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**OPEN PIT GEOMECHANICS AND MINE PLANNING INTEGRATION:  
DESIGN & ECONOMIC ASSESSMENT OF A SUBSURFACE SLOPE  
DEFORMATION MONITORING CAMPAIGN**

**TESIS PARA OPTAR AL GRADO DE MAGÍSTER EN MINERÍA**  
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La geomecánica y planificación minera son áreas de la minería a cielo abierto íntimamente relacionadas, ya que las restricciones geomecánicas limitan al diseño minero y, así, los planes mineros factibles. El diseño y los planes mineros han de empujar los límites de lo que la geomecánica permite, para asegurar operaciones mineras competitivas y mantener un nivel de riesgo al personal y operaciones aceptable. Luego, se requiere del monitoreo geotécnico para adquirir datos de calidad que permitan un diseño minero de alto nivel.

Sin embargo, la relación entre geomecánica y planificación minera no se extiende al diseño e implementación de programas de monitoreo. En general, los programas de monitoreo de deformaciones superficiales son diseñados con posterioridad al inicio de la operación del rajo y cuando se han identificado signos de inestabilidad en la superficie de los taludes.

El monitoreo de deformaciones del subsuelo permite alertar sobre fallas en desarrollo semanas antes de que estas se hagan notar en superficie. Luego, se debería diseñar campañas de monitoreo de deformaciones del subsuelo durante el proceso de planificación minera, considerando el diseño minero en la instalación de instrumentos geotécnicos previo a la construcción de la mina. Lo que permitiría registrar el proceso de relajación del macizo a medida que la construcción progresa y adquirir datos más exhaustivos del comportamiento del macizo rocoso (antes que con monitoreo superficial), con el fin de optimizar el diseño de taludes futuros y adoptar medidas correctivas para evitar fallas.

En esta tesis, fueron diseñadas una serie de campañas de monitoreo de deformaciones del subsuelo usando In-Place Inclinometers, ShapeAccelArrays y Networked Smart Markers (NSMs) como equipos de monitoreo. Las opciones fueron aplicadas a una mina teórica desarrollada como parte de la tesis y comparadas en términos de costos, cantidad y calidad de los datos recopilados.

Los resultados indican a la opción de NSMs cada 2[m] como la más eficiente en cuanto a costos ya que: (1) presenta el menor costo por unidad de datos adquiridos (US\$57.21) y (2) 5 veces mayor vida útil, lo que permitiría obtener el doble de datos que la siguiente mejor opción, (3) se financia con un aumento de 2° en el ángulo de talud y (4) aumenta el VAN del proyecto en 3.2%.

**ABSTRACT OF THE THESIS TO OPT TO THE DEGREE OF:** Mining Engineer and Master in Mining.

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**OPEN PIT GEOMECHANICS AND MINE PLANNING INTEGRATION:  
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Open pit geomechanics and mine planning are two closely related areas in the development of an open pit mine since geotechnical constrains limit the possible mine designs and, thus, the feasible mine plans. Mine designs and plans have to push the limits of what rock mass geomechanics allow to assure competitive mine operations, while maintaining acceptable levels of risk to operations and personnel. Therefore, geotechnical monitoring programs are required to acquire good quality data to be used as input for mine design.

However, the relation between geomechanics and mine planning does not extend to monitoring programs' design and implementation. Generally, surface deformation monitoring programs are designed after the project is in operation and signs of slope instability have been identified on the surface.

Subsurface deformation monitoring can alert about developing failures weeks before any sign of instability is noted on the surface. Therefore, subsurface deformation monitoring campaigns should be designed along the mine planning process and considering the mine's design to install geotechnical instrumentation prior to the construction of the slopes. This methodology would allow to register the rock mass relaxation process as construction progresses and to acquire more comprehensive data about rock mass behaviour, in advanced of surface monitoring, towards future slope design optimization and adoption of remedial measurements to avoid failure.

In this thesis, a series of subsurface deformation monitoring campaign were designed using In-Place Inclinometers, ShapeAccelArrays and Networked Smart Markers as monitoring devices. All options were applied to a theoretical open pit developed as part of this work. The campaigns were compared in terms of cost, quantity and quality of gathered data.

The results showed that the campaign using NSMs installed every 2 meters was the most cost-efficient option as it represented: (1) the lowest cost per unit of gathered data (US\$57.21), (2) five times longer lifespan, which allowed to gather twofold the amount of data compared with the next best option, (3) be financing of the campaign through steepening of the slopes by 2° and (4) increase in project's original NPV by 3.2%.

## ***DEDICATION***

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To my parents, sister and grandmother, without whom I would not have had the patience and fortitude to finish this work.

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# **TABLE OF CONTENT**

---

INTRODUCTION .....	1
1.1. Objectives .....	2
1.1.1. General Objective .....	2
1.1.2. Specific Objectives .....	2
1.1.3. Hypothesis .....	3
1.1.3.1. Hypothesis 1 .....	3
1.1.3.2. Hypothesis 2 .....	3
1.2. Justification of the R&D .....	3
1.3. Scope of Work .....	4
1.3.1. Introduction .....	4
1.3.2. Chapters Overview .....	4
1.4. Chapter Summary .....	6
LITERATURE REVIEW: OPEN PIT ROCK SLOPES STABILITY AND DEFORMATION MONITORING .....	7
2.1. Open Pit Slope Design and Stability .....	7
2.2. Importance of Geotechnical Instrumentation .....	11
2.3. Geotechnical Instrumentation for Civil Engineering Applications .....	12
2.3.1. Groundwater Pressure Monitoring Devices .....	12
2.3.2. Soil or Rock Mass Deformation Monitoring Devices .....	13
2.3.3. Load and Strain in Structural Members Monitoring Devices .....	15
2.3.4. Total Stress Monitoring Devices .....	16
2.3.5. Guidelines for Geotechnical Instrumentation .....	16
2.3.6. Monitoring Applications .....	17
2.4. Open Pit Mines Geotechnical Instrumentation & Monitoring .....	18
2.4.1. Groundwater Monitoring .....	19
2.4.2. Movement Monitoring .....	19
2.4.2.1. Surface Deformations .....	20
2.4.2.2. Subsurface deformation .....	23
2.4.3. Currently Available Subsurface Deformation Sensing Instruments' Limitations for Open Pit Mining Applications .....	25

2.4.4.	Guidelines for Open Pit Instrumentation and Monitoring .....	26
2.4.5.	Open Pit Deformation Monitoring Applications .....	27
2.5.	Open Pit Geomechanics and Mine Planning Integration.....	28
2.6.	Conclusions of the Literature Review .....	29
IMPLEMENTATION OF A NOVEL SUBSURFACE DEFORMATION SENSING TECHNOLOGY – NETWORKED SMART MARKERS CASE STUDY .....		31
3.1.	The Networked Smart Markers System .....	31
3.2.	Trial Site Description .....	32
3.3.	First NSM Open Pit Trial .....	34
3.3.1.	Laboratory Testing and System Preparation .....	34
3.3.2.	Installation of the System.....	35
3.4.	Operation of the System .....	36
3.4.1.	Improvements to the NSM System.....	39
3.5.	Second NSM Open Pit Trial .....	41
3.5.1.	System Installation Procedure .....	42
3.6.	Recommendations to Improve the System .....	43
3.6.1.	System’s Current Development .....	43
3.6.2.	System’s Future Developments .....	44
3.7.	Chapter Summary .....	44
MINE PLAN .....		45
4.1.	DeepMine.....	45
4.2.	Definition of the Mine Plan and Phases using DeepMine .....	46
4.2.1.	Block Model Characteristics.....	47
4.2.2.	GeoModel Definition .....	47
4.2.3.	Mining Environment Definition.....	48
4.2.4.	Pit Collection Definition.....	51
4.2.5.	Economic Environment Definition.....	52
4.2.6.	Mine Plan Settings .....	52
4.2.7.	Resulting Mine Plan.....	55
4.2.8.	Resulting Phases .....	58
4.3.	Pushbacks Design .....	58
4.4.	Chapter Summary .....	59

DESIGN OF A SLOPE DEFORMATION MONITORING CAMPAIGN PRIOR TO MINE CONSTRUCTION .....	61
5.1. Monitoring Campaign Design .....	61
5.1.1. Aspects to Be Assessed .....	62
5.1.2. Parameter to Be Measured.....	63
5.1.3. Remedial Measurements.....	63
5.1.4. Critical Sectors Selection .....	63
5.1.5. Shallow Angle Boreholes Instrumentation Campaigns.....	65
5.1.5.1. Phase V1 Monitoring – Shallow Angle Boreholes’ Layout ....	66
5.1.5.2. Phase V4 Monitoring – Shallow Angle Boreholes’ Layout ....	68
5.1.5.3. Phase V8 Monitoring – Shallow Angle Boreholes’ Layout ....	69
5.1.5.4. Phase V9 Monitoring – Shallow Angle Boreholes’ Layout ....	70
5.1.5.5. Shallow Angle Boreholes’ Drilling Campaign Summary .....	72
5.1.5.6. In-Place Inclinometers (IPIs) Shallow Angle Boreholes Installation.....	72
5.1.5.7. In-Place Inclinometers’ (IPIs) Shallow Angle Boreholes Campaign Costs .....	73
5.1.5.8. Networked Smart Markers Shallow Angle Boreholes Installation.....	74
5.1.5.9. NSM’s Shallow Angle Boreholes Campaign Costs.....	75
5.1.6. Steep Angle Boreholes Instrumentation Campaign .....	76
5.1.6.1. Phase V1 Monitoring – Steep Angle Boreholes’ Layout.....	76
5.1.6.2. Phase V4 Monitoring – Steep Angle Boreholes’ Layout.....	77
5.1.6.3. Phase V8 Monitoring – Steep Angle Boreholes’ Layout.....	79
5.1.6.4. Phase V9 Monitoring – Steep Angle Boreholes’ Layout.....	80
5.1.6.5. Steep Angle Boreholes Drilling Campaign Summary .....	81
5.1.6.6. In-Place Inclinometers Steep Angle Boreholes Campaign Installation.....	82
5.1.6.7. In-Place Inclinometer’s Steep Angle Boreholes Campaign Instrumentation Costs .....	82
5.1.6.8. ShapeAccelArrays Steep Angle Boreholes Campaign Installation.....	83
5.1.6.9. ShapeAccelArray’s Steep Angle Boreholes Campaign Costs	85

5.1.6.10. Networked Smart Markers Steep Angle Boreholes Campaign Installation .....	85
5.1.6.11. NSM’s Steep Angle Boreholes Campaign Costs.....	86
5.2. Alternatives Comparison .....	87
5.3. Potential Economic Gain .....	88
5.3.1. General .....	88
5.3.2. Analysis without Instrumentation Expenses.....	89
5.3.3. Analysis Considering Instrumentation Expenses.....	91
5.3.3.1. Shallow Angle Boreholes Instrumentation Campaign .....	91
5.3.3.2. Steep Angle Boreholes Instrumentation Campaign .....	92
5.3.4. Conclusions of the Economical Assessment .....	94
5.4. Recommendations.....	94
5.5. Chapter Summary .....	94
GENERAL DISCUSSION .....	96
6.1. Relevance of the Mine Plan .....	96
6.2. Networked Smart Marker System Validation .....	96
6.3. Monitoring Campaigns .....	97
6.3.1. Campaigns Configuration.....	97
6.3.2. Subsurface Deformation Detection at Great Depths.....	97
6.3.3. Campaigns Comparison .....	98
6.3.4. Economic Analysis .....	99
CONCLUSIONS AND RECOMMENDATIONS .....	101
7.1. General Conclusions .....	101
7.2. Recommendations.....	103
BIBLIOGRAPHY .....	104
APPENDICES .....	112
APPENDIX A : Diaphragm Piezometers and Rock Mass Deformation Sensing Technologies Characteristics.....	112
APPENDIX B : DeepMine Elements Description.....	116
APPENDIX C : Yearly Copper Cut-Off Grades for the Leaching and Concentrator Plants.....	120
APPENDIX D : Processing Plants Yearly Operation .....	120

APPENDIX E : Phases Geometry for the Theoretical Mine Obtained Using the Software DeepMine (Volumes).....	122
APPENDIX F : Phases Geometry for the Theoretical Mine Relaxed Using Vulcan (Volumes).....	124
APPENDIX G : Phases Geometry for the Theoretical Mine Relaxed Using Vulcan (Topography) .....	126
APPENDIX H : In-Place Inclinometers (IPIs) Shallow Angle Boreholes Campaign Costs Calculation .....	128
APPENDIX I : Quantity of Networked Smart Markers (NSMs) in Each Phase for a Shallow Angle Boreholes Campaign .....	131
APPENDIX J : Networked Smart Markers (NSMs) Shallow Angle Boreholes Campaign Costs Calculation .....	132
APPENDIX K : In-Place Inclinometers (IPIs) Steep Angle Boreholes Campaign Costs Calculation .....	137
APPENDIX L : Quantity of MEMS Sensors per Borehole Instrumented Using ShapeAccelArrays (SAAs).....	141
APPENDIX M : ShapeAccelArrays (SAAs) Steep Angle Boreholes Monitoring Campaign Costs Calculation .....	141
APPENDIX N : Quantity of Networked Smart Markers (NSMs) in Each Phase for a Steep Angle Boreholes Campaign .....	144
APPENDIX O : Networked Smart Markers (NSMs) Steep Angle Boreholes Campaign Costs Calculation .....	146
APPENDIX P : Implementation of Novel Subsurface Deformation Sensing Device for Open Pit Slope Stability Monitoring - The Networked Smart Markers (NSMs) System .....	152
APPENDIX Q : Understanding of Rock Mass Behaviour through the Development of an Integrated Sensing Platform .....	167

# ***LIST OF FIGURES***

---

Figure 1: Open Pit Mine Slope’s Configuration (Kliche, 2011) .....	8
Figure 2: Hoek’s (1970) Slope Angel v/s Slope Height (Lorig et al., 2009) ...	9
Figure 3: Haines and Terbrugge’s (1991) Slope Angel v/s Slope Height Chart (Lorig et al., 2009) .....	9
Figure 4: Networked Smart Marker .....	31
Figure 5: NSM System’s Antenna.....	31
Figure 6: Reader Station .....	32
Figure 7: Monitoring Campaign Sketch .....	33
Figure 8: First NSM Installation Diagram .....	36
Figure 9: Second NSM Installation Diagram .....	41
Figure 10: Leaching Plant Unsatisfactory Operation.....	50
Figure 11: Pit Shells Views – Plant (Left), East-West (Right Top), North-South (Right Bottom) .....	51
Figure 12: Ramps Setup (modified after Hustrulid et al., 2013) .....	53
Figure 13: Loading Area Setup .....	55
Figure 14: Mine Operation .....	57
Figure 15: Final Cash Flow.....	57
Figure 16: Boreholes’ Layout.....	65
Figure 17: Boreholes’ Layout in Plan View (a) – Boreholes’ Layout Looking North (b) – Shallow Angle Boreholes Campaign Phase V1 .....	67
Figure 18: Boreholes’ Layout in Plan View – Shallow Angle Boreholes Campaign Phase V4 .....	68
Figure 19: Boreholes’ Layout Looking North – Shallow Angle Boreholes Campaign Phase V4 .....	68
Figure 20: Boreholes’ Layout in Plan View – Shallow Angle Boreholes Campaign Phase V8 .....	69
Figure 21: Boreholes’ Layout Looking South – Shallow Angle Boreholes Campaign Phase V8 .....	69
Figure 22: Boreholes’ Layout Looking South – Shallow Angle Boreholes Campaign Phase V9 .....	70
Figure 23: Boreholes’ Layout – Shallow Angle Boreholes Campaign Phase V9 .....	71

Figure 24: Boreholes' Layout Plan View (Left) – Boreholes' Layout Looking North (Right) – Steep Angle Boreholes Campaign Phase V1 .....	77
Figure 25: Boreholes' Layout Plan View (Left) – Boreholes' Layout Looking North (Right) – Steep Angle Boreholes Campaign Phase V4 .....	78
Figure 26: Boreholes' Layout Looking South – Steep Angle Boreholes Campaign Phase V8 .....	79
Figure 27: Boreholes' Layout Plan View – Steep Angle Boreholes Campaign Phase V8 .....	79
Figure 28: Boreholes' Layout Plant View – Steep Angle Boreholes Campaign Phase V9 .....	80
Figure 29: Boreholes' Layout Looking South – Steep Angle Boreholes Campaign Phase V9 .....	81
Figure 30: Project's NPV Evolution as Slope Angle Increases .....	89
Figure 31: Total Waste Extraction .....	90
Figure 32: Total Metal (Cu) Production .....	90
Figure 33: Project's NPV Evolution as Slope Angle Increases – Shallow Angle Boreholes .....	92
Figure 34: Project's NPV Evolution as Slope Angle Increases – Steep Angle Boreholes .....	93
Figure. D.1: Leaching Plant Yearly Operation .....	121
Figure. D.2: Concentrator Plant Yearly Operation.....	121
Figure. E.1: DeepMine Phases 01 to 04 .....	122
Figure. E.2: DeepMine Phases 05 to 08 .....	122
Figure. E.3: DeepMine Phases 09 to 12 .....	122
Figure. E.4: DeepMine Phases 13 to 16 .....	123
Figure. E.5: DeepMine Phases 17 to 20 .....	123
Figure. E.6: DeepMine Phases 21 to 24 .....	123
Figure. E.7: DeepMine Phases 25 to 28 .....	123
Figure. E.8: DeepMine Phase 29 .....	124
Figure. F.1: Vulcan Phases.....	124
Figure. F.2: Vulcan Phases V1 to V4.....	124
Figure. F.3: Vulcan Phases V5 to V8.....	125
Figure. F.4: Vulcan Phases V9 to V12.....	125
Figure. G.1: Open Pit Phases V1 to V7 Geometry.....	126

Figure. G.2: Open Pit Phases V8 to V12 Geometry .....	127
Figure. P.1: Networked Smart Marker .....	155
Figure. P.2: First NSM installation diagram .....	158
Figure. P.3: NSM’s connectivity .....	158
Figure. P.4: Both ways signal strength .....	159
Figure. Q.1: Crown pillar defined at Palabora mine (after Glazer and Hepworth, 2004) .....	170
Figure. Q.2: Seismic monitoring at the site (after Glazer and Hepworth, 2004) .....	171
Figure. Q.3: Plan view of Los Bronces-Andina interaction area (after Google Maps, 2015) .....	171
Figure. Q.4: Summary of surface and underground geotechnical monitoring methods.....	172
Figure. Q.5: Smart Marker sensor.....	180
Figure. Q.6: Networked Smart Markers 3D data representation of six weeks .....	180
Figure. Q.7: Networked Smart Markers 2D data representation of six weeks .....	181
Figure. Q.8: Enhanced Networked Smart Markers performing as subsurface monitoring and later as cave trackers combined with conventional cave trackers in an open pit-underground interaction scenario.....	184

## ***LIST OF TABLES***

---

Table 1: NSM’s Connectivity.....	37
Table 2: Both Ways Signal Strength.....	38
Table 3: Troubleshooting Summary .....	39
Table 4: System Improvements .....	40
Table 5: Orebody’s Rock Type Distribution.....	47
Table 6: GeoModel Definition Summary.....	47
Table 7: Operational Costs and Capacities Summary.....	49
Table 8: Adjustment Factors Summary.....	50
Table 9: Economic Environment Definition Summary .....	52
Table 10: Mine Plan Settings.....	52
Table 11: Truck’s Fleet Estimation .....	53
Table 12: Ramps Dimensions .....	54
Table 13: Loading Area Dimensions .....	54
Table 14: DeepMine Phases Scheduling .....	56
Table 15: Redefined Phases Scheduling.....	59
Table 16: Boreholes’ Characteristics – Shallow Angle Boreholes Campaign Phase V1 .....	67
Table 17: Boreholes’ Characteristics – Shallow Angle Boreholes Campaign Phase V4 .....	69
Table 18: Boreholes’ Characteristics – Shallow Angle Boreholes Campaign Phase V8 .....	70
Table 19: Boreholes’ Characteristics – Shallow Angle Boreholes Campaign Phase V9 .....	71
Table 20: Shallow Angle Boreholes Campaign Drilling Summary .....	72
Table 21: Monitoring Time Span – IPI’s Shallow Angle Boreholes Campaign.....	73
Table 22: IPI Strings and Sensors Required in a Shallow Angle Boreholes Campaign.....	73
Table 23: In-Place Inclinometer’s Shallow Angle Boreholes Campaign Instrumentation Costs.....	74
Table 24: Monitoring Time Span – NSM’s Shallow Angle Boreholes Campaign .....	75

Table 25: Quantity of NSM Required in a Shallow Angle Boreholes Campaign .....	75
Table 26: Smart Marker’s Shallow Angle Boreholes Campaign Instrumentation Costs .....	76
Table 27: Boreholes’ Characteristics – Steep Angle Boreholes Campaign Phase V1 .....	77
Table 28: Boreholes’ Characteristics – Steep Angle Boreholes Campaign Phase V4 .....	78
Table 29: Boreholes’ Characteristics – Steep Angle Boreholes Campaign Phase V8 .....	80
Table 30: Boreholes’ Characteristics – Steep Angle Boreholes Campaign Phase V9 .....	81
Table 31: Steep Angle Boreholes Drilling Campaign Summary .....	82
Table 32: Monitoring Time Span – IPI’s and SAA’s Steep Angle Boreholes Campaign .....	82
Table 33: In-Place Inclinator’s Steep Angle Boreholes Campaign Instrumentation Costs .....	83
Table 34: SAA length and Quantity per Phase to be monitored .....	84
Table 35: ShapeAccelArray’s Steep Angle Boreholes Campaign Instrumentation Costs .....	85
Table 36: Quantity of NSM Required in a Steep Angle Boreholes Campaign	86
Table 37: Networked Smart Marker’s Steep Angle Boreholes Campaign Instrumentation Costs .....	86
Table 38: Monitoring Campaigns Comparison .....	87
Table 39: Shallow Angle Boreholes Instrumentation Campaign Costs over Time .....	91
Table 40: Steep Angle Boreholes Instrumentation Campaign Costs over Time .....	93
Table. A.1: Diaphragm Piezometers Characteristics .....	112
Table. A.2: Soil or Rock Mass Deformation Monitoring Devices .....	112
Table. A.3: Open Pit Subsurface Deformation Monitoring Devices .....	115
Table. C.1: Yearly Cut-off Grade .....	120
Table. H.1: In-Place Inclinator’s Shallow Angle Boreholes Campaign Layout Data .....	128
Table. H.2: In-Place Inclinator’s Costs .....	129

Table. H.3: In-Place Inclinator Shallow Angle Boreholes Campaign Costs .....	129
Table. H.4: In-Place Inclinator Shallow Angle Boreholes Campaign and Drilling Costs .....	130
Table. I.1: Quantity of NSMs per Borehole – Phase V1 Shallow Angle Boreholes Campaign .....	131
Table. I.2: Quantity of NSMs per Borehole – Phase V4 Shallow Angle Boreholes Campaign .....	131
Table. I.3: Quantity of NSMs per Borehole – Phase V8 Shallow Angle Boreholes Campaign .....	131
Table. I.4: Quantity of NSMs per Borehole – Phase V9 Shallow Angle Boreholes Campaign .....	132
Table. J.1: Networked Smart Markers Shallow Angle Boreholes Campaign Layout Data .....	132
Table. J.2: Networked Smart Markers Costs .....	133
Table. J.3: Networked Smart Markers 2-meter Spacing Shallow Angle Boreholes Campaign Costs.....	134
Table. J.4: Networked Smart Markers 4-meter Spacing Shallow Angle Boreholes Campaign Costs.....	136
Table. J.5: Networked Smart Markers 2 and 4-meter Spacing Shallow Angle Boreholes Campaign and Drilling Costs.....	137
Table. K.1: In-Place Inclinator Steep Angle Boreholes Campaign Layout Data .....	138
Table. K.2: In-Place Inclinator’s Costs.....	139
Table. K.3: In-Place Inclinator Steep Angle Boreholes Campaign Costs	139
Table. K.4: In-Place Inclinator Steep Angle Boreholes Campaign and Drilling Costs .....	140
Table. L.1: Quantity of ShapeAccelArray Measuring Points per Borehole ...	141
Table. M.1: ShapeAccelArray Steep Angle Boreholes Campaign Layout Data .....	142
Table. M.2: ShapeAccelArray’s Costs.....	143
Table. M.3: ShapeAccelArray Steep Angle Boreholes Campaign Costs .....	143
Table. M.4: ShapeAccelArray Steep Angle Boreholes Campaign and Drilling Costs .....	144
Table. N.1: Quantity of NSMs per Borehole – Phase V1 Steep Angle Boreholes Campaign .....	144

Table. N.2: Quantity of NSMs per Borehole – Phase V4 Steep Angle Boreholes Campaign .....	144
Table. N.3: Quantity of NSMs per Borehole – Phase V8 Steep Angle Boreholes Campaign .....	145
Table. N.4: Quantity of NSMs per Borehole – Phase V9 Steep Angle Boreholes Campaign .....	145
Table. O.1: Networked Smart Markers Steep Angle Boreholes Campaign Layout Data .....	146
Table. O.2: Networked Smart Markers Costs .....	147
Table. O.3: Networked Smart Markers 2-meter Spacing Steep Angle Boreholes Campaign Costs .....	148
Table. O.4: Networked Smart Markers 4-meter Spacing Steep Angle Boreholes Campaign Costs .....	149
Table. O.5: Networked Smart Markers 2 and 4-meter Spacing Steep Angle Boreholes Campaign and Drilling Costs.....	151
Table. P.1: Troubleshooting summary .....	160
Table. P.2: System improvements .....	161
Table. Q.1: Description of technologies for space-based monitoring .....	174
Table. Q.2: Description of technologies for airborne monitoring .....	175
Table. Q.3: Description of technologies for ground-based monitoring .....	176
Table. Q.4: Technologies applied in the mining industry for underground monitoring.....	178

# **CHAPTER 1**

---

## **INTRODUCTION**

Natural aging process experienced by large open pit mines around the world presents several challenges to mining companies to maintain a profitable operation. This is particularly evident in Chile, which presents a mature mining industry with several aged open pit currently in operation (four over 100 years old, one over 50 and several more with 20 years and expected lifespans over 50 years). These current conditions lead to increased operational costs during mine's lifespan due to higher stripping rates, longer hauling distances and higher stress levels, among others variables. In addition, with the continuous decrease in mineral grades the open pit mining system is slowly losing competitive advantage over time.

To remain competitive with open pit operation, the mining companies are considering steepening of open pits walls and assessing the feasibility of excavation with vertical slopes to lower the stripping ratio and increase the quantity of profitable ore. The slope steepening requires good understanding of the geotechnical/geological variables and other conditions affecting the slope design and governing its stability.

Stability assessments for open pit designs are currently based on Factors of Safety (FoS) and Probability of Failure (PoF). Both factors are highly dependent on the designers' experience and assumptions, introducing uncertainty into the stability assessments. Therefore, the determination of whether a certain design is stable requires the management of uncertainty levels while maintaining low risk levels of slope failures.

The levels of uncertainty in slope stability assessments can be decreased by incorporating different data sources as input to a standardized slope design process. Therefore, proper instrumentation and monitoring campaigns should be design and implemented as the data provides an insight into the actual rock mass behaviour subjected to mining operations. These campaigns or programmes would gather data related to deformations and other relevant phenomena occurring in the rock mass, as mining operations progress, to increase the knowledge of rock mass behaviour and enable informed decisions making in slope design and subsequent rock excavation.

## **1.1. Objectives**

### **1.1.1. General Objective**

The general objective of the R&D in this thesis was to design a geotechnical instrumentation and monitoring campaign for slope stability purposes with specific focus on obtaining data related to subsurface rock mass deformations and for implementation prior to construction of the open pit mines. For this purpose, the design of the geotechnical monitoring programme would use the mine plan and pushbacks design as input.

### **1.1.2. Specific Objectives**

The following activities were undertaken to accomplish the main objective of this thesis:

- Completion of a thorough literature review on open pit slope stability and on rock mass/slope deformation monitoring in metalliferous open pit mines – State-of-the-Art.
- Assessment of the technical feasibility to use new wireless geotechnical instruments, the Networked Smart Markers, for the design of a subsurface deformation monitoring programme in rock slopes.
- Development of a theoretical open pit design and the associated mine plan to be used as an input for the design of monitoring programme.
- Design of two different types of subsurface deformation monitoring programmes: (1) shallow angle boreholes campaign based on the usage of In-Place Inclinometers (IPI) and Networked Smart Markers (NSM) in boreholes inclined around 40° and (2) steep angle boreholes campaign based on the usage of In-Place Inclinometers (IPI), Networked Smart Markers (NSM) and ShapeAccelArrays (SAA) in boreholes inclined around 60°.
- Determination of implementation costs and benefits of all 5 subsurface deformation monitoring alternatives:
  - IPI shallow angle boreholes campaign.
  - NSM shallow angle boreholes campaign.
  - IPI steep angle boreholes campaign.
  - NSM steep angle boreholes campaign.
  - SAA steep angle boreholes campaign.
- Comparison of all campaigns in terms of operational lifespan, quantity of mine sectors to be monitored, quantity of monitored points, amount of gathered data, each campaign's total cost and the cost per unit of acquired data.
- Evaluation of the potential economic benefit of subsurface deformation monitoring based on the cost savings produced by steepening slopes' angles.

### **1.1.3. Hypothesis**

Currently, there is no common practice available for the implementation of open pit subsurface deformation monitoring campaign for slope stability assessment. Furthermore, a subsurface deformation monitoring campaign has never been designed to be implemented prior to mine construction.

#### *1.1.3.1. Hypothesis 1*

It is hypothesized that designing and implementing a monitoring campaign with instruments installed before mine's construction is technically feasible, economically affordable and will maximise the benefits obtained from such investment to:

1. Deliver higher quality and more abundant ground behaviour data for slope stability assessments.
2. Be technically feasible and economically affordable if undertaken in early stages of a mining project.
3. Focus on relevant zones of the mines, for instance, higher walls, pit slopes that expose more mineral and worst geotechnical quality zones.
4. Allow monitoring of the entire destressing process experienced by the rock mass as mine slopes are developed.
5. Provide more comprehensive data for slope stability assessments.

#### *1.1.3.2. Hypothesis 2*

It is hypothesized that the monitoring campaign based on the use of novel Networked Smart Markers (NSM) technology for deformation monitoring would overcome several disadvantages of currently available geotechnical instruments, including:

1. Short lifespan.
2. Limited application depth.
3. Limited number of sensors per borehole.
4. Limited coexistence of sensors in a single location inside a borehole.
5. Low tolerance to localized shear deformations.
6. Installation and maintenance issues due to the presence of cables inside boreholes.

### **1.2. Justification of the R&D**

Several events of slope failures in the past four decades (for example: at Bingham Canyon in Utah, U.S.A in 1967; Radomiro Tomic in Calama, Chile on March 23<sup>rd</sup>, 2013 and again at Bingham Canyon on April 10<sup>th</sup>, 2013) demonstrated the lack of understanding of geotechnical and geological variables involved in slope design process and slope's response to active

mining operations. This understanding becomes increasingly important as steeper, more aggressive slopes designs are implemented to reduce stripping ratios and to increase profitable ore quantity, while maintaining acceptable safety levels.

Slope failures, often life threatening with significant economic losses and damage to companies' corporate image, follow stability assessments based on highly variable rock mass classification systems and not on actual rock mass/slope behaviour as mine development progress. The rock mass behaviour can be assessed using geotechnical instrumentation. However, the selection and application of these instruments should be well-designed to yield the benefit of preventing or reducing the impact of slope failures.

Therefore, the thesis entitled: "Open Pit Geomechanics and Mine Planning Integration: Design and Economical Assessment of a Subsurface Slope Deformation Monitoring Campaign" addressed the design of a monitoring campaign to be implemented from the commencement of mining operations.

### **1.3. Scope of Work**

#### **1.3.1. Introduction**

Historically geotechnical instrumentation and monitoring research and developments have been directed at resolving mechanics issues in civil engineering. Often the guidelines and applications arising from this R&D cannot be transferred directly to monitoring the performance of rock slopes in open pit mines. Consequently, there is a need to develop geotechnical instrumentation procedures for monitoring the actual behavior of the rock mass in the pit walls as mining proceeds; this need was the starting point for the R&D outlined in this thesis.

The procedures followed and work performed during the study are described in the seven (7) chapters overviewed in the following section.

#### **1.3.2. Chapters Overview**

The framework of the seven (7) chapters in the thesis is outlined as follows:

Chapter 1 provides an overview of the scope of the thesis and the motivation to perform this study.

Chapter 2 presents a literature review of issues related to slope stability, geotechnical monitoring in open pit mines and integration of geomechanics and mine planning. It conducts critical analyses of surface and subsurface rock

mass deformation monitoring and analysis of the instruments characteristic including their advantages and disadvantages for open pit applications.

Chapter 3 describes the first implementation, in an open pit mine, of novel Networked Smart Markers (NSM) system for subsurface rock mass deformation sensing, with the assessment of the system's ability to communicate through rock and its suitability for becoming an integrated sensing platform coupling various sensors. The instrumentation case study is presented and analysed as follows:

1. Description of the Networked Smart Markers (NSM) technology.
2. Explanation of the NSMs first open pit trial.
3. Evaluation and recommendations based on the first trial of NSMs.
4. Improvements to the implementation procedure.
5. Development and implementation of the second NSM open pit trial.
6. Presentation of final results, evaluation and recommendations.

Chapter 4 develops a theoretical open pit mine design and its associated mine plan to be used as inputs in the design of the subsurface deformation monitoring programmes. The mine plan is obtained according to the following steps:

1. Select a block model to design an open pit mine.
2. Define mine's pushbacks.
3. Establish the production plan.
4. Define most critical sectors in terms of slope stability based on the pushbacks' geometry and geotechnical properties.

Chapter 5 presents the development of five different monitoring campaigns. First, a shallow angle boreholes campaign considering the development of boreholes following the slope's inclination to be instrumented using either In-Place Inclinometers or Networked Smart Markers. Then, a steep angle boreholes campaign using drill holes inclined at  $60^\circ$  to be instrumented using In-Place Inclinometers or Networked Smart Markers or ShapeAccelArrays. These campaigns are to be designed prior to mine construction and subject to variations in geotechnical domain, rock type and development stages of the open pit (pushbacks). The characteristics of the campaigns under consideration include: campaigns operational lifespan, quantity of mine sectors to be monitored, quantity of monitored points, amount of gathered data, each campaign's total cost and the cost per unit of acquired data. Finally, the potential economic benefit of subsurface deformation monitoring is evaluated. To design and evaluate the campaigns the following steps are followed:

1. Define five instrumentation campaigns for all critical zones:
  - a. Shallow angle boreholes campaign:
    - i. Using In-Place Inclinometers (IPI).
    - ii. Using Networked Smart Markers (NSM).
  - b. Steep angle boreholes campaign:
    - i. Using In-Place Inclinometers (IPI)
    - ii. Using Networked Smart Markers (NSM).
    - iii. Using ShapeAccelArray (SAA).
2. Compare quantity and quality of gathered data for each monitoring campaigns.
3. Perform an economic evaluation and comparison of the monitoring campaigns.

Chapter 6 develops a general discussion over the main outcomes of this thesis. The discussion covers the literature review, the relevance of mine planning in the design of monitoring campaigns, the validation of the novel Networked Smart Marker technology, the monitoring campaigns designs and the comparison of those designs.

Chapter 7 presents general conclusions and recommendation for further research and development.

#### **1.4. Chapter Summary**

This chapter provided an introductory information of the studies undertaken towards the completion of the thesis work entitled "Open Pit Geomechanics and Mine Planning Integration: Design and Economical Assessment of a Subsurface Slope Deformation Monitoring Campaign". The objectives, significance and rationale, hypotheses, the scope and the methodology of the research are briefly described.

This chapter also includes a brief overview of the thesis' chapters:

1. Literature review of open pit slope stability and rock mass deformation sensing;
2. Case study to analyse the first field installation of novel Networked Smart Markers (NSM);
3. Design of a theoretical open pit mine to be used as input to define subsurface deformation monitoring campaigns;
4. Design of subsurface deformation monitoring campaigns, and
5. Economic evaluation of all campaigns considering mine's expected extraction sequence.

## **CHAPTER 2**

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### **LITERATURE REVIEW: OPEN PIT ROCK SLOPES STABILITY AND DEFORMATION MONITORING**

The literature review aims to merge open pit slope design and stability knowledge with the state of the art in rock mass deformation monitoring techniques as slope stability and deformation monitoring are two very closely related aspects of open pit mining.

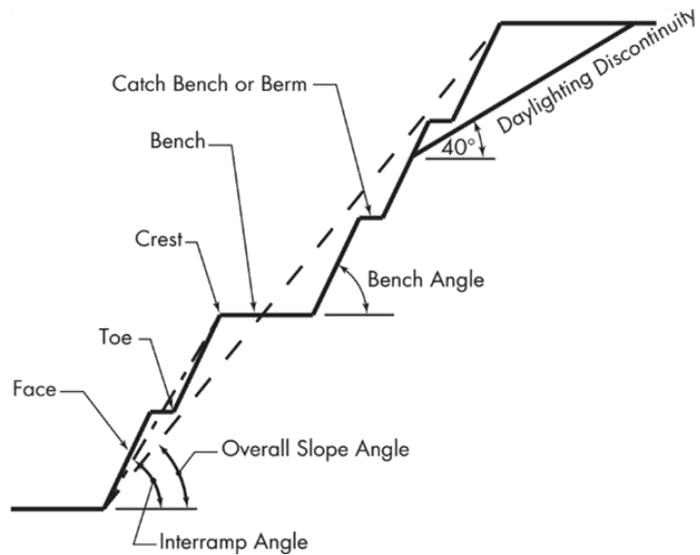
#### **2.1. Open Pit Slope Design and Stability**

Open pit slopes design has not changed significantly over the last few decades (since the 1960s) (Stacey et al., 2003) and still depends mainly on the designer's experience, quality of data and shovel-truck operations while dealing with many sources of uncertainty. However, open pit mines have undergone important changes during that time that have led to, for example, deeper pits (surpassing 1,000-meter in depth) and higher stress levels and tensile deformations (Stacey & Xianbin, 2004). These new conditions add complexity to achieving long lasting, stable mine slopes and to reaching slope design main objectives, i.e. fulfil mine's economic needs and maximize financial returns while minimizing risks to operations safety, reaching optimal ore recovery and minimizing waste extraction (Stacey, 2009).

Mine slope design process is a standardized activity. It is heavily influenced by the experience of the designer, who uses as main inputs a geological model, a structural model, material properties contained in a rock mass model and a hydrogeological model (Stacey, 2009). These models form part of the geotechnical model, which varies from one mine site to another and contains important sources of uncertainty as all its components attempt to explain the outcomes of random geological processes that originated the orebody for which the mine will be developed. For instance, for rock mass controlled failures, it is commonly assumed that rock mass is an isotropic mass (Lorig et al., 2009), which, in most cases, represents a simplistic approach. The uncertainty levels cannot be eliminated through the entire mine slope design and stability assessments process although, if adequate measures are taken, uncertainty can be reduced.

Rock slope design, including stability assessments, is an iterative process undertaken at three main scales: bench, inter-ramp and overall (Figure 1). Each one of them has to be defined for every geotechnical domain contained in the geotechnical model and is characterized by a certain slope failure mode that is most likely to occur in each particular geotechnical domain and at a certain scale (Lorig et al., 2009; Kliche, 2011; Wesseloo & Read, 2009).

The iterative process commences at a bench level; the bench parameters are defined and its stability evaluated. If the assessment results in unstable benches, the parameters are redefined and its stability re-evaluated. If benches are considered stable, their parameters and ramps' locations (result of mine planning) are used to define a preliminary inter-ramp slope angles, for which the stability is assessed. Subsequently, if this evaluation results in an unstable inter-ramp slope, the parameters are redefined and the stability is re-evaluated. If inter-ramp slope is considered stable, the overall slope angle will be defined by the inter-ramp slopes included within the overall slope. Finally, overall slope's stability is assessed to determine whether the entire pit slope is stable (Lorig et al., 2009).



**Figure 1: Open Pit Mine Slope's Configuration (Kliche, 2011)**

The type of stability assessment performed depends on the scale at which the evaluation is made. At bench scale, as failure is mainly controlled by structures near surface and the action of gravity, kinematic (stereonets) and limit equilibrium analyses are performed. For inter-ramp and overall scales, more complex failure modes, such as, rock mass failures and non-daylighting wedges can occur. Therefore, limit equilibrium, numerical modelling and rock mass analyses are performed (Lorig et al., 2009), since such failures behave in complex manners with influence of great scale structures and rock bridges breakage (rock mass properties).

In stability analysis at a rock mass scale, attempts are made to determine the potential of slope failure based on rock mass strength relying on rock mass classification systems, after inter-ramp stability evaluations have been performed and resulted in stable inter-ramp slopes.

Preliminary overall slope designs are developed at early stages of the project using slope angle versus slope height empirical charts, which are based on real cases of failed and stable pit slopes and their Factors of Safety (FoS)

(see Figure 2 and Figure 3) (Lorig et al., 2009; Hoek, 1970; Hoek & Bray, 1981; Sjöberg, 1999; Wyllie & Mah, 2004). The main drawback of these charts is that FoS are not comparable for different mines and that they do not consider rock mass properties. The latter has been addressed to a certain extent by Haines & Terbrugge's (1991) chart (Figure 3), which considers the MRMR rock mass classification system, and Sjöberg (2000), which considers rock hardness.

After an initial assessment using empirical charts, more sophisticated analyses are made using limit equilibrium methods, which assume homogeneous materials, and Hoek design charts based on circular failures (Hoek & Bray, 1981), which are not representative of rock slopes which, generally, present more complex failure modes.

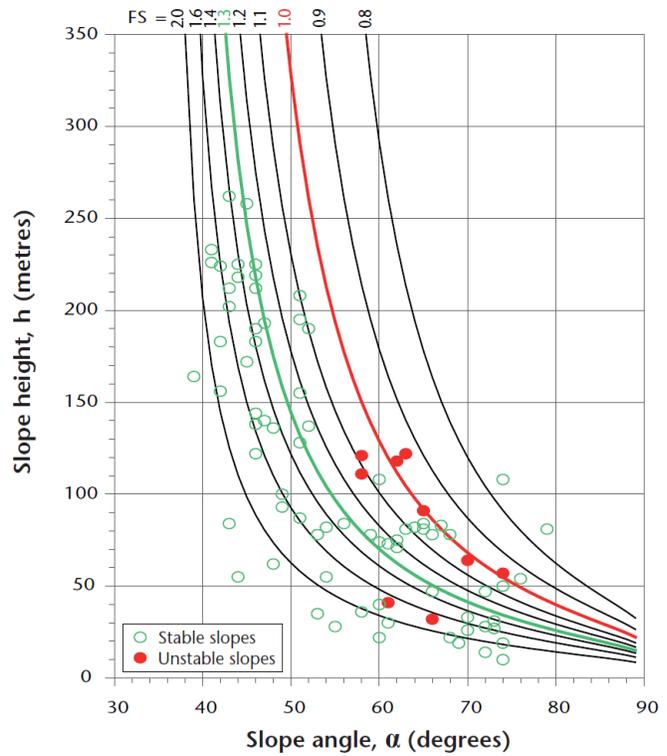


Figure 2: Hoek's (1970) Slope Angle v/s Slope Height (Lorig et al., 2009)

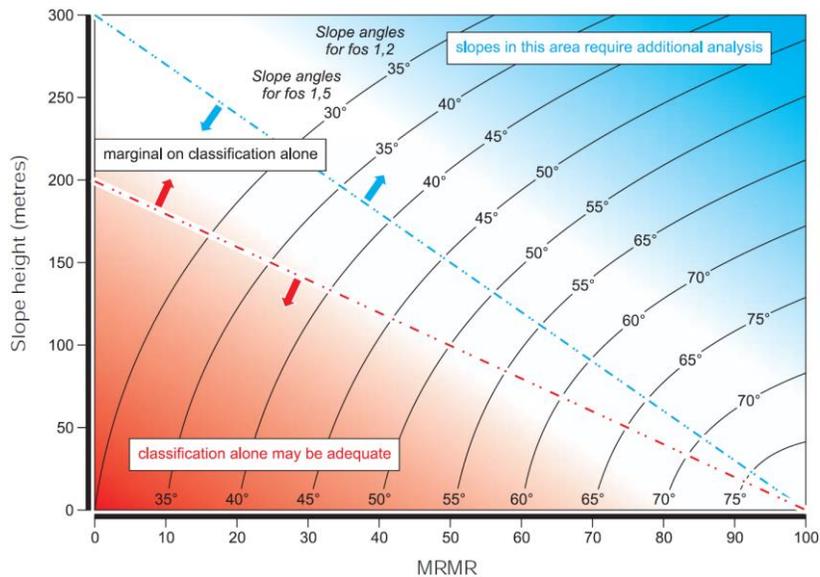


Figure 3: Haines and Terbrugge's (1991) Slope Angle v/s Slope Height Chart (Lorig et al., 2009)

For complex scenarios, numerical models are employed as they provide more representative solutions within acceptable margins of error and are able

to incorporate more particular characteristics of every problem, such as, precise problem's geometries, different rock types, ground water presence, explicit structures and rock mass defects. Numerical models are also able to determine potential deformation magnitudes and failing rock displacement (Lorig et al., 2009). However, high number of inputs requires extended time to undertake numerical modelling and often the solution must be developed specifically for a particular problem (case orientated solution) and even then the models might not capture all the variability and uncertainties of rock mass' anisotropic properties.

Regardless of the stability assessment techniques employed, the evaluation to determine if a certain design meets the stability requirements needed for the construction of stable slopes relies on factors that are calculated using parameters with some degree of uncertainty and that have an inherent risk component: (1) the Factor of Safety (FoS), defined as the ratio between nominal capacity of analysed structure and demands over it, (Wesseloo & Read, 2009) and (2) the Probability of Failure (PoF), defined as the joint probability of unsatisfactory slope performance (failure) occurring along any of the potential slip surfaces for a certain slope (El-Ramly, et al., 2002).

FoS equal to 1 represents limit equilibrium and a stable design, assuming that the data used to calculate this FoS is correct. However, for kinematic, limit equilibrium and numerical analyses, a tolerable value of FoS greater than 1 is defined to accept a certain structure as stable (bench, inter-ramp slope, overall slope scale). This value is defined by the designers based on their experience and/or based on a trial-and error process over time (Wesseloo & Read, 2009) in an attempt to account for the uncertainties in the data used to calculate the FoS of the design. Thus, there is no certainty whether the risk induced in the stability assessment, by the variability of material properties, is properly addressed by the FoS greater than 1. The experience-based acceptable value definition also causes the Factors of Safety not to be comparable from one mine site to another or even between different areas of the same mine. Consequently, any FoS may or may not be conservative depending on the input data variability and usage (Fillion & Hadjigeorgiou, 2015), a fact that introduces risk to all assessments based on FoS.

To account for the risk associated with every design, due to the variability in the parameters defining its FoS (mainly anisotropic characteristics of rock masses), the Probability of Failure (PoF) is introduced (Priest & Brown, 1983; McQuillan et al., 2015). However, even the PoF is highly dependent on the input parameters used, as shown by Venter (2015). In any case, it is the decision maker who defines the acceptable level of risk and determines which design to implement (Frith & Colwell, 2011). Thus, the selection of a certain design depends on personal experience, which generally results in over-

conservative designs being implemented, since it is known that the acceptance criteria (FoS and PoF) have important sources of variability.

This entire design process leads to the belief that implemented slope designs are, in most cases, over-conservative to meet safety objectives of slope design while moving away from the economic goals. On this basis, it is often endeavoured to steepen slope angles, when willing or requiring to lower operational costs to remain competitive, as explained by Stacey (2009). There are several documented examples of such redesigns (Brackley et al., 1985; Thompson, 1989; Schellman et al., 2006; Ekkerd et al., 2011; Hewson et al., 2011) or cases, such as the one presented by Rougier et al. (2015), where near vertical double benches (20-meter high) were implemented, including the construction and assessment of a 52-meter high pilot vertical slope at CODELCO's Mina Sur mine in northern Chile (CODELCO, 2014).

These new, more aggressive designs require more than just conservative assumptions to be used to maintain safe operations. They require more scientific approach based on actual data to better understand how a certain rock mass behaves when subjected to open pit mining operations. The understanding of that behaviour can be achieved by geotechnical data acquisition and its proper interpretation. Hence, an implementation of geotechnical monitoring programmes is required, as shown by Brackley et al. (1985), Thompson (1989), Schellman et al. (2006), Ekkerd et al. (2011), Hewson et al. (2011), CODELCO (2014), Hormazabal et al. (2011a) and Hormazabal et al. (2011b). In all those examples, geotechnical instrumentation was taken into consideration and applied after the open pit had been in operation for several years. However, much valuable information that could had been used for stability assessments purposes (relative to rock mass behaviour) produced in previous years had been lost and could not be applied to improve the state of knowledge about the rock mass and slope designs performance as mining operations progress.

## **2.2. Importance of Geotechnical Instrumentation**

Geotechnical instrumentation and performance monitoring have been widely studied for its application in civil engineering projects. Their importance and guidelines for application have been discussed in several publications such as Dunnicliff (1993a), Dunnicliff et al. (2012), Dunnicliff (2012) and Stern & Dunnicliff (1975). Their importance lies in the fact that soils and rock masses cannot be fully described and understood by using mean values of cohesion, friction angle and uniaxial compression strength as a result of the soil/rock inherent heterogeneous properties. Instead, empirical values of cohesion and friction angle are derived from rock mass rating schemes calibrated based on experience (Karzulovic & Read, 2009); an alternative that still represents a rough approximation to real conditions and does not consider important

sources of uncertainty such as the presence of defects within the rock (foliation planes, structures, faults), ground water behaviour, and blasting induced rock mass damage. Therefore, geotechnical instrumentation is particularly important for engineering projects where rock mass behaviour influences the outcomes since it allows registering real performance data of materials properties, which are difficult to assess by other means (Dunnicliff et al., 2012).

The data acquired from instrumentation and their proper interpretation during all stages of an engineering project serves investigative and monitoring purposes (Eberhardt & Stead, 2011): to minimize damage to adjacent structures, support use of the observational method, reveal unknown conditions, assess construction methods, design remedial measures to address future and/or developing problems, improve performance, document performance for evaluation of damages, show that monitored zone's performance is safe, warn about imminent failure or unsafe conditions, advance in the state-of-knowledge, control operations, fulfil regulations and inform stakeholder (Marr, 2013; Dunnicliff & Powderham, 2001). In addition, it is known (Dunnicliff et al., 2012), that during the construction of the geotechnical projects, monitoring campaigns save money by improving project's competitiveness. However, this approach has not been fully incorporated in the mining industry yet.

Geotechnical instrumentation can serve investigative purposes only if monitoring campaigns are properly design and propitiously implemented to gather reliable data intended to answer particular questions about ground performance; if there are no questions to be answered, there is no need for geotechnical monitoring (Dunnicliff et al., 2012).

## **2.3. Geotechnical Instrumentation for Civil Engineering Applications**

Geotechnical instrumentation for civil engineering projects can be organised by the type of variable that the instruments can measure. Those variables are: groundwater pressure, soil or rock mass deformation, load and strain in structural members and total stress.

### **2.3.1. Groundwater Pressure Monitoring Devices**

Groundwater pressure can be monitored using various types of piezometers (Dunnicliff, 1993b). These devices are differentiated based on the transducer used to transform water pressure into an electrical signal. The most common technologies are observation wells, open standpipe piezometers (Casagrande piezometer) (Fannin & Jaakkola, 1999), vibrating wire

piezometers, pneumatic piezometers, twin-tube hydraulic piezometers, flushable piezometers and fibre-optic piezometers (Dunnicliff, 2012).

Fibre-optic based devices are the latest developed technology and can be divided into Distributed Brillouin and Raman Scattering, Fibre Bragg Gratings (FBG) and Fabry-Pérot Interferometric, based on the fibre optic surveying technique used to register the pressure changes (Inaudi & Glisic, 2007).

Besides observation wells and open standpipe piezometers, piezometers are sealed devices that can be installed inside boreholes and at various depths to register multipoint pore water pressure (Eberhardt & Stead, 2011; Huang et al., 2012). The instruments are then sealed into position using sand, bentonite and/or grout (mixture of cement, sand, water and in some cases bentonite) to isolate all stratus crossed by the borehole, thus avoiding preferential water flow along the drill hole, which would cause erroneous readings (Casagrande, 1949; Contreras et al., 2008a; Contreras et al., 2008b).

APPENDIX A contains Table. A.1 that briefly describe the diaphragm piezometers, their strengths, drawbacks and precisions.

### **2.3.2. Soil or Rock Mass Deformation Monitoring Devices**

Soil or rock mass deformation can be divided into horizontal and vertical deformations, and tilt variations. This Section discusses the most common devices utilised in civil engineering projects to monitor the various types of deformations; it is not intended to give a thorough description of them.

The rates of horizontal and vertical deformations can be determined by using surveying methods: total stations and robotic total stations to determine the position of objectives (prisms) fixed to the zone to be monitored, as shown and explained by Cook (2006), Kontogianni et al. (2007) and Psimoulis & Stiros (2013). Several types of radar and GPS based monitoring stations, which are described further in this section, can also be employed for this task.

Probe extensometers and fixed borehole extensometers are instruments used to register distance variations between two or more points along a single axis and, thus, determine, for example, soil deformations along a borehole's axis. Their most common use is in determining vertical deformations, as explained and applied by Bayoumi (2011). Borehole extensometers are composed of tensioned rods anchored at several points along the borehole.

An alternative to borehole extensometers are the liquid level gauges. These devices are employed to determine relative vertical deformations

between two or more points in embankments (mainly settlement) either by interpretation of fluid pressure or liquid level in a monometer. Additionally, settlement platforms are devices meant to monitor settlement in embankments and soft ground as described by Dunnicliff (2012).

Tiltmeters are devices employed to register rotations (tilt changes) of structures or points located in or on the ground. In the latest years, Microelectromechanical Systems (MEMS) have been introduced as transducer for these sensors (Seller & Taylor, 2008; Sheahan et al., 2008) allowing determination of the inclination of a structure based on deviations from the direction of the gravitational force.

Time Domain Reflectometry (TDR) are instruments composed of a coaxial cable that can be scanned by an electric pulse to determine deformation or breakage of the cable. This is achieved by interpreting the velocity of the signal in the cable, the time of travel of an electric pulse and the impedance change along the cable. This information is then used to determine the location where ground deformations are occurring; it cannot, however, determine the magnitude of those deformations. TDRs are commonly installed in vertical boreholes, as explained in O'Connor & Dowding (1999).

Probe and in-place inclinometers are more sophisticated devices used to monitor subsurface horizontal displacements, when installed inside boreholes equipped with metallic casings to properly position the inclinometers (Dunnicliff, 2012). Probe inclinometers work in boreholes of up to 400-meter deep. The probe is lowered through a cased borehole and lifted at regular intervals. At each interval, one inclination measurement is taken. All those measurements are then used to determine a profile of deformation along the borehole. In-place inclinometer, on the other hand, consists of a series of probes connected together and placed permanently inside the borehole. This alternative can be used in boreholes of up to 100 meters deep. According to Mikkelsen (2003), to allow correct measurements, the deepest end of the string has to be installed 3 to 6 meters in stable ground, where no displacements are developed.

A novel type of device, to register deformations, is a fibre-optic based instrument, which uses the sensing technique mentioned for fibre-optic piezometers to register subsurface deformations as an in-place inclinometer (Pei et al., 2012).

An alternative for inclinometers are the more recently developed ShapeAccelArrays (SAAs) (Dunnicliff, 2012; Abdoun et al., 2010) which do not require casing to be installed in the boreholes as the space between SAA and the borehole's wall is filled using sand (Locat et al., 2010). The maximum

length for an SAA string is 100 meters, however, several strings can be installed in a single borehole to cover greater depths.

Crack gauges or jointmeters are devices used to measure the opening of tension cracks located on the surface of the rock mass while convergence gauges (tape extensometers) are designed to monitor convergence of reinforced excavations or tunnels (Dunnicliff, 2012).

Global positioning system (GPS) is used to monitor variations on points' position by sending timing signals to a ground receiver using satellites, which allows this system to track three dimensional variations in position of a certain point on the surface (Dunnicliff, 2012; Sakurai & Shimizu, 2006). The receivers located on Earth require connection to three (3) different satellites to determine their horizontal position and four (4) satellites for 3D positioning (including height determination).

Acoustic emission represents an early warning system mainly applied for early slope failure detection. It works by capturing and interpreting the sound waves generated by the stress acting over the soil or rock mass as they deform and/or break (Dunnicliff, 2012; Dixon et al., 2003).

For further reference about instruments description, strengths, drawbacks and precisions see Table. A.2 in APPENDIX A.

### **2.3.3. Load and Strain in Structural Members Monitoring Devices**

Load and strain in structural members of monitoring instruments are divided into two groups: load cells and strain gauges. Both devices measure extensions and compression that are then interpreted as load or strain. Strain gauges are used in applications where load cells cannot be installed (Dunnicliff, 2012).

Load cells' transducers are either electrical resistance or vibration wires (three or more) placed on the perimeter of a steel or aluminium alloy cylinder (Dunnicliff, 2012).

Surface-mounted strain gauges are divided according to the measuring method that the device employs according to four categories: mechanical, electrical resistance, vibrating wire and fibre optics (Bennett, 2008). The devices are typically welded to the structure to be monitored and come in two configurations of 50 mm and 100 to 200 mm long gauges (Dunnicliff, 2012).

Embedment strain gauges are devices meant to measure strain in concrete using mainly vibrating wire principles. They are available in two

configurations: the first is a 100-200 mm long device composed of two flanges holding a pre-tensioned bare vibrating wire (thus, it requires some protection to allow proper functioning) and the second is a mild steel cylinder containing a vibrating wire transducer in the middle of the steel bar (Dunnicliff, 2012).

#### **2.3.4. Total Stress Monitoring Devices**

Total stress can be monitored by using two main devices: embedment earth pressure cells and contact earth cells. They are used to gather data intended to improve feature designs (Dunnicliff, 2012).

Embedment earth pressure cells are devices design to measure stress inside the ground. The instrument is composed of two rectangular or circular (200 mm diameter) steel plates welded together at its perimeter. The cavity between plates is filled with liquid and is connected by tubing to a pressure transducer (Dunnicliff, 2012).

Contact earth pressure cells are devices meant to measure stress on the face of a structural element. These devices are similar in design to the embedment earth pressure cells but with one of the plates acting as an inactive face, which is thicker than the active plate (face) located on the surface of the structure to be monitored (Dunnicliff, 2012).

#### **2.3.5. Guidelines for Geotechnical Instrumentation**

There are several books and other publications on topics related to geotechnical monitoring from instruments descriptions (Dunnicliff, 2012) and application (Dunnicliff et al., 2012) to recommendations on how to contract monitoring services to receive the most value of such investment (Dunnicliff & Powderham, 2001).

Dunnicliff et al. (2012) in describing the benefits of geotechnical monitoring, defines a systematic approach to plan a geotechnical monitoring campaign and presents guidelines and application examples. Every monitoring programme has to be design and implemented as a support to the observational method, summarized by Dunnicliff et al. (2012) after Peck (1969), in the following eight (8) steps (explained in more detail in Patel (2012)):

1. Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.
2. Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions.
3. Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.

4. Selection of quantities as construction proceeds and calculations of their anticipated values on the basis of the working hypothesis.
5. Calculations of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.
6. Selection in advanced of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the bases of the working hypothesis.
7. Measurement of quantities to be observed and evaluation of actual conditions.
8. Modification of design to suit actual conditions.

Subsequently, the monitoring campaigns' design has to follow a well-defined systematic approach composed by the following steps (Dunnicliff et al. 2012):

1. Define the projects conditions.
2. Predict mechanisms that control the behaviour.
3. Define the geotechnical questions that need to be answered.
4. Identify, analyse, allocate and plan for control of risks.
5. Select the parameters to be monitored.
6. Predict magnitudes of change.
7. Devise remedial actions.
8. Assign tasks for the construction phase.
9. Select instruments.
10. Select instruments locations.
11. Plan documentation of factors that may influence measured data.
12. Establish procedures for ensuring data correctness.
13. List the specific purpose of each instrument.
14. Prepare budget.
15. Prepare instrumentation system design report.
16. Plan installation.
17. Plan regular calibration and maintenance.
18. Plan data collection and data management.
19. Prepare contract documents.
20. Update budget.

### **2.3.6. Monitoring Applications**

There are several examples of geotechnical monitoring application in literature applicable to a scenario that could, to a certain extent, resemble open pit mining characteristics, such as, natural rock slopes (Locat et al., 2010; Angeli et al., 2000; Gili et al., 2000; Kane et al., 1996), dams (Alba et al., 2006; Hofmann et al., 2015; Caci et al., 2015) and levees (similar to small scale tailing dumps) (Abdoun et al., 2010).

In all these cases, the most commonly monitored variables are groundwater pressure and surface and subsurface deformations for which the most frequently used monitoring devices are piezometers, extensometers, TDR, GPS, total stations and, lately, scanning laser.

## **2.4. Open Pit Mines Geotechnical Instrumentation & Monitoring**

Before any attempt to design and/or implement a geotechnical monitoring program is made, the purpose of the geotechnical instrumentation has to be defined to assist in answering specific questions about ground/structure interaction: if there are no questions, there should be no instrumentation (Dunnicliff et al., 2012; Eberhardt & Stead, 2011).

Since, in open pit mining projects, there is no control over the construction material (rock mass) properties, such as, its strength, there are many uncertainties in the open pit slopes design process, slope construction and, subsequently, slope performance, as explained in Section 2.1. Therefore, several questions relative to ground/structure interaction can be asked, particularly related to slope stability, which implies the need for geotechnical monitoring programmes implementation.

Geotechnical instrumentation for open pit mining serves investigative purposes, such as, acquiring better understanding of the ground conditions for pre-feasibility and design stages, providing input values for the design process and registering changing ground behaviour as mining progress. It also serves monitoring purposes by checking the performance of the design, validating models, delimiting design calculations and providing warning of unstable conditions, which allows remediation actions to improve safety and/or to reduce damages by, for instance, modifying the design (Eberhardt & Stead, 2011; Marr, 2013).

Geotechnical instrumentation also helps in the implementation of the observational method, which is appropriate to be applied when geotechnical behaviour is difficult to predict (Dunnicliff et al., 2012), as is the case for the majority of the open pit rock slopes.

There are many benefits of slope monitoring; more specific for open pit mining operations, as outlined by Hawley et al. (2009), are:

1. Maintain safe operating conditions to protect personnel and equipment.
2. Provide advance notice of zones of potentially unstable ground so that mine plans can be modified to minimise the impact of slope displacements.

3. Provide geotechnical information for analyses of any slope instability mechanism that develops, the design of appropriate remedial action plans and conducting future slope design.
4. Assess the performance of the implemented slope design.

Even though many variables can be monitor using geotechnical instrumentation, not all of them are relevant to open pit rock slopes stability. The four main variables that can be registered using geotechnical instrumentation are: groundwater pore pressure, soil or rock mass deformation, load and strain in structural members, and total stress (Dunnicliff, 2012).

In open pit mining projects, the behaviour of groundwater pressure and ground movement (displacement monitoring) are the main variables to be concerned with as they influence or give insight into rock slopes' performance and, thus, slope's stability at a given time or for the future (Hawley et al., 2009).

#### **2.4.1. Groundwater Monitoring**

The presence of groundwater within the rock mass induces positive pore pressure, which reduces the effective stress over the rock mass. This effect leads to a reduction in rock mass shear strength and affects the stability of slopes as pore pressure varies (Read et al., 2009 and Read et al., 2013).

Since groundwater is the only aspect of a slope design that can be artificially modified (Read et al., 2009), slope dewatering and depressurization is becoming a common practice to improve slope's stability by increasing the effective stress as result of lowering the water table. However, to determine whether a dewatering campaign is being effective, pore pressure monitoring is required (Lomberg et al., 2013) since something that is not measured cannot be improved.

In case of open pit mine operations, diaphragm piezometers, particularly vibrating wire piezometers, are the most commonly used devices to monitor pore pressure. A brief description of these devises can be found in the diaphragm piezometers Table. A.1 in APPENDIX A along with a list of piezometers' strengths, drawbacks and precisions.

#### **2.4.2. Movement Monitoring**

It has been stated (Hawley et al., 2009) that displacement monitoring should be established as soon as possible during early stages of open pit mining operations to address the various safety and investigative purposes already discussed (Eberhardt & Stead, 2011).

Furthermore, movement monitoring is of particular interest for open pit stability, since open pit projects are placed near surface in low-stress environments, which produces gravity driven failures. Therefore, detectable displacements are produced prior to failure (Hawley et al., 2009). The detection of these movements allows for early warning of developing or imminent failure.

In addition, not only quantitative but also qualitative deformation monitoring is important. The latter is mainly applied to surface deformations through visual inspection performed by mine personnel (Hawley et al., 2009).

The soil or rock mass movement in open pit mines can be divided into two separate categories: surface and subsurface deformations.

#### *2.4.2.1. Surface Deformations*

Surface deformation detection allows, in some cases, to identify developing failures from hours to weeks before occurrence (Hawley et al., 2009). This enables to take measurements, which could be used to take action to minimize damages and avoid loss of life, but which does not help in avoiding the failure.

The most common surface deformation monitoring techniques are visual inspection (quantitative), cross-crack measurements using crackmeters (wireline extensometers), survey monitoring, Global Positioning System (GPS), photogrammetry, ground-based and satellite-based Interferometric Synthetic Aperture Radar (InSAR) and laser scanning (LiDAR).

Visual inspections are observations of the terrain by mine site personnel looking for qualitative evidence of ground movements on a daily basis. It is performed by trained and experienced mine personnel who report rockfalls, new cracks' development and elongations of the old ones. This technique must be supported by geotechnical instrumentation to acquire quantitative data to characterize any detected movement (Hawley et al., 2009).

Crackmeters are used to monitor the development of tension crack mainly in the crest of the slope. The technique works by fixing steel pins at each side of a crack. The distance between pins is measured periodically using measuring tape, Vernier calliper or micrometer; thus, determining the progression of the crack. Alternatively, a wireline extensometer can be used to automate the process, which consist of a wire anchored to a side of the crack, passed over a pulley and tensioned using a weight. Changes in the weight's position or pulley's movements can be used to determine the displacement across the crack (Hawley et al., 2009).

Survey monitoring techniques allow to determine the absolute position of several points located on the surface of the pit. The most common technologies are electronic distance measurements (EDM), total stations and robotic total stations which determine the variations on prisms' 3D position between consecutive measurements with high precision (Hawley et al., 2009). This technique has the advantage of very precise measurements over short distances (few kilometres) from the point to be measured and, in the case of robotic total stations, not much personnel involvement is required. Some disadvantages are the need of prisms installed in the area of interest, changes in prisms' position not related to ground deformation, collection of point measurements, the dependence of the system's accuracy on atmospheric conditions (dust, temperature, pressure, humidity) among others. A better understanding of surveying methods in open pit mining with a case study can be found in Jooste & Cawood (2006). In this case study, several technologies from visual inspection to the GeoMos system are described.

Global positioning system (GPS) utilizes the same principle of differential mode described for civil engineering problems. For open pit mines monitoring, a network of GPS receivers is deployed in the area to be studied. This system allows to take measurements with a 5 to 10[mm] accuracy (Sakurai & Shimizu, 2006). Despite its precision, the system presents several drawbacks. For instance, the loss of satellite connection when GPS is installed in deep sectors of the pit and the system requires GPS receivers permanently installed in the position to be monitored or mine personnel touring the sector to be monitored with a handheld receiver to survey each point.

Photogrammetry is a technique that employs georeferenced digital photographs to map the pit walls and structures and perform 3D geotechnical measurements, such as, changes on pit faces over time with a precision of 5 to 10[mm] at 100 metres to the photographed rock face (Hawley et al., 2009). A description of the applications of a commercially available photogrammetry solution (Sirovision) can be found in Little (2006).

Ground-based SAR, airborne SAR and satellite-based SAR (InSAR) work using the same device, Interferometric Synthetic Aperture Radars. The three options differ only in the platform on which the synthetic aperture radar is mounted. This technology uses the principle of phase differentiation from the signal sent and returned to the radar to create topographic maps and monitor terrain deformations based on SAR images acquired at different times (Espinoza & Mora, 2012).

Ground-based SAR systems, such as, LiSALab and IBIS radars are versions of the SAR technology that uses a radar moving along a rail. These devices have to be installed within a couple of kilometres to the zone to be

monitored and have direct sight line. Ground-based SAR present the main advantage of near real time (5 to 10 minutes between scans) monitoring with a resolution ranging from 0.5 to 4 metres. They can detect movements in the scale of millimetres (as small as 0.1[mm]) without the need of reflector installed in the area of interest. However, these versions of SAR systems can cover an area of only around 5 square kilometres in the line of sight of the radar and measurements are affected by atmospheric conditions. Finally, if the displacements in the slope between measurements are greater than 5[mm] the signal phase can be ambiguous. The application of both radars are described in Kristensen & Blikra (2013) and Severin et al. (2011).

InSAR is a particular type of SAR technology that presents the main advantage of precise monitoring of broad areas. It can register millimetre ground movements; however, it does not produces good results in very steep areas, cannot work in areas covered with vegetation, does not work well with significant ground movements and depends on satellite availability, which at the best presents a 4-days satellite visit time. Therefore, real time monitoring is not possible (Hawley et al., 2009). Colombo & MacDonald (2015) list available satellites, which provide different visiting times and details on data processing while Jarosz & Wanke (2003) and Baran & Stewart (2003) present mine scale applications of InSAR technology.

Airborne SAR represents an alternative to the usage of InSAR that has not been applied to open pit mines monitoring yet. It has the advantage of providing more flexible observations schedule due to the independency from international satellite usage. However, to achieve optimal results, the exact location and altitude of the plane has to be determined during the entire process.

An alternative to the usage of ground-based SAR are the real aperture radars (RAR), such as, Reutech and GroundProbe radars. They register the travel time of a signal of known amplitude, wavelength and velocity when it is sent, reflected and received again in the radar. The displacement is calculated from the wave shift between the sent and received signal. The measurements obtained are similar to the ones obtained using ground-based SAR, but the former are less sensitive to atmospheric conditions. Both technologies present similar drawbacks. Bellett et al. (2015) compares both technologies (ground-based SAR and RAR) in terms of its functional principles and targeted and broad monitoring while Harries et al. (2006) present a mine scale application of a GroundProbe radar.

Terrestrial laser scanning (TLS) using light detection and ranging (LiDAR) is a technique to scan ground surface similar to radars, but using a different type of signal that produces less accurate results. Since this technology is less

accurate than radars and can only scan small areas (up to 10 square kilometres), it is not widely used for open pit slope stability monitoring purposes. However, it can be used to determine the topography of inaccessible slopes, such as, failed zones. When calibrated against reference targets LiDAR scanning can produce 3D representations of the scanned zone with a density over 10,000 points. The accuracy for such case can be in the centimetre scale at a range up to 2,000 metres (Hawley et al., 2009).

There are two main laser scanning technologies: time-of-flight and phase-shift scanners. The former works by measuring the elapse time between the generation and return of each laser pulse. That time is then used to determine the distance from the sensor to the reflective surface (Flood, 2001). The latter compares the light reflected by the surveyed zone with the emitted light to determine a phase shift that allows to determine range.

Hutchison & Howarth (2015) describe the application of ground-based LiDAR to monitor rockfall and slope failure in open pit mines.

For further information about all the technologies described in this section (brief description, strengths, drawbacks and precisions), see Table. A.2 in APPENDIX A.

#### 2.4.2.2. Subsurface deformation

Subsurface deformation monitoring is commonly less sophisticated than surface deformation monitoring and, in some cases, more expensive due to the cost of the boreholes required for instruments' installation. However, subsurface deformations monitoring produces more detailed and reliable information when is needed to locate a sliding surface or study the propagation of subsurface deformations (Hawley et al., 2009). Furthermore, this type of monitoring can detect evidence of a developing failure months before the deformations propagate to the surface of the slope, as shown by Lynch & Malovinchko (2006) and Little (2006), where seismic monitoring in the Navachab open pit provided a 6-week warning of a large slope failure before any movement detection using prisms in the surface was made. This fact may lead to the prediction of slope failures giving enough time to react and avoid the failure, for example, by implementing a change in design or removing overburden.

Subsurface deformation monitoring also helps to fulfil one of the steps embodied in the observational method, "*selection of quantities to be observed as construction proceeds and calculation of their anticipated values under the most unfavourable conditions compatible with the available data concerning the subsurface conditions*" (Dunnicliff et al., 2012). Data gathered can help decrease levels of uncertainty in open pit slope design and give a better

understanding of mine's performance almost in real time. Thus, it may become a valuable source of early notice of unexpected and potentially catastrophic failures and, therefore, diminishing risk levels involved in slope design, construction and mines' operation.

Generally, subsurface monitoring method in open pit mines relies on the usage of inclinometers, time domain reflectometers (TDRs), extensometers and micro-seismic arrays (Hawley et al., 2009). Besides those proven devices, in the late 10 years, a new technology developed for civil engineering projects is starting to be applied in open pit mines, e.g. the ShapeAccelArrays (SAAs), and a promising wireless technology is being currently developed specifically for its application in open pit mining, e.g. the Networked Smart Markers (NSMs). All these devices, with the exception of micro-seismic arrays and NSMs, were described in Section 2.3.2.

Micro-seismic arrays consist of the installation of several seismic sensors (geophones) surrounding a specific rock volume to be monitored (Lynch & Malovichko, 2006), usually near the surface and at the bottom of the monitored zone inside short vertical and long inclined boreholes. These sensors register the small seismic events produced by rock's brittle fracture development and locate them by triangulating the arrival time of the seismic wave to different geophones. The seismic events can be located and quantified. Hence, by routine monitoring, 3D data of where rock mass breakage or movement is occurring can be acquired before any sign of rock deformation can be detected on the surface (Hawley et al., 2009). However, gathered data need to be processed and analysed for further interpretation and the location of seismic events have many sources of uncertainty, such as, noise not related to seismic events, which may lead to location errors for a single event in the scale of metres.

Networked Smart Markers (NSMs) are wireless electronic devices developed by Elexon Electronics, specifically for open pit applications, (Whiteman, 2010) to register various variables of rock mass behaviour. 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. Each Marker has an identifying ID and needs to be activated before the device is installed and grouted in the ground. NSMs work as a system when several NSMs are installed sequentially inside a borehole: they 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 (5 metres). The NSMs are grouted into position inside the drill hole, permitting the Markers to move with the surrounding rock as the rock mass deforms. When operating, each Marker sends a signal to the next Marker in the string to contact it. This process is

repeated until the signal reaches an antenna positioned at the top of the borehole, which must be located no farther than 5 metres 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 (datalogger) (Widzyk-Capehart et al., 2015).

This type of communication through rock mass unlocks the possibility to merge different sensors inside the NSMs device. This development is currently in progress by integrating piezometers and accelerometers (to work as inclinometer) in the NSMs to create the Enhanced Network Smart Markers (ENSM). Finally, the absence of cables within the holes allows this system to monitor progressive deformations as well as shearing zones without Markers being broken.

For further information about all the technologies described in this section (brief description, strengths, drawbacks and precisions) see Table. A.3 in APPENDIX A.

#### **2.4.3. Currently Available Subsurface Deformation Sensing Instruments' Limitations for Open Pit Mining Applications**

Most geotechnical instruments have been developed to address civil engineering geotechnical problems, where slopes are designed to be stable in long term. Thus, when applied to open pit problems, they present limitations, which make it difficult to achieve optimal results for subsurface deformation monitoring. Since slopes in open pit mines are often temporary and must be excavated closer to the stability limit to meet the economic needs of an open pit project, subsurface deformation monitoring devices will have limited operational life and perhaps will fail even before being mined out (Cawood & Stacey, 2006).

Both probe or in-place inclinometers are employed in mining to measure horizontal displacements along vertical drill holes relative to the borehole's bottom. However, deformations usually occur due to sliding plans or are localized in thin shear zones, these devices present short operational life mainly due to excessive casing deformation (probe inclinometer) or components breakage (in-place inclinometers). Another limitation of this technology is the maximum array length of 100 meters (for in-place inclinometers). For probe inclinometer an important drawback is the inability to perform real time monitoring.

Time domain reflectometers (TDRs) are able to detect the location where ground deformation are occurring (localized shearing deformation) but cannot determine the magnitude of those deformations (Hawley et al., 2009). When

the cable is damaged or breaks at a certain point, no more data can be gathered from the cable breakage point downwards.

Borehole extensometers are best suited to monitor known structures (Girard, 2001) and are not intended to detect unexpected failures or spread subsurface deformations.

Micro-seismic arrays present problems when trying to identify different seismic events and when trying to precisely locate them. Micro-seismic arrays cannot define the magnitude of the deformation producing the seismic events. It is also difficult to identify real events from noise due to low signal to noise ratio; data sets have to be manually filtered to remove non-events in those cases (Wesseloo & Sweby, 2008). Meyer (2015) presents a case where seismic events originally located 150 metres apart needed the application of different events location methods and data processing to reduce them to a more accurate cluster with an extension of 5 metres. Although the geophones were installed in a compact seismic array. Vinoth et al. (2015) present a case study that employs a dense array of geophones (less than 200-metre spacing) in an attempt to achieve an accuracy in events location within 5 metres.

ShapeAccelArrays (SAAs) are presented as an alternative to traditional inclinometers with the main benefit of higher interrogation frequency, commonly, every one minute. SAAs have a maximum length of 100 metres, but several arrays can be installed in a single borehole to cover greater depths. Some drawbacks of this device are that each particular array has a different accuracy due to the nature of the calibration process, gathered data can exhibit significant drift (due to incorrect voltage supply) and, when installed in inclined boreholes, SAA cannot distinguish torsion from tilting of the array, which can lead to measure displacements that do not exist (Swarbrick & Clarke, 2015).

Despite the fact that Networked Smart Markers (NSMs) tests present promising results leading to overcoming the limitations of traditional subsurface deformation sensing technologies (Widzyk-Capehart et al., 2015; Whiteman, 2010) (when applied to open pit mining problems), NSMs and ENSMs still require more development and extensive testing to be considered as an alternative to the existing techniques.

#### **2.4.4. Guidelines for Open Pit Instrumentation and Monitoring**

There are no guidelines specifically designed for open pit slopes deformation monitoring. Eberhardt & Stead (2011) and Hawley et al. (2009) present guidelines, which are mainly the same ones presented and explained by Dunnicliff et al. (2012) and Dunnicliff (1993c) for civil engineering projects. These authors mainly highlight the importance, potential and utility of

geotechnical monitoring and give some qualitative recommendations for its application.

With regards to cut slopes in rock (like in open pit mines) Dunnicliff (2012) states that geotechnical instrumentation may not be appropriate to forewarn the instability since brittle fractures are expected and, thus, movements and failure will be sudden. However, several other authors (Eberhardt & Stead, 2011; Hawley et al., 2009; Zvarivadza, 2015 and Cawood & Stacey, 2006) disagree with this assessment for open pit mining projects. The latter opinion is reinforced by cases, such as, the one in Navachab mine (Naismith & Wessels, 2005) and Bingham Canyon mine (Pankow et al., 2014) where, due to geotechnical instrumentation, developing failures were detected weeks before their occurrence, which allow mine evacuation.

Cawood & Stacey (2006) went one step further from the standard guidelines for geotechnical instrumentation by recognizing the association between the slope design process and slope deformation monitoring campaign planning. They establish that an adequate geotechnical model and thorough understanding of the studied rock mass behaviour are required to answer questions, such as, where will movement take place? What magnitude of movement will occur? How rapidly will movement occur? The correct answers to these questions will lead to a properly designed and robust monitoring campaign and to its proper implementation in an open pit mine environment.

#### **2.4.5. Open Pit Deformation Monitoring Applications**

There are several case studies in the literature, describing the usage of deformation monitoring devices for mine slopes stability management, for instance, Little (2006), Naismith & Wessels (2005) and Chiwaye et al. (2015). These cases consider the usage of surface and subsurface deformation sensing technologies applied separately or simultaneously, mainly as a warning system. Hence, most of the studied cases do not consider the possibility of using all gathered geotechnical data in improving future slope designs and optimizing slope angles nor the detection of unknown instabilities located far from the areas already under survey. This situation leads to a suboptimal resources utilization.

Furthermore, all the cases lack planning of the monitoring campaign during the slope design process and a separate treatment given to surface and subsurface deformation data, despite the fact that both types of data are correlated, since they are part of the same process and used together can give a better estimation of the potential volume of material that may fail. Even in cases where extensive surface and subsurface deformation monitoring is performed (Chiwaye et al., 2015), the correlation is not studied; rather data correlation is limited to the integration of data from different instruments in a

single software platform to be able to trigger alarms due to a combination of factors (data coming from different type of devices) or ease the creation of reports (data management) (Ramsden et al., 2015).

## **2.5. Open Pit Geomechanics and Mine Planning Integration**

As stated by Eberhardt & Stead (2011), geotechnical instrumentation of mining operations extends from prefeasibility studies to mine closure or even beyond closure (Hawley et al., 2009). It helps to ensure economic feasibility and safety of mine operations. Other authors, such as, Hawley et al. (2009) and Cawood & Stacey (2006) state that displacement monitoring should be established as soon as possible during the early stages of open pit mining operations. The earliest stage possible is before mine operations begin prior to any excavation. This would allow registering of the entire deformation process suffered by the rock mass, as deformations begin with the rock mass perturbation i.e. with mining.

Monitoring programmes should be considered from the design stages of a mining project. This fact is considered by Cawood & Stacey (2006) and Stacey (2009) who recognised that geotechnical monitoring is an important aspect of the design process and established a close correlation between the slope design process and geotechnical monitoring since geotechnical instruments installed prior to any mine excavation can provide important benchmark information to validate designs assumptions, modify future designs and plan future monitoring campaigns (Hawley et al., 2009).

However, this task also requires coordination of the geotechnical and mine planning departments as only when slope's geotechnical model has been developed can there be any understanding of how the slope will behave and, therefore, what monitoring devices are appropriate (Cawood & Stacey, 2006). Geotechnical monitoring should be consider a part of the mine planning process, since monitoring represents a fundamental aspect of the design and, mine planning is the process prior to design operational implementation (Williams et al., 2009). The mine plan should be used as input to define how, when and where geotechnical monitoring systems should be installed.

There are no examples nor case studies where slope monitoring programs were designed prior to mines construction and/or as part of the mine plan. Williams et al. (2009) established that the relation between the geotechnical and mine planning group, regarding geotechnical monitoring, is mainly concentrated in the mine production planning stage. Therefore, it is not surprising that all cases reviewed present slope monitoring being implemented during mine's operation or after indication of slope deformation have been detected.

## **2.6. Conclusions of the Literature Review**

This chapter has established that, despite the major changes experienced by open pit mines over the last decades, the slope design process has remained practically the same; it has to deal with important sources of geotechnical uncertainty and relies on fudge factors, such as, the Factor of Safety (FoS) and the Probability of Failure (PoF) to deal with the uncertainty. This situation leads, in many cases, to over-conservative slope designs being implemented which increases the mine's operational cost. These designs ignore the behaviour of the rock mass (in qualitative terms) subjected to open pit mining in early stages of the mining process.

The inherent uncertainty associated to rock slope design implies that it is necessary to regularly monitor the implemented designs (open pit walls) performance to confirm their stability or take measurements when performance results to be substandard. Therefore, rock mass deformation monitoring programmes are required to identify instabilities before any sector of the mine becomes hazardous.

However, geotechnical monitoring technologies specifically designed for open pit applications are mainly focussed on rock mass' surface deformation sensing. These technologies perform adequately but only allow to warn about imminent failures when no measurements to avoid them can be taken anymore. To be able to predict failures with sufficient anticipation to take remedial measurements and avoid its occurrence, attention has to be paid to subsurface rock mass deformations. Although subsurface deformation sensing technologies have been developed to tackle civil engineering problems, thus these technologies present important flaws when applied in open pit mining projects, ending with short instruments operational life. To overcome those flaws, a new subsurface rock mass deformation sensing technology, specifically design for open pit mining usage is under development, the Enhanced Networked Smart Markers (ENSM). This new technology also considers the inclusion of piezometers in the same device. Hence, it will allow to monitor the most important variables for slope stability (groundwater pore pressure and rock mass subsurface deformation) using a single device.

However, once the problems relative to the instruments are solved a new problem arises: How to instrument mine slopes? There are no clear and specific guidelines to determine which sector of the open pit to monitor, using which devices and how many of them.

Open pit mines are, essentially, geotechnical projects in constant construction. Thus, it is important to advance in the state-of-knowledge about the material in which the project is placed. This means acquiring knowledge in a certain extraction phase and applying it in the upcoming phases. To fulfil this

objective, geotechnical instrumentation is crucial (Dunnicliff et al., 2012). , The author believes that subsurface deformation programmes have to be included as part of the mine plan, since subsurface deformations start with the construction of the mine. This will allow the installation of instrumentation in critical areas of the open pit as soon as possible, ideally before the extraction commences. Thus, allowing to capture data about the relaxation process experienced by the rock mas as the slope is constructed and about deformations occurred after the slope is totally constructed. This data can then be used to improve the slope designs for future pushbacks and to create slope stability alarms based on total displacements. Since the gathered data will allow to differentiate between expected deformations due to relaxation of the rock mass and deformations produced by developing failures.

## CHAPTER 3

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# IMPLEMENTATION OF A NOVEL SUBSURFACE DEFORMATION SENSING TECHNOLOGY – NETWORKED SMART MARKERS CASE STUDY

### 3.1. The Networked Smart Markers System

Networked Smart Markers (NSMs) are electronic devices developed by Elexon Electronics, company based in Brisbane Australia specialising in developing electronic solutions for various industrial applications.

The NSMs are based on an ore flow and recovery tracking device called Smart Markers (SM), but enhanced with the ability to communicate wirelessly between each other using radio frequency. The wireless communication enables signal transfer through rock up to a distance of five meters.

The devices are battery-operated with built-in radio transceivers in a 34.5[cm] long and 6.35[cm] diameter plastic casing filled with epoxy for improved blasting resistance (Figure 4). Each Marker has an identifying ID, which is activated when the Marker is installed in the ground and is transferred to the Reader Station (data acquisition system), where all data is gathered regularly.



Figure 4: Networked Smart Marker



Figure 5: NSM System's Antenna

NSM devices work as a system installed sequentially inside boreholes. For the borehole installation, a series of NSMs are tied together in a string, which allows installation within the borehole as long as the spacing between two consecutive NSMs does not exceed the maximum communication range. The NSMs are sealed inside the drill hole using grout, permitting them to move with the surrounding rock as the rock mass deforms. Each Marker sends a signal to the next Marker in the string, a process that continues until the signal reaches an antenna (Figure 5) positioned at the top of the grouted borehole. The antenna must be located no farther than 5 meters away from the uppermost NSM in the string and around 1 meter below ground surface. It consists of a modified NSM connected to a cable that links the grouted string of NSMs with the Reader Station

(Figure 6), located in an accessible, safe, and stable zone of the mine, where all data is gathered.

The radio signal strength registered between neighbouring NSMs is gathered regularly. Variations of signal strength indicate possible Markers' movement, which can then be used to establish a qualitative indicator of in-ground rock mass movement as a function of relative displacements between sensors. This type of communication unlocks new possibilities for the subsurface application of NSM technology in open pit mines.

The main objectives for the implementation of the NSM system and associated infrastructure in an operating open pit mine was to demonstrate that the system can be applied in open pit environments and can transmit a signal wirelessly through the rock mass without major interference to mining operations.



Figure 6: Reader Station

### 3.2. Trial Site Description

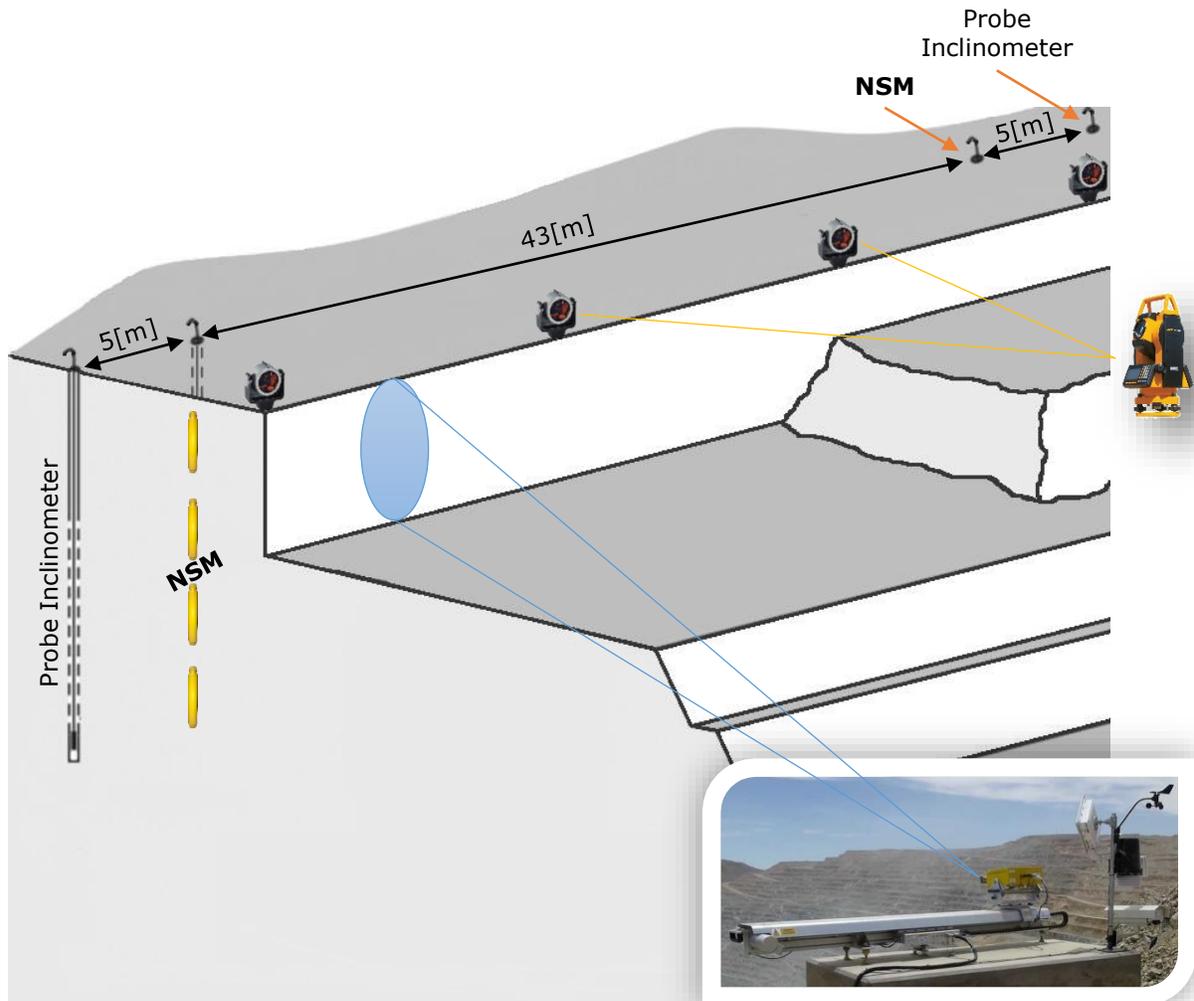
The first trial test of the NSM system for an open pit mine application was held at CODELCO's Mina Sur mine. Mina Sur mine is a mature copper mine located in the north of Chile, now approaching its closure date and which was being used to test new technologies for open pit operations.

The mine is characterized for the presence of a cemented gravel strata placed in the upper-most portion of the pit. This is a brittle, fairly homogeneous material without presence of geological structures which gives similar properties to the material in its whole extension. Based on these homogeneous geomechanical properties, CODELCO planned an innovation project to prove the feasibility of constructing vertical slopes in the highest sector of the mine (CODELCO, 2014). This more aggressive slope design allows the reduction in stripping rate, diminishing the mine's operational costs.

The proposed design consisted of a 150 meters long and 52 meters high vertical wall. It was constructed in four stages defined by four 13-meter high benches. The wall was developed using a regular shovel-truck fleet for the first two stages and a remotely operated fleet to finish the lowest portion of the slope in a zone without groundwater presence.

In parallel to the slope design process, the implementation of a geotechnical monitoring campaign was planned to register gravel's response during the construction of the vertical slope. This monitoring campaign considered surveying surface and subsurface rock mass deformation to

determine whether the vertical slope remains stable in the long term. Figure 7 shows geotechnical instrumentation installed at the trial site.



**Figure 7: Monitoring Campaign Sketch**

For surface monitoring, an IBIS radar was installed at the opposite side of the pit, in front of the vertical slope. This device periodically registered superficial deformations of the vertical slope and its vicinity. This data was used to define thresholds based on values of deformation rate to trigger safety alarms. Prisms were also installed at the crest of the slope and at the slope face as construction progressed. They were monitored using a total station located close to the radar.

For subsurface monitoring purposes, a probe inclinometer was considered and used in two cased boreholes located 48.5 meters away from each end of the vertical slope and 5 meters behind the crest of the slope.

In addition, it was decided to install two boreholes instrumented using NSMs. Each NSM borehole was located 2 meter away from an inclinometer drill hole as shown in Figure 7. This was conceived to allow comparisons between data gathered using both types of instruments.

### **3.3. First NSM Open Pit Trial**

#### **3.3.1. Laboratory Testing and System 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. Both ropes were able to withstand 1.5 times the weight of all NSMs in the finished string, preventing torsion of the NSM's chain assembly and keeping the devices in a vertical position during installation of the string down the borehole and subsequent grouting process. 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 once the grout sets and fix the Marker in the desired position.

The strings were completed using a 2 meters top to bottom spacing between two consecutive NSM in the chain. This allows redundancy in NSM's communication, since every device can reach 5 meters effective communication which allowing them to be connected to the two nearest NSMs in both directions. The strings assembling process was the following:

1. Every string was constructed from bottom up.
2. The lower-most NSM was placed on a table larger than the separation between consecutive NSMs.
3. The first cord was tied to the bottom of this NSM. It was fixed using electrical tape and then one of the moulding marks, located at opposite sides of each device, was used to guide the cord to the top of the NSM, where the cord was fixed again using electrical tape.
4. The lower knot was secured using a plastic strap.
5. The second cord was tied to the top of the lowest NSM in the string and align with the moulding mark located opposite to the one used to guide the first cord.
6. The second cord was fixed using electrical tape.
7. Both cords were secured in the top end of the NSM using three plastic straps.
8. All plastic straps were covered using duct tape.
9. The cords going alongside the NSM were covered using duct tape.

10. Both cords were marked at the spacing distance between two consecutive NSMs (2 meters in this case). Measurements were made from the top of the NSM already tied to the array.
11. The marks were placed in the lower end of the next NSM in the string.
12. Both cords were aligned to moulding marks and fixed using electrical tape to the bottom end of the Marker.
13. Cords were secured using a plastic strap around the NSM lowest end.
14. The moulding marks were used to guide both cords alongside the Marker.
15. Both cords were fixed, aligned to the moulding marks, to the top end of the Marker using electrical tape.
16. Cords were secured using three plastic straps around Marker's top end.
17. Plastic straps were covered using duct tape.
18. Both cords going beside the NSM were covered using duct tape.
19. Steps 10 to 18 were repeated until the array was completed.
20. Both cords were marked at the distance required between the NSM in the top of the array and the borehole's collar.
21. The numbers (ID) of all NSMs in the finished array were registered, to enable configuration of the Reader Station.

After two strings of Markers were fully assembled, 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 during site installation.

### **3.3.2. Installation of the System**

For the site trial, two 53-meter deep boreholes were drilled five meters behind the crest of the trial slope, approximately 43 meter away from each other and parallel to inclinometer's boreholes (Figure 7). Both drill holes were instrumented using 22 NSMs' strings and two meters spacing between consecutive devices. After each string was lowered into position, the end of the string was tied to a trestle located directly above borehole's collar, to hold the Markers in place.

Both boreholes were completed with an antenna placed two meters above the uppermost NSM in the string, around one meter below the ground surface. The antennas were connected by a cable to a Splitter-Box located approximately 50 meters away from the closest borehole along the bench. The main feedline was buried in a shallow ditch between the Splitter-Box and a Reader Station placed on a trolley approximately 100 meters away from the Splitter-Box (Figure 8).

Subsequently, the boreholes were sealed using cement-sand-water grout mixture, which was poured down the hole from the collar. Before both



The remaining borehole performed well for approximately 6 weeks. Table 1 shows the signal strength and NSM connectivity in this borehole, where 2.2 to 2.23 represent the NSMs in the string from top to the bottom (2.1 is not listed as it is the Reader). The boxes represent signal strength for neighbouring Markers at 2, 4, 6, 8 meters of distance in both directions, negative for overlaying and positive for underlying Markers. NSM # 2.2 does not show signal strength above it, because it is the upper-most Marker and NSM # 2.23 does not show signal strength below it because it is the lowest Marker. Colours represent signal strength links. Green for high signal strength links, yellow for average signal strength and orange for low signal strength.

**Table 1: NSM’s Connectivity**

Communication Distance [m]																											
Above	-8																					47					
	-6																			51	59						
	-4			23							25	38	40	36				30	27	30					48	57	58
	-2	54	42	56	47	56	53	60	59	52	29	57	52	54	48	51	54	51	55	57	56	59					
NSM #		2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	2.12	2.13	2.14	2.15	2.16	2.17	2.18	2.19	2.20	2.21	2.22	2.23				
Below	2	52	52	49	50	50	58	54	61	54	33	54	59	53	52	51	50	51	54	57	56	56					
	4	29					26	35	34	38			28	27	33					48	57	57					
	6																		52	57							
	8																			41							

Table 2 shows signal strength in both directions for every 2 and 4 meters distance links in the string, where the numbers written as “XX/YY” represent “Receiver-A-signal/Receiver-B-signal”, yellow boxes represent NSM’s position in the string and grey boxes, the grouted space that the signal has to cover between the markers. Regarding the directions of signal strength, green represents good quality signal strength and red poor quality. Table 2 also shows that only 55% of the NSM present 4 meters links, leaving no redundancy in communication at other points in the string. From those links, only 18% present good quality signal links i.e. 10% of the whole string. In addition, there is a single 2 meters link between Markers 2.11 and 2.12, which is of poor quality. It was observed, while on-site, that multiple attempts were sometimes needed to route packets deeper to this Marker.

The data in Table 1 and Table 2 also indicate that the NSMs located deeper in the borehole had higher signal strength 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 NSMs’ weight and the load caused by the grout poured from the top of the borehole. It was deduced that the NSMs at the bottom of the holes were closer than 2 meters from each other, while the NSMs further up the hole were farther than 2 meters apart.

**Table 2: Both Ways Signal Strength**

2 Meters Distance Links				4 Meters Distance Links					
NSM String	Both Directions Signal Strength	NSM String	Both Directions Signal Strength	NSM String	Both Directions Signal Strength	NSM String	Both Directions Signal Strength	NSM String	Both Directions Signal Strength
2.2				2.2					
Grout	52/54			Grout	29/23				
2.3		2.3		2.4		2.3			
		Grout	52/42			Grout	-	2.4	
2.4		2.4		2.5		2.5		Grout	-
Grout	49/56			Grout	-			2.6	
2.5		2.5		2.7		2.6			
		Grout	50/47			Grout	26/25	2.7	
2.6		2.6		2.8		2.8		Grout	35/38
Grout	50/56			Grout	34/40			2.9	
2.7		2.7		2.10		2.9			
		Grout	58/53			Grout	38/36	2.10	
2.8		2.8		2.11		2.11		Grout	-
Grout	54/60			Grout	28/30			2.12	
2.9		2.9		2.13		2.12			
		Grout	61/59			Grout	27/27	2.13	
2.10		2.10		2.14		2.14		Grout	33/30
Grout	54/52			Grout	-			2.15	
2.11		2.11		2.16		2.15			
		Grout	33/29			Grout	-	2.16	
2.12		2.12		2.17		2.17		Grout	-
Grout	54/57			Grout	-			2.18	
2.13		2.13		2.19		2.18			
		Grout	59/52			Grout	-	2.19	
2.14		2.14		2.20		2.20		Grout	48/48
Grout	53/54			Grout	57/57			2.21	
2.15		2.15		2.22		2.21			
		Grout	52/48			Grout	57/58		
2.16		2.16				2.23			
Grout	51/51								
2.17		2.17							
		Grout	50/54						
2.18		2.18							
Grout	51/51								
2.19		2.19							
		Grout	54/55						
2.20		2.20							
Grout	57/57								
2.21		2.21							
		Grout	56/56						
2.22		2.22							
Grout	56/59								
2.23									

After approximately 6 weeks of operation, the Reader Station stopped receiving new data. Therefore, troubleshooting and re-establishment of the NSM system’s connectivity was undertaken; this process extended for a period of 2 months.

### 3.4.1. Improvements to the NSM System

There were several improvements made to the system to improve its performance after the installation. For instance, cables were unearthed and installed inside galvanized conduit ducts, the Splitter Box was protected using a metal box and the motherboard inside the Reader Station was replaced by an up-to-dated version.

However, subsequently, communication to both boreholes was lost again. Laboratory testing was performed using spare NSMs, identifying several possible causes for this issue. Table 3 provides a list of identified faults and/or causes for this system’s malfunctioning and the level of contribution to the problem of each cause.

**Table 3: Troubleshooting Summary**

Detected Fault	Possibility	Comment	Likelihood Contribution
<b>Poor 2-hop Distance Connection</b>	Poor marker communication range	Different performance between individual NSMs. Antenna performance randomly distributed, causing short NSMs range.	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 low range.	Unlikely. Medium contribution.
	Poor RF properties of Earth/Ground	The ground and/or grout composition might be significantly different over borehole’s length.	Unlikely. Medium contribution.
<b>Markers Becoming Non-Contactable</b>	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 this.
	Broke installation rope	Possibly, the ropes broke during Marker installation leaving some NSMs out of rage.	Possible but unlikely. Rope breaking would have been noticed.
	Rope elongation	Rope stretch expanded the planned distance between Markers. The distance for 2-hop links exceeded the Markers’ communication rage.	Likely. Strong contribution.

A second installation with second generation prototype NSM was scheduled for the same trial site. Table 4 provides a summary of improvements made to the system prior to the second installation, which were deemed of high importance after the evaluation.

**Table 4: System Improvements**

Possible Issue	Improvements Made
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.
Uneven filling of the boreholes due to excessively viscous grout and to the pouring process.	A new, thinner grout mixture was employed.  The grout was pumped through PVC pipes from the bottom of the boreholes instead of just pouring it from the boreholes’ collar.
NSM testing after grouting.	NSM tested above ground.  NSM tested in the hole for an extended period (several days) before grouting.

### 3.5. Second NSM Open Pit Trial

A second mine site trial was planned to test the performance of the system with the improvements made to the installation procedures, the devices and the overall NSM system. For this purpose, two new boreholes, 10 and 40 meters deep, were drilled in the vicinity of the long-lasting working NSM borehole from the first trial. This time placed approximately 10 meters behind the crest of the slope. The 10-meter drill hole was located behind the first trial borehole, while the 40-meter borehole was perforated 10 meters away from those drill holes in the direction of the Splitter Box.

The drill holes used for the first trial were disconnected from the Splitter Box to allow connection of the antennas used for both newer boreholes. This allows the reutilization of NSM system associated infrastructure already installed in the mine (Splitter Box, main feedline and Reader Station) for the 10 and 40-meter boreholes (Figure 9).

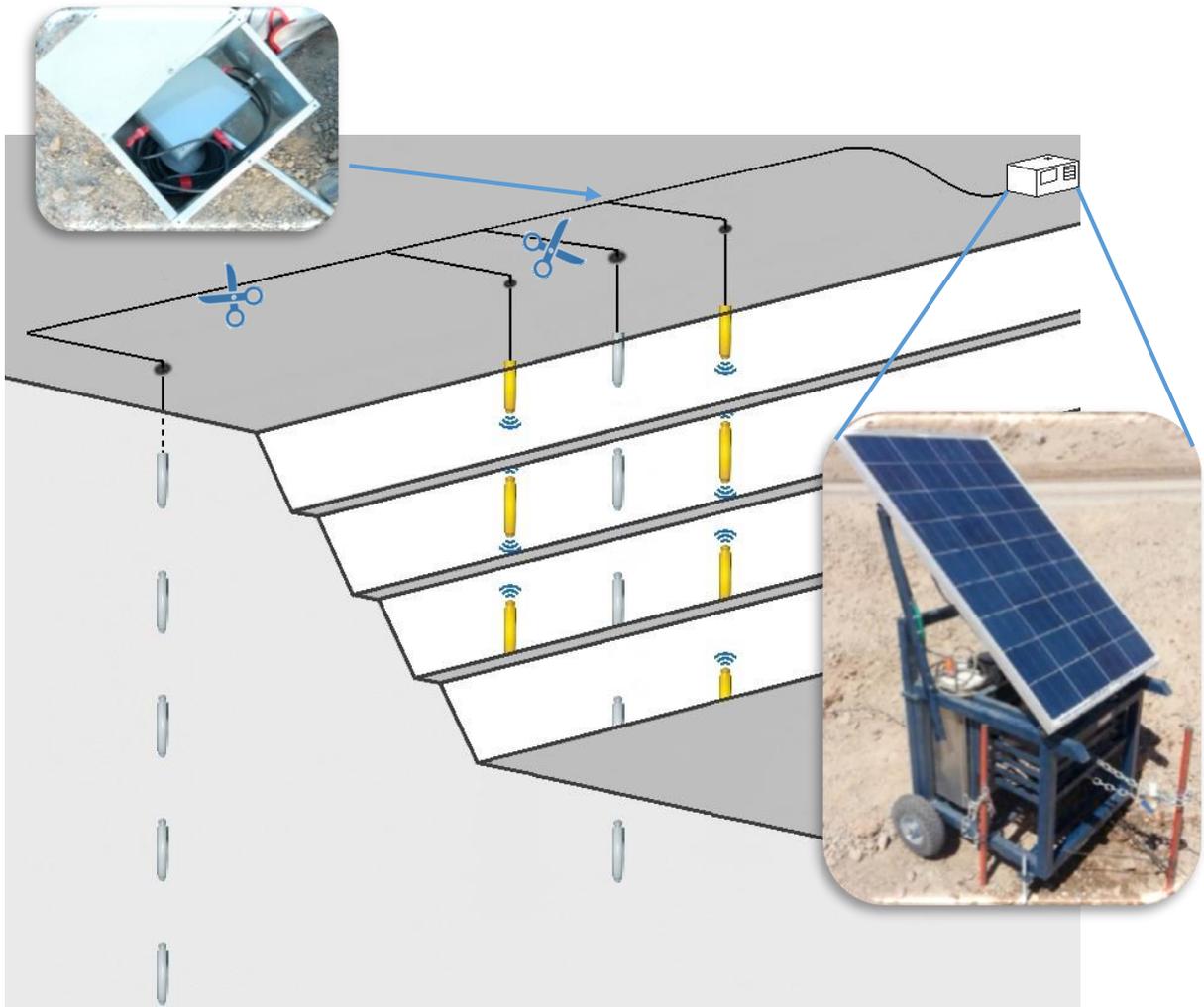


Figure 9: Second NSM Installation Diagram

Both boreholes were instrumented in sequence. The 10-meter borehole, with five NSMs at a 2-meter separation, allowed for initial testing of the installation before the deeper borehole was instrumented. The 40-meter drill hole was left with 35 NSM Markers (1-meter separation) hanging inside it. After the grout poured in the shallower drill hole set overnight and getting confirmation that the NSMs in that borehole were performing as planned, the second borehole was filled with grout. A final communication test was run after the deeper borehole had the antenna in position and was completely filled, thus verifying that the system was working under specifications.

### **3.5.1. System Installation Procedure**

During this installation, NSMs strings were put together using a climbing kernmantle rope capable of withstanding 3.5 times the weight of 35 devices in the string. This minimized elongation of the rope caused by NSM's weight. Cables from both antennas to the Splitter Box and the main feedline connecting the Reader Station with the Splitter Box were installed inside galvanized conduit ducts. The strings were left hanging and working inside the boreholes for one week before grouting them. This allowed to test signal strength and the detection of any possible communication problem.

The boreholes were sealed using an improved grouting procedure and 1:1:2.5 cement:sand:water grout. The grout mixture was pumped from the bottom of the drill hole to the top using 1½" inches diameter PVC tubes to: (1) avoid placing additional weight on the NSMs and the rope as the borehole was filled; (2) ensure that the borehole was completely filled, avoiding the formation of air gaps within the grout column; and (3) minimize NSMs' tilting and displacement. The NSM antennas were installed at last, located right above and in contact with the top-most NSM in the boreholes (0m spacing), placed approximately one meter below ground surface and sealed with sand instead of grout to make it possible to recover the antennas, if needed.

After the boreholes were fully grouted and the antennas buried with sand, a communication test was performed using the Reader Station. It showed that wireless linkage between NSMs grouted in the drill holes was successful.

The system's Reader Station was improved with the integration of a GSM modem. This modem enabled remote access to the Reader Station using wireless networks, simplifying the operation of the system as the operator was able to interact with the Reader from their office. The improvement also allowed software updates, firmware modifications and command execution related to data downloads without having to send an operator to the studied site.

Four months after the second trial installation, all NSMs in both boreholes were still reachable showing good quality links. Data was being gathered at short time intervals without problems. This test proved that the installation procedure for the second trial overcame the faults and problems registered during the first trial, ending up with a robust site installation. The system also demonstrated that, using NSMs, it was possible to have wireless data transmission through rock in open pit slopes.

### **3.6. Recommendations to Improve the System**

After both mine site trial installations, the ability of the NSM system to wirelessly transmit data through the rock mass under an operative open pit mine constrains was demonstrated.

Every faults and problems identified during the first trial were examined and taken into account for an improved installation in the second trial. This produced a reliable and robust installation procedure, applicable for similar installations. If an installation is planned for boreholes over 100 meters deep, installation procedures will need to be improved or changed.

With regards to the particular devices, NSMs demonstrated to be a robust solution for rock mass geotechnical instrumentation, being able to withstand particular conditions encountered in this type of material and overcoming common problems encountered when applying other geotechnical instruments in open pit mining environment. For instance, blocked boreholes, broken in-hole cables and boreholes' casing excessively deformed. All of these assures NSMs' long lifespan under open pit mining conditions, allowing 2-meter deformations while still having good quality communication and proper system functioning.

#### **3.6.1. System's Current Development**

It is planned to use the NSMs and their wireless data transmission capabilities as an in-ground platform for geotechnical monitoring. This platform will integrate different sensors to monitor subsurface variables in a single device, able to operate autonomously for over 10 years. Sensors' shortcomings for mining applications, such as, limitations related to in-ground cable connections will be overcome with this integration.

In that regard, a new version of NSMs called Enhanced Network Smart Markers (ENSM) is being developed to integrate further sensors. ENSM are being designed to overcome some limitations of the currently available and commonly used sensing technologies, such as:

- Limited depth application.

- Instruments' short lifespan.
- Low tolerance to abrupt shearing.
- Limited number of devices per borehole.
- Low coexistence of sensors in a single location.
- Installation and performance issues due to the presence of cables inside the boreholes.

### **3.6.2. System's Future Developments**

Future installations of the system will consider using ENSM. These devices will be deployed in more complex and fully operative open pit environments including groundwater presence, higher rates of subsurface deformations and complex interactions between mining operations.

Since future trials will be conducted with full-scale open pit slopes, it will be necessary to instrument 300-meter deep boreholes; in this case, using strings will be too heavy to be manually handled. These new conditions will require more specific installation procedures and specially design hardware to lower ENSM devices inside the boreholes.

Proper data gathering frequency has to be defined for the ENSM to capture changes experienced by studied variables in material with different properties. In brittle rock masses, it will require higher data collection frequencies to capture deformations than in ductile rock masses, which are characterised by more progressive deformations.

To obtain useful information from gathered data, tools to manipulate and process this data and a visualization software are being developed. These will allow near-real time data processing and variables monitoring (for all sensors integrated in ENSM).

Finally, ENSMs' enclosure will be redesign to allow easier construction of strings, facilitating the attachment of a large quantity of devices to a single string or easy handling with new installation method.

## **3.7. Chapter Summary**

This chapter provided a thorough description of the Networked Smart Marker (NSM) system and its associate infrastructure. It also included case studies for the two first open pit NSM installation, featuring installation procedures, problems and faults analyses and improvements of the NSM system from the first installation to the second one. Finally, it presented current and future developments of the system, which are intended to produce a more robust and widely applicable system for all different open pit mining conditions.

## **CHAPTER 4**

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### **MINE PLAN**

The first step to plan any geotechnical monitoring campaign is the definition of the conditions of the project to be monitored. Thus, during this research and prior to the design of any monitoring campaign, open pit's mine plan and pushbacks were obtained from a theoretical block model. For this tasks, the software DeepMine was used. The pushbacks defined in DeepMine were then relaxed using the software Vulcan to obtain smooth operative phases, avoiding major changes to assure that the obtained mine plan remained valid.

Since the purpose to develop a mine plan and associated phases (project conditions) is to guide the deployment of the instruments to obtain the best results from the monitoring campaign for slope stability assessments, the development of a detailed mine plan and fully operational phases design (including berms and ramps) was considered to be out of the scope of this chapter and thesis.

#### **4.1. DeepMine**

DeepMine (BOAMine SpA, 2015) is a software solution for strategic open pit mine planning from an economic perspective that avoids the usage of predefined phases (pushbacks). As output, it delivers the size of the mine considering amount of material to be mined and processed. It also delivers mine's lifespan and the value of the operation in terms of net present value (NPV). To do so, the software creates decision trees based on the studied mining configuration. Approximate dynamic programming is used to explore multiple branching in those decision trees to obtain the best outcome based on operation's economic value.

Pushbacks are automatically produced as the result of software's calculations, considering operational constrains using Lerchs and Grossman pit shells as input to define operative phases. The resulting pushbacks are associated with the mine plan and can be used as a guide for mine design e.g. a plan that establishes when every pushback has to be mined to obtain the best possible economical outcome.

To produce such results, DeepMine works with a block model given as an input used by the software to perform the calculations and with the definition of four elements in the mine planner: The *GeoModel*, the *Mining Environments*, the *Pit Collections* and the *Economic Environments*. These elements use the information contained in the block model and can be defined

to apply uncertainty on the resulting mine plans by, for example, modifying commodities prices, operational costs and taxes over time.

A brief description of all the modules that the user has to define to solve the mine plan is presented in the following list:

1. The *GeoModel* contains the block model representing the ore deposit and the topography. Here the maximum admissible overall slope angles have to be defined.
2. The *Mining Environments* define operational parameters related with mine, stocks plants and dumps' location, operations, capacities, investments and costs. All this data (extraction and processing information) is used to determine cash flows of the project per year.
3. The *Pit Collections* define a set of pit shells resulting from the application of Lerchs and Grossman algorithm to solve the ultimate pit problem using as input a *GeoModel*, a *Mining Environment* and a series of yearly prices for every commodity to be mined.
4. The *Economic Environments* define the first year of mine's operation, a discount rate for the cash flow, prices and selling costs per year for every commodity contained in the block model. Finally, a tax rate is defined for the entire operation.
5. The *Mine Plans* are the final output of the software. To produce them, the user defines the first year of operations, maximum life of mine (LOM), maximum sinking rate for a single phase in term of benches (number of block in a vertical section) per year, maximum number of active phases every year, maximum phase length, minimum phase width and, optionally, minimum and maximum phase weight. Finally, the *GeoModel*, *Mining Environment*, *Pit Collections* and *Economic Environment* are used as input.

Refer to APPENDIX B for further information regarding the components defined in DeepMine to obtain the mine plans.

## **4.2. Definition of the Mine Plan and Phases using DeepMine**

The definition of a coherent *Mine Plan* using DeepMine was an iterative process. This process involved working with a theoretical block model for a copper ore deposit. The four main areas of the software (*GeoModel*, *Mining Environment*, *Pit Collection* and *Economic Environment*) were defined at the very beginning and the iterations were focused on continuous modification of the *Mining Environment*. These modifications induced changes in the *Pit Collection* that were automatically processed by the software. The *GeoModel* and *Economic Environment* were not modified in this process.

All the iteration induced changes to the preliminary *Mine Plan* looking for smooth mine productions over time, plants operating at full capacity and stockpile/re-handling minimum usage.

#### 4.2.1. Block Model Characteristics

A theoretical block model was used to produce a mine plan with associated extraction phases. This model was constructed by 30[m] long, 30[m] wide and 15[m] high blocks, arranged in a volume of 1,620 by 1,620 meters (54x54 blocks) footprint and 720 meters (24 blocks) depth.

The model contained four different types of rock: waste, oxides, oxide/sulphide transition zone and sulphide ore. Every type of rock contains information about total copper and soluble copper content. The orebody presented an average copper grade of 0.16[%Cu]. Table 5 presents the orebody's main characteristics.

**Table 5: Orebody's Rock Type Distribution**

Rock Type	Weight [kton]	Average Copper Grade [%Cu]	Maximum Copper Grade [%Cu]
Oxide Ore	158,513.74	0.07	0.83
Sulphide/Oxide Transition Ore	255,104.36	0.20	1.24
Sulphide Ore	505,283.44	0.16	1.72
Waste Rock	1,177,483.74	0.03	0.30

#### 4.2.2. GeoModel Definition

The *GeoModel* was defined enabling the resulting phases to have different slope angles, representing with these sectors two different rock qualities. Good quality rock will have steeper slope angles compared to poor quality rock. Table 6 summarizes the definition of these zones, where bearing represents the dip direction of the slope with respect to the geographic North Pole and angle represents the overall slope's angle.

**Table 6: GeoModel Definition Summary**

Pit Zones	Bearing	Angle
Good Quality Rock Mass	0°	50°
Good Quality Rock Mass	90°	50°
Poor Quality Rock Mass	180°	40°
Poor Quality Rock Mass	270°	40°

### 4.2.3. Mining Environment Definition

The definition of a *Mining Environment* was an iterative process. It started by establishing 2015 as the first year of mine operation and the determination of the need to have two plants to process all different ores coming from the mine. A leaching plant for oxide and transition ores and a concentrator plant to process sulphide ores.

The iterative part of the process was made to define the combination of mine and processing plants' capacities that produced the best economic outcomes. The first step was to evaluate several mine's annual capacities in a range from 10,000[kton] up to 80,000[kton] matched with over dimensioned and fixed plants capacities. The resultant Mine Plan's NPVs (net present values) were assessed concluding that the higher values of this indicator were obtained with a mine capacity of 40,000[kton]. This evaluation also showed that the first plant entering into production was the leaching plant; this information was used to define the next step in the production of a feasible mine plan.

The next iterations involved the evaluation of different leaching plant capacities. All alternatives explored in this process considered that the leaching plant was going to be fed with oxide and oxide/sulphide transition ores and it was assumed copper recoveries of 75% for oxide ores and 65% for oxide/sulphide transition ores. The evaluation of a suitable plant capacity was based on the resulting LOM and then on the Mine Plan's NPV value, as it was observed that small plant capacities resulted in LOMs around 6 years, which was not coherent with an ore body as big as the one used for this project. This part of the process ended with an annual capacity for the leaching plant of 9,000[kton] and a lifespan of 13 years from 2015 to 2027.

Subsequently, the concentrator plant characteristics were established. The alternatives studied in these iterations considered that the concentrator plant was going to process all sulphide ores coming from the mine. The recovery in this plant was set at 90% for all copper contained in sulphide ores. The evaluation of suitable capacities was strongly influenced by resulting LOMs as small concentrators drastically reduced the lifespan of the mine. Mine Plan's NPV's showed that the most profitable concentrator capacity was 7,000[kton] per year. The operation of this plant had to start in year 2017, working for 15 years to end its operation in 2031. This result was obtained considering the previously described leaching plant.

Although the defined combination of mine, leaching plant and concentrator plant capacities gave the best result in terms of NPV, operationally it presented several concerns, including:

1. Mine production was uneven.

2. Plants presented some years of extremely low utilization.

Two different methods were used to overcome these issues based on the control of the amount of re-handled material feed into each plant and on limiting the surplus for both the leaching and concentrator plants.

To be able to control the re-handling, two stockpiles were defined. The first one was intended to stock oxide and oxide/sulphide transition ores to feed the leaching plant. It was configured to hold 18,000[kton] per year the, twofold of the leaching plant capacity. The second stockpile was meant to feed the concentrator plant and store exclusively sulphide ores. Its capacity was of 14,000[kton] per year, which was twofold the capacity of the concentrator plant. Thus, each stockpile could hold approximately one day of mine capacity. Table 7 summarizes all relevant costs and capacities.

As the stockpiles had to be defined by its yearly capacity, an important problem arose as the software tended to uncover high grade ores by producing large quantities of material that went directly to stockpiles. This produced the highest cash flows in early stages of the project and, thus, a better economic results, but it also produced high amounts of stocked material that lasted several years in such condition. The stockpile material was sent to the processing plants in the last years of the project. Another problem that emerged was that during the last years of plants' operation, no re-handling and surplus limits were defined while the plants were processing, mostly, stocked material, as shown in Figure 10.

**Table 7: Operational Costs and Capacities Summary**

	<b>Annual Capacities</b>	<b>Operational Costs</b>
<b>Mine</b>	40,000[kton]	2.25[US\$/ton]
<b>Concentrator</b>	7,000[kton]	9.40[US\$/ton]
<b>Leaching</b>	9,000[kton]	4.30[US\$/ton]
<b>Sulphide Ore Stockpile</b>	14,000[kton]	Assumed as part of concentrator's operational costs
<b>Oxide and Ox./Sulphide Transition Ore Stockpile</b>	18,000[kton]	Assumed as part of leaching's operational costs
<b>Dumps</b>	Unlimited	Assumed as part of mine's operational costs

To overcome these problems the surplus was limited. The definition of surplus limits was performed yearly for each plant. The results of this process is shown in Table 8. This constraint controlled the amount of material, in excess of the mined ore, to be sent to the processing plants that can be mined. The process resulted in lower extraction of stock material in early stages of mine's life and higher amounts of mined material sent directly to the plants.

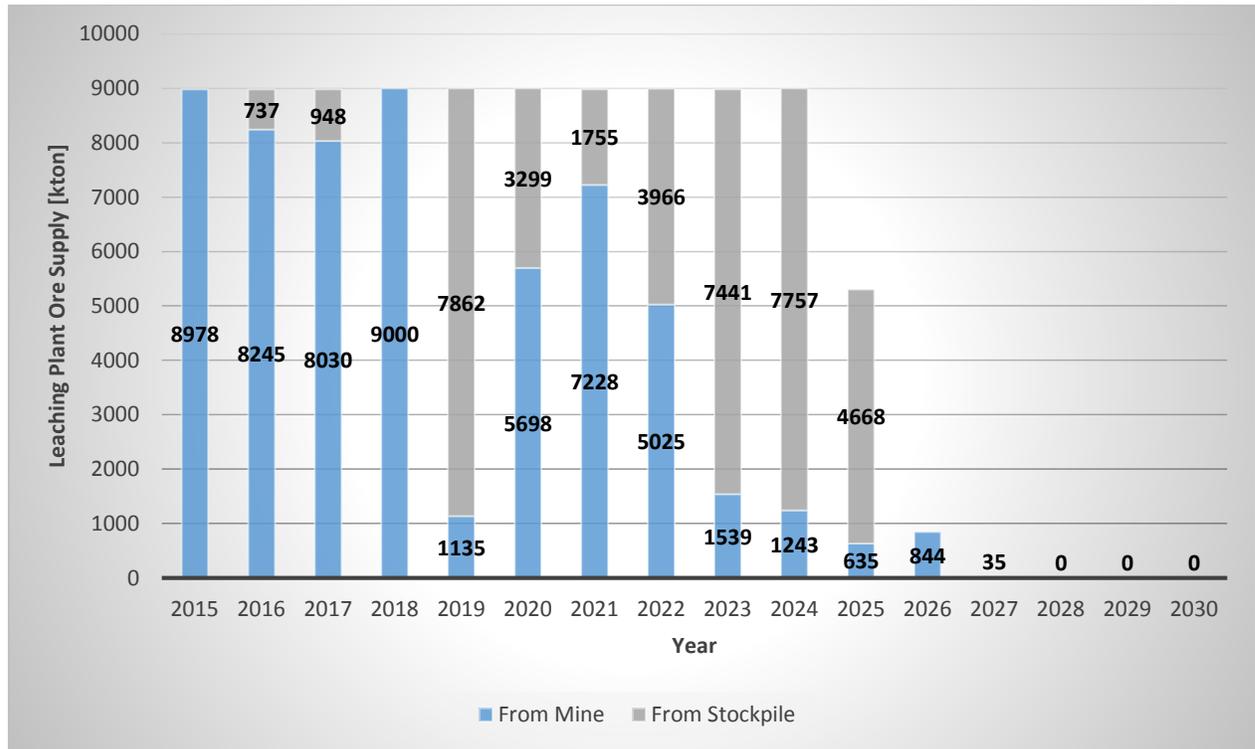


Figure 10: Leaching Plant Unsatisfactory Operation

Table 8: Adjustment Factors Summary

Year															
2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
<b>Concentrator Surplus Limit [kton]</b>															
0	0	0	4,000	5,000	1,000	5,000	1,000	0	5,000	3,000	0	5,000	0	0	0
<b>Leaching Surplus Limit [kton]</b>															
2,000	2,450	2,900	3,350	3,800	4,250	4,700	0	500	1,000	0	0	0	0	0	0
<b>Sulphide Ore Stockpile Re-handling Capacity [kton]</b>															
0	0	0	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400
<b>Oxide and Oxide/Sulphide Transition Ore Stockpile Re-handling Capacity [kton]</b>															
1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800	900	1,800	900	900	900	900

The amount of the re-handled material per year was defined for each plant in an iterative process year by year to further improve the distribution of plant's stock supply. This process started by setting the maximum amount of re-handled material at 20% of the matching plant capacity. Then, the values were reduced, when possible, to maximize the amount of mine material fed to the plant while saturating plants capacity. Table 8 summarizes the re-handled material per year for both plants.

#### 4.2.4. Pit Collection Definition

The *Pit Collection* for the *Mine Plan* was defined using a vector of 40 different prices for the copper. The prices defining that vector were homogeneously distributed between 0 and 3[US\$/lb].

The *GeoModel* was associated with the generation of *Pit Collection* to use slope angles contained in the *GeoModel* to define the precedence list for block's extraction.

This process should have resulted in 40 different pit shells. However, the first 8 pit shells did not contain any blocks because of the low commodity prices defined in the first eight intervals of the price vector. Figure 11 shows the 32 different pit shells resulting from this process.

Figure 11 also shows the different slope angles as defined in the *GeoModel* and captured by the pit shells. It is worth mentioning the importance of producing many pit shells as those will be used as guide to generate the extraction phases. More pit shells means more flexibility for DeepMine to generate the geometry of the phases and, thus, better results in producing operative phases.

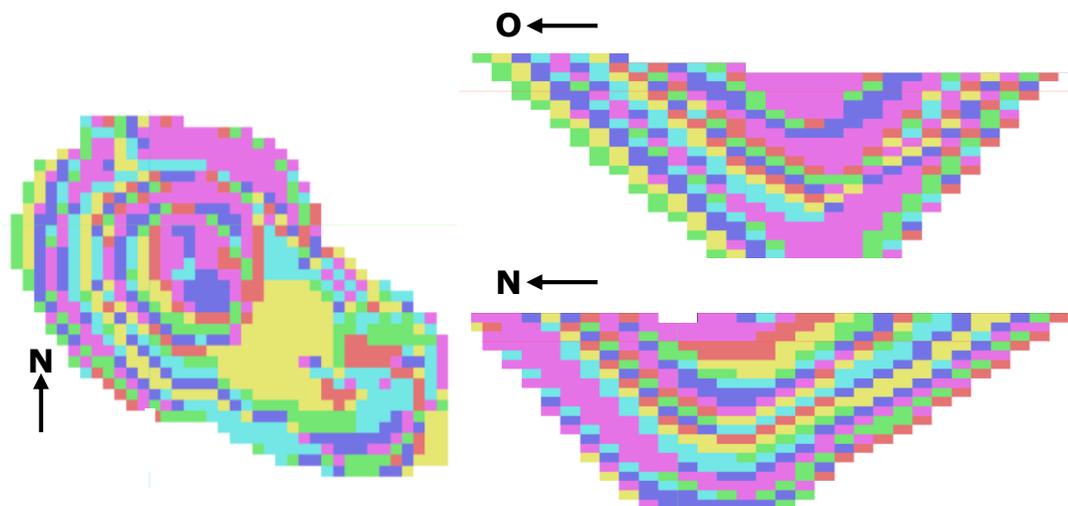


Figure 11: Pit Shells Views – Plant (Left), East-West (Right Top), North-South (Right Bottom)

#### 4.2.5. Economic Environment Definition

With regard to the *Economic Environment*, copper price was set at 3[US\$/lb] for the entire mine's lifespan. This value was established considering the price predictions made in August 2015 by the Chilean Central Bank (2.9[US\$/lb]). For simplicity, no taxes were considered. Table 9 contains all the parameters used to define the *Economic Environment*.

**Table 9: Economic Environment Definition Summary**

Economic Environment Definition	
Discount Rate	8[%]
Copper Price	3[US\$/lb]
Copper Sales Cost	0.4[US\$/lb]
Tax and Royalty	0[%]

#### 4.2.6. Mine Plan Settings

Before obtaining the final mine plan, some parameter had to be provided for the software to produce logical operative phases. These parameters are listed in Table 10.

Maximum Life of Mine (LOM) defines the maximum number of years that DeepMine will consider to do the extraction of the mine. In this case, the LOM's input value was defined as 30 years, which assured that every resulting mine plan had a shorter life than the input LOM. Therefore, any possible mine plan was not restricted by the LOM.

**Table 10: Mine Plan Settings**

Parameter	Magnitude
Maximum Life of Mine (LOM)	30[years]
Maximum Active Phases Simultaneously	5
Maximum Phase Length	1,000[m]
Minimum Phase Width	100[m]
Maximum Sinking Rate per Year	10[benches]

The number of active phases that can be operating simultaneously adds flexibility to mine planning, hence, it allows for more possible extraction alternatives.

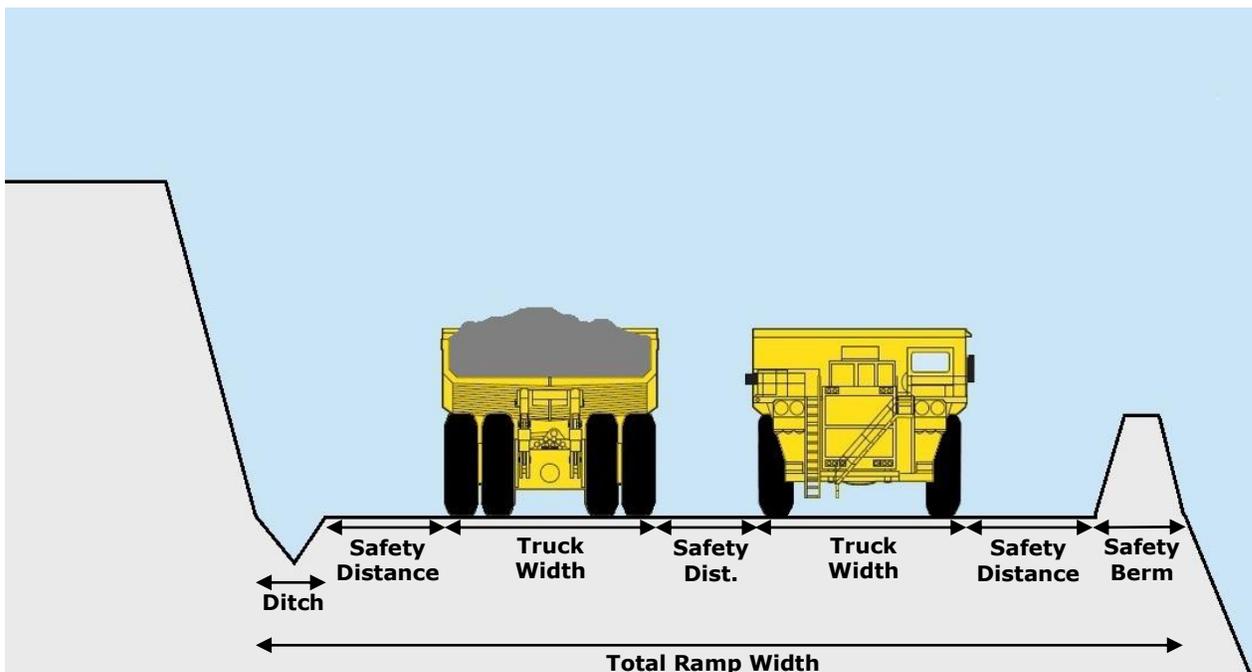
Minimum phase width is a critical parameter for the operation of the mine and, thus, for the definition of the phases; it has to be properly estimated. Therefore, an estimation of the shovel-truck fleet that this mine will need for its operation was required.

Since the mine has a production rate of 40,000[kton] per year, around 111,000[ton] of material have to be moved per day. It was assumed that a hauling cycle time would be 30[min] and an operational factor would be 65%, which gave 15.6 hours of operation per day. Table 11 shows the number of trucks that the mine would require fulfilling its production and their capacity.

**Table 11: Truck's Fleet Estimation**

Parameter	Magnitude								
Truck Capacity [ton/cycle]	18	20	32	46	68	78	120	160	180
Production [ton/hr]	36	40	64	92	136	156	240	320	360
Daily Production [ton/day]	561.6	624.0	998.4	1,435.2	2,121.6	2,433.6	3,744.0	4,992.0	5,616.0
Truck Fleet	198	178	111	77	52	46	30	22	20

A fleet of twenty 180[ton] capacity trucks were selected as reference for the determination of the ramp width. It was decided to consider two ways 24[m] wide ramps. This width was defined based on the dimensions listed in Table 12 and shown in Figure 12, which considered the dimensions of a Komatsu 730E truck.



**Figure 12: Ramps Setup (modified after Hustrulid et al., 2013)**

**Table 12: Ramps Dimensions**

Parameter	Magnitude
Ditch	1[m]
Safety Berm (Pit Side)	1.72[m]
Truck Width (x2)	7.54[m]
Safety Berm (Bench Side)	0[m]
Safety Distances (Total)	6[m]
Total Ramp Width	24[m]

In the next step, a shovel was selected to match the Komatsu 730E trucks. A simple operational rule was used for preliminary shovels selection: a shovel had to be able to load a truck in less than 3 cycles. As the selected trucks had a capacity of 111[m<sup>3</sup>], shovel's bucket had to have a capacity of at least 37[m<sup>3</sup>]. Hence, a Komatsu PC8000-6 shovel with a bucket capacity of 42[m<sup>3</sup>] was selected.

The minimum loading width was calculated based on the dimensions of selected trucks and shovel plus safety distances as listed in Table 13 and shown in Figure 13 where one truck - shove configuration is considered.

**Table 13: Loading Area Dimensions**

Parameter	Magnitude
Safety Berm (Pit Side)	1.72[m]
Truck Width	7.54[m]
Safety Distances	6[m]
Shovel Width	18.6[m]
Spalling	5[m]
Total Loading Width	39[m]

The worst case scenario is the occurrence of a loading area alongside a hauling ramp. This combination required an operational width of 63[m] but, as this was not a detailed design, important contingencies might be expected. It was decided to work with a minimum phase width of 100[m].

The maximum sinking rate is referred to the number of benches that can be vertically mined as part of a single phase. This, again, allows for more possible extraction alternatives.

Finally, the Mine Plan was solved using *Deep Mode* and a *Guidance Amount* of 80%. *Deep Mode* allows the software to explore all possible alternatives to generate a mine plan under the defined parameters and constrains given in DeepMine.

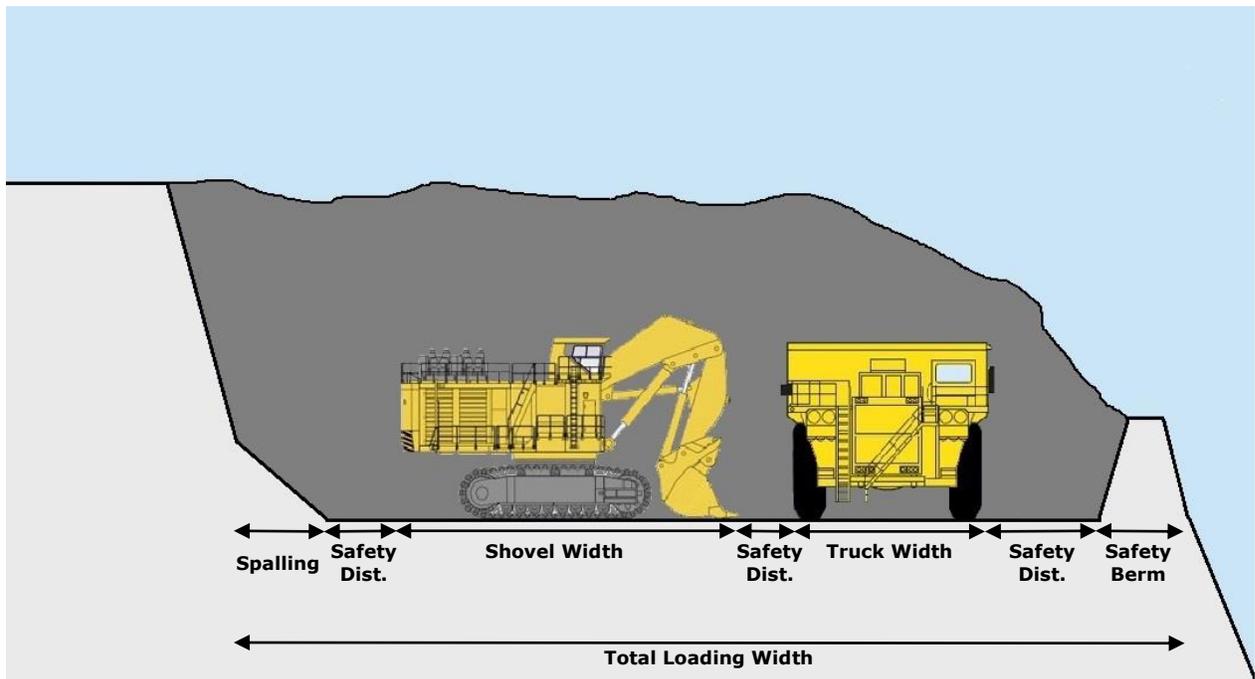


Figure 13: Loading Area Setup

#### 4.2.7. Resulting Mine Plan

DeepMine calculations resulted in 16 years of operation divided into 29 different phases. It considered the extraction of 355,029.04[kton] of material, 88,163.04[kton] of sulphide ores were processed in the concentrator plant and 95,306.37[kton] of oxide and oxide/sulphide transition ores were processed in the leaching plant. Mine's stripping rate was 1.28. The scheduling of the 29 phases is shown in Table 14.

The mine started its production in year 2015, operating to supply the leaching plant since that year, while the concentrator plant started its operation in year 2017. The minimum cut-off grades were 0.10%Cu for the leaching plant and 0.18%Cu for the concentrator plant. APPENDIX C presents the cut-off grades per year for each plant.

Figure 14 shows mine operational levels, which started its regimen in 2018, with around 33,000[kton] per year, until 2026 when mine production began to decrease. It also shows an anomaly in year 2022, when mine production had an abrupt drop, which was not of concern as it occurred in the 8<sup>th</sup> year of mine production, when hauling fleet reached its operational life. Thus, it was planned to renew the hauling fleet close to the date, where the drop in mine production was produced, process that considered the decrease in production. Furthermore, this abrupt drop in mine production was accepted as the mine plan was not the main focus of this thesis.

Table 14: DeepMine Phases Scheduling

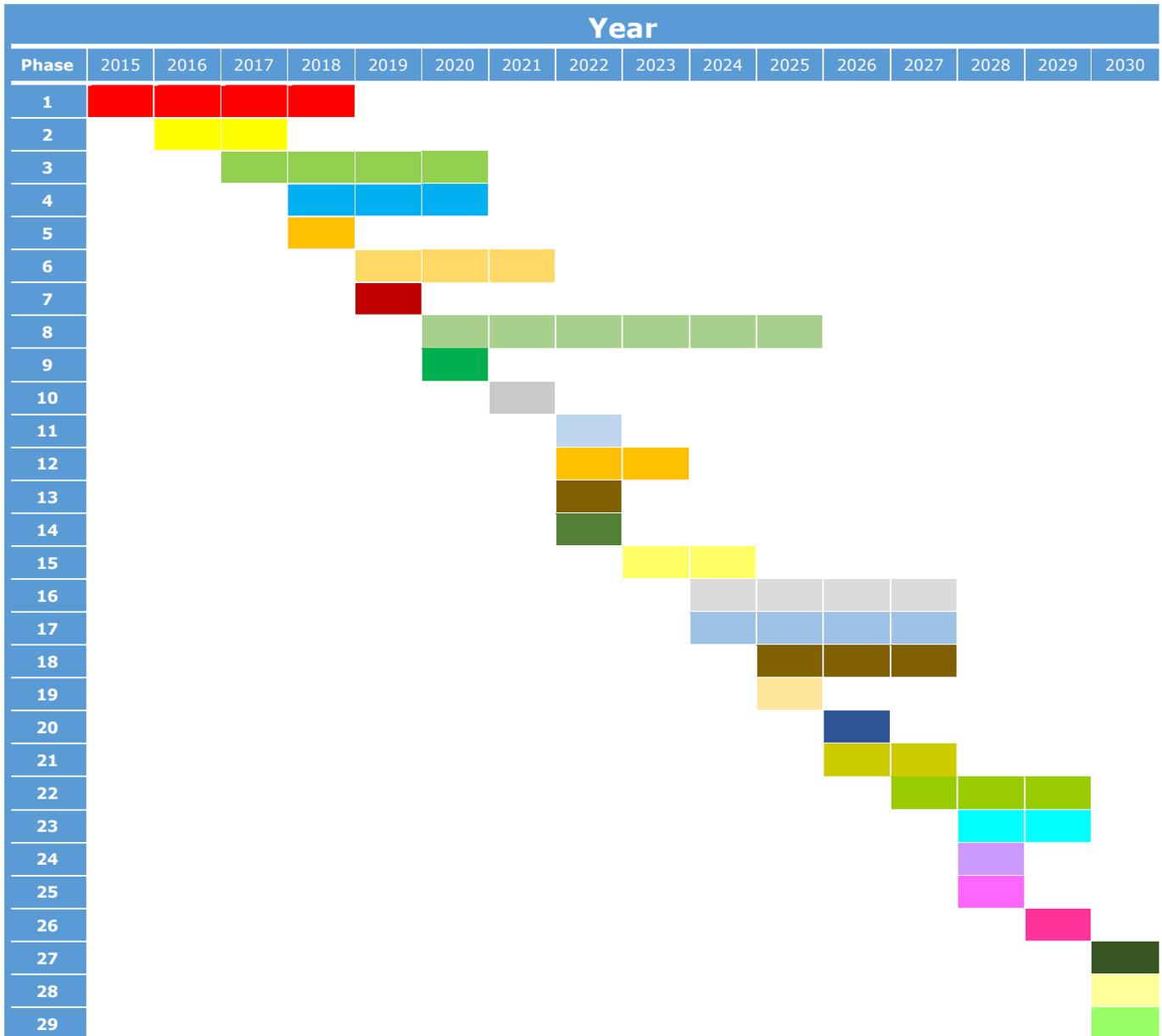


Figure. D.1 and Figure. D.2, which show operations for both plants over time can be found in APPENDIX D.

In terms of the economic value, DeepMine results established a project’s NPV of 644.27[MMUS\$]. However, this value did not consider capital expenses; investments in the mine, leaching plant and concentrator plant construction. This simplification facilitated the iteration process that led to the described results.

However, the investments were incorporated in the manual calculations of the new NPV values as follows:

1. 142.11[MMUS\$] for mine's capital expenses in year 2014.
2. 148.07[MMUS\$] for leaching plant's capital expenses in year 2014.
3. 167.47[MMUS\$] for concentrator plant's capital expenses in year 2016.

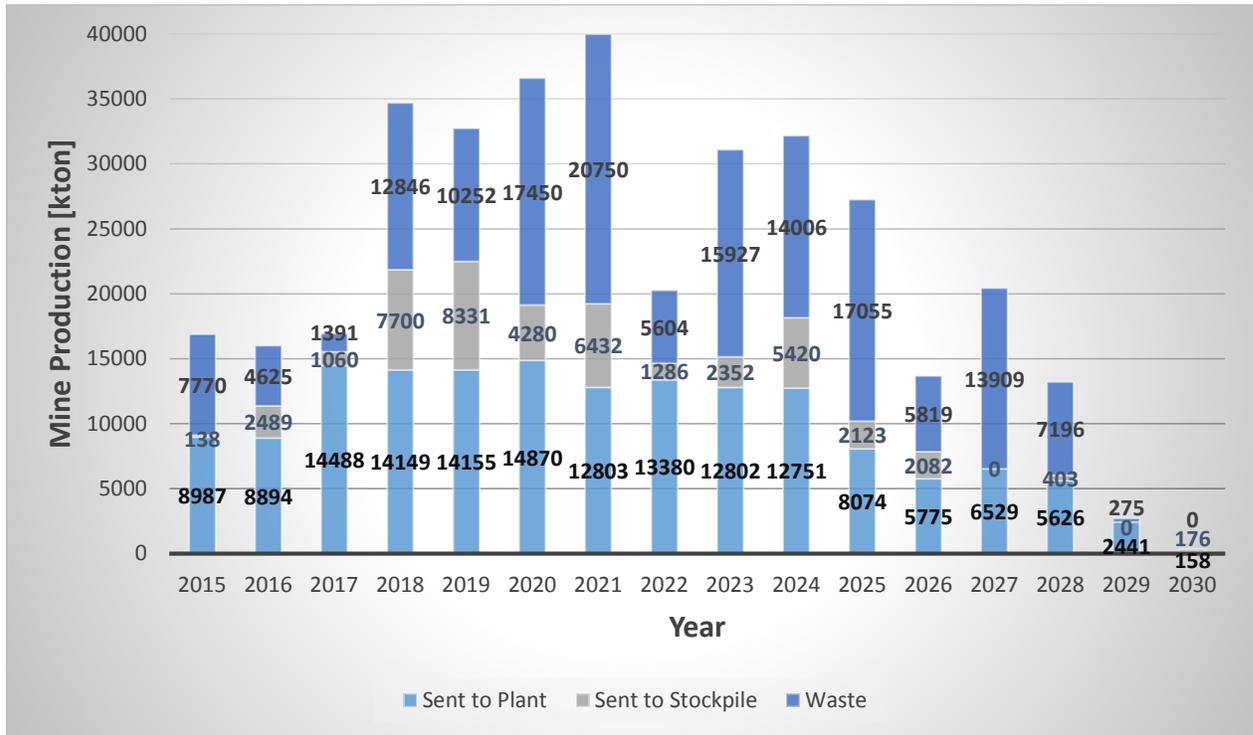


Figure 14: Mine Operation

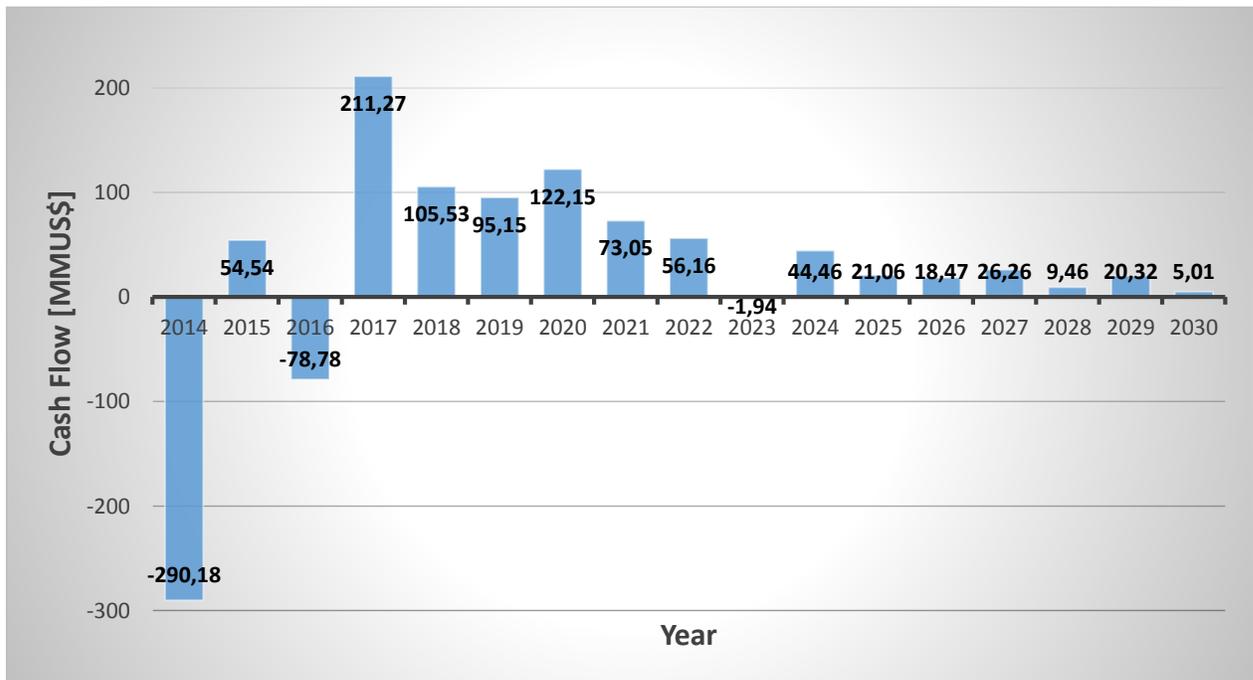


Figure 15: Final Cash Flow

Therefore, the NPV was calculated to be 210.51[MMUS\$]. Figure 15 shows the final cash flow of the project, which considers capital expenses for the mine and plants.

#### **4.2.8. Resulting Phases**

Generated phases were analysed considering two main aspects: geometry and extraction period.

With respect to the geometry, several disperse phases composed of isolated blocks and phases formed by too few blocks to be operationally feasible were found. Both cases represented a major problem for mine's operations, which needed to be solved to generate an operative open pit.

Adjacent phases that were planned to be extracted in the same period or in sequence were also found. There was no reason to have those phases as separate pushbacks as they would have complicated the extraction of the mine adding unnecessary phases and creating scheduling problems.

Hence, a modification and/or a merger of phases presenting problems in terms of geometry an extraction period was made. APPENDIX E presents isometric views of all 29 phases generated by DeepMine arranged by their extraction sequence.

#### **4.3. Pushbacks Design**

The phases' geometries that had to be modified and/or merged into bigger and continuous pushbacks were constructed using Vulcan.

Each phase' size, its position within the block model and the year when they were planned to be extracted was analysed. It is assumed that the mine plan and economic revenue would not suffer major changes as a result of this process as the period in which every phase was planned to be extracted remained the same and no blocks were added or erased from the phases. The process also maintained bench height (15 meters) and overall slope angles defined in DeepMine. Berms design was not considered and bench face angle remained vertical as it was defined by blocks' faces.

The modifications produced 12 phases as follow (see APPENDIX E for further information regarding this process):

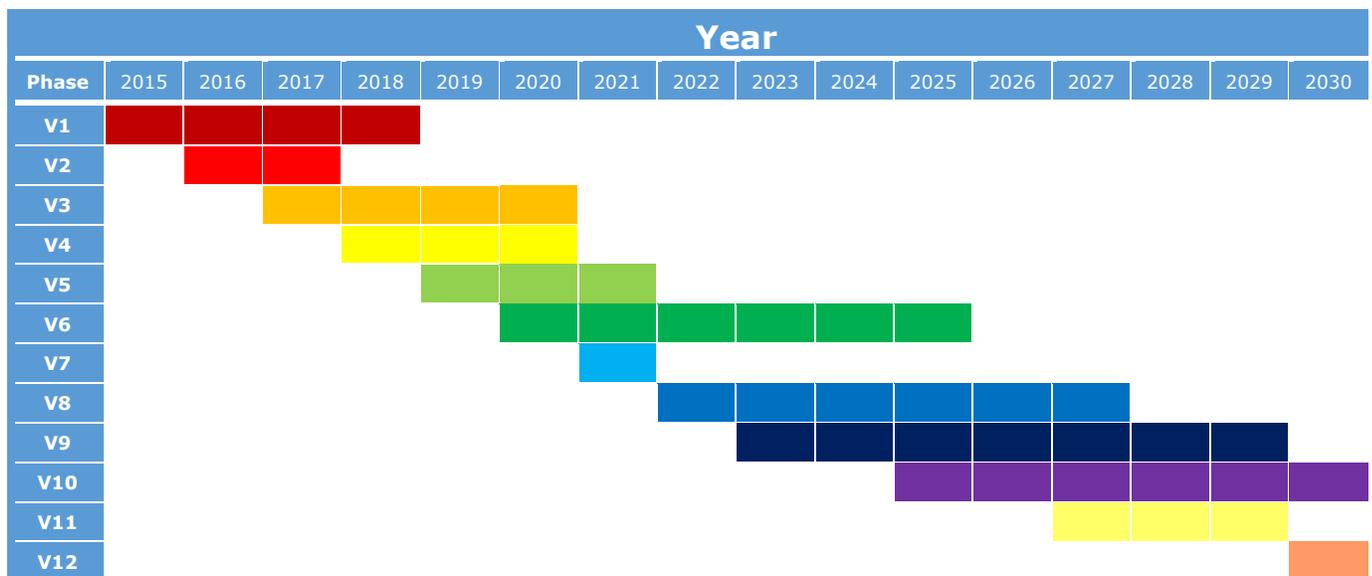
1. Phase V1: It was formed by DeepMine's phase 01 plus the narrow portions of phase 02 and one isolated block form phase 03.
2. Phase V2: It was formed by DeepMine's phase 02 without its narrow portions.

3. Phase V3: It was formed by merging phase 05 with phase 03 without the isolated block that was added to phase V1.
4. Phase V4: It was formed by DeepMine’s phase 04 without their isolated blocks.
5. Phase V5: It was formed by merging the phases 06, 07 and 09 plus the isolated blocks from phase 04.
6. Phase V6: It was formed by merging the phases 08, 11 and 14, and adding an isolated block from phase 16.
7. Phase V7: It was formed by DeepMine’s phase 10.
8. Phase V8: It was formed by merging the phases 12, 13 and 17.
9. Phase V9: It was formed by merging the phases 15, 16, 23 and 25.
10. Phase V10: It was formed by merging the phases 18, 19, 20, 21, 24, 26, 27 and 28.
11. Phase V11: It was formed by phase 22.
12. Phase V12: It was formed by phase 29.

This process ended with the extraction of the mine scheduled as shown in Table 15.

APPENDIX F presents isometric views of the 12 phases.

**Table 15: Redefined Phases Scheduling**



#### 4.4. Chapter Summary

This chapter presented the development of a mine plan for the extraction of a theoretical orebody. The process was developed using the software DeepMine with a model composed of 69,984 blocks containing information about copper grades with an average grade of 0.16[%Cu] for the entire

orebody. The mine plan called for the duration of 16 years divided into 12 phases.

## **CHAPTER 5**

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### **DESIGN OF A SLOPE DEFORMATION MONITORING CAMPAIGN PRIOR TO MINE CONSTRUCTION**

Drilling campaigns are commonly performed to understand the mechanisms involved in mine slopes failure. This campaigns are carried out after failure has occurred aiming to gather data, such as UCS values, and for structural analyses to be used as input for back analyses and redefinition of geotechnical domains. It does not have preventive value and does not study the actual rock mass' behaviour under mining conditions. Therefore, open pit mines' geotechnical monitoring always responds to processes or failures observed as mining develops. It is a reactive response and, thus, it does not capture the development of the whole failure, as the process triggering the observed failure has been occurring for a long time and all data from this development period has already been lost. Furthermore, the data, if obtained, is not transformed into information that can be used to reassess or redesign mine slopes for future pushbacks. For example, when steepening slope angles in geotechnical domains, where rock mass behaves outstandingly and where, if slope angle is increased by few degrees, tens of millions tonnes of waste material may not be extracted from the mine producing important savings in mine costs. This could extend mine's lifespan or allow economical extraction of new marginal, superficial orebodies.

To overcome the gap in the knowledge about rock mass behaviour before failure, mines' geotechnical monitoring should be considered and designed from feasibility stages of the project. In this Chapter, monitoring campaigns to register subsurface rock mass deformation will be designed considering mine's pushbacks geometry and mine plan throughout mine's lifespan.

The objective of this Chapter is to design instrumentation campaigns for subsurface rock mass deformation monitoring using three different instruments: Networked Smart Markers (NSM), In-Place Inclinometers (IPI) and ShapeAccelArrays (SAAs). The mine plan and the geometry of mine's phases (project conditions) will be used as guidance to determine where and how to deploy the instruments to achieve the best results from the monitoring campaigns designed towards better assessment of mine slope stability.

#### **5.1. Monitoring Campaign Design**

The nature of the project to be instrumented has been described from the mine planning perspective in Chapter 4. Due to the scale of the phases to be monitored (rock mass scale), the failure mode of interest corresponds to rock mass failures. Toppling, wedge and plane failure (structurally controlled

failures) are less likely to be detected by the proposed campaigns, since there are better techniques to do this, such as, visual inspection and various surface deformation monitoring techniques.

### **5.1.1. Aspects to Be Assessed**

Every geotechnical instrumentation campaign has to be designed to answer specific questions relative to ground performance, i.e. it has to have a purpose. To define the questions that justify the implementation of instrumentation campaigns in open pit mining, the effort was focused on the biggest concerns of mining industry and particularly of open pit mines operations: safety and competitiveness.

From the safety perspective, the main concern is pit slope performance and stability. Thus, the following questions arose:

1. What is the initial geotechnical condition of the rock mass prior to slope construction?
2. Do the mine slopes constructed in complex areas perform satisfactorily during all of mine's operational lifespan?
3. Do final pit slopes perform satisfactorily until the end of mine operations?

These questions focus the efforts on monitoring slopes constructed in the worsts geotechnical domains and, since long term Factors of Safety are difficult to assess, also on the slope with the longest service life to account for the loss of competence experimented by the rock mass degradation process.

With respect to competitiveness, to lower the operational costs is a common alternative, which can be achieved by steepening slope angles to diminish waste extraction. However, this solution requires a good understanding of ground performance which leads to the question:

1. Is it possible to steepen the slope angle while maintaining low risks conditions for personnel and operational safety?

This question led to the instrumentation of the walls with greater potential for steeper slopes' angles, i.e. slopes with shallower angles initially.

Therefore, the selection of critical sectors of the mine was led to monitor slopes constructed in the worsts geotechnical domains, the slope with the longest service life and slopes with shallower angles. The monitoring might also allow fulfilling other purposes not considered as main goals of this monitoring campaign, such as, assessing whether slopes' constructions

sequences are adequate, identifying excessive deformation and/or heave and identifying unforeseen hazards.

### **5.1.2. Parameter to Be Measured**

In open pit mining projects, it is difficult to determine whether a slope is performing safely, since failure processes not only depend on rock mass strength but also on the type of failure under development. Thus, it was decided to measure subsurface deformations as, depending on its progression, subsurface deformations can indicate the development of non-daylighting failures and allows detection of developing failures prior to the observation of any sign of failure on the surface. This might also allow to undertake corrective measures before the failure becomes imminent.

The rock mass's behaviour greatly varies from one project to another and also within the same open pit project. Thus, it is important to answer the first question to have reference values and to define warning levels and safety thresholds: What is the initial geotechnical condition of the rock mass prior to slope construction for each project?

Three different instruments were considered to fulfil the purpose of this campaign: an established technology, the In-Place Inclinometers (IPI); a technology that is starting to be utilized in mining projects, the ShapeAccelArrays (SAAs); and a novel technology, the Networked Smart Markers (NSM).

### **5.1.3. Remedial Measurements**

If it is identified that a certain pit slope is not performing safely, remedial measurements have to be undertaken. These measurements have to be defined beforehand and could consider:

1. Evacuation of the sector.
2. Reduction of slope's angle.
3. Removal of overburden.
4. Redesign of mine slopes.
5. Construction of catch berms.
6. Closure and abandonment of the sector.

### **5.1.4. Critical Sectors Selection**

The sectors of the open pit to be instrumented were selected following the criteria explained in Section 5.1 and by answering the questions raised in that Section under Point 5.1.1.

For safety concerns, it was decided to instrument the south-western part of phase V1 to account for the understanding of the initial conditions of the poorest quality rock mass.

In an attempt to account for the assessment to steepen slope angles in future phases, it was decided to monitor the southern part of phase V4, as this was one of the shallowest slopes in the pit. The data acquired from these sectors could influence steepening neighbouring phases V5, V6, V9 and/or V10. Data gathered from monitoring phase V1, at early stages of the project, could also be used to fulfil this purpose, as this phase was also located in poor quality rock mass and presented the shallowest slope angle. Then, the instrumentation installed to monitor phase V1 could help in assessing safety concerns and steepening of the slopes.

To assess long term stability, attention was placed on phases V8, V9, V10 and V11, as those phases unveil the final pit's wall. Particularly, the northern side of phase V8 was selected as a critical area, since it is the first phase to unveil the final pit's wall. Furthermore, this portion of the pit's final wall is the longest standing one: nine (9) years from the moment it starts to be unveiled and four (4) years from the moment it is totally uncovered, lasting in operation until mine's closure (year 2030). Another aspect taken into consideration when selecting phase V8 over the others was that phase V8 unveiled the steepest side of the pit's final wall, which made it the less conservatively designed pit slope.

Some areas of particular concern for stability are convex pit walls (bullnoses), as those sectors experiment a stress relaxation due to a lack of confinement. This situation reduces rock mass strength and cause instability problems.

Pit's walls uncovered by the extraction of phase V4 and phase V9 presented such condition; hence, both sectors were selected as critical areas to be instrumented. In phase V4, only surface monitoring was advised for bullnoses as they remain in service for less than one year and do not cover the whole depth of the pit at this stage. On the other hand, the bullnoses in the eastern wall of phase V9 remained in service for more than 3 years until the end of mine's operations along the entire depth of the final pit. Thus, subsurface deformation monitoring was advised and will be described further on.

The monitoring plan of all the selected sectors fulfilled the objectives established in Section 5.1, point 5.1.1 and provided a possibility to also study the sectors adjacent to the monitored areas.

Therefore, two campaigns were design: a shallow angle boreholes campaign (IPIs and NSMs) and a steep angle boreholes campaign (IPIs, SAAs and NSMs).

The shallow angle boreholes campaign considered boreholes that followed the inclination of pit's walls, instrumented using NSMs and IPIs. This campaign assured a relatively constant distance from every borehole to the pit's wall regardless of the depth.

The steep angle boreholes campaign was intended to allow a comparison among NSMs, IPIs and ShapeAccelArrays (SAAs), which would have required boreholes dipping at around  $60^\circ$  and that moved farther from the pit's wall as depth increased.

### 5.1.5. Shallow Angle Boreholes Instrumentation Campaigns

The shallow angle boreholes campaign had intended to entirely fulfil the purpose described before trying to understand the rock mass behaviour by monitoring mine slopes at full scale. Therefore, the campaign was designed to capture information of the entire relaxation (decompression) process experienced by the rock mass as each phase was extracted, exposing the limits of a subsequent phase. It also intended to register the eventual initiation of rock mass failures at the deeper portion of a slope.

Hence, for this purpose, the instruments were deployed inside incline boreholes located 10 meters behind the external limit of the phase before phase's extraction began, as shown in Figure 16.

The 10-meter distance had to be measured after considering the berm width, otherwise the drill holes might have outcrop. Boreholes had to be inclined to follow slope's inclination to allow the instruments to capture useful data. If vertical boreholes were used, the deepest instruments will be installed more than two hundred meters behind pit's wall were no displacements were expected to develop.

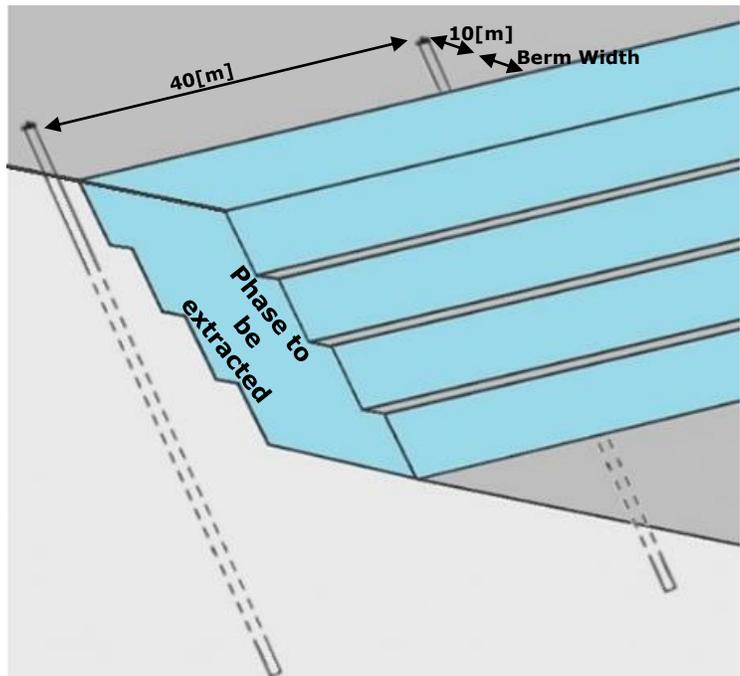


Figure 16: Boreholes' Layout

The boreholes had to be drilled up to 15 meters (measured vertically) below the deepest bench in the phase to be monitored. This allowed to install several instruments in a portion of the rock mass not directly affected by the relaxation process experienced by the rock as the phase was extracted. These instruments would then gather data that would be used to contrast the data obtained in the zone influenced by the extraction of the phase as a mean to assure data correctness.

To define the separation between instrumented boreholes, an influence area was established, over the pit's wall, of 2,000 square meters as a failure area of concern for mine's operation and safety. The relaxation process is a transitional state of the rock mass and is highly dependent on the transition zone between the exposed pit wall and the intact material i.e. around the blasted material zone (approximately 15 meters high). Then the influence zone of every instrumented boreholes moves down the wall as it is being exposed. This prompted the definition of a mobile influence zone 50 meters high, 40 meters wide and moving vertically down the pit's wall centred in the transition between intact material and exposed wall. Hence, the separation between boreholes was defined at 40 meters (Figure 16).

In addition, if rock mass failures are assumed to be a great scale circular failures, the proposed layout was still able to register the occurrence of the most dangerous failures. Furthermore, if a circular failure of 2,000 square meters footprint on the slope (approximately 25 meters radius) had developed between two instrumented boreholes, both drill holes would have been able to register the displacements produced by the developing failure.

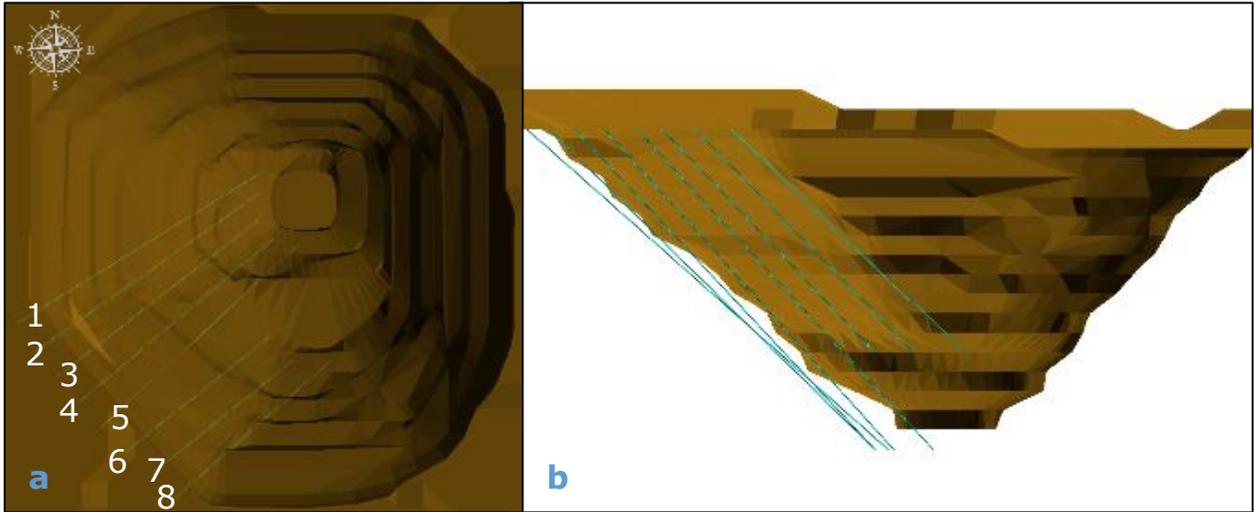
This shallow angle boreholes campaign would require to drill boreholes dipping at around 40°. Thus, ShapeAccelArrays (SAAs), was not a feasible alternative as they had to slide in the borehole under the force of gravity, which limits boreholes' dipping angle to a minimum of approximately 60°. Subsequently, the proposed campaign was only feasible using In-place Inclinometers (IPI) that could be placed into position using placement tubes and using Networked Smart Markers (NSMs), discrete devices (not a string per se), which could be pushed inside the boreholes to their final position.

#### *5.1.5.1. Phase V1 Monitoring – Shallow Angle Boreholes' Layout*

To monitor phase V1, boreholes were drilled 10 meters behind the limits of this phase in its south-western part, considering the berm width in the crest of the slope, as shown in Figure 16. This was in the area, where phase V3 was located, as shown and enumerated in Figure 17(a) showing the pit after the extraction of phase V1. Figure 17(b) also shows the drill holes in a vertical section looking north. The separation between boreholes diminished with depth due to the geometry of the sector. Borehole's deepest ends were

separated by 30.3 meters (boreholes 1 to 5) and 40 meters for boreholes 6, 7 and 8.

This sector of the pit covered a length of 320[m] measured at the crest of the slope and thus would have needed 8 boreholes to be monitored. The characteristics of each borehole are listed in Table 16. Where length represents the distance between both ends of each borehole.



**Figure 17: Boreholes' Layout in Plan View (a) – Boreholes' Layout Looking North (b) – Shallow Angle Boreholes Campaign Phase V1**

**Table 16: Boreholes' Characteristics – Shallow Angle Boreholes Campaign Phase V1**

Borehole	Height [m]	Length [m]	Angle of Dip
1	277.50	439.64	39.14°
2	277.50	423.39	40.95°
3	277.50	411.95	42.35°
4	277.50	409.64	42.64°
5	277.50	424.98	40.77°
6	192.96	290.35	41.65°
7	187.50	285.90	40.98°
8	187.50	307.20	37.61°

### 5.1.5.2. Phase V4 Monitoring – Shallow Angle Boreholes’ Layout

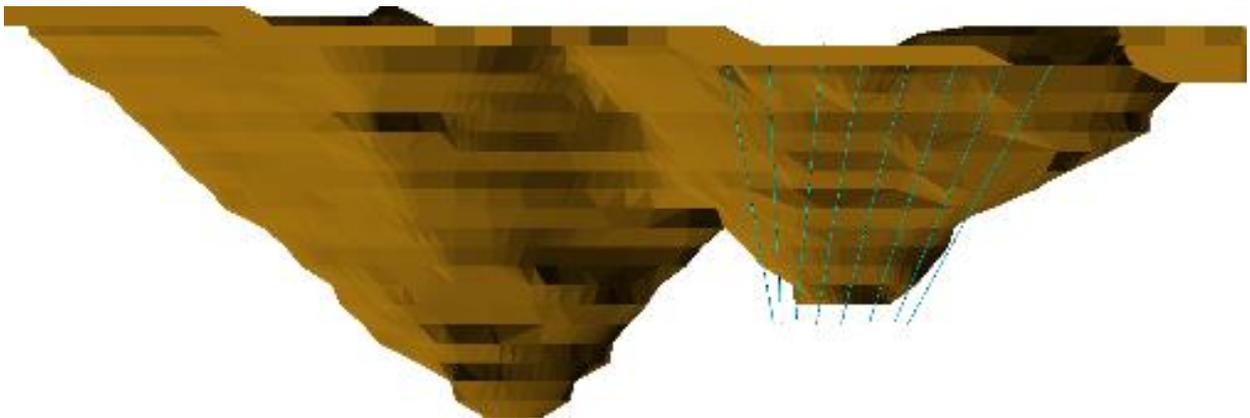
To monitor phase V4, boreholes were drilled 10 meters behind the limits of the phase in its southern part, as shown in Figure 16, i.e. considering the berm width in the crest of the slope, which occurred in phase V5 (southern part of the pit), as shown in Figure 18. Figure 19 shows a vertical section looking north to better understand the boreholes’ layout.

This sector of phase V5 covered a length of 320[m] and thus will require 8 boreholes to be monitored. The characteristics of each borehole are listed in Table 17.

Boreholes in this sector also decreased their separation as depth increased. Thus, all the boreholes were separated by 21.7 meters at their deepest end.



**Figure 18: Boreholes’ Layout in Plan View – Shallow Angle Boreholes Campaign Phase V4**



**Figure 19: Boreholes’ Layout Looking North – Shallow Angle Boreholes Campaign Phase V4**

**Table 17: Boreholes' Characteristics – Shallow Angle Boreholes Campaign Phase V4**

Borehole	Height [m]	Length [m]	Angle of Dip
9	227.57	376.85	37.15°
10	217.50	352.28	38.13°
11	217.50	349.70	38.46°
12	215.18	347.84	38.22°
13	202.50	316.86	39.72°
14	202.50	313.00	40.31°
15	202.50	322.83	38.85°
16	202.50	342.64	36.23°

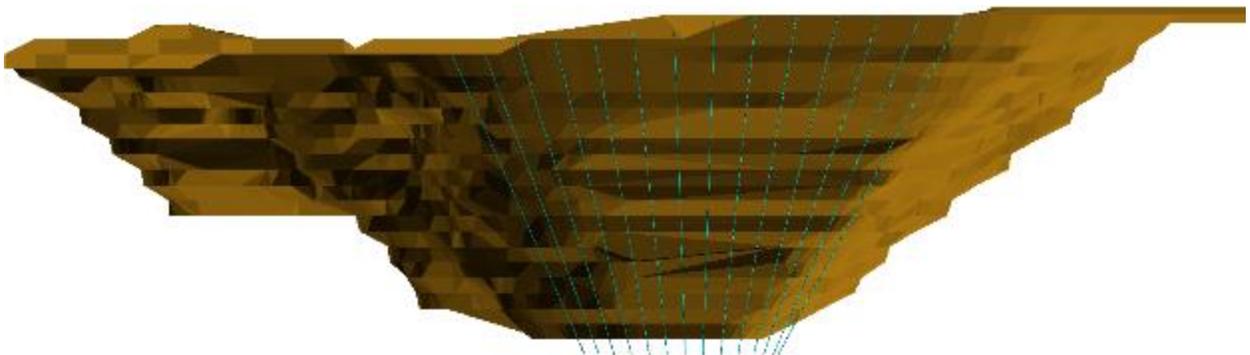
**5.1.5.3. Phase V8 Monitoring – Shallow Angle Boreholes' Layout**

To monitor phase V8, boreholes were drilled 10 meters behind the limits of this phase in its northern part, as shown in Figure 16, considering the berm width in the crest of the slope. The sector was located outside of the final pit's northern limit, as shown in Figure 20. Figure 21 shows the drill holes in a vertical section looking south.

This particular sector of the pit wall covered a length of 561[m] along the crest of the slope and thus needed 14 boreholes to be monitored. The characteristics of each borehole are listed in Table 18.



**Figure 20: Boreholes' Layout in Plan View – Shallow Angle Boreholes Campaign Phase V8**



**Figure 21: Boreholes' Layout Looking South – Shallow Angle Boreholes Campaign Phase V8**

Again, the separation of the boreholes decreased with depth up to 17.4 meters at their deepest end.

**Table 18: Boreholes' Characteristics – Shallow Angle Boreholes Campaign Phase V8**

Borehole	Height [m]	Length [m]	Angle of Dip
17	330.00	495.18	41.79°
18	330.00	475.22	43.98°
19	330.00	458.11	46.08°
20	330.00	442.71	48.19°
21	330.00	433.30	49.61°
22	330.00	428.58	50.35°
23	326.28	422.21	50.60°
24	313.14	404.09	50.80°
25	312.43	402.43	50.93°
26	310.49	397.09	51.44°
27	308.49	393.10	51.70°
28	307.50	392.35	51.60°
29	292.50	374.65	51.33°
30	292.50	374.90	51.28°

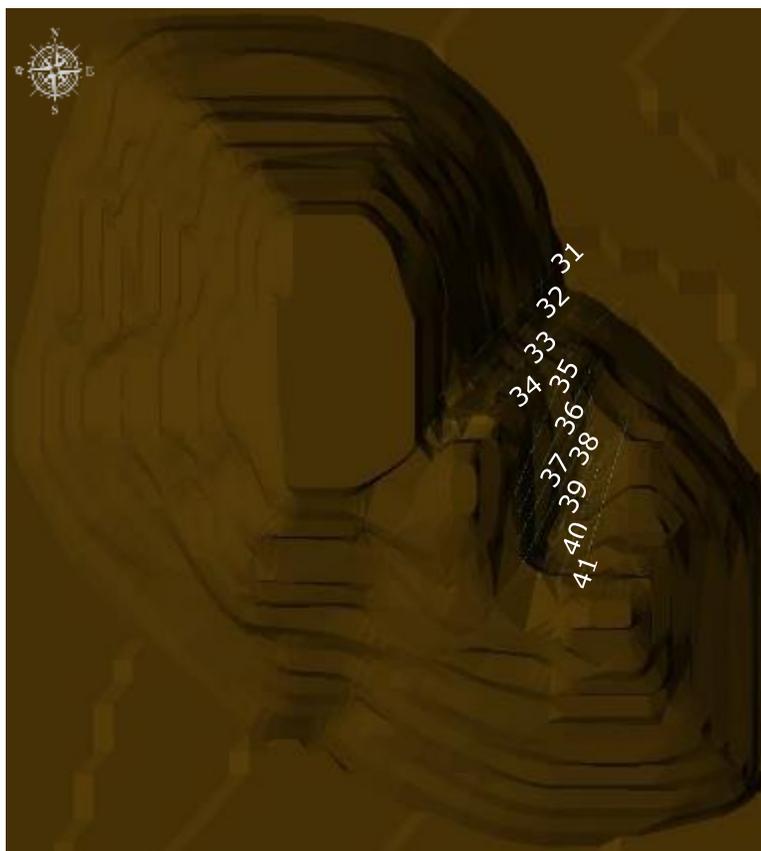
**5.1.5.4. *Phase V9 Monitoring – Shallow Angle Boreholes' Layout***

To monitor phase V9 boreholes were drilled 10 meters behind the limits of this phase, as shown in Figure 16, considering the berm width in the crest of the slope. This was in the bullnose located in the eastern wall of the open pit and outside the final pit's wall, as shown in Figure 23 (plan view). Figure 22 shows the drill holes in a vertical section looking south.

This sector of the mine covered a length of 440[m] divided in two different areas (two bullnoses) and thus needed 11 boreholes to be monitored.



**Figure 22: Boreholes' Layout Looking South – Shallow Angle Boreholes Campaign Phase V9**



**Figure 23: Boreholes' Layout – Shallow Angle Boreholes Campaign Phase V9**

The characteristics of each borehole are listed in Table 19 (borehole's deepest end separation is 37.8 meters for boreholes 31 to 34 and 31.7 meters for boreholes 35 to 41).

**Table 19: Boreholes' Characteristics – Shallow Angle Boreholes Campaign Phase V9**

Borehole	Height [m]	Length [m]	Angle of Dip
31	318.06	441.08	46.14°
32	322.50	450.59	45.70°
33	322.50	462.93	44.16°
34	322.50	447.35	46.13°
35	120.00	241.45	29.80°
36	120.00	262.24	27.23°
37	120.00	255.24	28.04°
38	120.00	244.19	29.43°
39	120.00	214.81	33.96°
40	120.00	236.29	30.52°
41	120.00	255.61	28.00°

For further references on critical sectors selection and plan views of all mine’s pit geometries, after the extraction of every phase, can be found in APPENDIX G.

**5.1.5.5. Shallow Angle Boreholes’ Drilling Campaign Summary**

In summary, a total of 41 boreholes had to be drilled in four stages. These stages were defined by the year when the phase to be monitored started to be extracted. Boreholes had to be drilled the year before the extraction of the phase to be monitored starts.

The entire shallow angle boreholes campaign totalized 15,120.75 meters to be drilled and an investment around 4,536,000[US\$], as shown in Table 20, considering the cost of 300[US\$] per drilled meter.

**Table 20: Shallow Angle Boreholes Campaign Drilling Summary**

Phase	Total Number of Boreholes	Meters to be Drilled [m]	Total Cost [US\$]
V1	8	2,993.05	897,915
V4	8	2,722.00	816,600
V8	14	5,893.92	1,768,176
V9	11	3,511.78	1,053,534
<b>Total</b>	<b>41</b>	<b>15,120.75</b>	<b>4,536,225</b>

**5.1.5.6. In-Place Inclinometers (IPIs) Shallow Angle Boreholes Installation**

In-Place Inclinometers (IPI) are a proven technology used to register subsurface displacement along a borehole with a high level of precision and resolution at a millimetre scale. However, they can only monitor displacement in boreholes up to 100-meter long. In addition, it is not feasible to install more than three IPI arrays in the same borehole due to constrains related to borehole’s casing and the space to accommodate the instruments and cables placed beside them within the hole. Furthermore, IPI cannot resist the effects of nearby blasting and is not possible to retrieve them from the boreholes once the casing starts to bend due to rock mass deformations.

These IPI characteristics forced modifications within the ideal plan for the monitoring campaign, which considered the instrumentation of the slope prior to its construction. Firstly, as IPI have a maximum monitoring length of 100 meters, only the deepest 100 meters of every borehole will be instrumented, which aims to detect the initiation of a potential great scale failure. Secondly, the devices had to be installed after the wall was completely exposed to avoid IPI’s damage due to blasting. These constrains makes it impossible to monitor Phases V1 and V4 as the phases where the instruments have to be deployed (V3 and V5 respectively) start to be extracted before the

walls unveiled by phase V1 and V4 are fully exposed. Table 21 presents the starting date for the monitoring period and the end of this period and summarizes the period of time that every phase could be monitored using IPIs.

**Table 21: Monitoring Time Span – IPI’s Shallow Angle Boreholes Campaign**

Phase	Start of Monitoring Period	End of Monitoring Period	Monitoring Feasibility	Monitoring Time Span [Years]
V1	End of 2018	Beginning of 2017	Not Feasible	0
V4	End of 2020	Beginning of 2019	Not Feasible	0
V8	End of 2027	End of 2030	Feasible	3
V9	End of 2029	End of 2030	Feasible	1

Table 22 presents the number of 100-meter long IPI strings that will be required to monitor every critical sector and the number of 2-meter long sensors composing these IPI strings. However, to simplify the installation, IPI’s had to be installed as 3 separate strings in each borehole. The deepest string was composed of 10 sensors and the remaining 2 strings composed of 20 sensors.

**Table 22: IPI Strings and Sensors Required in a Shallow Angle Boreholes Campaign**

Phase	Quantity of IPI Strings	Quantity of Sensors
V8	42	700
V9	33	550
<b>Total</b>	<b>41</b>	<b>1,250</b>

**5.1.5.7. In-Place Inclometers’ (IPIs) Shallow Angle Boreholes Campaign Costs**

To estimate the cost of this particular campaign configuration, the following factors were considered:

1. The IPIs to be installed in each borehole were divided in 3 strings to ease the installation due to the low borehole’s inclination.
2. The deepest string was composed of 10 sensors, the middle string of 20 sensors and the upper-most string of 20 sensors, totalling 50 sensors in a 100-meter length IPI.
3. The inclinometer casing was installed along the entire length of the borehole.
4. Placement tubing was used to place the 3 strings in every boreholes.

5. Each string was connected to a datalogger (located 100 meters away from slope’s crest) using its own signal cable.
6. Signal cables running from each borehole’s collar to the datalogger were protected inside galvanized conduit pipes.
7. Each datalogger can gather data from a maximum of 5 IPI strings.

These consideration were used in calculating the monitoring cost as shown in Table 23. This cost does not include drilling cost.

**Table 23: In-Place Inclinometer’s Shallow Angle Boreholes Campaign Instrumentation Costs**

Phase	Investment Year	Instrumentation Cost [US\$]
V8	End of 2027	1,288,976
V9	End of 2029	921,412
<b>Total</b>	-	<b>2,210,387</b>

For more detail information about In-Place Inclinometers’ shallow angle boreholes campaign costs calculation see APPENDIX H.

**5.1.5.8. Networked Smart Markers Shallow Angle Boreholes Installation**

Network Smart Marker is a sensing platform that allows registering different variables of the rock mass while installed in vertical, incline or horizontal boreholes. The variables that this instrument can register depends on the sensors embedded in each device. For example, subsurface displacements can be measured using MEMS accelerometers and magnetometer or groundwater pressure by using piezometers.

Since NSMs can communicate with each other wirelessly using radio frequency signals, they can be installed to any depth as long as the spacing between NSMs does not exceed their communication range. Designed to be blasting resistant, they can be installed prior to the construction of the pit’s wall to be monitored, thus registering deformations that account for the relaxation process experienced by the rock mass due to: the extraction of material, weathering of the rock mass (induced deformations), blasting damage and/or unknown causes. This characteristics allow to cover all the requirements of the shallow angle boreholes monitoring campaign proposed in this work.

Table 24 presents the starting date for the monitoring period and the end of this period.

**Table 24: Monitoring Time Span – NSM’s Shallow Angle Boreholes Campaign**

Phase	Start of Monitoring Period	End of Monitoring Period	Monitoring Feasibility	Monitoring Time Span [Years]
V1	End of 2014	Beginning of 2017	Feasible	2
V4	End of 2017	Beginning of 2019	Feasible	1
V8	End of 2021	End of 2030	Feasible	9
V9	Ends of 2022	End of 2030	Feasible	8

Two different campaign settings were proposed. The first one considered an installation of one NSM every 2 meters inside every borehole. The other one considered the installation of one NSM every 4 meters in every borehole. A summary of both alternatives is presented in Table 25.

**Table 25: Quantity of NSM Required in a Shallow Angle Boreholes Campaign**

Phase	Quantity of NSMs (2-meter spacing)	Quantity of NSMs (4-meter spacing)
V1	1,491	743
V4	1,357	677
V8	2,942	1,467
V9	1,751	872
<b>Total</b>	<b>7,541</b>	<b>3,759</b>

APPENDIX I contains detailed information about quantities of NSMs per borehole in each phase.

#### 5.1.5.9. NSM’s Shallow Angle Boreholes Campaign Costs

The costs for this particular campaign were estimated taking the following assumptions:

1. The boreholes had a diameter of 11.43[cm] (4.5”).
2. The entire length of every drill hole was instrumented and monitored.
3. No casing was installed.
4. The devices were fully grouted in position within the borehole.
5. Each instrumented borehole has an antenna placed close to the collar, one meter below surface.
6. Every antenna is connected via cable to a splitter box with a maximum of 6 antennas per splitter box.
7. Each splitter box is connected via cable to a single reader station (datalogger) located 100 meter away from slope’s crest.
8. The signal cables running from each borehole’s collar to the splitter box and from there to the reader station are protected inside galvanized conduit pipes.

The costs presented in Table 26 were obtained based on these considerations; drilling costs were not considered.

**Table 26: Smart Marker’s Shallow Angle Boreholes Campaign Instrumentation Costs**

Phase	Investment Year	Instrumentation Cost (2-meter spacing) [US\$]	Instrumentation Cost (4-meter spacing) [US\$]
V1	End of 2014	809,789	689,796
V4	End of 2017	738,513	629,429
V8	End of 2021	1,587,734	1,351,117
V9	Ends of 2022	956,225	815,218
<b>Total</b>	-	<b>4,092,261</b>	<b>3,485,559</b>

Refer to APPENDIX J for further information about the costs calculation for the Smart Marker’s shallow angle boreholes campaign.

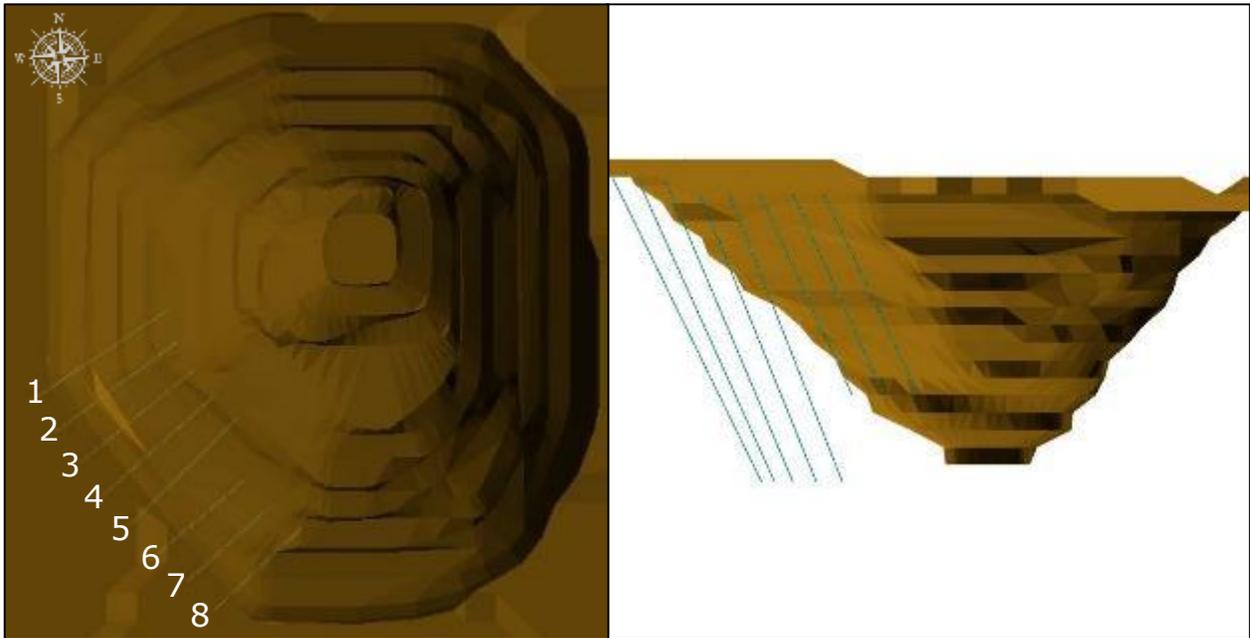
### **5.1.6. Steep Angle Boreholes Instrumentation Campaign**

Three different alternatives were considered as possible choices to monitor the slopes using a steep angle boreholes instrumentation campaign: a proven technology, In-Place Inclinometers (IPIs), an instrument that is starting to be utilized to monitor subsurface displacements in mining operations, the ShapeAccelArray (SAA) and a novel technology, the wireless Networked Smart Markers (NSMs).

Since the critical sectors selected were the same for the shallow angle boreholes and steep angle boreholes monitoring campaign, the location of all boreholes on the surface remained the same as well as their quantity. However, the angle of dip had to be restricted to a minimum of about 60° to avoid problems during the installation of the ShapeAccelArrays (SAAs). Thus, the position of all boreholes’ deepest end was changed, they were positioned further from the pit’s wall in the steep angle boreholes campaign as compared to the shallow angle boreholes scenario. Boreholes’ separation at their lowest end also changed and became more variable than in the shallow angle boreholes campaign setup.

#### **5.1.6.1. Phase V1 Monitoring – Steep Angle Boreholes’ Layout**

The steep angle boreholes monitoring campaign for Phase V1 required the development of eight (8) boreholes located in the south-wester part of the pit produced after the extraction of Phase V1 (Figure 24). Table 27 presents boreholes’ vertical height, total length from collar to bottom, dipping angle and the separation of the deepest end of every drill hole to the pit’s wall.



**Figure 24: Boreholes' Layout Plan View (Left) – Boreholes' Layout Looking North (Right) – Steep Angle Boreholes Campaign Phase V1**

**Table 27: Boreholes' Characteristics – Steep Angle Boreholes Campaign Phase V1**

Borehole	Height [m]	Length [m]	Angle of Dip	Deepest End's Distance to Wall
1	277.50	321.54	59.7°	175.78 [m]
2	277.50	318.12	60.7°	170.31 [m]
3	277.50	316.19	61.4°	169.15 [m]
4	277.50	315.80	61.5°	172.65 [m]
5	277.50	317.25	61.0°	178.40 [m]
6	192.96	225.56	58.8°	121.55 [m]
7	187.50	219.15	58.8°	121.43 [m]
8	187.50	223.25	57.1°	122.72 [m]

**5.1.6.2. Phase V4 Monitoring – Steep Angle Boreholes' Layout**

With regards to Phase V4, the steep angle boreholes campaign involved the instrumentation of eight (8) boreholes dipping between 62° and 56°, as shown in Figure 25. Boreholes' average separation from pit's wall, at its deepest end, was 152 meters. Table 28 summarizes the most relevant characteristics of these holes, such as, total length and dipping angle.



**Figure 25: Boreholes' Layout Plan View (Left) – Boreholes' Layout Looking North (Right) – Steep Angle Boreholes Campaign Phase V4**

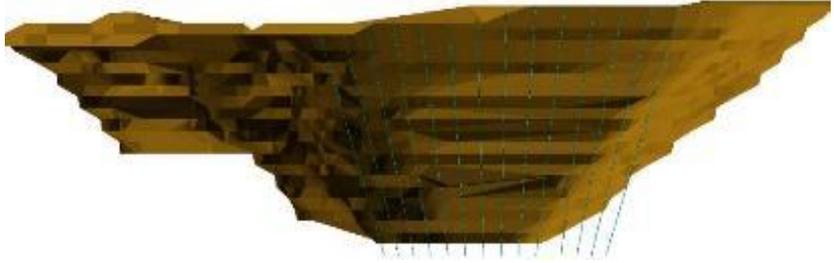
**Table 28: Boreholes' Characteristics – Steep Angle Boreholes Campaign Phase V4**

Borehole	Height [m]	Length [m]	Angle of Dip	Deepest End's Distance to Wall
<b>9</b>	227.57	261.02	60.7°	152.44
<b>10</b>	217.50	245.96	62.2°	151.71
<b>11</b>	217.50	249.24	60.8°	151.25
<b>12</b>	215.18	251.68	58.8°	151.21
<b>13</b>	202.50	230.06	61.7°	150.84
<b>14</b>	202.50	229.45	62.0°	150.95
<b>15</b>	202.50	234.91	59.5°	153.13
<b>16</b>	202.50	243.13	56.4°	153.25

5.1.6.3. Phase V8 Monitoring – Steep Angle Boreholes’ Layout

Phase V8 steep angle boreholes campaign required the drilling of 14 boreholes located as shown in Figure 26 and Figure 27.

The characteristics of these boreholes and the separation of their deepest end from the pit’s wall are presented in Table 29.



**Figure 26: Boreholes’ Layout Looking South – Steep Angle Boreholes Campaign Phase V8**



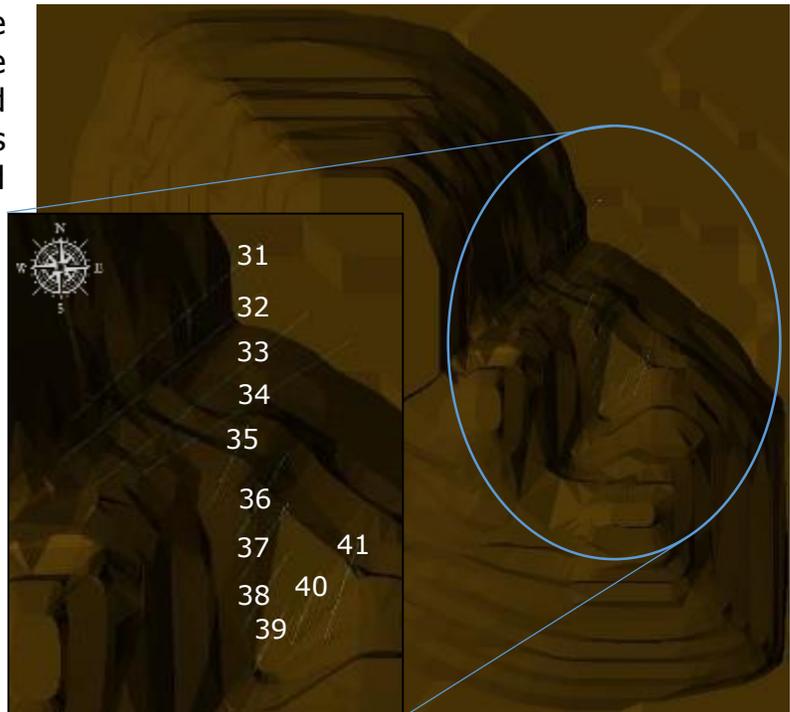
**Figure 27: Boreholes’ Layout Plan View – Steep Angle Boreholes Campaign Phase V8**

**Table 29: Boreholes' Characteristics – Steep Angle Boreholes Campaign Phase V8**

Borehole	Height [m]	Length [m]	Angle of Dip	Deepest End's Distance to Wall
17	330.00	393.57	57.0°	164.71 [m]
18	330.00	384.14	59.2°	157.50 [m]
19	330.00	374.65	61.7°	151.91 [m]
20	330.00	367.57	63.9°	150.77 [m]
21	330.00	388.05	58.3°	99.78 [m]
22	330.00	385.08	59.0°	96.11 [m]
23	326.28	379.02	59.4°	96.02 [m]
24	313.14	361.36	60.1°	95.77 [m]
25	312.43	359.57	60.3°	95.78 [m]
26	310.49	354.31	61.2°	96.13 [m]
27	308.49	351.26	61.4°	96.40 [m]
28	307.50	350.70	61.3°	96.01 [m]
29	292.50	332.58	61.6°	97.29 [m]
30	292.50	333.09	61.4°	95.61 [m]

**5.1.6.4. Phase V9 Monitoring – Steep Angle Boreholes' Layout**

With regards to Phase V9, the steep angle boreholes campaign involved the usage of 11 boreholes dipping between 64° and 57°. These drill holes were divided into two groups to monitor different bullnoses presented in the pit as shown in Figure 28 and Figure 29. Boreholes' average separation from pit's wall, at its deepest end, was 103 meters. Table 30 presents the most relevant characteristics of these eleven drill holes.



**Figure 28: Boreholes' Layout Plant View – Steep Angle Boreholes Campaign Phase V9**



**Figure 29: Boreholes' Layout Looking South – Steep Angle Boreholes Campaign Phase V9**

**Table 30: Boreholes' Characteristics – Steep Angle Boreholes Campaign Phase V9**

Borehole	Height [m]	Length [m]	Angle of Dip	Deepest End's Distance to Wall
31	318.06	376.05	57.8°	107.54 [m]
32	322.50	384.78	56.9°	97.28 [m]
33	322.50	393.14	55.1°	104.39 [m]
34	322.50	382.94	57.4°	125.59 [m]
35	120.00	138.68	59.9°	83.38 [m]
36	120.00	143.22	56.9°	87.76 [m]
37	120.00	139.07	59.6°	81.49 [m]
38	120.00	137.76	60.6°	89.30 [m]
39	120.00	133.35	64.1°	100.52 [m]
40	120.00	133.52	64.0°	126.95 [m]
41	120.00	141.88	57.8°	131.09 [m]

#### 5.1.6.5. Steep Angle Boreholes Drilling Campaign Summary

In summary, similarly to the shallow angle boreholes campaign, the steep angle boreholes campaign required a total of 41 boreholes to be drilled in four stages. These boreholes had to be drilled the year before the extraction of the phase to be monitored starts.

As shown in Table 31, the entire steep angle boreholes campaign totalled 15,120.75 meters to be drilled and an investment of around 4,536,000[US\$]. This value assumes a cost of 300[US\$] per drilled meter.

**Table 31: Steep Angle Boreholes Drilling Campaign Summary**

Phase	Total Number of Boreholes	Meters to be Drilled [m]	Total Cost [US\$]
V1	8	2,256.86	677,057
V4	8	1,945.45	583,634
V8	14	5,114.94	1,534,481
V9	11	2,504.40	751,319
<b>IPI Total</b>	<b>25</b>	<b>4,202.30</b>	<b>2,285,800</b>
<b>NSM Total</b>	<b>41</b>	<b>11,821.64</b>	<b>3,546,491</b>

#### 5.1.6.6. In-Place Inclinometers Steep Angle Boreholes Campaign Installation

Since all boreholes drilled for the steep angle boreholes monitoring campaign exceeded 100 meters, the number of IPIs to be used remained the same as for the shallow angle boreholes campaign (for further information check section 5.1.5.6).

However, as the boreholes were steeper than in the shallow angle boreholes campaign, it arose the possibility to monitor, partially, the deepest portion of phases V1 and V4 once phases V3 and V6 were completely extracted. Then, phase V1 could have been monitored once the extraction of phase V3 ended until the extraction of phase V6 began. Phase V4 could have been monitored when the extraction of phase V6 ended until the extraction of phase V9 began. Albeit, due to the scheduling of phases, this was not feasible, as shown in Table 32.

**Table 32: Monitoring Time Span – IPI’s and SAA’s Steep Angle Boreholes Campaign**

Phase	Start of Monitoring Period	End of Monitoring Period	Monitoring Feasibility	Monitoring Time Span [Years]
V1	End of 2020	Beginning of 2020	Not Feasible	0
V4	End of 2025	Beginning of 2023	Not Feasible	0
V8	End of 2027	End of 2030	Feasible	3
V9	End of 2029	End of 2030	Feasible	1

Therefore, the number of IPIs for the shallow angle boreholes and steep angle boreholes campaigns were the same.

#### 5.1.6.7. In-Place Inclinometer’s Steep Angle Boreholes Campaign Instrumentation Costs

To estimate the cost of this particular campaign configuration, the following factors were considered:

1. The IPIs to be installed in each borehole were divided in 3 strings to facilitate the installation, due to the low borehole’s inclination.

2. The deepest string was composed of 10 sensors, the middle string of 20 sensors and the upper-most string of 20 sensors, totalling 50 sensors in a 100-meter length IPI.
3. The casing was installed along the entire length of the borehole.
4. Placement tubing was used to place the 3 strings in every borehole.
5. Each string was connected to a datalogger (located 100 meters behind slope's crest) using its own signal cable.
6. Signal cables running from each borehole's collar to the datalogger were protected inside galvanized conduit pipes.
7. Each datalogger can gather data from a maximum of 5 strings.

These considerations were used in calculating the monitoring cost as shown in Table 33. This cost does not include drilling cost.

**Table 33: In-Place Inclinator's Steep Angle Boreholes Campaign Instrumentation Costs**

Phase	Investment Year	Instrumentation Cost [US\$]
V8	End of 2027	1,225,164
V9	End of 2029	838,890
<b>Total</b>	-	<b>2,064,054</b>

For more detail information about In-Place Inclinator's steep angle boreholes campaign costs calculation see APPENDIX K.

#### 5.1.6.8. ShapeAccelArrays Steep Angle Boreholes Campaign Installation

ShapeAccelArrays are relatively new instruments developed to register displacements in all directions perpendicular to a borehole's axis regardless of its angle of dip (inclination). However, due to technical constraints SAA cannot be installed in boreholes shallower than 60°.

These devices started to be applied in soils and now are being increasingly applied to monitor mine slopes. However, SAA cannot resist nearby blasting and has a maximum length of 100 meters.

These limitations of the SAA forced the modification of some of the aspects of the shallow angle boreholes monitoring campaign, which considers the instrumentation of the slope prior to its construction. Thus, drill holes will have to be drilled after the pit wall to be monitored is fully exposed, which makes it impossible to register the deformations produced by the relaxation process experimented by the rock mass as the wall is excavated.

Table 32 presents the starting date for the monitoring period and the end of this period defined by the date when the instrumented zone starts to be mined. These dates also define the feasibility to monitor a certain sector

using SAAs, as in some cases the phase where SAAs have to be located begins to be mined before the wall to be monitored is fully exposed.

To monitor a wall at full scale, several SAA have to be installed in sequence inside a single borehole. The lowest portion of the boreholes would be instrumented with 100-meter long SAA while the remaining portion (less than 100 meters) would be instrumented with a custom length SAA (uppermost SAA). Table 34 shows the quantity and length of the SAA to be installed, per phase and borehole.

**Table 34: SAA length and Quantity per Phase to be monitored**

Phase	Borehole	Quantity of 100-meter SAA	Uppermost SAA Length [m]	Total Quantity of SAA Strings
V8	17	3	93.5	4
	18	3	84.0	4
	19	3	74.5	4
	20	3	67.5	4
	21	3	88.0	4
	22	3	85.0	4
	23	3	79.0	4
	24	3	61.0	4
	25	3	59.5	4
	26	3	54.0	4
	27	3	51.0	4
	28	3	50.5	4
	29	3	32.5	4
	30	3	33.0	4
	<b>Total</b>	<b>42</b>	<b>-</b>	<b>56</b>
V9	31	3	76.0	4
	32	3	84.5	4
	33	3	93.0	4
	34	3	82.5	4
	35	1	38.5	2
	36	1	43.0	2
	37	1	39.0	2
	38	1	37.5	2
	39	1	33.0	2
	40	1	33.5	2
	41	1	41.5	2
	<b>Total</b>	<b>19</b>	<b>-</b>	<b>30</b>

APPENDIX L presents the number of MEMS sensors in every borehole using the described configuration of SAA.

#### 5.1.6.9. ShapeAccelArray's Steep Angle Boreholes Campaign Costs

SAA's cost estimation was performed considering the following assumptions:

1. HQ boreholes (96[mm] outer diameter) were considered for SAA installation.
2. No casing was required to install the devices in the boreholes.
3. A maximum of three (3) SAA strings were installed in each drill hole.
4. The entire length of each borehole was instrumented and monitored.
5. No especial hardware was required for the installation.
6. Each string was connected to a datalogger (located 100 meters away from slope's crest) using its own signal cable.
7. The signal cables running from each borehole's collar to the datalogger were protected inside galvanized conduit pipes.
8. Each datalogger can gather data from a maximum of 20 strings.
9. The space between the SAAs and the borehole's wall was filled with sand once the SAAs were in its installation position.

Table 35 presents the estimated costs without considering drilling expenses.

**Table 35: ShapeAccelArray's Steep Angle Boreholes Campaign Instrumentation Costs**

Phase	Investment Year	Instrumentation Cost [US\$]
V8	End of 2027	2,386,785
V9	End of 2029	1,169,829
<b>Total</b>	-	<b>3,556,614</b>

Refer to APPENDIX M for further information about ShapeAccelArray's steep angle boreholes campaign costs calculation.

#### 5.1.6.10. Networked Smart Markers Steep Angle Boreholes Campaign Installation

The monitoring periods for every phase was the same for both the steep angle and shallow angle boreholes campaign (Table 24).

The NSM's characteristics already described in Section 5.1, point 5.1.5.6 fulfilled all the requirements of the steep angle boreholes monitoring campaign. The only difference between the shallow angle and steep angle boreholes campaign was the number of NSMs per borehole, as the boreholes in the steep angle boreholes campaign were shorter.

Two different campaign settings were proposed. The first one considered the installation of one NSM every 2 meters inside each borehole. The second considered the installation of one NSM every 4 meters. A summary of both alternatives is presented in Table 36.

**Table 36: Quantity of NSM Required in a Steep Angle Boreholes Campaign**

Phase	Quantity of NSMs (2-meter spacing)	Quantity of NSMs (4-meter spacing)
V1	1,124	560
V4	968	482
V8	2,551	1,272
V9	1,246	621
<b>Total</b>	<b>5,889</b>	<b>2,935</b>

APPENDIX N presents detail information about quantities of NSMs per borehole in each phase (Table. N.1 through Table. N.4).

**5.1.6.11. NSM's Steep Angle Boreholes Campaign Costs**

The costs for NSM's steep angle boreholes campaign were estimated taking into account the same considerations as for the NSM's shallow angle boreholes campaign. However, the inclination and, thus, length of the boreholes were different for this case, since a steep angle boreholes campaign considered steeper and shorter drill holes.

Table 37 summarizes the costs of instrumentation per phase but the cost of drilling is not included.

**Table 37: Networked Smart Marker's Steep Angle Boreholes Campaign Instrumentation Costs**

Phase	Investment Year	Instrumentation Cost [US\$] (2-meter spacing)	Instrumentation Cost [US\$] (4-meter spacing)
V1	End of 2014	615,529	525,054
V4	End of 2017	533,302	455,339
V8	End of 2021	1,381,756	1,176,581
V9	Ends of 2022	689,956	589,695
<b>Total</b>	<b>-</b>	<b>3,220,544</b>	<b>2,746,669</b>

For more detailed information about Networked Smart Marker's steep angle boreholes campaign costs calculation see APPENDIX O.

## 5.2. Alternatives Comparison

All campaigns defined in this work were compared according to six criteria, as shown in Table 38. These criteria were: the number of years that every campaign was able to monitor the pit's walls, the number of critical sector that each campaign could have monitored monitor i.e. number of phases to be monitored, the amount of monitoring points, the amount of gathered data, total cost of the campaign (including drilling costs) and cost per quantity of acquired data in each campaign.

The amount of gathered data was calculated as the product of the monitoring period and monitored points. Thus, it allowed for a more accurate comparison towards which campaign allowed to gather more information of a certain critical sectors that required to be studied.

**Table 38: Monitoring Campaigns Comparison**

	Shallow Angle Boreholes Campaign			Steep Angle Boreholes Campaign			
	NSM 2[m]	NSM 4[m]	IPI 2[m]	NSM 2[m]	NSM 4[m]	IPI 2[m]	SAA 0.5[m]
<b>Monitoring Period [Years]</b>	20	20	4	20	20	4	4
<b>Monitored Phases</b>	4	4	2	4	4	2	2
<b>Monitored Points</b>	7,541	3,759	1,250	5,889	2,935	1,250	15,230
<b>Amount of Gathered Data</b>	150,820	75,180	5,000	117,780	58,700	5,000	60,920
<b>Total Cost [US\$]</b>	8,628,486	8,021,784	5,032,097	6,767,035	6,293,160	4,349,854	5,842,414
<b>Acquired Data Cost [US\$]</b>	57.21	106.70	1,006.42	57.45	107.21	869.97	95.90

Based on the predefined criteria, NSM technology showed to be the only one, in both 2-meter and 4-meter spacing configurations, able to fulfil all the requirements of the shallow angle boreholes campaign. It had the longest lifespan of all alternatives, surpassing the others by 16 years and thus could have gathered the greatest amount of data among all the alternatives. Finally, both the shallow angle and steep angle boreholes 2-meter spacing NSM's configurations also presented the lowest cost per unit of acquired data.

IPIs could be deployed in either shallow angle or steep angle boreholes campaigns being in both cases the cheapest alternative in terms of total costs. However, this alternative could have monitored only 100-meter boreholes or the deepest 100 meters in drill holes of greater depth and could have only been installed to monitor final pit's walls. These constrains resulted in the highest cost per unit of acquired data among all alternatives.

It is worth mentioning that by using IPIs, the data processing would need to correct the data and account for borehole's inclination. This might have led to additional costs and work for mine site personnel.

With regards to SAA, this alternative could have only been used in steep angle boreholes campaigns to monitor final pit's walls. SAAs allowed for the greatest number of monitored points per borehole and thus per monitoring campaign but, due to the short lifespan of this alternative, the amount of gathered data was practically the same as in the least extensive (4-meter spacing) NSM campaign. In addition, the data gathered by SAAs covered a much smaller area and time frame than the NSM alternative, which ended with similar costs per unit of acquired data compared with the 4-meter separation NSM campaign and significantly higher costs per unit of acquired data compared with the 2-meter separation NSM campaign ( $\approx 67\%$  higher for SAAs).

### **5.3. Potential Economic Gain**

This section presents an assessment of the potential economic gain obtained due to steepening of the wall, based on the modification of the open pit developed in Chapter 4. The evaluation considers the economic benefits obtained due to the reduction of the stripping rate (reduction in mine costs) and to the increase of mine recovery (increase in benefits) when the slopes are steepened by  $1^\circ$  at a time.

Since open pit slopes performance data acquisition may allow to safely steepen the pit's walls in future pushbacks, the economic assessment will rely on projects Net Present Values (NPVs) to incorporate the effect of temporality and scheduling for every slope angle scenario.

#### **5.3.1. General**

To estimate the potential economic benefit that steeper slopes may render and that could justifies the investment in subsurface slope deformation monitoring campaigns, the mine plan developed in Chapter 4 is used as a starting point (base case). This mine presents two types of slopes, the first one, is located in good quality rock mass, covers the north and west portions of the pit and has an overall slope angle of  $50^\circ$ . The second slope type is located in poor quality rock mass, covers the south and east portions of the pit and has an overall slope angle of  $40^\circ$ .

The economic assessment is performed through a sensibility analysis using DeepMine that studies the evolution of the project's NPV as the slope angles for the entire perimeter ( $50^\circ$  and  $40^\circ$  slopes) of the open pit are steepened simultaneously by  $1^\circ$  at a time up to a  $60^\circ/50^\circ$  slope angles

scenario. At first, this process is carried out without considering the installation of instrumentation to understand the evolution of ore and waste extraction and their relation with NPV evolution. Then, the same process is repeated incorporating the instrumentation expenses for all monitoring campaigns proposed in this thesis (IPI, SAA and NSM) to determine the scenario where instrumentation produces economic benefits to the project.

**5.3.2. Analysis without Instrumentation Expenses**

For this case, no instrumentation expenses were considered when steepening the slope angle simultaneously in the good and poor quality rock mass from 50° to 60° and from 40° to 50°, respectively. This evaluation produced the expected increase in NPV showed in Figure 30, as slope angles increased.



**Figure 30: Project’s NPV Evolution as Slope Angle Increases**

Figure 30 shows an unexpected behavior with the first increased degree. In this case, a steeper slope angle produces a lower NPV, which can be a consequence of the trade-off between the case in which the only change is a steeper slope and the case in which the savings produced by a steeper slope allow to deepen the pit and access more ore. The consequences of this trade-off can be seen in Figure 31 and Figure 32.

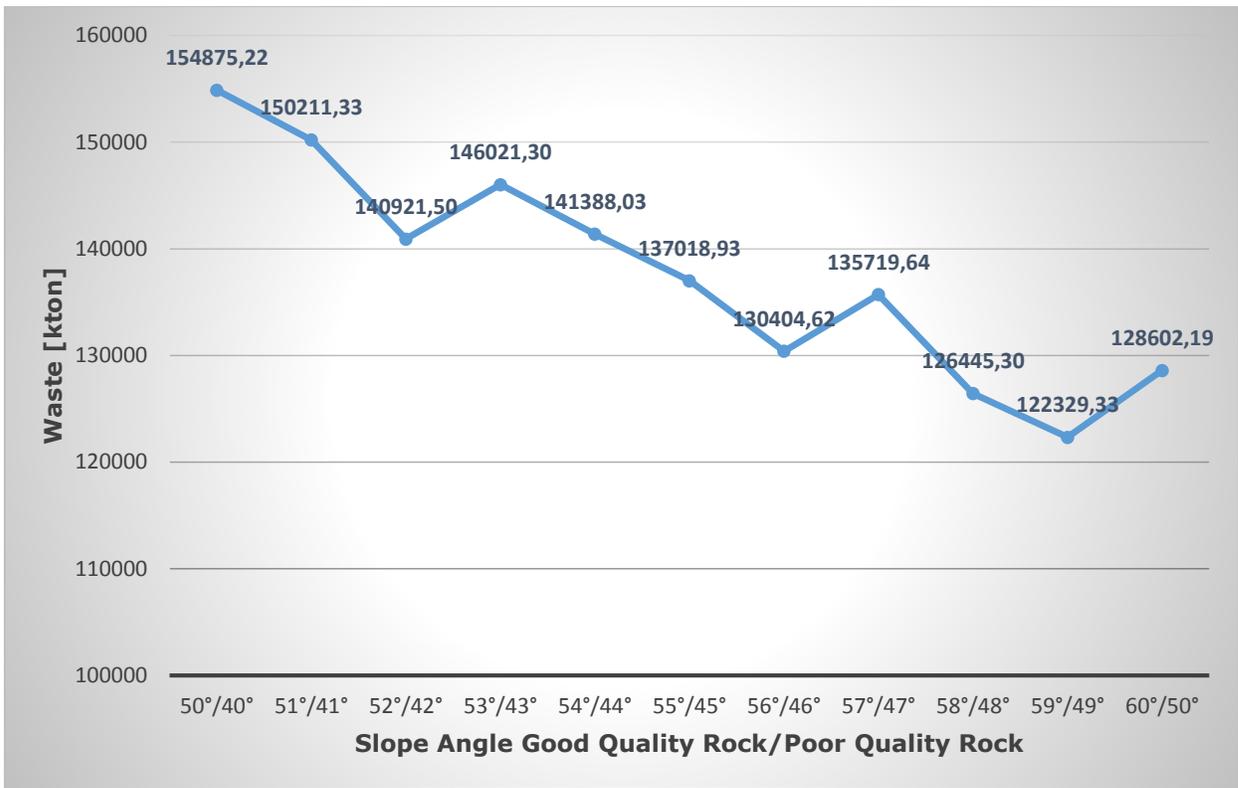


Figure 31: Total Waste Extraction

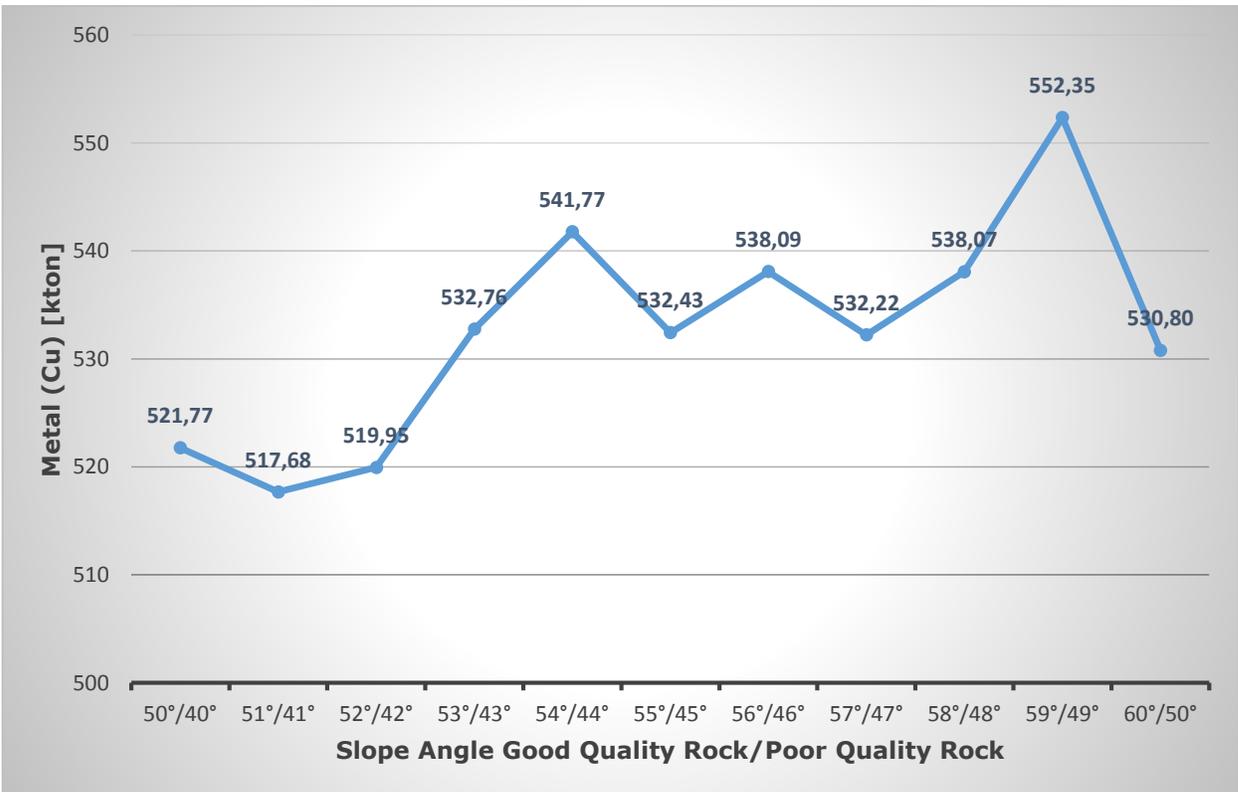


Figure 32: Total Metal (Cu) Production

As shown in Figure 31 and Figure 32, the NPV evolution in the first scenarios (50°/40°, 51°/41° and 52°/42°) is mainly produced by the reduction in waste extraction while the amount of produced copper remains approximately the same. The fourth scenario (53°/43°) shows a change in the tendency. In this case, both the waste extraction and produced metal increase, thus the increase in NPV is due to new ore that is accessible (and extracted) due to deepening of the open pit, which also requires the extraction of more waste. Between the 53°/43° and 56°/46° scenarios, waste extraction diminishes due to steeper slopes and metal production remains approximately the same. Finally, between the 53°/43° and 56°/46° scenarios, the pit is deepened again.

### 5.3.3. Analysis Considering Instrumentation Expenses

To perform this analysis, the costs associated with every instrumentation campaign proposed in this thesis were incorporated into the NPV calculations for all variations in slope angles.

#### 5.3.3.1. Shallow Angle Boreholes Instrumentation Campaign

This scenario considers two instrumentation alternatives: (1) In-Place Inclinometers (IPI) and (2) Networked Smart Markers (NSM).

To account for the cost of deploying these campaigns, the costs of the boreholes, instruments and their installation were incorporated into the NPV calculation as variable costs distributed over time, as presented in Table 39.

**Table 39: Shallow Angle Boreholes Instrumentation Campaign Costs over Time**

Year	2014	2017	2021	2022	2027	2029
IPI Costs [MMUS\$]	0.00	0.00	0.00	0.00	3.06	1.97
2m NSM Costs [MMUS\$]	1.71	1.56	3.36	2.01	0.00	0.00
4m NSM Costs [MMUS\$]	1.59	1.45	3.12	1.87	0.00	0.00

However, according to the conclusions from point 5.2 of this chapter, IPI can only be applied to monitor final pit slopes. Then, the IPI campaign does not produce information that could justify steeper slopes. Therefore, there is no potential economic benefits rendered by a reduction in waste extraction or an increase in ore recovery. The benefit of such a campaign could only be in verifying that the final slopes are stable; this economic benefit is not assessed in this thesis. This issue reduces the analysis only to NSMs alternatives.

The 2m and 4m spacing NSM campaigns reduced the project's NPV from the original 210.51[MMUS\$] to 204.52[MMUS\$] and 204.94[MMUS\$], respectively. This represents only a 2.85% decrease for the 2m spacing alternative and 2.65% decrease for the 4m spacing NSM campaign. In both

cases, the costs due to instrumentation are recovered by steepening the slopes by 2°, which produces a 3.21% NPV increase considering the 2m spacing campaign or a 3.41% NPV increase considering the 4m spacing campaign, as shown in Figure 33.

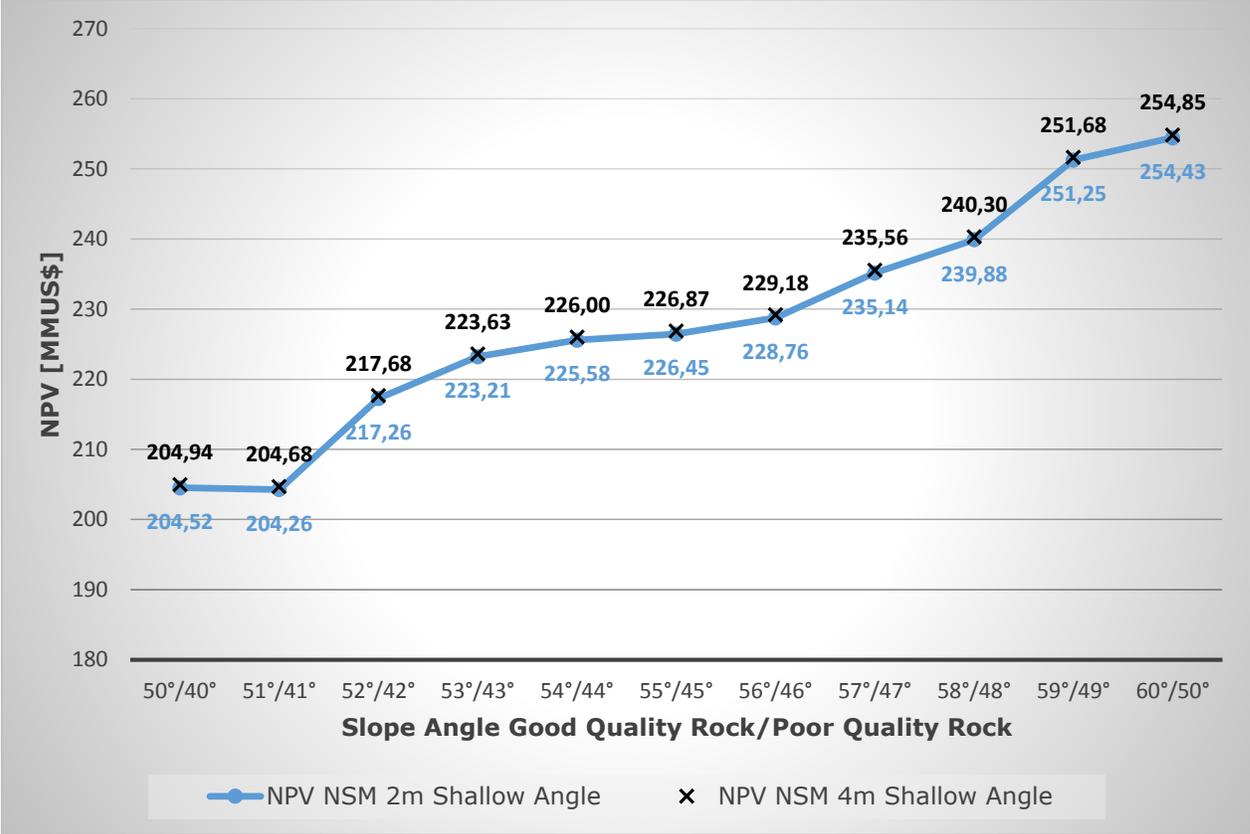


Figure 33: Project’s NPV Evolution as Slope Angle Increases – Shallow Angle Boreholes

5.3.3.2. Steep Angle Boreholes Instrumentation Campaign

This scenario considers three instrumentation alternatives: (1) In-Place Inclinerometers (IPI), (2) ShapeAccelArrays (SAA) and (3) Networked Smart Markers (NSM).

To account for the cost of deploying these campaigns, the costs of the boreholes, instruments and their installation were incorporated into the NPV calculation as variable costs distributed over time, as presented in Table 40.

However, as established in point 5.2 of this chapter, IPI and SAA can only be applied to monitor final pit slopes. Thus, the IPI and SAA campaigns do not produce information that could justify steeper slopes. Therefore, there is no potential economic benefits rendered by a reduction in waste extraction or an increase ore recovery when applying those campaigns. The benefit of such a

campaign could only be in verifying that the final slopes are stable; this economic benefit is not assessed in this thesis.

Therefore, the analysis focused only on the two most expensive (in terms of total cost) instrumentation alternatives: 2m and 4m spacing NSMs steep angle boreholes campaigns.

**Table 40: Steep Angle Boreholes Instrumentation Campaign Costs over Time**

Year	2014	2017	2021	2022	2027	2029
IPI Costs [MMUS\$]	0.00	0.00	0.00	0.00	2.76	1.59
SAA Costs [MMUS\$]	0.00	0.00	0.00	0.00	3.92	1.92
2m NSM Costs [MMUS\$]	1.29	1.12	2.92	1.44	0.00	0.00
4m NSM Costs [MMUS\$]	1.20	1.04	2.71	1.34	0.00	0.00

The 2m and 4m spacing NSM campaigns reduced the project’s NPV from the original 210.51[MMUS\$] to 205.85[MMUS\$] and 206.18[MMUS\$], respectively (Figure 34). This represents only a 2.21% decrease for the 2m spacing alternative and 2.06% decrease for the 4m spacing NSM campaign.



**Figure 34: Project's NPV Evolution as Slope Angle Increases – Steep Angle Boreholes**

In both cases, the costs due to instrumentation are recovered by steepening the slopes by  $2^\circ$ , which produces a 3.84% NPV increase considering the 2m spacing campaign or a 4.00% increase considering the 4m spacing campaign.

#### **5.3.4. Conclusions of the Economical Assessment**

The previous economic assessments showed that in both the shallow and steep boreholes instrumentation campaigns, an increase of  $2^\circ$  in the pit's slopes allow to cover the expenses for the two most expensive monitoring campaigns: the 2m spacing NSM campaigns with a cost of US\$8,628,486 for the shallow angle boreholes configuration and US\$6,293,160 for the steep angle boreholes configuration.

However, as shown in Figure 33 and Figure 34, the NPV's change from the  $50^\circ/40^\circ$  scenario to the  $51^\circ/41^\circ$  scenario represents an atypical case, as the NPV decreases. If the expected behaviour would occur and the NPV increased by an amount equal to half the difference between the NPV's for the  $50^\circ/40^\circ$  and  $52^\circ/42^\circ$  scenarios, the NPV for the  $51^\circ/41^\circ$  scenario would be 210.89[MMUS\$] for the shallow and 212.22[MMUS\$] for the steep angle boreholes campaigns instrumented with NSM installed every 2 meters. Subsequently, in both cases, a  $1^\circ$  slope angle increase would pay for the most expensive monitoring campaigns proposed in this thesis.

#### **5.4. Recommendations**

Albeit surface deformation monitoring was not part of the scope of this thesis, it is recommended to compliment the subsurface deformation monitoring campaigns proposed in this work with surface deformation monitoring programmes. For instance, slope deformation radars could be used to monitor the behaviour of large areas of the open pit and correlate surface deformation data with subsurface deformation data. Another recommendation is to use prisms and/or GPS to monitor the position of the instrumented boreholes' collar assuring that the boreholes used to monitor subsurface deformations do not move as rigid blocks.

#### **5.5. Chapter Summary**

In this chapter two different subsurface deformation monitoring campaigns were designed. The first was a shallow angle boreholes campaign, which considered the deployment of either 100-meter long In-Place Inclometers (IPI) or Networked Smart Markers (NSMs). The second, a steep angle boreholes campaign, was meant to use either 100-meter long IPI, ShapeAccelArrays (SAAs) or NSMs.

All campaigns were compared in terms of quantity of gathered data and costs. This process showed NSMs as the devices that provided data at the lowest cost.

Finally, an assessment of the potential economic benefit due to steepening of the entire perimeter of the open pit by  $1^\circ$  at a time, from a  $50^\circ/40^\circ$  (slope angle in good quality rock /slope angle in poor quality rock) configuration up to a  $60^\circ/50^\circ$  was made.

This evaluation showed how a  $1^\circ$  slope angle increase could finance the most expensive subsurface deformation monitoring campaign proposed in this thesis, the 2m spacing NSM shallow angle boreholes monitoring campaign. It also showed that a  $2^\circ$  produces a 3.21% NPV increase considering the 2m spacing campaign or a 3.41% increase considering the 4m spacing shallow angle boreholes campaign and a 3.84% NPV increase considering the 2m spacing campaign or a 4.00% increase considering the 4m spacing in a steep angle boreholes monitoring campaign.

## **CHAPTER 6**

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### **GENERAL DISCUSSION**

This chapter presents a thorough discussion of all the results obtained in this thesis and explain how all the aspects of this work are interrelated.

#### **6.1. Relevance of the Mine Plan**

The elaboration of a mine plan and pushbacks design allowed to define the project conditions. These project conditions were used as the main inputs to define the monitoring campaigns, particularly, for the selection of the open pit sectors to be monitored.

Based on the overall mine design, critical sectors were defined; these were sectors with high probability to present stability issues. Subsequently, mine's pushbacks coupled with their extraction scheduling (coming from the mine plan) were considered to assess the feasibility to instrument the selected critical sector of the mine. This allows to discard some sectors that could not be instrumented because by the time they would had been instrumented, extraction would have already started, prematurely disabling the instruments.

Another relevant aspect of early monitoring campaign design was that drilling campaigns intended for other purposes, such as, geotechnical or geological survey could be adapted to house geotechnical instrumentation in the future. This would have made the subsurface deformation monitoring campaigns more economic, since drilling cost represented more than half of the cost for the entire monitoring campaign.

#### **6.2. Networked Smart Marker System Validation**

After two mine scale trials, the Networked Smart Marker System demonstrated its ability to transmit data wirelessly through rock and grout, fulfilling the objective of both trials. This presented the NSMs as a possible platform to extend the sensing capabilities to other variables within the rock mass, such as, ground water pore pressure and subsurface deformations. These results allowed to consider such a novel technology (NSMs) as a valid alternative for the monitoring campaigns proposed in this thesis.

Furthermore, NSMs are a promising alternative to overcome major drawbacks of other devices considered for the monitoring campaigns (SAA and IPI). For instance, NSMs eliminate problems related to in-hole cables, minimise the possibility of device breakage due to localized shear deformations, eliminate the need for boreholes' casing, do no present limits for application

depth and quantity of NSMs per drill hole and allow the coexistence of various sensors and thus measurements at the same point.

In addition, the NSM system is flexible allowing for operation even when some NSMs in the string do not function properly (as long as those NSMs are not consecutive ones that would extend the communication range between working sensors beyond the upper limit) or, if some NSMs in the upper portion of the borehole are mined out, the rest of the string can be rehabilitated by installing a new antenna at the top of the remaining portion of the NSM string.

However, NSMs do present some drawbacks, for example, the system needs boreholes with diameter greater than 11.4 centimetres (4.5 inches) and NSMs' sealing requires greater amounts of grout than the alternative technologies.

## **6.3. Monitoring Campaigns**

### **6.3.1. Campaigns Configuration**

From the three alternative devices, NSM, IPI and SAA, selected and evaluated, NSM is the only technology that can fulfil all the requirements for a shallow angle boreholes monitoring campaign and be installed prior to the extraction of the pushback that exposes the slope to be monitored. This is possible because NSMs are the only blasting resistance technology. IPI can be installed in boreholes with a shallow angle configuration, i.e. inclined following the inclination of the slope to be monitored, but they have to be deployed after the slope is fully exposed. Hence, IPI cannot register the slope relaxation process. The same conditions are applicable to SAA installed in a steep angle boreholes configuration. In addition, both IPI and SAA technologies can only be utilized to monitor final walls.

Regardless of the type of instrument installed in the boreholes, the collar of each drill hole should be monitored using surface deformation monitoring technologies, such as, GPS or prisms. This will allow to assure that the boreholes are not moving as a rigid block i.e. that, despite the fact that no movement is registered along the borehole, the instrumented portion of the slope is moving as one piece. It is also advisable to complement subsurface deformation monitoring with spread surface deformation monitoring using, for example, slope radars. These will gather near real time data which when coupled with subsurface deformation data, would generate a more precise estimation of the amount of material that is moving and might fail.

### **6.3.2. Subsurface Deformation Detection at Great Depths**

It is known (Stacey et al., 2003) that the strain behind a pit's wall increases in horizontal extension with depth. This increment is highly

dependent on *in situ stress ratio k*. For 400-metre high slopes (similar to the open pit designed for this thesis) strain can extend horizontally between 10 ( $k=0.5$ ) and 110 ( $k=2.0$ ) metres behind slope's face. Then, it is crucial to have a good estimation of the  $k$  value for the mine site to be monitored to determine whether a campaign using boreholes dipping  $60^\circ$  will produce useful data or not.

Therefore, a steep angle boreholes campaign instrumented using IPI is feasible only if  $k$  values for the studied mine are 2.0 or higher because the lowest ends of all boreholes are located, on average, 109 metres behind the slope's face and the instruments are installed only in the deepest 100 metres of every borehole. At such depth, movements are unlikely to occur and, if some movement is produced, it will be of very small magnitude and thus it will be difficult to register it.

In the case of NSMs or SAAs, the steep angle boreholes campaign can be modified to install the devices up to a depth where important levels of deformation are expected to occur. This situation will reduce or produce the loss of important data from deformations occurring at the slope's toe. This problem will not occur for the shallow angle boreholes campaign as boreholes' distance to the slope's face is 10 metres (constant at any depth). Thus, even with  $k$  values close to 0.5 deformations should be registered.

### **6.3.3. Campaigns Comparison**

After comparing the three types of instruments considered in this thesis, it has been established that the best performing alternative is the NSM system. This conclusion is based on its application flexibility, which allows the installation in sectors where the other technologies cannot be used. This advantage over IPI and SAA is heavily influenced by the NSM's resistance to nearby blasting and by lack of restriction on installation depth or inclination.

NSMs present a practical life longer than IPI and SAA even though NSMs have a maximum operational life due to the usage of batteries as oppose to IPI and SAA. This condition is due to NSMs resistance to harsh mining conditions and wireless communication through rock (no in-hole cables are required).

In terms of costs, the NSMs installed every 2 metres showed to be the most cost-effective alternative. This configuration presents the lowest cost per unit of gathered data and will be reinforced with the addition of further sensors within the same NSM enclosure i.e. with the Enhanced Networked Smart Markers (ENSM). Since ENSM configuration will increase the quantity of acquired data by measuring various rock mass variables at a single point (deformation, groundwater pore pressure, micro-seismic and others).

#### **6.3.4. Economic Analysis**

This thesis addressed the economic benefits of the geotechnical monitoring by evaluating its influence on safe increase of the slope's angle to improve the project's economic performance by reducing costs associated with the extraction of waste and increasing the economic benefits associated with the higher ore extraction.

The evaluation showed that:

1. The In-Place Inclinometer and ShapeAccelArray alternatives being able only to monitor final slopes (in the shallow and the steep angle boreholes configuration) do not generate the potential to steepen future slopes. Thus, these technologies do not generate economic benefits from the point of view analysed in this thesis and only generate the benefit of determining whether the final slopes are stable or not.
2. All the Networked Smart Marker (NSM) alternatives reported significant economic benefits to the project when allowing to increase the slope angle by 2°. However, if the expected behaviour occurs, a 1° slope angle increase allows to finance any NSM monitoring campaign and to report some minor economic benefit.
3. Both NSM configurations in shallow and steep angle boreholes campaigns present marginal differences in terms of NPV. The difference between the most economic and most expensive alternatives, in terms of NPV, is 1.66[MMUS\$], which represents a 0.79% of the project's original NPV.

Since all the NSM monitoring campaigns are economically feasible and the cost differences between the various alternatives are minimal, the selection of the NSM campaign configuration should be based on the quality and quantity of acquired data.

These economic benefits (NPV behaviour) should be increased in open pits greater in depth than the one studied in this thesis, since a deeper open pit implies greater amounts of stripped material and thus greater cost savings when steepening the slopes. Thus, it is not only technically feasible to implement the instrumentation campaigns described in this thesis but also it is economically efficient.

Other benefits, which were not studied from an economic perspective in this thesis but which could contribute to justify the investment in subsurface deformation monitoring using NSMs might be the avoidance of harm to personnel and/or damage to the equipment (cost saving) due to early warning

of imminent failure. If failure was avoided, the operation would benefit from cost savings due to remedial measurements (remediation costs) that were not necessary, as there was no failure to amend.

# CONCLUSIONS AND RECOMMENDATIONS

## 7.1. General Conclusions

This thesis commenced with a thorough literature review of open pit slope stability and the importance of rock mass deformation monitoring for open pit mining projects. It was stated that slope monitoring plays a fundamental role in slope stability assessments and open pit slopes' design. This literature review also established the State-of-the-Art of rock mass/slope deformation monitoring techniques in metalliferous open pit mines. It acknowledged that there are no geotechnical instrumentation guidelines specially developed to address the various characteristics of open pit mines' rock slopes. It was thus concluded that:

- The slope design process deals with a large amount of uncertainty sources and attempts to account for these uncertainty using fudge factors, such as FoS and PoF. However, this approach tend to produce over-conservative slope designs.
- The actual slope behaviour has to be studied to account for the uncertainties involved in the slope design process. This behaviour can be studied through data obtained using geotechnical instrumentation to monitor surface and subsurface rock mass deformations.
- Subsurface rock mass deformation monitoring allows to predict developing failures before the failure becomes imminent and thus allows to take corrective measurements towards avoiding the failure.
- Most geotechnical instruments used to register subsurface rock mass deformations have been developed to monitor civil engineering projects. Therefore, they present several limitation when applied to open pit mining projects:
  - Short lifespan.
  - Limited application depth.
  - Limited number of sensors per borehole.
  - Limited coexistence of sensors in a single location inside a borehole.
  - Low tolerance to localized shear deformations.
  - Installation and maintenance issues due to the presence of cables inside boreholes.

A new geotechnical monitoring technology, the Networked Smart Markers (NSM), promises to overcome those drawbacks by enabling through rock wireless data transmission. The technical feasibility of this wireless data

transmission was proven after testing of these devices in two mine scale trials for sixteen months, as describe in this thesis.

Five subsurface deformation monitoring campaigns were designed aiming to achieve the highest possible revenue due to subsurface deformation monitoring and the surface monitoring campaigns commonly deployed in the most important open pits in the world. These campaigns were designed as an integral part of the slope design process and closely related to the mine plan. This allowed to focus the monitoring effort on the most relevant zones for a particular open pit project.

The campaigns consisted of a shallow angle and a steep angle boreholes installation both with boreholes drilled in the same location but with different inclinations. The shallow angle boreholes campaign used IPI or NSM devices installed in boreholes with the same inclination of the slope's face at a distance of 10 metres plus the berm width behind the slope face. The steep angle boreholes installation used NSM, IPI or SAA devices installed in boreholes with a minimum inclination around  $60^\circ$  at a distance of 10 metres plus the berm width behind the slope face.

All alternatives were compared in terms of campaigns' operational lifespan, quantity of mine sectors to be monitored, quantity of monitored points, amount of gathered data, total cost and the cost per unit of acquired data.

The results obtained clearly show that the proposed campaigns are technically feasible, with NSMs installation being the most technically advantageous.

Moreover, an economical evaluation was undertaken considering the evolution of the instrumented mine project's NPV when steepening the slope angle by  $1^\circ$  at a time. This assessment incorporated the potential benefit of lower waste stripping ratio and additional ore extraction, which showed the economic viability of all studied alternatives. The campaigns using NSMs were the most advantageous, in particular, the campaign that considered the installation of one NSM every four metres, which presented the lowest cost per unit of gathered data.

Therefore, it has been proven that with these campaigns more abundant ground behaviour and better quality data, including slope decompression process monitoring, can be obtained due to longer monitoring periods. This results in more comprehensive database that allows to differentiate normal deformations, due to slope decompression, from deformations produced by developing failures.

However, it was also established that, among all the NSM alternative campaigns, the cost was a variable of marginal relevance and that the choice among NSM campaigns had to be founded on the quantity and quality of gathered data that each campaign configuration would produce.

In terms of quantity of gathered data, both 2m spacing NSM campaigns produce the greatest quantity of subsurface deformation data. With regards to quality of data, the shallow angle boreholes configuration provided better results for the reasons explained and discussed in Chapter 6, such as, the boreholes' constant distance to the slope's face at any depth. Thus, the 2m spacing NSMs shallow angle boreholes monitoring campaign proved to be the best alternative to implement from a techno-economic perspective.

The information obtained from this campaign can also be complemented with surface deformation monitoring data allowing better estimation of the amount of moving rock mass.

## **7.2. Recommendations**

Since the first two trials described in this thesis were conducted prior to the development of this work and were intended to prove wireless data transitions, it is recommended to develop further trials incorporating the methodology and parameters used in this thesis.

The objective of these trials would be to compare the new generation of NSMs, the Enhanced Networked Smart Markers (ENSMs), with proven technologies, such as, IPI and piezometers installed in close vicinity to the ENSMs. The mine scale trials can be less extensive in terms of the amount of instrumented boreholes. It could involve two to five boreholes over 100 metres deep, ideally covering the entire depth of the slope to be monitored, instrumented using NSMs and IPIs.

These trial should also be used to prove the numerical results obtained by Stacey et al., (2003) relative to the horizontal and vertical extension of the strain induced behind the slope due to mining.

## CHAPTER 8

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## CHAPTER 9

### APPENDICES

#### APPENDIX A: Diaphragm Piezometers and Rock Mass Deformation Sensing Technologies Characteristics

Table. A.1: Diaphragm Piezometers Characteristics

Technology	Description	Strengths & Drawbacks	Precision
<b>Piezometers</b>	Piezometers are designed to measure fluid or groundwater pore 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 industry.	<ul style="list-style-type: none"> <li>• Acceptable time response to pressure variations.</li> <li>• Easy to adapt it to an automatic recording device.</li> <li>• Grouting properties are critical to prevent surface water from altering piezometer data.</li> <li>• Long cables are susceptible to damage due to borehole movements.</li> <li>• Not possible to check the calibration of the instrument once installed.</li> </ul>	±0.1% F.S. for the vibrating wire type.

Table. A.2: Soil or Rock Mass Deformation Monitoring Devices

Technique	Description	Strengths & Drawbacks	Precision
<b>Robotic Total Stations (Prisms Monitoring)</b>	Robotic 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.	<ul style="list-style-type: none"> <li>• Ability to provide 3D position of the point of interest.</li> <li>• Unable to monitoring during misty weather.</li> <li>• Installation of monitoring prisms at the suspected likely unstable slope zone or area of interest.</li> </ul>	Accuracy from 0.6 to 3 mm.  Range from 1,000 up to 3,000 m
<b>Borehole Extensometers</b>	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.	<ul style="list-style-type: none"> <li>• Automated and remote readings.</li> <li>• Possible to measure multiple points.</li> <li>• Complicated to install in long boreholes.</li> </ul>	Up to 0.005 mm.
<b>Tilt Meters</b>	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.	<ul style="list-style-type: none"> <li>• High precision measurements obtained.</li> <li>• Used to monitor movements that are expected to contain a rotational component.</li> <li>• Expensive in comparison with radar monitoring. For a 500 x 500 meters area is approximately 36,000\$/month.</li> <li>• Require additional calibration after some time to maintain the same accuracy as initially.</li> </ul>	1 nanoradian (0.0002 arcseconds)

**Table. A.2 (CONTINUATION)**

Technique	Description	Strengths & Drawbacks	Precision
<b>Time Domain Reflectometry (TDR)</b>	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.	<ul style="list-style-type: none"> <li>• High precision on fault location.</li> <li>• Inability to measure large ground displacements due to the breakage of the wires and thus loss of a signal.</li> <li>• Useful to sense localized shear and concentrated shear strain.</li> </ul>	±1% of the cable distance.
<b>Inclinometers</b>	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.	<ul style="list-style-type: none"> <li>• Very detailed displacement path.</li> <li>• In large boreholes and big ground movements, they have short lifespan due to breakage of the casing and/or in-hole cable.</li> <li>• Very useful to study gradual inclination changes.</li> </ul>	They can detect differential movements of 0.5–1.0 mm per 10 m length of borehole.
<b>ShapeAccelArray (SAA)</b>	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. The arrays goes from 30 cm to 100 m long.	<ul style="list-style-type: none"> <li>• Installed in vertical holes to obtain horizontal deformation data in real time.</li> <li>• Also possible to install horizontally to measure vertical deformation.</li> </ul>	± 1.5 mm for 32 m SAA.
<b>Cross-Crack Measurements</b>	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.	<ul style="list-style-type: none"> <li>• Provides an insight to in-ground movements.</li> <li>• Simple monitoring devices.</li> <li>• Potentially unstable working area.</li> </ul>	0.1 mm.
<b>Global Positioning System (GPS)</b>	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.	<ul style="list-style-type: none"> <li>• Line-of-sight is not required between receivers.</li> <li>• Not dependent on weather conditions.</li> <li>• Requires mine personnel to go to all the different points to be surveyed.</li> <li>• Requires unobstructed line of sight to four or more GPS satellites.</li> <li>• Satellite visibility is obstructed in deep point of the pit.</li> </ul>	Under 20 mm.
<b>Visual Inspection</b>	Visual observation of the studied zone to detect the occurrence of cracks, or the evidence displacements.	<ul style="list-style-type: none"> <li>• Requires experienced geotechnical staff.</li> <li>• It must be complemented by instrumentation to provide a quantitative basis for defining the exact amount of movement.</li> </ul>	Qualitative.
<b>Photogrammetry</b>	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.	<ul style="list-style-type: none"> <li>• 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.</li> <li>• Provides a permanent 3D record of the mapped areas.</li> <li>• Provides low cost geological mapping.</li> <li>• Only one person needed to use this technique.</li> <li>• Digital imaging systems require ground proofing and cannot be used to determine the physical features of the structures.</li> </ul>	Accuracy ranges from 2 cm at a distance of 50 m to 10 cm at distances of up to 3 km.

**Table. A.2 (CONTINUATION)**

Technique	Description	Strengths & Drawbacks	Precision
<b>Ground-Based SAR</b>	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.	<ul style="list-style-type: none"> <li>• Measurements can be taken during day and night and in any weather conditions.</li> <li>• Provides high spatial density of observations.</li> <li>• Fast (5-10 min monitoring period).</li> <li>• Short range (&lt;5 km)</li> <li>• Limited field of view, which may cause shadowing problems.</li> <li>• Not intended to monitor broad areas.</li> </ul>	Resolution of about 0.5 – 4 m, depending on the monitoring distance and the atmospheric conditions. Precision in the scale of millimeters.
<b>Airborne Synthetic Aperture Radar (Airborne-SAR)</b>	It uses the same principles as the InSAR but, in this case, the instrument is mounted on an airplane.	<ul style="list-style-type: none"> <li>• Independency from international satellites for data gathering.</li> <li>• It uses a relatively unstable platform.</li> <li>• Very important to know the exact location of the plane for best results.</li> </ul>	-
<b>Interferometric Synthetic Aperture Radar (InSAR)</b>	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.	<ul style="list-style-type: none"> <li>• It works in all weather conditions.</li> <li>• It allows to monitor inaccessible sector of the pit.</li> <li>• Good technique to monitor broad areas.</li> <li>• Dependency on international satellites availability for data gathering.</li> <li>• It may not produce good results when monitoring steep zones.</li> <li>• Real time monitoring is not feasible.</li> <li>• If displacements between successive SAR images is higher than 23 cm InSAR may not be able to quantify it.</li> </ul>	On the scale of centimeters to millimeters.
<b>Light Detection and Ranging (LiDAR)</b>	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.	<ul style="list-style-type: none"> <li>• Able to create a high accurate 3D digital elevation model.</li> <li>• High resolution images.</li> <li>• Relatively inexpensive.</li> <li>• Flexible data collection and processing system.</li> <li>• Can be used to monitor relatively small areas to survey (from 1 to 10 square kilometers).</li> <li>• Need for experienced personnel to understand the limitations of the TLS.</li> <li>• Necessity for a proper data collection campaign to avoid shadowed regions.</li> </ul>	<p>Systematic errors are +/- 25mm at 1,000 meters.</p> <p>Random errors are generally between 0 and 10 mm.</p>

**Table. A.3: Open Pit Subsurface Deformation Monitoring Devices**

Technology	Description	Strengths & Drawbacks	Precision
<b>Seismic or Micro-seismic Monitoring</b>	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 seismographs, 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.	<ul style="list-style-type: none"> <li>• Very unique system to locate fractures developing within the rock mass.</li> <li>• Geophones don't need power to operate.</li> <li>• Signal degradation if the sensors are far from the target.</li> <li>• Limitation to response to high-frequency waves.</li> <li>• Geophones are used to triangulate the position of the movement that originated the measured wave.</li> </ul>	For a IMS 4.5Hz Geophone the distortion measurement frequency is 12 Hz.
<b>Smart Markers</b>	Autonomous electronic devices capable of monitoring mineral flow and ore recovery in block/panel and sublevel caving mines.	<ul style="list-style-type: none"> <li>• Each device has its own identifying ID, allowing to pinpoint its location when installed in the rock mass.</li> <li>• 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.</li> <li>• The actual path of the marker from its installation position to its extraction position (drawpoint) cannot be registered.</li> </ul>	Qualitative.
<b>Networked Smart Markers (NSM)</b>	Autonomous electronic devices capable of monitoring relative displacement between Markers.	<ul style="list-style-type: none"> <li>• Each device has its own identifying ID, allowing to pinpoint its location when installed in the rock mass.</li> <li>• The devices do not require in borehole wires.</li> <li>• The devices are blasting resistant.</li> <li>• Allow to detect slipping surface location.</li> <li>• The Markers are capable of hosting different types of sensors (Enhanced Networked Smart Markers configuration).</li> </ul>	Qualitative.
<b>Enhanced Networked Smart Markers (ENSM)</b>	Autonomous electronic devices capable of monitoring various geotechnical variables, such as, groundwater pore pressure and rock mass subsurface deformation.	<ul style="list-style-type: none"> <li>• Each device maintains all the advantages of NSMs.</li> <li>• Able to register the behavior of various variables at the same point.</li> <li>• Able to work, simultaneously, as piezometer, inclinometer and extensometer.</li> </ul>	Depends on the characteristics of the installed sensors.

## **APPENDIX B: DeepMine Elements Description**

DeepMine is a software solution for strategic open pit mine planning from an economic perspective that avoids the usage of predefined phases. As output, it delivers the size of the mine considering amount of material to be mined and processed. It also delivers mine's lifespan and the value of the operation in terms of net present value (NPV). To do so, the software creates decision trees based on the studied mining configuration. Approximate dynamic programming is used to explore multiple branching in those decision trees to obtain the best outcome based operation's economic value.

Pushbacks are automatically produced as the result of software's calculations, considering operational constrains using and Lerchs and Grossman pit shells as input to define operative phases. The resulting pushbacks are associated with the mine plan and can be used as a guide for mine design e.g. a plan that establishes when every pushback has to be mined to obtain the best possible economical outcome.

To produce such results, DeepMine works with a block model given as an input and with the definition of four elements in the mine planner: The *GeoModel*, the *Mining Environments*, the *Pit Collections* and the *Economic Environments*. These elements use the information contained in the block model and can be defined to apply uncertainty on the resulting mine plans by, for example, modifying commodities prices, operational costs and taxes over time.

### **Block Model Description**

The block model is the main input used by the software to perform their calculations, as the information contained in it is technical data.

This model contains data, such as, block's size and position, ore grade of different commodities contained in the block, weight, density, rock type, topography and can also have user defined variables.

### **GeoModels**

The *GeoModel* contains the block model representing the ore deposit and topography. Here the blocks are arranged in a three-dimensional, regular grid containing only one block in each position.

To define a *GeoModel*, the block model to be used has to be selected, block model's orientation has to be defined and the variables contained in it identified for the DeepMine to recognize them as inputs to generate the mine plan.

When the block model is properly loaded to the *GeoModel*, maximum admissible overall slope angles have to be defined. This can be done by defining several bearing-slope pairs that define the maximum slope inclination for a particular bearing.

## **Mining Environments**

*Mining Environments* define operational parameters related with mine and plants' operations. They are divided into general, operation, mine, plants, stockpiles and dumps.

In the section on general information, the user provides a name for the *Mining Environment*, a description of it and defines the first year of operation.

For the operation section, the user can define fixed operational costs per year of operation, investments to be made each year, depreciation over investment also per year of mine's operation and closure costs to be applied on the last year of mine's operation. All this data is used to determine cash flows of the project per year.

Mine defines the open pit's properties. The user provides mining costs and mine's production capacity per year and, optionally, a cost adjustment factor.

Plants section is where the user defines the different processing plants needed to process all types of ore coming from the mine. This section is divided into four parts: basic properties, costs & capacities, recoveries and filters. In basic properties, the user gives a name to the plant and its description; optionally, he/she can define the plant's location and whether it is set as the primary plant or not. For costs & capacities, the user has to define a base plan cost and processing capacity per year. In addition, processing costs per block, average transport cost to the plant, surplus limits and other user defined restrictions can be set in this section. Surplus limits restricts the amount of ore exceeding plants capacity that can be mined in a certain period, i.e. it limits the amount of ore that goes directly to stockpiles and thus reducing the re-handling in future periods. In the recoveries section, the user defines which rock type will be processed in each plant, the commodity that will be recovered and the percentage of its recovery. Plants section ends with the definition of filters to stablish limitations to the plant based on block's properties.

Stockpiles are defined by basic properties, costs & capacities, associations, initial state and filters. In the section of basic properties, a name and description is given to the stockpile and, optionally, its location. Costs & capacities is where the user has to define the total capacity of the stock, its

maximum re-handling capacity per year. It also gives the option to add an average transport cost from the mine to that particular stockpile. In the association tab, every stockpile is designated to feed a certain plant; this designation includes an associated re-handling cost. The definition of initial state for the stockpile establishes the quantity of material contained in the stock at the beginning of operations. This is optional and assumes homogeneous mixing among rock type fractions and average grades per commodity. The user can also define filters to establish limitations to stocks operations based on block's properties.

Finally, dumps require the definition of its basic properties and costs & capacities. In basic properties, the user individualises every dump with a name, its description and location. Costs & capacities tag is where the user defines an average transport cost to every dump and their maximum capacity.

### **Pit Collections**

*Pit Collections* define a set of pit shells resulting from the application of Lerchs and Grossman algorithm to solve the ultimate pit problem. To do this, *Pit Collections* has to be associated with a predefined *GeoModel* and *Mining Environment*. It also requires the definition of four tabs: general, extraction, plants and prices.

*Pit Collections* are defined with a name associated with a specific *GeoModel* and *Mining Environment* in the general tab. The *GeoModel* provides slopes angles used to define a block precedence list for the Lerchs and Grossman algorithm. While the *Mining Environment* provides all the operational parameters for mine and planta operation, which can be verified in two tabs: extraction and plants. In the extraction tab, the user can verify that the dumps are located in a suitable place and that the extraction and transport to dumps costs are correct. The plants section is the same plants tab in the *Mining Environment* section. The user can also modify the value of the parameters obtained from the *Mining Environment*. These new values will not modify the selected *Mining Environments*; they will only be defined in the *Pit Collections*.

The only tab that the user has to define for the *Pit Collections* is prices. A series of increasing prices is defined for every commodity to be mined. The quantity of pit shell generated will be the same as the quantity of different prices defined in this part.

### **Economic Environments**

The *Economic Environments* are defined by four tabs: general, commodity prices, sales costs and taxes & royalties.

In the general tab, the *Economic Environments* is defined by a name, establishing the first year of mine's operation and setting a discount rate for the cash flow. Then, in the next two tabs, prices and selling costs are given per year for every commodity contained in the block model. Finally, a tax rate is set for the entire operation.

## **Mine Plan**

*Mine Plans* are the final output of the software. The user has to configure the *Mine Plan* choosing among deterministic, stochastic and flexible mine plans.

Subsequently, the user defines the general properties of the *Mine Plan*, establishes the first year of operations and selects a *GeoModel*, *Mining Environment*, *Pit Collections* and *Economic Environment* to serve as inputs to *Mine Plan's* calculations. In the next step, he/she assigns the basic parameter for the resolution of the problem. These parameter are the maximum life of mine (LOM), maximum sinking rate for a single phase in term of benches (number of block in a vertical section) per year, maximum number of active phases every year, maximum phase length, minimum phase width and, optionally, minimum and maximum phase weight.

*Pit Collection Guidance* percentage can be used to relax how the *Pit Collection* used for the *Mine Plan* determines the geometry of the resulting phases.

The user has to select the solver mode used by DeepMine. The user has three possible options from the fastest to the slowest: *quick mode*, *balance mode* and *deep mode*. Since DeepMine uses approximate dynamic programming to solve the *Mine Plan*, the more time spent in calculations the better the results.

Finally, the maximum *Sinking Rate* for the *Mine Plan* has to be defined. This means the maximum number of benches that can be extracted in every phase in a year.

The resulting *Mine Plan* delivers a yearly extraction sequence for the mine presenting the destination and processing of each block and operations data, such as, cut-of grades, plants utilization and stripping rates. In addition, extraction phases that do not consider optimum design but can be used as a robust guide to design operative phases are also provided.

## APPENDIX C: Yearly Copper Cut-Off Grades for the Leaching and Concentrator Plants

Table. C.1 present the cut-off grades per year of operation for each plant.

**Table. C.1: Yearly Cut-off Grade**

Cut-off Grades [%Cu]		
Year	Leaching Plant	Concentrator Plant
2015	0.11	-
2016	0.11	-
2017	0.14	0.20
2018	0.15	0.32
2019	0.14	0.27
2020	0.19	0.23
2021	0.11	0.22
2022	0.14	0.18
2023	0.13	0.19
2024	0.10	0.27
2025	-	0.25
2026	-	0.23
2027	-	0.18
2028	-	0.18
2029	-	0.20
2030	-	0.24
<b>Mean</b>	<b>0.13</b>	<b>0.23</b>

## APPENDIX D: Processing Plants Yearly Operation

Figure. D.1 shows leaching plant’s operation during the mine’s life. It presents an even supply of ore (9,000[kton] per year) from the first year of production and dropping in year 2023, close to plants closure. Year 2024 represents a particular case where the leaching plant is mainly supplied with long term stocked material (low grade material).

Figure. D.2 presents concentrator’s plant operation. This plan starts operating in year 2017 and starts its regimen in year 2018 maintaining a processing rate of around 7,000[kton] per year until year 2029 when production starts to decrease. The last year of plant’s operation (2030) was mainly supplied with long-term stocked material (low-grade material). Figure. D.2 also presents the possibility of processing only stocked material in year 2031, however, this possibility was not considered in the mine plan as it was decided to finish al mine’s operations in year 2030.

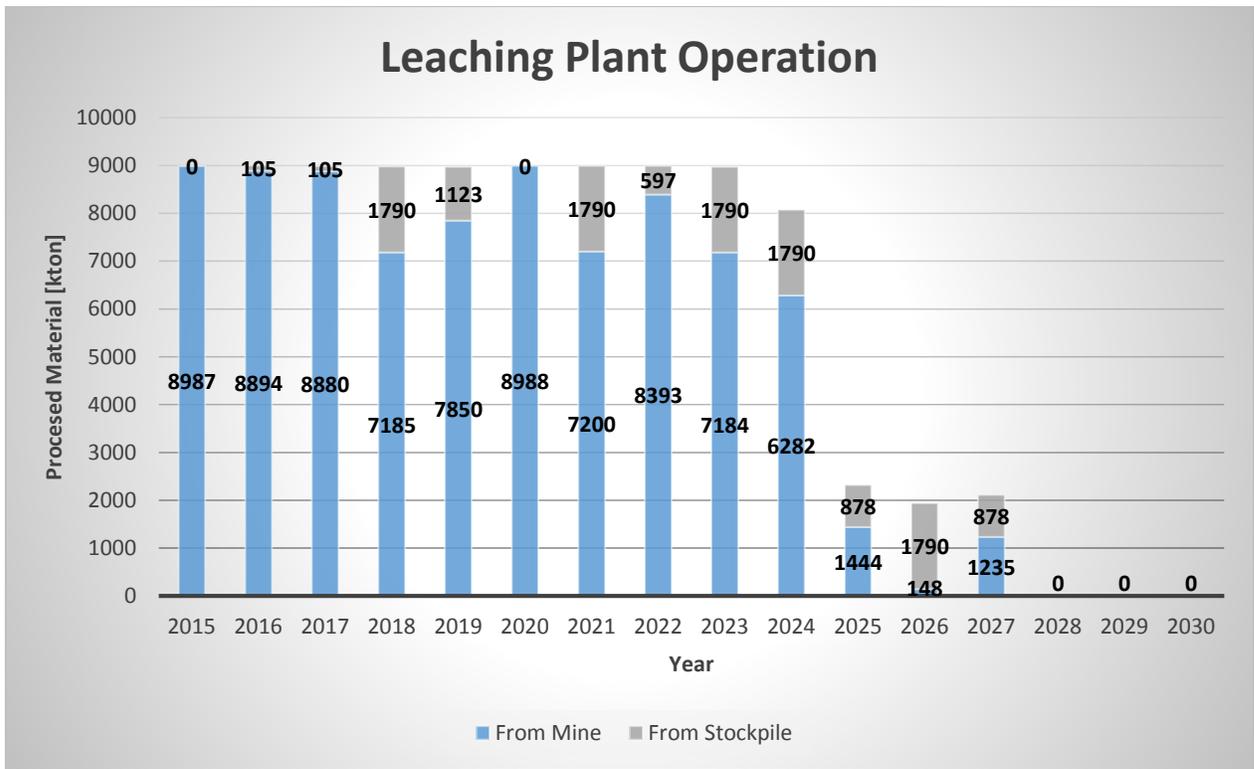


Figure. D.1: Leaching Plant Yearly Operation

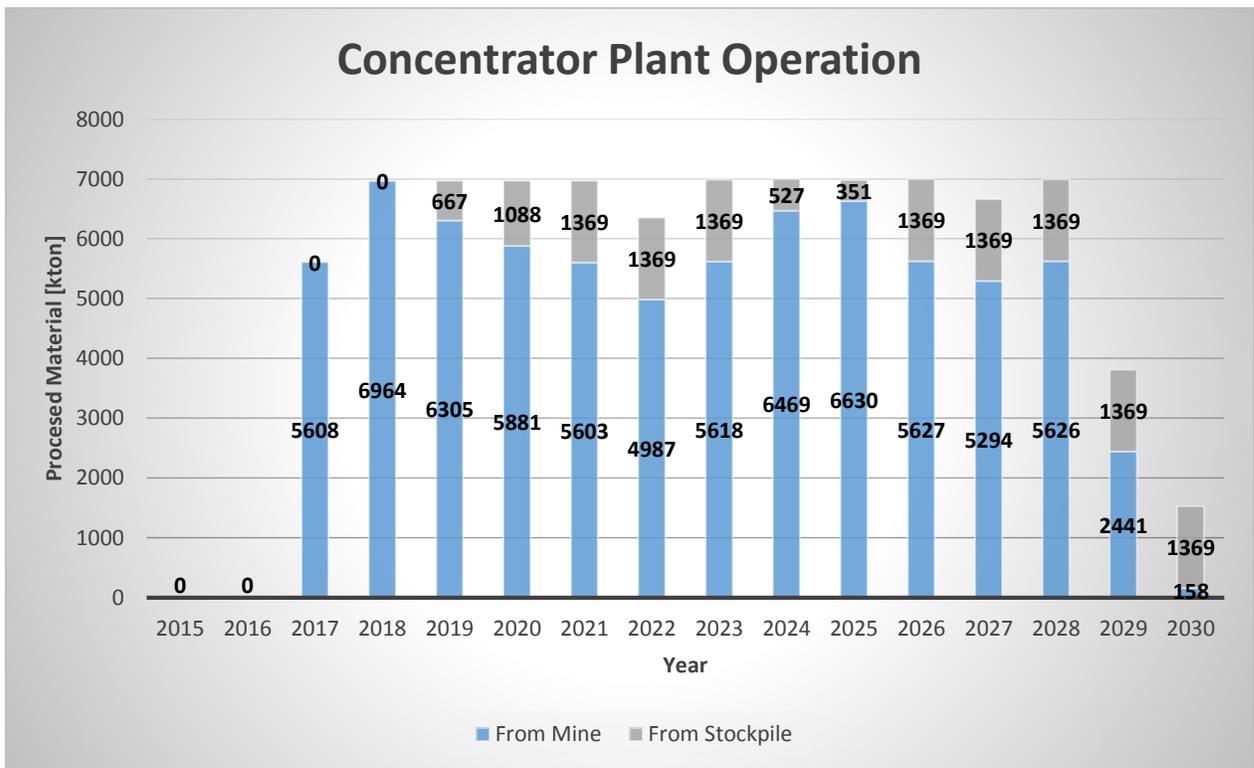


Figure. D.2: Concentrator Plant Yearly Operation

## APPENDIX E: Phases Geometry for the Theoretical Mine Obtained Using the Software DeepMine (Volumes)

This appendix contains isometric views of the 29 phases produced by DeepMine (Figure. E.1 to Figure. E.8). Portions of some phases are enclosed in red circles because they are isolated or too small to be extracted. It is evident that phases 5, 7, 9, 14, 19, 20, 21, 25, 26, 27, 28 and 29 are too small to be consider as single phases.



Figure. E.1: DeepMine Phases 01 to 04

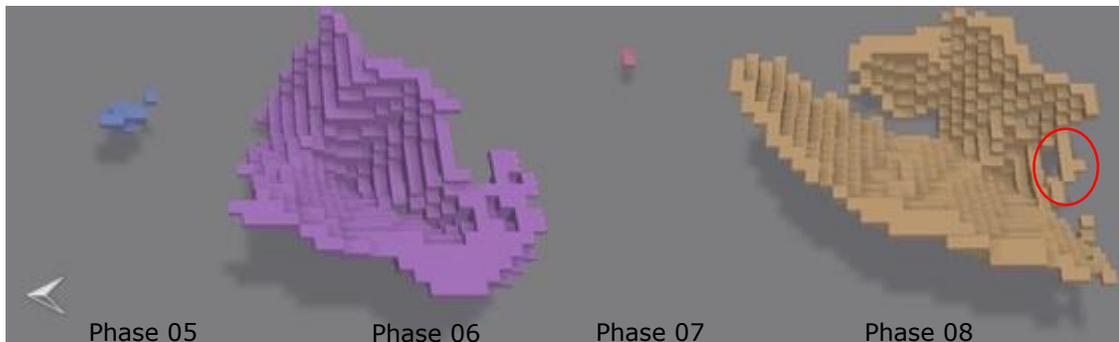


Figure. E.2: DeepMine Phases 05 to 08

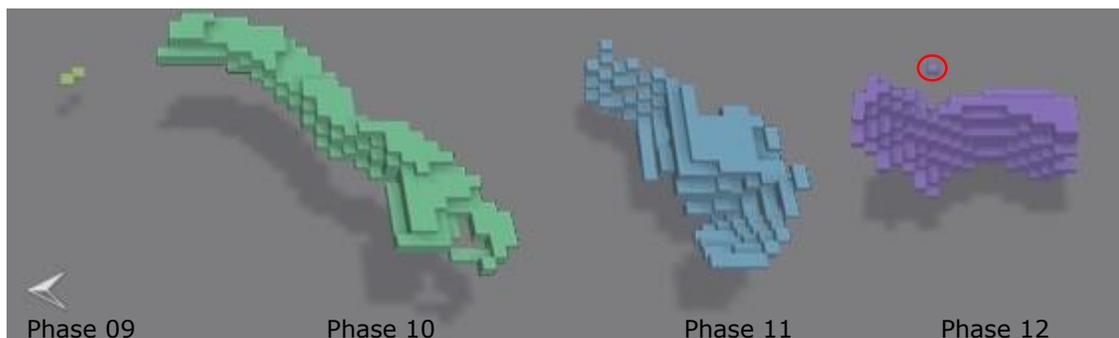
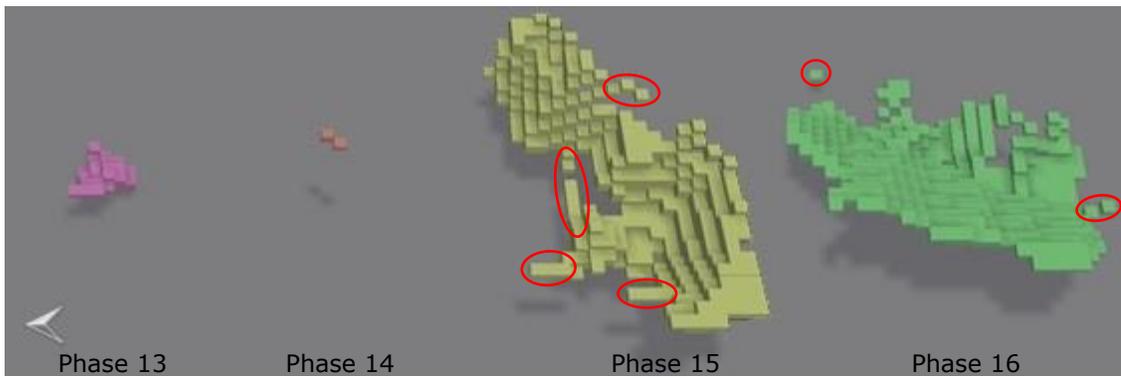
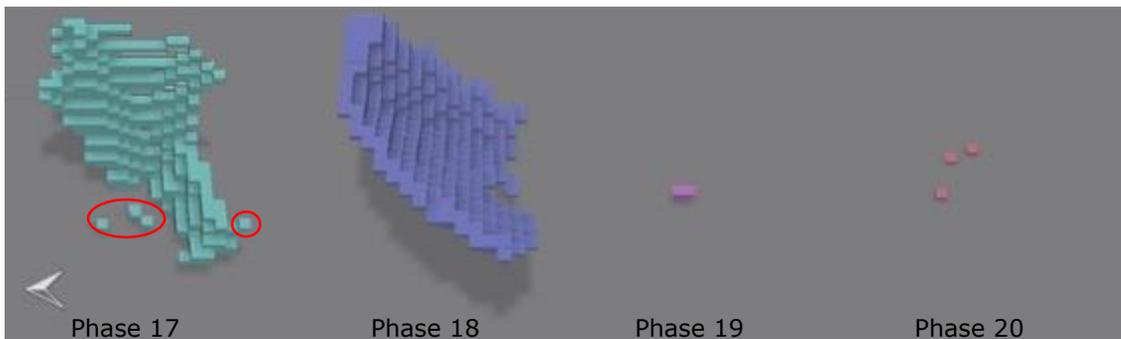


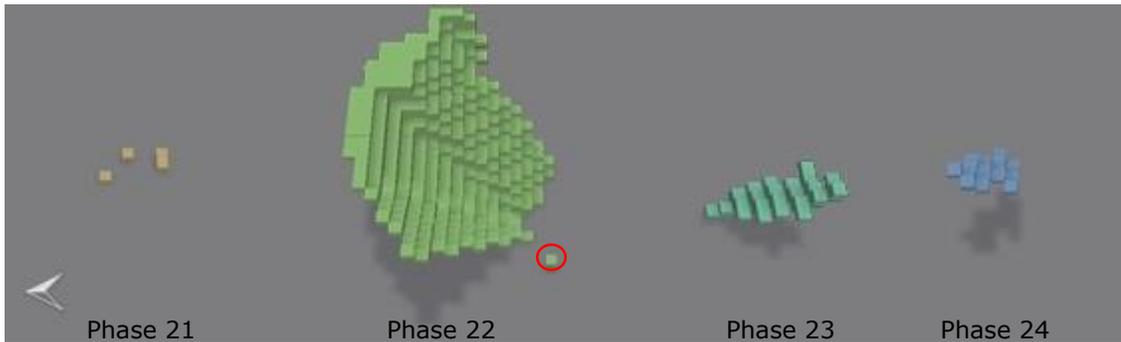
Figure. E.3: DeepMine Phases 09 to 12



**Figure. E.4: DeepMine Phases 13 to 16**



**Figure. E.5: DeepMine Phases 17 to 20**



**Figure. E.6: DeepMine Phases 21 to 24**



**Figure. E.7: DeepMine Phases 25 to 28**



Figure. E.8: DeepMine Phase 29

## APPENDIX F: Phases Geometry for the Theoretical Mine Relaxed Using Vulcan (Volumes)

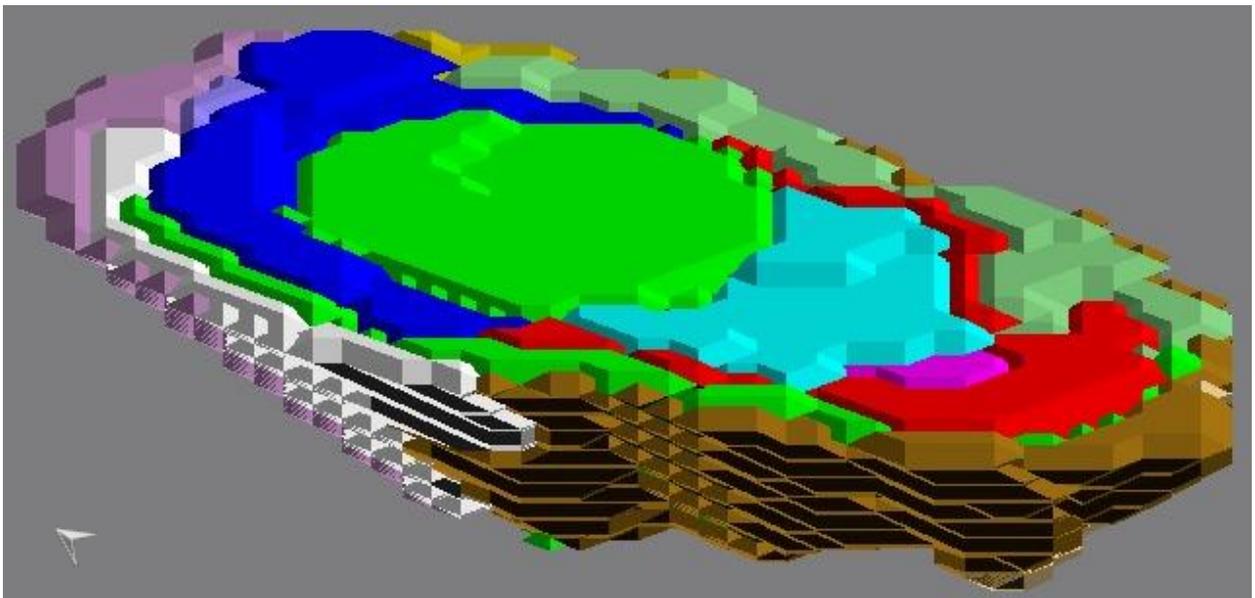


Figure. F.1: Vulcan Phases

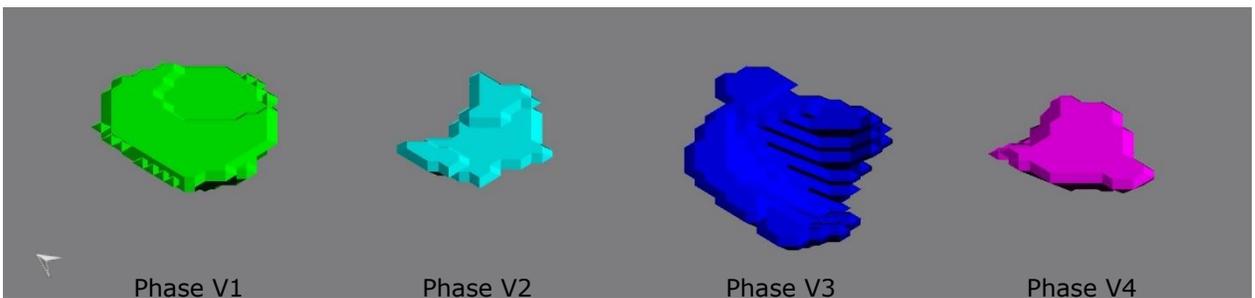
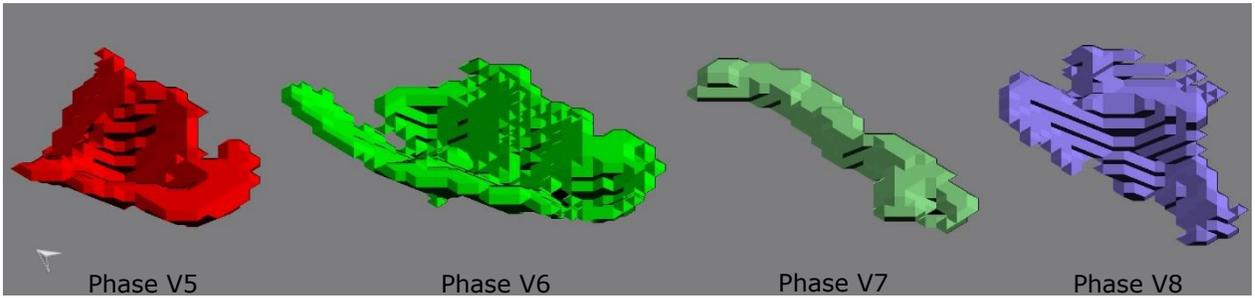
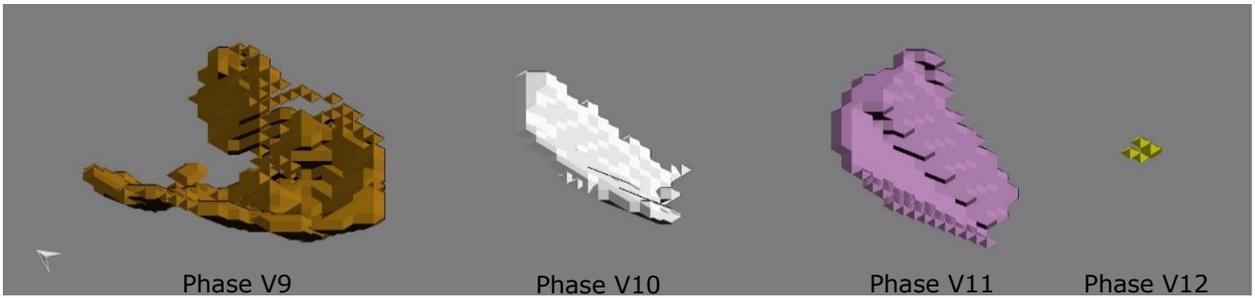


Figure. F.2: Vulcan Phases V1 to V4



**Figure. F.3: Vulcan Phases V5 to V8**



**Figure. F.4: Vulcan Phases V9 to V12**

## APPENDIX G: Phases Geometry for the Theoretical Mine Relaxed Using Vulcan (Topography)

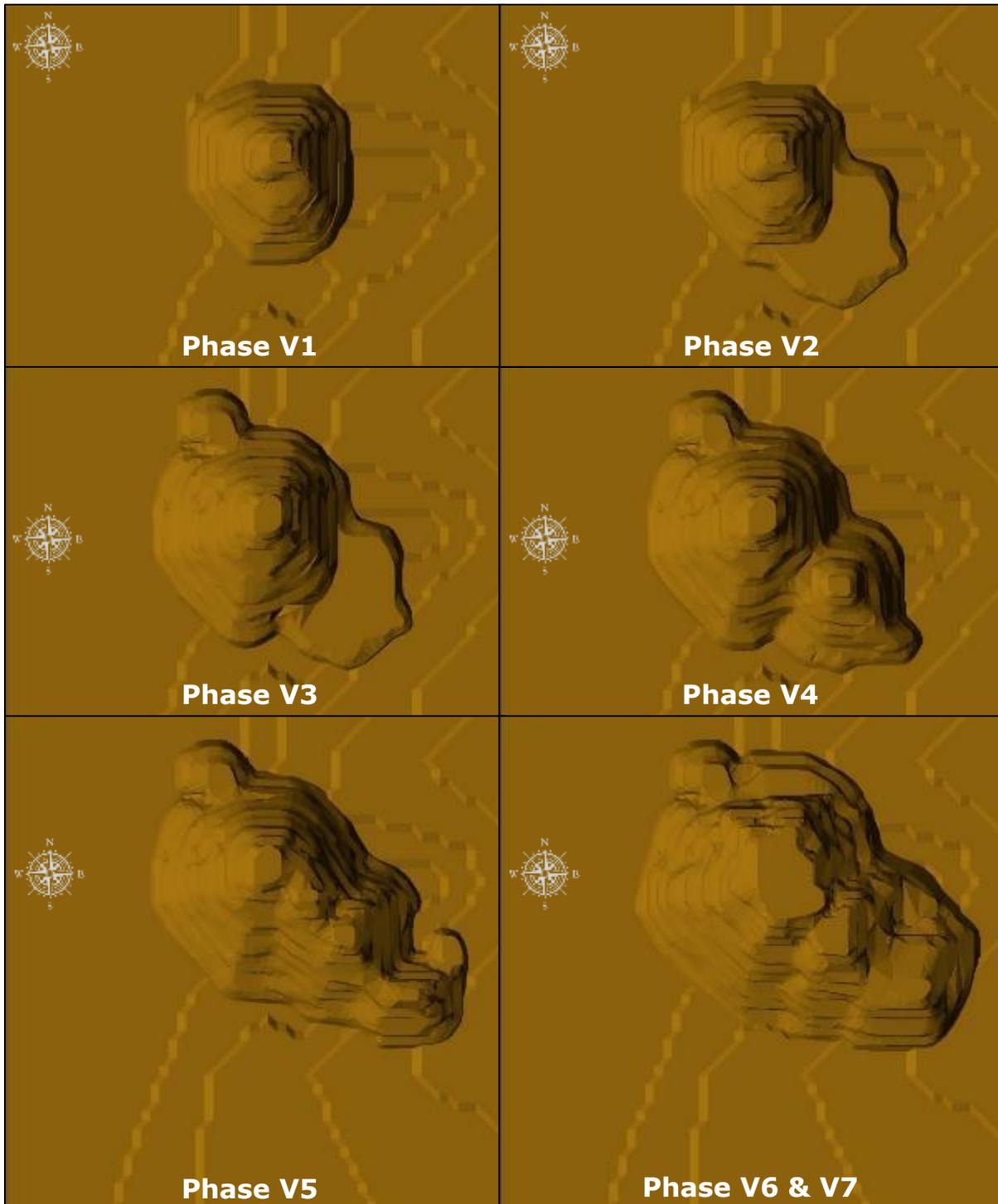


Figure. G.1: Open Pit Phases V1 to V7 Geometry



**Figure. G.2: Open Pit Phases V8 to V12 Geometry**

## APPENDIX H: In-Place Inclinometers (IPIs) Shallow Angle Boreholes Campaign Costs Calculation

Table. H.1 presents data about the system’s layout. It contains the quantity of dataloggers per phases and shows which borehole is connected to a particular datalogger. It also contains the distances form every borehole’s collar to its corresponding datalogger. Since every borehole contains 3 IPI strings and each datalogger can receive information from only 5 strings, there are some boreholes connected to different dataloggers.

**Table. H.1: In-Place Inclinometers Shallow Angle Boreholes Campaign Layout Data**

Phase	Borehole’s ID	Datalogger ID		Distance from Borehole’s Collar to Datalogger [ m ]	
Phase V8	17	1	-	98.14	-
	18	1	2	105.68	97.07
	19	2	-	100.00	-
	20	2	3	118.00	97.49
	21	3	-	106.40	-
	22	4	-	103.61	-
	23	4	5	103.83	101.93
	24	5	-	100.09	-
	25	5	6	105.45	104.00
	26	6	-	100.00	-
	27	7	-	100.91	-
	28	7	8	101.31	101.25
	29	8	-	99.36	-
	30	8	9	106.69	100.00
<b>Total</b>	-	9		2,051.19	
Phase V9	31	1	-	91.70	-
	32	1	2	111.95	118.78
	33	2	-	100.00	-
	34	2	3	98.26	100.00
	35	4	-	99.89	-
	36	4	5	109.06	68.63
	37	5	-	100.00	-
	38	5	6	135.98	77.19
	39	6	-	108.38	-
	40	7	-	109.25	-
	41	7	8	78.36	100.00
<b>Total</b>	-	8		1,607.43	
<b>TOTAL</b>	-	<b>17</b>		<b>3,658.62</b>	

Table. H.2 presents all data required to estimate the costs for the In-Place Inclinerometers' shallow angle boreholes campaign.

**Table. H.2: In-Place Inclinerometer's Costs**

In-Place Inclinerometers - Unitary Costs	
Casing [US\$/m]	29.67
Casing Coupling [US\$/m]	8.17
Locking Cap [per borehole]	46.00
MEMS IPI Gage Tube [US\$/m]	25.25
Serial IPI Biaxial Sensor [US\$/m]	437.50
Sensor wheels [US\$/m]	73.50
Top Wheel [per borehole]	157.00
IPI Placement Tubing [US\$/m]	16.67
IPI Placement Tubing Coupling [US\$/m]	11.67
In-Line Wheels [US\$/m]	24.50
Jumper Cable [per borehole]	256.50
Bus Cable [per borehole]	189.00
Signal Cable [US\$/m]	5.25
Conduit [US\$/m]	2.00
Datalogger [US\$]	700.00

**Table. H.3: In-Place Inclinerometer Shallow Angle Boreholes Campaign Costs**

In-Place Inclinerometers Shallow Angle Boreholes Campaign						
Phase	Borehole's ID	IPIs [US\$]	Cable IPI-Collar [US\$]	Cable Collar-Datalogger [US\$]	Conduit [US\$]	Datalogger [US\$]
Phase V8	17	79,763.50	16,034.50	-	-	-
	18	79,763.50	14,399.44	-	-	-
	19	79,763.50	12,997.84	-	-	-
	20	79,763.50	11,736.33	-	-	-
	21	79,763.50	10,965.49	-	-	-
	22	79,763.50	10,578.85	-	-	-
	23	79,763.50	10,057.04	-	-	-
	24	79,763.50	8,572.71	-	-	-
	25	79,763.50	8,436.73	-	-	-
	26	79,763.50	7,999.29	-	-	-
	27	79,763.50	7,672.44	-	-	-
	28	79,763.50	7,611.00	-	-	-
	29	79,763.50	6,161.08	-	-	-
30	79,763.50	6,181.56	-	-	-	
<b>Total</b>	-	1,116,689	139,404	22,473	4,110	6,300

Table. H.3 (CONTINUATION)						
Phase	Borehole's ID	IPIs [US\$]	Cable IPI-Collar [US\$]	Cable Collar-Datalogger [US\$]	Conduit [US\$]	Datalogger [US\$]
Phase V9	31	79,763.50	11,602.80	-	-	-
	32	79,763.50	12,381.83	-	-	-
	33	79,763.50	13,392.68	-	-	-
	34	79,763.50	12,116.42	-	-	-
	35	79,763.50	-4,750.22	-	-	-
	36	79,763.50	-3,047.17	-	-	-
	37	79,763.50	-3,620.59	-	-	-
	38	79,763.50	-4,525.77	-	-	-
	39	79,763.50	-6,932.48	-	-	-
	40	79,763.50	-5,172.91	-	-	-
41	79,763.50	-3,590.28	-	-	-	
<b>Total</b>	-	877,398	17,854.31	17,338	3,221	5,600

The information contained in Table. H.1 and Table. H.2 presents all data required to estimate the costs for the In-Place Inclinerometers' shallow angle boreholes campaign.

Table. H.2 was used to calculate the costs presented in Table. H.3 and Table. H.4. Table. H.3 presents the different items involved in the cost estimation for an IPI monitoring campaign per borehole. Table. H.4 shows the total cost of the campaign with and without the drilling cost.

**Table. H.4: In-Place Inclinerometer Shallow Angle Boreholes Campaign and Drilling Costs**

	In-Place Inclinerometers Shallow Angle Boreholes Campaign	
	Instrumentation Cost [US\$]	Instrumentation plus Drilling Cost [US\$]
Phase V8	1,288,976	3,057,152
Phase V9	921,412	1,974,946
<b>Total</b>	<b>2,210,387</b>	<b>5,032,097</b>

## APPENDIX I: Quantity of Networked Smart Markers (NSMs) in Each Phase for a Shallow Angle Boreholes Campaign

**Table. I.1: Quantity of NSMs per Borehole – Phase V1 Shallow Angle Boreholes Campaign**

Phase	Borehole	Quantity of NSMs (2-meter)	Quantity of NSMs (4-meter)
<b>V1</b>	<b>1</b>	219	109
	<b>2</b>	211	105
	<b>3</b>	205	102
	<b>4</b>	204	102
	<b>5</b>	212	106
	<b>6</b>	145	72
	<b>7</b>	142	71
	<b>8</b>	153	76
	<b>Total</b>	<b>1,491</b>	<b>743</b>

**Table. I.2: Quantity of NSMs per Borehole – Phase V4 Shallow Angle Boreholes Campaign**

Phase	Borehole	Quantity of NSMs (2-meter)	Quantity of NSMs (4-meter)
<b>V4</b>	<b>9</b>	188	94
	<b>10</b>	176	88
	<b>11</b>	174	87
	<b>12</b>	173	86
	<b>13</b>	158	79
	<b>14</b>	156	78
	<b>15</b>	161	80
	<b>16</b>	171	85
	<b>Total</b>	<b>1,357</b>	<b>677</b>

**Table. I.3: Quantity of NSMs per Borehole – Phase V8 Shallow Angle Boreholes Campaign**

Phase	Borehole	Quantity of NSMs (2-meter)	Quantity of NSMs (4-meter)
<b>V8</b>	<b>17</b>	247	123
	<b>18</b>	237	118
	<b>19</b>	229	114
	<b>20</b>	221	110
	<b>21</b>	216	108
	<b>22</b>	214	107
	<b>23</b>	211	105
	<b>24</b>	202	101
	<b>25</b>	201	100
	<b>26</b>	198	99
	<b>27</b>	196	98
	<b>28</b>	196	98
	<b>29</b>	187	93
	<b>30</b>	187	93
<b>Total</b>	<b>2,942</b>	<b>1,467</b>	

**Table. I.4: Quantity of NSMs per Borehole – Phase V9 Shallow Angle Boreholes Campaign**

Phase	Borehole	Quantity of NSMs (2-meter)	Quantity of NSMs (4-meter)
V9	31	220	110
	32	225	112
	33	231	115
	34	223	111
	35	120	60
	36	131	65
	37	127	63
	38	122	61
	39	107	53
	40	118	59
	41	127	63
	<b>Total</b>	<b>1,751</b>	<b>872</b>

## **APPENDIX J: Networked Smart Markers (NSMs) Shallow Angle Boreholes Campaign Costs Calculation**

Table. J.1 and Table. J.2 present all data required to estimate NSM’s costs.

**Table. J.1: Networked Smart Markers Shallow Angle Boreholes Campaign Layout Data**

Phase	Reader Station	Borehole’s ID	Antenna-Splitter Box Distance [m]	Splitter Box-Reader Distance [m]	Total Distance [m]
Phase V1	Reader 1	1	114.81	50	164.81
		2	79.38		129.38
		3	53.72		103.72
		4	53.51		103.51
		5	77.79		127.79
		6	113.76		163.76
	Reader 2	7	53.77	50	103.77
		8	53.34		103.34
<b>Total</b>	2	-	600.07	100	<b>1,000.07</b>
Phase V4	Reader 3	9	121.11	50	171.11
		10	93.57		143.57
		11	58.70		108.70
		12	46.01		96.01
		13	82.50		132.50
		14	113.54		163.54
	Reader 4	15	57.08	50	107.08
		16	49.76		99.76
<b>Total</b>	2	-	622.26	100	<b>1,022.26</b>

Table. J.1 (CONTINUATION)					
Phase	Reader Station	Borehole's ID	Antenna-Splitter Box Distance [m]	Splitter Box-Reader Distance [m]	Total Distance [m]
Phase V8	Reader 5	17	110.29	50	160.29
		18	75.78		125.78
		19	52.53		102.53
		20	55.24		105.24
		21	81.04		131.04
		22	115.52		165.52
	Reader 6	23	113.95	50	163.95
		24	82.75		132.75
		25	56.08		106.08
		26	57.16		107.16
		27	81.06		131.06
		28	114.98		164.98
	Reader 7	29	53.57	50	103.57
		30	53.41		103.41
<b>Total</b>	3	-	1,103.36	150	1,803.36
Phase V9	Reader 8	31	71.73	50	121.73
		32	75.84		125.84
		33	60.68		110.68
		34	72.02		122.02
	Reader 9	35	86.39	50	136.39
		36	49.96		99.96
		37	56.81		106.81
		38	84.60		134.60
		39	119.54		169.54
		40	87.70		137.70
	Reader 10	41	50.00	50	100.00
<b>Total</b>	3	-	815.27	150	1,365.27
<b>TOTAL</b>	<b>10</b>	-	<b>3,140.97</b>	<b>500.00</b>	<b>5,190.97</b>

**Table. J.2: Networked Smart Markers Costs**

Networked Smart Markers - Unitary Costs	
Antenna [US\$]	505
ENSM with Embedded Accelerometer [US\$]	180
ENSM with Embedded Piezometer [US\$]	540
Reader Station [US\$]	7,026
Signal Cable [US\$/m]	1
Galvanized Conduit Pipe [US\$/m]	2

Table. J.1 presents data about the system’s layout. It contains the quantity of readers per phases and shows which borehole is connected to a certain Reader Station. It also contains the distances form every borehole’s collar to the Splitter Box and from there to its corresponding Reader Station.

The information contained in Table. J.1 and Table. J.2 was used to calculate the costs presented in the following three tables. Table. J.3 presents the costs of a campaign using NSM spaced by 2 meters. Table. J.4 shows the costs of a campaign using NSM with a 4-meter spacing. Finally, Table. J.5 summarizes the previous two tables adding the corresponding drilling costs to each campaign.

**Table. J.3: Networked Smart Markers 2-meter Spacing Shallow Angle Boreholes Campaign Costs**

Networked Smart Markers Shallow Angle Boreholes Campaign 2-meter Spacing							
Phase	Borehole’s ID	NSMs [US\$]	Cable Antenna-Splitter Box [US\$]	Conduit [US\$]	Grout [US\$]	Datalogger [US\$]	Total [US\$]
Phase V1	1	39,925	112.99	230.05	76,561.31	-	-
	2	38,485	78.12	159.06	73,729.59	-	-
	3	37,405	52.86	107.64	71,743.27	-	-
	4	37,225	52.66	107.22	71,338.04	-	-
	5	38,665	76.55	155.87	74,002.41	-	-
	6	26,605	111.95	227.94	50,555.95	-	-
	7	26,065	52.91	107.73	49,796.35	-	-
	8	28,045	52.49	106.88	53,498.01	-	-
	Reader-Splitter Box	0	98.41	200.37	0	-	-
<b>Total</b>	-	272,420	688.93	1,402.77	521,224.9	14,052	809,789
Phase V4	9	34,345	119.18	242.68	65,621.27	-	-
	10	32,185	92.08	187.48	61,337.83	-	-
	11	31,825	57.76	117.62	60,902.54	-	-
	12	31,645	45.28	92.19	60,580.07	-	-
	13	28,945	81.18	165.30	55,176.58	-	-
	14	28,585	111.73	227.50	54,505.89	-	-
	15	29,485	56.17	114.38	56,215.71	-	-
	16	31,285	48.97	99.71	59,662.95	-	-
	Reader-Splitter Box	0	98.41	200.37	0	-	-
<b>Total</b>	-	248,300	710.77	1,447.23	474,002.8	14,052	738,513

Table. J.3 (CONTINUATION)							
Phase	Borehole's ID	NSMs [US\$]	Cable Antenna- Splitter Box [US\$]	Conduit [US\$]	Grout [US\$]	Datalogger [US\$]	Total [US\$]
Phase V8	17	44,965	108.54	220.99	86,226.81	-	-
	18	43,165	74.57	151.84	82,751.99	-	-
	19	41,725	51.70	105.26	79,762.12	-	-
	20	40,285	54.36	110.69	77,086.72	-	-
	21	39,385	79.75	162.38	75,454.13	-	-
	22	39,025	113.68	231.48	74,625.28	-	-
	23	38,485	112.13	228.32	73,512.59	-	-
	24	36,865	81.43	165.81	70,356.56	-	-
	25	36,685	55.19	112.37	70,070.87	-	-
	26	36,145	56.25	114.52	69,147.59	-	-
	27	35,785	79.77	162.43	68,452.99	-	-
	28	35,785	113.15	230.39	68,315.06	-	-
	29	34,165	52.72	107.35	65,236.27	-	-
	30	34,165	52.56	107.02	65,282.25	-	-
	Reader-Splitter Box	0	147.61	300.56	0	-	-
<b>Total</b>	-	536,630	1,233.41	2,511.42	1,026,281	21,078	1,587,734
Phase V9	31	40,105	70.59	143.74	76,806.54	-	-
	32	41,005	74.63	151.96	78,457.52	-	-
	33	42,085	59.71	121.58	80,609.35	-	-
	34	40,645	70.87	144.31	77,900.85	-	-
	35	22,105	85.01	173.10	42,052.80	-	-
	36	24,085	49.17	100.12	45,660.68	-	-
	37	23,365	55.91	113.83	44,451.70	-	-
	38	22,465	83.26	169.53	42,517.52	-	-
	39	19,765	117.63	239.52	37,408.27	-	-
	40	21,745	86.30	175.72	41,143.04	-	-
	41	23,365	49.20	100.19	44,519.75	-	-
	Reader-Splitter Box	0	147.61	300.56	0	-	-
<b>Total</b>	-	320,735	949.91	1,934.16	611,528	21,078	956,225

Table. J.5 table summarizes the previous two tables adding the corresponding drilling costs to each campaign.

**Table. J.4: Networked Smart Markers 4-meter Spacing Shallow Angle Boreholes Campaign Costs**

Networked Smart Markers Shallow Angle Boreholes Campaign 4-meter Spacing							
Phase	Borehole's ID	NSMs [US\$]	Cable Antenna-Splitter Box [US\$]	Conduit [US\$]	Grout [US\$]	Datalogger [US\$]	Total [US\$]
Phase V1	1	20,125	112.99	230.05	78,715.32	-	-
	2	19,405	78.12	159.06	75,805.27	-	-
	3	18,865	52.86	107.64	73,760.20	-	-
	4	18,865	52.66	107.22	73,335.40	-	-
	5	19,585	76.55	155.87	76,078.09	-	-
	6	13,465	111.95	227.94	51,985.44	-	-
	7	13,285	52.91	107.73	51,186.66	-	-
	8	14,185	52.49	106.88	55,005.82	-	-
	<b>Reader-Splitter Box</b>	0	98.41	200.37	0	-	-
<b>Total</b>	-	137,780	688.93	1,402.77	535,872.2	14,052	689,796
Phase V4	9	17,425	119.18	242.68	67,461.97	-	-
	10	16,345	92.08	187.48	63,061.04	-	-
	11	16,165	57.76	117.62	62,606.17	-	-
	12	15,985	45.28	92.19	62,283.69	-	-
	13	14,725	81.18	165.30	56,723.55	-	-
	14	14,545	111.73	227.50	56,033.28	-	-
	15	14,905	56.17	114.38	57,801.85	-	-
	16	15,805	48.97	99.71	61,347.00	-	-
	<b>Reader-Splitter Box</b>	0	98.41	200.37	0	-	-
<b>Total</b>	-	125,900	710.77	1,447.23	487,318.6	14,052	629,429
Phase V8	<b>17</b>	22,645	108.54	220.99	88,654.97	-	-
	<b>18</b>	21,745	74.57	151.84	85,082.24	-	-
	<b>19</b>	21,025	51.70	105.26	82,014.04	-	-
	<b>20</b>	20,305	54.36	110.69	79,260.31	-	-
	<b>21</b>	19,945	79.75	162.38	77,568.98	-	-
	<b>22</b>	19,765	113.68	231.48	76,720.55	-	-
	<b>23</b>	19,405	112.13	228.32	75,588.27	-	-
	<b>24</b>	18,685	81.43	165.81	72,334.33	-	-
	<b>25</b>	18,505	55.19	112.37	72,048.64	-	-
	<b>26</b>	18,325	56.25	114.52	71,086.20	-	-
	<b>27</b>	18,145	79.77	162.43	70,372.02	-	-
	<b>28</b>	18,145	113.15	230.39	70,234.09	-	-
	<b>29</b>	17,245	52.72	107.35	67,076.98	-	-
	<b>30</b>	17,245	52.56	107.02	67,122.95	-	-
	<b>Reader-Splitter Box</b>	0	147.61	300.56	0	-	-
<b>Total</b>	-	271,130	1,233.41	2,511.42	1,055,165	21,078	1,351,117

Table. J.4 (CONTINUATION)							
Phase	Borehole's ID	NSMs [US\$]	Cable Antenna-Splitter Box [US\$]	Conduit [US\$]	Grout [US\$]	Datalogger [US\$]	Total [US\$]
Phase V9	31	20,305	70.59	143.74	78,960.55	-	-
	32	20,665	74.63	151.96	80,670.28	-	-
	33	21,205	59.71	121.58	82,880.86	-	-
	34	20,485	70.87	144.31	80,094.02	-	-
	35	11,305	85.01	173.10	43,227.71	-	-
	36	12,205	49.17	100.12	46,953.08	-	-
	37	11,845	55.91	113.83	45,704.95	-	-
	38	11,485	83.26	169.53	43,712.02	-	-
	39	10,045	117.63	239.52	38,465.69	-	-
	40	11,125	86.30	175.72	42,298.37	-	-
	41	11,845	49.20	100.19	45,772.99	-	-
		Reader-Splitter Box	0	147.61	300.56	0	-
<b>Total</b>	-	162,515	949.91	1,934.16	628,740.5	21,078	815,218

**Table. J.5: Networked Smart Markers 2 and 4-meter Spacing Shallow Angle Boreholes Campaign and Drilling Costs**

	NSMs Shallow Angle Boreholes Campaign 2-meter Spacing		NSMs Shallow Angle Boreholes Campaign 4-meter Spacing	
	Instrumentation Cost [US\$]	Instrumentation plus Drilling Cost [US\$]	Instrumentation Cost [US\$]	Instrumentation plus Drilling Cost [US\$]
Phase V1	809,789	1,707,704	689,796	1,587,711
Phase V4	738,513	1,555,113	629,429	1,446,029
Phase V8	1,587,734	3,355,910	1,351,117	3,119,293
Phase V9	956,225	2,009,759	815,218	1,868,752
<b>Total</b>	<b>4,092,261</b>	<b>8,628,486</b>	<b>3,485,559</b>	<b>8,021,785</b>

## **APPENDIX K: In-Place Inclometers (IPIs) Steep Angle Boreholes Campaign Costs Calculation**

Table. K.1 and Table. K.2 present all data required to estimate the costs for an In-Place Inclometers' steep angle boreholes campaign.

Table. K.1 presents data about the system's layout. It contains the quantity of dataloggers per phases and shows which borehole is connected to a particular datalogger. It also contains the distances from every borehole's collar to its corresponding datalogger. Since every borehole contains 3 IPI

strings and each datalogger can receive information from only 5 strings, there are some boreholes connected to different dataloggers.

**Table. K.1: In-Place Inclinometers Steep Angle Boreholes Campaign Layout Data**

In-Place Inclinometers Steep Angle Boreholes Campaign					
Phase	Borehole's ID	Datalogger ID		Distance from Borehole's Collar to Datalogger [m]	
Phase V8	17	1	-	98.14	-
	18	1	2	105.68	97.07
	19	2	-	100.00	-
	20	2	3	118.00	97.49
	21	3	-	106.40	-
	22	4	-	103.61	-
	23	4	5	103.83	101.93
	24	5	-	100.09	-
	25	5	6	105.45	104.00
	26	6	-	100.00	-
	27	7	-	100.91	-
	28	7	8	101.31	101.25
	29	8	-	99.36	-
	30	8	9	106.69	100.00
<b>Total</b>	-	9		2,051.19	
Phase V9	31	1	-	91.70	-
	32	1	2	111.95	118.78
	33	2	-	100.00	-
	34	2	3	98.26	100.00
	35	4	-	99.89	-
	36	4	5	109.06	68.63
	37	5	-	100.00	-
	38	5	6	135.98	77.20
	39	6	-	108.38	-
	40	7	-	109.25	-
		41	7	8	78.36
<b>Total</b>	-	8		1,607.43	
<b>TOTAL</b>	-	<b>17</b>		<b>3,658.62</b>	

The information contained in Table. K.1 and Table. K.2 was used to calculate the costs presented in the following two tables. Table. K.3 presents all different items involved in the cost estimation for an IPI monitoring

campaign per borehole. Table. K.4 shows the total cost of the campaign with and without considering the drilling cost.

**Table. K.2: In-Place Inclinator's Costs**

In-Place Inclinator's - Unitary Costs	
Casing [US\$/m]	29.67
Casing Coupling [US\$/m]	8.17
Locking Cap [per borehole]	46.00
MEMS IPI Gage Tube [US\$/m]	25.25
Serial IPI Biaxial Sensor [US\$/m]	437.50
Sensor wheels [US\$/m]	73.50
Top Wheel [per borehole]	157.00
IPI Placement Tubing [US\$/m]	16.67
IPI Placement Tubing Coupling [US\$/m]	11.67
In-Line Wheels [US\$/m]	24.50
Jumper Cable [per borehole]	256.50
Bus Cable [per borehole]	189.00
Signal Cable [US\$/m]	5.25
Conduit [US\$/m]	2.00
Datalogger [US\$]	700.00

**Table. K.3: In-Place Inclinator Steep Angle Boreholes Campaign Costs**

In-Place Inclinator Steep Angle Boreholes Campaign						
Phase	Borehole's ID	IPIs [US\$]	Cable IPI-Collar [US\$]	Cable Collar-Datalogger [US\$]	Conduit [US\$]	Datalogger [US\$]
Phase V8	17	79,763.50	7,710.78	-	-	-
	18	79,763.50	6,938.39	-	-	-
	19	79,763.50	6,161.41	-	-	-
	20	79,763.50	5,581.03	-	-	-
	21	79,763.50	7,258.43	-	-	-
	22	79,763.50	7,015.39	-	-	-
	23	79,763.50	6,519.22	-	-	-
	24	79,763.50	5,072.41	-	-	-
	25	79,763.50	4,925.53	-	-	-
	26	79,763.50	4,495.14	-	-	-
	27	79,763.50	4,244.64	-	-	-
	28	79,763.50	4,199.26	-	-	-
	29	79,763.50	2,714.44	-	-	-
30	79,763.50	2,756.62	-	-	-	
<b>Total</b>	-	1,116,689.00	75,592.67	22,472.59	4,110.07	6,300.00

Table. K.3 (CONTINUATION)						
Phase	Borehole's ID	IPIs [US\$]	Cable IPI-Collar [US\$]	Cable Collar-Datalogger [US\$]	Conduit [US\$]	Datalogger [US\$]
Phase V9	31	79,763.50	6,275.60	-	-	-
	32	79,763.50	6,991.06	-	-	-
	33	79,763.50	7,676.05	-	-	-
	34	79,763.50	6,840.33	-	-	-
	35	79,763.50	-13,168.55	-	-	-
	36	79,763.50	-12,797.22	-	-	-
	37	79,763.50	-13,137.26	-	-	-
	38	79,763.50	-13,243.91	-	-	-
	39	79,763.50	-13,605.25	-	-	-
	40	79,763.50	-13,591.32	-	-	-
41	79,763.50	-12,906.66	-	-	-	
<b>Total</b>	-	877,398.50	-64,667.15	17,337.81	3,220.88	5,600.00

**Table. K.4: In-Place Inclinometer Steep Angle Boreholes Campaign and Drilling Costs**

	In-Place Inclinometers Steep Angle Boreholes Campaign	
	Instrumentation Cost [US\$]	Instrumentation plus Drilling Cost [US\$]
Phase V8	1,225,164	2,759,645
Phase V9	838,890	1,590,209
<b>Total</b>	<b>2,064,054</b>	<b>4,349,854</b>

## APPENDIX L: Quantity of MEMS Sensors per Borehole Instrumented Using ShapeAccelArrays (SAAs)

Table. L.1: Quantity of ShapeAccelArray Measuring Points per Borehole

Phase	Borehole	Quantity of Measuring Points in 100-meter SAA	Quantity of Measuring Points in Uppermost SAA	Total Quantity of Measuring Points
V8	17	600	187	787
	18	600	168	768
	19	600	149	749
	20	600	135	735
	21	600	176	776
	22	600	170	770
	23	600	158	758
	24	600	122	722
	25	600	119	719
	26	600	108	708
	27	600	102	702
	28	600	101	701
	29	600	65	665
	30	600	66	666
	<b>Total</b>	<b>8,400</b>	<b>1,826</b>	<b>10,226</b>
V9	31	600	152	752
	32	600	169	769
	33	600	186	786
	34	600	165	765
	35	200	77	277
	36	200	86	286
	37	200	78	278
	38	200	75	275
	39	200	66	266
	40	200	67	267
	41	200	83	283
	<b>Total</b>	<b>3,800</b>	<b>1,204</b>	<b>5,004</b>

## APPENDIX M: ShapeAccelArrays (SAAs) Steep Angle Boreholes Monitoring Campaign Costs Calculation

Table. M.1 and Table. M.2 present all data required to estimate the costs for a ShapeAccelArray's steep angle boreholes campaign. Table. M.1 presents data about the system's layout. It contains the quantity of dataloggers per

phases and shows which borehole is connected to a particular datalogger. It also contains the distances from every borehole's collar to its corresponding datalogger. In this case every datalogger can be connected to a maximum of 20 SAA strings.

**Table. M.1: ShapeAccelArray Steep Angle Boreholes Campaign Layout Data**

ShapeAccelArray Steep Angle Boreholes Campaign			
Phase	Borehole's ID	Datalogger ID	Distance from Borehole's Collar to Datalogger [m]
Phase V8	17	1	2,768.20
	18	1	2,285.30
	19	1	2,100.00
	20	1	2,252.88
	21	1	2,678.26
	22	2	2,417.65
	23	2	2,008.00
	24	2	2,100.00
	25	2	2,333.10
	26	2	2,899.97
	27	3	2,535.18
	28	3	1,883.91
	29	3	2,219.97
	30	3	2,518.28
<b>Total</b>	-	3	33,000.70
Phase V9	31	1	2,337.01
	32	1	2,605.62
	33	1	2,315.75
	34	1	2,388.06
	35	2	1,216.86
	36	2	983.20
	37	2	1,245.51
	38	2	1,577.55
	39	2	1,943.93
	40	2	1,599.53
	41	2	1,267.16
<b>Total</b>	-	2	19,480.17
<b>TOTAL</b>	-	<b>5</b>	<b>52,480.87</b>

The information contained in Table. M.1 and Table. M.2 was used to calculate all costs presented in Table. M.3 and Table. M.4. Table. M.3 presents the different items involved in the cost estimation for a SAA steep angle

boreholes monitoring campaign (per borehole). Table. M.4 shows the total cost of the campaign with and without considering the drilling cost.

**Table. M.2: ShapeAccelArray's Costs**

SAA Steep Angle Boreholes Campaign - Unitary Costs	
ShapeAccelArray [US\$/m]	450.00
Signal Cable [US\$/m]	5.30
Conduit [US\$/m]	2.00
Datalogger [US\$]	4,000.00

**Table. M.3: ShapeAccelArray Steep Angle Boreholes Campaign Costs**

ShapeAccelArray Steep Angle Boreholes Campaign							
Phase	Borehole's ID	SAA's [US\$]	Cable SAA-Collar [US\$]	Cable Collar-Datalogger [US\$]	Conduit [US\$]	Sand [US\$]	Datalogger [US\$]
Phase V8	17	177,075.00	3,047.63	2,768.20	264.13	104.31	-
	18	172,800.00	2,898.00	2,285.30	218.06	101.79	-
	19	168,525.00	2,748.38	2,100.00	200.37	99.27	-
	20	165,375.00	2,638.13	2,252.88	214.96	97.42	-
	21	174,600.00	2,961.00	2,678.26	255.55	102.85	-
	22	173,250.00	2,913.75	2,417.65	230.68	102.05	-
	23	170,550.00	2,819.25	2,008.00	191.60	100.46	-
	24	162,450.00	2,535.75	2,100.00	200.37	95.69	-
	25	161,775.00	2,512.13	2,333.10	222.62	95.30	-
	26	159,300.00	2,425.50	2,899.97	276.71	93.84	-
	27	157,950.00	2,378.25	2,535.18	241.90	93.04	-
	28	157,725.00	2,370.38	1,883.91	179.76	92.91	-
29	149,625.00	2,086.88	2,219.97	211.82	88.14	-	
30	149,850.00	2,094.75	2,518.28	240.29	88.27	-	
<b>Total</b>	-	2,300,850.0	36,429.8	33,000.7	3,148.8	1,355.34	12,000.0
Phase V9	31	169,200.00	2,772.00	2,337.01	222.99	99.67	-
	32	173,025.00	2,905.88	2,605.62	248.62	101.92	-
	33	176,850.00	3,039.75	2,315.75	220.96	104.18	-
	34	172,125.00	2,874.38	2,388.06	227.86	101.39	-
	35	62,325.00	202.13	1,216.86	232.22	36.71	-
	36	64,350.00	225.75	983.20	187.63	37.91	-
	37	62,550.00	204.75	1,245.51	237.68	36.85	-
	38	61,875.00	196.88	1,577.55	301.05	36.45	-
	39	59,850.00	173.25	1,943.93	370.97	35.26	-
	40	60,075.00	175.88	1,599.53	305.24	35.39	-
41	63,675.00	217.88	1,267.16	241.82	37.51	-	
<b>Total</b>	-	1,125,900.0	12,988.5	19,480.2	2,797.0	663.22	8,000.0

**Table. M.4: ShapeAccelArray Steep Angle Boreholes Campaign and Drilling Costs**

	ShapeAccelArray Steep Angle Boreholes Campaign	
	Instrumentation Cost [US\$]	Instrumentation plus Drilling Cost [US\$]
Phase V8	2,386,785	3,921,266
Phase V9	1,169,829	1,921,148
<b>Total</b>	<b>3,556,614</b>	<b>5,842,414</b>

## **APPENDIX N: Quantity of Networked Smart Markers (NSMs) in Each Phase for a Steep Angle Boreholes Campaign**

**Table. N.1: Quantity of NSMs per Borehole – Phase V1 Steep Angle Boreholes Campaign**

Phase	Borehole	Quantity of NSMs (2-meter spacing)	Quantity of NSMs (4-meter spacing)
<b>V1</b>	<b>1</b>	160	80
	<b>2</b>	159	79
	<b>3</b>	158	79
	<b>4</b>	157	78
	<b>5</b>	158	79
	<b>6</b>	112	56
	<b>7</b>	109	54
	<b>8</b>	111	55
	<b>Total</b>	<b>1,124</b>	<b>560</b>

**Table. N.2: Quantity of NSMs per Borehole – Phase V4 Steep Angle Boreholes Campaign**

Phase	Borehole	Quantity of NSMs (2-meter spacing)	Quantity of NSMs (4-meter spacing)
<b>V4</b>	<b>9</b>	130	65
	<b>10</b>	122	61
	<b>11</b>	124	62
	<b>12</b>	125	62
	<b>13</b>	115	57
	<b>14</b>	114	57
	<b>15</b>	117	58
	<b>16</b>	121	60
	<b>Total</b>	<b>968</b>	<b>482</b>

**Table. N.3: Quantity of NSMs per Borehole – Phase V8 Steep Angle Boreholes Campaign**

Phase	Borehole	Quantity of NSMs (2-meter spacing)	Quantity of NSMs (4-meter spacing)
V8	17	196	98
	18	192	96
	19	187	93
	20	183	91
	21	194	97
	22	192	96
	23	189	94
	24	180	90
	25	179	89
	26	177	88
	27	175	87
	28	175	87
	29	166	83
	30	166	83
	<b>Total</b>	<b>2,551</b>	<b>1,272</b>

**Table. N.4: Quantity of NSMs per Borehole – Phase V9 Steep Angle Boreholes Campaign**

Phase	Borehole	Quantity of NSMs (2-meter spacing)	Quantity of NSMs (4-meter spacing)
V9	31	188	94
	32	192	96
	33	196	98
	34	191	95
	35	69	34
	36	71	35
	37	69	34
	38	68	34
	39	66	33
	40	66	33
	41	70	35
		<b>Total</b>	<b>1,246</b>

## APPENDIX O: Networked Smart Markers (NSMs) Steep Angle Boreholes Campaign Costs Calculation

Table. O.1 and Table. O.2 present all data required to estimate the costs of a NSM steep angle boreholes monitoring campaign. Table. O.1 presents data about the system's layout. It contains the quantity of readers per phases and shows which borehole is connected to a certain Reader. It also contains the distances form every borehole's collar to the Splitter Box and from there to the Reader.

**Table. O.1: Networked Smart Markers Steep Angle Boreholes Campaign Layout Data**

Phase	Reader Station	Borehole's ID	Antenna to Splitter Box Distance [m]	Splitter Box to Reader Distance [m]	Total Distance [m]
Phase V1	Reader 1	1	114.81	50	164.81
		2	79.38		129.38
		3	53.72		103.72
		4	53.51		103.51
		5	77.79		127.79
		6	113.76		163.76
	Reader 2	7	53.77	50	103.77
		8	53.34		103.34
<b>Total</b>	2	-	600.07	100	1,000.07
Phase V4	Reader 3	9	121.11	50	171.11
		10	93.57		143.57
		11	58.70		108.70
		12	46.01		96.01
		13	82.50		132.50
		14	113.54		163.54
	Reader 4	15	57.08	50	107.08
		16	49.76		99.76
<b>Total</b>	2	-	622.26	100	1,022.26
Phase V8	Reader 5	17	110.29	50	160.29
		18	75.78		125.78
		19	52.53		102.53
		20	55.24		105.24
		21	81.04		131.04
		22	115.52		165.52
	Reader 6	23	113.95	50	163.95
		24	82.75		132.75
		25	56.08		106.08
		26	57.16		107.16
		27	81.06		131.06
		28	114.98		164.98
	Reader 7	29	53.57	50	103.57
30		53.41	103.41		
<b>Total</b>	3	-	1,103.36	150	1,803.36

Table. O.1 (CONTINUATION)					
Phase	Reader Station	Borehole's ID	Antenna to Splitter Box Distance [m]	Splitter Box to Reader Distance [m]	Total Distance [m]
Phase V9	Reader 8	31	71.73	50	121.73
		32	75.84		125.84
		33	60.68		110.68
		34	72.02		122.02
	Reader 9	35	86.39	50	136.39
		36	49.96		99.96
		37	56.81		106.81
		38	84.60		134.60
		39	119.54		169.54
	40	87.70	137.70		
	Reader 10	41	50.00	50	100.00
<b>Total</b>	3	-	815.27	150	1,365.27
<b>TOTAL</b>	<b>10</b>	-	<b>3,140.97</b>	<b>500</b>	<b>5,190.97</b>

The information contained in Table. O.1 and Table. O.2 was used to calculate the costs presented in the following three tables. Table. O.3 presents the costs of a campaign using NSM spaced by 2 meters. Table. O.4 shows the costs of a campaign using NSM with a 4-meter spacing. Table. O.5 summarizes the previous two tables adding the drilling costs to each campaign.

**Table. O.2: Networked Smart Markers Costs**

Unitary Costs	
Antenna [US\$]	505
ENSM with Embedded Accelerometer [US\$]	180
ENSM with Embedded Piezometer [US\$]	540
Reader Station [US\$]	7,026
Signal Cable [US\$/m]	1
Galvanized Conduit Pipe [US\$/m]	2

**Table. O.3: Networked Smart Markers 2-meter Spacing Steep Angle Boreholes Campaign Costs**

NSMs 2-meter Spacing							
Phase	Borehole's ID	NSMs [US\$]	Cable Antenna-Splitter Box [US\$]	Conduit [US\$]	Grout [US\$]	Datalogger [US\$]	Total [US\$]
Phase V1	1	29,305.00	112.99	230.054	55,997.70	-	-
	2	29,125.00	78.12	159.057	55,389.08	-	-
	3	28,945.00	52.86	107.639	55,052.81	-	-
	4	28,765.00	52.66	107.222	55,000.67	-	-
	5	28,945.00	76.55	155.865	55,248.85	-	-
	6	20,665.00	111.95	227.938	39,287.65	-	-
	7	20,125.00	52.91	107.733	38,166.31	-	-
	8	20,485.00	52.49	106.884	38,882.61	-	-
	Reader-Splitter Box	-	98.41	200.37	0	-	-
<b>Total</b>	-	206,360	688.94	1,402.7	393,025.7	14,052	615,529
Phase V4	9	23,905.00	119.18	242.68	45,455.16	-	-
	10	22,465.00	92.08	187.48	42,842.29	-	-
	11	22,825.00	57.76	117.62	43,407.05	-	-
	12	23,005.00	45.28	92.19	43,836.55	-	-
	13	21,205.00	81.18	165.30	40,056.09	-	-
	14	21,025.00	111.73	227.50	39,963.67	-	-
	15	21,565.00	56.17	114.38	40,909.21	-	-
	16	22,285.00	48.97	99.71	42,341.98	-	-
	Reader-Splitter Box	-	98.41	200.37	0	-	-
<b>Total</b>	-	178,280	710.76	1,447.2	338,812	14,052	533,302
Phase V8	17	35,785.00	108.54	220.99	68,539.05	-	-
	18	35,065.00	74.57	151.84	66,883.39	-	-
	19	34,165.00	51.70	105.26	65,237.01	-	-
	20	33,445.00	54.36	110.69	64,012.41	-	-
	21	35,425.00	79.75	162.38	67,562.72	-	-
	22	35,065.00	113.68	231.48	67,056.26	-	-
	23	34,525.00	112.13	228.32	66,001.12	-	-
	24	32,905.00	81.43	165.81	62,929.32	-	-
	25	32,725.00	55.19	112.37	62,619.17	-	-
	26	32,365.00	56.25	114.52	61,692.12	-	-
	27	32,005.00	79.77	162.43	61,168.92	-	-
	28	32,005.00	113.15	230.39	61,067.04	-	-
	29	30,385.00	52.72	107.35	57,909.91	-	-
	30	30,385.00	52.56	107.02	58,004.62	-	-
Reader-Splitter Box	-	147.61	300.56	0	-	-	
<b>Total</b>	-	466,250	1,233.41	2,511.4	890,683	21,078	1,381,756

Table. O.3 (CONTINUATION)							
Phase	Borehole's ID	NSMs [US\$]	Cable Antenna-Splitter Box [US\$]	Conduit [US\$]	Grout [US\$]	Datalogger [US\$]	Total [US\$]
Phase V9	31	34,345.00	70.59	143.74	65,473.78	-	-
	32	35,065.00	74.63	151.96	67,001.64	-	-
	33	35,785.00	59.71	121.58	68,461.08	-	-
	34	34,885.00	70.87	144.31	66,682.84	-	-
	35	12,925.00	85.01	173.10	24,152.64	-	-
	36	13,285.00	49.17	100.12	24,947.09	-	-
	37	12,925.00	55.91	113.83	24,222.89	-	-
	38	12,745.00	83.26	169.53	24,003.03	-	-
	39	12,385.00	117.63	239.52	23,231.01	-	-
	40	12,385.00	86.30	175.72	23,262.27	-	-
	41	13,105.00	49.20	100.19	24,720.98	-	-
	Reader-Splitter Box	-	147.61	300.56	0	-	-
<b>Total</b>	-	229,835	949.89	1,934.2	436,159.3	21,078	689,956

**Table. O.4: Networked Smart Markers 4-meter Spacing Steep Angle Boreholes Campaign Costs**

NSMs 4-meter Spacing							
Phase	Borehole's ID	NSMs [US\$]	Cable Antenna-Splitter Box [US\$]	Conduit [US\$]	Grout [US\$]	Datalogger [US\$]	Total [US\$]
Phase V1	1	14,905	112.99	230.05	57,564.25	-	-
	2	14,725	78.12	159.06	56,955.63	-	-
	3	14,725	52.86	107.64	56,599.78	-	-
	4	14,545	52.66	107.22	56,547.64	-	-
	5	14,725	76.55	155.87	56,795.82	-	-
	6	10,585	111.95	227.94	40,384.24	-	-
	7	10,225	52.91	107.73	39,243.32	-	-
	8	10,405	52.49	106.88	39,979.20	-	-
	Reader-Splitter Box	0	98.41	200.37	0	-	-
<b>Total</b>	-	104,840	688.94	1,402.7	404,070	14,052	525,054
Phase V4	9	12,205	119.18	242.68	46,727.99	-	-
	10	11,485	92.08	187.48	44,036.78	-	-
	11	11,665	57.76	117.62	44,621.13	-	-
	12	11,665	45.28	92.19	45,070.21	-	-
	13	10,765	81.18	165.30	41,191.84	-	-
	14	10,765	111.73	227.50	41,079.84	-	-
	15	10,945	56.17	114.38	42,064.54	-	-
	16	11,305	48.97	99.71	43,536.48	-	-
	Reader-Splitter Box	0	98.41	200.37	0	-	-
<b>Total</b>	-	90,800	710.76	1,447.2	348,328	14,052	455,338

**Table. O.4 (CONTINUATION)**

Phase	Borehole's ID	NSMs [US\$]	Cable Antenna-Splitter Box [US\$]	Conduit [US\$]	Grout [US\$]	Datalogger [US\$]	Total [US\$]
Phase V8	17	18,145	108.54	220.99	70,458.08	-	-
	18	17,785	74.57	151.84	68,763.26	-	-
	19	17,245	51.70	105.26	67,077.71	-	-
	20	16,885	54.36	110.69	65,813.94	-	-
	21	17,965	79.75	162.38	69,462.17	-	-
	22	17,785	113.68	231.48	68,936.12	-	-
	23	17,425	112.13	228.32	67,861.40	-	-
	24	16,705	81.43	165.81	64,691.69	-	-
	25	16,525	55.19	112.37	64,381.54	-	-
	26	16,345	56.25	114.52	63,434.91	-	-
	27	16,165	79.77	162.43	62,892.13	-	-
	28	16,165	113.15	230.39	62,790.25	-	-
	29	15,445	52.72	107.35	59,535.21	-	-
	30	15,445	52.56	107.02	59,629.92	-	-
		<b>Reader-Splitter Box</b>	0	147.61	300.56	0	-
<b>Total</b>	-	236,030	1,233.41	2,511.4	915,728	21,078	1,176,581
Phase V9	31	17,425	70.59	143.74	67,314.49	-	-
	32	17,785	74.63	151.96	68,881.50	-	-
	33	18,145	59.71	121.58	70,380.11	-	-
	34	17,605	70.87	144.31	68,562.71	-	-
	35	6,625	85.01	173.10	24,838.00	-	-
	36	6,805	49.17	100.12	25,652.04	-	-
	37	6,625	55.91	113.83	24,908.25	-	-
	38	6,625	83.26	169.53	24,668.82	-	-
	39	6,445	117.63	239.52	23,877.22	-	-
	40	6,445	86.30	175.72	23,908.48	-	-
	41	6,805	49.20	100.19	25,406.35	-	-
		<b>Reader-Splitter Box</b>	0	147.61	300.56	0	-
<b>Total</b>	-	117,335	949.89	1,934.2	448,398	21,078	589,695

**Table. O.5: Networked Smart Markers 2 and 4-meter Spacing Steep Angle Boreholes Campaign and Drilling Costs**

	2-meter Spacing		4-meter Spacing	
	Instrumentation Cost [US\$]	Instrumentation plus Drilling Cost [US\$]	Instrumentation Cost [US\$]	Instrumentation plus Drilling Cost [US\$]
<b>Phase V1</b>	615,529	1,292,586	525,054	1,202,111
<b>Phase V4</b>	533,302	1,116,936	455,338	1,038,973
<b>Phase V8</b>	1,381,756	2,916,237	1,176,581	2,711,062
<b>Phase V9</b>	689,956	1,441,275	589,695	1,341,014
<b>Total</b>	<b>3,220,544</b>	<b>6,767,035</b>	<b>2,746,669</b>	<b>6,293,160</b>

# **APPENDIX P: Implementation of Novel Subsurface Deformation Sensing Device for Open Pit Slope Stability Monitoring - The Networked Smart Markers (NSMs) System**

## **Authors**

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## **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 analysing 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.

## **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.

## **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).

## **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.

## **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. P.1). 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. P.1: Networked Smart Marker**

### Networked Smart Markers (NSM)

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.

## **Case Study**

### **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. P.2).

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. P.2), 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.

### **System Operation**

The system performed well for approximately 6 weeks. Figure. P.3 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). Coloured boxes indicate signal strength for neighbouring 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.

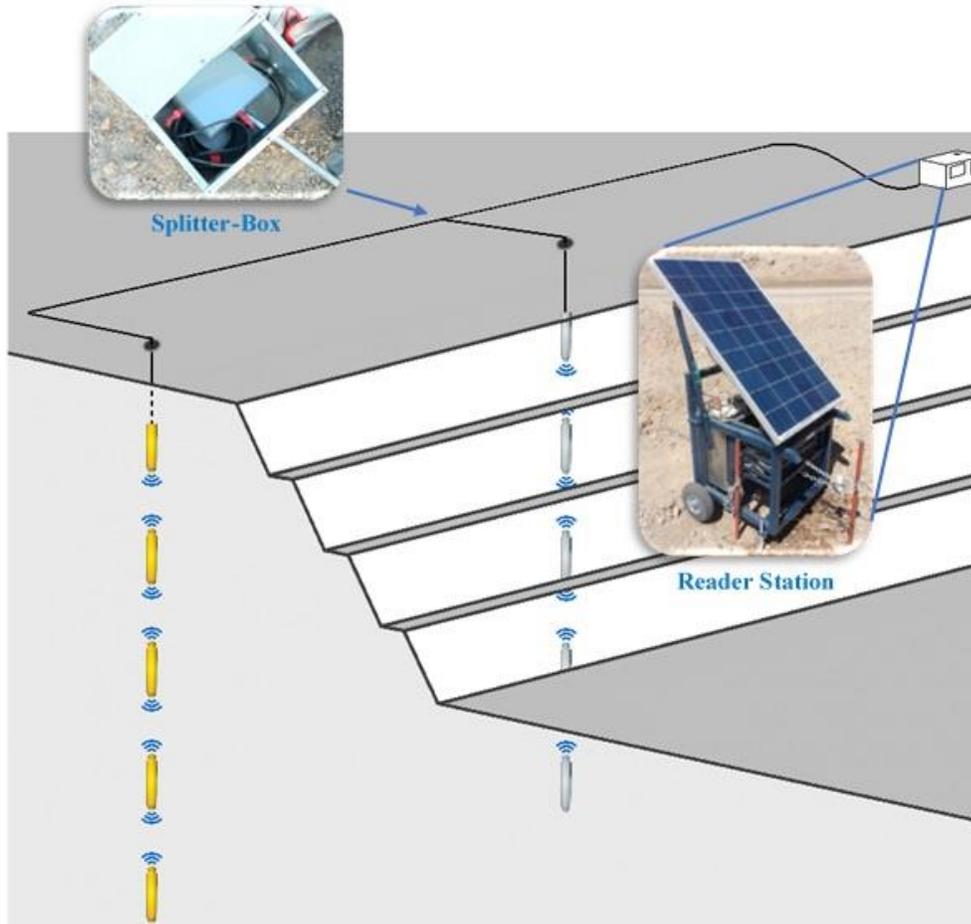


Figure. P.2: First NSM installation diagram

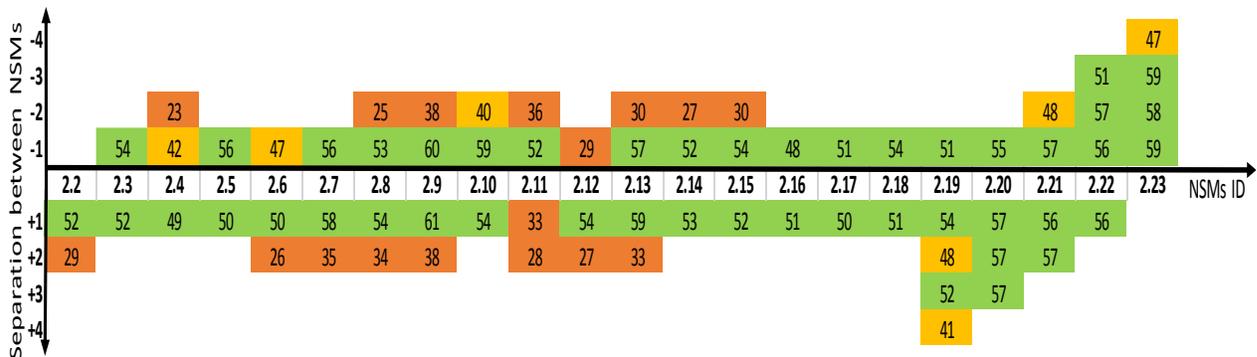


Figure. P.3: NSM's connectivity

Figure. P.4 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. P.4 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. P.4: Both ways signal strength**

The data in Figure. P.3 and Figure. P.4 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. P.1 provides a summary of detected faults and/or deduced reasons for the interruptions of the system functionality.

**Table. P.1: Troubleshooting summary**

<b>Detected Fault</b>	<b>Possibility</b>	<b>Comment</b>	<b>Likelihood Contribution</b>
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. P.2 provides a summary of improvements made to the system prior to the second installation, which were deemed of high importance after the evaluation.

**Table. P.2: System improvements**

<b>Possible Issue</b>	<b>Improvements</b>
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.

### **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 times 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.

### **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.

## **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.

## **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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# **APPENDIX Q: Understanding of Rock Mass Behaviour through the Development of an Integrated Sensing Platform**

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## **ABSTRACT**

This paper summarises 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 behaviour. 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 behaviour.

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 behaviour (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.

## **INTRODUCTION**

A good understanding of rock mass behaviour 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.

## **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 (eg 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 optimise the benefit of the mining exploitation. As the mineralised 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. Q.1 and Figure. Q.2), 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).

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).

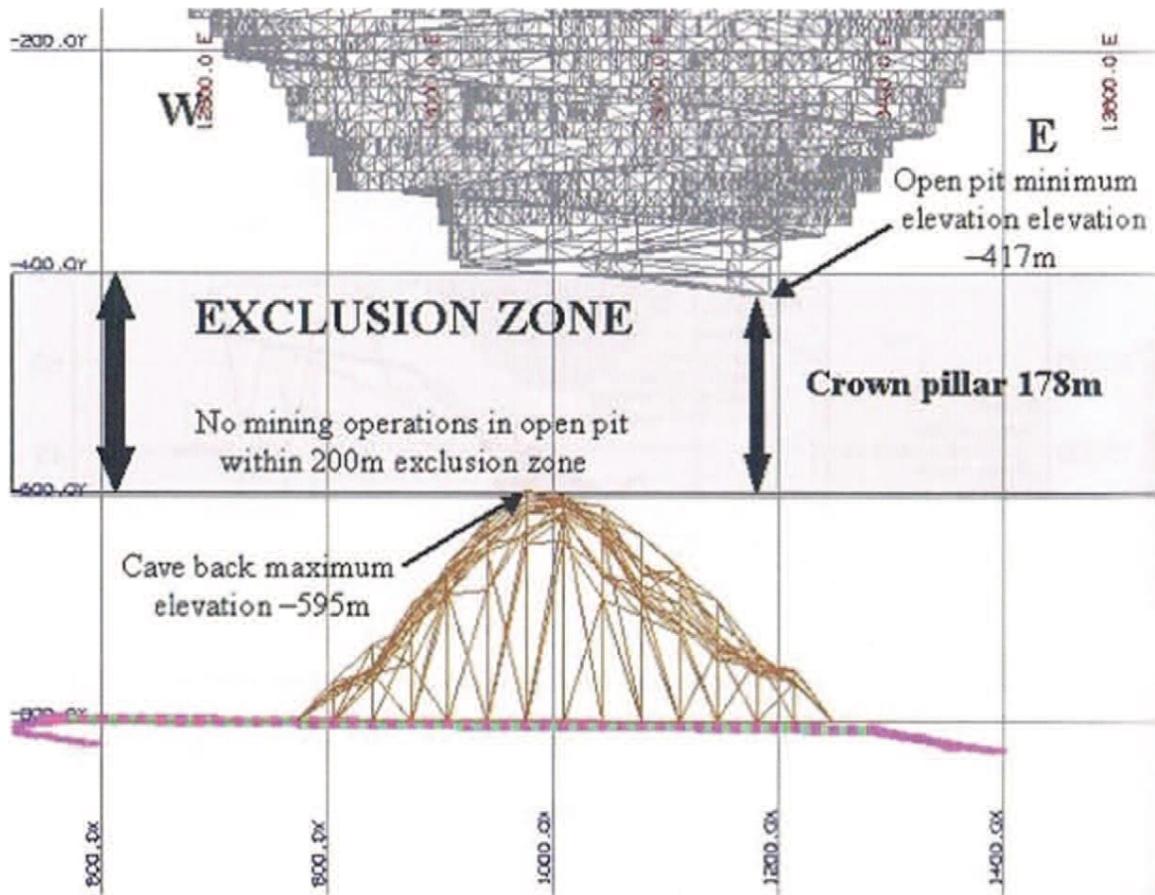


Figure. Q.1: Crown pillar defined at Palabora mine (after Glazer and Hepworth, 2004)

### 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 neighbouring 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. Q.3). 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.

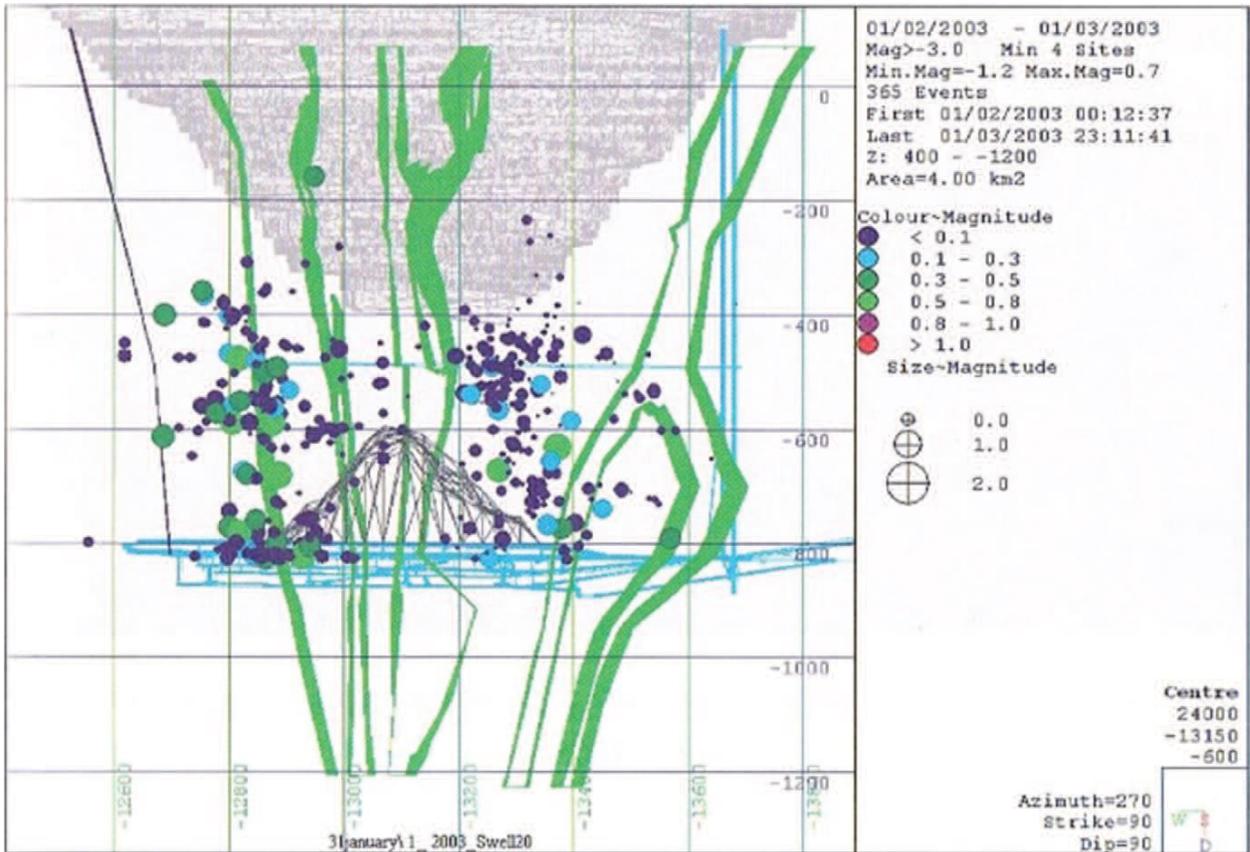


Figure. Q.2: Seismic monitoring at the site (after Glazer and Hepworth, 2004)

### 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

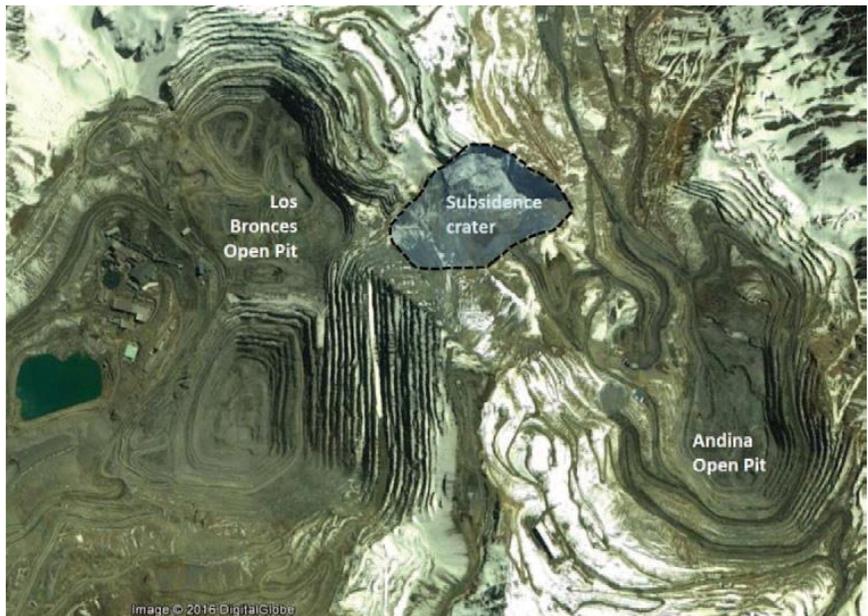


Figure. Q.3: Plan view of Los Bronces-Andina interaction area (after Google Maps, 2015)

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. Q.4.

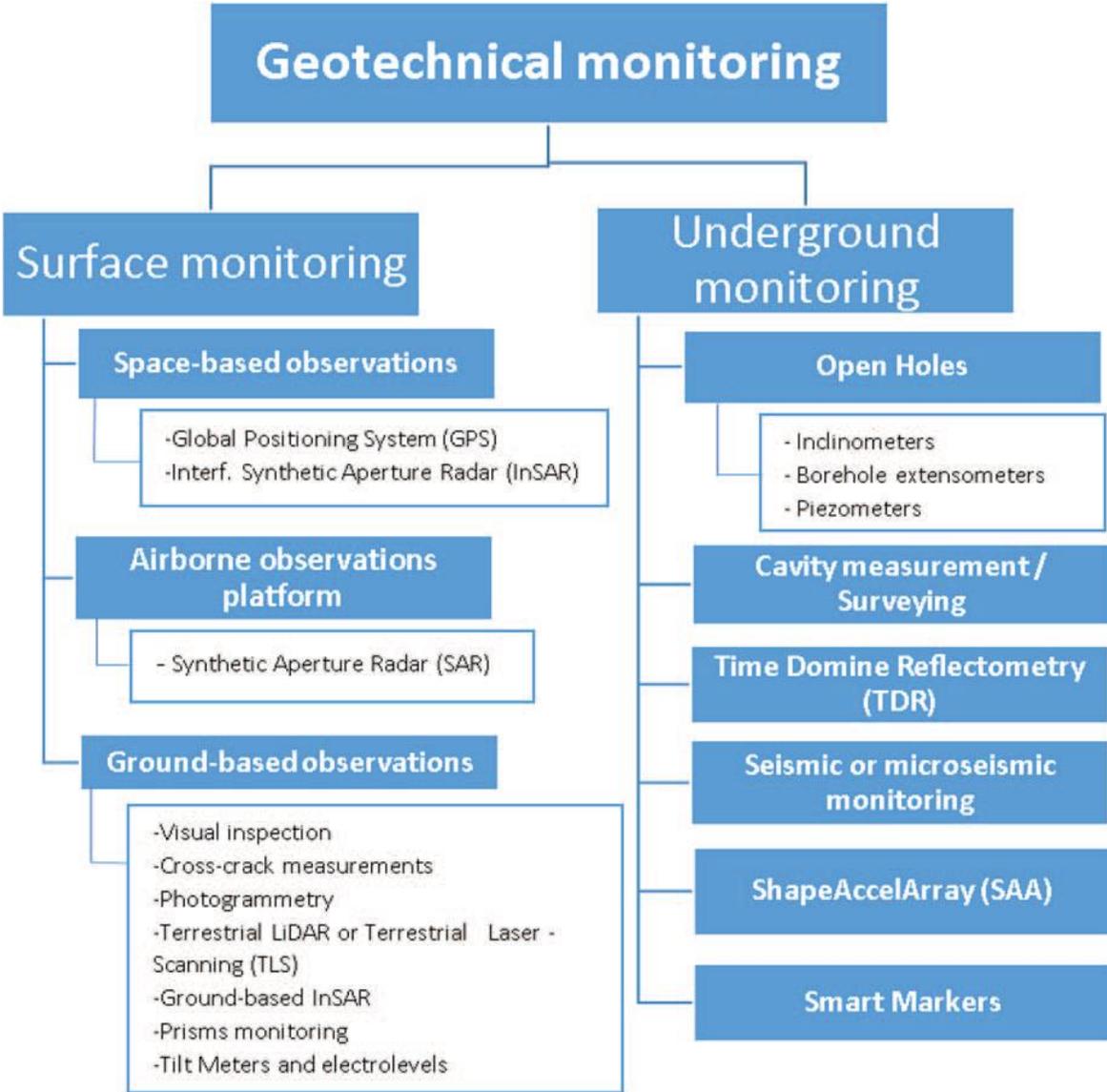


Figure. Q.4: Summary of surface and underground geotechnical monitoring methods

## **Surface monitoring**

As shown in Figure. Q.4, 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 Codelco's Rio Blanco mine. InSAR helps to identify the general areas of movement at different scales (in the range of metres, centimetres and millimetres), 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. Q.1, Table. Q.2 and Table. Q.3 respectively. 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).

## **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 microseismic monitoring.

**Table. Q.1: Description of technologies for space-based monitoring**

<b>Technique</b>	<b>Description</b>	<b>Strengths and drawbacks</b>	<b>Precision</b>
Global Positioning system (GPS)	<p>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 of the satellites.</p> <p>These distances allow for precise determination of the position of the receiver.</p>	<ul style="list-style-type: none"> <li>• Line of sight is not required between receivers.</li> <li>• Not dependent on weather conditions.</li> <li>• Requires mine personnel to go to all the different points to be surveyed.</li> <li>• Requires unobstructed line of sight to four or more GPS satellites.</li> <li>• Satellite visibility is obstructed in deep point of the pit.</li> </ul>	Under 20 mm
Interferometric synthetic aperture radar (InSAR)	<p>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.</p>	<ul style="list-style-type: none"> <li>• Works in all weather conditions.</li> <li>• Allows monitoring of inaccessible sectors of the pit.</li> <li>• Good technique for monitoring broad areas.</li> <li>• Dependent on international satellites' availability for data gathering.</li> <li>• May not produce good results when monitoring steep zones.</li> <li>• Real-time monitoring is not feasible.</li> <li>• If displacement between successive SAR images is higher than 23 cm,</li> <li>• InSAR may not be able to quantify it.</li> </ul>	On the scale of centimetres to millimetres

These methods, which are described in detail in Table. Q.4, 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, Widiyanto 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.

**Table. Q.2: Description of technologies for airborne monitoring**

<b>Technique</b>	<b>Description</b>	<b>Strengths and drawbacks</b>	<b>Precision</b>
Synthetic aperture radar (SAR)	Uses the same principles as InSAR but the instrument is mounted on an airplane.	<ul style="list-style-type: none"> <li>• Independency from international satellites for data gathering.</li> <li>• Uses a relatively unstable platform.</li> <li>• Very important to know the exact location of the plane for best results.</li> </ul>	-

## **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.

### **Sensors developments and applications**

#### 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. Q.5). 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).

**Table. Q.3: Description of technologies for ground-based monitoring**

<b>Technique</b>	<b>Description</b>	<b>Strengths and drawbacks</b>	<b>Precision</b>
Visual inspection	Visual observation of the studied zone to detect the occurrence of cracks or evidence displacements.	<ul style="list-style-type: none"> <li>• Requires experienced geotechnical staff.</li> <li>• Must be complemented by instrumentation to provide a quantitative basis for defining the exact amount of movement.</li> </ul>	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 a measuring tape, Vernier calliper or micrometer to determine the crack aperture.	<ul style="list-style-type: none"> <li>• Provides an insight into in-ground movements.</li> <li>• Simple monitoring devices.</li> <li>• Potentially unstable working area.</li> </ul>	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 (i.e. orientation, length and spacing) can be determined using this technique.	<ul style="list-style-type: none"> <li>• Integration of photogrammetry with mine planning software systems makes it possible to use the data in real time for mine design, mine planning and mine operating purposes.</li> <li>• Provides a permanent 3D record of the mapped areas.</li> <li>• Provides low-cost geological mapping.</li> <li>• Only one person needed to use the technique.</li> <li>• Digital imaging systems require ground proofing and cannot be used to determine the physical features of the structures.</li> </ul>	Accuracy ranges from 2 cm at a distance of 50 m to 10 cm at distances of up to 3 km
LiDAR	This technique uses laser pulses reflected by the surface to be measured to create a 3D representation of the scanned target with a density of >10 000 points/m <sup>2</sup> . 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.	<ul style="list-style-type: none"> <li>• Able to create a highly accurate 3D digital elevation model.</li> <li>• High-resolution images.</li> <li>• Relatively inexpensive.</li> <li>• Flexible data collection and processing system.</li> <li>• Can be used to monitor relatively small areas (from 1 to 10 km<sup>2</sup>).</li> <li>• Need for experienced personnel to understand the limitations of the terrestrial laser scanning.</li> <li>• Requires a proper data collection campaign to avoid shadowed regions.</li> </ul>	Systematic errors are ±25 mm at 1000 m, random errors are generally between 0 and 10 mm

<b>Table. Q.3 (CONTINUATION)</b>			
<b>Technique</b>	<b>Description</b>	<b>Strengths and drawbacks</b>	<b>Precision</b>
Ground-based interferometric synthetic aperture radar	Uses the same principle as the satellite-based method but the images are acquired by a radar moving along a rail a couple of kilometres away from the area of interest. The monitored zone can be up to 4 km from the radar.	<ul style="list-style-type: none"> <li>• Measurements can be taken during day and night and in any weather conditions.</li> <li>• Provides high spatial density of observations.</li> <li>• Fast (5–10 min monitoring period).</li> <li>• Short range (&lt;5 km)</li> <li>• Limited field of view, which may cause shadowing problems.</li> <li>• Not intended to monitor broad areas.</li> </ul>	Resolution of about 0.5–4 m, depending on the monitoring distance and the atmospheric conditions, precision in the scale of millimetres
Robot total stations (prisms monitoring)	Robot total stations are devices that combine a theodolite with electromagnetic distance measurement 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.	<ul style="list-style-type: none"> <li>• Ability to provide 3D position of the point of interest.</li> <li>• Unable to monitor during misty weather.</li> <li>• Installation of monitoring prisms at a likely unstable slope zone or area of interest.</li> </ul>	Accuracy from 0.6 to 3 mm, range from 1000–3000 m
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.	<ul style="list-style-type: none"> <li>• High-precision measurements obtained.</li> <li>• Used to monitor movements that are expected to contain a rotational component.</li> <li>• Expensive in comparison with radar monitoring. A 500 × 500 m area costs approximately \$36 000/month.</li> <li>• Requires additional calibration after some time to maintain accuracy.</li> </ul>	1 nanoradian (0.0002 arcseconds)

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

### 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.

**Table. Q.4: Technologies applied in the mining industry for underground monitoring**

<b>Technique</b>	<b>Description</b>	<b>Strengths and drawbacks</b>	<b>Precision</b>
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.	<ul style="list-style-type: none"> <li>• Very detailed displacement path.</li> <li>• Short lifespan in large boreholes and big ground movements due to breakage of the casing.</li> <li>• Very useful to study gradual inclination changes.</li> </ul>	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.	<ul style="list-style-type: none"> <li>• Automated and remote readings.</li> <li>• Possible to measure multiple points.</li> <li>• Complicated to install in long boreholes.</li> </ul>	Up to 0.005 mm
Piezometers	Designed to measure fluid or pore-water pressure in a variety of applications. They are typically installed in boreholes in in situ soils, rocks, foundations or earth/rock fills and are grouted with a specific mixture. Closed piezometers are the most commonly used in the mining environment.	<ul style="list-style-type: none"> <li>• Acceptable time response to pressure variations.</li> <li>• Easy to adapt to an automatic recording device.</li> <li>• Grouting properties are critical to preventing surface water from contaminating piezometer data.</li> <li>• Long lines are susceptible to damage due to borehole movements.</li> <li>• Not possible to check the calibration of the instrument once installed.</li> </ul>	±0.1 per cent 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 a combination of them.	<ul style="list-style-type: none"> <li>• Conventional survey techniques are very reliable methods if well done.</li> <li>• In most cases, they require an experienced operator to gather the information correctly.</li> </ul>	Depends on the method used
Seismic or Microseismic monitoring	Microseismic 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 by different seismograms, the seismic event's origin time, source parameters, deformation and location can be estimated. Geophones are usually used in mining applications.	<ul style="list-style-type: none"> <li>• Very unique system to locate fractures developing within the rock mass.</li> <li>• Geophones don't need power to operate.</li> <li>• Signal degradation if the sensors are far from the target.</li> <li>• Only to respond to high-frequency waves.</li> <li>• Geophones are used to triangulate the position of the movement that originated the measured wave.</li> </ul>	For an Institute of Mine Seismology 4.5 Hz geophone, the distortion measurement frequency is 12 Hz

<b>Table. Q.4 (CONTINUATION)</b>			
<b>Technique</b>	<b>Description</b>	<b>Strengths and drawbacks</b>	<b>Precision</b>
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, the TDR detects the exact distance to that point.	<ul style="list-style-type: none"> <li>• High precision on fault location.</li> <li>• Inability to measure large ground displacements due to the breakage of the wires and thus loss of signal.</li> <li>• Useful to sense localised and concentrated shear strain.</li> </ul>	±1 per cent of the cable distance
ShapeAccelArray (SAA)	Electronic instruments with triaxial micro-electromechanical system accelerometers inside a 30 cm rigid segment. Several segments can be put together to measure 3D ground deformation in depths from 30 cm to 100 m.	<ul style="list-style-type: none"> <li>• Installed in vertical holes to obtain horizontal deformation data in real time.</li> <li>• Also possible to install horizontally to measure vertical deformation.</li> </ul>	±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.	<ul style="list-style-type: none"> <li>• Each device has its own identifying ID, allowing its location to be pinpointed when installed in the rock mass.</li> <li>• When recovered in a drawpoint, the marker is identified by a reader.</li> <li>• Ore flow can be inferred from the initial and final positions of the devices.</li> <li>• The actual path of the marker from its installation position to its extraction position (drawpoint) cannot be registered.</li> </ul>	Qualitative

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. Q.6 and Figure. Q.7). The semi-horizontal axis indicates the marker's number, organised 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. 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. Q.6 and Figure. Q.7 show the average value of one week compared with the average values obtained during the subsequent five weeks (six weeks are represented in total).



Figure. Q.5: Smart Marker sensor

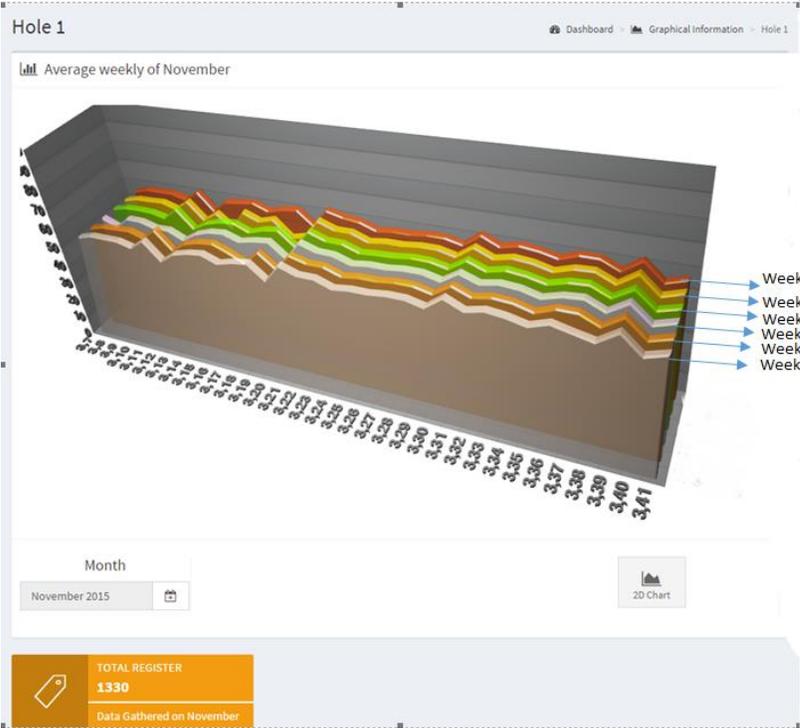


Figure. Q.6: Networked Smart Markers 3D data representation of six weeks

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.

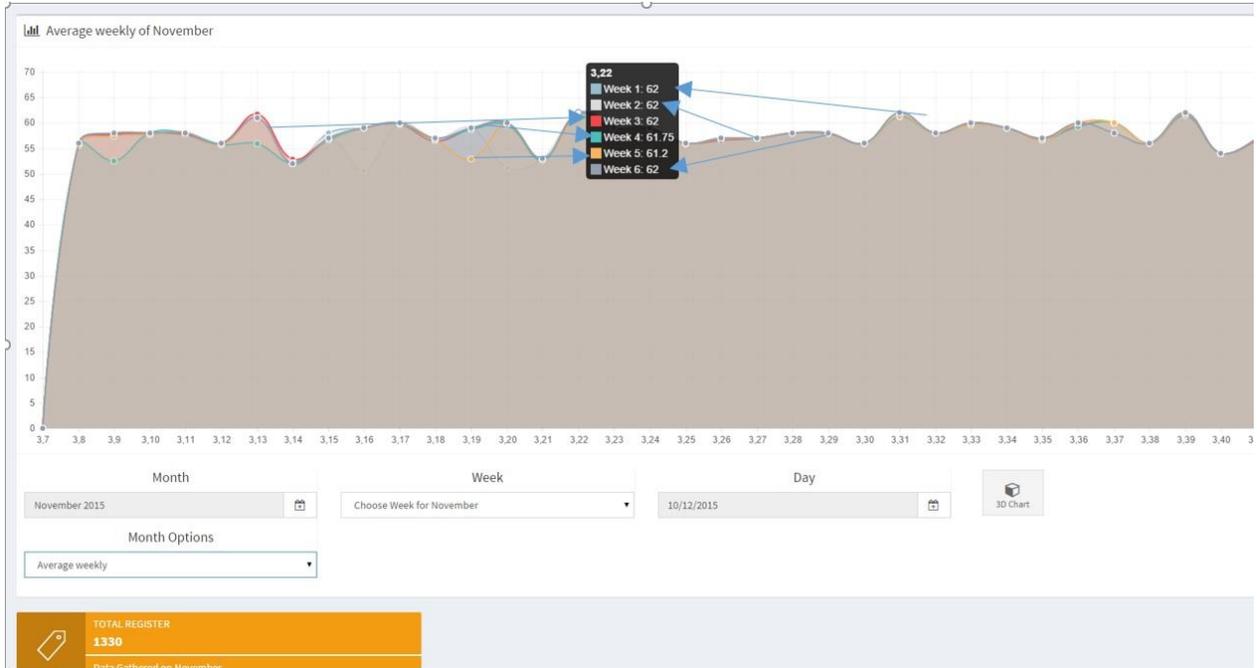


Figure. Q.7: Networked Smart Markers 2D data representation of six weeks

## 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 millimetres. 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 behaviour associated with ground deformation and pore pressure monitoring.

### 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.

### **Pore pressure sensor**

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 stabilise 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 thinfilm 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 neighbouring 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.

### **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 behaviour 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 microseismic monitoring data and the geological, geotechnical, and structural models of the mine, which would improve understanding of the mechanisms of mobilisation 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.

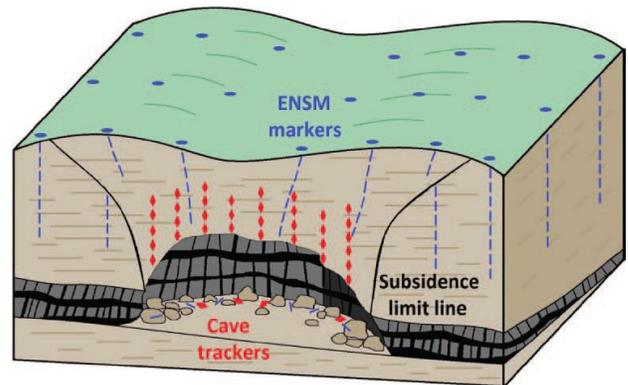
- Indication of the cave back limit. Once a critical hydraulic radius has been reached and caving has begun, the integration of ENSM data will help to improve the definition of the cave back's limit, which can be estimated based on the position of the last marker in the hole within the yielding zone. 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 behaviour. Once ENSMs start to behave as cave trackers, they will provide information related to the ore flow within the mobilised column. This data can be used to improve cave management, mainly in terms of draw rates and the strategy of drawpoint extraction.

Figure. Q.8 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.

### 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. Q.8: Enhanced Networked Smart Markers performing as subsurface monitoring and later as cave trackers combined with conventional cave trackers in an open pit-underground interaction scenario**

## 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.

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