A STUDY OF APPLICABILITY OF DIFFERENT FACING TYPES IN SOIL NAILING

Buddhika Indramal Kumarage

168965F

Degree of Master of Engineering

Department of Civil Engineering

University of Moratuwa

Sri Lanka

March 2021

A STUDY OF APPLICABILITY OF DIFFERENT FACING TYPES IN SOIL NAILING

B.I Kumarage

168965F

Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree of Master of Engineering in Geotechnical Engineering

Department of Civil Engineering

University of Moratuwa

Sri Lanka

March 2021

Declaration

I declare that this is my own work and this thesis does not incorporate without acknowledgment any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of our knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgment is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books)

Signature of the candidate: …….. Date: ……..

B.I. Kumarage

The above candidate has carried out research for the Master's thesis under my supervision.

Signature of the supervisor: …….. Date: ……..

Professor S.A.S Kulathilaka,
BSc. Eng. Hons (Moratuwa), PhD (Monash), CEng, MIE(SL)
Department of Civil Engineering,
University of Moratuwa,
Sri Lanka.

Abstract

Soil nailing has been used in Sri Lanka lately, in a wide range of infrastructure projects, as a cost-effective stabilization technique that can be implemented quickly. However, detailed designs with rigor, for nailhead/ facing are not often carried out in the local practice. Full face shotcrete, grid beams connecting nail heads, isolated nail heads (Pillows), and combinations of all these facings types used in the local practice. When the full face shotcreting is not used vegetation is used as a surface protection cover in between the nail heads with the help of a geotextile and nail heads are combined with a wire mesh of specified tensile strength. The mesh is expected to provide stability against any local shallow failures. The versions without full-face shotcrete blend nicely with the natural environment and have gained greater acceptance.

In this research design guidelines for different facing types available in published literature are critically reviewed to assess the suitability under high rainfall intensities in local residual soil formations. A number of sites rectified with soil nailing with different types of facing have now experienced few seasons of rainfall and their performance is assessed. The cost-effectiveness and construction difficulties are also reviewed.

Based on these factors some guidelines are developed to decide on the most appropriate type of facing depending on the prevailing local conditions.

keywords; slope rectification, soil nailing, facing types for soil nailing

B I Kumarage (NBRO) S A S Kulathilaka (University of Moratuwa)

Acknowledgment

Firstly, I would like to express my sincere thankfulness to my supervisor, Prof. S.A.S. Kulathilaka for his guidance and support as well as the encouragement provided throughout the research work. His profound insight and vast experience in the field of geotechnical engineering made the suggestions and comments he made extremely versatile and contributed immensely to the success of this research. Also, my sincere thanks go to Dr. L.I.N. De Silva as the course coordinator and all the academic staff of Geotechnical Engineering: Prof. U.G.A. Puswewala, Dr. U.P. Nawagamuwa, and Dr. (Mrs.) A.S. Ranathunga for supporting in various means with regards to the academic works with excellent cooperation and guidance.

I am enormously grateful to Dr. Asiri Karunawardena, Director General, National Building Research Organisation (NBRO) for his guidance, support, and continual encouragement that was given throughout the process. I also owe my gratitude to Mr. U.K.N.P. Dharmasena, Senior Engineer (Construction) of the CRIP-Road Project for his support throughout the project period and after. Last but not least, I extend my gratitude for the continued support and insight provided by Eng. P.R.C. Ariyarathne, who was the in-charge of the Design Unit of NBRO, as well as all the other colleagues of NBRO for supporting in every possible way.

Table of Contents

Chapter 1. Introduction 1
1.1 Background 1
1.2 Soil Nail Facings 2
1.3 Failures in Soil-Nailed Systems 3
1.4 Use of Soil Nail Facings in Sri Lanka 4
1.5 Scope and Objectives of the Research 6
1.6 Methodology Followed 6
1.7 Structure of the Thesis 8
Chapter 2. Review of Literature 10
2.1 Research Carried out on Facings 10
2.1.1 Experimental Full-scale Structures and Laboratory Model Tests 10
2.1.2 Field Studies 16
2.2 Commonly used Facing Design Approaches 18
2.2.1 British approach 19
2.2.2 US-FHWA approach 20
2.2.3 French approach 21
2.2.4 Japanese approach 21
2.2.5 Hong Kong approach 22
2.2.6 The approach presented in CIRIA report C637 22
2.3 General Rules for Selecting the Facing Type 23
2.4 Nailhead Load – Tensile Force at the Nailhead 26
2.4.1 Introduction 26
2.4.2 Methods proposed by FHWA 28
2.4.3 Method proposed by the Japan Highway Public Corporation 30
2.4.4 Suggestions in GEO Reports No. 175 31
2.4.5 Method proposed by French National Project Clouterre 33
2.4.6 Safety factors used to be used with nailhead load or resistance 34
2.5 Full-Face Shotcrete Facings 36
2.5.1 Introduction 36

2.5.2 Method proposed by FHWA 38
2.5.3 Methods presented in CIRIA c637 (2005) 42
2.5.4 Method proposed in Clouterre (1991) 44
2.6 Grid Beam Facings 47
2.6.1 Introduction 47
2.6.2 Method proposed by GEO and HKIE for loose fills 48
2.6.3 The usefulness of FHWA (1998) and CIRIA c637 methods of Shotcrete facing design 55
2.7 Flexible Structural Facings 56
2.7.1 Introduction 56
2.7.2 Suggestions in CIRIA c637 for designing flexible structural facings .. 58
2.7.3 Analysis carried out in GEO report No. 175 61
2.7.4 The design approach presented by Ruegger et. al 62
2.7.5 Mechanical properties of the mesh 69
2.8 Isolated Nailheads 70
2.8.1 Introduction 70
2.8.2 Method for obtaining the capacity of the bearing plate 71
2.8.3 Bearing capacity of isolated nailheads 73
2.9 Relationship Between Soil Nail facing and the Factor of Safety of the Soil Nail system 78
Chapter 3. Estimation of the Nailhead Load 80
3.1 Background 80
3.2 Procedure for Obtaining Nailhead Load 82
3.3 Application for a Case History – Landslide Rectification at Hakgala 83
3.3.1 Obtaining the nailhead load 83
3.3.2 Evaluation of nailhead forces for different nailing arrangements 90
3.3.3 Evaluation of nailhead forces for different methods and slope conditions 92
Chapter 4. Design of Shotcrete Facings 96
4.1 Background 96
4.1.1 Design for flexure 96

4.1.2 Design for shear 97
4.2 Proposing a procedure for the design of shotcrete facings 97
4.3 Application for a Case History 100
4.3.1 Shotcrete facing design for Hakgala landslide mitigation project using the proposed method 100
4.3.2 Design of shotcrete facing for different nailing arrangements 104
4.3.3 Design of Shotcrete facing using alternative methods 105
Chapter 5. Design of Grid Beams (Concrete Crib) 116
5.1 Background 116
5.1.1 Flexural Resistance of Grid Beams 117
5.1.2 Shearing Resistance of Grid Beams 123
5.2 Proposing a method for designing Grid Beam facings 125
5.3 Application for a Case History 130
5.3.1 Grid Beam facing design for Hakgala landslide mitigation project using the proposed method 130
5.3.2 Design of grid beam for the case history for different nailing arrangements 134
5.3.3 Grid Beam facing design for the case history using alternative methods 135
Chapter 6. Design of Flexible Structural Facings 142
6.1 Background 142
6.2 Procedure for designing the flexible facing 143
6.3 Application for a Case History 149
6.3.1 Flexible facing design for Hakgala landslide mitigation using the presented procedure 149
6.3.2 Design of flexible facing for different nail spacings and excavation angles 154
6.3.3 The effect of cohesion 156
6.3.4 Flexible facing design for the case history using different methods .. 157
6.3.5 Conclusion 159
Chapter 7. Design of Isolated Nailheads 161
7.1 Background 161

7.2 Procedure for designing Isolated Nailheads 161
7.3 Application for a Case History 164
7.3.1 Isolated nailhead design for Hakgala landslide mitigation project using the proposed method 164
7.3.2 Design of isolated nailheads for different nailing arrangements 168
7.3.3 Design of isolated nailheads for different slope excavation angles ... 169
Chapter 8. Performance Assessment of Facings on Field 171
8.1 Introduction 171
8.2 Assessment Criteria 171
8.3 Assessment of facing the condition 173
8.3.1 Southern Expressway CH 42+500 173
8.3.2 Kandy Mahiyangana Road A026 - Location 2 175
8.3.3 Kandy Mahiyangana Road A026 - Location 3 177
8.3.4 Kandy Mahiyangana Road A026 - Location 4 178
8.3.5 Kandy Mahiyangana Road A026 - Location 7 180
8.4 Recent developments in Shotcrete facings 182
Chapter 9. Comparison of Costs of Different Facing Types 184
9.1 Cost factors of soil nail system constructions 184
9.2 Costs of facing construction 188
9.2.1 Cost of isolated nailhead construction 189
9.2.2 Cost of grid beam construction 189
9.2.3 Cost of full-face shotcrete construction 190
9.2.4 Cost of bearing plate with high tensile wire facing 191
9.2.5 Conclusion 191
Chapter 10. Discussion and Conclusion 193
References 1
Appendix A Cost Input from Contractors 1

List of figures

Figure 2-1. Earth Pressure Behind Facing (Gässler & Gudehus (1981)) 10

Figure 2-2. Stability of Excavation (after Plumelle and Schlosser, 1990) 11

Figure 2-3. Instrumentation of Model Slope Reinforced with Metal Strips and Facing (after Gutierrez and Tatsuoka, 1988) 12

Figure 2-4. Surcharge load and displacement relationship of soil nailed slopes (after Gutierrez and Tatsuoka, 1988) 13

Figure 2-5. Slope Facing Types and Reinforced Slope Deformation Modes (after Muramatsu et al, 1992) 14

Figure 2-6. Distribution of Tensile Force Along Soil Nails with Different Facing Types (after Muramatsu et al, 1992) 15

Figure 2-7. Horizontal Displacements Related to Facing Roughness and Flexibility (after Tei et al, 1998) 16

Figure 2-8. Distribution of Tensile Force in Reinforcing Bars (after Muramatsu et al, 1992) 17

Figure 2-9. Allowable Nail Load Support Diagram (After FHWA) 20

Figure 2-10. Shear stress distribution of grout-soil interface (Carlos A. Lazarte, et al., 2015) 26

Figure 2-11. Distribution of tensile force along the soil nail (Carlos A. Lazarte, et al., 2015) 27

Figure 2-12. Normalized Nailhead Load (F_F) Distribution (Byrne, Cotton, Porterfield, Wolshlag, & Ueblacker, 1998) 28

Figure 2-13. Nail Force Coefficient μ (after Japan Highway Public Corporation, 1998) 31

Figure 2-14. T_0/T_{max} distribution of isolated nailheads via finite element analysis (Shiu & Chang, 2004) 32

Figure 2-15. Typical details of shotcrete facing used in Sri Lanka (after NBRO design documents) 37

Figure 2-16. Bending mechanism of shotcrete facing (FHWA 1998) 39

Figure 2-17. Varying soil pressure acting behind the facing (FHWA 1998) 40

Figure 2-18. Punching Shear Mechanism of a Nailhead, (Byrne, Cotton, Porterfield, Wolshlag, & Ueblacker, 1998) 41

Figure 2-19. Details of a typical Grid Beam system used in Sri Lanka 47

Figure 2-20. Limit equilibrium model to determine stabilizing surface pressure (Geotechnical Engineering Office, Hong Kong Institution of Engineers, 2013) 50

Figure 2-21. Example calculation of earth pressure presented in GEO & HKIE (2013) report 51

Figure 2-22. Soil pressure distribution behind the nailhead (After GEO & HKIE (2013)) 54

Figure 2-23. Typical details of a flexible facing system (Phear, et al., 2005) 56

Figure 2-24. Local instability between nailheads (Shiu & Chang, 2004) 57

Figure 2-25. Ways to estimate potential out-of-balance forces for the design of flexible facings (CIRIA, 2005) 59

Figure 2-26. Forces on the two-wedge mechanism (The Highways Agency, 1994) . 60

Figure 2-27. Failure mode of local instabilities considered in the GEO report No. 175 61

Figure 2-28. Vertical critical distance (after GEO report No. 175) 62

Figure 2-29. Forces acting on a sliding body soil parallel to the slope face (Cala, Flum, Rüegger, Roduner, & Wartmann, 2020) 64

Figure 2-30. Forces considered for the one-body mechanism (Cala, Flum, Rüegger, Roduner, & Wartmann, 2020) 65

Figure 2-31. Forces considered for the two-body mechanism (Ruegger & Flum, 2000) 66

Figure 2-32. Typical Detail of an Isolated Nailhead (Pillow) (NBRO Design Documents) 70

Figure 2-33. Forces acting on the bearing plate, Cross-section 72

Figure 2-34. Nailhead Bearing Capacity (lower bound solution) (after HA 68/94) .. 74

Figure 2-35. Failure mode considered in the upper bound solution for bearing resistance of nailhead (The Highways Agency, 1994) 75

Figure 2-36. Nailhead size requirement FLAC analysis vs Lower bound method HA 68/94 (Shiu & Chang, 2004) 76

Figure 2-37.Typical Details of a Soil-nail Head for a Shallower Slope (Geotechnical Engineering Office, 2008) 77

Figure 2-38. Effect of nailhead on the distribution of tensile forces along soil nails (Shiu & Chang, 2004) 79

Figure 2-39. Effect of the types of facing on the maximum tensile force along soil nails (Shiu & Chang, 2004) 79

Figure 3-1. Nailhead load calculation procedure 82

Figure 3-2. Image of Hakgala major landslide before implementing mitigations 83

Figure 3-3. Contour map and plan view of cross-sections – Hakgala landslide 84

Figure 3-4. Existing Stability analysis - CS5 – Hakgala landslide 86

Figure 3-5. Stability analysis soil nail at 2m - CS5 – Hakgala landslide..... 86

Figure 3-6. Soil Nail forces obtained from Slope/ W software 87

Figure 3-7. Stability analysis soil nails at 2.5m - CS5 – Hakgala landslide 90

Figure 3-8. Stability analysis with Sv=1.5 m - CS5 – Hakgala landslide..... 91

Figure 3-9. Nailhead Load vs Slope angle for different ϕ' values of soil (FHWA 1998 method) 95

Figure 4-1. Flexural resistance, $T_o$ult vs Nail Spacing for the Shotcrete section considered for CS5 of Hakgala landslide mitigation 110

Figure 4-2. Punching shear resistance, $T_o$ult vs Nail Spacing for the Shotcrete section considered for CS5 of Hakgala landslide mitigation 111

Figure 4-3. Punching shear resistance, $T_o$ult vs Bearing plate size for the Shotcrete section considered for CS5 of Hakgala landslide mitigation..... 112

Figure 4-4. Punching shear resistance, $T_o$ult vs Facing thickness for the Shotcrete facing considered for CS5 of Hakgala landslide mitigation 113

Figure 4-5. Envelope Nailhead resistance, $T_o$ult vs Facing thickness for the Shotcrete facing considered for CS5 of Hakgala landslide mitigation 114

Figure 4-6. Shotcrete facings with strengthened nailhead area..... 115

Figure 5-1. Approximate bending moments of a continuous slab 118

Figure 5-2. Yield pattern of grid beams at the nailhead (modified after FHWA 1998) 119

Figure 5-3. Punching shear area of shotcrete vs grid beam 123

Figure 5-4. Flexural resistance, $T_o$ult vs Nail Spacing for the Grid Beam considered for CS5 of Hakgala landslide mitigation..... 138

Figure 5-5. Shear resistance, $T_o$ult vs Nail Spacing for the Grid Beam considered for CS5 of Hakgala landslide mitigation 139

Figure 5-6. Flexural resistance vs Sv [CIRIA] for the Grid beam section used in the case study 140

Figure 5-7. Flexural resistance vs Sv [FHWA] for the Grid beam section used in the case study 140

Figure 6-1. Failure geometry of soil in-between the nailheads (Ruegger & Flum, 2000) 144

Figure 6-2. Mechanism of two-part-wedge failure considered for obtaining flexible facing load..... 144

Figure 6-3. Physical parameters of a flexible metallic mesh (Geobrugg product datasheet)..... 147

Figure 6-4. Force in the flexible mesh vs Slope angle considered for CS5 of Hakgala landslide mitigation..... 155

Figure 6-5. Force on the flexible mesh vs Nail spacings considered for CS5 of Hakgala landslide mitigation..... 155

Figure 6-6. Force on the flexible mesh vs Cohesion considered for CS5 of Hakgala landslide mitigation..... 156

Figure 8-1. Vegetation cover on steep shotcrete slope (before and after) 182

Figure 8-2. Shotcrete Vegetation Mulching Technique - Taiwan (After Fan et. al.) 183

List of tables

Table 2-1. Ultimate Friction Angles for Dissimilar Materials (AASHTO, 2002) 30

Table 2-2. Facing Pressure Factors (FHWA,1998) 40

Table 3-1. Soil parameters used in CS5 stability analysis 85

Table 3-2. Soil nail forces obtained from the stability analysis (2.0 m x 2.0 m arrangement) 88

Table 3-3. Soil nail forces obtained from the stability analysis (2.5 m x 2.5 m arrangement) 90

Table 3-4. Variation of Nailhead Load with Nail Spacing 92

Table 3-5. $T_{0,ult}$ values obtained from FHWA (1998) method for different nail spacings 94

Table 3-6. Comparison of the T_o,ult obtained from the two methods Clouterre (1991) and FHWA (1998) 94

Table 4-1. Summary of possible Shotcrete designs for alternative nail spacings 104

Table 5-1. Design bending moments and shear forces (BS 8110, Part 1, 1997) 121

Table 5-2. Summary of possible Grid Beam designs for alternative nail spacings . 135

Table 5-3. Values of Flexural Resistance, Rff of shotcrete facings (after FHWA 2015) 141

Table 6-1. Tested properties of a proprietary metallic mesh used for slope rectification 147

Table 6-2. Tested properties of a proprietary metallic mesh used for slope rectification 152

Table 6-3. Comparison of punching force requirement of pillow method and grid beam method 160

Table 7-1. Required size of isolated nailhead vs nail spacing considered for CS5 of Hakgala landslide mitigation 169

Table 7-2. Variation of Bearing Resistance of Nailheads, Lower bound method, considered for CS5 of Hakgala landslide mitigation 169

Table 9-1. Cost per unit area of each facing type 191