better, as that is a relative term depending on the characteristics of the site. However, a recommendation for when economic concerns are not a variable in the decision, the guidelines proposed in Chapter 5 can provide some guidance on the type of sensor required.

Table 6.2 shows that the difference in cost between both types of technologies is not significant in terms of the project as a whole (0.39% of the investment of the project). It also shows that integrating a single pore water pressure monitoring campaign, with all of its associated activities and infrastructure, to the mine schedule does have a significant impact in the cash flow of the project. However, it is important to mention that this impact in the cash flow goes beyond the extra investment and operational expenses required to install the instruments, as a monitoring campaign also generates value for the project.

The added value that a monitoring campaign gives to a mining project is extremely difficult to quantify. For the research conducted in this thesis as well as in some studies in real mine sites monitoring adds monetary value to project by allowing the extraction of more ore and less waste thus increasing the income and by avoiding problems and damages that may cause massive losses to the company.

Table 6.2: Effect of implementing geotechnical campaign on cash flow

	ENSM	**VWP**
Cost of instrumentation [US$]	1,225,446	957,489
Discounted cost of instrumentation [US$]	766,142	600,016
Mine's total investment [US$]	68,780,000	68,780,000
Instrumentation cost/Total investment [%]	1.78	1.39
Mine's original VPN [US$]	246,685,913	246,685,913
Mine's updated VPN [US$]	276,275,378	276,441,505
Extra income as result of steeper walls [US$]	29,589,465	29,755,592

CHAPTER 7: CONCLUSIONS & FUTURE WORK

From the work carried out in this thesis several conclusions can be made that relate closely to the objectives established when the research began. The main goal of the research was to develop guidelines for the application of geotechnical instrumentation focused on devices used to measure groundwater pore pressure in open pit mines.

These guidelines were successfully developed through the review of suppliers and manufacturers and studying datasheets and specifications to provide a guide to select the appropriate type of instrument based on their technical characteristics. Some guidelines previously developed to discern between types of devices based on geological characteristics of the site and type of measurement were studied and updated using the gathered information.

7.1. Conclusions

Based on the mentioned review of sensing technology, it was concluded that:

- Currently in the market, there is an ample range of available instruments from different manufacturers whose products are not limited to transducers and sensors, but to the full extent of services that include the measuring devices, their installation and posterior analysis of the gathered data. Therefore, it can be noted that technology providers have expanded and evolved their share in the market.

- That ample range of instruments has not prevented new advances in the field of geotechnical instrumentation in the form of consecutive generations of device developments to monitor geotechnical variables in a more efficient way. In this thesis, the novel NSM technology was analyzed, which, after being installed in a mine in the north of Chile, was deemed as a viable alternative to wirelessly transmit data through rock. Therefore, it can be used, as soon as the new developments are completed, to perform monitoring of subsurface deformations and pore water pressure.

From the work undertaken in this thesis, various recommendations on when and how to apply different sensing technologies (established and in development) were successfully developed considering their differences and limitations. Several conclusions were reached:

- It is evident that each application case is unique and there are no general guides that would apply in every situation. Geology, lithology, hydrogeology, geotechnical issues, geometry of the mine and discontinuities are different for every mine and all of those characteristics should be considered when determining the way that monitoring should be performed.

- It is possible to integrate a geotechnical instrumentation program to a theoretical mine plan, establishing periods for the installation of devices based on the extraction schedule of the mine. However, as each mine has its own particular set of characteristics that may require a continuous update of the mine plan and design, it is highly recommended for these integration to be attempted in a study case of a real mine.

Finally, from the comparison made between sensing technologies, certain observations were made:

- With additional research to determine whether the implementation of these sensors inside the Markers is possible, Enhanced NSMs have the potential to perform multi-point pore water measurements with a much higher density of points than current sensing technologies.
- The economic appraisal proved that the emergent technology, Enhanced NSM, is comparable to the established instruments as the cost difference between monitoring campaigns was not significant in terms of the entire project value.
- The positive impact of a monitoring program is difficult to quantify as it is hard to establish a direct link between the extra information extracted from the gathered data and the way the slopes performance improves until a real case scenario is evaluated over an extended period.

7.2. Future Work & Recommendations

As the work undertaken in this thesis was being completed, new ideas for research were contrived as a way to expand on this research and obtain more conclusive results.

As a recommendation, it is proposed to apply the developed guidelines to select the type of instrument for a certain site to study cases in real mines. Observing the performance of different instruments on real and varying environments may provide information that can be used to improve and refine the proposed guidelines, thus reducing uncertainty and establishing more direct links between the characteristics of a site and the most appropriate device to monitor it.

The author also proposes that, all the attempts of integrating geotechnical monitoring to mine planning should also be applied to a study case involving a real mine. Updating the guidelines with the obtained results will be of aid since contingencies can be added to the list for changes in the mine schedule, varying commodity prices and mining costs, changes in design and all the other issues that the deterministic model used in this thesis may have overlooked.

Integrating monitoring programs to a real mine plan represents an opportunity to perform tasks that could not be carried out in this research for limitations on time and geotechnical information, such as a numerical modelling to check the effect that steepening the wall has on the expected pore pressure. It can also provide an opportunity to adapt the guidelines for different devices and propose new tables and recommendations to measure different variables in an open pit mine.

Finally, to have a better understanding of the influence of a proper monitoring and remedial actions on the cash flow of a mining project, the author proposes developing a risk management program and design a draining campaign to incorporate the cost of drilling relief wells or draining holes/adits. Thus, the effects of the entire pore water pressure management program can be quantified and explicitly expressed in the cash flow beyond the expected profit for extracting more ore material and less waste.

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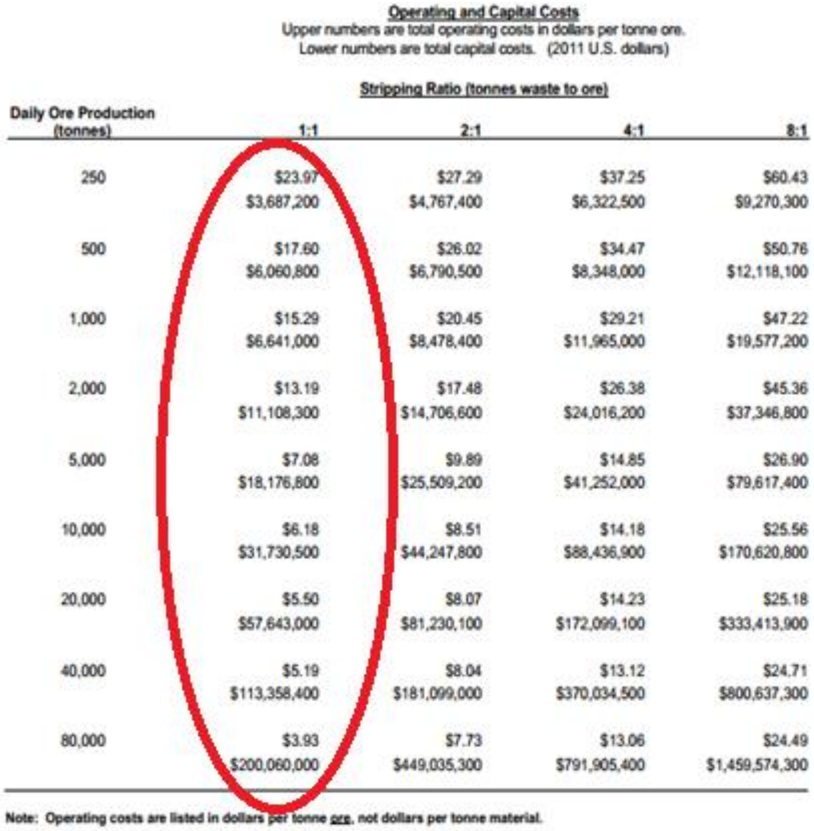
CHAPTER 9: APPENDIX

9.1. Appendix A: Mine Costs based on Extraction Rates

Table 9.1: Table of Operating and Capital Costs, retrieved from the Mine and Mill Equipment Estimator's Guide 2011.



Operating and Capital Costs
Upper numbers are total operating costs in dollars per tonne ore.
Lower numbers are total capital costs. (2011 U.S. dollars)

Daily Ore Production (tonnes)	Stripping Ratio (tonnes waste to ore) 1:1	2:1	4:1	8:1
250	$23.97 $3,687,200	$27.29 $4,767,400	$37.25 $6,322,500	$60.43 $9,270,300
500	$17.60 $6,060,800	$26.02 $6,790,500	$34.47 $8,348,000	$50.76 $12,118,100
1,000	$15.29 $6,641,000	$20.45 $8,478,400	$29.21 $11,965,000	$47.22 $19,577,200
2,000	$13.19 $11,108,300	$17.48 $14,706,600	$26.38 $24,016,200	$45.36 $37,346,800
5,000	$7.08 $18,176,800	$9.89 $25,509,200	$14.85 $41,252,000	$26.90 $79,617,400
10,000	$6.18 $31,730,500	$8.51 $44,247,800	$14.18 $88,436,900	$25.56 $170,620,800
20,000	$5.50 $57,643,000	$8.07 $81,230,100	$14.23 $172,099,100	$25.18 $333,413,900
40,000	$5.19 $113,358,400	$8.04 $181,099,000	$13.12 $370,034,500	$24.71 $800,637,300
80,000	$3.93 $200,060,000	$7.73 $449,035,300	$13.06 $791,905,400	$24.49 $1,459,574,300

Note: Operating costs are listed in dollars per tonne ore, not dollars per tonne material.

Table 9.2: Updated Table for OPEX and CAPEX per Extraction Rate.

Ore [t/day]	Total Material [t/day]	OPEX [US$/t]	CAPEX [US$]	CAPEX [MMUS$]
250	500	11.985	3,687,200	3.6872
500	1,000	8.8	6,060,800	6.0608
1,000	2,000	7.645	6,641,000	6.641
2,000	4,000	6.595	11,108,300	11.1083
5,000	10,000	3.54	18,176,800	18.1768
10,000	20,000	3.09	31,730,500	31.7305
20,000	40,000	2.75	57,643,000	57.643
40,000	80,000	2.595	113,358,400	113.3584
80,000	160,000	1.965	200,060,000	200.06

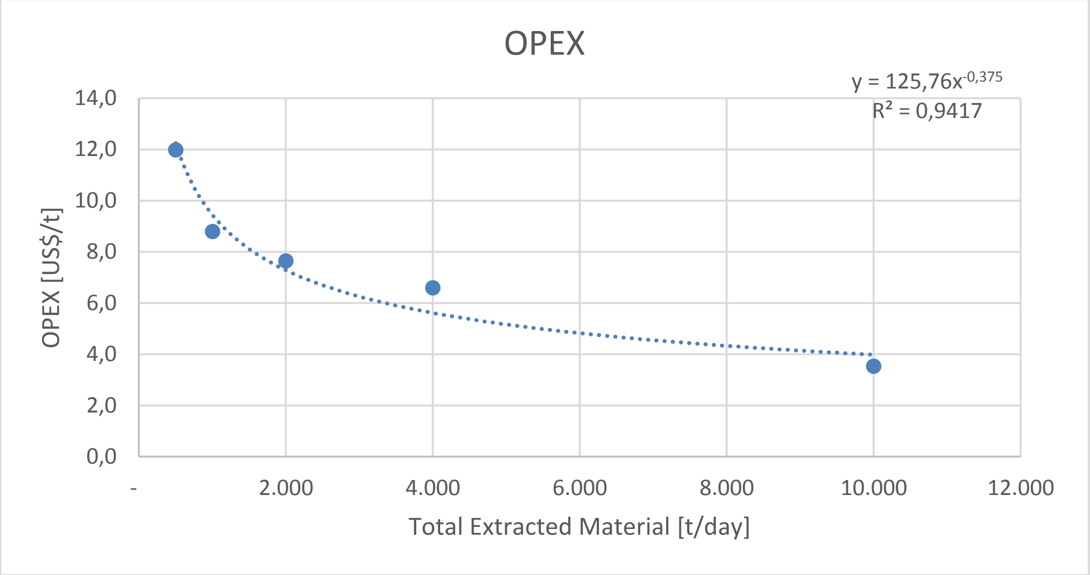


Figure 9.1: Calculated function to determine OPEX based on the Extraction Rate of the mine.

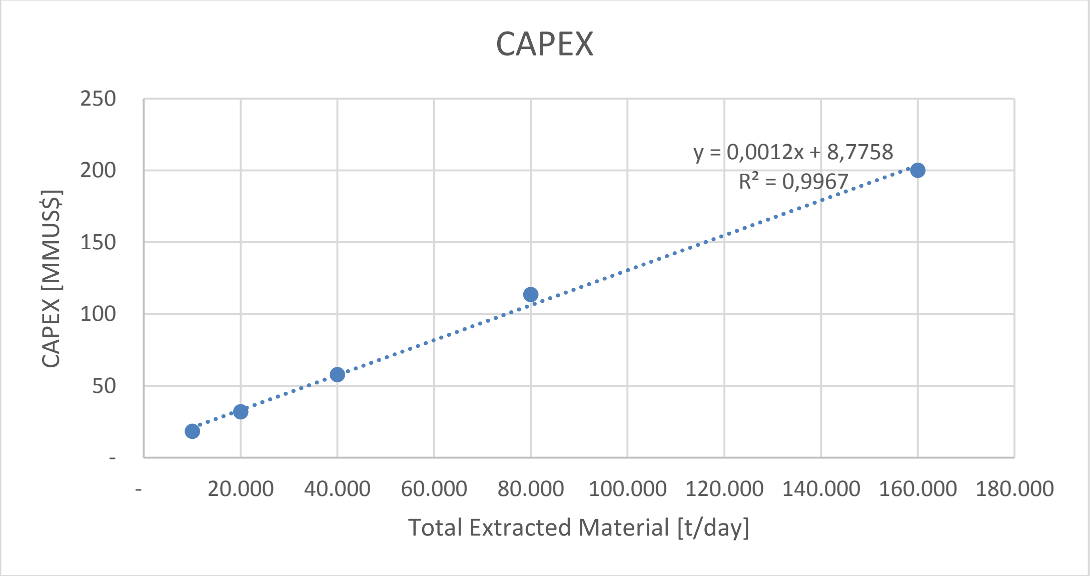


Figure 9.2: Calculated function to determine CAPEX based on the Extraction Rate of the mine.

9.2. Appendix B: Processing Plants Costs based on Processing Capacities

Table 9.3: Table of Operating and Capital Costs for Concentrator Plant, retrieved from the Mine and Mill Equipment Estimator's Guide 2011.

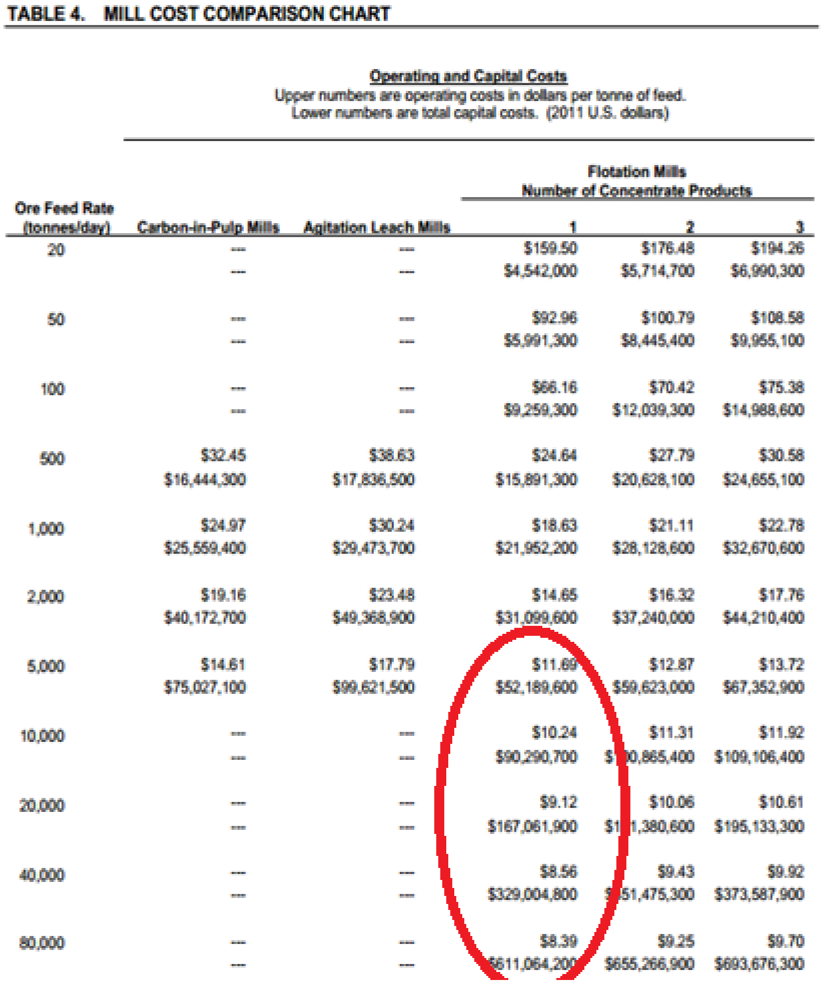


TABLE 4. MILL COST COMPARISON CHART

Operating and Capital Costs
Upper numbers are operating costs in dollars per tonne of feed.
Lower numbers are total capital costs. (2011 U.S. dollars)

Ore Feed Rate (tonnes/day)	Carbon-in-Pulp Mills	Agitation Leach Mills	Flotation Mills Number of Concentrate Products 1	 2	 3
20	--- ---	--- ---	$159.50 $4,542,000	$176.48 $5,714,700	$194.26 $6,990,300
50	--- ---	--- ---	$92.96 $5,991,300	$100.79 $8,445,400	$108.58 $9,955,100
100	--- ---	--- ---	$66.16 $9,259,300	$70.42 $12,039,300	$75.38 $14,988,600
500	$32.45 $16,444,300	$38.63 $17,836,500	$24.64 $15,891,300	$27.79 $20,628,100	$30.58 $24,655,100
1,000	$24.97 $25,559,400	$30.24 $29,473,700	$18.63 $21,952,200	$21.11 $28,128,600	$22.78 $32,670,600
2,000	$19.16 $40,172,700	$23.48 $49,368,900	$14.65 $31,099,600	$16.32 $37,240,000	$17.76 $44,210,400
5,000	$14.61 $75,027,100	$17.79 $99,621,500	$11.69 $52,189,600	$12.87 $59,623,000	$13.72 $67,352,900
10,000	--- ---	--- ---	$10.24 $90,290,700	$11.31 $1[illegible]0,865,400	$11.92 $109,106,400
20,000	--- ---	--- ---	$9.12 $167,061,900	$10.06 $1[illegible]1,380,600	$10.61 $195,133,300
40,000	--- ---	--- ---	$8.56 $329,004,800	$9.43 $[illegible]51,475,300	$9.92 $373,587,900
80,000	--- ---	--- ---	$8.39 $611,064,200	$9.25 $655,266,900	$9.70 $693,676,300

Table 9.4: Updated Table for OPEX and CAPEX per ton of Processed Ore in Concentrator Plants.

Ore Feed Rate [t/day]	OPEX [US$/t]	CAPEX [US$]
5,000	11.69	52,189,600
10,000	10.24	90,290,700
20,000	9.12	167,061,900
40,000	8.56	329,004,800
80,000	8.39	693,676,300

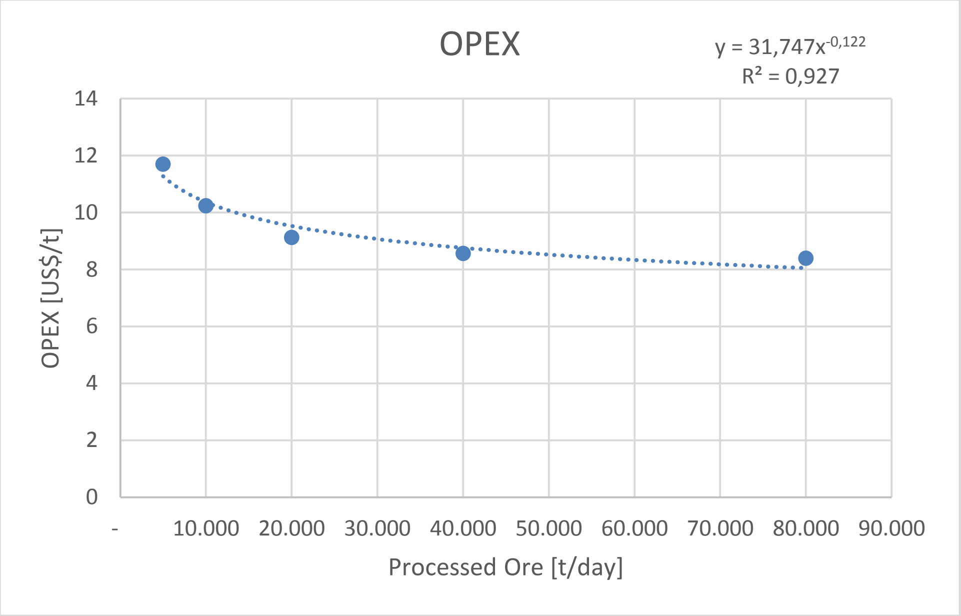


Figure 9.3: Calculated function to determine OPEX based on the Processing Capacity of the Concentrator Plant.

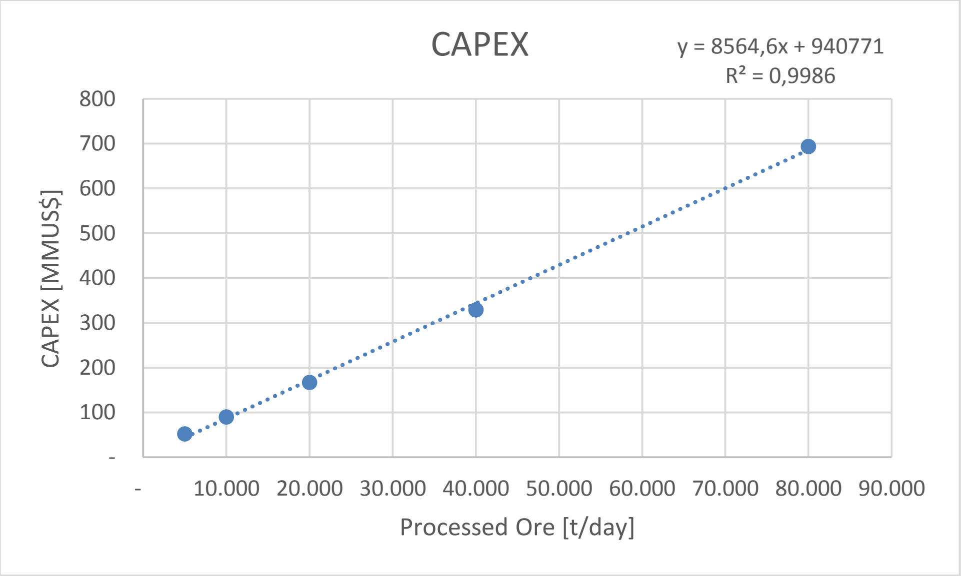
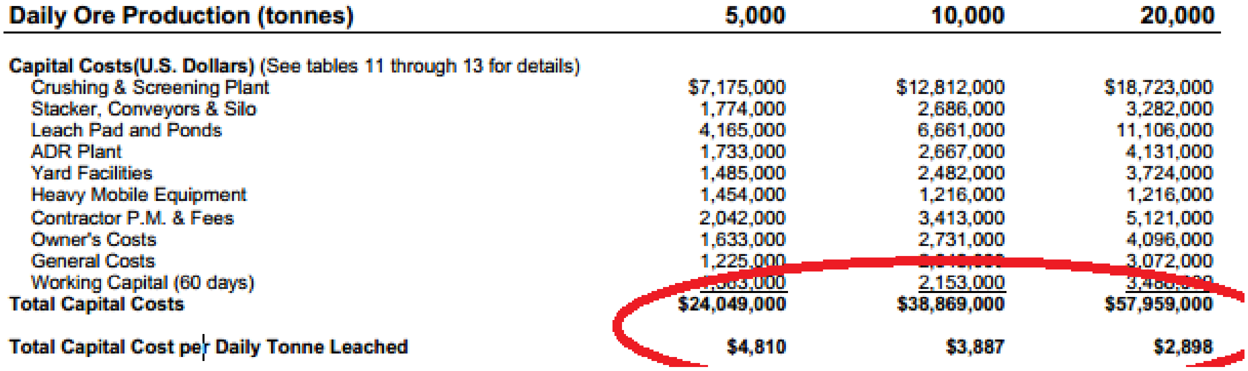


Figure 9.4: Calculated function to determine CAPEX based on the Processing Capacity of the Concentrator Plant.

Table 9.5: Table of Operating and Capital Costs for Leaching Plant, retrieved from the Mine and Mill Equipment Estimator's Guide 2011.



Daily Ore Production (tonnes)	**5,000**	**10,000**	**20,000**
Capital Costs(U.S. Dollars) (See tables 11 through 13 for details)			
Crushing & Screening Plant	$7,175,000	$12,812,000	$18,723,000
Stacker, Conveyors & Silo	1,774,000	2,686,000	3,282,000
Leach Pad and Ponds	4,165,000	6,661,000	11,106,000
ADR Plant	1,733,000	2,667,000	4,131,000
Yard Facilities	1,485,000	2,482,000	3,724,000
Heavy Mobile Equipment	1,454,000	1,216,000	1,216,000
Contractor P.M. & Fees	2,042,000	3,413,000	5,121,000
Owner's Costs	1,633,000	2,731,000	4,096,000
General Costs	1,225,000	[illegible]	3,072,000
Working Capital (60 days)	1,383,000	2,153,000	3,488,000
Total Capital Costs	**$24,049,000**	**$38,869,000**	**$57,959,000**
Total Capital Cost per Daily Tonne Leached	**$4,810**	**$3,887**	**$2,898**

Table 9.6: Updated Table for OPEX and CAPEX per ton of Processed Ore in Leaching Plants.

Ore Feed Rate [t/day]	Ore Feed Rate [Mt/year]	OPEX [US$/t]	CAPEX [US$]
5,000	1.8	7.54	51,043,360
10,000	3.6	5.98	82,497,106
20,000	7.2	4.83	123,013,436

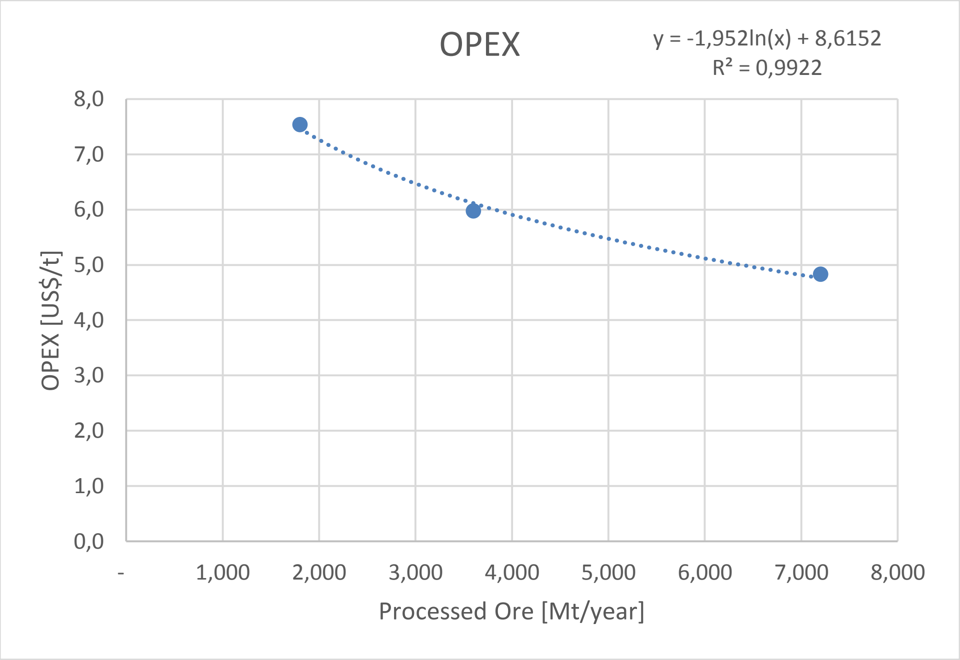


Figure 9.5: Calculated function to determine OPEX based on the Processing Capacity of the Leaching Plant.

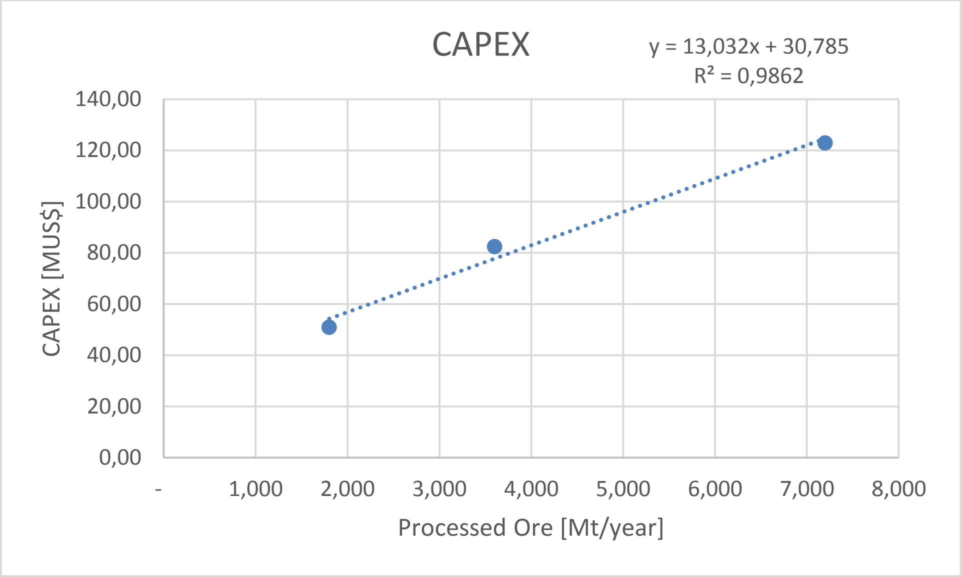


Figure 9.6: Calculated function to determine CAPEX based on the Processing Capacity of the Leaching Plant.

9.3. Appendix C: DeepMine’s Pushback Design for Initial Mine Plan

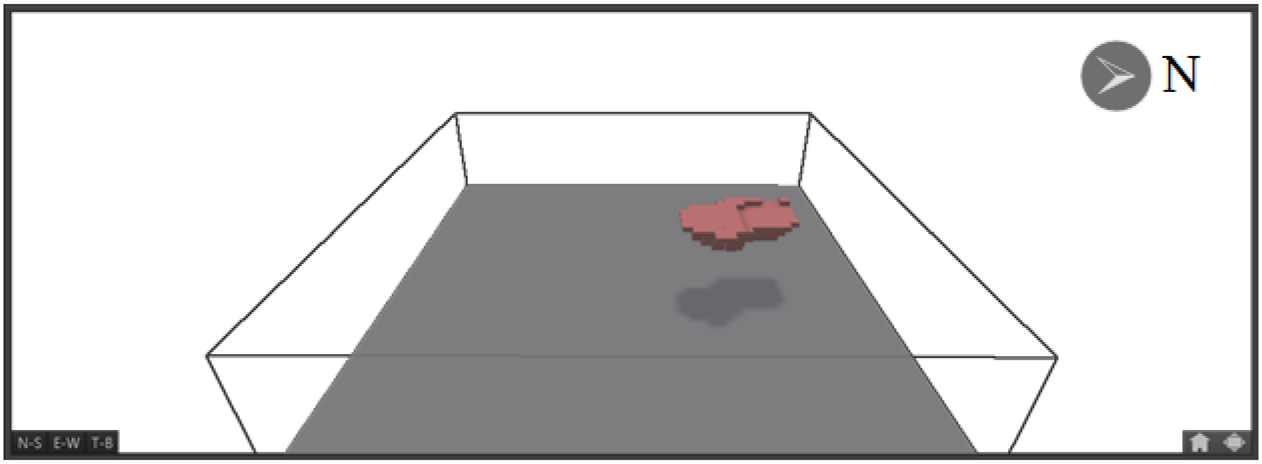


Figure 9.7: DeepMine's visualization for pushback 1

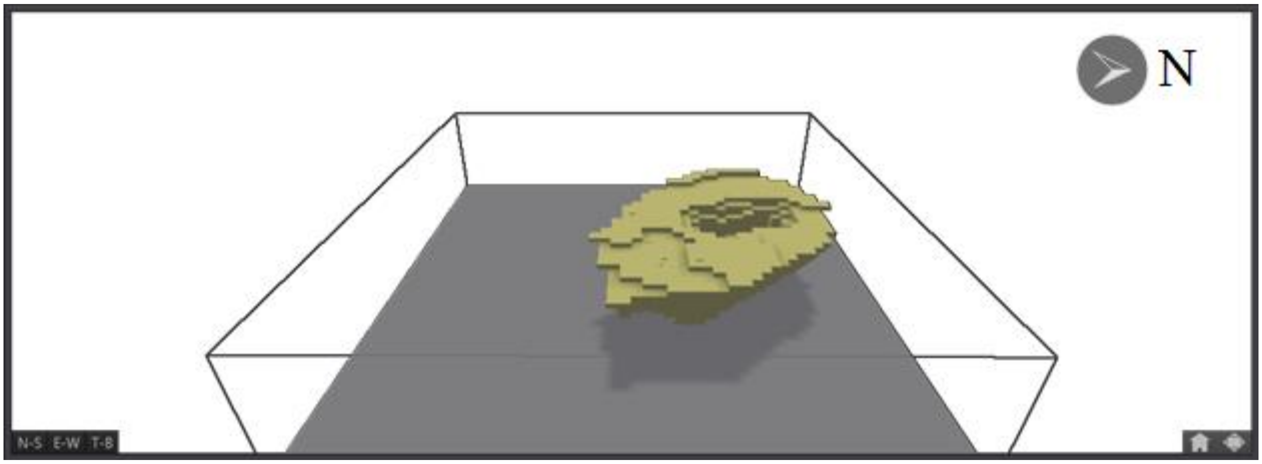


Figure 9.8: DeepMine's visualization for pushback 2

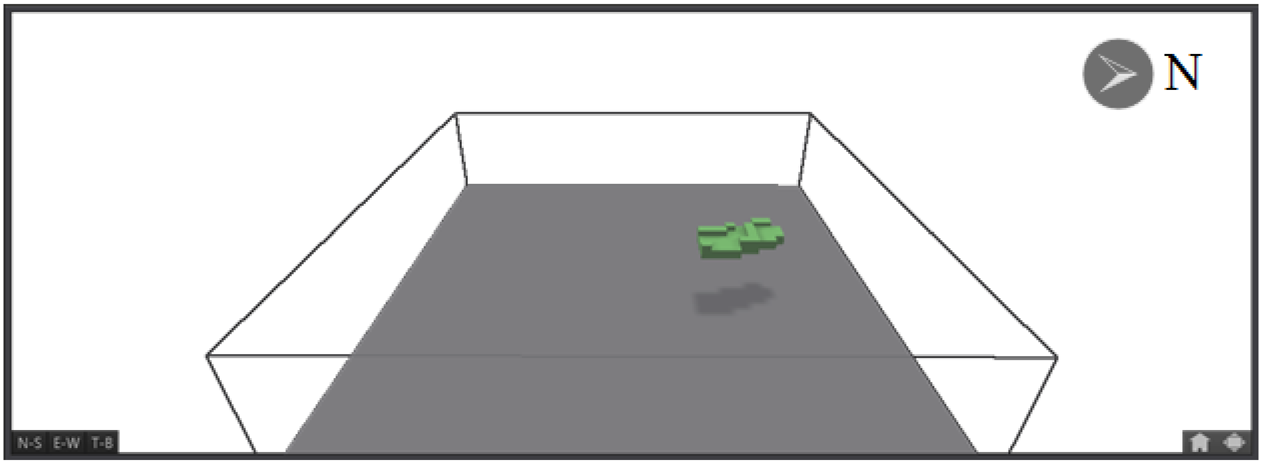


Figure 9.9: DeepMine's visualization for pushback 3

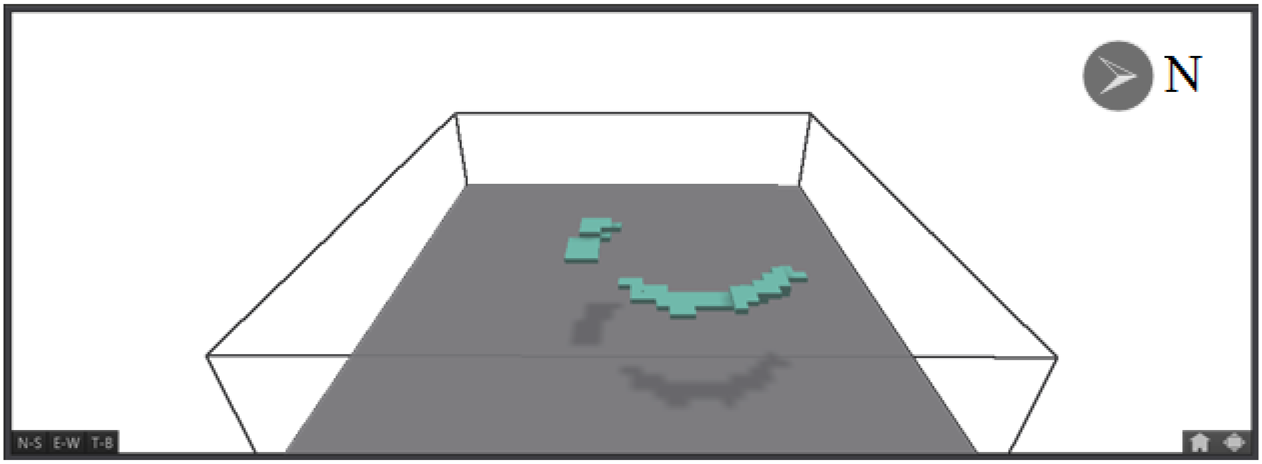


Figure 9.10: DeepMine's visualization for pushback 4

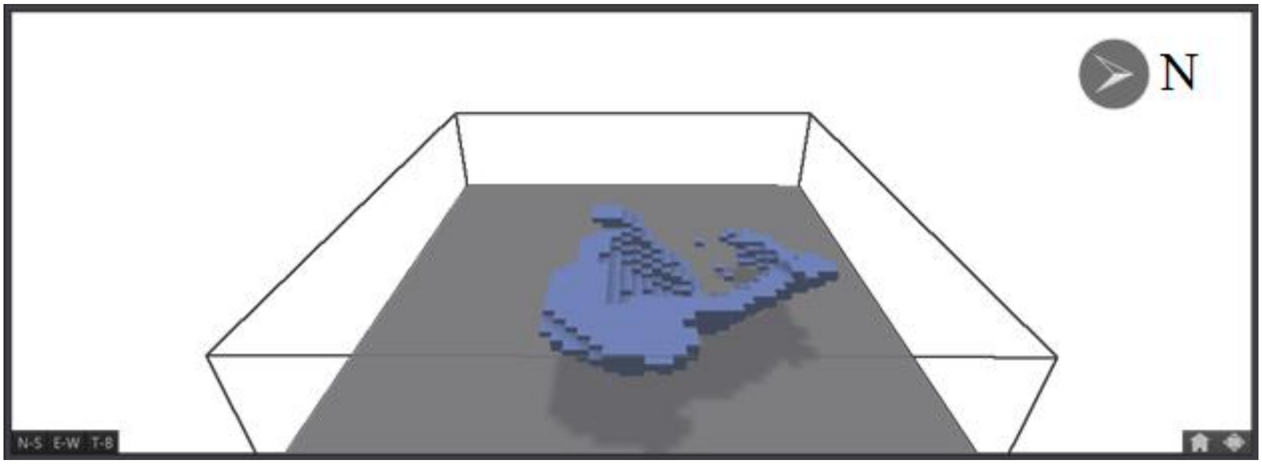


Figure 9.11: DeepMine's visualization for pushback 5

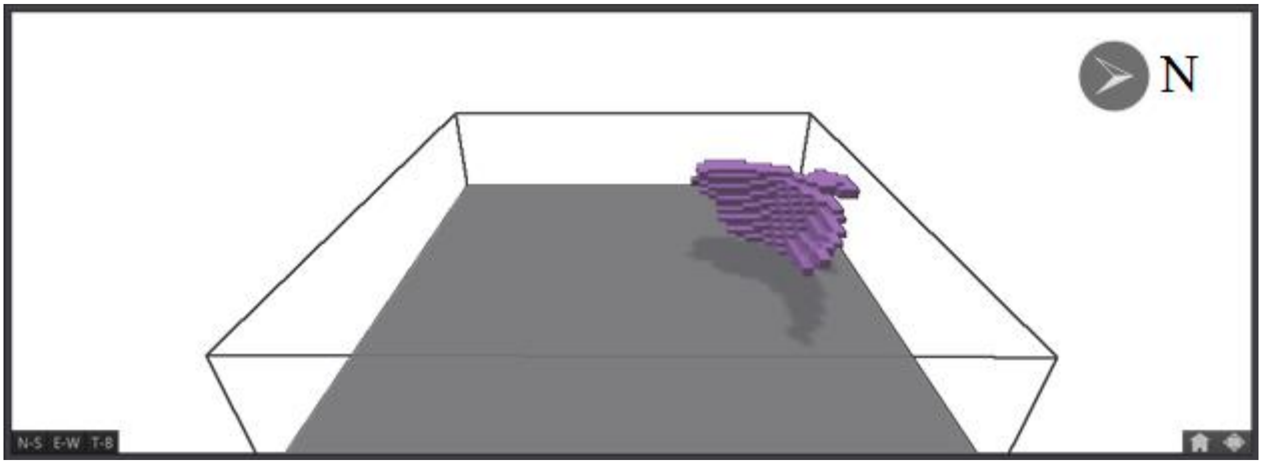


Figure 9.12: DeepMine's visualization for pushback 6

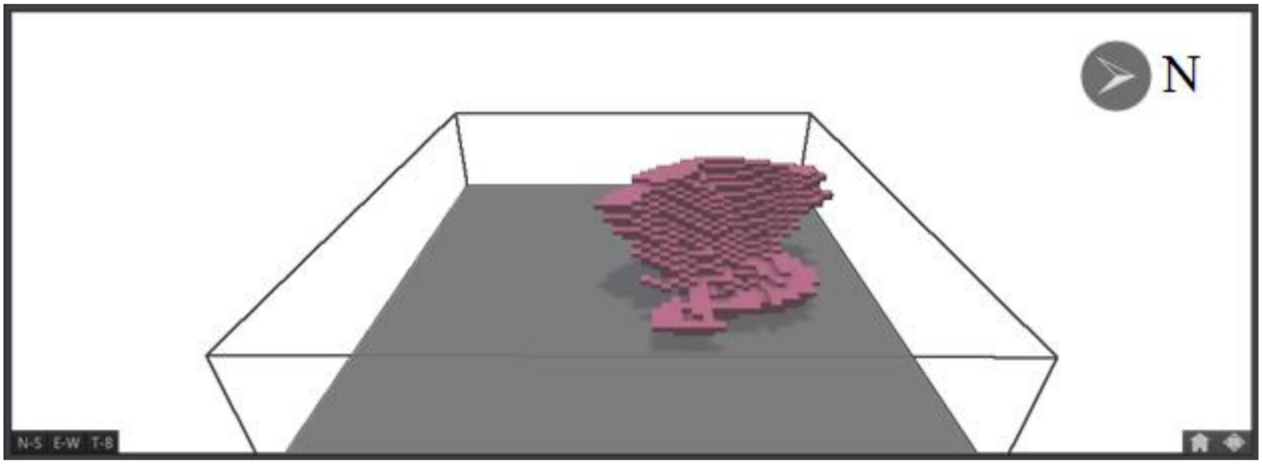


Figure 9.13: DeepMine's visualization for pushback 7

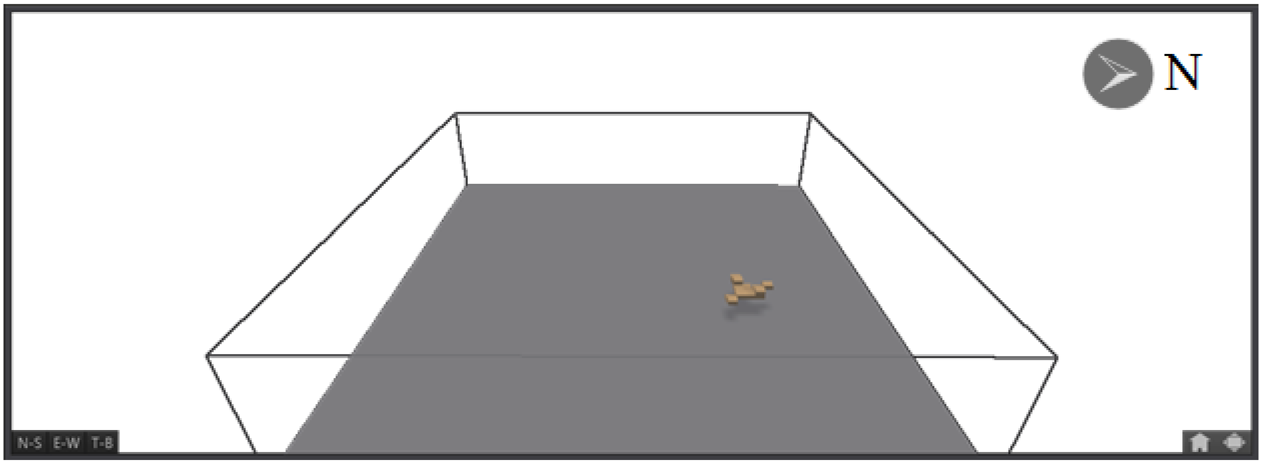


Figure 9.14: DeepMine's visualization for pushback 8

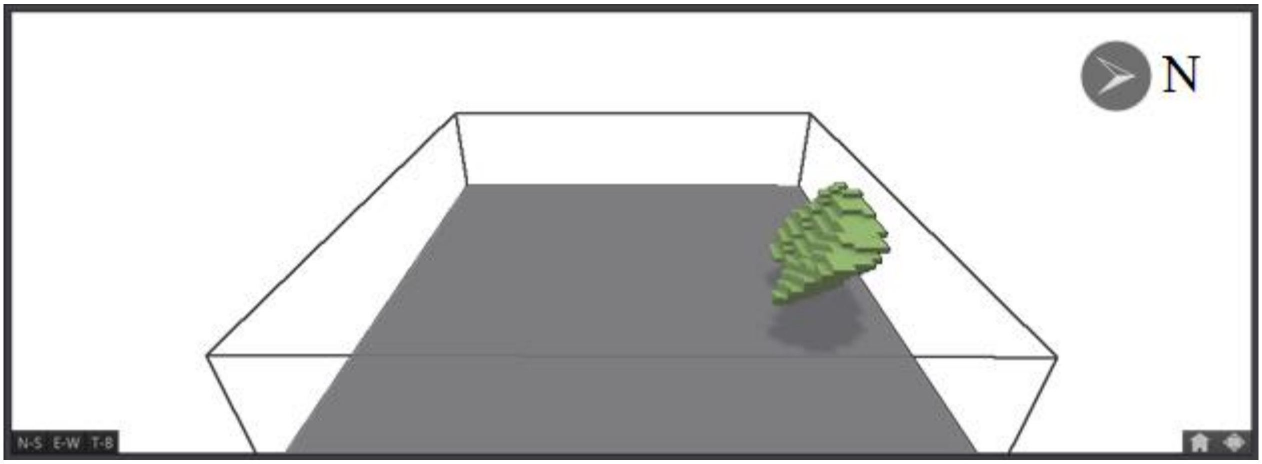


Figure 9.15: DeepMine's visualization for pushback 9

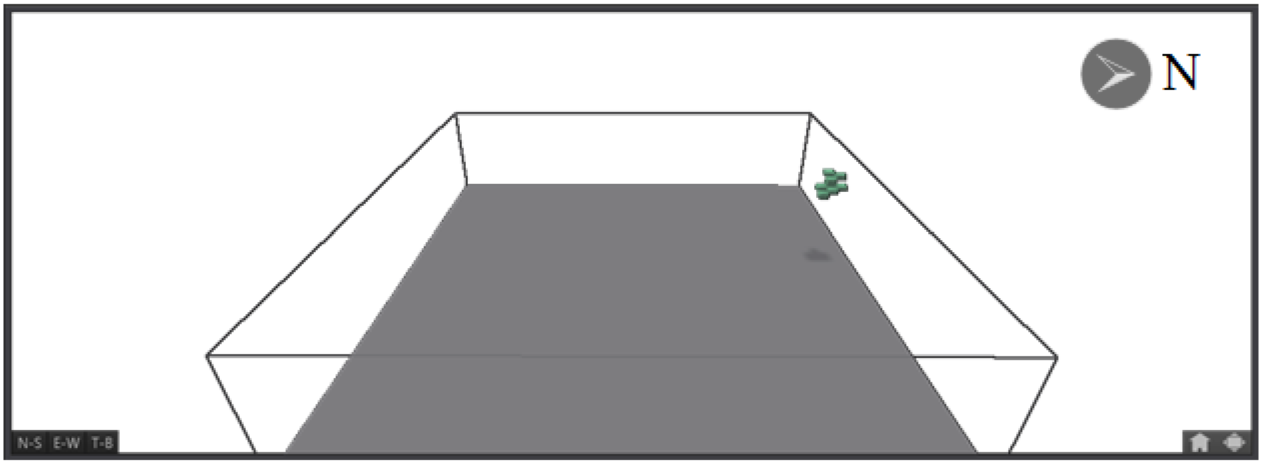


Figure 9.16: DeepMine's visualization for pushback 10

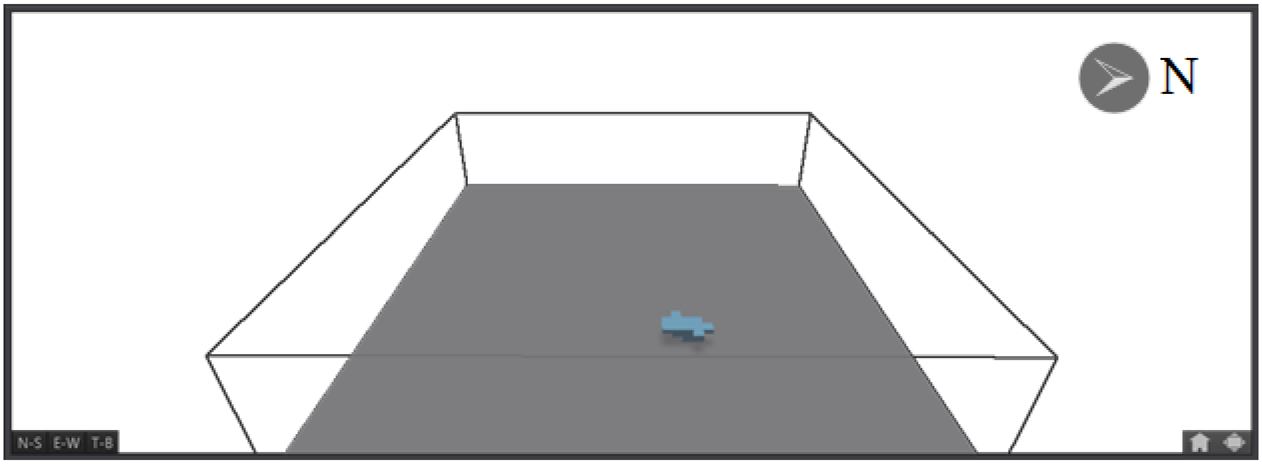


Figure 9.17: DeepMine's visualization for pushback 11

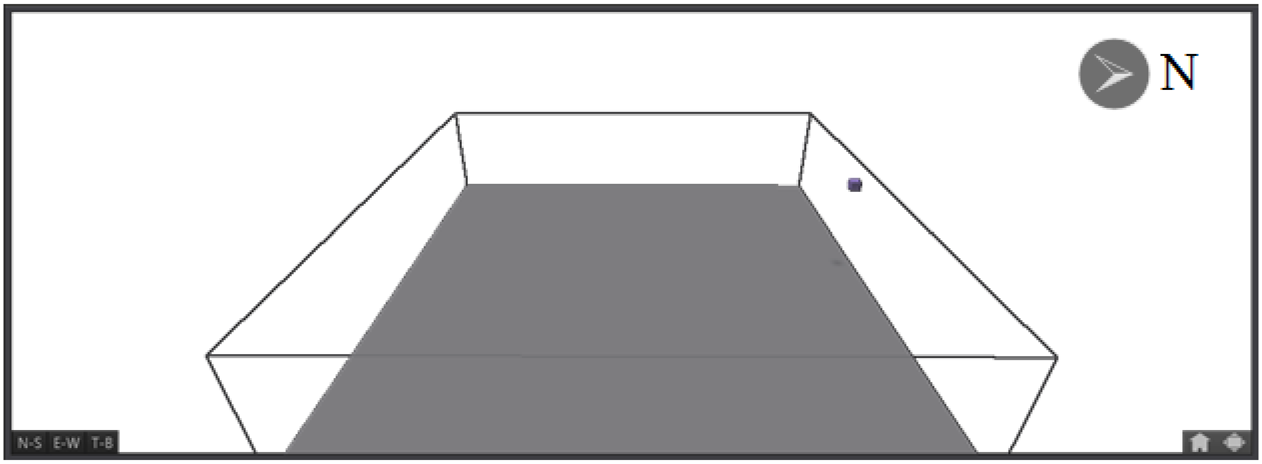


Figure 9.18: DeepMine's visualization for pushback 12

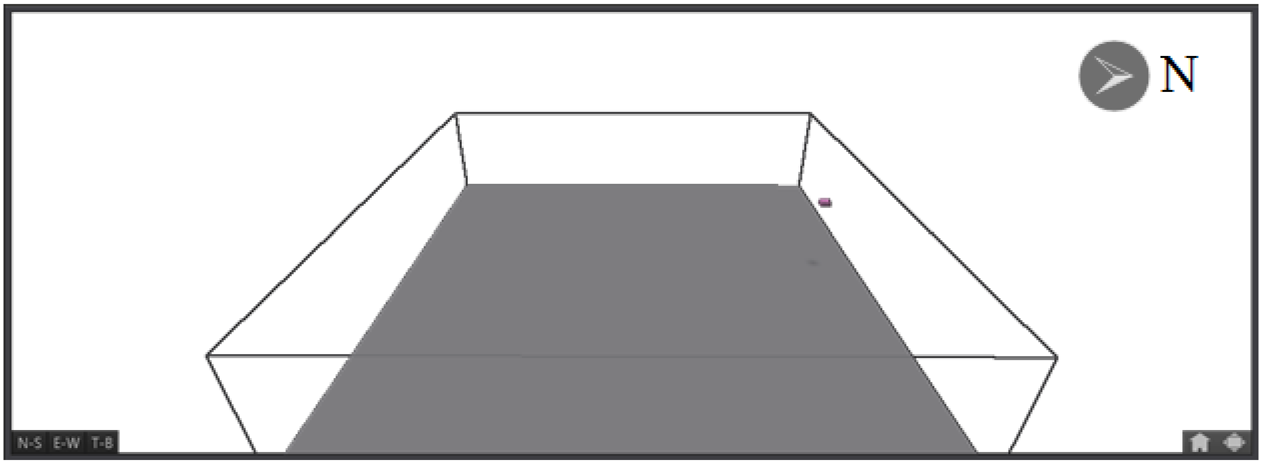


Figure 9.19: DeepMine's visualization for pushback 13

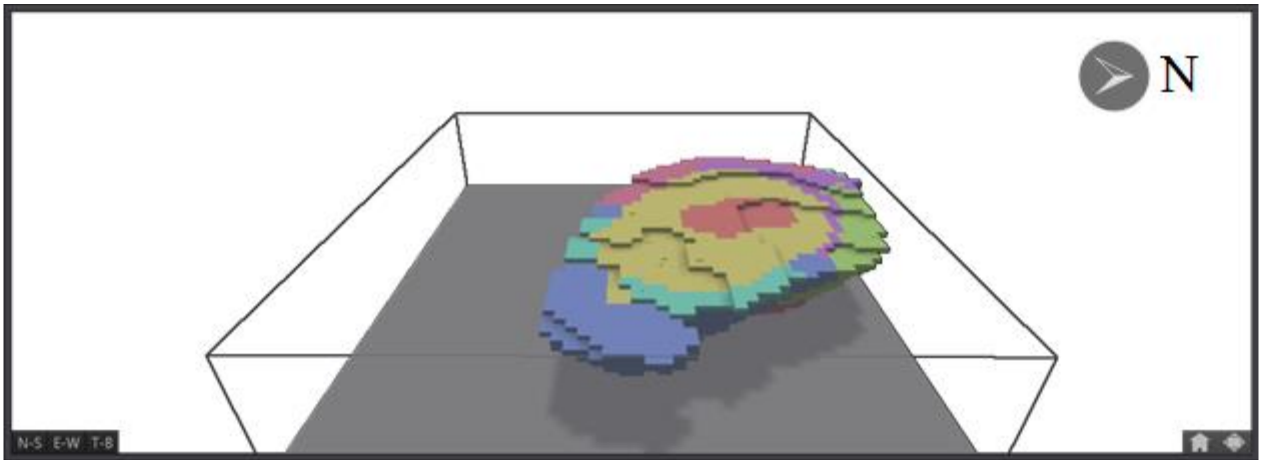


Figure 9.20: DeepMine's visualization for the final pit

9.4. Appendix D: Topography changes as Pushbacks Progress in Optimized Mine Plan

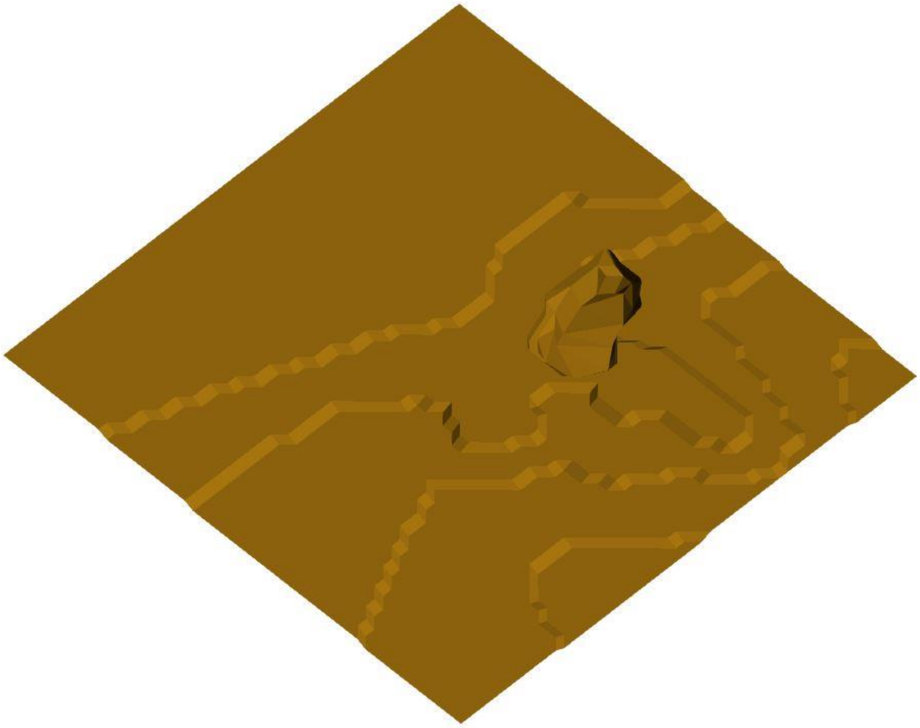


Figure 9.21: Excavation of pushback 1

Figure 9.22: Excavation of pushback 2

Figure 9.23: Excavation of pushback 3

Figure 9.24: Excavation of pushback 4

Figure 9.25: Excavation of pushback 5

Figure 9.26: Excavation of final pit

9.5. Appendix E: Nested Pit Analysis

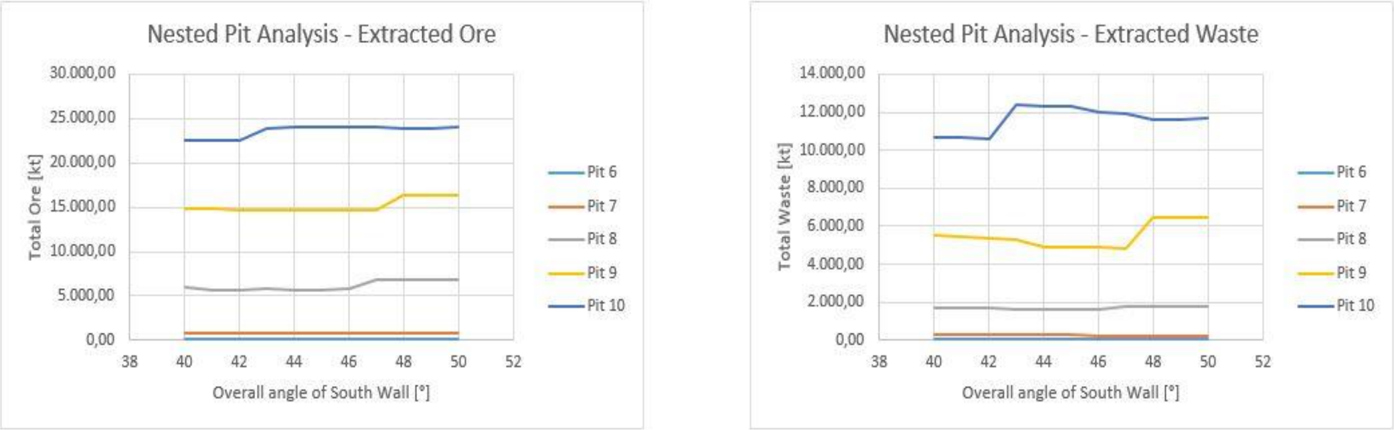


Figure 9.27: Behavior of extracted ore and waste for pits 6 to 10

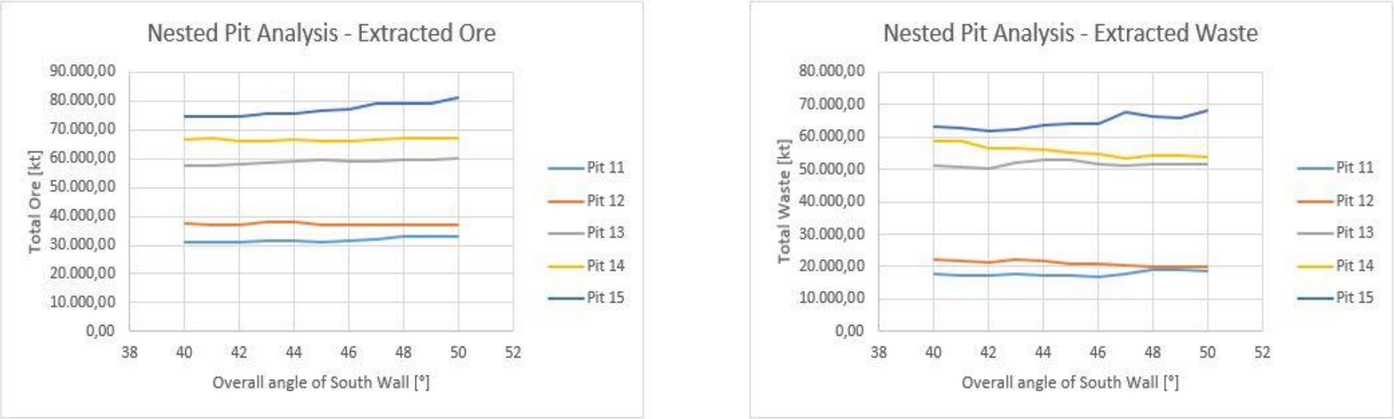


Figure 9.28: Behavior of extracted ore and waste for pits 11 to 15

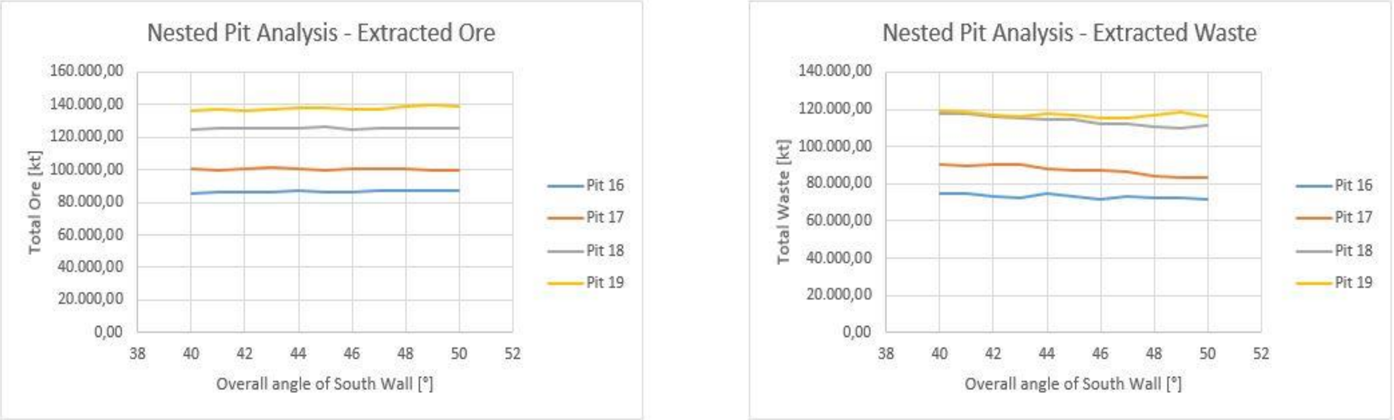


Figure 9.29: Behavior of extracted ore and waste for pits 16 to 19

9.6. Appendix F: Types of Geotechnical Instruments and Applications

Table 9.7: Technologies for Surface Monitoring based on Space-Based Observations

Technology	Description	Strengths and Drawbacks	Precision
Global Positioning System (GPS)	Space-based satellite navigation system provides points location using the timing of signals sent by different satellites to ground receivers located in the position to be surveyed. The time is used to determine the distance from the receiver to all those satellites. These distances allow to precisely determine the position of the receiver.	• Line-of-sight is not required between receivers. • Not dependent on weather conditions • Requires mine personnel to go to all the different points to be surveyed. • Requires unobstructed line of sight to four or more GPS satellites. • Satellite visibility is obstructed in deep point of the pit.	Under 20 mm
Interferometric Synthetic Aperture Radar (InSAR)	It uses the difference in phases between successive SAR images to determine ground movement. SARs send microwave signals to the zone to be monitored and register the reflection of the sent signal. Then, interferometric techniques are used to obtain information about 3D deformation from the phase difference between the waves sent and received by the satellite.	• It works in all weather conditions. • It allows to monitor inaccessible sector of the pit. • Good technique to monitor broad areas. • Dependency on international satellites availability for data gathering. • It may not produce good results when monitoring steep zones. • Real time monitoring is not feasible. • If displacements between successive SAR images is higher than 23 cm InSAR may not be able to quantify it.	On the scale of centimeters to millimeters.

Table 9.8: Technologies for Surface Monitoring based on Airborne Observations

Technology	Description	Strengths and Drawbacks	Precision
Synthetic Aperture Radar (SAR)	It uses the same principles as the InSAR but, in this case, the instrument is mounted on an airplane.	• Independency from international satellites for data gathering. • It uses a relatively unstable platform. • Very important to know the exact location of the plane for best results.	-

Table 9.9: Technologies for Surface Monitoring based on Ground-Based Observations

Technology	Summary	Strengths and Drawbacks	Precision
Visual Inspection	Visual observation of the studied zone to detect the occurrence of cracks, or the evidence displacements.	• Requires experienced geotechnical staff. • It must be complemented by instrumentation to provide a quantitative basis for defining the exact amount of movement.	Qualitative
Cross-Crack Measurements	Crackmeters are devices composed of a steel rod installed at either side of the crack. The distance between steel rods is measured periodically using measuring tape, Vernier caliper or micrometer to determine the crack aperture.	• Provides an insight to in-ground movements. • Simple monitoring devices. • Potentially unstable working area.	0.1 mm
Photogrammetry	Integrates 3D spatial data with 2D visual data to create spatially accurate representations of the surface topology of the rock. Structural properties (orientation, length, spacing, and others) can be determined using this technique.	• Integration of the photogrammetry with mine planning software systems makes possible to use the data in real time for mine design, mine planning and mine operating purposes. • Provides a permanent 3D record of the mapped areas. • Provides low cost geological mapping. • Only one person needed to use this technique. • Digital imaging systems require ground proofing and cannot be used to determine the physical features of the structures	Accuracy ranges from 2 cm at a distance of 50 m to 10 cm at distances of up to 3 km
Light Detection and Ranging (LiDAR)	This technique uses laser pulses reflected by the surface to be measured to create a three-dimensional (3D) representation of the scanned target with a density of >10.000 points per square meter. It is an optical remote sensing technique that uses the properties of scattered reflected light to determine the range between the monitored object and the sensor.	• Able to create a high accurate 3D digital elevation model. • High resolution images. • Relatively inexpensive. • Flexible data collection and processing system. • Can be used to monitor relatively small areas to survey (from 1 to 10 square kilometers). • Need for experienced personnel to understand the limitations of the TLS. • Necessity for a proper data collection campaign to avoid shadowed regions.	Systematic errors are +/- 25mm at 1000 meters Random errors are generally between 0 and 10 mm

Ground-Based InSAR	Uses the same principle as the satellite-based method but the images are acquired by a radar moving along a rail a couple of kilometers away from the area of interest. The monitored zone can be up to four kilometers away from the radar.	• Measurements can be taken during day and night and in any weather conditions. • Provides high spatial density of observations. • Fast (5-10 min monitoring period). • Short range (<5 km) • Limited field of view, which may cause shadowing problems. • Not intended to monitor broad areas.	Resolution of about 0.5 – 4 m, depending on the monitoring distance and the atmospheric conditions. Precision in the scale of millimeters.
Robot Total Stations (Prisms Monitoring)	Robot Total Stations are devices that combine a theodolite with Electromagnetic Distance Measurement (EDM) system to measure horizontal and vertical angles along with distance. This allows the surveyor to measure 3D coordinates of points remotely, typically targeted by the placement of reflective prisms.	• Ability to provide 3D position of the point of interest. • Unable to monitoring during misty weather. • Installation of monitoring prisms at the suspected likely unstable slope zone or area of interest.	Accuracy from 0.6 to 3 mm accuracy Range from 1000 up to 3000 meters
Tilt Meters	Tilt meters use the bubble principle to measure the gradient of inclination of a ground point. The bubble movements are measured and then converted into an estimate of the instrument's tilt.	• High precision measurements obtained. • Used to monitor movements that are expected to contain a rotational component. • Expensive in comparison with radar monitoring. For a 500 x 500 meters area is approximately 36.000$/month. • Require additional calibration after some time to maintain the same accuracy as initially they	1 nanoradian (0.0002 arcseconds)

Table 9.10: Technologies for Subsurface Monitoring

Technology	Description	Strengths and Drawbacks	Precision
Inclinometers	Generally used to measure lateral subsurface displacement in vertical holes. Inclination measured by the device is used to determine the movement perpendicular to the drill hole axis.	• Very detailed displacement path. • In large boreholes and big ground movements, they have short lifespan due to breakage of the casing. • Very useful to study gradual inclination changes.	They can detect differential movements of 0.5–1.0 mm per 10 m length of hole.
Borehole Extensometers	Designed to monitor directional or axial deformations in the rock mass. Individual wires are attached to an anchor at the bottom of the hole, and the axial movement relative to the anchor is recorded.	• Automated and remote readings • Possible to measure multiple points. • Complicated to install in long boreholes	Up to 0.005 mm
Piezometers	Piezometers are designed to measure fluid or pore-water pressures in a variety of applications. They are typically installed in boreholes in in situ soils, rocks, foundations or earth/rock fills, grouted with a specific mixture. Closed piezometers type are the most commonly used on the mining environment.	• Acceptable time response to pressure variations. • Easy to adapt it to an automatic recording device. • Grouting properties are critical to prevent surface water from contaminating piezometer data. • Long lines are susceptible to damage due to borehole movements. • Not possible to check the calibration of the instrument once installed.	±0.1% Full Scale for the vibrating wire type
Cavity Measurements / Surveying	Traditional methods of general survey measurement and positioning such as, levels, total stations, photogrammetric cameras or the combination of them.	• Conventional survey techniques are very reliable methods if well done. • In most of the cases they require an experienced operator to gather the information correctly.	Depends on the method used

Seismic or Micro-seismic Monitoring	Micro-seismic monitoring is the passive observation of very small-scale earthquakes as a result of human activities or industrial processes such as mining. Brittle fractures in rock radiate seismic waves, and if they are recorded sufficiently clearly by different seismograms, the seismic event’s origin time, location and source parameters, deformation and location can be estimated. Geophones are usually the sensor of choice in most mining applications.	• Very unique system to locate fractures developing within the rock mass. • Geophones don’t need power to operate. • Signal degradation if the sensors are far from the target. • Limitation to response to high-frequency waves. • Geophones are used to triangulate the position of the movement that originated the measured wave.	For a IMS 4.5Hz Geophone the distortion measurement frequency is 12 Hz
Time Domain Reflectometry (TDR)	TDR is an electronic instrument that locates faults in metallic cables. If the coaxial cable installed in a vertical hole suffers an impedance change due to kinking of the cable, the TDR detects the exact distance to the point.	• High precision on fault location. • Inability to measure large ground displacements due to the breakage of the wires and thus loss of a signal. Useful to sense localized shear and concentrated shear strain.	±1% of the cable distance
ShapeAccelArray (SAA)	Electronic instruments with triaxial MEMS accelerometers inside a 30cm rigid segment. Several segments can be put together to measure 3-D ground deformation in depths that goes from 30cm to 100m.	• Installed in vertical holes to obtain horizontal deformation data in real time. • Also possible to install horizontally to measure vertical deformation. •	± 1.5 mm for 32 m SAA
Smart Markers	Autonomous electronic devices capable of monitoring mineral flow and ore recovery in block/panel and sublevel caving mines.	• Each device has its own identifying ID, allowing to pinpoint its location when installed in the rock mass. • When recovered in a drawpoint the Marker is identified by a Reader. • Having both the initial and final positions of the devices, ore flow can be inferred. • The actual path of the marker from its installation position to its extraction position (drawpoint) cannot be registered	Qualitative

9.7. Appendix G: Pore Pressure Monitoring Devices

Table 9.11: Technical specifications for Standpipe Piezometers from Ace Instruments Co.

Ace Instruments Co. - Standpipe Piezometer

Range [m]	Accuracy	Resolution	Model	Diameter	Length	Material
50	ISO first grade	1 [mm]	4650	39 [mm]	365 [mm]	Polyethylene/Ceramic filter
100	ISO first grade	1 [mm]	4650	39 [mm]	365 [mm]	Polyethylene/Ceramic filter
200	ISO first grade	1 [mm]	4650	39 [mm]	365 [mm]	Polyethylene/Ceramic filter
300	ISO first grade	1 [mm]	4650	39 [mm]	365 [mm]	Polyethylene/Ceramic filter
350	ISO first grade	1 [mm]	4650	39 [mm]	365 [mm]	Polyethylene/Ceramic filter
500	ISO first grade	1 [mm]	4650	39 [mm]	365 [mm]	Polyethylene/Ceramic filter

Table 9.12: Technical specifications for Standpipe Piezometers from Durham Geo Slope Indicator

Durham Geo Slope Indicator - Standpipe Piezometer

Range [m]	Accuracy	Resolution	Model	Diameter	Length	Material
30	-	1 [mm]	-	38.1 [mm]	305/610 [mm]	Polyethylene/Porous Stone
50	-	1 [mm]	-	38.1 [mm]	305/610 [mm]	Polyethylene/Porous Stone
100	-	1 [mm]	-	38.1 [mm]	305/610 [mm]	Polyethylene/Porous Stone
150	-	1 [mm]	-	38.1 [mm]	305/610 [mm]	Polyethylene/Porous Stone
200	-	1 [mm]	-	38.1 [mm]	305/610 [mm]	Polyethylene/Porous Stone
300	-	1 [mm]	-	38.1 [mm]	305/610 [mm]	Polyethylene/Porous Stone

Table 9.13: Technical specifications for Standpipe Piezometers from Encardiorite

Encardiorite - Standpipe Piezometer

Range [m]	Accuracy	Resolution	Model	Diameter	Length	Material
30	-	1[mm]	EPP-10	37 [mm]	200/400/600 [mm]	Carborundum/Alundum
50	-	1[mm]	EPP-10	37 [mm]	200/400/600 [mm]	Carborundum/Alundum
100	-	1[mm]	EPP-10	37 [mm]	200/400/600 [mm]	Carborundum/Alundum
150	-	1[mm]	EPP-10	37 [mm]	200/400/600 [mm]	Carborundum/Alundum
200	-	1[mm]	EPP-10	37 [mm]	200/400/600 [mm]	Carborundum/Alundum
300	-	1[mm]	EPP-10	37 [mm]	200/400/600 [mm]	Carborundum/Alundum
30	-	1[mm]	EPP-10SP	50[mm]	1[m]	PVC covered w/ geo-textile
50	-	1[mm]	EPP-10SP	50[mm]	1[m]	PVC covered w/ geo-textile
100	-	1[mm]	EPP-10SP	50[mm]	1[m]	PVC covered w/ geo-textile
150	-	1[mm]	EPP-10SP	50[mm]	1[m]	PVC covered w/ geo-textile
200	-	1[mm]	EPP-10SP	50[mm]	1[m]	PVC covered w/ geo-textile
300	-	1[mm]	EPP-10SP	50[mm]	1[m]	PVC covered w/ geo-textile

Table 9.14: Technical specifications for Standpipe Piezometers from Geo-Instruments

Geo-Instruments – Standpipe Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
No relevant information available in the website						

Table 9.15: Technical specifications for Standpipe Piezometers from Geotechnical Systems

Geotechnical Systems - Standpipe Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Water Level Indicator System dependent			1000	33.3 [mm]	354 [mm]	PVC
			1050	33.3 [mm]	354 [mm]	Galvanized Steel

Table 9.16: Technical specifications for Standpipe Piezometers from Itmsoil Interfels

Itmsoil Interfels - Standpipe Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Water Level Indicator System dependent			Porous plastic	43 [mm]	300/1,000 [mm]	PVC

Table 9.17: Technical specifications for Standpipe Piezometers from Marton Geotechnical Services

Marton Geotechnical Services - Standpipe Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Water Level Indicator System dependent			Porous plastic	27 [mm]	320 [mm]	HDPE
			Porous plastic	27 [mm]	1,000 [mm]	HDPE
			Ceramic	50 [mm]	200 [mm]	Alumo Silicate
			Ceramic	50 [mm]	310 [mm]	Alumo Silicate

Table 9.18: Technical specifications for Standpipe Piezometers from Roctest

Roctest - Standpipe Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Water Level Indicator System dependent			CP1	19 [mm]	350 [mm]	PVC
			CP15	38 [mm]	150-600 [mm]	PVC

Table 9.19: Technical specifications for Standpipe Piezometers from Gage Technique

Gage Technique – Standpipe Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Gage Technique commercializes Durham Geo Slope Indicator's Standpipe Piezometer						

Table 9.20: Technical specifications for Standpipe Piezometers from RST

RST - Standpipe Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Water Level Indicator System dependent			PP0306	33.5 [mm]	52.4 [mm]	PVC
			PP0312	33.5 [mm]	304.8 [mm]	PVC
			PP0318	33.5 [mm]	457.2 [mm]	PVC
			PP0324	33.5 [mm]	609.6 [mm]	PVC
			PP0360-1.5	38.1 [mm]	1,524 [mm]	PVC

Table 9.21: Technical specifications for Standpipe Piezometers from Sisgeo

Sisgeo - Standpipe Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Water Level Indicator System dependent			P112	61.5 [mm]	200 [mm]	Polyethylene
			P112A	61.5 [mm]	200 [mm]	Polyethylene
			P101	61.5 [mm]	200 [mm]	Polyethylene
			TFH	25.4 [mm]	3,000 [mm]	PVC
			TFH	38.1 [mm]	3,000 [mm]	PVC
			TFH	50.8 [mm]	3,000 [mm]	PVC
			TFH	76.2 [mm]	3,000 [mm]	PVC

Table 9.22: Technical specifications for Standpipe Piezometers from Solinst

Solinst - Standpipe Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Water Level Indicator System dependent			601	26.7 [mm]	150 [mm]	PVC
			601	26.7 [mm]	300 [mm]	PVC
			601	26.7 [mm]	600 [mm]	PVC
			601	26.7 [mm]	900 [mm]	PVC

Table 9.23: Technical specifications for Pneumatic Piezometers from Ace Instruments Co.

Ace Instrument Co. - Pneumatic Piezometer						
Range [kPa] (kg/cm^2)	Accuracy	Resolution	Model	Diameter	Length	Material
0-1,470 (0-15)	± 0.5% F.S.R.	Indicator dependent	2510	20 [mm]	80 [mm]	Nylon mold

Table 9.24: Technical specifications for Pneumatic Piezometers from Durham Geo Slope Indicator

Durham Geo Slope Indicator - Pneumatic Piezometer						
Range [kPa] (bar)	Accuracy	Resolution	Model	Diameter	Length	Material
2,750 (27.5)	± 0.25% F.S.	-	-	25.4 [mm]	-	ABS & PVC

Table 9.25: Technical specifications for Pneumatic Piezometers from Geotechnical Systems

Geotechnical Systems - Pneumatic Piezometer						
Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
0-14,000	± 0.4 [kPa]	Readout dependent	1100	16 [mm]	63 [mm]	-

Table 9.26: Technical specifications for Pneumatic Piezometers from Geotechnical Systems

Geotechnical Systems - Pneumatic Piezometer						
Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
30-1,000	± 2.0% F.S.	Readout dependent	W3	38 [mm]	-	Brass/PVC

Table 9.27: Technical specifications for Pneumatic Piezometers from Roctest

Roctest - Pneumatic Piezometer						
Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
0-1,000	± 0.25% F.S.	-	FCP-2 Standard	32 [mm]	28 [mm]	Brass, Stainless Steel
0-3,500	± 0.25% F.S.	-	FCP-2 High Pressure	32 [mm]	28 [mm]	Brass, Stainless Steel

Table 9.28: Technical specifications for Pneumatic Piezometers from Gage Technique

Gage Technique - Pneumatic Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Gage Technique commercializes Durham Geo Slope Indicator's Standpipe Piezometer						

Table 9.29: Technical specifications for Pneumatic Piezometers from RST

RST - Pneumatic Piezometer						
Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
0-14,000	± 0.25% F.S.	1 [kPa] (0.1 [kPa] w/ readout)	P-100	1.59 [cm]	6.3 [cm]	Nylon 12, EP diaphragm
0-14,000	± 0.25% F.S.	1 [kPa] (0.1 [kPa] w/ readout)	P-100-1	3.35 [cm]	22.8 [cm]	Nylon 12, EP diaphragm
0-14,000	± 0.25% F.S.	1 [kPa] (0.1 [kPa] w/ readout)	P-104	4.06 [cm]	9.34 [cm]	Nylon 12, EP diaphragm
0-14,000	± 0.25% F.S.	1 [kPa] (0.1 [kPa] w/ readout)	P-104-D	2.54 [cm]	6.68 [cm]	Nylon 12, EP diaphragm

Table 9.30: Technical specifications for VW Multi-point Piezometers from Ace Instruments Co.

Ace Instrument Co. - VW Multi-point Piezometer						
Range[kPa] (kg/cm^2)	Accuracy	Resolution	Model	Diameter	Length	Material
196-6,864 (2-70)	± 0.1% F.S.R.	0.025% F.S.R.	1500	38 [mm]	-	Stainless Steel, epoxy resin potting

Table 9.31: Technical specifications for Vibrating Wire Piezometers from Ace Instruments Co.

Ace Instrument Co. - Vibrating Wire Piezometer						
Range[kPa] (kg/cm^2)	Accuracy	Resolution	Model	Diameter	Length	Material
196-6,864 (2-70)	± 0.1% F.S.R.	0.025% F.S.R.	1510	19.8 [mm]	169.5 [mm]	Stainless Steel, epoxy resin potting
98/147/196 (1/1.5/2)	± 0.1% F.S.R.	0.025% F.S.R.	1515	25.4 [mm]	169.5 [mm]	Stainless Steel, epoxy resin potting
196-6,864 (2-70)	± 0.1% F.S.R.	0.025% F.S.R.	1530	25.4 [mm]	151 [mm]	Stainless Steel, epoxy resin potting
196-6,864 (2-70)	± 0.1% F.S.R.	0.025% F.S.R.	1540	19.8 [mm]	169.5 [mm]	Stainless Steel, epoxy resin potting
196-6,864 (2-70)	± 0.1% F.S.R.	0.025% F.S.R.	1500S	17.5 [mm]	169.5 [mm]	Stainless Steel, epoxy resin potting

Table 9.32: Technical specifications for VW Vented Piezometers from Ace Instruments Co.

Ace Instrument Co. - VW Vented Piezometer						
Range [kPa] (kg/cm^2)	Accuracy	Resolution	Model	Diameter	Length	Material
0-6,864 (0-70)	± 0.1% F.S.R.	0.025% F.S.R.	1560	19.8 [mm]	169.5 [mm]	-

Table 9.33: Technical specifications for Vibrating Wire Piezometers from Durham Geo Slope Indicator

Durham Geo Slope Indicator - Vibrating Wire Piezometer						
Range [kPa] (bar)	Accuracy	Resolution	Model	Diameter	Length	Material
350-700 (3.5-7)	± 0.1% F.S.	0.025% F.S.	Standard	19 [mm]	155 [mm]	Stainless Steel
1,700-3,500 (17-35)	± 0.3% F.S.	0.025% F.S.	Standard	19 [mm]	155 [mm]	Stainless Steel
350-700 (3.5-7)	± 0.1% F.S.	0.025% F.S.	Heavy-Duty	29 [mm]	191 [mm]	Stainless Steel
1,700-3,500 (17-35)	± 0.3% F.S.	0.025% F.S.	Heavy-Duty	29 [mm]	191 [mm]	Stainless Steel
70-180 (0.7-1.8)	± 0.1% F.S.	0.025% F.S.	Low-Pressure	29 [mm]	191 [mm]	Stainless Steel
700 (7)	± 0.1% F.S.	0.025% F.S.	Corrosion-Resistant	29 [mm]	191 [mm]	Stainless Steel
1,700 (17)	± 0.3% F.S.	0.025% F.S.	Corrosion-Resistant	29 [mm]	191 [mm]	Stainless Steel

Table 9.34: Technical specifications for VW Titanium Piezometers from Durham Geo Slope Indicator

Durham Geo Slope Indicator - Titanium Piezometer						
Range [kPa] (psi)	Accuracy	Resolution	Model	Diameter	Length	Material
138/345/689/1,724 (20/50/100/250)	-	0.02% F.S.	-	15.9 [mm] (0.625")	146.1 [mm] (5.75")	Titanium

Table 9.35: Technical specifications for Vibrating Wire Piezometers from Encardiorite

Encardiorite - Vibrating Wire Piezometer						
Range [kPa]	Accuracy (Optional)	Resolution	Model	Diameter	Length	Material
200/350/500/700	± 0.25 (0.1)% F.S.	-	EPP-30V	42 [mm]	185 [mm]	Stainless Steel
1,000/1,500/2,000	± 0.25 (0.1)% F.S.	-	EPP-30V	42 [mm]	185 [mm]	Stainless Steel
3,500/5,000/10,000	± 0.25 (0.1)% F.S.	-	EPP-30V	42 [mm]	185 [mm]	Stainless Steel

Table 9.36: Technical specifications for VW Slim Piezometers from Encardiorite

Encardiorite - Vibrating Wire Slim Piezometer						
Range [kPa]	Accuracy (Optional)	Resolution	Model	Diameter	Length	Material
350/500/700	± 0.2 (0.1)% F.S.	-	EPP-40V	19 [mm]	155 [mm]	Stainless Steel
1,000/2,000	± 0.2 (0.1)% F.S.	-	EPP-40V	19 [mm]	155 [mm]	Stainless Steel

Table 9.37: Technical specifications for VW Low Pressure Piezometers from Encardiorite

Encardiorite - Vibrating Wire Low Pressure Piezometer						
Range [kPa]	Accuracy (Optional)	Resolution	Model	Diameter	Length	Material
35	± 0.25 (0.1)% F.S.	-	EPP-60V	30 [mm]	160 [mm]	Stainless Steel
70	± 0.25 (0.1)% F.S.	-	EPP-60V	30 [mm]	160 [mm]	Stainless Steel

Table 9.38: Technical specifications for Vibrating Wire Piezometers from Geo-Instruments

Geo-Instruments - Vibrating Wire Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
50	± 0.1% F.S.	0.025% F.S.	GEO-VW-PZO-50	19 [mm] (0.75")	197 [mm] (7.75")	Stainless Steel
100	± 0.1% F.S.	0.025% F.S.	GEO-VW-PZO-100	19 [mm] (0.75")	197 [mm] (7.75")	Stainless Steel

Table 9.39: Technical specifications for VW Heavy Duty Piezometers from Geokon

Geokon - Heavy Duty Piezometers						
Range	Accuracy	Resolution	Model	Diameter	Length	Material
−100-70/170/350/700 [kPa]	± 0.1% F.S.	0.025% F.S.	4500HD	38.1 [mm]	203 [mm]	Stainless Steel
1/2/3/5/7.5 [MPa]	± 0.1% F.S.	0.025% F.S.	4500HD	38.1 [mm]	203 [mm]	Stainless Steel

Table 9.40: Technical specifications for VW Small Diameter Piezometers from Geokon

Geokon - Small Diameter Piezometers						
Range	Accuracy	Resolution	Model	Diameter	Length	Material
−100-350/700 [kPa]	± 0.1% F.S.	0.025% F.S.	4500B	17.5 [mm]	133 [mm]	Stainless Steel
1/2/3 [MPa]	± 0.1% F.S.	0.025% F.S.	4500B	17.5 [mm]	133 [mm]	Stainless Steel
−100-350/700 [kPa]	± 0.1% F.S.	0.05% F.S.	4500C	11 [mm]	165 [mm]	Stainless Steel

Table 9.41: Technical specifications for VW Standard Piezometers from Geokon

Geokon - Standard Piezometers						
Range	Accuracy	Resolution	Model	Diameter	Length	Material
−100-350/700 [kPa]	± 0.1% F.S.	0.025% F.S.	4500S/SV	19.1 [mm]	133 [mm]	Stainless Steel
1/2/3 [MPa]	± 0.1% F.S.	0.025% F.S.	4500S/SV	19.1 [mm]	134 [mm]	Stainless Steel
−100-5/7.5/10/20 [MPa]	± 0.1% F.S.	0.025% F.S.	4500SH	25.4 [mm]	194 [mm]	Stainless Steel
70/170 [kPa]	± 0.1% F.S.	0.025% F.S.	4500AL/ALV	25.4 [mm]	133 [mm]	Stainless Steel

Table 9.42: Technical specifications for VW High Temperature Piezometers from Geokon

Geokon - High Temperature Piezometers						
Range	Accuracy	Resolution	Model	Diameter	Length	Material
−100-700 [kPa]	± 0.1% F.S.	0.025% F.S.	4500HT	19 [mm]	188 [mm]	Stainless Steel
1/2/3/5 [MPa]	± 0.1% F.S.	0.025% F.S.	4500HT	19 [mm]	188 [mm]	Stainless Steel
7.5/10/25/50/75/100/150 [MPa]	± 0.1% F.S.	0.025% F.S.	4500HT	25 [mm]	210 [mm]	Stainless Steel

Table 9.43: Technical specifications for VW Multilevel Piezometers from Geokon

Geokon - Multilevel Piezometers						
Range	Accuracy	Resolution	Model	Diameter	Length	Material
−100-70/170/350/700 [kPa]	± 0.1% F.S.	0.025% F.S.	4500MLP	100-150 [mm]	-	Stainless Steel
1/2/3/5/7.5 [MPa]	± 0.1% F.S.	0.025% F.S.	4500MLP	100-150 [mm]	-	Stainless Steel

Table 9.44: Technical specifications for VW Autoresonant Piezometers from Geokon

Geokon - Autoresonant Piezometers						
Range	Accuracy	Resolution	Model	Diameter	Length	Material
7/17/35/70/170/350/700 [kPa]	± 0.1% F.S.	0.025% F.S.	4500AR	Depends on range	Depends on range	Stainless Steel
1/2/3/5/7.5/10/20 [MPa]	± 0.1% F.S.	0.025% F.S.	4500AR	Depends on range	Depends on range	Stainless Steel
25/35/50/75/100/150 [MPa]	± 0.1% F.S.	0.025% F.S.	4500AR	Depends on range	Depends on range	Stainless Steel

Table 9.45: Technical specifications for VW Titanium Piezometers from Geokon

Geokon - Titanium Piezometers

Range	Accuracy	Resolution	Model	Diameter	Length	Material
−100-350/700 [kPa]	± 0.1% F.S.	0.025% F.S.	4500Ti	25.4 [mm]	125 [mm]	Titanium
1/2/3/5/7.5 [MPa]	± 0.1% F.S.	0.025% F.S.	4500Ti	25.4 [mm]	125 [mm]	Titanium

Table 9.46: Technical specifications for Vibrating Wire Piezometers from Geonor

Geonor - Vibrating Wire Piezometer

Range [kPa] (bar)	Accuracy	Resolution	Model	Diameter	Length	Material
200-3,000 (2-30)	< ± 0.5% F.S.	< 0.025% F.S.	M-610	30 [mm]	135 [mm]	Stainless Steel
200-3,000 (2-30)	< ± 0.5% F.S.	< 0.025% F.S.	M-610A	30 [mm]	165 [mm]	Stainless Steel

Table 9.47: Technical specifications for Vibrating Wire Piezometers from Geostar

Geostar - Vibrating Wire Piezometer

Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
175/350/700/1,000	± 0.1% F.S.	0.025% F.S.	Type A	19 [mm]	131.5 [mm]	Stainless Steel
70/175	± 0.1% F.S.	0.025% F.S.	Type B	25.5 [mm]	127 [mm]	Stainless Steel
350/700/1,000	± 0.1% F.S.	0.025% F.S.	Type C	11.5 [mm]	125 [mm]	Stainless Steel
70/175/350/700/1,000	± 0.1% F.S.	0.025% F.S.	Type D	32.5 [mm]	185 [mm]	Stainless Steel

Table 9.48: Technical specifications for Vibrating Wire Piezometers from Itmsoil Interfels

Itmsoil Interfels - Vibrating Wire Piezometer

Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
300/500/700/1,000	± 0.1% F.S.	0.025% F.S.	W9	19 [mm]	-	316 Stainless Steel
1,500/2,000/4,000	± 0.1% F.S.	0.025% F.S.	W9	19 [mm]	-	316 Stainless Steel
150/300/500/700/1,000	± 0.1% F.S.	0.025% F.S.	W4	28 [mm]	-	317 Stainless Steel
1,500/2,000/4,000/6,000	± 0.1% F.S.	0.025% F.S.	W4	28 [mm]	-	318 Stainless Steel
10,000/15,000	± 0.1% F.S.	0.025% F.S.	W4	28 [mm]	-	319 Stainless Steel

Table 9.49: Technical specifications for Vibrating Wire Piezometers from Geotechnical Systems

Geotechnical Systems - Vibrating Wire Piezometer						
Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
250/350/700	< ± 0.5% F.S.	0.025% F.S.	1200	22 [mm]	136 [mm]	Stainless Steel
2,000/3,500/5,000	< ± 0.5% F.S.	0.025% F.S.	1200	22 [mm]	136 [mm]	Stainless Steel

Table 9.50: Technical specifications for VW Multi-Level Piezometers from Roctest

Roctest - Vibrating Wire Multi-Level Piezometer						
Range [MPa]	Accuracy	Resolution	Model	Diameter	Length	Material
0.2/0.35/0.5/0.75	± 0.1% F.S.	0.025% F.S.	PWS	19 [mm]	200 [mm]	Stainless Steel
1/1.5/2/3/5	± 0.1% F.S.	0.025% F.S.	PWS	19 [mm]	200 [mm]	Stainless Steel

Table 9.51: Technical specifications for Vibrating Wire Piezometers from Roctest

Roctest - Vibrating Wire Piezometer						
Range [MPa]	Accuracy	Resolution	Model	Diameter	Length	Material
0.2/0.35/0.5/0.75	± 0.1% F.S.	0.025% F.S.	PWS	19 [mm]	200 [mm]	Stainless Steel
1/1.5/2/3/5/7	± 0.1% F.S.	0.025% F.S.	PWS	19 [mm]	200 [mm]	Stainless Steel
0.2/0.35/0.5/0.75	± 0.1% F.S.	0.025% F.S.	PWF	28.6 [mm]	200 [mm]	Stainless Steel
1/1.5/2/3/5/7	± 0.1% F.S.	0.025% F.S.	PWF	28.6 [mm]	200 [mm]	Stainless Steel
0.2/0.35/0.5/0.75	± 0.1% F.S.	0.025% F.S.	PWC	19 [mm]	213 [mm]	Stainless Steel
1/1.5/2/3/5/7	± 0.1% F.S.	0.025% F.S.	PWC	19 [mm]	213 [mm]	Stainless Steel
0.035/0.07	± 0.1% F.S.	0.025% F.S.	PWL	38 [mm]	200 [mm]	Stainless Steel

Table 9.52: Technical specifications for Vibrating Wire Piezometers from Sisgeo

Sisgeo - Vibrating Wire Piezometer						
Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
170-3,500	< ± 0.25% F.S.	0.025% F.S.	PK45S	28 [mm]	200 [mm]	Stainless Steel
170-3,500	< ± 0.25% F.S.	0.025% F.S.	PK45A	28 [mm]	200 [mm]	Stainless Steel
170-3,500	< ± 0.25% F.S.	0.025% F.S.	PK20S	20 [mm]	180 [mm]	Stainless Steel
170-3,500	< ± 0.25% F.S.	0.025% F.S.	PK20A	20 [mm]	180 [mm]	Stainless Steel
350/700	< ± 0.25% F.S.	0.025% F.S.	PK45C	28/30 [mm]	230 [mm]	Stainless Steel
350-30,000	< ± 0.25% F.S.	0.025% F.S.	PK45H	28 [mm]	180 [mm]	Stainless Steel
700-3,500	< ± 0.25% F.S.	0.025% F.S.	PK45M	48.3 [mm]	250 [mm]	Stainless Steel

Table 9.53: Technical specifications for Vibrating Wire Piezometers from RST

RST - Vibrating Wire Piezometer						
Range [MPa]	Accuracy	Resolution	Model	Diameter	Length	Material
0.35/0.7/1/2/3	± 0.1% F.S.	0.025% F.S.	VW2100	19 [mm]	130 [mm]	Stainless Steel
0.35/0.7/1/2/3/5/7.5/10	± 0.1% F.S.	0.025% F.S.	VW2100-HD	25.4 [mm]	146 [mm]	Stainless Steel
1/2/3/5/7.5/10	± 0.1% F.S.	0.025% F.S.	VW2100-XHD	38.1 [mm]	146 [mm]	Stainless Steel
5/7.5/10/25/50/75/100	± 0.1% F.S.	0.025% F.S.	VW2100-HHP	25.4 [mm]	143 [mm]	Stainless Steel
0.07/0.175	± 0.1% F.S.	0.025% F.S.	VW2100-L	25 [mm]	133 [mm]	Stainless Steel
0.07/0.175	± 0.1% F.S.	0.025% F.S.	VW2100-LV	25 [mm]	133 [mm]	Stainless Steel
0.35/0.7/1/2/3	± 0.1% F.S.	0.025% F.S.	VW2100-M	17.5 [mm]	133 [mm]	Stainless Steel
0.35/0.7	± 0.1% F.S.	0.025% F.S.	VW2100-MM	11.1 [mm]	165 [mm]	Stainless Steel
0.35/0.7/1/2/3/5/7.5/10	± 0.1% F.S.	0.025% F.S.	PPA0094	25.4 [mm]	146 [mm]	Stainless Steel

Table 9.54: Technical specifications for Vibrating Wire Piezopress from Solexperts

Solexperts - Vibrating Wire Piezopress						
Range [kPa] (bar)	Accuracy	Resolution	Model	Diameter	Length	Material
0-2,000 (0-20)	± 0.01% F.S.	-	-	25.4 [mm]	-	Stainless Steel

Table 9.55: Technical specifications for Vibrating Wire Piezometers from Toyoko Elmes

Toyoko Elmes - Vibrating Wire Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
No relevant information available in the website						

Table 9.56: Technical specifications for Vibrating Wire Piezometers from Jewell Instruments

Jewell Instruments - Vibrating Wire Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Jewell Instruments commercializes Geokon's Vibrating Wire Piezometers						

Table 9.57: Technical specifications for Vibrating Wire Piezometers from Gage Technique

Gage Technique - Vibrating Wire Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Gage Technique commercializes Durham Geo Slope Indicator's Standpipe Piezometer						

Table 9.58: Technical specifications for Vibrating Wire Piezometers from Measurand Inc.

Measurand Inc. - SAAPZ: Vibrating Wire Piezometer						
Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
Measurand commercializes Geokon's 4500S Standard Piezometer in a SAA configuration						

Table 9.59: Technical specifications for Semiconductor Piezometers from Ace Instruments Co.

Ace Instrument Co. - FSG/Semiconductor Piezometer						
Range [kPa] (kg/cm^2)	Accuracy	Resolution	Model	Diameter	Length	Material
196-3,432 (2-35)	± 1% F.S.R.	-	4510	-	-	Stainless Steel, epoxy resin potting
98-1,961 (1-20)	± 0.5% F.S.R.	-	4515	-	-	Stainless Steel, epoxy resin potting

Table 9.60: Technical specifications for Semiconductor Piezometers from Geokon

Geokon - Semiconductor Piezometers & Pressure Transducers						
Range	Accuracy	Resolution	Model	Diameter	Length	Material
100/250/400/600 [kPa]	± 0.25% F.S.	-	3400	32 [mm]	194 [mm]	Stainless Steel
1/2/5/6 [MPa]	± 0.25% F.S.	-	3400	32 [mm]	194 [mm]	Stainless Steel

Table 9.61: Technical specifications for Electric Piezometers from Itmsoil Interfels

Itmsoil Interfels - 4-20mA Piezometers						
Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
100/200/350/700/2,000/3,500	± 0.1% F.S.	± 0.025% F.S.	W12	19 [mm]	-	316 Stainless Steel

Table 9.62: Technical specifications for Strain Gauge Piezometers from RST

RST - Strain Gauge Piezometers

Range [-]	Accuracy	Resolution	Model	Diameter	Length	Material
-	± 0.1% F.S.	-	-	21 [mm]	109 [mm]	316 Stainless Steel

Table 9.63: Technical specifications for Single Piezometers from Alert Solutions

Alert Solutions - Single Piezometers

Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
250-700	0.02% F.S.	0.004% F.S.	ACE-250/700	22 [mm]	170 [mm]	316 Stainless Steel

Table 9.64: Technical specifications for Resistive Piezometers from Sisgeo

Sisgeo - Resistive Piezometers

Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
100/200/500/1,000	< 0.3% F.S.	0.01% F.S.	P252R	28 [mm]	200 [mm]	Stainless Steel
200/500/1,000/2,000/5,000	< 0.3% F.S.	0.01% F.S.	P252S	28 [mm]	200 [mm]	Stainless Steel
200/500/1,000/2,000	< 0.3% F.S.	0.01% F.S.	P252TI	27 [mm]	200 [mm]	Titanium
200/500	< 0.3% F.S.	0.01% F.S.	P252C	28/30 [mm]	230 [mm]	Stainless Steel
100-20,000	< 0.3% F.S.	0.01% F.S.	P252A	28 [mm]	180 [mm]	Stainless Steel

Table 9.65: Technical specifications for Piezoresistive Piezopress from Sisgeo

Solexperts - Piezoresistive Piezopress

Range [kPa] (bar)	Accuracy	Resolution	Model	Diameter	Length	Material
0-2,000 (0-20)	± 0.05% F.S.	-	-	25.4 [mm]	-	Stainless Steel
0-1,000 (0-10)	± 0.05% F.S.	-	-	25.4 [mm]	-	Stainless Steel

Table 9.66: Technical specifications for Twin Tube Piezometers from Encardiorite

Encardiorite - Twin Tube Hydraulic Piezometer

Range [kPa]	Accuracy (Optional)	Resolution	Model	Diameter	Length	Material
200/350/500	± 0.25 (0.1)% F.S.	-	EHP-10	6 [mm]	-	Nylon 12

Table 9.67: Technical specifications for Electric Piezometers from Simstrumenti

Simstrumenti - Electric Piezometer						
Range [kPa] (bar)	Accuracy	Resolution	Model	Diameter	Length	Material
5-100 (0.05-1)	< 0.02% F.S.	5 kPa (0.05 bar)	LV610-AS-FS	25 [mm]	144 [mm]	Stainless Steel
100-1,000 (1-10)	< 0.02% F.S.	50 kPa (0.5 bar)	LV610-AS-FS	25 [mm]	144 [mm]	Stainless Steel
5-100 (0.05-1)	< 0.02% F.S.	5 kPa (0.05 bar)	LV610-RL-FS	25 [mm]	144 [mm]	Stainless Steel
100-1,000 (1-10)	< 0.02% F.S.	50 kPa (0.5 bar)	LV610-RL-FS	25 [mm]	144 [mm]	Stainless Steel

Table 9.68: Technical specifications for Hydraulic Piezometers from Itmsoil Interfels

Itmsoil Interfels - Hydraulic Piezometers						
Range [kPa]	Accuracy	Resolution	Model	Diameter	Length	Material
−5-2,000	± 0.1% F.S.	-	W2	18 [mm]	-	Nylon sheathed in Polythene
0-1,500	± 0.25% F.S.	-	W2	16 [mm]	-	Nylon sheathed in Polythene

9.8. Appendix H: Understanding Rock Mass Behavior through the Development of an Integrated Sensing Platform

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9.8.1. Abstract

This paper summarizes the research, development and initial application of a sensing platform that has the potential to monitor subsurface deformations, pore pressure and other variables simultaneously to gain a better understanding of rock mass behavior. The platform is based on Networked Smart Markers (NSMs) devices, which, with their ability for wireless communication between individual sensors and the possibility of real-time data acquisition and processing, will assist in the development of predictive tools to better assess rock mass behavior.

A good opportunity to implement this technology is in the specific application of transitioning from an open pit mine to an underground caving operation. One of the key elements to maintaining the mining business during such a transition is having a good understanding of the unique geotechnical conditions of mutual influence created during the open pit to underground interaction. The knowledge acquisition will require the implementation of a robust platform for geotechnical monitoring, which could be enhanced by incorporating the NSMs. The integration of sensors within the NSMs would enable the collection of additional data about rock mass behavior (i.e. caving propagation and crown pillar fracturing), which could be used to improve the management of mining operations and, specifically, allow the development of reliable predictive tools based on the data collected.

9.8.2. Introduction

A good understanding of rock mass behavior can only be obtained through geotechnical monitoring using adequate instrumentation. A monitoring campaign implemented throughout the mine life gathers evidence of the rock mass’s response to mining activities, which could be used in future mine design processes to achieve safer and more efficient operations. At the same time, the proactive use of monitoring information can reduce the possibility or seriousness of incidents occurring, such as slope failures (Blachowski, Ellefmo and Ludvigsen, 2011), which can have serious consequences for operations. There are numerous benefits associated with implementing a robust monitoring program, including improved risk management related to mining operation

(Marr, 2013) and an empirical comprehension of operational performance when a specific mining plan is introduced or changes in production rates are implemented or made. Thus, efforts towards collecting more and better-quality data are fundamental for improving the mining business.

While not new, the concept of geotechnical monitoring is critical for the future continuation of the mining business, specifically the transition from large open pit (OP) operations to mass underground (UG) cave mines. In this context, understanding the geomechanical aspects related to OP and UG interaction is one of the key elements towards enabling successful transitions. A monitoring platform should assess at least the following aspects:

- Caving propagation, in terms of the cave back position
- Crown pillar response, which is significant for the period of simultaneous OP–UG operation
- The progression of subsidence, which allows risk-prone areas to be identified
- Slope stability.

In this paper, the OP–UG transition problem is described, including the currently available technology that could be applied or has already been applied in similar mining environments for geotechnical monitoring. Networked Smart Marker (NSM) technology is introduced, and its benefits are highlighted when it is incorporated into a monitoring campaign as a sensing platform.

9.8.2.1. Open pit–underground interaction

During the mine life, economic considerations (mainly) can lead to a decision to change the exploitation method (transitioning from OP to UG or from UG to OP) or to carry out OP and UG operations simultaneously. Whatever the case, it is very probable that there will be periods with high levels of interaction between the two operations, which can generate highly complex scenarios from the perspective of geotechnical management. Several cases have occurred where it has been possible to anticipate significant levels of interaction between mines operated using OP and UG block caving methods within the same mining area.

Open pit to underground

Nowadays, the transition from surface to UG mining and OP mines operating over old UG workings are the most prominent case of OP–UG interaction. Currently, there are several large OP mines (e.g. Chuquicamata, Chile; Grasberg, Indonesia; Bingham Canyon, USA and Resolution, USA) conducting engineering studies to make the transition from OP to UG mining via caving methods (Flores and Karzulovic, 2002; Flores, 2006; Brown, 2007). The reason to move to UG mining is essentially to extend the mine life and/or optimize the benefit of the mining exploitation. As the mineralized zone goes deeper, the cost of the next pushback to access the ore may become less economically viable than the development of an UG mine. However, the transition point is not unique, with a range of options possible (Snowden, 2015; Finch, 2012) depending on the criteria assumed for the estimation. The ultimate solution relies on economic and risk factors and production rates, among other factors.

The decision to choose caving methods to continue surface mining is often based on production targets (cost and volume), the variables of which are of similar orders of magnitude for the two mining methods (Flores, 2004).

As part of the transition process, it is expected that a period of simultaneous exploitation will take place to mitigate the lower production volumes of the UG mine during ramp up (Flores, 2006). During this process, one of the main geotechnical challenges is to maintain the stability of the crown pillar (see Figure 9.30 and Figure 9.31), which is the portion of rock between the bottom of the pit and the position of the cave back. Managing the stability of the crown pillar is important to reduce the likelihood and severity of undesirable events such as instability of the pit slopes, mud rush, air blast and the entry of dilution in the UG mine (Stacey and Terbrugge, 2000; Flores, 2006).

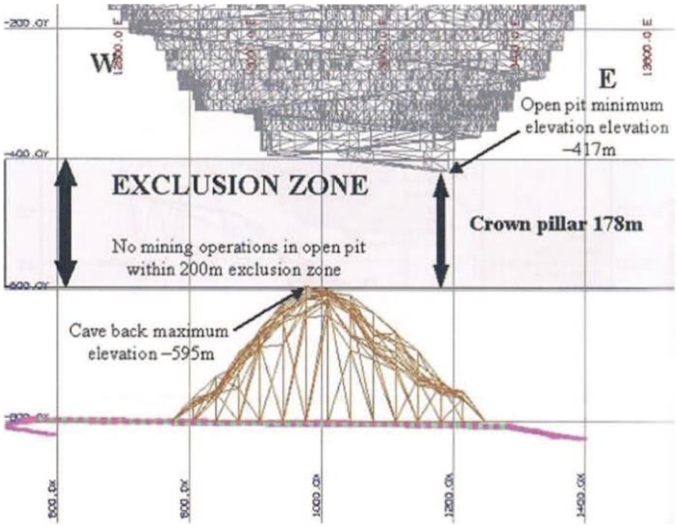


Figure 9.30: Crown pillar defined at Palabora mine (after Glazer and Hepworth, 2004).

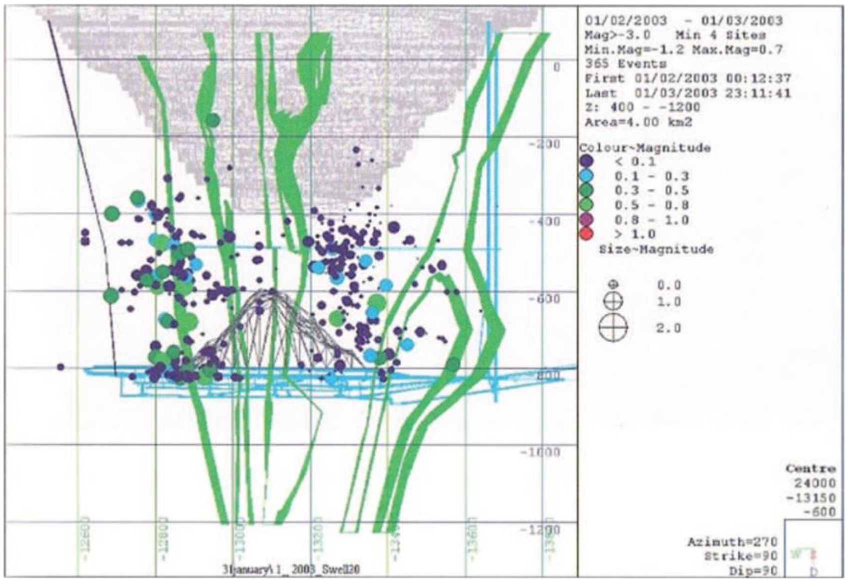


Figure 9.31: Seismic monitoring at the site (after Glazer and Hepworth, 2004).

The Palabora mine was the first mine to successfully perform the transition from a large OP to a block caving mine (Brown, 2007). The operational management of the crown pillar at the site, with all of the associated problems encountered during the process, has been discussed in detail by various authors (Glazer and Hepworth, 2004; Moss, Diachenko and Townsed, 2006; Brummer, Moss and Casten, 2006).

Simultaneous operations

The El Teniente mine in Chile is one of the largest UG mines in the world. Since 2013, it has been operating as an OP mine located at the edge of the subsidence crater generated by the caving process (Codelco, 2014). Different conditions have been identified in the interaction between Anglo American's OP mine Los Bronces in Chile and Codelco Andina Division's neighboring block caving mine, Rio Blanco (Díaz, 2014). Both mines are active operations, which implies a strong interaction between the east wall of the pit and the active subsidence crater of Andina (Figure 9.32). In this instance, the main challenges for the OP mine are to meet the objectives of the mining plan and, simultaneously, to maintain safe operating conditions while the crater expands towards the Los Bronces area.

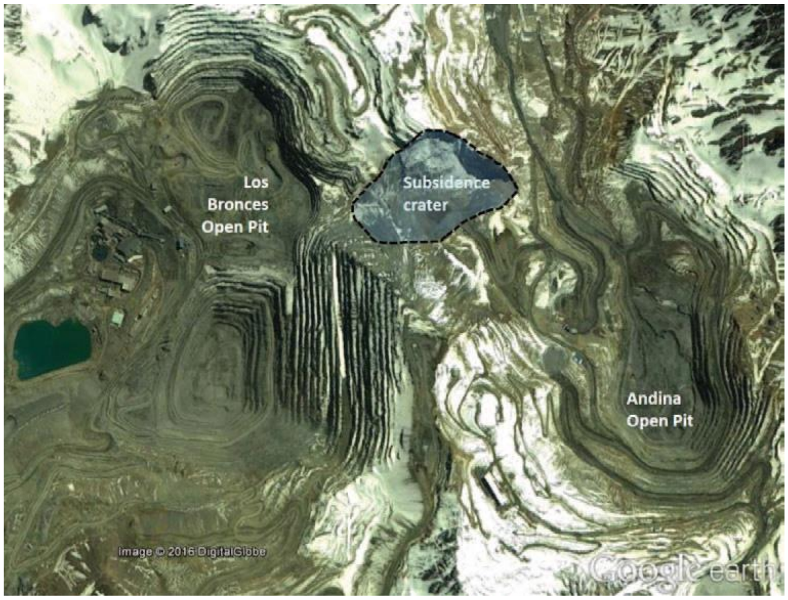


Figure 9.32: Plan view of Los Bronces–Andina interaction area (after Google Maps, 2015).

9.8.2.2. Geotechnical monitoring of open pit– underground interaction

Currently, there are not enough real cases of OP to UG transition to establish general empirical rules for generating safe operational conditions during the transition phase. For the same reason, the few attempts undertaken to define interaction design guidelines, in particular the work done by Flores (2006), have not yet been sufficiently validated. To date, when subsidence craters have developed, the general recommendation has been to avoid surface mining in the subsidence zone where large-scale fracturing can be observed (Díaz, 2014). Even if design guidelines did exist, continuous geotechnical monitoring is crucial for managing a successful transition process. Two phenomena are of particular interest:

1. The process of initiation and propagation of caving

2. The surface displacements generally associated with subsidence caused by the progression of caving towards the surface.

A general overview of the most widely applied instrumentation techniques for geotechnical monitoring of the aforementioned critical aspects is shown in Figure 9.33.

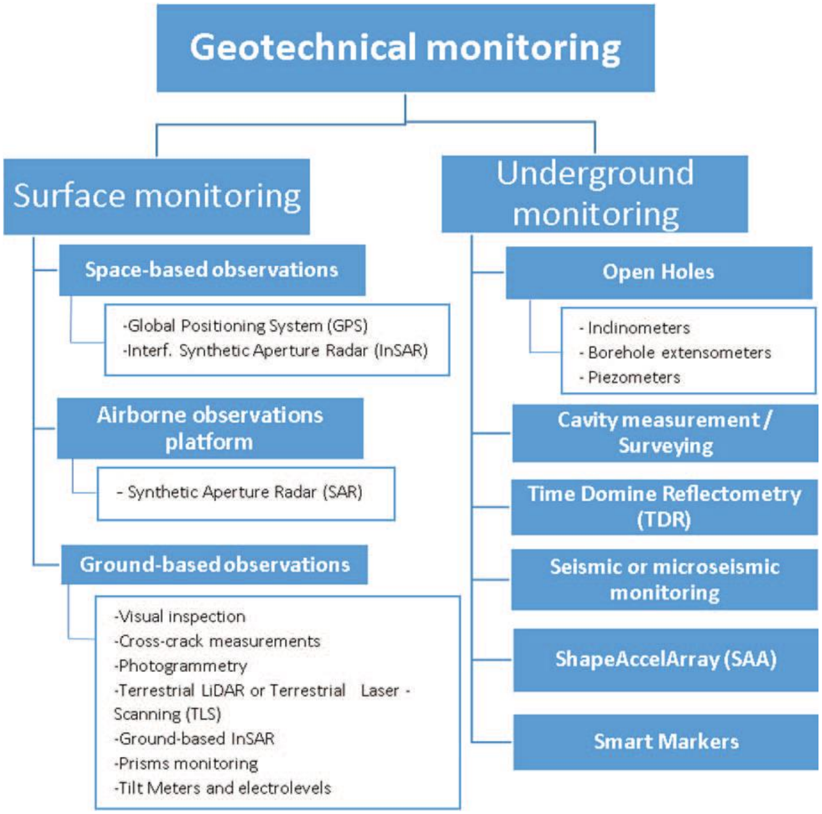


Figure 9.33: Summary of surface and underground geotechnical monitoring methods.

9.8.2.3. Surface Monitoring

As shown in Figure 9.33, there is a wide variety of available technology to monitor ground movement, which can be classified into three categories: space, airborne and ground-based observations. Examples of the application of these techniques are given by Díaz (2014), who mainly described the technologies currently used at the Los Bronces mine to monitor surface movements but also covered the entire spectrum of instrumentation, including total station, radar, crack meters, time domain reflectometry (TDR) cables, photogrammetry and interferometric synthetic aperture radar (InSAR). InSAR and radar are used to monitor the pit slopes and infrastructure in the areas of interaction with the active subsidence crater of Coldelco’s Rio Blanco mine. InSAR helps to identify the general areas of movement at different scales (in the range of meters, centimeters and millimeters), while radar generates a real-time inspection of the ground displacements.

In his work, Díaz (2014) also presented a benchmarking of the geomechanical instrumentation applied for controlling subsidence in four other mines (Kiruna, Perseverance, El Teniente and the Deep Ore Zone (DOZ)). His work confirmed that the strategy of combining real-time data acquisition with various instrumentation/techniques to detect movement at a larger scale is currently the standard in the mining industry. Díaz (2014) highlights the experience of the El Teniente mine, which operates as an OP mine on the edge of a subsidence crater (Espinoza and Mora, 2012; Espinoza, Mora and Sánchez, 2014), where mainly InSAR was applied. Photogrammetry and InSAR have also been applied in other mining environments, as described by Mora, Álvarez and Amor (2013).

Brief descriptions of the space-based, airborne and ground-based monitoring techniques are compared in Table 9.7, Table 9.8 and Table 9.9 respectively (Appendix E). This is presented for subsequent comparison with the proposed in-ground monitoring platform based on NSMs. The main references used for developing this review were Raghu, Singh and Ghose (2006), Mawell (2014), Hawley et al (2009), Patikova (2004) and McClusky and Tregoning (2013).

9.8.2.4. Underground Monitoring

According to Brown (2007), the following four techniques are the most commonly used for assessing cave propagation:

1. Methods based on open holes.

2. Cavity measurement or surveying.

3. TDR.

4. Seismic or micro seismic monitoring.

These methods, which are described in detail in Table 9.10, are generally used in combination, but only the last two have proven to be versatile enough to apply systematically.

A good example of TDR application can be seen in Szwedzicki, Widijanto and Sinaga (2004), which describes the application of this technique at the DOZ mine in Indonesia to monitor changes in the size and shape of the cavity and simultaneously estimate the rate of cave propagation.

The application of the seismic method at the Palabora mine for monitoring the response of the crown pillar is described in detail by Glazer and Hepworth (2004). The method consisted of installing recording stations around the cave on different levels. Nine of these stations were installed on the production and development levels, four in the OP and eight in an abandoned exploration shaft and a deep borehole. Some of the important factors to take into account are the sensitivity of the recording stations to locate events with an acceptable level of accuracy and the extent of the sensor network to provide reliable and precise data. Glazer and Hepworth (2004) remarks that mine seismology studies cannot solve problems on their own and that they must be supplemented with other data, such as seismic passive tomography.

9.8.3. Networked Smart Markers

Currently available subsurface deformation sensing technologies have some important constraints in their application in OPs, including a limited number of sensors per borehole, limited application depth, short lifespan and a low tolerance to abrupt shear deformation due to the presence of cables for data transfer. The technology presented in this paper, the NSM system, aims to address these drawbacks and thus create a new method for sub superficial monitoring of rock mass to assess slope stability and/or subsidence effects at a UG mine.

9.8.3.1. Sensor development and application

Smart Markers

Smart Markers were developed as an autonomous electronic device that is capable of monitoring mineral flow and ore recovery. The device consists of a battery and built-in radio transceiver placed within a high-impact resistant plastic case that is filled with epoxy to improve blasting resistance (see Figure 9.34). The markers have been developed by Elexon Electronics, and each device weighs 1.26 kg, is 34.5 cm long and 6.35 cm in diameter (Widzyk-Capehart et al, 2015). The markers are placed in an orebody that is to be extracted using the caving method and are then automatically identified via radio transmission when the load-haul-dump (LHD) machine extracts the fragmented material containing the marker through the drawpoint. The markers are detected by readers located in the vicinity of the LHD’s path. To date, Smart Markers have been successfully tested as gravity flow trackers in block caving operations (Steffen and Kuiper, 2014; Viera et al, 2014) and sublevel caving mines (Steffen and Kuiper, 2014; Whiteman, 2010).

The application of Smart Markers in underground mines allows a better understanding of mineral flow behavior and ore recovery. However, they cannot identify the location or track the evolution of the cave back as can be done with micro seismic monitoring.

Figure 9.34: Smart Marker sensor.

Networked Smart Markers

NSMs are Smart Markers equipped with an antenna for data transmission via radio frequency, enabling wireless communication between sensors through rock (Steffen et al, 2016). The signal strength variation between the markers indicates the relative distance between communicating markers as the rock moves.

These new communication capabilities opened up a number of new applications for NSMs. NSMs were recently installed at an OP mine to determine their applicability to monitor deformations behind the pit slope (Widzyk-Capehart et al, 2015). The NSMs were installed sequentially inside a borehole using several NSMs tied to a single cord. After installation of the markers, the boreholes were grouted so as to fix the NSMs in their initial placement position until the occurrence of deformations, which would force the sensors to move with the surrounding rock.

The installation distance between consecutive markers must not exceed the current maximum communication range of 5 m to enable uninterrupted signal transfer between markers. The radio signal transfer between markers is repeated until the signal reaches a modified NSM near the surface that functions as an antenna and is connected via cable to the reader station, where all data is regularly gathered at predefined intervals (Widzyk-Capehart et al, 2015). The data acquired from the sensors is downloaded into the reader and then sent via 3G modem to a predefined online server, which makes it possible to obtain the data remotely.

The raw data is processed and can be represented in a graphical form (Figure 9.35 and Figure 9.36). The semi-horizontal axis indicates the marker's number, organized according to a predefined order of installation, with the closest to the XYZ origin being the closest to the surface. The vertical axis refers to the signal strength between two consecutive markers and is called the 'received signal strength indicator' (RSSI). The RSSI values range from 0 to 64. Signal strength depends on the distance between markers and the propagation media. When installed, the initial values of RSSI are not important. This only becomes important to measure the difference in values after the installation.

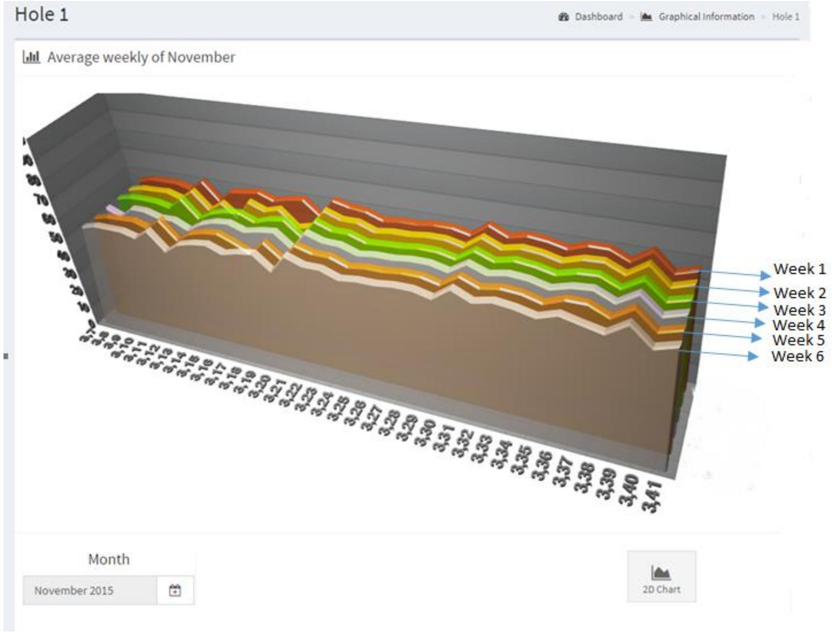
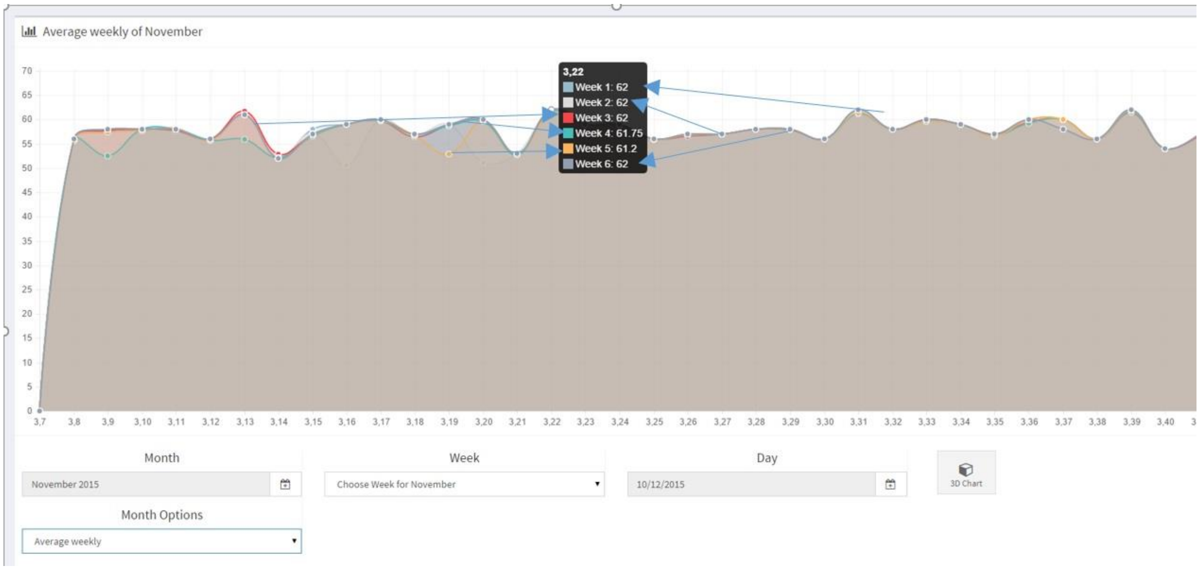


Figure 9.35: Networked Smart Markers 3D data representation of six weeks.



Month: November 2015
Week: Choose Week for November
Day: 10/12/2015
Month Options: Average weekly

Figure 9.36: Networked Smart Markers 2D data representation of six weeks.

Laboratory tests indicate that short-term fluctuations of five to ten in the RSSI values may be the result of temporary changes in the surrounding conditions. If the distance between markers is static and the conditions stable, the maximum change in RSSI values is around three points. The Z axis corresponds to the average weekly values obtained during consecutive weeks. Figure 9.35 and Figure 9.36 show the average value of one week compared with the average values obtained during the subsequent five weeks (six weeks are represented in total).

It is important to observe the variation of RSSI values of the same marker over time as it represents the change in distance between markers, which enables the assessment of rock movement. The change in distance between markers is due to the movement of the rock in the vicinity of the marker's initial installation.

9.8.4. Enhanced Networked Smart Markers

The qualitative assessment of rock mass movement is based on the variations of the registered signals' strengths, which does not provide the sensitivity to measure small-scale ground movement in the range of millimeters. However, the

NSM sensing platform and data transmission method allows for enhancement of the markers with sensors. This concept foresees the integration of other sensors within the current NSM, which can be accomplished within the same robust and field-validated platform. Thus, a new version of NSM, Enhanced Networked Smart Markers (ENSMs), is currently under development to enable a quantitative assessment of rock mass behavior associated with ground deformation and pore pressure monitoring.

9.8.4.1. Accelerometer

Tilt measurement can be performed by placing an accelerometer and magnetometer within the ENSM. To detect movement before the material reaches its yield strength, the accelerometers need to have sufficient accuracy. The required accuracy depends on the material where the system will be installed – brittle material will fail at smaller strain levels than ductile material. To cover a wide range of materials, a sensor with a high tilt resolution has been chosen. The accuracy of the selected accelerometer will be confirmed by performing validation testing in the laboratory and at mine environments in 2016.

9.8.4.2. Pore Pressure Sensors

Considering the overall benefits of geotechnical instrumentation, groundwater monitoring is a highly important task. Pore pressure is closely related to rock mass strength as a reduction in groundwater pressure increases the effective stress of the in situ rock mass and, consequently, increases the shear strength. In some cases, dewatering the rock mass is the only alternative that mine personnel have to increase resistance and reduce the probability of slope failure (Beale, Price and Waterhouse, 2013).

Currently, the most common instruments used to measure pore pressure are piezometers, which are classified according to the type of transducer employed to register variations in water pressure (Lomberg et al, 2013). An open standpipe piezometer is the least sophisticated variant, consisting of a plastic pipe with a perforated lower section within a filter element composed of coarse sand sealed by a layer of compacted bentonite pellets on top. However, the major limitation of this type of instrument is its slow response to piezometric change (Dunnicliff, 1993). In addition, these piezometers register the average pressure in a column of water but do not allow for measurements at a single point. Thus, they are not widely used in mining environments.

Diaphragm piezometers measure pressure by allowing water to enter the sensor through a porous filter. After the water enters the sensor, it fills the space between the filter and a diaphragm, deforming the latter. The instrument uses a transducer to measure the deformation and relate it to a pressure value. These sensors typically rely on pneumatic, vibrating wire, twin-tube hydraulic, flushable, semiconductor and piezoresistive transducers to make a reading.

Diaphragm piezometers stabilize after a pressure change over a period that ranges from seconds to several minutes. While pneumatic piezometers are unable to measure negative pore pressure, vibrating wire piezometers can measure pressure of 50 kPa below atmospheric pressure. Electrical piezometers have a significantly smaller time lag than pneumatic, hydraulic and flushable sensors as the volume of water displaced at the diaphragm is extremely small. These characteristics give electrical sensors an advantage over pneumatic sensors (Mikkelsen and Green, 2003).

Electronic pore pressure sensors and accelerometers are currently being implemented inside the NSMs. The exterior of the pore pressure sensor is covered with a mesh screen, which protects the sensor from getting clogged up by grout or other fines, but will allow water to pass through it. The pore pressure sensor marker uses a piezoelectric transducer with an accuracy of 0.1 per cent of full scale. The piezo transducer is used in ranges of up to 30 bar and can withstand an overpressure of at least 300 per cent (i.e. three times the nominal pressure). Above 30 bar, the transducer is a thin film Wheatstone measuring bridge and has an accuracy of between 0.15 and 0.2 per cent of full scale. It can withstand an overpressure of at least 200 per cent. Temperature compensation is applied to maintain accuracy across the marker’s operating range of 0–50°C.

A string of vibrating wire piezometers can be installed in a single borehole to provide multipoint measurements. Generally, only two to five sensors are installed in the same hole as technical issues prevent the installation of more. However, six or more instruments can be installed in HQ or RC holes (Read et al, 2013). The use of ENSMs will make it possible to install a greater number of pore pressure sensors. This will enable the definition of hydrostatic profiles with more measurement points in a single borehole because the wireless data transmission capabilities of the devices allow for any number of NSMs to be installed as long as the distance between neighboring markers is kept below their transmission range.

ENSMs would therefore allow mine personnel to correlate the pore pressure change rate with the propagation of deformation in the rock mass.

9.8.4.3. Monitoring open pit–underground interaction

As discussed previously, ENSMs could be used for subsurface monitoring of deformations or as gravity flow trackers for a caving mine. The information gathered from these sensors could then be integrated with all the other mine site data to improve the understanding of the rock mass behavior during the interaction, adding valuable new information such as:

- Understanding crown pillar response. Information captured from ENSMs could be used to identify locations experiencing deformation within the crown pillar. The data from the ENSMs could be combined with micro seismic monitoring data and the geological, geotechnical, and structural models of the mine, which would improve understanding of the mechanisms of mobilization and thus increase confidence in the predictions of rock mass response. This new system provides information that could improve risk management associated with subsidence, which could influence the decision to extend OP life during the interaction period. This could have a subsequent positive effect on ore recovery and business performance.

- Indication of the cave back limit. Once a critical hydraulic radius has been reached and caving has begun, the integration of ENSM data will help to improve the definition of the cave back's limit, which can be estimated based on the position of the last marker in the hole within the yielding zone. It is assumed that the markers located at the bottom of each hole are continuously incorporated into the pile of broken material due to the growth of the cave, thus losing communication with devices still arranged in the column.

- Gravity flow behavior. Once ENSMs start to behave as cave trackers, they will provide information related to the ore flow within the mobilized column. This data can be used to improve cave management, mainly in terms of draw rates and the strategy of drawpoint extraction. Figure 9.37 shows a schematic arrangement of the ENSMs distributed in the subsidence area that spans the distance from the OP to the UG operation, highlighting the recovery of cave trackers at the extraction level.

9.8.4.4. Enhanced Networked Smart Marker advantages

The advantages of the new ENSM platform are envisioned to be:

- Savings related to the installation procedure due to the possibility of installing different monitoring devices in the same borehole
- The elimination of cables and the risk of them getting damaged by ground movement
- More data from a single hole
- Diverse data time and location correlated from a single hole.

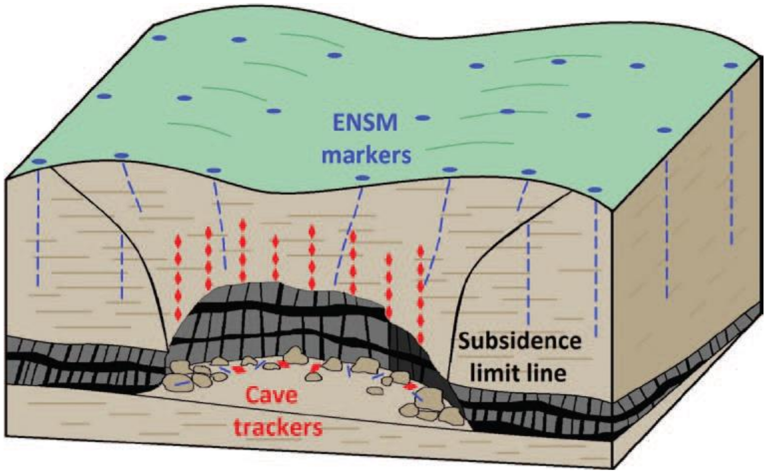


Figure 9.37: Enhanced Networked Smart Markers performing initially as subsurface monitoring and later as cave trackers combined with conventional cave trackers in an open pit–underground interaction scenario.

9.8.5. Conclusions

This paper presents NSMs as a new tool for monitoring subsurface deformation and pore pressure. NSMs are able to perform measurements through an array of autonomous sensors with wireless communication capability.

ENSMs are currently being developed to include a tilt meter and pore pressure sensor that will simultaneously measure the subsurface movement and pore pressure along the entire length of the borehole. When processed in real time, this data will provide an improved understanding of the effects of various operational activities, including UG mining in the vicinity of the OP, on rock mass behaviour.

The main advantages of ENSMs are their wireless communication capabilities and the ability to collect disparate data (displacement and pore pressure) at the same time and location.

9.8.6. Acknowledgements

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9.9. Appendix I: Implementation of Novel Subsurface Deformation Sensing Device for Open Pit Slope Stability Monitoring - The Networked Smart Markers System

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9.9.1. Abstract

Comprehensive and rigorous surface and subsurface monitoring to determine slope displacement in open pit mining is one of the most important means for assessing overall slope performance. The monitoring campaigns are aimed towards achieving and maintaining safe operating conditions, providing advance notice of zones of potentially unstable ground, providing geotechnical information for analyzing any slope instability mechanism that develops, designing appropriate remedial action plans, and assessing the performance of the implemented slope design.

Today’s surface displacement monitoring instruments are sophisticated; they include automated wireline extensometers, universal EDM total stations, 3D digital photogrammetry and laser scanning, and ground-based and satellite-based radar. Together, they can provide a real-time 3D record of any surface movements that may be taking place around the walls of the pit. However, in-ground displacement monitoring instruments are less sophisticated. Typically, they include shear strips and/or time domain reflectometers (TDRs), extensometers, and inclinometers placed in boreholes to locate or examine the propagation of subsurface movement after evidence of subsurface deformation has been detected at the surface. Less regularly, they are placed where it is anticipated that movement may not be detected by surface instruments. Rarely, if ever, they are able to detect in real-time subsurface deformation as it develops and propagates to the surface.

This paper describes the first steps in the implementation of the novel Networked Smart Markers (NSM) technology for subsurface deformation monitoring in large open pits. A case study of the trial installation at an open pit mine in Chile shows the importance of a well-designed installation, resulting in a robust and successful installation. This procedure would lead towards a more comprehensive monitoring campaign with further development of the NSM platform for multi-sensor, multi-variable monitoring.

9.9.2. Slope Design and Stability

Geological processes responsible for rock mass generation create ore bodies with variable geotechnical, structural and hydrogeological characteristics across the mine sites Read and Stacey (2009), yet the process of rock slope design and construction is standardized across the sites. Generally, rock slope designers rely on information acquired through experience and summarized as guidelines for designing slope angles as a function of slope's height and rock mass quality Wyllie and Mah (2004).

Rock mass quality, assessed according to rock mass classification systems, enables definition of rock mass competence based on qualitative criteria (Karzulovic and Read, 2009). However, these systems only provide a common base to assess rock mass quality or resistance; they do not overcome the problem of uncertainties when determining the actual strength of rock masses and when designing the slopes, which increases the risk of slope failure.

9.9.3. Slope Monitoring Instrumentation

Slope monitoring and proper data interpretation is essential in any surface mining operation as monitoring devices add value at any stage of the project (from pre-feasibility to closure). On one hand, they serve monitoring purposes to satisfy safety regulations through monitoring and reporting on changing conditions as mining progresses, verifying if the slope performance is acceptable and warning of future failures or unsafe slope conditions. On the other hand, the data allows better understanding of ground characteristics, a knowledge which can be used as input toward an optimized design, as it reveals information related to instabilities, means and methods used by personnel involved in geotechnical projects, management of mine developments or operations, delivery of objective report to stakeholders, evaluation of damage to mine site infrastructure, enhancement to operational performance and improvements to the state-of-art (Eberhardt and Stead, 2011; Marr, 2013).

These functions of slope monitoring can assist in overcoming uncertainties in slope design, reducing risks and improving understanding of rock mass' response to mining activities. It is, thus, highly desirable and recommended to implement geotechnical instrumentation for monitoring subsurface and surface deformations at each stage of a mining project (Dunnicliff, 1993; Hawley et al., 2009). This is particularly crucial when aggressive slope designs are planned or implemented in deep pits to overcome difficulties inherent to older open pits, such as, lower ore grades, higher operational costs, as a result of greater stripping rates, optimum balance between ore recovery, safety conditions and financial returns (Stacey, 2009).

9.9.3.1. Current practices on Open Pit Slope Deformation Monitoring

Nowadays, slope monitoring practices show a clear dichotomy between monitoring of surface and subsurface deformations, as the data is analysed separately, except perhaps for some cases in natural slopes, such as outlined by Locat et al., 2010. Several authors (Mphathiwa and Cawood, 2014; Wessels and Naismith, 2005; Mc Gavigan, 2006; Kayesa , 2006; Little, 2006; Severin et al., 2011) have shown that more effort is applied to surface deformation monitoring based mainly on the application of slope stability radar systems, LiDAR, geodetic prisms and GPS for near real-time monitoring covering large areas. In addition, space-borne InSAR technology can be used to remotely detect deformations at a scale of millimetres to centimetres over large areas that might be inaccessible for the installation of other types of instruments or when real-time monitoring is not mandatory. The satellite-based microwave radar generates an image based on the difference between two successive phase measurements in the flight path of the satellite (Eberhardt and Stead, 2011). Some instruments are better suited to specific failure modes; for instance, surface wireline extensometers can obtain a direct measurement of the displacement in a toppling failure by monitoring the crack width changes at the crest of a slope (Wyllie and Mah, 2004).

Subsurface monitoring tends to be less extensive relying on less sophisticated instruments, such as, TDRs, shear strips, extensometers, Shape Acceleration Array (SAA) (Abdoun et al., 2009), geophones (Lynch and Malovichko, 2006), and probe and in-place inclinometers. Generally, these devices have initially been developed to address civil engineering problems and, subsequently, have been applied in mining environments (Abdoun et al., 2009). For instance, inclinometers and SAA, which register progressive deformations, do not perform well under localized shear deformation as experienced in mining rock masses (Dowding and O'Connor, 2000). Therefore, these instruments are not fully applicable to open pit monitoring in their current forms, yet are applied successfully in civil engineering areas. Their apparent lack of compatibility or adaptability to mining conditions could be the main reason why they are not widely applied in mining yet, despite the fact that, in principle, these instruments provide functional data of the moving rock volume and early notice of deformations.

Among other instruments, probe inclinometers, which measure subsurface deformations in open pit mine operations, show a short operational lifespan as the large stiffness of rock generates high localized shear causing kinking of inclinometer casings that would stop the probe's movement through the casing. However, Dowding and O'Connor (2000) have stated that installing a metallic coaxial cable through or outside the casing and grouting it to be used as a TDR system, at the same time as the inclinometer, can extend the life of the inclinometer borehole by several months. Their experience serves to show the importance of using appropriate instruments to conduct accurate measurements and to add value of having several instruments in the same measurement area.

Lynch and Malovichko (2006) have shown that surface instruments can measure ground movement a couple of months after its surface initiation is detected by in-ground instruments.

9.9.3.2. Networked Smart Markers (NSM) System

Smart Markers

Smart Markers are electronic devices developed by Elexon Electronics (Whiteman, 2010). They are battery-operated, radio transceivers built-in a 34.5[cm] long and 6.35[cm] diameter plastic casing filled with epoxy for improved blasting resistance (Figure 9.38). Each Marker has an identifying ID, which is activated when the marker is installed in the ground, and is read by the Reader (data acquisition system), when the Marker is placed in close vicinity to the acquisition system.

Smart Markers have been used in underground caving mines to track ore flow and ore recovery. A large number of Smart Markers have been installed within drill holes near sublevel caving production blast-rings or in the orebody of block caves. Smart Markers' deployment into the subsidence cave has also been accomplished (Steffen and Kuiper, 2014).

In underground caving mines, the Markers are retrieved by an LHD at the draw point and identified by the Readers installed in the ceiling of the drawpoints, cross cuts, perimeter drives or ore-passes, as the LHD passes the Reader (Whiteman, 2010). The data gathered can then be retrieved from the Reader using a hand-held Scanner or be downloaded directly to the mine office if the Reader is connected to a mine's LAN or WiFi network. This data allows to infer rock movement and flow patterns for the fragmented material inside the caving operation (Whiteman, 2010).

Figure 9.38: Networked Smart Marker

Networked Smart Markers (NSMs)

Smart Markers enhanced with the ability to communicate wirelessly between each other using radio frequency are called Networked Smart Markers (NSMs). Currently, the wireless communication enables signal transfer through rock up to a distance of five meters. This type of communication unlocks new possibilities for the subsurface application of NSM technology in open pits. First prototypes of the NSMs were tested in an underground block cave and have been in operation now for more than two years.

NSMs work as a system installed sequentially inside a borehole. A series of NSMs are tied together in a string, which allows installation to any depth within the borehole as long as the spacing between two consecutive NSMs in the string does not exceed the maximum communication range. The NSMs are then sealed inside the drill hole with grout, permitting the NSMs to move with the surrounding rock as the rock mass deforms and each Marker sends a signal to the next marker in the string. This process continues until the signal reaches an antenna positioned at the top of the borehole, which must be located no farther than 5 meters away from the uppermost NSM in the string. The antenna is a modified NSM connected to a cable that links the grouted string of NSMs with the Reader Station.

The radio signal strength registered between neighbouring NSMs is gathered regularly. Variations of signal strengths indicate possible movement of the Markers, which can then be used to establish a qualitative indicator of in-ground rock mass movement as a function of relative displacements of the sensors.

9.9.4. Case Study

9.9.4.1. First NSM Open Pit Installation

The main objectives for the implementation of the NSM system and associated infrastructure in an operating open pit mine were to demonstrate that the system can be applied in open pit environment and can transmit a signal wirelessly through the rock mass.

Trial Preparation

First generation prototype NSMs were tested during the manufacturing process and subsequently at the Advanced Mining Technology Centre (AMTC) facilities at the University of Chile, Santiago. For the tests at the AMTC, the NSMs were arranged in a sequence and tied together using two ropes placed on diametrically opposed sides of each marker. The ropes were able to withstand 1.5 times the weight of all NSMs attached in-line (each NSM weights 1.26 [kg]), preventing torsion of the roped-NSM assembly and keeping the NSMs in a vertical position during installation of the string down the borehole. This arrangement also ensured that the ropes could be cut within the borehole, due to roughness of the rock material, allowing the markers to move freely with the deforming rock mass.

After the Markers´ arrays were completed, the ropes were marked above the topmost NSM indicating the depth at which the array should be placed inside the borehole. These marks were placed at the collar of the drill hole.

Installation

For the first site trial, two 53-meter deep boreholes were drilled five meters behind the crest of the trial slope and approximately 47 meter away from each other. The boreholes were instrumented with NSMs; a string of twenty two NSMs was installed in each borehole, with a two meter spacing between each consecutive NSM. Each string was complete with an antenna placed two meters above the uppermost NSM in the borehole and approximately one meter below the ground surface (Figure 9.39).

After each string of NSMs was lowered into the borehole, the end of the string was tied to a trestle to hold the Markers in place. Subsequently, the boreholes were sealed using cement-sand-water mixture, which was poured down the hole from the collar. Before both boreholes were completely sealed, the antenna was placed in the upper end of each hole at the required depth of approximately one meter below the collar. The antennas were connected via a cable with a Splitter-Box located approximately 50 meters away from the closest borehole along the bench.

The main feedline was installed between the Splitter-Box and the Reader Station and was buried in a shallow ditch for protection. The Reader Station was installed on a trolley, approximately 100 meters away from the Splitter-Box (Figure 9.39), and placed in an accessible, safe, and stable zone of the mine.

The Reader Station was powered using solar energy, allowing it to work autonomously. Data from NSMs was gathered at a set frequency and was stored on the Reader until manually retrieved using a hand-held scanner.

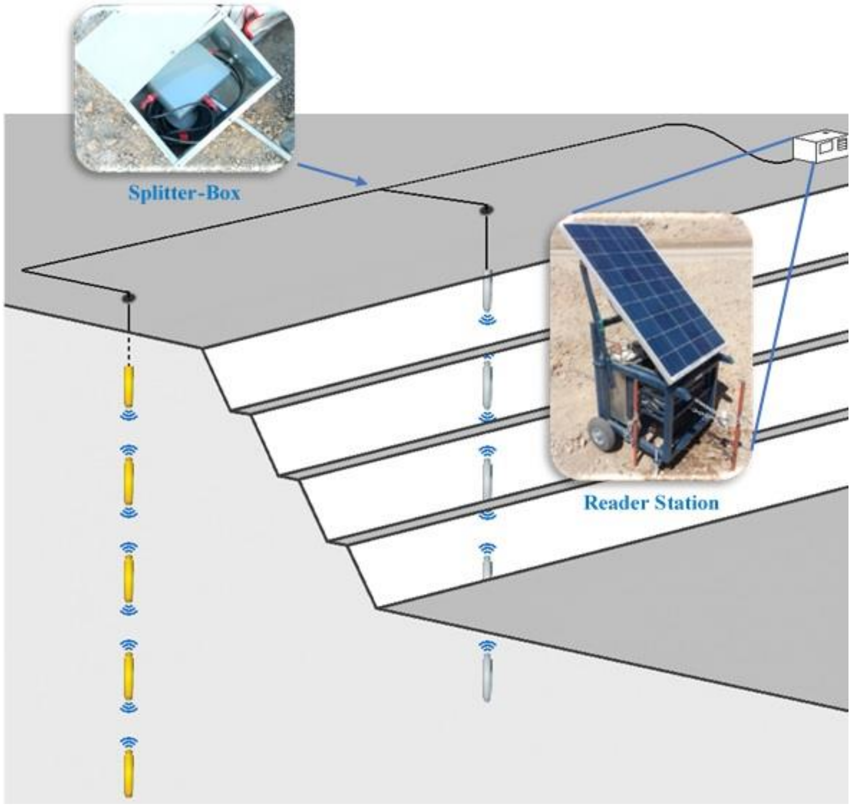
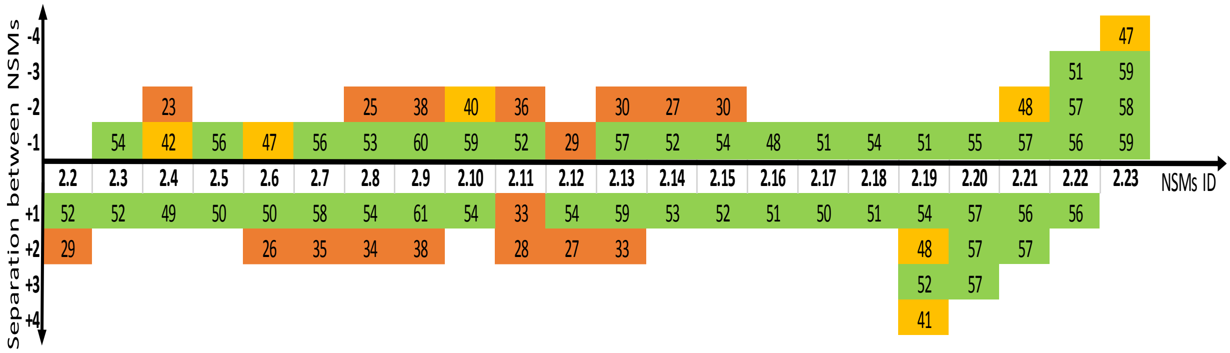


Figure 9.39: First NSM installation diagram

9.9.4.2. System Operation

The system performed well for approximately 6 weeks. Figure 9.40 shows an example of the signal strength and NSM connectivity in one of the instrumented boreholes where the consecutive numbers starting from 2.2 and ending in 2.23 represent the NSMs in the drill hole from top to the bottom (2.1 is not listed as it is the Reader). Colored boxes indicate signal strength for neighboring markers at 1, 2, 3, 4 hops of distance in each direction (up and down). NSM # 2.2 does not show signal strength above it and NSM # 2.23 does not show signal strength below it because they are at the end of the chain of Markers. Green boxes represent high signal strength links, yellow boxes indicate an average signal strength, and orange boxes specify low signal strength.



Separation between NSMs / NSMs ID	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	2.12
-4											
-3											
-2			23				25	38	40	36	
-1		54	42	56	47	56	53	60	59	52	29
+1	52	52	49	50	50	58	54	61	54	33	54
+2	29				26	35	34	38		28	27
+3											
+4											

Separation between NSMs / NSMs ID	2.13	2.14	2.15	2.16	2.17	2.18	2.19	2.20	2.21	2.22	2.23
-4											47
-3										51	59
-2	30	27	30						48	57	58
-1	57	52	54	48	51	54	51	55	57	56	59
+1	59	53	52	51	50	51	54	57	56	56	
+2	33						48	57	57		
+3							52	57			
+4							41				

Figure 9.40: NSM's connectivity

Figure 9.41 presents signal strength in both directions for every 1 and 2 hop link in the string, where “XX/YY” is “Receiver-A-signal/Receiver-B-signal”. Figure 9.41 shows that only 55% of the NSM present 2-hop links, leaving no redundancy in communication at other points in the string. In addition, there is a single 1-hop link between Markers 2.11 and 2.12, which is of poor quality. For these Markers, it was observed that multiple attempts were sometimes needed to route packets deeper to this marker.

Single Hop Links:

52/54 49/56 50/56 54/60 54/52 54/57 53/54 51/51 51/51 57/57 56/59
52/42 50/47 58/53 61/59 33/29 59/52 52/48 50/54 54/55 56/56

Two Hop Links:

29/23 - 34/40 28/30 - - 57/57
- 26/25 38/36 27/27 - - 57/58
- 35/38 - 33/30 - 48/48

>2 Hop Links:

52/51
57/59
41/47

Figure 9.41: Both ways signal strength

The data in Figure 9.40 and Figure 9.41 also indicate that the NSMs located at the bottom of the borehole had higher signal strength readings between Markers than those at the uppermost part of the borehole. This difference was thought to be the result of an elongation of the ropes caused by the weight of the NSMs and the impact of the grout poured from the top of the borehole. It was deduced that the NSMs at the bottom of the holes were closer to each other than 2 meters, while the NSMs further up the hole were farther than 2 meters apart.

After approximately 6 weeks of operation, the Reader stopped receiving new data. Therefore, over a period of 2 months, troubleshooting and re-establishment of the NSM system’s connectivity was attempted.

System Improvements

The improvements addressed several areas of the installed system to provide a better overall performance. For example, cables were disconnected and re-installed inside galvanized conduit ducts, the Splitter Box was protected inside a metal box and the motherboard inside the Reader was replaced by an updated version.

However, after the improvements were in place, communication was again lost to both boreholes. Through laboratory testing of spare NSMs and thorough examination of the installation, a number of possible causes for lost communications were identified.

Table 9.69 provides a summary of detected faults and/or deduced reasons for the interruptions of the system functionality.

Table 9.69: Troubleshooting summary

Detected Fault	Possibility	Comment	Likelihood Contribution
Poor 2-hop distance communication	Poor Marker Communication Range	Performance difference between individual markers. Marker antenna performance randomly distributed causing short range in some NSMs.	Likely Strong contribution
	Atmospheric noise penetrating bench	Bottom-Markers may have more success in 2-hop links due to them receiving less background RF atmospheric noise. Markers receiving higher background noise will have reduced range.	Unlikely Medium contribution
	Poor RF Properties of Earth/Ground	The ground and/or grout composition might be significantly different over the length of the borehole.	Unlikely Medium contribution
Markers becoming non-contactable	Marker Software Problem	A possible firmware fault was discovered that could cause a Marker to get stuck in an un-contactable state.	Likely Strong contribution
	Marker Battery Problem	Batteries may have drained during shipment of NSMs for this trial because they were shipped "pre-activated" to simplify the installation procedure.	Unlikely May have strong contribution in the case of a flat battery, but no NSMs showed drained batteries
	Broken Installation Rope	Possibly, the ropes broke during Marker installation leaving some NSMs out of rage.	Highly likely (for at least one hole due to total weight of sensors/grouting) Strong contribution
	Rope Elongation	Rope stretch expanded the planned distance between Markers. The distance for 2-hop links exceeded the Markers' communication rage.	Likely Strong contribution

Table 9.70 provides a summary of improvements made to the system prior to the second installation, which were deemed of high importance after the evaluation.

Table 9.70: System improvements

Possible Issue	Improvements
Out-of-spec antenna tuning, which may result in poor marker communication range.	Automatic testing of Marker´s antenna tuning during manufacturing. Antenna ranges tested in the ground before grouting the hole.
Software locking up on individual Markers.	Second generation software resolved known bugs and significantly improved reliability. New generation release was and continues to be extensively tested at Elexon.
Limited access to Reader required site visits, which placed additional work load on mine personnel and Project Team.	Remote access to Reader with a GSM modem to enable administrative tasks to be performed by AMTC and Elexon remotely.
Antenna cabling getting damaged.	Antenna cable protected with specifically designed cover to prevent physical impact damage.
NSM testing after grouting.	NSM tested above ground. NSM tested in the hole for an extended period (several days) before grouting.

9.9.4.3. Second NSM Open Pit Installation

A second installation with second generation prototype NSM was scheduled for the same trial site.

The second mine site trial was intended to test the improvements made to the installation procedures, the devices and the overall NSM system. For this installation, two new boreholes, 10 and 40 meters deep, were drilled in the same sector of the mine, approximately 10 meters behind the crest of the slope. The 10-meter drill hole was located behind the 52-meter borehole closest to the Splitter Box from the first installation, while the 40-meter borehole was placed 10 meters away from the 10-meter drill hole in the direction of the Splitter Box.

The boreholes were instrumented in sequence. The 10-meter borehole, equipped with five NSMs, allowed for initial testing of the installation before the deeper hole was instrumented. The 40-meter drill hole was instrumented with 35 NSM markers and grouted after confirmation that the installation in the shallower hole was performing as planned.

Installation Procedure

The NSMs were tied together using a single climbing kernmantle rope (capable of holding 3.5 time the weight of 35 connected NSMs) to prevent an extensive elongation of the rope due to weight of the NSMs. Cables from both boreholes to the Splitter Box and the main feedline to the Reader Station were installed inside galvanized conduit ducts. The NSMs were left hanging within the boreholes for one week before sealing them with grout. This allowed for testing of the signal strength and the detection of any possible communication losses.

An improved grouting procedure was used to seal the boreholes. The grouting was poured from the bottom of the hole to the top to: (1) avoid placing additional weight on the NSMs and the rope; (2) minimise disturbance to the NSMs positions; and (3) ensure an even filling of the boreholes without air gaps inside the grout column. The NSM antennas were installed at zero spacing (0 m) from the top-most NSM in the boreholes (approximately one meter below ground surface) and sealed with sand to make it possible to retrieve the antennas, if needed.

After both boreholes were sealed, communications were tested from the Reader Station showing successful wireless communications between the NSMs inside the hole. Three months after the second installation, new data was still being gathered at short time intervals showing good quality linkage between all NSM in both boreholes. This proves that the second installation procedure was robust and addressed the shortcomings of the first installation. The system also demonstrated that wireless data transmission through rock in open pit installation is possible.

9.9.5. Other Considerations

All issues encountered during the first installation of the instruments were identified and properly addressed prior and during the second installation to establish reliable and robust installation procedures that can be applied for similar open pit implementations in the future. Common problems of other devices, such as in-hole cable breakage, boreholes' blockage and excessive casing deformation, have been eliminated or reduced to minimum likelihood of occurrence. Deformations of up to two meters will still allow proper system functioning. To-date, the NSMs proved to be robust to guarantee long term reliability and operation lifespan under open pit mining conditions.

However, the Networked Smart Marker System is still in a prototype stage and requires more research, development and field testing. A number of desirable characteristics have been identified, which are still being investigated, such as:

- Increasing the through-ground radio communication range. A longer range would make installation more resilient to variance in installation distances and signal loss.
- Creating smaller and more easily deployable Readers.
- Implementing a more user-friendly user interface, which would enable any mine site operator to interact with the system. The current Reader's user-interface still requires special training.

9.9.6. Conclusions

Both field tests have proven that the Networked Smart Marker system can be applied in open pit mine environment to transmit data wirelessly through the rock mass with the second installation working without problems for several months. The implementation of the NSMs in the field showed an importance of thorough preparation and understanding of the issues among all the parties involved in the field trials.

Currently, a new version of NSMs called Enhanced Network Smart Markers (ENSM) is under development to integrate other sensors within the NSM platform. It is expected that the ENSM will overcome some of the limitations of the currently available and used sensing technologies, such as:

- Limited coexistence of sensors in a single location,
- Limited number of sensors per borehole,
- Instruments´ short lifespan,
- Limited depth application,
- Low tolerance to abrupt shear deformations, and
- Installation and maintenance issues due to the presence of cables inside boreholes.

9.9.7. Future Developments

It is envisaged that NSMs will be used as a monitoring technology platform to integrate various sensors to monitor subsurface variables. As the NSM platform is designed to provide the wireless data transmission through the rock and an autonomous operation for up to 10 years, it is reasonable to assume that it will overcome the shortcomings of other sensing devices and/or their cable-based connections, which can be damaged by ground movement.

Future installations of the ENSMs are planned to be carried out in higher slope walls, which would involve boreholes up to 300 meters deep. This will require modifications to the installation procedure for lowering the NSMs into boreholes, including specially designed hardware to lower the strings of NSMs as the sensors´ weight will be difficult to handle manually.

In addition, the future implementations would need to consider more complex and fully operative mining environments with ground water presence and high rates of deformation.

Determination of proper data collection frequency for the ENSM to register variations of studied variables depending on rock mass’ characteristics at various depths would be investigated towards inclusion in the future system. For example, brittle materials will require a higher frequency of deformation measurements than ductile rock masses.

The integration of a GSM modem within the Reader Station is under development and testing to enable remote access to the Reader Station via wireless networks, allowing the operators to interact with the Reader directly without having to be physically present at the monitored site. This implementation will allow remote software updates, firmware modifications and command execution related to data downloads.

Visualization software and tools to manipulate data are being developed for real or near-real time data processing. For following stages of development, this software will include capabilities to process data from sensors integrated within the ENSMs.

Finally, a redesign of the ENSM enclosure to make it easier to connect large numbers of sensors in one string will be investigated.

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9.10. Appendix J: Slope stability management: coupling deformation measurements with pore pressure data using novel Networked Smart Markers platform

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9.10.1. Abstract

While the understanding of hydrogeology in hard rock mining has increased significantly over the past 15 years, there is still a tendency to oversimplify approaches for assessing pore pressure distributions. Historically, analytical and numerical design work for pit slopes has used a simple water table or phreatic surface as input to the geotechnical models updated with data from pore pressure sensors installed at few selected locations within the rock mass around the pit. With this methodology, a thorough understanding of the groundwater conditions relevant to the mining project is seldom achieved.

The development and application of Networked Smart Markers for in-ground deformation measurements in recent months have presented an opportunity to improve in-situ pore pressure measurements programs. The proposed approach would allow for data collection at multitude locations without considerable increase in the cost of installation and for coupling the pore pressure measurement with rock mass deformation data.

In this paper, the initial development of the Networked Smart Markers enhanced with the pore pressure transducers, including the description of the laboratory testing of the new sensing platform using a pressure vessel, is presented.

9.10.2. Introduction

9.10.2.1. Water in Mines

Presence of water in open pit mines is a critical operational issue because the pore pressure in rock reduces the strength of the materials that make up the mine, thus having a negative effect on slope stability. In addition, water can flow into the working area when mining is occurring below the water level, which will further reduce the overall efficiency of the operation by inundating accesses, affecting drilling and blasting holes (wet holes) and accelerating the wear of equipment (Read et al., 2013).

Pore pressure is defined as the pressure of the groundwater occurring within the pore spaces of the rock or soil. Under hydrostatic conditions, the pore pressure is the result of the weight of the column of water above the depth of interest. It can vary under hydrodynamic conditions if vertical components of the groundwater gradient are present. At any given location, the degree of vertical pore pressure variation will depend on the distribution of permeability that occurs below the potentiometric surface and the elevation of groundwater recharge and discharge points (Beale, 2009).

Pore water pressure requires appropriate management with dewatering programs being one of the most effective ways to manage the influx of water into open pit mines. Depressurization campaigns are currently the only feasible way that mine personnel have to actually increase the rock mass strength and decrease the probability of slope failure.

For groundwater control by dewatering to be effective, a thorough knowledge of the site’s hydrogeological properties is required. In addition to the rock’s permeability, porosity and location of the water table, the vertical distribution of pore pressure and the charge and discharge rates of water within the rock mass need to be characterized.

9.10.2.2. Pore Pressure Measurements

Below the water table, pore pressure is determined by measuring the height of a column of water at a given point (depth and location) within the rock mass. In general, the deeper the point below the water table, the higher the pore pressure (Beale, 2009). Accurate characterization of the vertical distribution of pore pressure requires taking in-situ pressure measurements at different depths and is particularly important if vertical gradients are relevant in the area. This is very likely to occur when the mine excavation progresses below the water table and/or the drainage systems start to work. It is worth mentioning that groundwater flow in a mine site setting (in underground mine as in an open pit) is generally three-dimensional (3-d) with components in X, Y and Z direction.

Currently, several types of instruments are being used to measure pore pressure; they are generically known as piezometers. Some authors use the term "piezometer" to refer exclusively to those instruments that are sealed into the ground and thus respond only to the groundwater pressure in the vicinity of the instruments and not to groundwater pressure at other elevations (Dunnicliff, 2012). Piezometers are usually classified based on the type of transducer employed to register the variations in water pressure (Lomberg et al., 2013). Regardless of the device used to measure the pore pressure, the main concerns in the use of the piezometers are: (1) the proper sealing of the device in the ground to ensure that pressure measurement truly corresponds to a single point measurement and (2) the limited number of piezometers that can be installed in a single borehole for multi-point measurement purpose.

This is especially important in mining as one of the main constrains in the development of hydrogeological models of mines and pit slopes is the lack of sufficient in-depth pore pressure data. It’s not uncommon to have only a few pore pressures measurements, obtained in a dispersed manner, at only three or four different depth levels, from a total of few (10 or less) boreholes for the entire mine.

9.10.3. Networked Smart Markers

9.10.3.1. Smart Markers: Current Status

Smart Markers are autonomous electronic devices developed by Elexon Electronics (Whiteman, 2010) capable of monitoring mineral flow and ore recovery in block/panel and sublevel caving mines. These devices consist of a battery and built-in radio transceivers, enclosed within a high impact resistance plastic case. The Smart Marker weights 1.26 kg with dimensions of 34.5 cm long and 6.35 cm in diameter (Widzyk-Capehart et al., 2015).

Figure 9.42: Networked Smart Marker

The Networked Smart Markers (NSMs) are devices developed as an enhancement of the Smart Markers with the ability of communicating wirelessly between each other; they are equipped with an inner antenna used for data transmission via radio frequency, which allows wireless communication by transferring the signal through rock for a distance of up to 5 metres (Steffen et al., 2016).

NSMs work as a system installed sequentially inside a borehole. A series of NSMs are tied together in a string, which allows installation to any depth within the borehole as long as the spacing between two consecutive NSMs in the string does not exceed the maximum communication range. The NSMs are then sealed inside the drill hole with grout and each marker sends a signal to the next marker in the string. This process continues until the signal reaches an antenna positioned at the top of the borehole.

The first prototypes of the NSMs were tested in an underground block caving mines and have been in operation now for more than two years. Recently, these instruments were trialled at an open pit mine to determine their applicability to monitor subsurface deformations behind the slope's wall (Widzyk-Capehart et al., 2015)..

Currently, NSM technology is able to perform a qualitative assessment of rock mass movement based on the variations of the registered radio signals´ strengths of the devices in a borehole. Continuous monitoring of the variation of the signal strength values of the same Marker over time is essential as the rate of radio signal variation represents the magnitude of the change in distance between Markers, which subsequently indicates the movement of the rock mass.

9.10.3.2. Smart Markers: Current Development

The integration of additional sensors within the NSM technology, together with the data transmission method, allows for improvements to be made within the same robust, field-validated platform. A new version of NSM, the Enhanced Networked Smart Markers (ENSM), is currently under development to enable a more sensitive quantitative assessment of ground deformation and the measurement of pore pressure.

The use of Enhanced NSMs to monitor pore water pressure in mining environments has the potential of allowing multi-point measurements at a scale that cannot be achieved by any other technology currently in use. Theoretically, in a 300[m] deep borehole an approximate of 60 Markers can be installed, thus increasing the data gathering points in a column by one order of magnitude when compared to other multi-point measurement systems.

9.10.4. NSM Enhancement – Pore Pressure Sensor

Part of the fundamental aspects when integrating the measurement of pore pressure in NSMs devices are, at this first stage of development: the selection of the pressure transducer to use and the porous filter to protect the diaphragm to prevent clogging of the sensor as well as how both the transducer and the filter are to be integrated into the casing device. Enlargement of the electronic circuits and upgrade of the microcontroller unit will also be redesigned.

All the components (individually and together) are being tested under laboratory conditions (with grouting and water as well as with and without pressure). The results of the initial tests are presented in this paper.

9.10.4.1. Pore Pressure Sensor System - Considerations

The pressures that the transducer will have to measure once installed in the borehole can differ considerably from those that the transducer will be exposed to during the installation process. Once in operation, the pore pressure measurements will be related to groundwater levels, while during the installation process the measurements will be related to the height of grout above the sensor and thus to the depth at which the device will be installed. During the grouting process, and before the grout hardens, pressure sensors are exposed to head pressures dependent on the borehole depth and grout density, in which case, the head-pressure exerted by the grout mix is larger than the head-pressure of an equivalent water column due to the higher density of grout. Therefore, the sensor must withstand large ranges of pressures while maintaining an accuracy that provide scientifically significant results.

Most electronic sensors´ technologies have an accuracy that is related to its measurement range: the larger the range the lower the absolute accuracy of the sensor. The sensor’s ability to withstand high pressures without being damaged is called the sensor’s overpressure tolerance. Larger overpressure ratings of sensors´ technologies are advantageous because they enable a selection of a sensor that is rated for a pressure range that is close to the expected in-situ pressure (Pollock, 2013).

Transducer Selection

The pressure transducer selected to be integrated into ENSM devices is called OEM TI-1 pressure transducer, manufactured by the German company Wika (Wika, 2015). It has been chosen to fit within the existing Smart Marker layout and construction. It can also cover a wide pressure sensing range while providing high accuracy and precision. This transducer was selected because:

- It met the technical requirements, including being:
  - Supplied as the bare sensor and housing or with conditioning electronics.
  - Small enough to fit into either end of the existing Marker casing.
  - A piezoelectric transducer with high accuracy.
  - Able to be used in ranges of up to 30 bar and able to withstand an overpressure of at least 300%.
  - A transducer with a high accuracy thin-film Wheatstone measuring bridge above 30 bar.
  - Temperature compensated to maintain accuracy across the Marker’s operating range from 0 to 50°C.
- It provided conditioning electronics and temperature compensation, which accelerates integration with the Marker´s electronics (Pollock, 2013).

The selected transducer uses two different measurement techniques, depending on the pressure range. At low pressure ranges, the transducer is based on a piezo device while for pressure ranges above 20 bar of the full scale the sensor element is a thin film arranged as a strain gauge, Wheatstone bridge. The piezo sensor is also available as absolute pressure transducers for up to 30 bar full scale, with full scale ranging from 0.4 bar to 1000 bar.

The transducer will be incorporated into the Marker´s end cap, which is a part of the existing Marker casing. Early prototype will adapt the existing cap for the purpose but future versions are likely to be adapted to include two built-in layers of filtration mesh and a threaded hole to accept the transducer (Figure 9.43).

The Marker design will not need to be changed to house different types of transducers; this will allowed, in the future, to choose different pressure transducers to suite different applications and pressure ranges, if necessary.

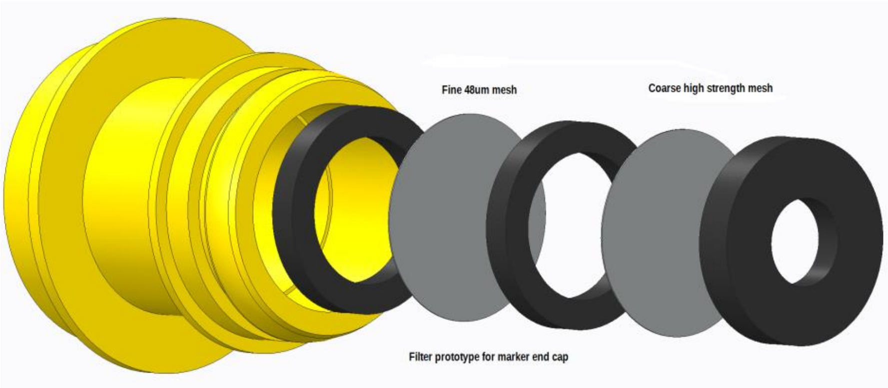

Figure 9.43: Filter Prototype

Porous Filter Selection

As previously mentioned, the sensors will be subjected to grouting conditions (Portland cement and bentonite clay powder) and water pressure while in operation. This means that the filter must protect the sensor but allow the passage of water. If the filter is significantly weakened due to grouting or initial water pressure, or does not allow passage of water, the sensor may measure incorrect pressure.

Table 9.71 shows a comparison of filters available on the market and their basic characteristics (Sanchez, 2015). The review of available filtering media led to the selection of the stainless steel mesh for testing in the laboratory, details of which are provided in the section "*Laboratory testing*". Subsequently, a stainless steel mesh with a 48µm screen was selected for testing.

Table 9.71: Comparison of available filters

FEATURES	Metallic	Ceramic	Stainless steel mesh
Pressure resistance	3,5MPa	0,1MPa	-
T° Resistance	-20°C to +100°C	-20°C to +100°C	-40°C to 200°C
Opening	40 µ	1 µ	1 to 1670 µ
Diameter	Standard	Standard	Variable
Installation	More complex	More complex	Simple
Cost	Intermediate	Expensive	Cheap
Grouting resistance	High	High	Unknown
Advantages	Very resistant Used in current piezometers	Resistant and highly porous. Very precise measurements of pore pressure	Easy to attach to any sensor. Multiple layers can be combined with different openings for greater protection of the sensor
Disadvantages	Measures of standard filters for piezometers. Difficult to attach to other sensors.	Measures of standard filters for piezometers. Difficult to attach to other sensors.	Need for testing prior to installation to ensure resistance to various external agents

Structural Redesign

Originally, the Smart Marker sensor was designed to be installed close to the boreholes containing explosives and to withstand the detonation. With the introduction of the pressure transducer inside the device, the redesign of the casing is necessary as the pressure transducer requires a port or a connection to the outside of the casing while having an electronic components embedded within the core of the Marker (Figure 9.44). In addition, the enhanced sensor needs to maintain an air pocket behind the sensing surface, which places limitations on the mechanical structure of the selected pressure sensor device as the Markers are solidly filled with an epoxy and fiberglass. In the new design, the exterior access to the transducer is intended to be covered by a screening mesh to protect the sensor from becoming clogged by grout or other fines but allowing water to pass through it.

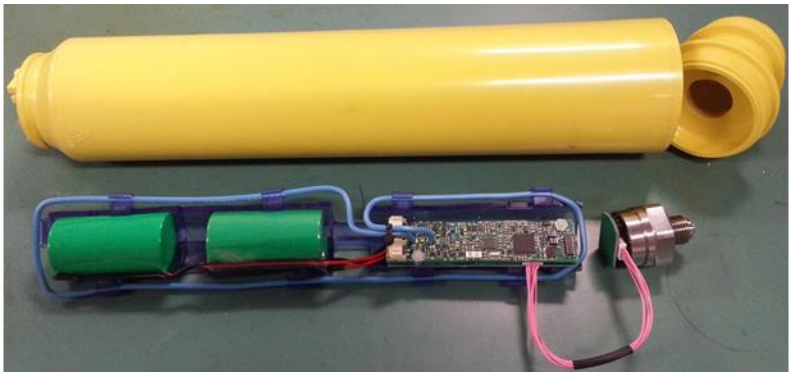

Figure 9.44: Prototype boards assembled with batteries, antenna and pressure transducer

9.10.4.2. Pore Pressure Sensor System – Laboratory Testing

Transducer Testing

Test 1 Pore Pressure Sensor Test (outside of the Pressure Vessel):

The pore pressure sensor transducers were factory tested on the manufactures' production line. They were shipped with a five point table from zero to full scale, showing the results at room temperature. These results were also available on-line using the devices individual serial number.

Currently, preparation for laboratory testing to confirm the manufacturing data are being made. Several sensors, in a single pressure range, will be checked against a laboratory grade instrument with a certified accuracy of 0.025% full scale for that same range. The sensors will be tested in a climate controlled environment at various fixed temperatures covering the normal operating temperature range for NSMS. The sensor under test will be hydraulically coupled to the high accuracy device for comparison. At each temperature a schedule of pressures will be applied to each sensor under test with an appropriate settling time between each.

Test 2 Pore Pressure Sensor Test (inside Pressure Vessel):

A high value of sensor´s overpressure is advantageous as it allows a more accurate transducer to be used for a given application. The probability of an overpressure occurring rises when a deep borehole is filled with grout above the transducer. The desired range for measuring pore pressure in the installed location may be as low as 5 bar; however, if the depth of the hole is 200 meters or more, the pressure under the weight of grout could be up to 30 bar or more until the grout sets. As accuracy is proportional to the full pressure scale of a transducer, a high tolerance to overpressure means that the lowest possible range can be selected with the best possible accuracy.

The integrity and characteristics of the sensor under pressure (0 to 10 bar) and a temperature range of 0 to 50 degrees centigrade were tested inside a pressure vessel. The hypothesis was that if the selected sensor was not suitable for these conditions, the sensor would break. The data obtained during the tests under pressure of up to 10 bar were compared to a laboratory grade pressure gauge kept at room temperature. The results showed measurement accuracy better than 0.25%. Thus, in conditions of 0-10 bar and room temperature, the OEM IT-1 pore pressure sensor performed according to required specification.

Filter Testing

Porous Filter – Test 1:

A 48µm stainless steel mesh was installed on the end of a small pipe of 18 mm of diameter which covered a pipe with a diameter of 103 mm and length of 200 mm. The mesh was covered with a mixture of Bentonite clay and Portland cement. Neither the Bentonite nor the cement particles pass through the mesh and the mesh was not blocked by the grout, allowing the passage of water (Figure 9.45).

Figure 9.45: Filter Test 1

The tests showed that this candidate mesh, in addition to filtering properties, was able to protect the pore pressure sensor and was deemed suitable for implementation in the first round of Markers´ prototypes.

Porous Filter – Test 2:

Two small PVC pipes of 18 mm of diameter and length of 6 cm were attached to a large PVC pipe with a diameter of 103 mm and length of 2.5 meters. One of the smaller pipes was covered with a 48µ mesh gauze mounted in a way to simulate a likely pressure sensor filter (Figure 9.46). After the grout was poured into the large pipe, it was left to harden for 48 hours. Subsequently, the pipe was filled with water and the flows were monitored for any difference out of the two small pipes.

Figure 9.46: Porous filter test: two small PVC pipes (with and without filter) attached to a large PVC pipe

As shown in the Figure 9.47, the pressure readings taken using the PVC pipe without filter at the commencement of the experiment were higher but they stabilized after approximately 6 hours. For the PVC pipe equipped with a filter, initially, the pressure reading were lower than for the PVC pipe without filter and followed a linear distribution but they also stabilize after approximately 6 hours.

Therefore, it can be concluded that the water pressure values obtained with and without filter equalize after approximately 6 hours, which indicates that, in the event these filters are used to protect the pore pressure sensors, the measured results will be equally valid if enough time passes for the sensor and filter to stabilize with the grouting. This is likely to be the case for any instruments protected by filters. The tests also showed that the mesh used resisted the ingress of grouting.

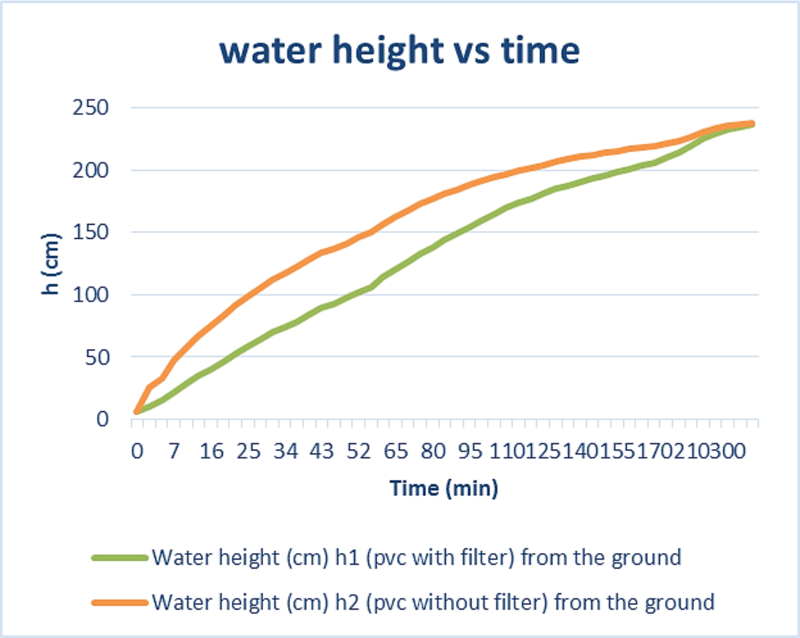

Figure 9.47: Pressure readings using PVC pipes with and without filter

Casing Testing

The Marker’s casing is not perfectly rigid and the effects of high external pressures may lead to some strain on the casing, which can, in turn, reduce the space behind the transducer diaphragm distorting the measured pressure. This effect needs to be mechanically modelled and tested to determine the effect of the high external pressures and then tested in a hydraulic pressure test chamber. Early testing of up to 10 bar showed no measurable effect on the size of the space behind the transducer.

9.10.5. Conclusions and Future Work

There exists a technology gap in the instruments currently available on the market to perform accurate and reliable multi-point measurements of pore water pressure at the open pit mines as installing a large number of devices inside a single boreholes proves difficult due to technical restrictions given by cables, pipes and infrastructure.

Enhanced Networked Smart Markers appear as an alternative to the established technologies due to their ability to transmit data gathered by the sensors wirelessly. Furthermore, additional sensors are being implemented within the ENSM to allow quantitative monitoring of subsurface deformation and pore water pressure simultaneously.

Review and laboratory testing of the pore pressure sensors until now confirmed that the selected OEM IT-1 sensor has the precision and pressure resistance required to be a good candidate to be incorporated within the Marker´s assembly.

In addition, the initial laboratory testing has been successfully conducted for the stainless steel mesh with a 48μm screen, which allowed the passage of water but not the passage of grouting; thus protecting the sensor but not altering the measurements of the water pressure, as long as the time required to stabilize the medium is accomplished.

The future work will consist of additional laboratory testing of the various components of the pore pressure system, including the testing of:

- Sensors with the filter and grout at different pressures (0 to 16 bar) and temperatures (0 to 50°C) in the pressure vessel to check the accuracy of the sensors before they are incorporated within the Markers´ casings.

- Sensors for up to 30 bar of pressure before they are incorporated within the Makers´ casings.

- Marker with the pore pressure sensor installed within it, under various pressures and temperature ranges. This will be performed inside a pressure test chamber, which is rated up to 200 bar.

Assuming the next series of test of the sensors with filters at different temperatures and pressures are successful, the Networked Smart Markers will be manufactured with the pore pressure measurement system and available for the field testing at the mine sites in mid-year 2016.

9.10.6. Acknowledgements

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