

*STABILITY EVALUATION OF OPENCAST MINE DUMP
SLOPE STRUCTURES*



Thesis submitted in partial fulfillment
for the Award of Degree
Doctor of Philosophy

by
GAGAN GUPTA


“DEPARTMENT OF MINING ENGINEERING”
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI – 221005

CERTIFICATE

This is to certify that the revised thesis entitled “Stability Evaluation of Opencast Mine Dump Slope Structures” is being submitted by Mr. Gagan Gupta in partial fulfillment for the award of Ph.D. in Department/School of Mining Engineering, IIT(BHU), Varanasi is a record of bonafide work carried out by him.

Date of Submission: 09/10/2023


9/10/2023
(Supervisor)


(Co-supervisor)
(If any)

Forwarded by:

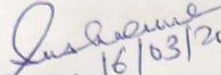

HoD/COS/HEAD
खनन अभियांत्रिकी विभाग
Dept. of Mining Engg.
(Signature with Seal)
Indian Institute of Technology (Bihar) Varanasi
Varanasi-221005

CERTIFICATE

CERTIFICATE

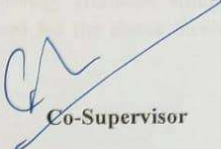
It is certified that the work contained in the thesis titled "STABILITY EVALUATION OF OPENCAST MINE DUMP SLOPE STRUCTURES" by "GAGAN GUPTA" has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.


16/03/2023
Supervisor

Prof. Sanjay K. Sharma

Professor
Department of Mining Engineering
IIT (BHU) Varanasi


Co-Supervisor

Dr. G.S.P. Singh

Associate professor
Department of Mining Engineering
IIT (BHU) Varanasi

Dr. Sanjay K. Sharma
Professor
Department of Mining Engg.
Indian Institute of Technology (B.H.U.)
Varanasi-221005 (U.P.) India

DECLARATION

DECLARATION BY THE CANDIDATE

I, "GAGAN GUPTA", certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of "Prof. S.K. SHARMA and Dr. G.S.P. SINGH" from "JULY 2018" to "MARCH 2023", at the "DEPARTMENT OF MINING ENGINEERING", Indian Institute of Technology (B.H.U), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

Date: 16/03/2023

Place: IIT (BHU) Varanasi

(GAGAN GUPTA)

CERTIFICATE BY THE SUPERVISOR(S)

It is certified that the above statement made by the student is correct to the best of our knowledge.

16/3/2023
Supervisor

Prof. Sanjay K. Sharma

Professor
Department of Mining Engineering
IIT (BHU) Varanasi

Dr. Sanjay K. Sharma
Professor
Department of Mining Engg.
Indian Institute of Technology (B.H.U.)
Varanasi-221005 (U.P.) India

Co-Supervisor

Dr. G.S.P. Singh

Associate professor
Department of Mining Engineering
IIT (BHU) Varanasi

विभागाध्यक्ष/HEAD
Signature of Head of Department/Coordinator of School
SEAL OF THE DEPARTMENT/SCHOOL

भारतीय प्रौद्योगिकी संस्थान (भारतीय प्रौद्योगिकी संस्थान)
Indian Institute of Technology (Bharatiya Prayogiki Sansthan)
वाराणसी-221005/Varanasi-221005

COPYRIGHT

COPYRIGHT TRANSFER CERTIFICATE

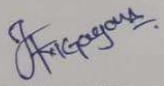
Title of the Thesis: Stability Evaluation of Opencast Mine Dump Slope Structures.

Name of the Student: GAGAN GUPTA

COPYRIGHT TRANSFER

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the "Doctor of Philosophy".

Date: 16/03/2023
Place: IIT (BHU)Varanasi


(GAGAN GUPTA)

Note: However, the author may reproduce or authorise others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and Institute's copyright notice are indicated.

ACKNOWLEDGEMENT

I would like to express my deep and sincere gratitude to my supervisors, Professor Sanjay Kumar Sharma and Dr GSP Singh, Department of Mining Engineering, Indian Institute of Technology – Banaras Hindu University, Varanasi, India, for their erudite and constructive criticisms, competent and rational guidance, and requisite facilities throughout the research period.

I am also grateful to my supervisors for believing in me and providing me the opportunity to work on several live projects related to the stability of highwall and dump slope structures of opencast mines. I am also obliged to my research progress evaluation committee members, Dr. Nawal Kishore, Department of Mining Engineering, and Dr. P. Bala Ramudu, Department of Civil Engineering, IIT (BHU)-Varanasi, India, for their insightful and valuable suggestions in shaping this research work.

I would also like to express my sincere thanks to the institute, IIT (BHU)-Varanasi, and the Department of Mining Engineering, for their continuous support. I am also grateful to my colleagues, Underground Space Technology and Simulation Research Group and other members of the department for their support and guidance.

Finally, I owe a huge debt of gratitude to my family and friends for their unwavering love and support throughout this entire endeavor.

मैं सबसे ज्यादा आभारी भगवान जी का हूँ जिन्होंने मुझे इतने अच्छे परिवार में जन्म दिया और उनका अमूल्य प्यार दिया। मैं काशी विश्वनाथ बाबा का भी आभारी हूँ जिन्होंने मुझे अपने नगरी में स्थान दिया और पंडित मदन मोहन मालवीय जी के बगिया का फूल बनाया।

(Gagan Gupta)

CONTENTS

| | |
|---|----------|
| CERTIFICATE | iii |
| DECLARATION BY THE CANDIDATE | v |
| COPYRIGHT TRANSFER CERTIFICATE | vii |
| ACKNOWLEDGEMENT | ix |
| ABSTRACT | xi |
| CONTENTS | xiii |
| LIST OF TABLES | xvii |
| LIST OF FIGURES | xxi |
| ABBREVIATIONS AND SYMBOLS | xxv |
| CHAPTER 1: INTRODUCTION | 1 |
| 1.1 Introduction | 1 |
| 1.2 Background | 1 |
| 1.3 Scope and Objectives | 4 |
| 1.4 Organization of the Thesis | 5 |
| CHAPTER 2: LITERATURE REVIEW | 9 |
| 2.1 Introduction | 9 |
| 2.2 Parameters Governing Dump Slope Stability | 9 |
| 2.3 Classification of Dump Slope Stability and Hazards | 11 |
| 2.3.1 Stability Rating | 11 |
| 2.3.2 Factor of Safety | 19 |
| 2.3.3 Probability of Failure vis-a-vis Factor of Safety | 22 |
| 2.4 Dump Material Characterization | 25 |
| 2.5 @RISK Software | 27 |
| 2.6 Research Gaps | 28 |

| | | |
|--|---|-----------|
| 2.7 | Summary | 28 |
| CHAPTER 3: RESEARCH METHODOLOGY | | 31 |
| 3.1. | Introduction | 31 |
| 3.2. | Identification of the Crucial Parameters Governing Dump Slope Stability | 32 |
| 3.3. | Formulation of Numerical Models | 32 |
| 3.4 | Laboratory Characterisation of Dump Materials | 34 |
| 3.5. | Parameters for Assessment of Dump Slope Stability | 36 |
| 3.6. | Parametric Study of Dump Slope Stability | 37 |
| 3.7. | Development of Statistical Model | 39 |
| 3. 8 | Effect of Water Table | 40 |
| 3.9. | Dump Slope Stability Classification | 44 |
| 3.10. | Development of Stability Rating and Hazard Quantification System | 45 |
| 3.11. | Model Validation | 47 |
| 3.12. | Summary | 48 |
| CHAPTER 4: PARAMETRIC STUDY THROUGH NUMERICAL MODELLING | | 51 |
| 4.1. | Introduction | 51 |
| 4.2. | Effect of the Total Dump Height | 51 |
| 4.3. | Effect of the Bench Height | 56 |
| 4.4. | Effect of the Bench Slope Angle | 58 |
| 4.5. | Effect of the Bench Width | 61 |
| 4.6. | Effect of the Cohesion | 64 |
| 4.7. | Effect of the Density | 67 |
| 4.8. | Effect of the Friction Angle | 69 |
| 4.9. | Summary | 72 |

| | |
|--|-----|
| CHAPTER 5: DEVELOPMENT OF THE PREDICTIVE MODEL | 73 |
| 5.1. Introduction | 73 |
| 5.2. Statistical Model | 73 |
| 5.3. Sensitivity Analysis of Output Parameters | 75 |
| 5.4. Stability State Classification and Mapping of Instability Prone Zone | 77 |
| 5.5. Study of the Effect of Water Table | 84 |
| 5.6. Summary | 95 |
| CHAPTER 6: DEVELOPMENT OF THE STABILITY RATING AND HAZARD CLASSIFICATION SYSTEM | 97 |
| 6.1. Introduction | 97 |
| 6.2. Variables and their Range | 97 |
| 6.3. Identification of the Probability Distribution Function | 98 |
| 6.4. Geometry Parameters for the Stable Dump Slope Structures | 100 |
| 6.5. Estimation of the Slope Instability Hazard | 101 |
| 6.5.1. Effect of the Total Dump Height | 102 |
| 6.5.2. Effect of the Bench Height | 103 |
| 6.5.3. Effect of the Bench Slope Angle | 105 |
| 6.5.4. Effect of the Bench Width | 106 |
| 6.5.5. Effect of the Shear Strength Parameters | 107 |
| 6.5.6. Effect of the Unit Weight of the Dump Material | 109 |
| 6.6. Slope Instability Rating | 111 |
| 6.7. Summary | 121 |
| CHAPTER 7: MODEL VALIDATION | 123 |
| 7.1. Introduction | 123 |
| 7.2. Case Study of Mine “X” | 124 |

| | | |
|--|---|-----|
| 7.2.1. | Internal Dump A | 125 |
| 7.2.2. | Internal Dump B | 127 |
| 7.2.3. | Internal Dump C | 129 |
| 7.3. | Case Study of Mine “Y” | 131 |
| 7.3.1. | External Dump D | 132 |
| 7.4. | Case Study of Mine “Z” | 134 |
| 7.5. | Summary | 137 |
| CHAPTER 8: RESULTS AND DISCUSSIONS | | 139 |
| 8.1 | Introduction | 139 |
| 8.2 | Numerical Simulation | 139 |
| 8.3 | Prediction of Factor of Safety of Dump Slopes | 140 |
| 8.4 | Effect of Water Table on the Stability Indicators | 141 |
| 8.5 | Stability Rating and Hazard Quantification | 141 |
| 8.6 | SAHARA System | 143 |
| CHAPTER 9: CONCLUSIONS, LIMITATIONS AND SCOPE FOR FUTURE WORK | | 145 |
| 9.1 | Conclusions | 145 |
| 9.2 | Limitations of the Current Work | 147 |
| 9.3 | Scope for Future Work | 148 |
| REFERENCES | | 149 |
| ANNEXURE I: DUMP MATERIAL CHARACTERIZATION | | 163 |
| ANNEXURE II: NUMERICAL MODELING RESULTS | | 167 |
| ANNEXURE III: WATER TABLE PARAMETRIC RESULTS | | 179 |
| ANNEXURE IV: LIST OF PUBLICATIONS AND AWARDS | | 183 |

LIST OF TABLES

| Table | Title | Page |
|------------------|---|-------------|
| CHAPTER 1 | | |
| 1.1 | Statistics of the consequences of waste rock slope instability | 3 |
| 1.2 | Statistics of displaced material during failure of dump slopes | 3 |
| CHAPTER 2 | | |
| 2.1 | Dump stability parameters and their rating | 12 |
| 2.2 | Classification of hazards based on dump stability rating | 13 |
| 2.3 | Waste dump and stockpile stability rating | 14 |
| 2.4 | Waste dump and stockpile stability rating based hazard classification | 16 |
| 2.5 | The range and the ratings of the parameters | 17 |
| 2.6 | Vulnerability index (VI) and the associated risk | 18 |
| 2.7 | Dump slope rating | 19 |
| 2.8 | Dump slope rating based hazard classification | 19 |
| 2.9 | MESA 1975 stability acceptance criteria | 20 |
| 2.10 | CANMET 1977 stability acceptance criteria | 21 |
| 2.11 | USBM 1982 stability acceptance criteria | 21 |
| 2.12 | BCMWRPRC 1991 stability acceptance criteria | 22 |
| 2.13 | Probability of failure against safety factor for waste rock dump slopes | 23 |
| CHAPTER 3 | | |
| 3.1 | Boundary conditions | 34 |
| 3.2 | Range and base value of parameters governing stability | 37 |

| | | |
|------------------|--|-----|
| 3.3 | Stability governing parameters of water table study | 42 |
| 3.4 | Factor of safety value for stability analysis | 45 |
| 3.5 | Expected performance level based on Reliability Index and Probability of Failure | 46 |
| CHAPTER 5 | | |
| 5.1 | Coefficients and P-value of independent parameters | 74 |
| 5.2 | Range of independent parameters incorporated in the statistical model | 75 |
| 5.3 | Classification of dump slope stability assessment parameters based on stability states | 79 |
| 5.4 | Stability governing and output parameters of different stability states | 80 |
| CHAPTER 6 | | |
| 6.1 | Distribution of the random variables | 98 |
| 6.2 | Stability states based on distribution functions | 99 |
| 6.3 | Mean, standard deviation, and reliability index for various distribution functions | 99 |
| 6.4 | Stable state based input and output parameters | 100 |
| 6.5 | Input parameters, range, and base value for hazard quantification | 100 |
| 6.6 | Weightage and ranking of input parameters | 111 |
| 6.7 | Rating calculation based on a reduction factor of friction angle | 112 |
| 6.8 | Stability rating and hazard of input parameters | 119 |
| 6.9 | Stability rating and hazard of dump slope structure | 121 |
| CHAPTER 7 | | |

| | | |
|------|---|-----|
| 7.1 | Dump A slope stability state analysis based on rating and PoF | 126 |
| 7.2 | Actual and predicted conditions using the SAHARA system of Dump A | 127 |
| 7.3 | Dump B slope stability state analysis based on rating and PoF | 128 |
| 7.4 | Actual and predicted condition using the SAHARA system of Dump B | 129 |
| 7.5 | Dump C slope stability state analysis based on rating and PoF | 130 |
| 7.6 | Actual and predicted conditions using the SAHARA system of Dump C | 131 |
| 7.7 | Dump slope stability state analysis of Mine “Y” based on rating and PoF | 133 |
| 7.8 | Actual and predicted conditions using the SAHARA system of Dump D | 134 |
| 7.9 | Dump slope stability state analysis of Mine “Z” based on rating and PoF | 136 |
| 7.10 | Actual and predicted conditions using the SAHARA system of Mine “Z” dump | 137 |

CHAPTER 8

| | | |
|-----|--|-----|
| 8.1 | Range of performance measuring parameters based on stability states | 143 |
|-----|--|-----|

CHAPTER 9

| | | |
|-----|--|-----|
| 9.1 | Summary of stability classification system | 146 |
|-----|--|-----|

This Page Intentionally Left Blank

LIST OF FIGURES

| Figure | Title | Page |
|------------------|--|------|
| CHAPTER 1 | | |
| 1.1 | Trend of overburden removal and coal production during 2009-22 | 2 |
| CHAPTER 2 | | |
| 2.1 | The general layout of the dump slope structure | 9 |
| 2.2 | Risk matrix for the design and stability acceptance criteria | 25 |
| 2.3 | Grain size distribution of OB material | 26 |
| 2.4 | Statistical distribution of geotechnical parameters (a) density (b) cohesion (c) friction angle based on case studies | 27 |
| CHAPTER 3 | | |
| 3.1 | Flow chart of research methodology | 31 |
| 3.2 | Slope model parameters | 33 |
| 3.3 | Statistical distribution of geotechnical parameters (a) density (b) cohesion (c) friction angle for parametric study | 38 |
| 3.4 | Statistical distribution of geometrical parameters (a) total dump height (b) bench height (c) bench width (d) bench slope angle for parametric study | 39 |
| 3.5 | The phreatic surface under drained condition | 41 |
| 3.6 | Water table variation in a dump slope structure | 42 |
| 3.7 | Statistical distribution of (a) specific gravity, (b) void ratio, (c) porosity, (d) saturated density of OB dump material | 44 |
| CHAPTER 4 | | |
| 4.1 | Total Dump Height versus Factor of Safety | 52 |

| | | |
|------|--|----|
| 4.2 | Total Dump Height versus Max Horizontal Displacement | 52 |
| 4.3 | Total Dump Height versus Max Shear Strain Increment | 53 |
| 4.4 | Zone of influence corresponding to dump height | 55 |
| 4.5 | Bench Height versus Factor of Safety | 56 |
| 4.6 | Bench Height versus Max Horizontal Displacement | 57 |
| 4.7 | Bench Height versus Max Shear Strain Increment | 57 |
| 4.8 | Zone of influence corresponding to bench height | 58 |
| 4.9 | Bench Slope Angle versus Factor of Safety | 59 |
| 4.10 | Bench Slope Angle versus Max Horizontal Displacement | 59 |
| 4.11 | Bench Slope Angle versus Max Shear Strain Increment | 60 |
| 4.12 | Zone of influence corresponding to bench slope angle | 61 |
| 4.13 | Bench Width versus Factor of Safety | 62 |
| 4.14 | Bench Width versus Max Horizontal Displacement | 62 |
| 4.15 | Bench Width versus Max Shear Strain Increment | 63 |
| 4.16 | Zone of influence corresponding to bench width | 64 |
| 4.17 | Cohesion versus Factor of Safety | 65 |
| 4.18 | Cohesion versus Max Horizontal Displacement | 65 |
| 4.19 | Cohesion versus Max Shear Strain Increment | 66 |
| 4.20 | Zone of influence corresponding to cohesion | 66 |
| 4.21 | Density versus Factor of Safety | 67 |
| 4.22 | Density versus Max Horizontal Displacement | 68 |
| 4.23 | Density versus Max Shear Strain Increment | 68 |
| 4.24 | Zone of influence corresponding to density | 69 |
| 4.25 | Friction Angle versus Factor of Safety | 70 |
| 4.26 | Friction Angle versus Max Horizontal Displacement | 70 |

| | | |
|------|---|----|
| 4.27 | Friction Angle versus Max Shear Strain Increment | 71 |
| 4.28 | Zone of influence corresponding to friction angle | 72 |

CHAPTER 5

| | | |
|------|---|----|
| 5.1 | Actual versus Predicted factor of safety | 74 |
| 5.2 | Factor of Safety versus Max Horizontal Displacement | 76 |
| 5.3 | Factor of Safety versus Max Shear Strain Increment | 77 |
| 5.4 | Stability state classification of dump slope structure | 79 |
| 5.5 | Horizontal displacement (a) and shear strain (b) plot of stable dump slope structure | 81 |
| 5.6 | Horizontal displacement (a) and shear strain (b) plot of critically stable dump slope structure | 82 |
| 5.7 | Horizontal displacement (a) and shear strain (b) plot of unstable dump slope structure | 83 |
| 5.8 | Change in safety factor ratio with water table | 85 |
| 5.9 | Change in horizontal displacement ratio with water table | 86 |
| 5.10 | Change in shear strain increment ratio with water table | 88 |
| 5.11 | Maximum horizontal displacement of 30 m dump height | 89 |
| 5.12 | Shear strain increment of 30 m dump height | 90 |
| 5.13 | Maximum horizontal displacement of 150 m dump height | 91 |
| 5.14 | Shear strain increment of 150 m dump height | 92 |
| 5.15 | Maximum horizontal displacement of 270 m dump height | 93 |
| 5.16 | Shear strain increment of 270 m dump height | 94 |

CHAPTER 6

| | | |
|-----|---|-----|
| 6.1 | Probability of occurrence of stability states | 101 |
| 6.2 | Stability state distribution based on the total dump height | 103 |

| | | |
|------|---|-----|
| 6.3 | Stability state distribution based on the bench height | 104 |
| 6.4 | Stability state distribution based on the bench slope angle | 106 |
| 6.5 | Stability state distribution based on the bench width | 107 |
| 6.6 | Stability state distribution based on the cohesion | 108 |
| 6.7 | Stability state distribution based on the friction angle | 109 |
| 6.8 | Stability state distribution based on the density | 110 |
| 6.9 | Rating variation of friction angle | 112 |
| 6.10 | Rating variation of total dump height | 113 |
| 6.11 | Rating variation of bench height | 114 |
| 6.12 | Rating variation of slope angle | 114 |
| 6.13 | Rating variation of bench width | 115 |
| 6.14 | Rating variation of cohesion | 116 |
| 6.15 | Rating variation of density | 116 |

CHAPTER 7

| | | |
|-----|---|-----|
| 7.1 | Mine “X”, opencast coal mine (SECL), Chhattisgarh, India | 124 |
| 7.2 | Internal Dump A, Mine “X”, India | 125 |
| 7.3 | Internal Dump B, Mine “X”, India | 128 |
| 7.4 | Internal Dump C, Mine “X”, India | 130 |
| 7.5 | Mine “Y”, opencast coal mine of Singrauli coalfields (NCL), India | 132 |
| 7.6 | Profile of proposed Dump D | 132 |
| 7.7 | Mine “Z” opencast coal mine (SECL), Korba, Chhattisgarh, India | 135 |
| 7.8 | Dump slope structure profile of Mine “Z” opencast coal mine | 136 |

ABBREVIATIONS AND SYMBOLS

| | |
|-----------------|---|
| SAHARA | Stability Analysis and HAZard RAting |
| OB | Overburden |
| Mm ³ | Million cubic meters |
| Mte | Million tonnes |
| LEM | Limit Equilibrium Method |
| SRM | Strength Reduction Method |
| FEM | Finite Element Method |
| BEM | Boundary Element Method |
| FDM | Finite Difference Method |
| DEM | Discrete Element Method |
| BCMWRPRC | British Columbia Mine Waste Rock Pile Research Committee |
| DSR | Dump Stability Rating |
| m | meter |
| ° | degree |
| WSRHC | Waste Dump and Stockpile Stability Rating and Hazard Classification |
| WSR | Waste Dump and Stockpile Stability Rating |
| WHCs | Waste Dump and Stockpile Hazard Classes |
| RES | Rock Engineering System |
| VI | Vulnerability Index |
| FoS | Factor of Safety |
| DSR | Dump Slope Rating |
| kPa | Kilo Pascale |

| | |
|-------------------|---|
| MESA | US Mine Enforcement and Safety Administration |
| CANMET | Canadian Centre for Mining and Metallurgy |
| USBM | US Bureau of Mines |
| PoF | Probability of Failure |
| XDIS | Maximum Horizontal Displacement |
| SSI | Maximum Shear Strain Increment |
| kg/m ³ | Kilogram per Cubic Meter |
| R ² | Coefficient of Determination |
| MPa | Mega Pascale |
| β | Reliability Index |
| CIL | Coal India Limited |
| SECL | South Eastern Coalfields Limited |
| NCL | Northern Coalfields Limited |
| FLAC | Fast Lagrangian Analysis of Continua |
| 2D | Two Dimension |
| SD | Standard Deviation |
| % | Percentage |
| T | Total Dump Height |
| H | Bench Height |
| A | Bench Slope Angle |
| W | Bench Width |
| C | Cohesion |
| φ | Friction Angle |
| ρ | Density |
| mm | Millimeter |

| | |
|-------------|---|
| $\gamma(d)$ | Dry Density |
| $\gamma(s)$ | Saturated Density |
| G | Specific Gravity |
| e | Void Ratio |
| n | Porosity |
| $\gamma(w)$ | Water Density |
| PERT | Program Evaluation and Review Technique |
| sq. km | Square Kilometer |
| MTPA | Mte Per Annum |
| max | Maximum |