

# TABLE OF CONTENTS

## **CHAPTER 1 RESEARCH PROPOSAL**

1.1 RESEARCH BACKGROUND.....	2
1.2 PROBLEM STATEMENT.....	4
1.3 RESEARCH OBJECTIVES.....	5
1.4 RESEARCH LIMITATION.....	6
1.5 RESEARCH CONTRIBUTION .....	6
1.6 RESEARCH METHODOLOGY.....	7
1.7 DOCUMENT ORGANIZATION.....	8

## **CHAPTER 2 BACKGROUND**

2.1 INTRODUCTION.....	11
2.2 VR SIMULATOR SYSTEM.....	12
2.2.1 <i>Definition of Virtual Reality Simulator</i> .....	12
2.2.2 <i>VR Simulator Architecture and Pipeline</i> .....	13
2.3 VR EXCAVATING MACHINE SIMULATORS .....	16
2.3.1 <i>Graphical Simulator</i> .....	16
2.3.2 <i>Realism-Enhanced Graphical Simulator</i> .....	19
2.3.3 <i>Hybrid Simulators</i> .....	20
2.3.4 <i>Physics-Based Simulator</i> .....	22
2.4 TOOL-INDUCED SOIL RESISTANCE MODELS.....	23
2.4.1 <i>Empirical Models</i> .....	23
2.4.2 <i>Analytical Resistance Models (Universal Earth-Moving Equation Models)</i> .....	25
2.5 PENETRATION MECHANISM AND THEORIES.....	30
2.5.1 <i>Penetrability, Separability and Versatility</i> .....	30
2.5.2 <i>Penetration Theories</i> .....	32
2.6 SECONDARY SEPARATION MECHANISM.....	38

2.7 CONCLUSION .....	39
----------------------	----

### **CHAPTER 3 RESEARCH FRAMEWORK**

3.1 INTRODUCTION.....	42
3.2 FRAMEWORK FOR ANALYZING EXCAVATOR DIGGING PROCESS.....	43
3.3 ARCHITECTURE AND CALCULATION FLOW OF A VR EXCAVATOR SIMULATOR SYSTEM...	45
3.4 CONCLUSION .....	48

### **CHAPTER 4 EXCAVATOR COMPUTATIONAL MODEL**

4.1 INTRODUCTION.....	51
4.2 FUNDAMENTALS OF HYDRAULIC EXCAVATORS.....	52
4.3 HYDRAULIC EXCAVATOR REPRESENTATION.....	55
4.3.1 <i>Internal Representation (Hydraulic System &amp; Control Units)</i> .....	55
4.3.2 <i>External Representation (Excavator Structure)</i> .....	56
4.3.3 <i>Calculation Scheme for Bucket Spatial Information and Bucket Forces</i> .....	56
4.4 CONCLUSION.....	67

### **CHAPTER 5 MATHEMATICAL MODEL OF EXCAVATOR DIGGING**

5.1 INTRODUCTION.....	70
5.2 IDEALIZED EXCAVATOR BUCKET.....	71
5.3 GENERALIZED SEPARATION MODEL.....	75
5.3.1 <i>Idealized Soil Failure Wedge</i> .....	76
5.3.2 <i>Identification of Forces Related to Separation Failure</i> .....	78
5.3.3 <i>Derivation of Separation Resistance (<math>R_s</math>)</i> .....	80
5.4 PENETRATION MODEL.....	88
5.4.1 <i>Identification of Forces Forming Penetration Resistance (<math>R_p</math>)</i> .....	88

5.4.2 Assumptions on Cavity Expansion Theory for Bucket Tooth Penetration.....	92
5.4.3 Penetration Process.....	94
5.5 EXCAVATOR DIGGING MODES.....	96
5.5.1 Digging Mode I: Separation.....	99
5.5.2 Digging Mode II: Penetration.....	100
5.5.3 Digging Mode III: Separation and Penetration.....	102
5.5.4 Digging Mode IV: Penetration and Secondary Separation.....	104
5.5.5 Digging Mode V: Penetration, Separation and Secondary Separation.....	105
5.6 CONCLUSION.....	106

## **CHAPTER 6    CALCULATION METHODOLOGY**

6.1 INTRODUCTION.....	109
6.2 DYNAMIC VIEW OF CALCULATION FLOW FOR A VR EXCAVATOR SIMULATOR SYSTEM..	110
6.2.1 Calculation Route 1 (Excavator Digging).....	116
6.2.2 Calculation Route 0 (Digging Operation Idle).....	119
6.2.3 Calculation Route 2 (Free Air Movement).....	119
6.3 DIGGING MODE SELECTION.....	120
6.3.1 Challenges in Digging Mode Selection.....	120
6.3.2 Digging Mode Selection Algorithm.....	121
6.3.3 Algorithm of Imaginary Joint Calculation of Multi-Joint Circular Trajectory....	134
6.4 APPROXIMATION OF SOIL FAILURE ANGLE.....	141
6.4.1 Summary of the Generalized Separation Model.....	141
6.4.2 Sensitivity Analysis.....	143
6.5 APPROXIMATION OF BUCKET TRAVEL DISTANCE BETWEEN SEPARATION FAILURES.....	148
6.5.1 Characteristics of Separation and Penetration Soil Failures.....	148
6.5.2 Bucket Travel Distance between Separation Failures.....	150
6.6 CONCLUSION.....	152

**CHAPTER 7 SUMMARY, CONCLUSIONS AND FUTURE RESEARCH**

7.1 SUMMARY OF RESULTS .....155

    7.1.1 *Mathematical Model of Excavator Digging*.....155

    7.1.2 *Calculation Methodology*.....157

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH.....158

    7.2.1 *Recommendations on the Mathematical Model of Excavator Digging* .....158

    7.2.2 *Recommendations on the Excavator Computational Model*.....159

    7.3.3 *Recommendations on the Soil Medium Representation*.....159

    7.3.4 *Recommendations on User Perception Improvement*.....160

**REFERENCES** .....161

**APPENDIX A**

**PROCEDURE FOR CALCULATING CAVITY EXPANSION PRESSURE**.....166

**APPENDIX B**

**$R_s - \rho$  DIAGRAMS**.....168

**APPENDIX C**

**$\rho - \beta$  DIAGRAMS FOR DIFFERENT ANGLES OF  $\alpha$**  .....217

**VITA** .....222