CONTENTS

CHAPTER 1: INTRODUCTION ........................................................................................................... 1
  1.1. Introduction ........................................................................................................................... 1
  1.2. Hypothesis ........................................................................................................................... 1
  1.3. Objectives ............................................................................................................................ 1
  1.4. Context of the Research ....................................................................................................... 2
  1.5. Scope of the work .................................................................................................................. 3
    1.5.1. Geotechnical Instrumentation ....................................................................................... 3
    1.5.2. Chapter Overview .......................................................................................................... 4
  1.6. Methodology ....................................................................................................................... 5

CHAPTER 2: LITERATURE REVIEW ................................................................................................. 6
  2.1. Introduction ........................................................................................................................ 6
  2.2. Slope Design ....................................................................................................................... 6
    2.2.1. Geotechnical Model ...................................................................................................... 7
    2.2.2. Experience Based Design ............................................................................................ 8
    2.2.3. Optimized Designs ....................................................................................................... 10
  2.3. Slope Stability ..................................................................................................................... 11
    2.3.1. Acceptance Criteria ..................................................................................................... 11
    2.3.2. Geotechnical Instrumentation ..................................................................................... 12
    2.3.3. Groundwater effect on Slope Stability .......................................................................... 12
  2.4. Groundwater Control .......................................................................................................... 13
  2.5. Applications of Groundwater Monitoring ......................................................................... 14
  2.6. Instrumentation for Groundwater Monitoring ................................................................. 15
    2.6.1. Water Table Monitoring ............................................................................................... 15
    2.6.2. Pore Pressure Monitoring ............................................................................................ 17
  2.7. Considerations for Piezometer Installation ....................................................................... 21
    2.7.1. Hydrodynamic Time-lag .............................................................................................. 21
    2.7.2. Grouting ....................................................................................................................... 22
    2.7.3. Multi-point Measurements ........................................................................................... 23
    2.7.4. Design of an Instrumentation Program ........................................................................ 24

CHAPTER 3: INSTRUMENTATION TRIAL .................................................................................... 25
  3.1. Networked Smart Marker Technology .............................................................................. 25
  3.2. Trial Setup .......................................................................................................................... 26
CHAPTER 5: DEVELOPMENT OF GROUNDWATER MONITORING PROGRAMS

3.3. Characteristics of the Trial Site ................................................................. 26
3.4. NSM’s Trial Installation in Open Pit ............................................................ 27
  3.4.1. Preparation .......................................................................................... 27
  3.4.2. Installation ......................................................................................... 28
3.5. Performance of the System in Operation ...................................................... 30
  3.5.1. System Evaluation ............................................................................. 31
  3.5.2. System Upgrades ............................................................................. 33
3.6. Second NSM’s Trial Installation in Open Pit ............................................... 34
  3.6.1. Updated Installation Procedure .......................................................... 35
3.7. Development of Pore Pressure Measurement Capabilities ......................... 36

CHAPTER 4: DEVELOPMENT OF A MINE PLAN ............................................. 37

4.1. Introduction ............................................................................................... 37
4.2. Mine Planning ........................................................................................... 37
  4.2.1. Block Model Characteristics ............................................................... 38
  4.2.2. Mining Environment ......................................................................... 39
  4.2.3. Pit Collections .................................................................................. 42
  4.2.4. Economic Environment .................................................................... 42
  4.2.5. Mine Plan ......................................................................................... 43
  4.2.6. Results .............................................................................................. 44
4.3. Pushback Design ...................................................................................... 46
  4.3.1. Export/Import Mine Plan ................................................................. 46
  4.3.2. Pushback Limitations ...................................................................... 47
  4.3.3. Pushbacks Design ........................................................................... 51
4.4. Optimization of the Existing Design .......................................................... 53
  4.4.1. Effects of steepening slope angle ...................................................... 54

CHAPTER 5: DEVELOPMENT OF GROUNDWATER MONITORING PROGRAMS .... 57

5.1. Effects of Steepening of South Wall .......................................................... 57
5.2. Selection of pore water pressure monitoring instruments ............................ 57
  5.2.1. Guidelines for Instrument Selection .................................................... 57
  5.2.2. Instrument Selection for the Mine Plan ............................................. 62
  5.2.3. Guidelines for Instrument Deployment ............................................. 62
5.3. Design of Pore Water Pressure Monitoring Programs ............................. 65
  5.3.1. Groundwater Monitoring Campaigns .............................................. 65
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.8.5. Conclusions</td>
<td>130</td>
</tr>
<tr>
<td>9.8.6. Acknowledgements</td>
<td>130</td>
</tr>
<tr>
<td>9.8.7. References</td>
<td>131</td>
</tr>
<tr>
<td>9.9.1. Abstract</td>
<td>134</td>
</tr>
<tr>
<td>9.9.2. Slope Design and Stability</td>
<td>134</td>
</tr>
<tr>
<td>9.9.3. Slope Monitoring Instrumentation</td>
<td>135</td>
</tr>
<tr>
<td>9.9.4. Case Study</td>
<td>138</td>
</tr>
<tr>
<td>9.9.5. Other Considerations</td>
<td>143</td>
</tr>
<tr>
<td>9.9.6. Conclusions</td>
<td>144</td>
</tr>
<tr>
<td>9.9.7. Future Developments</td>
<td>144</td>
</tr>
<tr>
<td>9.9.8. Acknowledgements</td>
<td>145</td>
</tr>
<tr>
<td>9.9.9. References</td>
<td>145</td>
</tr>
<tr>
<td>9.10. Appendix J: Slope stability management: coupling deformation measurements with pore pressure data using novel Networked Smart Markers platform</td>
<td>148</td>
</tr>
<tr>
<td>9.10.1. Abstract</td>
<td>148</td>
</tr>
<tr>
<td>9.10.2. Introduction</td>
<td>148</td>
</tr>
<tr>
<td>9.10.3. Networked Smart Markers</td>
<td>150</td>
</tr>
<tr>
<td>9.10.4. NSM Enhancement – Pore Pressure Sensor</td>
<td>151</td>
</tr>
<tr>
<td>9.10.5. Conclusions and Future Work</td>
<td>157</td>
</tr>
<tr>
<td>9.10.6. Acknowledgements</td>
<td>158</td>
</tr>
<tr>
<td>9.10.7. References</td>
<td>158</td>
</tr>
</tbody>
</table>
# TABLES

Table 1.1: Types of instruments to be reviewed, based in Common Instruments chart by W. A. Marr (2013) .......................................................... 3

Table 3.1: System Improvements .................................................................................................................................................. 34

Table 4.1: Processing Plant Characteristics .................................................................................................................................. 39

Table 4.2: Stockpile Characteristics ................................................................................................................................................. 40

Table 4.3: DeepMine's optimum mine plan .................................................................................................................................. 44

Table 4.4: Processing Plants operation summary ......................................................................................................................... 45

Table 4.5: Truck fleet calculation ....................................................................................................................................................... 48

Table 4.6: Shovel fleet calculation ..................................................................................................................................................... 49

Table 4.7: Optimized operative mine plan .................................................................................................................................. 52

Table 4.8: Increase on extracted material with improved mine plan .................................................................................................... 54

Table 5.1: Instruments to consider for monitoring cut slopes in rock (Dunicliff, 2012) ................................................................ 58

Table 5.2: Instruments to consider for monitoring joint water pressure in cut slopes, both in rock and soil .............................................................................................................................. 59

Table 5.3: Summary of Instruments for Measuring Groundwater Pressure ..................................................................................... 60

Table 5.4: Summary of Instruments for Measuring Groundwater Pressure (Continued) ................................................................. 61

Table 5.5: Number and spacing of piezometers in boreholes for the first monitoring stage ............................................................. 66

Table 5.6: Number and spacing of piezometers in boreholes for the second monitoring stage ........................................................ 66

Table 5.7: Number and spacing of Enhanced NSMs in the initial boreholes ..................................................................................... 67

Table 5.8: Number and spacing of Enhanced NSMs in the additional boreholes ............................................................................ 67

Table 5.9: Costs of Vibrating Wire Piezometers and related equipment .......................................................................................... 68

Table 5.10: Ratio of materials for grout mix ........................................................................................................................................ 68

Table 5.11: Cost of materials used for piezometer installation ......................................................................................................... 68

Table 5.12: Summary of costs for first VW Piezometer installation ............................................................................................... 69

Table 5.13: Summary of costs for second VW Piezometer installation ........................................................................................... 69

Table 5.14: Costs of Enhanced NSMs and related equipment ........................................................................................................... 69

Table 5.15: Summary of costs for first Enhanced NSM installation ................................................................................................. 70

Table 5.16: Summary of costs for second Enhanced NSM installation ............................................................................................ 70

Table 5.17: NPV for different configurations of the project ................................................................................................................. 72

Table 6.1: Guidelines to integrate geotechnical instrumentation to the mine plan ........................................................................ 74

Table 6.2: Effect of implementing geotechnical campaign on cash flow ........................................................................................ 77

Table 9.1: Table of Operating and Capital Costs, retrieved from the Mine and Mill Equipment Estimator's Guide 2011 ..................................................................................................................................... 85
Table 9.2: Updated Table for OPEX and CAPEX per Extraction Rate .................. 85
Table 9.3: Table of Operating and Capital Costs for Concentrator Plant, retrieved from the Mine and Mill Equipment Estimator's Guide 2011. ................................................................. 87
Table 9.4: Updated Table for OPEX and CAPEX per ton of Processed Ore in Concentrator Plants. .................................................................................................................. 87
Table 9.5: Table of Operating and Capital Costs for Leaching Plant, retrieved from the Mine and Mill Equipment Estimator's Guide 2011. ........................................................................ 89
Table 9.6: Updated Table for OPEX and CAPEX per ton of Processed Ore in Leaching Plants. 89
Table 9.7: Technologies for Surface Monitoring based on Space-Based Observations .......... 100
Table 9.8: Technologies for Surface Monitoring based on Airborne Observations................. 100
Table 9.9: Technologies for Surface Monitoring based on Ground-Based Observations......... 101
Table 9.10: Technologies for Subsurface Monitoring...................................................... 103
Table 9.11: Technical specifications for Standpipe Piezometers from Ace Instruments Co. ..... 105
Table 9.12: Technical specifications for Standpipe Piezometers from Durham Geo Slope Indicator.......................................................................................................................... 105
Table 9.13: Technical specifications for Standpipe Piezometers from Encardiorite ............ 105
Table 9.14: Technical specifications for Standpipe Piezometers from Geo-Instruments ....... 106
Table 9.15: Technical specifications for Standpipe Piezometers from Geotechnical Systems... 106
Table 9.16: Technical specifications for Standpipe Piezometers from Itmsoil Interfels......... 106
Table 9.17: Technical specifications for Standpipe Piezometers from Marton Geotechnical Services.......................................................................................................................... 106
Table 9.18: Technical specifications for Standpipe Piezometers from Roctest ..................... 106
Table 9.19: Technical specifications for Standpipe Piezometers from Gage Technique.......... 107
Table 9.20: Technical specifications for Standpipe Piezometers from RST......................... 107
Table 9.21: Technical specifications for Standpipe Piezometers from Sisgeo...................... 107
Table 9.22: Technical specifications for Standpipe Piezometers from Solinst...................... 107
Table 9.23: Technical specifications for Pneumatic Piezometers from Ace Instruments Co. .... 108
Table 9.24: Technical specifications for Pneumatic Piezometers from Durham Geo Slope Indicator.......................................................................................................................... 108
Table 9.25: Technical specifications for Pneumatic Piezometers from Geotechnical Systems.. 108
Table 9.26: Technical specifications for Pneumatic Piezometers from Geotechnical Systems.. 108
Table 9.27: Technical specifications for Pneumatic Piezometers from Roctest .................. 108
Table 9.28: Technical specifications for Pneumatic Piezometers from Gage Technique......... 108
Table 9.29: Technical specifications for Pneumatic Piezometers from RST......................... 109
| Table 9.30: Technical specifications for VW Multi-point Piezometers from Ace Instruments Co. | 109 |
| Table 9.31: Technical specifications for Vibrating Wire Piezometers from Ace Instruments Co. | 109 |
| Table 9.32: Technical specifications for VW Vented Piezometers from Ace Instruments Co. | 110 |
| Table 9.33: Technical specifications for Vibrating Wire Piezometers from Durham Geo Slope Indicator | 110 |
| Table 9.34: Technical specifications for VW Titanium Piezometers from Durham Geo Slope Indicator | 110 |
| Table 9.35: Technical specifications for Vibrating Wire Piezometers from Encardiorite | 110 |
| Table 9.36: Technical specifications for VW Slim Piezometers from Encardiorite | 111 |
| Table 9.37: Technical specifications for VW Low Pressure Piezometers from Encardiorite | 111 |
| Table 9.38: Technical specifications for Vibrating Wire Piezometers from Geo-Instruments | 111 |
| Table 9.39: Technical specifications for VW Heavy Duty Piezometers from Geokon | 111 |
| Table 9.40: Technical specifications for VW Small Diameter Piezometers from Geokon | 111 |
| Table 9.41: Technical specifications for VW Standard Piezometers from Geokon | 112 |
| Table 9.42: Technical specifications for VW High Temperature Piezometers from Geokon | 112 |
| Table 9.43: Technical specifications for VW Multilevel Piezometers from Geokon | 112 |
| Table 9.44: Technical specifications for VW Autoresonant Piezometers from Geokon | 112 |
| Table 9.45: Technical specifications for VW Titanium Piezometers from Geokon | 113 |
| Table 9.46: Technical specifications for Vibrating Wire Piezometers from Geonor | 113 |
| Table 9.47: Technical specifications for Vibrating Wire Piezometers from Geostar | 113 |
| Table 9.48: Technical specifications for Vibrating Wire Piezometers from Itmsoil Interfels | 113 |
| Table 9.49: Technical specifications for Vibrating Wire Piezometers from Geotechnical Systems | 114 |
| Table 9.50: Technical specifications for VW Multi-Level Piezometers from Roctest | 114 |
| Table 9.51: Technical specifications for Vibrating Wire Piezometers from Roctest | 114 |
| Table 9.52: Technical specifications for Vibrating Wire Piezometers from Sisgeo | 114 |
| Table 9.53: Technical specifications for Vibrating Wire Piezometers from RST | 115 |
| Table 9.54: Technical specifications for Vibrating Wire Piezopress from Solexperts | 115 |
| Table 9.55: Technical specifications for Vibrating Wire Piezometers from Toyoko Elmes | 115 |
| Table 9.56: Technical specifications for Vibrating Wire Piezometers from Jewell Instruments | 115 |
| Table 9.57: Technical specifications for Vibrating Wire Piezometers from Gage Technique | 116 |
| Table 9.58: Technical specifications for Vibrating Wire Piezometers from Measurand Inc. | 116 |
Table 9.59: Technical specifications for Semiconductor Piezometers from Ace Instruments Co. .......................................................... 116
Table 9.60: Technical specifications for Semiconductor Piezometers from Geokon ........... 116
Table 9.61: Technical specifications for Electric Piezometers from Itmsoil Interfels .......... 116
Table 9.62: Technical specifications for Strain Gauge Piezometers from RST............... 117
Table 9.63: Technical specifications for Single Piezometers from Alert Solutions.......... 117
Table 9.64: Technical specifications for Resistive Piezometers from Sisgeo................. 117
Table 9.65: Technical specifications for Piezoresistive Piezopress from Sisgeo............. 117
Table 9.66: Technical specifications for Twin Tube Piezometers from Encardiorite........... 117
Table 9.67: Technical specifications for Electric Piezometers from Simstrumenti .......... 118
Table 9.68: Technical specifications for Hydraulic Piezometers from Itmsoil Interfels...... 118
Table 9.69: Troubleshooting summary ....................................................................... 141
Table 9.70: System improvements ............................................................................. 142
Table 9.71: Comparison of available filters ............................................................... 153
FIGURES

Figure 2.1: Typical open pit slope geometry (Wyllie & Mah, 2004) .............................................. 7
Figure 2.2: Chart for slope angle and slope height (Haines & Terbrugge, 1991) ......................... 9
Figure 2.3: Chart of rock slope vs slope height for stable and unstable cases (Hoek, 1970) .... 9
Figure 2.4: Potential impact of steeper slopes in open pit mines (Stacey, 2009) ...................... 10
Figure 2.5: Horizontal drains and pumping wells in open pit mines (Sperling et al., 1992) ....... 14
Figure 2.6: Flow net illustrating seepage forces in a slope (Brawner, 1982) ............................. 15
Figure 2.7: Installation diagram: (a) Standpipe piezometer (b) diaphragm piezometer (Mikkelsen & Green, 2003) ................................................................. 22
Figure 3.1: Networked Smart Marker ......................................................................................... 25
Figure 3.2: Mina Sur's slope monitoring early trial's diagram .................................................... 26
Figure 3.3: NSM array hanging from the stairs to test rope's resistance ................................. 27
Figure 3.4: Floor Plan of the Instrumented Slope ...................................................................... 28
Figure 3.5: Networked Smart Marker installation ..................................................................... 28
Figure 3.6: Grouting process ..................................................................................................... 29
Figure 3.7: NSM Antenna .......................................................................................................... 29
Figure 3.8: NSM Installation diagram ....................................................................................... 30
Figure 3.9: NSM’s connectivity .................................................................................................. 31
Figure 3.10: Floor Plan of the second trial installation ................................................................. 34
Figure 4.1: DeepMine's initial screen with its five elements to create a mine plan .................. 38
Figure 4.2: First results on concentrator plant's life ................................................................. 40
Figure 4.3: Surplus Limit for Concentrator Plant per year ......................................................... 40
Figure 4.4: Surplus Limit for Leaching Plant per year ............................................................... 40
Figure 4.5: Re-handling capacity for Concentrator Stockpile per year ................................... 41
Figure 4.6: Re-handling capacity for Leaching Stockpile per year ............................................ 41
Figure 4.7: Leaching Plant Operation ....................................................................................... 41
Figure 4.8: Concentrator Plant Operation .................................................................................. 41
Figure 4.9: Visualization for calculated nested pits ................................................................. 42
Figure 4.10: Phase dimensions (DeepMine 2.2 User Manual) .................................................. 43
Figure 4.11: Ore movement from the Mine Operation ............................................................... 43
Figure 4.12: Mine Plan's Cash Flow .......................................................................................... 46
Figure 4.13: Block model's visualization per phase ................................................................. 46
Figure 4.14: Komatsu HD1500-7 speed chart .......................................................................... 47
Figure 4.15: Komatsu HD1500-7 section views ................................................................. 48
Figure 4.16: Shovel-Truck Matching ................................................................. 49
Figure 4.17: Komatsu PC5500-6 radius of gyration .................................................. 50
Figure 4.18: Proposed configuration for truck loading ............................................. 50
Figure 4.19: Combination of several phases into one ............................................. 51
Figure 4.20: Section view of the block model .......................................................... 51
Figure 4.21: Outline of the final pit ........................................................................ 52
Figure 4.22: Visualization for re-calculated nested pits ......................................... 53
Figure 4.23: Outline of the improved pit ................................................................. 54
Figure 4.24: Nested Pit Analysis ........................................................................... 55
Figure 5.1: Initial setup for instrumentation campaign in the South-East walls of the open pit ... 63
Figure 5.2: Final setup for instrumentation campaign in the South-East walls of the open pit .... 64
Figure 5.3: Cement/Bentonite/Water ratios for two grout mixes (Mikkelsen & Green, 2003) ..... 65
Figure 9.1: Calculated function to determine OPEX based on the Extraction Rate of the mine. . 86
Figure 9.2: Calculated function to determine CAPEX based on the Extraction Rate of the mine. 86
Figure 9.3: Calculated function to determine OPEX based on the Processing Capacity of the Concentrator Plant ................................................................. 88
Figure 9.4: Calculated function to determine CAPEX based on the Processing Capacity of the Concentrator Plant ................................................................. 88
Figure 9.5: Calculated function to determine OPEX based on the Processing Capacity of the Leaching Plant ................................................................. 89
Figure 9.6: Calculated function to determine CAPEX based on the Processing Capacity of the Leaching Plant ................................................................. 90
Figure 9.7: DeepMine's visualization for pushback 1 ............................................. 91
Figure 9.8: DeepMine's visualization for pushback 2 ............................................. 91
Figure 9.9: DeepMine's visualization for pushback 3 ............................................. 91
Figure 9.10: DeepMine's visualization for pushback 4 ........................................... 92
Figure 9.11: DeepMine's visualization for pushback 5 ........................................... 92
Figure 9.12: DeepMine's visualization for pushback 6 ........................................... 92
Figure 9.13: DeepMine's visualization for pushback 7 ........................................... 93
Figure 9.14: DeepMine's visualization for pushback 8 ........................................... 93
Figure 9.15: DeepMine's visualization for pushback 9 ........................................... 93
Figure 9.16: DeepMine's visualization for pushback 10 ......................................... 94
Figure 9.17: DeepMine's visualization for pushback 11 ......................................... 94
Figure 9.18: DeepMine's visualization for pushback 12 .................................................. 94
Figure 9.19: DeepMine's visualization for pushback 13 .................................................. 95
Figure 9.20: DeepMine's visualization for the final pit ..................................................... 95
Figure 9.21: Excavation of pushback 1 ........................................................................... 96
Figure 9.22: Excavation of pushback 2 ........................................................................... 96
Figure 9.23: Excavation of pushback 3 ........................................................................... 97
Figure 9.24: Excavation of pushback 4 ........................................................................... 97
Figure 9.25: Excavation of pushback 5 ........................................................................... 98
Figure 9.26: Excavation of final pit ................................................................................ 98
Figure 9.27: Behavior of extracted ore and waste for pits 6 to 10 ................................. 99
Figure 9.28: Behavior of extracted ore and waste for pits 11 to 15 ............................... 99
Figure 9.29: Behavior of extracted ore and waste for pits 16 to 19 ............................... 99
Figure 9.30: Crown pillar defined at Palabora mine (after Glazer and Hepworth, 2004) .. 121
Figure 9.31: Seismic monitoring at the site (after Glazer and Hepworth, 2004) ............... 121
Figure 9.32: Plan view of Los Bronces–Andina interaction area (after Google Maps, 2015) ... 122
Figure 9.33: Summary of surface and underground geotechnical monitoring methods .... 123
Figure 9.34: Smart Marker sensor .................................................................................. 125
Figure 9.35: Networked Smart Markers 3D data representation of six weeks ............... 126
Figure 9.36: Networked Smart Markers 2D data representation of six weeks ............... 127
Figure 9.37: Enhanced Networked Smart Markers performing initially as subsurface monitoring and later as cave trackers combined with conventional cave trackers in an open pit–underground interaction scenario ........................................ 130
Figure 9.38: Networked Smart Marker ........................................................................... 137
Figure 9.39: First NSM installation diagram ................................................................... 139
Figure 9.40: NSM’s connectivity ..................................................................................... 139
Figure 9.41: Both ways signal strength .......................................................................... 140
Figure 9.42: Networked Smart Marker .......................................................................... 150
Figure 9.43: Filter Prototype ......................................................................................... 153
Figure 9.44: Prototype boards assembled with batteries, antenna and pressure transducer .... 154
Figure 9.45: Filter Test 1 ............................................................................................. 155
Figure 9.46: Porous filter test: two small PVC pipes (with and without filter) attached to a large PVC pipe ........................................................................................................ 156
Figure 9.47: Pressure readings using PVC pipes with and without filter ....................... 156