

# CONTENTS

|   |       |
|---|-------|
| <b>CERTIFICATE</b> .....  | i     |
| <b>ACKNOWLEDGMENT</b> .....   | iv    |
| <b>CONTENTS</b> .....   | vi    |
| <b>LIST OF FIGURES</b> .....  | ix    |
| <b>LIST OF TABLES</b> .....   | xii   |
| <b>ABSTRACT</b> .....   | xviii |
| <b>CHAPTER 1</b> .....  | 1     |
| <b>INTRODUCTION</b> .....   | 1     |
| 1.1 Background and motivation .....                                       | 1     |
| 1.2 Statement of problem .....  | 9     |
| 1.3 Objectives of the study .....   | 10    |
| 1.4 Organization of the thesis.....                                       | 11    |
| <b>CHAPTER 2</b> .....  | 13    |
| <b>LITERATURE REVIEW</b> .....  | 13    |
| 2.1 Introduction.....   | 13    |
| 2.2 Rock breakage by blasting .....                                       | 14    |
| 2.3 Assessment of blast performance.....                                  | 18    |
| 2.3.1 Fragmentation.....  | 19    |
| 2.3.2 Air overpressure .....  | 20    |
| 2.3.3 Fly rock.....   | 21    |
| 2.3.4 Powder factor .....   | 22    |
| 2.3.5 Ground vibration .....  | 22    |
| 2.4 Concept of scaled distance in ground vibrations.....                  | 23    |
| 2.5 Powder Factor .....   | 24    |
| 2.5.1 Factors influencing PF.....   | 26    |
| 2.5.2 Approaches for Prediction of Powder factor .....                    | 26    |
| 2.5.3 Approaches for prediction of ground vibrations due to blasting..... | 28    |
| 2.6 Recent Approaches for prediction of PPV and PF .....                  | 35    |
| 2.6.1 Statistical approach.....   | 35    |
| 2.6.2 Artificial intelligence approach .....                              | 37    |
| 2.7 Summary of literature review.....                                     | 39    |

|   |           |
|---|-----------|
| <b>CHAPTER 3.....</b>   | <b>40</b> |
| <b>CASE DESCRIPTION.....</b>  | <b>40</b> |
| 3.1 Introduction.....   | 40        |
| 3.2 Significant Properties of Nimbahera limestone formation.....    | 41        |
| 3.3 Field description.....  | 42        |
| 3.4 Details of blasting design for the three quarries.....          | 43        |
| 3.4.1 Blasting Pattern details for Quarry ‘A’ .....                 | 43        |
| 3.4.2 Blasting Pattern details for Quarry ‘B’ .....                 | 47        |
| 3.4.3 Blasting Pattern details for Quarry ‘C’ .....                 | 51        |
| <b>CHAPTER 4.....</b>   | <b>54</b> |
| <b>RESEARCH METHODOLOGY .....</b>                                   | <b>54</b> |
| 4.1 Outline of Research Methodology .....                           | 54        |
| 4.1.1 Field identification and data collection .....                | 54        |
| 4.1.2 Measurement of Ground vibrations.....                         | 57        |
| 4.1.3 Estimation of Powder Factor (PF).....                         | 58        |
| 4.1.4 Statistical and ANN based analysis and validation .....       | 59        |
| 4.2 Validation and Verification.....                                | 68        |
| 4.2.1 Validation with PCA.....                                      | 70        |
| 4.2.2 Validation with SSE.....                                      | 70        |
| 4.2.3 Verification by MLP Technique .....                           | 70        |
| <b>CHAPTER 5.....</b>   | <b>71</b> |
| <b>RESULTS AND DISCUSSION FOR Peak Particle Velocity (PPV).....</b> | <b>71</b> |
| 5.1 Results obtained for all the quarries .....                     | 71        |
| 5.2 Results from PCA technique.....                                 | 74        |
| 5.2.1 Results obtained for quarry A using PCA .....                 | 74        |
| 5.2.2 Results obtained for quarry B using PCA.....                  | 79        |
| 5.2.3 Results obtained for quarry C using PCA.....                  | 84        |
| 5.3 Results from SSE technique.....                                 | 89        |
| 5.3.1 Results obtained for quarry A using SSE .....                 | 89        |
| 5.3.2 Results obtained for quarry B using SSE .....                 | 92        |
| 5.3.3 Results for quarry C using SSE .....                          | 96        |
| 5.4 Results of validation and Verification.....                     | 99        |
| 5.4.1 Validation results .....                                      | 99        |
| 5.4.2 Verification Results.....                                     | 103       |
| 5.5 Discussion .....  | 112       |

|   |            |
|---|------------|
| 5.5.1 Identified blasting design parameters affecting PPV by PCA and SSE..... | 113        |
| 5.6 Overview of the results for all the three quarries.....                   | 116        |
| <b>CHAPTER 6.....</b>   | <b>118</b> |
| <b>RESULTS AND DISCUSSION FOR POWDER FACTOR (PF) .....</b>                    | <b>118</b> |
| 6.1 Results of PF estimation.....   | 118        |
| 6.2 Results from PCA .....  | 119        |
| 6.2.1 Results for quarry A using PCA .....                                    | 119        |
| 6.2.2 Results for quarry B using PCA .....                                    | 114        |
| 6.2.3 Results for quarry C using PCA .....                                    | 129        |
| 6.3 Results from SSE technique.....   | 134        |
| 6.3.1 Results for quarry A using SSE.....                                     | 134        |
| 6.3.2 Results for quarry B using SSE.....                                     | 137        |
| 6.3.3 Results for quarry C using SSE.....                                     | 140        |
| 6.4 Results of validation and Verification.....                               | 144        |
| 6.4.1 Validation results.....   | 144        |
| 6.4.2 Verification Results.....   | 147        |
| 6.5 Discussion .....  | 154        |
| 6.5.1 Identified blasting design parameters affecting PPV by PCA and SSE..... | 155        |
| 6.6 Overview of results for PF .....  | 156        |
| <b>CHAPTER 7.....</b>   | <b>158</b> |
| <b>CONCLUSION .....</b>   | <b>158</b> |
| 7.1 Conclusions.....  | 158        |
| 7.2 Limitations of the future work .....                                      | 159        |
| 7.3 Suggestions for future work.....  | 159        |
| <b>REFERENCES .....</b>   | <b>160</b> |
| <b>APPENDIX.....</b>  | <b>187</b> |
| A.1: Blasting data set of quarry A .....                                      | 187        |
| A.2: Blasting data set of quarry B.....                                       | 191        |
| A.3: Blasting data set for quarry C .....                                     | 194        |
| A.4: Validation data set for quarry A .....                                   | 197        |
| A.5: Validation data set for quarry B.....                                    | 199        |
| A.6: Validation data set for quarry C.....                                    | 193        |
| A.7: Sequential Screenshot of SSE method.....                                 | 203        |
| A.8: MLR technique after feeding the blasting design parameters.....          | 204        |
| <b>LIST OF PUBLICATIONS .....</b>   | <b>205</b> |

## List of Figures

|   |    |
|---|----|
| Figure 2.1: Schematic illustration of processes occurring in the rock around a blast hole, showing formation of crushed zones, fractured zones and fragmented zones | 17 |
| Figure 2.2: Blast induced nuisances   | 17 |
| Figure 2.3: Energy release and distribution of Seismic waves  | 18 |
| Figure 2.4: Architecture of MLP   | 38 |
| Figure.3.1: Location of the study quarries  | 40 |
| Figure 3.2: Representative drilling and firing pattern for quarry A with two rows (not to scale)  | 44 |
| Figure 3.3: Representative drilling and firing pattern for quarry A with three rows (not to scale)  | 44 |
| Figure 3.4: Representative blast hole section (diameter 115 mm) (not to scale)  | 45 |
| Figure 3.5: Representative blast hole section (diameter 152 mm) (not to scale)  | 45 |
| Figure 3.6: Blasting operation in Quarry ‘A’  | 46 |
| Figure 3.7: Post-blasting muck profile in Quarry ‘A’  | 46 |
| Figure 3.8: Representative drilling and firing pattern for quarry B with two rows (not to scale)  | 47 |
| Figure 3.9: Representative drilling and firing pattern for quarry B with three rows (not to scale)  | 48 |
| Figure 3.10: Representative blast hole section (diameter 115 mm) (not to scale)   | 49 |
| Figure 3.11: Representative blast hole section (diameter 152 mm) (not to scale)   | 49 |
| Figure 3.12: Blasting operation in Quarry ‘B’   | 50 |
| Figure 3.13: Post-blasting muck profile in Quarry ‘B’   | 50 |
| Figure 3.14: Representative drilling and firing pattern for quarry C with two rows (not to scale)   | 51 |
| Figure 3.15: Representative drilling and firing pattern for quarry C with three rows (not to scale)   | 52 |

|  |     |
|--|-----|
| Figure 3.16: Representative drilling and firing pattern for quarry C with four rows (not to scale) | 52  |
| Figure 3.17: Representative blast hole section (diameter 150 mm) (not to scale)                    | 53  |
| Figure 3.18: Representative blast hole section (diameter 115 mm) (not to scale)                    | 53  |
| Figure 4.1: A representative graphical output of seismograph record                                | 57  |
| Figure 4.2: Research design  | 60  |
| Figure 4.3: Block diagram of PCA method  | 62  |
| Figure 4.4: Results of PCA and Sequential screenshots of PCA method                                | 62  |
| Figure 4.5: Block diagram of SSE method  | 63  |
| Figure 4.6: Linear regression graph between dependent and independent variable                     | 65  |
| Figure 4.7: Regression curve between PPV and SD  | 66  |
| Figure 4.8: Scaled conjugate gradient method architecture  | 68  |
| Figure 4.9: Flowchart of validation  | 69  |
| Figure 4.10: MLP technique after entering the variable   | 70  |
| Figure 5.1: Scree plot indicating PC groups for PPV in quarry A                                    | 75  |
| Figure 5.2: Scree plot indicating principal component groups for PPV in quarry B                   | 80  |
| Figure 5.3: Scree plot indicating principal component groups for PPV in quarry C                   | 85  |
| Figure 5.4: Comparison of measured and predicted PPV values for quarry A                           | 100 |
| Figure 5.5: Comparison of measured and Predicted PPV Values for quarry B                           | 101 |
| Figure 5.6: Comparison of measured and predicted PPV values for quarry C                           | 102 |
| Figure 5.7: Plot between measured and predicted PPV by ANN (quarry A)                              | 105 |
| Figure 5.8: Independent variables importance chart for PPV (quarry A)                              | 106 |
| Figure 5.9: Plot between measured and predicted PPV by ANN (quarry B)                              | 108 |
| Figure 5.10: Independent variables importance chart for PPV (quarry B)                             | 109 |
| Figure 5.11: Plot between measured and predicted PPV by ANN (quarry C)                             | 111 |
| Figure 5.12: Independent variables importance chart for PPV (quarry C)                             | 112 |

|  |     |
|--|-----|
| Figure 6.1: Scree plot indicating principal component groups for PF in quarry A          | 120 |
| Figure 6.2: Scree plot indicating principal component groups for PF in quarry B          | 125 |
| Figure 6.3: Scree plot indicating principal component groups for PF in quarry C          | 130 |
| Figure 6.4: Comparison of measured and Predicted PF Values for quarry A.                 | 144 |
| Figure 6.5: Comparison of measured and predicted PF values for quarry B                  | 145 |
| Figure 6.6: Comparison of measured and predicted PF values for quarry C                  | 146 |
| Figure 6.7: Plot between measured and predicted value of PF by ANN technique (quarry A)  | 148 |
| Figure 6.8: Independent variables importance chart for PF (quarry A)                     | 149 |
| Figure 6.9: Plot between measured and predicted value of PF by ANN technique (quarry B)  | 150 |
| Figure 6.10: Independent variable importance chart for PF (Quarry B)                     | 151 |
| Figure 6.11: Plot between measured and predicted value of PF by ANN technique (quarry C) | 153 |
| Figure 6.12: Independent variables importance chart for PF (quarry C)                    | 154 |

## List of Tables

|   |    |
|---|----|
| Table 1.1: Regulatory limit of ground vibration as per USBM and DIN criteria  | 07 |
| Table 1.2: Safe blasting limits as per DGMS   | 07 |
| Table 2.1: Analysis of Blast Design Variables on Ground Vibration   | 31 |
| Table 3.1: Geological properties of Nimbahera limestone formation   | 41 |
| Table 3.2: Geotechnical properties of Nimbahera limestone formation   | 41 |
| Table 3.3: Mineralogical properties of Nimbahera limestone formation  | 42 |
| Table 3.4: Mineralogical properties of Nimbahera limestone formation  | 42 |
| Table 4.1: Representative data set of quarry ‘A’  | 55 |
| Table 4.2: Representative data sets of quarry ‘B’   | 56 |
| Table 4.3: Representative data sets of quarry ‘C’   | 56 |
| Table 5.1: Principal descriptive statistics of the blasting data set for prediction of PPV and PF (Quarry A, B and C) | 73 |
| Table 5.2: Data matrix explaining variance for the study quarry A (for PPV prediction)                                | 74 |
| Table 5.3: Identification of PCs in the study quarry A (for PPV prediction)   | 75 |
| Table 5.4: The 7 identified PC groups by PCA for PPV (quarry A)   | 76 |
| Table 5.5: MLR results for all the identified 16 PCs  | 76 |
| Table 5.6: Blast design parameters with multi-collinearity (VIF>10) for PPV(quarry A)                                 | 77 |
| Table 5.7: Blast design parameters without multi-collinearity (VIF<10) for PPV (quarry A)                             | 77 |
| Table 5.8: Descriptive statistics of 7 parameters for developing predictor Eq. for PPV                                | 78 |
| Table 5.9: MLR based descriptive statistics for the parameters used in Eq. 5.1  | 78 |
| Table 5.10: Data matrix explaining variance for the study quarry B (for PPV prediction)                               | 79 |
| Table 5.11: Identification of PCs in the study quarry B (for PPV prediction)  | 80 |
| Table 5.12: The 6 identified PC groups by PCA for PPV (quarry B)  | 81 |
| Table 5.13: MLR results for all the identified 16 PCs   | 82 |
| Table 5.14: Blast design parameters with multi-collinearity (VIF >10) for PPV (quarry B)                              | 82 |

|  |    |
|--|----|
| Table 5.15: Blast design parameters without multi-collinearity (VIF <10) for PPV (quarry B)        | 82 |
| Table 5.16: Descriptive statistics of 9 parameters for developing predictor Eq. for PPV            | 83 |
| Table 5.17: MLR based descriptive statistics for the parameters used in Eq.5.2                     | 83 |
| Table 5.18: Data matrix explaining variance for the study quarry C (for PPV prediction)            | 84 |
| Table 5.19: Identification of PCs in the study quarry C (for PPV prediction)                       | 85 |
| Table 5.20: The 7 identified PC groups by PCA for PPV (quarry C)                                   | 86 |
| Table 5.21: MLR results for all the identified 15 PCs  | 86 |
| Table 5.22: Blast design parameters with multi-collinearity (VIF >10) for PPV (quarry C)           | 87 |
| Table 5.23: Blast design parameters without multi-collinearity (VIF <10) for PPV (quarry C)        | 87 |
| Table 5.24: Descriptive statistics of 9 parameters for developing predictor eq. for PPV            | 88 |
| Table 5.25: MLR based descriptive statistics for the parameters used in Eq. 5.3                    | 88 |
| Table 5.26: Correlation matrix with significance values with respect to PPV (quarry A)             | 89 |
| Table 5.27: MLR results for predicting PPV using the identified 9 parameters                       | 90 |
| Table 5.28: Blast design parameters with multi-collinearity (VIF>10) for PPV (quarry A)            | 90 |
| Table 5.29: Blast design parameters free from multi-collinearity VIF<10 for PPV (quarry A)         | 90 |
| Table 5.30: Descriptive statistics of 6 parameters for developing predictor eq. for PPV (quarry A) | 91 |
| Table 5.31: MLR based descriptive statistics the parameters used in equation for Eq. 5.4           | 91 |
| Table 5.32: Summary of models prepared by MLR using SSE for PPV (quarry A)                         | 92 |
| Table 5.33: Correlation matrix with significance values with respect to PPV                        | 92 |

|   |     |
|---|-----|
| (quarry B)  |     |
| Table 5.34: MLR results for predicting PPV using the identified 13 parameters               | 93  |
| Table 5.35: Blast design parameters with multi-collinearity (VIF >10) for PPV (quarry B)    | 93  |
| Table 5.36: Blast design parameters without multi-collinearity (VIF <10) for PPV (quarry B) | 94  |
| Table 5.37: Descriptive statistics of 6 parameters for developing predictor eq. for PPV     | 94  |
| Table 5.38: MLR based descriptive statistics for the parameters used in Eq. 5.5             | 95  |
| Table 5.39: Summary of models prepared by MLR using SSE for PPV (quarry B)                  | 95  |
| Table 5.40: Correlation matrix with significance values with respect to PPV (quarry C)      | 96  |
| Table 5.41: MLR for predicting PPV using the identified 12 parameters                       | 97  |
| Table 5.42: Blast design parameters with multi-collinearity (VIF >10) for PPV (quarry C)    | 97  |
| Table 5.43: Blast design parameters without multi-collinearity (VIF <10) for PPV (quarry C) | 97  |
| Table 5.44: Descriptive statistics of 7 parameters for developing predictor eq. for PPV     | 98  |
| Table 5.45: MLR based descriptive statistics for the parameters used in Eq.5.6              | 98  |
| Table 5.46: Summary of models prepared by MLR using SSE for PPV (quarry C)                  | 99  |
| Table 5.47: Model summary for PPV using ANN (quarry A)                                      | 104 |
| Table 5.48: Model summary for PPV using ANN (quarry B)                                      | 107 |
| Table 5.49: Model Summary foe PPV using ANN (quarry C)                                      | 110 |
| Table 5.50: Results at a glance for PPV (Quarry A, B and C)                                 | 117 |
| Table 6.1: Discrepancy in theoretical and actual PF   | 118 |
| Table 6.2: Data matrix explaining variance for the study quarry A (for PF prediction)       | 119 |

|  |     |
|--|-----|
| Table 6.3: Identification of PCs in the study quarry A for PF                              | 120 |
| Table 6.4: The 6 identified PC groups by PCA for PF (quarry A)                             | 121 |
| Table 6.5: MLR results for the identified 14 PCs   | 121 |
| Table 6.6: Blast design parameters with multi-collinearity (VIF>10) for PF (quarry A)      | 122 |
| Table 6.7: Blast design parameters with multi-collinearity (VIF<10) for PF (quarry A)      | 122 |
| Table 6.8: Descriptive statistics of 6 parameters for developing predictor eq. for PF      | 123 |
| Table 6.9: MLR based descriptive statistics for the parameters used in Eq. 6.1             | 123 |
| Table 6.10: Data matrix explaining variance for the study quarry B (for PF prediction)     | 124 |
| Table 6.11: Identification of PCs in study quarry B for PF                                 | 125 |
| Table 6.12: The 6 identified PC groups by PCA for PF (quarry B)                            | 126 |
| Table 6.13: MLR results for the identified 15 PCs  | 126 |
| Table 6.14: Blast design parameters with multi-collinearity (VIF >10) for PF (quarry B)    | 127 |
| Table 6.15: Blast design parameters without multi-collinearity (VIF <10) for PF (quarry B) | 127 |
| Table 6.16: Descriptive statistics of 9 parameters for developing predictor eq. for PF     | 128 |
| Table 6.17: MLR based descriptive statistics for the parameters used in Eq. 6.2            | 128 |
| Table 6.18: Data matrix explaining variance for the study quarry C (for PF prediction)     | 129 |
| Table 6.19: Identification of PCs in the study quarry C for PF                             | 130 |
| Table 6.20: The 7 identified PC groups by PCA for PF (quarry C)                            | 131 |
| Table 6.21: MLR results for all the identified 12 PCs                                      | 131 |
| Table 6.22: Blast design parameters with multi-collinearity (VIF >10) for PF (quarry C)    | 132 |
| Table 6.23: Blast design parameters without multi-collinearity (VIF <10) for PF (quarry C) | 132 |
| Table 6.24: Descriptive statistics of 8 parameters for developing predictor eq.            | 133 |

|  |     |
|--|-----|
| for PF   |     |
| Table 6.25: MLR based descriptive statistics for the parameters used in Eq. 6.3            | 133 |
| Table 6.26: Correlation matrix with significance values with respect to PF (quarry A)      | 134 |
| Table 6.27: MLR results for predicting PF using the identified 9 parameters                | 134 |
| Table 6.28: Blast design parameters with multi-collinearity (VIF >10) for PF (quarry A)    | 135 |
| Table 6.29: Blast design parameters without multi-collinearity (VIF <10) for PF (quarry A) | 135 |
| Table 6.30: Descriptive statistics of 4 parameters for developing predictor eq. for PF     | 136 |
| Table 6.31: MLR based descriptive statistics for the parameters used in the Eq. 6.4        | 136 |
| Table 6.32: Summary of models prepared by MLR using SSE for PF (quarry A)                  | 137 |
| Table 6.33: Correlation matrix with significance values with respect to PF (quarry B)      | 137 |
| Table 6.34: MLR results for predicting PF using the identified 11 parameters               | 138 |
| Table 6.35: Blast design parameters with multi-collinearity (VIF >10) for PF (quarry B)    | 138 |
| Table 6.36: Blast design parameters without multi-collinearity (VIF <10) for PF (quarry B) | 138 |
| Table 6.37: Descriptive statistics of 8 parameters for developing predictor eq. for PF     | 139 |
| Table 6.38: MLR based descriptive statistics for the parameters used in Eq. 6.5            | 139 |
| Table 6.39: Summary of models prepared by MLR using SSE for PF (quarry B)                  | 140 |
| Table 6.40: Correlation matrix with significance values with respect to PF (quarry C)      | 140 |
| Table 6.41: MLR for predicting PF using the identified 8 parameters                        | 141 |
| Table 6.42: Blast design parameters with multi-collinearity (VIF <10) for                  | 141 |

|  |     |
|--|-----|
| PF (quarry C)  |     |
| Table 6.43: Blast design parameters without multi-collinearity (VIF >10) for PF (quarry C) | 142 |
| Table 6.44: Descriptive statistics of 6 parameters for developing predictor eq. for PF     | 142 |
| Table 6.45: MLR based descriptive statistics for the parameters used in Eq. 6.6            | 143 |
| Table 6.46: Summary of models prepared by MLR using SSE for PF (quarry C)                  | 143 |
| Table 6.47: Model Summary for PF using ANN (quarry A)                                      | 148 |
| Table 6.48: Model Summary of PF using ANN (quarry B)                                       | 150 |
| Table 6.49: Model Summary of PF using ANN (quarry C)                                       | 152 |
| Table 6.50: Results at a glance for PF (Quarry A, B and C)                                 | 157 |