


FLOW MECHANISM AND SUCTION DISTRIBUTION IN HETEREGENOUS
RESIDUAL SOIL SLOPE UNDER RAINFALL INFILTRATION

ZAIHASRA BINTI ABU TALIB



A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy in (Civil Engineering)

School of Civil Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

AUGUST 2019

DEDICATION

Anak-anak tercinta,

Puteri Alisya Sofea binti Mohd Khaire

Muhammad Afif Syaqib bin Mohd Khaire

Puteri Aisyah Shafiyyah binti Mohd Khaire

Bonda Salmah binti Sardan

Dalam ingatan selalu

Mohd Khaire bin Hj Mohd Nor (Al-Fatihah).

ACKNOWLEDGEMENT

Assalamualaikum w.b.t

In the name of Allah, the Most Generous and the Most Merciful

I would like to express my profound gratitude to my supervisor, Prof Ir Dr Azman bin Kassim and co-supervisor, Associate Prof Dr Ahmad Safuan bin A. Rashid for their valuable support, encouragement, supervision and useful suggestion throughout this research work. Their moral support and patiently guidance enable me to complete this project.

I would like to take this opportunity to thank everyone who has contributed either directly or indirectly throughout this thesis and project. To my colleagues, staff and lecturer in the Faculty of Engineering, highest appreciation and thanks for their helps and suggestion regarding to this project.

I am as ever, especially to my beloved children for their love, endless moral support and encouragement throughout my life. I am also thankful to all my siblings who guide me about the path of life. Your contribution and sacrifices will always remember.



ABSTRACT

An imperative factor in rainfall induced slope failure is infiltration rate. Water that infiltrates into residual soil is predominantly controlled by two factors, i.e. rainfall intensity and saturated permeability of soil, which varies with depth as a result of weathering processes. Variation in permeability may either prevent or allow water to seep into deeper soil layers. Therefore, this study aimed to investigate the behaviour of suction distribution in a two-layered residual soil system consisting of Grade V and Grade VI residual soils with various saturated permeability functions using a laboratory physical slope model, in-situ or field work, and numerical modeling. The laboratory physical slope model was developed for the purpose of facilitating infiltration tests with three different permeability functions for each of the Grade V and Grade VI soils. A total of 42 infiltration tests were performed. The two-layered slope was then numerically simulated using SEEP/W GeoStudio software, which served to verify field data and determine the best modelling scheme that later be applied to signify the suction distribution behaviour of the residual soil slope model. Burrow holes present in the Grade VI soil layer caused the loss of the capillary barrier effect, which in turn allowed more rainfall to infiltrate into the soil layers. It was also found that when the ratio of permeability function between Grade V and Grade VI soils was high, an increase in the breakthrough time with corresponding decrease in the breakthrough matric suction occurred. From the seepage analysis, the numerical model incorporating burrow holes in Grade VI residual layer coupled with the effect of two sets of relict joints in Grade V yielded significant improvement in heterogeneous residual soil slope modelling. The findings of this study were then validated with previous findings using Prediction Accuracy (PA) analysis. It was established that burrow holes and two sets of relic joints conclusively improved the modelling of heterogeneous residual soil slope particularly at depths of 1.0 m and 1.5 m.

ABSTRAK

Faktor penting dalam kegagalan cerun disebabkan oleh hujan ialah kadar penyusupan. Air yang menyusup ke tanah sisa kebanyakannya dikawal oleh dua faktor, iaitu intensiti hujan dan kebolehtelapan tepu tanah, yang bervariasi dengan kedalaman akibat proses luluhawa. Variasi kebolehtelapan ini samada mencegah atau membenarkan air untuk menyusup masuk ke dalam lapisan yang lebih dalam. Oleh itu, objektif kajian ini adalah untuk mengenal pasti taburan sedutan bagi dua lapisan sistem tanah iaitu Gred V dan Gred VI dengan ciri-ciri fungsi kebolehtelapan tepu yang berlainan melalui fizikal model cerun makmal, data di tapak dan juga pemodelan berangka. Satu model fizikal cerun telah dibangunkan dalam makmal untuk ujian penyusupan dimana tiga kebolehtelapan yang berbeza bagi setiap lapisan Gred V dan Gred VI. Sebanyak empat puluh dua (42) ujian penyusupan telah dilakukan. Cerun dengan dua lapisan tanah itu kemudiannya disimulasi secara berangka menggunakan perisian SEEP/W GeoStudio, yang berfungsi untuk mengesahkan data lapangan dan menentukan skema pemodelan terbaik yang kemudiannya digunakan untuk mengesahkan taburan matrik yang terdapat di dalam cerun tanah baki. Kehadiran lubang jara pada Gred VI menyebabkan berlakunya kehilangan penghalang kapilari dan ini membenarkan lebih banyak air menyusup masuk ke dalam lapisan tanah. Keputusan juga mendapati bahawa apabila nisbah fungsi kebolehtelapan di antara Gred V dan Gred VI terlalu tinggi, akan meningkatkan masa keadaan bulus dan mengurangkan sedutan matrik pada keadaan bulus. Daripada analisis resipan, pembangunan pemodelan berangka dengan mengambil kira kehadiran lubang jara di lapisan Gred VI tanah berbaki bersama-sama dengan kesan dua set ketakselajaran relikta di lapisan Gred V menunjukkan penambahbaikan yang ketara di dalam pemodelan cerun keheterogenan tanah berbaki. Kajian ini kemudiannya disahkan dengan dapatan kajian lepas dengan menggunakan kaedah Ketepatan Ramalan (PA). Didapati lubang jara dan dua set ketakselajaran rekta secara menyeluruh telah menambak pemodelan berangka cerun keheterogenan tanah berbaki terutama pada kedalaman 1.0 m dan 1.5 m.

TABLE OF CONTENTS

	TITLE	PAGE
	DECLARATION	iii
	DEDICATION	iv
	ACKNOWLEDGEMENT	v
	ABSTRACT	vi
	ABSTRAK	vii
	TABLE OF CONTENTS	ix
	LIST OF TABLES	xiv
	LIST OF FIGURES	xvi
	LIST OF ABBREVIATIONS	xxi
	LIST OF SYMBOLS	xxii
	LIST OF APPENDICES	xxiii
CHAPTER 1	INTRODUCTION	1
1.1	Background of study	1
1.2	Problem statement	3
1.3	Objectives	4
1.4	Scopes of the study	5
1.5	Significance of study	6
1.6	Thesis organization	6
CHAPTER 2	LITERATURE REVIEW	9
2.1	Introduction	9
2.2	Tropical Residual Soil	10
2.2.1	Heterogeneity of residual soil	12
2.2.2	Burrow holes in residual soil	14
2.3	Rainfall-Induced Slope Failure	15
2.3.1	Rainfall Induced Slope Failure Mechanism	17
2.4	Unsaturated Soil Behaviour	18

2.4.1	Soil Water Characteristics Curve (SWCC)	19
2.4.2	Hydraulic conductivity function	21
2.5	Rainfall Infiltration	22
2.6	Capillary Barrier Effect	23
2.7	Physical Modelling for Infiltration Test	26
2.8	Numerical modeling	29
2.9	Concluding Remarks	31
CHAPTER 3	METHODOLOGY	33
3.1	Introduction	33
3.2	Input and Output Parameters	36
3.3	Soil Characterization	36
3.4	Index properties of soil	38
3.4.1	Sieve analysis test	38
3.4.2	Atterberg limit tests	39
3.4.3	Specific gravity test (Gs)	39
3.5	Engineering properties of soil	39
3.5.1	Compaction test	40
3.5.2	Shear strength test	40
3.5.3	Permeability test	40
3.5.4	Modified permeability test	40
3.6	Rainfall Characteristic	42
3.7	Field Work	44
3.8	Laboratory Physical Modeling	47
3.8.1	Sample preparation	52
3.9	Experimental program	54
3.10	Numerical Simulator	58
3.11	Prediction Accuracy (PA)	58
3.12	Concluding remarks	59
CHAPTER 4	PRELIMINARY DATA	61
4.1	Introduction	61
4.2	Soil Properties	61

4.2.1	Index properties	62
4.2.2	Engineering properties	65
4.3	Modified Permeability Test	67
4.3.1	Permeability for two relict joint	67
4.3.2	Permeability for burrow holes	69
4.3.3	Comparison between permeability of one relict joint and two relict joint	71
4.4	Concluding remarks	72
CHAPTER 5	LABORATORY MODELLING	73
5.1	Introduction	73
5.2	Water Infiltration and Runoff Analysis	74
5.3	Comparison of Suction Distribution for One Relict Joint and Two Relicts Joint	75
5.3.1	Suction Distribution due to 1-hour Rainfall intensity	75
5.3.2	Suction Distribution due to 24-hour Rainfall	79
5.3.3	Suction Distribution due to 7-day Rainfall	84
5.4	Suction distribution for Grade V with two relict joint and Grade VI without burrow holes	88
5.4.1	Suction Distribution due to 1-hour Rainfall intensity	88
5.4.2	Suction Distribution due to 24-hour Rainfall intensity	91
5.4.3	Suction Distribution due to 7-day Rainfall intensity	95
5.5	Suction distribution for Grade V with two relict joint and Grade VI with burrow holes	99
5.5.1	Suction distribution for Grade V with two relict joint and Grade VI with burrow holes with 6.98×10^{-4} m/s permeability	100
5.5.1.1	Suction Distribution due to 1-hour Rainfall intensity	100
5.5.1.2	Suction Distribution due to 24-hour Rainfall intensity	105
5.5.1.3	Suction Distribution due to 7-day Rainfall intensity	108

5.5.2	Suction distribution for Grade V with two relict joint and Grade VI with burorw holes with 1.14×10^{-3} m/s permeability	112
5.5.2.1	Suction Distribution due to 1-hour Rainfall intensity	113
5.5.2.2	Suction Distribution due to 24-hour Rainfall intensity	117
5.5.2.3	Suction Distribution due to 7-day Rainfall intensity	121
5.6	Controlling factors	125
5.6.1	Effect of relict joint	125
5.6.2	Effect of Burrow holes	126
5.6.3	Effect of field scale heterogeneity on suction distribution	129
5.6.4	Effect of ratio permeability between Grade V and Grade VI	134
5.7	Conclusion	137
CHAPTER 6	LABORATORY MODELLING	141
6.1	Introduction	141
6.2	Modelling Scheme	142
6.3	Comparison simulated suction between previous researcher and Scheme I	145
6.4	Comparison simulated suction between previous researcher and Scheme II	147
6.5	6.5 Comparison simulated suction between previous researcher and Scheme III	150
6.6	Comparison simulated suction between previous researcher and Scheme IV	152
6.7	Comparison simulated suction between previous researcher and Scheme V	155
6.8	Comparison of suction distribution on numerical modeling using PA	158
6.9	Conclusion	161
CHAPTER 7	CONCLUSIONS AND RECOMMENDATIONS	163
7.1	Conclusions	163

7.1.1	Permeability of saprolitic layer (Grade V)	163
7.1.2	Permeability of lateritic layer (Grade VI)	163
7.1.3	Suction distribution behavior and flow mechanism on two-layered residual soil with relict joint set and burrow hole subjected to various rainfall intensity and duration.	164
7.1.4	Modelling Concept in Heterogeneous Residual Soils	165
7.2	Recommendations	166
7.2.1	Effect of multiple orientation of relict joint and area and depth of burrow holes	166
7.2.2	Improvement of laboratory and site instrumentations	167
7.2.3	Full scale modeling under field condition	167
7.2.4	Studies on infiltration rate at interface	167

REFERENCES

169

LIST OF PUBLICATIONS

179



PT TA UTHAM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	Majors factors affecting soil formation (Singh et al., 2004)	11
Table 3.1	Testing for index properties of soil	38
Table 3.2	Coefficients for IDF curve for several place in Johor	43
Table 3.3	Technical details of the new rainfall simulator	50
Table 3.4	Experimental scheme for rainfall intensity with two relict joints	54
Table 3.5	Experimental scheme for rainfall intensity with one relict joint	55
Table 3.6	Experimental scheme test for rainfall intensity with two relict joint and burrow hole	56
Table 3.7	Permeability properties for each layer	57
Table 4.1	Properties of Grade V soil	64
Table 4.2	Properties of Grade VI soil	64
Table 4.3	Soil water characteristics curve parameter of Grade V and Grade VI soils	66
Table 4.4	Fitting for SWCC	66
Table 4.5	Saturated permeability for Grade V or Silty Gravel with 2 relict joint	68
Table 4.6	Saturated permeability for Grade VI or sandy silt with existing burrow hole	70
Table 5.1	Rainfall and runoff amount data during infiltration test	74
Table 5.2	Comparison of matric suction at interface for initial condition and the end of testing for one relict joint and two relict joint for 1 hour rainfall intensity	78
Table 5.3	Breakthrough data for one relict joint and two relict joint due to 24-hour rainfall intensity	83
Table 5.4	Breakthrough data for one relict joint and two relict joint due to 7-day rainfall intensity	87
Table 5.5	Breakthrough data for 24-hour rainfall in a two-layered soil with two relict joint in Grade V soil	95

Table 5.6	Breakthrough data due to 7-day rainfall in a two-layered soil with two relict joint in Grade V soil	99
Table 5.7	Breakthrough data due to 24-hour rainfall in a two-layered soil with Grade VI 6.98×10^{-4} m/s permeability and two relict joint in Grade V soil	108
Table 5.8	: Breakthrough data due to 7-day rainfall in a two-layered soil with Grade VI 6.98×10^{-4} m/s permeability and two relict joint in Grade V soil	111
Table 5.9	Breakthrough data due to 24-hour rainfall in a two-layered soil with Grade VI 1.13×10^{-3} m/s permeability and two relict joint in Grade V soil	121
Table 5.10	Breakthrough data due to 7-day rainfall in a two-layered soil with Grade VI 1.13×10^{-3} m/s permeability and two relict joint in Grade V soil	124
Table 5.11	Ratio of q/K_{sat} for all type of rainfall and soil layer Grade VI	128
Table 5.12	Ratio between Grade VI and Grade V permeability	134
Table 6.1	Modelling scheme for numerical analysis	144
Table 6.2	PA analysis between previous researcher and current study with site data	160

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	Classification of weathering profile (Mclean & Gribble, 1979)	12
Figure 2.2	Illustration of macropore flow (Hendrickx & Flury, 2001)	15
Figure 2.3	Four phases in unsaturated soil (Liu <i>et al.</i> , 2011)	19
Figure 2.4	Soil water characteristics curve (SWCC)	20
Figure 2.5	Hydraulic conductivity function for several types of soil (Rahadjo <i>et. al</i> 2012)	21
Figure 2.6	Capillary barrier system in residual soil slope (Morris & Stormont, 1999)	24
Figure 2.7	SWCC for fine-grained soil and coarse-grained soil to determine the breakthrough suction (Li, Du, Chen, & Zhang, 2013)	25
Figure 2.8	Hydraulic conductivity curve for fine-grained soil and also coarse grained soil (Li <i>et al.</i> , 2013)	25
Figure 3.1	Flow chart of research study	35
Figure 3.2	Location of study area	37
Figure 3.3	Cross section of the trial pit	37
Figure 3.4	Modified permeability equipment	41
Figure 3.5	Artificial relict joint	41
Figure 3.6	Artificial burrow holes	42
Figure 3.7	Field set up for data collection	45
Figure 3.8	Cross section for field set up	45
Figure 3.9	Tensiometer used in field work	46
Figure 3.10	Rain gauge used in field data	47
Figure 3.11	Rainfall collector used in the field data	47
Figure 3.12	Infiltration model box	48
Figure 3.13	Schematic diagram for infiltration model box	49
Figure 3.14	Rainfall simulator	49

Figure 3.15	Set up for the infiltration test	51
Figure 3.16	Schematic diagram of the infiltration test setup	52
Figure 3.17	Artificial relict joints	53
Figure 3.18	Artificial burrow holes	53
Figure 4.1	Balai Cerapan Soil profile (Kassim et al., 2012)	62
Figure 4.2	Particle size distribution of Grade V (Silty gravel) and Grade VI (Sandy silt)	63
Figure 4.3	Soil water characteristics curve of Grade V and Grade VI soils	66
Figure 4.4	Hydraulic conductivity of Grade V and Grade VI by using Van Genutchen method (1980)	67
Figure 4.5	Coefficient of saturated permeability of Grade VI with two relict joint	69
Figure 4.6	Coefficient of saturated permeability of Grade VI with existing of burrow hole	70
Figure 4.7	Permeability of Grade V (silty gravel) with one relict joint and two relict joint	71
Figure 5.1	Suction distribution due to 1-hour rainfall in a two-layered soil with one relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing	76
Figure 5.2	Suction distribution due to 1-hour rainfall in a two-layered soil with two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing	77
Figure 5.3	Suction distribution for 1 relict joint and 2 relict joint at interface due to 1-hour rainfall intensity	78
Figure 5.4	Suction distribution due to 24-hour rainfall in a two-layered soil with one relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing	80
Figure 5.5	Suction distribution due to 24-hour rainfall in a two-layered soil with two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing	81
Figure 5.6	Suction distribution for 1 relict joint and 2 relict joint at interface due to 24-hour rainfall intensity	82
Figure 5.7	Suction distribution due to 7-day rainfall in a two-layered soil with one relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing	85

Figure 5.8	Suction distribution due to 7-day rainfall in a two-layered soil with two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing	86
Figure 5.9	Suction distribution for 1 relict joint and 2 relict joint at interface due to 7-day rainfall intensity	88
Figure 5.10	Suction distribution due to 1-hour rainfall in a two-layered soil with two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing	90
Figure 5.11	Suction distribution due to 24-hour rainfall in a two-layered soil with two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing	93
Figure 5.12	Suction distribution due to 1-hour rainfall in a two-layered soil with two relict joint in Grade V soil	95
Figure 5.13	Suction distribution due to 7-day rainfall in a two-layered soil with two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing	97
Figure 5.14	Suction distribution due to 7-day rainfall in a two-layered soil with two relict joint in Grade V soil	99
Figure 5.15	Suction distribution due to 1-hour rainfall in a two-layered soil with Grade VI 6.98×10^{-4} m/s permeability and two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing	103
Figure 5.16	Suction distribution at interface due to 1-hour rainfall in a two-layered soil with Grade VI 6.98×10^{-4} m/s permeability and two relict joint in Grade V soil	104
Figure 5.17	Suction distribution due to 24-hour rainfall in a two-layered soil with Grade VI 6.98×10^{-4} m/s permeability and two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing	106
Figure 5.18	Suction distribution due to 24-hour rainfall in a two-layered soil with Grade VI 6.98×10^{-4} m/s permeability and two relict joint in Grade V soil	108
Figure 5.19	Suction distribution due to 7-day rainfall in a two-layered soil with Grade VI 6.98×10^{-4} m/s permeability and two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing	110
Figure 5.20	Suction distribution at interface due to 7-day rainfall in a two-layered soil with Grade VI 6.98×10^{-4} m/s permeability and two relict joint in Grade V soil	112

Figure 5.21	Suction distribution due to 1-hour rainfall in a two-layered soil with Grade VI 1.13×10^{-3} m/s permeability and two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing	115
Figure 5.22	Suction distribution at interface due to 1-hour rainfall in a two-layered soil with Grade VI 1.13×10^{-3} m/s permeability and two relict joint in Grade V soil	116
Figure 5.23	Suction distribution due to 24-hour rainfall in a two-layered soil with Grade VI 1.13×10^{-3} m/s permeability and two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing.	119
Figure 5.24	: Suction distribution at interface due to 24-hour rainfall in a two-layered soil with Grade VI 1.13×10^{-3} m/s permeability and two relict joint in Grade V soil	120
Figure 5.25	Suction distribution due to 7-day rainfall in a two-layered soil with Grade VI 1.13×10^{-3} m/s permeability and two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing.	123
Figure 5.26	Suction distribution at interface due to 7-day rainfall in a two-layered soil with Grade VI 1.13×10^{-3} m/s permeability and two relict joint in Grade V soil.	125
Figure 5.27	Suction distribution for 1 hour time for different ratio of q/k_{sat}	128
Figure 5.28	Infiltrating water penetrate in the burrow hole	129
Figure 5.29	Resultant suction for 1-hour rainfall intensity in a two-layered soil with different permeability in Grade VI and two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing	131
Figure 5.30	Resultant suction for 24-hour rainfall intensity in a two-layered soil with different permeability in Grade VI and two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing	132
Figure 5.31	Resultant suction for 7-day rainfall intensity in a two-layered soil with different permeability in Grade VI and two relict joint in Grade V soil (a) 100 mm spacing (b) 200 mm spacing (c) 300 mm spacing (d) 400 mm spacing	133
Figure 5.32	Samples taken for moisture content test	134
Figure 5.33	Moisture content changes with depth for different ratio (Grade VI / Grade V) (a) at crest (b) at toe	136
Figure 5.34	Matric suction changes with depth for different ratio (Grade VI / Grade V) (a) at crest (b) at toe	137

Figure 6.1	Schematic diagram for modeling residual soil slope	143
Figure 6.2	Comparison simulated suction between previous researcher and Scheme I for 0.5 m depth	146
Figure 6.3	Comparison simulated suction between previous researcher and Scheme I for 1.0 m depth	146
Figure 6.4	Comparison simulated suction between previous researcher and Scheme I for 1.5 m depth	147
Figure 6.5	Comparison simulated suction between previous researcher and Scheme II for 0.5 m depth	148
Figure 6.6	Comparison simulated suction between previous researcher and Scheme II for 1.0 m depth	149
Figure 6.7	Comparison simulated suction between previous researcher and Scheme II for 1.5 m depth	149
Figure 6.8	Comparison simulated suction between previous researcher and Scheme III for 0.5 m depth	151
Figure 6.9	Comparison simulated suction between previous researcher and Scheme III for 1.0 m depth	151
Figure 6.10	Comparison simulated suction between previous researcher and Scheme III for 1.5 m depth	152
Figure 6.11	Comparison simulated suction between previous researcher and Scheme IV for 0.5 m depth	153
Figure 6.12	Comparison simulated suction between previous researcher and Scheme IV for 1.0 m depth	154
Figure 6.13	Comparison simulated suction between previous researcher and Scheme IV for 1.5 m depth	154
Figure 6.14	Comparison simulated suction between previous researcher and Scheme V for 0.5 m depth	157
Figure 6.15	Comparison simulated suction between previous researcher and Scheme V for 1.0 m depth	157
Figure 6.16	Comparison simulated suction between previous researcher and Scheme V for 1.5 m depth	158
Figure 6.17	Suction distribution (a) wet condition (b) dry condition	160

LIST OF ABBREVIATIONS

AEV	–	Air-Entry Value
IDF	–	Intensity Duration Frequency
PA	–	Prediction Accuracy
SWCC	–	Soil Water Characteristics Curve



LIST OF SYMBOLS

α	–	Coefficient of Hydraulic Conductivity Function
θ_r	–	Residual Water Content
ϕ	–	Inclination Angle
γ_w	–	Unit Weight of Water
h_a	–	Air-Entry Head of Fine Soil Layer
h_w	–	Air-Entry Head of Coarse Soil Layer
k_{sat}	–	Coefficient of Permeability
$P_{(t)}$	–	total input (rainfall intensity, irrigation)
Q	–	Storage Capacity
q	–	Infiltration Rate
R_t	–	The average Rainfall Intensity (mm/hr) for ARI and duration



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	Programming For Data Logger	177



CHAPTER 1

INTRODUCTION

1.1 Background of Study

Rainfall-induced slope failures are common problems in many tropical areas covered by residual soil. Basically the soil profile in the area is from granitic formation and the existing of rainfall that decreased the matric suction caused a shallow rotational failure (Jamaludin & Hussein, 2006). Slope stability in residual soil and rainfall infiltration has a close relationship between each other. Experience has shown that many slopes failure occurred during or shortly after rainfall (Gavin and Xue, 2007). In general, many factors could govern the slope stability. Rainfall induced slope failure are normally governed by two factors, which are, rainfall intensity and coefficient of saturated permeability, k_{sat} (Chao *et al.*, 2013).

The tropical residual soil mantle derived from igneous rocks mainly consists of materials dominantly decomposed to Grades IV and V according to the six-fold weathering classification system of International Society for Rock Mechanics (ISRM) (1981) of saprolitic soils, and true or matured residual soil (Grade VI) of laterites (Bland & Rolls, 1998; Taylor & Eggleton, 2001; Aydin, 2006). The weathering process involved in the formation of residual soil introduces variation in material scale and also in field scale. In material scale, the weathering process cause the igneous rock to decompose to Grade IV (lateritic layer) and V (saprolitic layer). Therefore, it produced variations in grain size, porosity, mineralogy, lithologic texture, rock mechanical properties, structure and diagenetic processes. In field scale, the variation in residual soil because of discontinuities in soil mass such as relict joints, bedding planes, foliations, faults and shears happen in saprolitic layer. While in lateritic layer, insect population such as burrow holes govern the properties of soil such as density and hydraulic properties of soil (Bastardie, Capowiez, De Dreuzy, & Cluzeau, 2003). The permeability of lateritic layer can be as high as to 0.01 m/s

within 1 m depth with the existence of burrow holes (Keith, 1992). Meanwhile, the permeability of saprolitic soil varies with depth, and the variation is within two orders of magnitude (Agus, Leong, & Rahardjo, 2005; Harianto Rahardjo, Satyanaga, Leong, Ng, & Pang, 2012).

Residual soil is commonly found in an unsaturated state because of the location of ground water table is well below the soil layer and possesses high matric suction, especially during dry seasons. However, the different in permeability in the soil layers, results in variation in suction distribution in the residual soil. This permeability value is a dominant factor that contributes to the changes of suction distribution in residual soil. At relatively dry conditions or high matric suctions, the fine-grained soil has a high coefficient of permeability, while the coarse-grained layer has an extremely low coefficient of permeability. When the infiltrating water starts to infiltrate from the surface, the coefficient of permeability of the fine grained layer increases gradually, while that of the coarse grained layer remains extremely low. As the infiltrating water accumulates and reaches the fine-coarse interface, the matric suction of the coarse-grained layer begins to decrease significantly. Once the matric suction of the coarse grained layer reaches its water-entry" value, (ψ_w), the coefficient of permeability of the coarse-grained layer increases rapidly and may exceed the coefficient of permeability of the fine-grained layer (Ross, 1990).

Many studies such as Kassim *et al.*, (2012), Kim and Lee, (2013), Lee, *et al.* (2011) and Trandafir *et al.* (2008) concluded that matric suction plays an important role in slope stability especially in residual soil. The slope failure happens due to total or partial loss of matric suction during rainfall infiltration and causes the shear strength of soil to decrease. At initial condition, when the matric suction is high, there is a greater initial factor of safety and hence the slope is stable. However, during rainfall, the matric suction decreases which eventually decreases the factor of safety of the slope. Previous studies have already demonstrated that matric suction contributes to the shear strength of soil. The rainfall intensity and duration affect the suction distribution in soil with an intermediate saturated permeability such as sandy silt, which is common type of residual soil (Gofar and Lee, 2008). Suction distribution in coarse-grained soil is greatly influenced by short and intense rainfall.

REFERENCES

- Agus, S. S., Leong, E.-C., & Rahardjo, H. (2005). Estimating permeability functions of Singapore residual soils. *Engineering Geology*, 78(1–2), 119–133.
- Alaoui, A., Caduff, U., Gerke, H. H., & Weingartner, R. (2011). A Preferential Flow Effects on Infiltration and Runoff in Grassland and Forest Soils. *Vadose Zone Journal*, 10(1), 367.
- Arikan, F., & Aydin, N. (2012). Influence of Weathering on the Engineering Properties of Dacites in Northeastern Turkey. *ISRN Soil Science*. 2012, 1.
- Aydin, A. (2006). Stability of saprolitic slopes: nature and role of field scale heterogeneities. *Natural Hazards & Earth System Sciences*, (1984), 89–96.
- Aydin, A., & Duzgoren-Aydin, N. (2002). Indices for scaling and predicting weathering-induced changes in rock properties. *Environmental & Engineering Geoscience*. 8(2), 121-135
- Bastardie, F., Capowiez, Y., De Dreuzy, J. R., & Cluzeau, D. (2003). X-ray tomographic and hydraulic characterization of burrowing by three earthworm species in repacked soil cores. *Applied Soil Ecology*, 24(1), 3–16.
- Beven, K., & Peter Germann. (1982). Macropores and Water Flow in Soils. *Water Resources Research*, 18(October), 1311–1325.
- Bland, W. and Rolls, D. (1998). *Weathering: An Introduction to the Scientific Principles*. Arnold, Hodder Headline, PLC.
- Blight, G.E. (1985). *Residual Soils in South Africa*. Technical Committee on Sampling and Testing of Residual Soils, International Society for Soil Mechanics and Foundation Engineering: 159-168.
- Brand, E. W. and Philipson, H. B. (1985). Sampling and Testing of Residual Soils - A Review of International Practices. Technical Committee on Sampling and Testing of Residual Soils. *International Society for Soil Mechanics and Foundation Engineering*. 7-22
- Chao, W., Min, L., Cai, H., Jie, H., Dai, F. C., & Long, M. (2013). Combined roles of saturated permeability and rainfall characteristics on surficial failure of homogeneous soil slope, *153*, 105–113.

- Chen, H., Lee, C.F. and Law, K.T. (2004). Causative Mechanism of Rainfall-Induced Fill Slopes Failures. *Journal of Geotechnical and Geoenvironmental Engineering*. 130(6) : 593-602
- Cho, S. E. (2016a). Stability analysis of unsaturated soil slopes considering water-air flow caused by rainfall infiltration. *Engineering Geology*, 211, 184–197.
- Cho, S. E. (2016b). Stability analysis of unsaturated soil slopes considering water-air flow caused by rainfall infiltration. *Engineering Geology*. 211, 184-197
- Cho, S., & Lee, S. (2001). Instability of unsaturated soil slopes due to infiltration. *Computers and Geotechnics*. 28, 185–208.
- Dai, F.C., Lee, C.F. and Wang, S.J. (2003). Characterization of Rainfall-induced Landslides. *International Journal of Remote Sensing*. 24(23), 4817-4834.
- Day, R. and Axten, G. (1989). Surficial Stability of Compacted Clay Slopes. *Journal of Geotechnical Engineering*. 115(4), 577-580.
- Dearman, W.R. (1976). Weathering Classification in the Characterisation of Rocks: A Revision. *Prediction Soil Mechanics*. London: Thomas Telford.
- Fourie, A.B. (1996). Predicting Rainfall-Induced Slope Instability. *Proceedings of the Institution of Civil Engineer - Geotechnical Engineering*. 119, 211-218.
- Fredlund, D.G. (1995). The Scope of Unsaturated Soil Mechanics: An Overview. *Proceedings of the First International Conference on Unsaturated Soils*. Paris, France: Balkema, Rotterdam, the Netherlands, 1155-1177
- Fredlund, D.G. and Rahardjo, H. (1993). *Soil Mechanis for Unsaturated Soils*. John Wiley & Sons, Inc.
- Fredlund, D.G., Sheng, D. and Zhao, J. (2011). Estimation of Soil Suction from the Soil-Water Characteristics Curve. *Canadian Geotechnical Journal*. 48(2), 186-198.
- Gasmo, J., Rahardjo, H., & Leong, E. (2000). Infiltration effects on Stability of a Residual Soil Slope. *Computers and Geotechnics*. 26, 145–165.
- Gavin, K. and Xue, J. (2007). A simple method to analyze infiltration into unsaturated soils slopes. *Computer Geotech*. 3(2), 223-230.
- GEO-SLOPE International Ltd. (2007). *Seepage Modelling with SEEP/W*. Calgary, Alta., Canada.
- Gerscovich, D.M.S., Vargas Jr, E.A. and de Campos, T.M.P. (2006). On the Evaluation of Unsaturated Flow in a Natural Slope in Rio de Janeiro, Brazil. *Engineering Geology*. 88(1-2), 23-40.

- Gofar, N., & Lee, L. M. (2008). Response of Suction Distribution to Rainfall Infiltration in Soil Slope Selection of Study Areas. *Electronic Journal of Geotechnical Engineering*, (2008).
- Gofar, N., Lee, M., & Kassim, A. (2012). Effect of surface boundary condition on rainfall infiltration. *Jurnal Teknologi*. 44, 63–70.
- Gofar, N., & Min Lee, L. (2008). Extreme rainfall characteristics for surface slope stability in the Malaysian Peninsular. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*. 2(2), 65–78.
- Gui, M.-W., & Wu, Y.-M. (2014). Failure of soil under water infiltration condition. *Engineering Geology*. 181, 124–141.
- Hakro, M. R., & Harahap, I. S. H. (2015). Laboratory experiments on rainfall-induced flowslide from pore pressure and moisture content measurements. *Natural Hazards and Earth System Sciences Discussions*. 3(2), 1575–1613.
- Hendrickx, J. M. H., & Flury, M. (2001). Uniform and Preferential Flow Mechanisms in the Vadose Zone. *Conceptual models of flow and transport in the fractured vadose zone*.
- Huat, B. B. K., Ali, F. H. J., & Low, T. H. (2006). Water infiltration characteristics of unsaturated soil slope and its effect on suction and stability. *Geotechnical and Geological Engineering*. 24(5), 1293–1306.
- IAEG (1980). Rock and Soil Description for Engineering Geological Mapping. *International Association of Engineering Geology Bulletin*. 24, 235-274
- Ibrahim, A., Mukhlisin, M., & Jaafar, O. (2013). Numerical assessment of rainfall infiltration into soil column for the unsaturated layered residual forest soil. *Jurnal Teknologi (Sciences and Engineering)*. 65(2), 121–127.
- Irfan, T. Y. (1998). Structurally controlled landslides in saprolitic soils in Hong Kong. *Geotechnical and Geological Engineering*, 16(3), 215–238.
- ISRM (1981). Basic Geotechnical Description for Rock Masses. *International Journal of Rock Mechanics, Mining Science and Geomechanics*. 18, 85-110
- Jamaludin, S., & Hussein, A. N. (2006). Landslide hazard and risk assessment : The Malaysian experience. In *IAEG 2006*, 1–10.
- Jarvis, N., Koestel, J., & Larsbo, M. (2016). Understanding Preferential Flow in the Vadose Zone: Recent Advances and Future Prospects. *Vadose Zone Journal*. 15(12).
- Kassim, A. (2011). *Modelling the Effect of Heterogeneities on Suction Distribution*

Behaviour in Tropical Residual Soil. Phd Thesis UTM.

- Kassim, A., Gofar, N., Lee, L. M., & Rahardjo, H. (2012). Modeling of suction distributions in an unsaturated heterogeneous residual soil slope. *Engineering Geology*. 131–132, 70–82.
- Keith, S. R. J. (1992). The Relation of Earthworms to Soil Hydraulic Properties. *Soil Biology Biochemical*. 24(12), 1539–1543.
- Kim, Y.-T., & Lee, J.-S. (2013). Slope Stability Characteristic of Unsaturated Weathered Granite Soil in Korea considering Antecedent Rainfall. *Geo-Congress 2013*, 394–401.
- Kim, J., Jeong, S. and Sharma, J. (2004). Influence of Rainfall-Induced Wetting on the Stability of Slopes in Weathered Soils. *Engineering Geology*. 75(3-4), 251-262.
- Klaus, J., Zehe, E., Elsner, M., Külls, C., & McDonnell, J. J. (2013). Macropore flow of old water revisited: Experimental insights from a tile-drained hillslope. *Hydrology and Earth System Sciences*. 17(1), 103–118.
- Krisdani, H., Rahardjo, H., & Leong, E.C. (2006). Experimental study of 1-D Capillary Barrier Model using Geosynthetic material as the Coarse-grained Layer. In *Geotechnical Special Publication*. 1683–1694.
- Kung, K.-J. S. (1990). Preferential Flow in a Sandy Vadose Zone: 1. Field observation. *Geoderma*. 46(1–3), 51–58.
- Laloui, L., Tombolato, S., Pisoni, G., Munoz, J. J., Rojas, J. C., De Gennaro, V., Tarantino, A. (2011). Benchmark of experimental techniques for measuring and controlling suction. *Géotechnique*. 61(4), 303–312.
- Lee, L. M., Kassim, A., & Gofar, N. (2011). Performances of two instrumented laboratory models for the study of rainfall infiltration into unsaturated soils. *Engineering Geology*. 117(1–2), 78–89.
- Lee, M.L., Ng, K.Y., Huang, Y.F. and Li, W.C. (2014). Rainfall-Induced Landslides in Hulu Kelang Area, Malaysia. *Natural Hazards*. 70(1), 353-375.
- Li, J. H., Du, L., Chen, R., & Zhang, L. M. (2013). Numerical Investigation of the Performance of Covers with Capillary Barrier effects in South China. *Computers and Geotechnics*. 48, 304–315.
- Little, A.L. (1969). The Engineering Classification of Residual Tropical Soils. *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering*. Mexico. 1, 1-10

- Liu, C., He, P., & Huang, Q. (2011). Influence of matrix suction on engineering properties of unsaturated soil. *2011 Second International Conference on Mechanic Automation and Control Engineering*. (1), 2250–2253.
- Lv, M., Hao, Z., Liu, Z., & Yu, Z. (2013). Conditions for Lateral Downslope Unsaturated Flow and effects of Slope Angle on Soil Moisture Movement. *Journal of Hydrology*. 486, 321–333.
- Maail, S., Huat, B., & Jamaludin, S. (2004). Index, Engineering Properties and Classification of Tropical Residual Soils. *Tropical Residual Soils*. 37–55.
- Macdonald, A. M., Maurice, L., Dobbs, M. R., Reeves, H. J., & Auton, C. A. (2012). Relating in situ Hydraulic Conductivity, Particle Size and Relative Density of Superficial Deposits in a Heterogeneous Catchment. *Journal of Hydrology*. 434–435, 130–141.
- Matsushi, Y., Hattanji, T. and Matsukura, Y. (2006). Mechanism of Shallow Landslides on Soil-Mantled Hillslopes with Permeable and Impermeable Bedrocks in the Boso Peninsula, Japan. *Geomorphology*. 76 (1-2), 92 -108
- Mclean, A.C. and Gribble, C.D. (1979). Geology for Civil Engineers. *Publication of: Allen (George) and Unwin*.
- Md. Noor, M.J. (2011). *Understanding Rainfall-Induced Landslide*. UiTM Press: Universiti Teknologi Mara, Shah Alam, Malaysia.
- Morris, C. E., & Stormont, J. C. (1999). Parametric Study of Unsaturated Drainage Layers in a Capillary Barrier. *Journal of Geotechnical and Geoenvironmental Engineering*. 125(12), 1057–1065.
- Moye, O.G. (1955). Engineering Geology for Snowy Mountain Scheme. *Journal of Institution Engineers*. Australia 27, 281-299.
- Mukhlisin, M., & Taha, M. R. (2012). Numerical model of antecedent rainfall effect on slope stability at a hillslope of weathered granitic soil formation. *Journal of the Geological Society of India*. 79(5), 525–531.
- Muller, J.R. and Martel, S.J. (2000). Numerical Models of Translational Landslide Rupture Surface Growth. *Pure and Applied Geophysics* 157: 1009-1038.
- Nimmo, J. R., Survey, U. S. G., & Park, M. (2012). Preferential flow occurs in unsaturated conditions, 789(September 2011), 786–789.
- Novák, V., Šimáunek, J., & Genuchten, M. T. van. (2000). Infiltration of Water into Soil with Cracks. *Journal of Irrigation and Drainage Engineering*.
- Oh, W. T., & Vanapalli, k S. (2013). Integrated Slope Stability Analyses of

- Wastewater Storage Structure extending the Capillary Barrier Technique. *Geotechnical Special Publication*, (ASCE 2013), 363–372.
- Public Works Institute Malaysia (1996). Tropical Weathered In-Situ Materials. *Geoguides*: 1-5.
- Rahardjo, H., Aung, K., Leong, E., & Rezaur, R. (2004). Characteristics of residual soils in Singapore as formed by weathering. *Engineering Geology*, 73(1–2), 157–169.
- Rahardjo, H., Aung, K. K., Leong, E. C., & Rezaur, R. B. (2002). Effects of Pore-Size Distribution on Engineering Properties of Residual Soils. *World Engineering*. 70–76.
- Rahardjo, H., Leong, E., & Rezaur, R. (2008). Effect of antecedent rainfall on pore-water pressure distribution characteristics in residual soil slopes under tropical rainfall. *Hydrological Processes*. 523(October 2007), 506–523.
- Rahardjo, H., Li, X., Toll, D., and Leong, E. (2001). The effect of antecedent rainfall on slope stability. *Unsaturated Soil Concepts and Their Application on Geotechnical Practices*. 19, 371-399.
- Rahardjo, H., & Lim, T. (1995). Shear-strength characteristics of a residual soil. *Canadian Geotechnical Journal*. 31(1), 60-77
- Rahardjo, H., Nio, A. S., Leong, E. C., & Song, N. Y. (2010). Effects of Groundwater Table Position and Soil Properties, (November), 1555–1564.
- Rahardjo, H., Santoso, V. A., Leong, E. C., Ng, Y. S., & Hua, C. J. (2012). Performance of an Instrumented Slope Covered by a Capillary Barrier System. *Journal of Geotechnical and Geoenvironmental Engineering*, 138(4), 481–490.
- Rahardjo, H., Satyanaga, A., & Leong, E.C. (2013). Effects of flux boundary conditions on pore-water pressure distribution in slope. *Engineering Geology*, 165, 133–142. <https://doi.org/10.1016/j.enggeo.2012.03.017>
- Rahardjo, H., Satyanaga, A., Leong, E.-C., Ng, Y. S., & Pang, H. T. C. (2012). Variability of residual soil properties. *Engineering Geology*, 141–142, 124–140.
- Rahman, Z., & Hamzah, U. (2010). Influence of oil contamination on geotechnical properties of basaltic residual soil. *American Journal of Applied Science*, 7(7), 954–961.
- Regmi, R. K., Nakagawa, H., Kawaike, K., & Baba, Y. (2011). Experimental and Numerical Study of Rainfall Induced Slope Failure. *Annuals of Disaster Prevention Resistant Instrumentations, Kyoto Univ.* (54).

- Ross, B. (1990). The diversion capacity of capillary barriers. *Water Resources Research*. 26(10), 2625–2629.
- Ruxton, B.P. and Berry, L. (1957). Weathering of Granite and Associated Erosional Features in Hong Kong. *Bulletin in Geological Society America*. 68, 1263-1292.
- Singh, H., Huat, B., Sew, G., & Ali, F. (2004). Origin, formation and occurrence of tropical residual soils. *Tropical Residual Soils*. 1–19.
- Sowers, G.F. (1985). *Residual Soils in the United States*. Technical Committee on Sampling and Testing of Residual Soils, International Society for Soil Mechanics and Foundation Engineering.
- Steenhuis, T.S., Parlange, J. and Kung, K.J.S. (1991). Comment on "The Diversion Capacity of Capillary Barrier." by Benjamin Ross. *Water Resources Research*. 27(8), 2155-2156.
- Sun, D., Zang, Y., & Semprich, S. (2015). Effects of Airflow Induced by Rainfall Infiltration on Unsaturated Soil Slope Stability. *Transport in Porous Media*. 107(3), 821–841.
- Talib, Z. A., Kassim, A., & Yunusa, G. H. (2016). Influence of Relict Joints on Permeability of Residual Soil. *IOP Conference Series: Materials Science and Engineering*. 136(1), 6–12.
- Tami, D., Rahardjo, H., Leong, E.-C., & Fredlund, D. (2004). A Physical Model for Sloping Capillary Barriers. *Geotechnical Testing Journal*. 27(2), 11431.
- Taylor, G. and Eggleton, R. A. (2001). *Regolith geology and geomorphology*. John Wiley and Sons, New York.
- Trandafir, A.C., Sidle, R.C., Gomi, T. and Kamai, T. (2008). Monitored and Simulated Variations in Matric Suction during Rainfall in a Residual Soil Slope. *Environmental Geology*. 55, 951-961.
- Tsaparas, I., Rahardjo, H., Toll, D., & Leong, E. (2002). Controlling parameters for rainfall-induced landslides. *Computers and Geotechnics*. 29(1), 1–27.
- Wang, D., Lowery, B., Norman, J. M., & Mc Sweeney, K. (1996). Ant burrow effects on water flow and soil hydraulic properties of Sparta sand. *Soil Tillage Res*. 37, 83–93.
- Wang, L., & Liu, C. R. (2012). Analysis of the Influences of Matric Suction of Unsaturated Soil on the Slope Stability. *Applied Mechanics and Materials*, 170–173, 3186–3189.
- Weiler, M. (2005). An infiltration model based on flow variability in macropores:

- development, sensitivity analysis and applications. *Journal of Hydrology*. 310, 1–4,
- Wu, L. Z., Zhou, Y., Sun, P., Shi, J. S., Liu, G. G., & Bai, L. Y. (2017a). Laboratory characterization of rainfall-induced loess slope failure. *CATENA*. 150, 1–8.
- Wu, L. Z., Zhou, Y., Sun, P., Shi, J. S., Liu, G. G., & Bai, L. Y. (2017b). Laboratory characterization of rainfall-induced loess slope failure. *Catena*. 150(September), 1–8.
- Yubonchit, S., Chinkulkijniwat, A., Horpibulsuk, S., Jothityangkoon, C., Arulrajah, A., & Suddepong, A. (2017). Influence Factors Involving Rainfall-Induced Shallow Slope Failure: Numerical Study. *International Journal of Geomechanics*. 17(7).
- Zêzere, J.L., Trigo, R.M. and Trigo, I.F. (2005). Shallow and deep landslide induced by Rainfall in the Lisbon Region (Portugal). Assessment of Relationship with the North Atlantic Oscillation. *Natural Hazards and Earth System Science*. 5(3), 331-344.
- Zhai, Q., & Rahardjo, H. (2012). Determination of soil–water characteristic curve variables. *Computers and Geotechnics*. 42, 37–43.
- Zhan, T., & Ng, C. (2004). Analytical analysis of rainfall infiltration mechanism in unsaturated soils. *International Journal of Geomechanics*. (December), 273–284.
- Zhang, J., Jiao, J. J., & Yang, J. (2000). In situ rainfall infiltration studies at a hillside in Hubei Province, China. *Engineering Geology*. 57(1–2), 31–38.
- Zhang, L.L., Zhang, J., Zhang, L.M. and Tang, W.H. (2011). Stability Analysis of Rainfall-Induced Slope Failure. *Proceedings of the Institution of Civil Engineering - Geotechnical Engineering*. 164(GE5), 299-316.
- Zhang, X., Zhu, Y., & Fang, C. (2009). The Role Fore Air Flow in Soil Slope Stability Analysis. *Journal of Hydrodynamics, Ser. B*. 21(5), 640–646.

LIST OF PUBLICATIONS

a) Journal Paper

Zaihasra Abu Talib, A Kassim, and G H Yunusa (2015). Response of Suction Distribution due to Variations of Permeability in Residual Soil Slope. *Jurnal Teknologi*

Okello Nelson, Azman Kassim*, Gambo Haruna Yunusa, **Zaihasra Abu Talib** (2015). Modelling the Effect of Wind Forces on Landslide occurrence in Bududa District, Uganda. *Jurnal Teknologi* .

G. H. Yunusa, A. Kassim and **Zaihasra Abu Talib** (2015). Numerical Investigation of Performance of Capillary Barrier System with Transport Layer. *Jurnal Teknologi* .

Zaihasra Abu Talib, Azman Kassim, Gambo Haruna Yusak, Mohd Fairus Mohd Yusof, Felix Ling Ngee Leh (2019). Influence of Burrow Holes in Residual Soil Slope Infiltration. *International Journal of Integrated Engineering*.

b) Proceeding Paper

Zaihasra Abu Talib, A Kassim, and G H Yunusa (2016): Influence of Relict Joints on Permeability of Residual Soil Proceeding, of Soft Soil Engineering International Conference 2015 (SEIC2015) 27th. – 29th. October, 2015. Resort World Langkawi, Kedah, Malaysia.