PHYSICAL CLASSIFICATIONS AND ENGINEERING CHARACTERISTICS OF IN SITU BOULDERS IN TROPICALLY WEATHERED GRANITE

MOHD FIRDAUS B MD DAN @ AZLAN

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

Faculty of Civil Engineering
Universiti Teknologi Malaysia

OCTOBER 2016

In the name of Allah, the Supremely Merciful and the Most Kind,

To my beloved family, who those never give up to give me spiritual support and pray.

ACKNOWLEDGEMENT

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيم

Alhamdulillah, first of all, I wish to express my profound gratitude and thanksgiving to the Almighty God for His guidance, protection, permittance and love over the years for my family and me. My sincere gratitude goes to Universiti Tun Hussein Onn Malaysia (UTHM) and Ministry of Higher Education of Malaysia for providing me with the opportunity and funding under SLAB/SLAI scheme as well as granting me the capability to pursue my PhD study at Universiti Teknologi Malaysia (UTM), Skudai.

My heartfelt gratitude goes to my main supervisor, Assoc. Prof. Dr. Hj. Edy Tonnizam Bin Mohamad and co-supervisor, Emeritus Professor Dato' Dr. Ibrahim Bin Komoo for their great patience and continued guidance which they bestowed on me from the earlier stages to the successful completion of the research work. Assoc. Prof. Dr. Hj. Edy Tonnizam Bin Mohamad has always been supportive, persistently proposing ideas and insightful discussions and offering valuable advice to enable an excellent continuity of the research. He has also played an important role in shaping the research from the earlier stage until it appears in its current form. I would also like to thank Emeritus Prof. Dato' Dr. Ibrahim Bin Komoo for his vast experience and knowledge in the field of geological engineering research coupled with all the valuable and constructive comments, suggestions and encouragements in ensuring that the objective of the study is achieved.

I am also very grateful to all the people of UTM, especially Assoc. Prof. Mohd For Bin Mohd Amin, Prof. Ir. Dr. Azman Bin Kassim and Prof. Dr. Azman Bin A. Ghani for their useful discussions, suggestions, critical comments and detailed review during the preparation of the thesis. Thanks also to the geological and geotechnical technician teams of UTM and UTHM, especially Mr. Zulkifli, Mr. Hidayat, Miss Tuan Puan, Madam Ros, Madam Adila, Mr. Fairus, Mr. Fazli, Mr. Tarmizi and Mr. Faizal for helping me in many different ways with your excellent technical assistance. To my friends in UTM especially in the department of Geotechnics and Transportation, Faizal Bin Pakir, Nurul Hidayah, Wan Hamizah, Aimullah, Amanda, Fifi, Alam, Dr. Kenny, Dr. Tan and Dr. Ma as well as friends from UTHM, Azuan, Hafizal, Fani and Nuradila, thank you very much for the sweet memories we share together along the PhD journey and hoping that our mutual friendship will continue in the future. My colleagues in the engineering geology field who have completed their research were always a great source of technical advices, great discussions and useful insight during the writing process. Just to name a few: Maybelle, Nini, Kumar and Danial, I wish all of you the very best luck in your future undertakings.

I cannot finish without thanking my family. Deepest appreciation and warm thanks goes to my lovely sweet wife, Dayang Salwan Binti Abang Abdul Rahman, my beloved parents and my mother and father-in-law for their material and spiritual support in all aspects of my life. Not to forget my thanks to my siblings for their patience, encouragement, motivation, support and pray which have kept me going in numerous ways. Special appreciation also goes to my younger brother, Mohd Rafiq for providing his great assistance during the sampling works in the field, which is very much appreciated. There are no words that could be described to thank those who are very kind to me. May Allah give you all the best in return and may we come back to Him with clean and sincere heart. Amiin.

ABSTRACT

The issues of boulder in tropically weathered granitic rock masses have roused a lot of problems and risks to the work performances and design quality in civil engineering. Although the presence of in situ boulder could be predicted through several methods and classified in several weathering classification schemes, the behaviour of tropically weathered in situ boulder is not well understood. The aim of this study is to establish physical classification and engineering characteristics of granite boulders and to catalogue the boulders in tropical weathering profile. A total of 46 panels of granitic profile consist of 88 in situ boulders from five quarry sites located in Johor, Malaysia were investigated involving several field and laboratory test programs. The field test programs conducted include geological field mapping, discontinuity survey and classification of physical characteristics of boulder as well as its surrounding material in various weathering zones. The physical characteristics examined include occurrence of boulders in moderately to completely weathered zone, shape, size and rindlets characteristics from respective weathering zone. The laboratory test programs involve determination of physico-mechanical properties and mineralogical analysis. The field study revealed five dominant weathering profiles with different significant types of weathering zone and occurrence of in situ boulder. This finding indicated that in situ boulder is the main character in the formation of heterogeneous zone in weathering profile especially in the moderately weathered (Zone 3), highly weathered (Zone 4) and completely weathered zone (Zone 5). The angularity, size and rindlets characteristics of the boulder from moderately to completely weathering zones significantly differ from each other. Due to these significant differences, the in situ boulders formed in completely, highly and moderately weathered zones are classified into three major types, namely Type A, Type B and Type C, respectively. Boulder Type A is surrounded by double rindlets zones which classified as inner and outer rindlets, while boulder Type B possess single rindlets zone which is classified as inner rindlets. On the other hand, boulder Type C has no rindlets and it is surrounded by joints and fractures. The differences in physical characteristics of boulders Type A, B and C could be used to predict their existence in different weathering zones. The result obtained from the laboratory study revealed the physico-mechanical properties which include dry density, porosity, durability, strength and permeability of rindlets and saprolites found in completely weathered zone showed significant variance compared to highly and moderately weathered zone. In conclusion, the in situ boulders formed in moderately to completely weathered zones possessed significant variance of physical and mechanical characteristics which can be used as an indicator in weathering classification and engineering design purposes.

ABSTRAK

Isu kewujudan batuan tongkol dalam jasad batuan granit terluluhawa tropika menimbulkan banyak masalah dan risiko kepada prestasi kerja dan kualiti rekabentuk kejuruteraan awam. Walaupun kehadiran batuan tongkol dalam jasad batuan terluluhawa boleh diramal melalui beberapa kaedah dan dikelaskan dalam beberapa skema klasifikasi luluhawa, pencirian granit terluluhawa tropika masih belum difahami dengan baik. Tujuan kajian ini adalah mengkaji ciri-ciri fizikal dan kejuruteraan batuan tongkol granit semulajadi dan mengkatalog batuan tersebut dalam jasad granit terluluhawa tropika. Sebanyak 46 panel profil granit terluluhawa terdiri daripada 88 biji batuan tongkol daripada lima lokasi kuari di Johor, Malaysia telah dikaji melibatkan program ujian lapangan dan makmal. Program ujian lapangan termasuk pemetaan geologi, kajian ketakselanjaran, dan pengkelasan ciri-ciri fizikal batuan tongkol serta bahan sekitarnya dalam zon luluhawa berbeza. Ciri-ciri fizikal yang dikaji termasuk kewujudan batuan tongkol dalam zon luluhawa sederhana hingga zon luluhawa lengkap, bentuk, saiz serta ciri-ciri fizikal *rindlets* di setiap zon luluhawa. Program ujian makmal termasuk penentuan sifat indeks, sifat mekanik, dan analisis mineralogi. Kajian ini merungkai lima profil luluhawa dominan yang jelas berbeza dengan kewujudan batu tongkol pada zon luluhawa tertentu. Keputusan menunjukkan batuan tongkol adalah ciri utama pembentukan zon heterogen dalam profil granit terluluhawa terutama dalam zon luluhawa sederhana (Zon 3), zon luluhawa tinggi (Zon 4) dan zon luluhawa lengkap (Zon 5). Kesegian, saiz dan ciri-ciri fizikal *rindlets* batuan tongkol daripada zon luluhawa sederhana hingga luluhawa lengkap adalah jelas berbeza antara satu sama lain. Disebabkan perbezaan ketara ini, batuan tongkol dalam profil granit terluluhawa dikelaskan kepada tiga jenis utama iaitu Jenis A, B dan C yang terbentuk dalam zon luluhawa lengkap, luluhawa tinggi, dan luluhawa sederhana. Batuan tongkol Jenis A dikelilingi oleh dua zon *rindlets* yang dikelaskan sebagai *rindlets* dalaman dan luaran, manakala Jenis B mempunyai *rindlets* tunggal yang diklasifikasikan sebagai *rindlets* dalaman. Batuan tongkol Jenis C tidak mempunyai *rindlets* tetapi ia dikelilingi oleh ketakselanjaran dan keretakan. Perbezaan ketara ciri-ciri fizikal batuan Jenis A, B dan C ini dapat meramal kewujudan batuan tongkol dalam zon luluhawa berbeza. Keputusan kajian makmal juga menunjukkan ciri-ciri fizikal-mekanikal termasuk ketumpatan kering, keliangan, ketahanan, kekuatan dan kebolehtelapan *rindlets* dan *saprolites* yang terbentuk di sekeliling batuan tongkol dalam zon luluhawa lengkap mempunyai perbezaan signifikan berbanding zon luluhawa tinggi dan sederhana. Dapat disimpulkan kewujudan batuan tongkol dalam zon luluhawa sederhana hingga ke zon luluhawa lengkap mempamerkan ciri-ciri perbezaan yang signifikan daripada segi ciri-ciri fizikal dan mekanikal yang boleh digunakan sebagai petunjuk dalam pengklasifikasian luluhawa dan reka bentuk kejuruteraan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

α	-	Angle between Measuring Tape and Joint Set, (˚)
A	-	Minimum Cross Sectional Area, (mm^2)
A_c	-	Corrected Cross Section Area, (mm^2)
A_o	-	Actual Cross Section Area, (mm)
cm	-	Centimeter (SI Unit)
C	-	Corestone
CW	-	Completely Weathered
d_m	-	Actual distance between two joints, (m)
σ_{dry}	-	Dry Density, (g/cm^3)
De	-	Equivalent Core Diameter, (mm)
D	-	Diametrically Test Core of 50 mm Diameter
ε	-	Axial Strain
F	-	Fresh Rock
F	-	Size Correction Factor
Δh	-	Change in Measured Axial Length, (mm)
h_o	-	Original Measured Axial Length, (mm)
HW	-	Highly Weathered
i	-	Hydraulic Gradient, (mm)
Id_1	-	First Cycle Slake Durability Index, (%)
Id_2	-	Second Cycle Slake Durability Index, (%)
Ij	-	Jar Slake Index
IR	-	Inner Rindlets
$I_{S(50)}$	-	Point Load Strength, (MPa)
σ_c	-	Axial Stress, (MPa)
K	-	Wax Density, (g/cm^3)
K_v	-	Coefficient of Permeability, (m/s)

L	-	Height of Sample, (mm)
mm	-	Millimeter (SI Unit)
m	-	Meter (SI Unit)
MW	-	Moderately Weathered
M	-	Mass of Dry Solid Material, (m)
n	-	Porosity, (%)
OR	-	Outer Rindlets
ρ_{gr}	-	Grain Density, (g/cm^3)
ρ_{wtr}	-	Density of Water, 1.0 g/cm^3
p_1	-	Back Pressure, (kPa)
P_{wax}	-	Weight of Wax-Coated Sample in Air, (g)
P	-	Failure Load, (MPa)
q	-	Flow Rate, (ml/min)
δQ	-	Difference Cumulative Flow of Water, (ml)
RS	-	Residual Soil
SW	-	Slightly Weathered
S	-	Saprolites
S	-	Suspended Weight of Wax-Coated Specimen in Water, (g)
S_c	-	Corrected Joint Spacing, (m)
δt	-	Interval Flow Time, (min)
UCS	-	Uniaxial Compressive Strength, (MPa)
V	-	Total Volume, (m^3)
V_b	-	Bulk Volume of Sample, (m^3)
V_g	-	Actual Grain Volume, (cm^3)
V_1	-	Volume of Wax-Coated Sample, (cm^3)
V_2	-	Volume of Wax used for Coat Sample, (cm^3)
W_{dry}	-	Initial Dry Weight of Sample, (g)
π	-	3.142

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The presence of in situ boulder in saprolite zone beneath ground level has resulted in the formation of heterogeneous zone in the weathering profile. This issue has also brought a lot of difficulty in tunneling, borehole drilling, foundation excavation and slope cutting which significantly affects the work performance and quality of construction (Tang and Quek, 1986; Boone *et al*., 1998; Poot *et al*., 2000; Medley, 2002; Veneziano and Van Dyck, 2005; Jee and Ha, 2007; Felletti and Beretta, 2009; Filbà *et al*., 2016). In most cases, the presence of in situ boulders beneath the ground level has caused significant construction schedule delays, increased claims and unexpected cost related to the civil engineering works due to boulder removal and redesigning of earthworks plans. It becomes worst when the presence of in situ boulder was misjudged as bedrock, which may eventually lead to the misjudgment in engineering design. The misjudgment of engineering design can definitely cause high risks and possible death to the civilians. Furthermore, the occurrence of in situ boulder beneath the ground surface is difficult to be predicted due to the fact that the boulder is naturally formed in scattered and unpredictable manner as well as presented individually or clustered with various sizes and shapes (Veneziano and Van Dyck, 2005; Jee and Ha, 2007; Felletti and Beretta, 2009; Filbà *et al*., 2016). It has been reported by many researchers that in situ boulders could be found abundantly in different weathering zones such as moderately weathered zone (Zone 3), highly weathered zone (Zone 4) and completely weathered zone (Zone 5) which are located in between the bedrock zone and residual soil zone (Ruxton and Berry, 1957; Raj, 1985; Komoo 1985, 1989; Tsidzi, 1997; Tuğrul and Gürpinar, 1997; Fookes, 1997; Shaw, 1997; Alavi *et al*., 2016; Borrelli *et al*., 2016). Unfortunately, the understanding on the behaviour and characteristics of in situ boulder exists in various weathering zones, especially in tropical granite, which is still not well understood and further investigated. Therefore, the current research acts as an attempt to better understand the characteristics of in situ boulder in weathering granite profile of wet tropics.

1.2 Problem Statement

In recognising that in situ boulder has been affecting most of the earthworks, several methods have been developed to predict the occurrences boulder in weathered rock mass as a preliminary study for further action purposes. However, most of the prediction methods are biased to the boulder size and distributions. These limited parameters have caused minimum understanding of the physical characteristics of boulder in weathered rock mass. Furthermore, the occurrence of in situ boulders in weathering profile was used as one of the parameters in mass weathering classification. Unfortunately, the use of boulder in weathering classification is limited and mostly referred to rock to soil ratio. A few studies had used the boulder shape and its surrounding material as one of the weathering classification parameters. However, the physical and engineering characteristics of boulder and its surrounding material in different weathering zones of weathered granite are not completely understood, determined and classified. It is believed that these parameters are important in weathering classification for geotechnical and geological engineering designs. Therefore, a classification scheme of in situ boulder in weathered granite profile is highly needed for engineering purposes.

1.3 Research Aims and Objectives

The primary aim of the current research is to establish the physical and engineering characteristics of in situ boulders and to catalogue the boulders in the weathering profile, which can be achieved through the following objectives:

i. To catalogue the pattern and relationship of occurrences of in situ boulders with topography, weathering profile and geomorphology of rock mass in wet tropical region.

ii. To investigate the physical characteristics of in situ boulder formed in weathering profile of wet tropical region.

iii. To determine the distinction of engineering properties of in situ boulder within different weathering zones in wet tropical region.

iv. To develop a catalogue of in situ boulder in weathered granite profile of wet tropical region based on its geomorphology and physico-mechanical properties for engineering purposes.

1.4 Scope of the Study

In order to carry out the research in effective and manageable manners, the research scopes of this study are presented as follows:

i. The samples of in situ boulders studied are naturally formed in weathered granite mass. Five locations in Johor, Malaysia, namely Ulu Tiram, Batu Pahat, Kulai, Pulai and Kota Tinggi were selected for the field study and as the sampling for laboratory testing. The laboratory study was carried out in geological laboratory of Universiti Teknologi Malaysia and Universiti Tun Hussein Onn Malaysia.

ii. The main elements analysed, tested and classified in this study are corestone boulder, the natural material that is formed at the surrounding of the boulder and the saprolites where the boulder is formed in weathering granite profile.

iii. The assessments of weathering profile are mainly based on the physical characteristics, the degree of weathering, the frequency and distribution of boulder, its shapes and sizes and its surrounding material in various weathering zones.

iv. Engineering properties are selected based on the basic parameters that are commonly applied in geotechnical and geological engineering designs such as bulk density, porosity, slake durability index, jar slake index, point load strength, uniaxial compressive strength and permeability.

v. The mineralogical studies that include the scanning electron microscopy (SEM), petrographical study and X-Ray Diffraction (XRD) analysis are focused on the concentric sheets of weathered rock at the surrounding of the boulder.

Both field and laboratory test programs are carried out to establish the physical and engineering properties of in situ boulders in the weathering profile. The combination of all these parameters are used to catalogue and classify the in situ boulders in weathered granite mass for engineering purposes.

1.5 Significance of the Study

The classification of physical and engineering properties of in situ boulder in weathered granite profile is developed in this study. The presence and characteristics of boulder in weathered granite mass could be possibly predicted during earthwork explorations by understanding and classifying the characterisation of in situ boulder in various weathering zones. Furthermore, the parameters that are developed and classified can be used as a reference or guideline in geotechnical and geological engineering designs in tropical weathered granite profile. This classification is hoped to be useful in geotechnical and/or geological fields which are related to the occurrence of in situ boulder in the tropics. It is also expected to massively contribute to the knowledge and enhancement of the tropical rock engineering field.

1.6 Expected Outcomes

The ultimate aim of this study is to develop a catalogue of in situ boulder in weathered granitic profile based on its different physical characteristics and engineering properties. Therefore, the expected outcomes are as follows:

i. Contribution to the knowledge on the occurrence, pattern and relationship of in situ boulders in weathering granite mass in the wet tropical region.

ii. Contribution to the knowledge on the weathering profile of boulder as well as its physical and geomechanical characteristics in wet tropical region.

iii. Contribution to the knowledge on the distinction of engineering properties and geomechanical characteristics between in situ boulder and different weathered granite zones in wet tropical region.

iv. Development of weathering profile classification which consists of in situ boulders with different physical and engineering properties in wet tropical region which could be used for engineering purposes, especially in geotechnical and geological designs.

1.7 Outline of the Thesis

This thesis is organised into five chapters and the outlines are briefly summarised as follows:

Chapter 1 introduces the context and briefly discusses the background of the recent study. This chapter also outlines the problem statement of the recent study, research aims and objectives, scopes of the study, significance of the study and finally, the expected outcomes of the study.

Chapter 2 provides some reviews of previous studies related to the current study. This chapter further discusses the definition of boulder, boulder types and its general issues affecting the civilians and engineering constructions. This chapter also discusses the formation of in situ boulder, the boulder prediction methods, the use of boulder in weathering classification and the physical characteristics of boulder used for engineering purposes. At the end of this chapter, the gaps of this study are discussed and revealed for further investigation.

Chapter 3 presents the methodology of laboratory and field test programs conducted in this study. It also describes the procedure involved in the field and laboratory tests programs in order to obtain the data for physical and engineering classification purposes. The field sampling is also discussed in this chapter.

Chapter 4 summarises and discusses the data obtained from the field and laboratory test programs. The result from both programs are analysed, discussed and classified in detail for the purpose of establishing the physical characteristics and engineering properties of boulder in different weathering zones of weathered granite profile. At the end of this chapter, the catalogue of weathered granite profile that consists of different boulder characteristics is classified, discussed and presented for engineering purposes.

Chapter 5 summarises the findings of this study. The conclusions are made according to the findings and the objectives stated in the early chapter of this study.

Some recommendations are also provided for future direction of the research related to this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides background of the thesis and detailed analysis of relevant aspects of boulder assessments method, rock weathering parameters and boulder characteristics in weathering profile for the purpose of revealing the gap of this study. Section 2.2 emphasizes the definition of boulder according to different field of studies. Next, boulder types and its general issues related to civilians and civil engineering works are highlighted in Section 2.3. In the following section, a discussion on weathering in granite rock mass is included. The morphology of in situ boulder is outlined in Section 2.5. Another important discussion related to the physical characteristics of in situ boulder is identified in Section 2.6. The methods established by previous researchers to predict the occurrence of boulder in weathered rock mass are included in Section 2.7. The next section is followed by an analysis of the use of in situ boulder in weathering classification, including its parameters in prediction and classification purposes. Finally, section 2.9 analyses the problems of in situ boulders in weathering profile for engineering purposes as well as emphasizes the gap of this study. These reviews are expected to further help the author to reveal the gap of this study and identify the necessary parameters in order to achieve the aim and objectives of this study.

2.2 Definition of Boulder

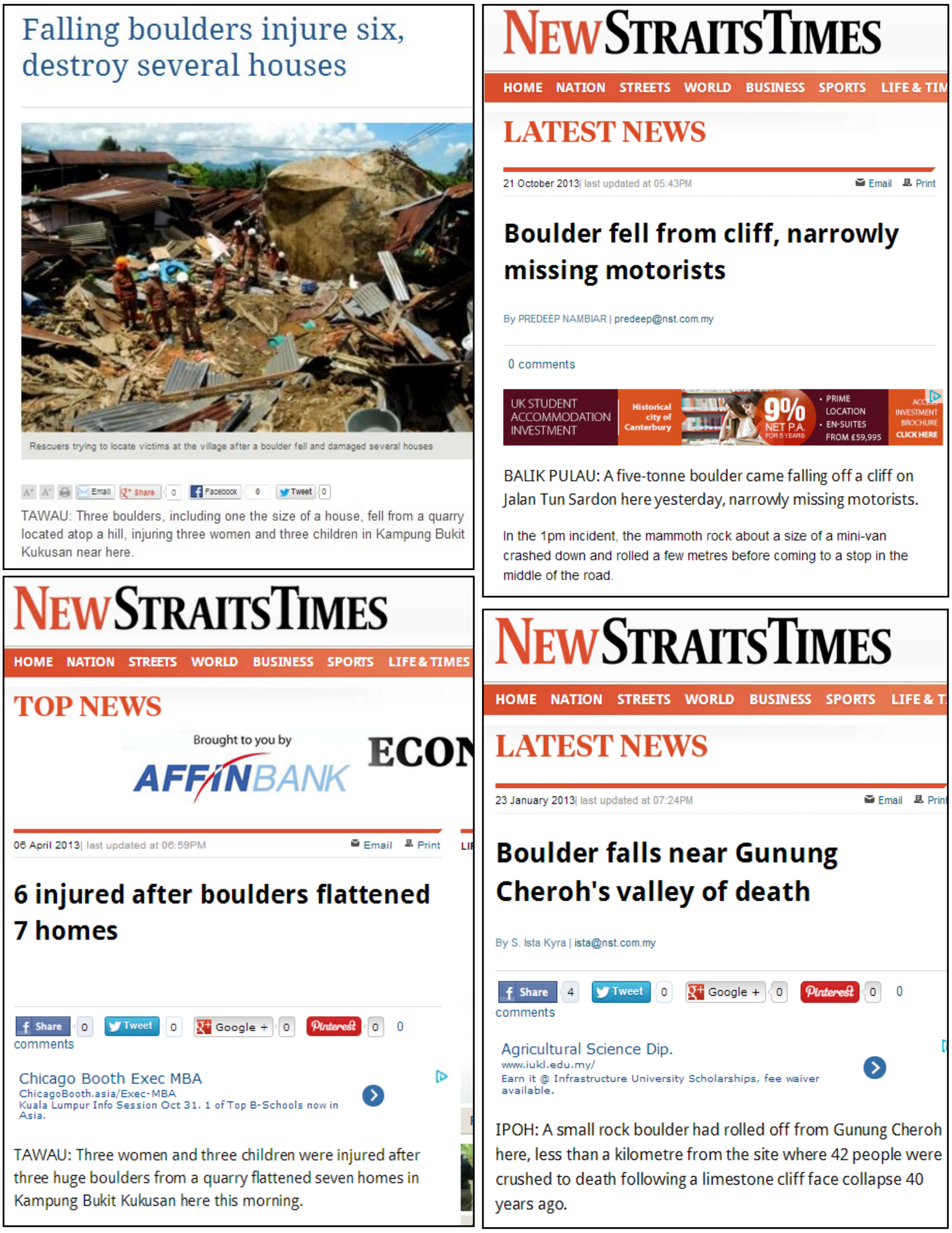
There are various definitions of boulder provided by different field of studies. In geological and geomorphological study, "bowlder" or also known as boulder is a corestone that is made of various sizes and shapes as well as surrounded by concentric shell, sheets, or layers of weathered rock caused by spheroidal weathering, spalling, chemical exfoliation, disintegration and fracturing (Ollier, 1971; Twidale, 1982; Sarracino *et al.*, 1987; Sarracino and Prasad 1989; Turkington *et al*., 2005; Gordon and Dorn, 2005; Elliott, 2006; Smith, 2009). In the study of chemical geology, boulder is referred as a corestone that is formed as a result of the reaction of spheroidal weathering on fractured bedrock and surrounded by some concentric of weathered rock with the thickness ranging from 0.2 cm to 2.0 m, which is known as rindlets (Turner *et al*., 2003; Fletcher *et al*., 2006; Buss *et al*., 2008; Brantley *et al*., 2011). From the engineer's point of view, boulder is defined as an obstruction or problematic material that is discovered during underground excavations which is usually found in various spherical shapes and size that is larger than 0.3 m, which is located at unpredictable locations in weathered rock mass (Tang and Quek, 1986; Boone *et al*., 1998; Poot *et al*., 2000; Medley, 2002; Veneziano and Van Dyck, 2005; Felletti and Beretta, 2009). According to the definitions provided by previous researchers, it can be concluded that boulder is one of the weathered products that consist of a corestone surrounded by some concentric sheets of weathered rock. It is formed through the reaction of spheroidal weathering mechanisms and its presence in weathered rock mass might cause problems to the civil engineering works.

2.3 Boulders and Its General Issues

Generally, boulder was reported to have been naturally formed in different weathered igneous rock mass such as granite (Ruxton and Berry, 1957; Dearman and Fookes, 1974; Durgin, 1977; Dearman *et al*., 1978; Raj, 1985; Komoo, 1989; Tsidzi, 1997; Braga *et al*., 2002; Kirschbaum *et al*., 2005; Dethier and Bove, 2011), quartz diorite (Turner *et al*., 2003; Fletcher *et al*., 2006; Buss *et al*., 2008; Brantley *et al*., 2011; Chabaux *et al*., 2013) and basalt (Gurocak and Kilic, 2005; Røyne *et al*., 2008; Ehlmann *et al*., 2008). Boulder can be found at ground surface (Turner *et al*., 2003; Buss *et al*., 2004; Alejano *et al*., 2010; Chabaux *et al*., 2013) or embedded beneath ground surfaces (Ruxton and Berry, 1957; Twidale 1982, 1986; Veneziano and Van Dyck, 2005; Jee and Ha, 2007; Alavi *et al*., 2016). Essentially, boulder can be divided into four types, namely (1) landslide boulder (Komoo, 1997; Alejano *et al*., 2010; Chigira *et al*., 2011; de Almeida and Kullberg, 2011), (2) sedimentary boulder (Ditlevsen, 2005; Kumar *et al*., 2007; Ehlmann *et al*., 2008; Velde and Meunier, 2008), (3) tsunami boulder (Imamura *et al*., 2008; Switzer and Burston, 2010; Paris *et al*., 2010; Nandasena and Tanaka, 2013) and (4) in situ boulder (Ruxton and Berry, 1957; Komoo, 1985; Raj, 1985; Tsidzi, 1997; Tuğrul and Gürpinar, 1997; Fookes, 1997; Alavi *et al*., 2014a, 2016). It is important to note that each boulder type possesses some issues.

2.3.1 Landslide Boulder

Landslide boulder refers to the remnant boulder that rolls down the slopes or rock fall avalanche due to the instability of the slope during rainy periods (De Costa Nunes, 1969; Barata, 1969; Durgin, 1977). The landslide or slope failure is caused by the infiltration of rainwater that changes the pore water pressure and shear strength which is located in the unsaturated zones (Rahardjo *et al*., 2009; Alejano and Carranza-Torres, 2011). The force of gravity leads to the movement of a large amount of soil and boulder of various sizes from the unstable condition on the slope to a stable condition at the lower plains (Barata, 1969; Velde and Meunier, 2008; Chigira *et al*., 2011). Landslide commonly occurs in the border of highly weathered (Zone 4) and completely weathered zone (Zone 5) and in the border of slightly weathered (Zone 2) and moderately weathered zone (Zone 3), which are dominated by boulders (Komoo, 1995). In many cases, the presence of boulder in the landslide is usually the result of massive damage caused by public facilities, housing, injuries and death (Barata, 1969; Chigira *et al*., 2011). For instance, Figure 2.1 shows the hazard of landslide boulders to the civilian as reported by the news.



Falling boulders injure six, destroy several houses

Rescuers trying to locate victims at the village after a boulder fell and damaged several houses

TAWAU: Three boulders, including one the size of a house, fell from a quarry located atop a hill, injuring three women and three children in Kampung Bukit Kukusan near here.

NEW STRAITS TIMES

HOME NATION STREETS WORLD BUSINESS SPORTS LIFE & TIM

LATEST NEWS

21 October 2013| last updated at 05:43PM Email Print

Boulder fell from cliff, narrowly missing motorists

By PREDEEP NAMBIAR | predeep@nst.com.my

0 comments

BALIK PULAU: A five-tonne boulder came falling off a cliff on Jalan Tun Sardon here yesterday, narrowly missing motorists.

In the 1pm incident, the mammoth rock about a size of a mini-van crashed down and rolled a few metres before coming to a stop in the middle of the road.

NEW STRAITS TIMES

HOME NATION STREETS WORLD BUSINESS SPORTS LIFE & TIMES

TOP NEWS

Brought to you by AFFINBANK

06 April 2013| last updated at 06:59PM Email Print

6 injured after boulders flattened 7 homes

Share 0 Tweet 0 Google + 0 Pinterest 0 0 comments

TAWAU: Three women and three children were injured after three huge boulders from a quarry flattened seven homes in Kampung Bukit Kukusan here this morning.

NEW STRAITS TIMES

HOME NATION STREETS WORLD BUSINESS SPORTS LIFE & T

LATEST NEWS

23 January 2013| last updated at 07:24PM Email Print

Boulder falls near Gunung Cheroh's valley of death

By S. Ista Kyra | ista@nst.com.my

Share 4 Tweet 0 Google + 0 Pinterest 0 0 comments

IPOH: A small rock boulder had rolled off from Gunung Cheroh here, less than a kilometre from the site where 42 people were crushed to death following a limestone cliff face collapse 40 years ago.

Figure 2.1 Hazards of landslide boulders to civilians and properties

2.3.2 Sedimentary Boulder

Sedimentary boulder refers to boulder that settled in the river bed or alluvial fans caused by the erosion activity and soil movement along the river bank (Ditlevsen, 2005; Kumar *et al*., 2007; Ehlmann *et al*., 2008; Velde and Meunier, 2008). Sedimentary boulder commonly possesses spherical to lozenge shapes with smooth surfaces (Twidale 1982, 1986; Tang and Quek, 1986; Felletti and Beretta, 2009; Filbà *et al*., 2016). The rounding and the size decrement of the boulder are caused by water reaction, particle breakage, wear and attrition, which tend to be more progressive along the river (Stanley and Victoria 2006). Sedimentary boulders can also be found embedded in many soil deposits such as sedimentary deposits (Tang and Quek, 1986; Jee and Ha, 2007) and glacial tills deposits (Ditlevsen, 2006; Felletti and Beretta, 2009). The densely accumulation and settlement of the boulders in the alluvial fan help to reduce the performance of underground excavation, especially the tunneling works (Jee and Ha, 2007; Felletti and Beretta, 2009; Filbà *et al*., 2016). The presence of sedimentary boulder causes the cutter tools and the structure of the cutter head to be seriously broken during excavation (Filbà *et al*. 2016).

2.3.3 Tsunami Boulder

Tsunami boulder or Tsunami deposited boulder which is also called *tsunami-ishi* (stone) refers to transported rock block from offshore that are deposited on the beach or inland due to high velocity and energy of tsunami waves (Imamura *et al*., 2008; Switzer and Burston, 2010; Paris *et al*., 2010; Nandasena and Tanaka, 2013). The tsunami wave with high energy is able to remove and transport huge boulder of more than 10 ton over a few hundred meters on the ground from the tidal flat (Nott, 2000; Imamura *et al*., 2008; Paris *et al*., 2009). The transportation of tsunami boulder is the result of rolling or saltation and it depends on the shape and hydraulic force of the tsunamis (Goto *et al*., 2007; Goff *et al*., 2010). The boulder can be further transported after the process of rolling and saltation through sliding movement due to the reduced friction and the effect of centrifugal force (Imamura *et al*. 2008).

The tsunami boulders can be found accumulated on coastal rock platforms, cliff tops and ramps as well as presented either in isolated or single boulder in scattered or clustered form (Switzer and Burston, 2010; Nandasena and Tanaka, 2013). The characteristics of tsunami boulder such as size, shapes and distribution are dependent on the morphology of the boulder sources which can possibly be coral reef, beach rock, platform, or seawall (Nott 2000; Paris *et al*. 2009, 2010). The weight and shape of the boulder can be used to determine the minimum current velocity or wave height (Nott, 2003; Noormets *et al.*, 2004). Tsunami boulder can be found in angular block, cubic, well-rounded, or ellipsoid shape, without sharp broken edges (Goto *et al*., 2007; Imamura *et al*., 2008; Paris *et al*., 2010; Nandasena and Tanaka, 2013). It is well known that tsunami has resulted in massive damage of facilities, housing injuries and death, not only because of the moving boulder but also the massive impact of energy and velocity of water flow (Nott and Bryant, 2003; Paris *et al*., 2009; Nandasena and Tanaka, 2013).

2.3.4 In Situ Boulder

In situ boulder is also known as residual boulder which is formed in weathered rock mass due to the reaction of spheroidal weathering on the jointed rock block (Ruxton and Berry, 1957; Dearman, 1974; Twidale, 1982). It can be seen on the exposed slope cutting, quarries and natural cliffs (Twidale, 1982; Tsidzi, 1997; Dethier and Lazarus, 2006; Alavi *et al*., 2016). In situ boulder is commonly surrounded by discontinuities or concentric sheets of weathered rock that are naturally formed in situ, which is not found on transported boulder (Ollier, 1971; Raj, 1985; Sarracino and Prasad, 1989). Therefore, it can easily be distinguished from the transported boulder based on the roughening, the fracturing surfaces and the texture preservation of the concentric sheets at the surrounding of the boulder (Ollier, 1967, 1971; Twidale, 1982; Ehlmann *et al*., 2008).

In situ boulder can be found to be fully embedded or half exposed in the outcrop or ground surface (Ditlevsen, 2006). For those exposed to the ground surface, it is the result of the evacuations of friable weathered debris on the upper surface during the erosion or denudation process (Twidale, 1982, 1986). This phenomenon might expose some fracturing patterns that are formed in the rock mass, which is the so called hierarchical fractures (Røyne *et al.*, 2008). Through the hierarchical fractures, the rock mass is broken up into smaller sub domain through the reaction of reactive surface (Røyne *et al.*, 2008). The formation of sub domain is due to the process of onion skin spalling on the fractured block and the increment of internal elastic stress until it becomes large enough to crack the entire unit (Røyne *et al.*, 2008; Jamtveit and Hammer, 2011). The reaction of spheroidal weathering on the rock block finally alters the sizes of fractured block from smaller sub domain into rounded shapes (Røyne *et al.*, 2008).

In civil engineering practice, the occurrence of in situ boulder or rock block beneath soil stratum are often predicted based on the Rock Quality Designation (RQD) analysis from borehole drilling (Tang and Quek, 1986; Şen and Eissa, 1991; Lu and Latham, 1999; Medley, 2002). Unfortunately, the core run sample from borehole drilling does not necessarily represent the rock block or the boulder (Tang and Quek, 1986; Palmström, 2001). In addition, the presence of irregular and discontinuous jointing in weathered rock mass results in the formation of in situ boulder which makes it difficult to be recognised and predicted (Şen and Eissa, 1991; Choi and Park, 2004; Palmström, 2005). Furthermore, some drilling methods such as hollow sterm-augering cannot be used to penetrate the boulder, thus it has caused difficulties in studying the characteristics of in situ boulder from drilling sample (Strickland and Korleski, 2007).

The insufficient information of in situ boulder can lead to the misjudgement of the material and hence, could result to error in sub-structure design (Boone *et al.*, 1998; Frank *et al.*, 2000; Felletti and Beretta, 2009). This problem may cause project delays and an increase of unexpected cost. For instance, as reported by The Sunday Daily (2013), the presence of boulder beneath soil stratum has delayed the construction work of eight storeys of car park near the foot of Penang Hill, Malaysia. The delay was up to six months due to the occurrence of massive quantity of rocks and boulders beneath the construction site that needed to be removed during piling works. The removal work of the boulders and delay probability could increase the cost of the project from RM6.75 million to RM10 million (The Sunday Daily, 2013).

There are four types of boulder that can be found, namely landslide, sedimentation in the river or at the alluvial fans, tsunami boulder and in situ boulder. Due to their movement from one location to another, three types of boulders including landslide boulder, sedimentary boulder and tsunami boulder can be concluded as transported boulder or non in situ boulder. In contrast, in situ boulder is formed in situ without any disturbance by preserving the original structure and texture at the surrounding of the boulder. According to the fact that the in situ boulder is a problematic material in underground earthworks, therefore, this chapter reviews in detail the characteristics of the in situ boulder and its influence on civil engineering works.

2.4 Weathering in Granite Rock Mass

Weathering reaction plays an important role in the formation of granite boulder beneath soil stratum (Ollier, 1971; Ehlmann *et al*., 2008; Smith, 2009; Dethier and Bove, 2011). Weathering can be defined as a coupled process that involves physical disintegration and chemical decomposition on the rock structure caused by the exposure of the rock to the denudation agents such as water, temperature, wind and organic fluids (Dearman, 1974; Fookes, 1997; Borrelli *et al*., 2014).

Physical disintegration is commonly influenced by open fracture and nature of discontinuity (Baynes *et al*., 1978; Panthi, 2006; Hall *et al*., 2012). The discontinuity presents in rock mass provides the avenue for the water to infiltrate the discontinuity, disintegration and decomposition of the rock mass to be turned into weathered rock (Twidale, 1982, 1986; Ehlmann *et al*., 2008; Velde and Meunier, 2008). The presence of water decomposed and rotted the rock through the reaction of mineral dissolution, which finally creates a weathered zone known as regolith (Twidale, 1986; Buss *et al*., 2004; Dethier and Lazarus, 2006; Dethier and Bove, 2011).

Meanwhile, chemical decomposition is defined as the decomposition of minerals through the process of solution, hydration, carbonation and oxidation (Eggleton and Banfield, 1985; Lednicka and Kalab, 2012; Freire-Lista *et al*., 2015). The chemical decomposition on granite is identified based on the behavior of a single group of minerals, named feldspar and biotite (Dearman, 1974; Eggleton and Banfield, 1985). During granite alteration, the feldspar and biotite turn into clay and chlorite respectively, but the quartz grains still remain (Ollier, 1983; Dearman, 1974; Baynes and Dearman, 1978a; Que and Allen, 1996; Kirschbaum *et al*., 2005; Lednicka and Kalab, 2012; Borrelli *et al*., 2016). In other words, feldspar and biotite could be indicators for weathered granite in determining its weathering stages (Ollier, 1983; Thuro and Scholz, 2003; Kirschbaum *et al*., 2005). The alteration of mineral contents could increase the action of chemical decomposition as well as the porosity of weathered rock (Baynes and Dearman, 1978b; Thuro and Scholz, 2003; Freire-Lista *et al*., 2015).

Due to the weathering reaction in weathered granite mass, various weathering profiles with several weathering zones were formed. Komoo (1989) found that there are two weathering profiles of weathered granite, which are classified as Type-A and Type-B. The difference between both of them is the presence of boulder in moderately weathered zone. Alavi *et al*. (2014a) reported that there were four dominant weathering profiles in tropical weathered granite that possess three to four weathering zones, which are classified as Type A, Type B, Type C and Type D. However, boulder is not the main character in classifying the weathering profile. Based on Alavi *et al*. (2014a) classification, the occurrence of boulder is only found in highly weathered zone in dominant weathering profile Type D.

2.5 Morphology of In Situ Boulder

In humid tropics, deep weathering is one of the triggering factors in creating boulder through the joints present in the weathered rock mass (Ruxton and Berry, 1957; Huber, 1987; Koita *et al.*, 2013). Deep weathering occurs in the thickness of down to 100 m from ground level and up to 10 m to 30 m deep for granitic weathered rock (Komoo 1985, 1989; Chigira *et al.*, 2011). The presence of water triggers the weathering reaction in the rock mass (Twidale, 1986; Velde and Meunier, 2008; Alejano and Carranza-Torres, 2011). Additionally, the presence of discontinuities in the rock mass provides avenues for water to attack the rock and continue the weathering process in the rock mass to form rock blocks as shown in Figure 2.2 (Twidale, 1982). This process obviously indicates that the presence of mutual intersection of discontinuity with different spacing and orientation in the rock mass can lead to the formation of individual rock block (Raj, 1985; Goodman and Shi, 1985; Lu and Latham, 1999; Wang *et al.*, 2003; Palmström, 2005; Stavropoulou, 2014).

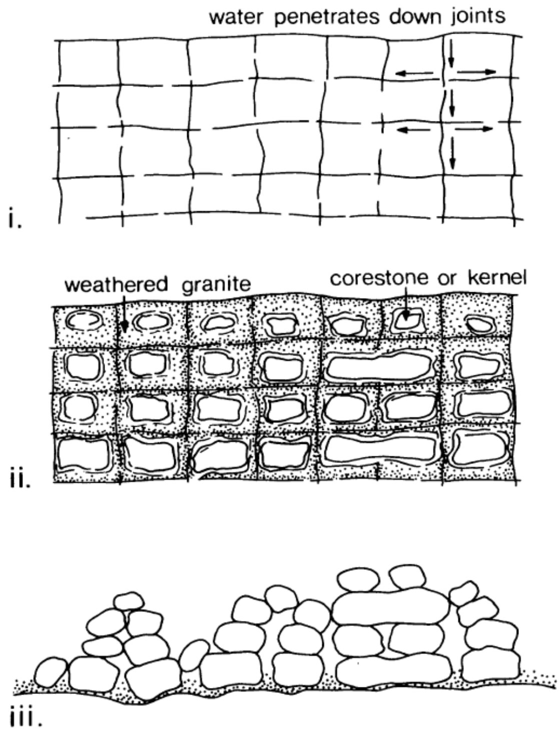


Figure 2.2 Stage of boulder development; (i) percolation of water into the rock joints, (ii) sub-surface weathering process, (iii) evacuation of friable weathered debris exposes the corestones (Twidale, 1982)

The rock block commonly interlocks and possesses angular edges and corners on the outer surface (Hoek, 1983; Twidale, 1986; Cai *et al.*, 2004; Jamtveit and Hammer, 2011). The continuous spheroidal weathering at steady-state denudation transforms the angular rock block into spherical or rounded shape (Ruxton and Berry, 1957; Ollier, 1971; Sarracino *et al.*, 1987; Sarracino and Prasad, 1989). In addition, the angular surfaces of rock block expose a greater surface area to the weather, which is faster than the flat surfaces to become rounded or spherical boulder (Ruxton and Berry, 1957; Røyne *et al.*, 2008; Alejano *et al.*, 2010).

The spheroidal weathering reaction at the surrounding of the rock block includes chemical decomposition and physical disintegration such as exfoliation, flaking, spalling and fracturing (Ruxton and Berry, 1957; Ollier, 1967, 1971; Sarracino *et al.*, 1987; Sarracino and Prasad, 1989; Røyne *et al.*, 2008; Jamtveit and Hammer, 2011). The chemical decomposition and physical disintegration in spheroidal weathering are the most vital processes in the formation of rounded boulder (Ruxton and Berry, 1957; Ollier, 1971). The alteration of chemical-mineral composition and physical disintegration at the surrounding of the rock block can be seen in Figure 2.3, Table 2.1 and Table 2.2 (Ruxton and Berry, 1957).

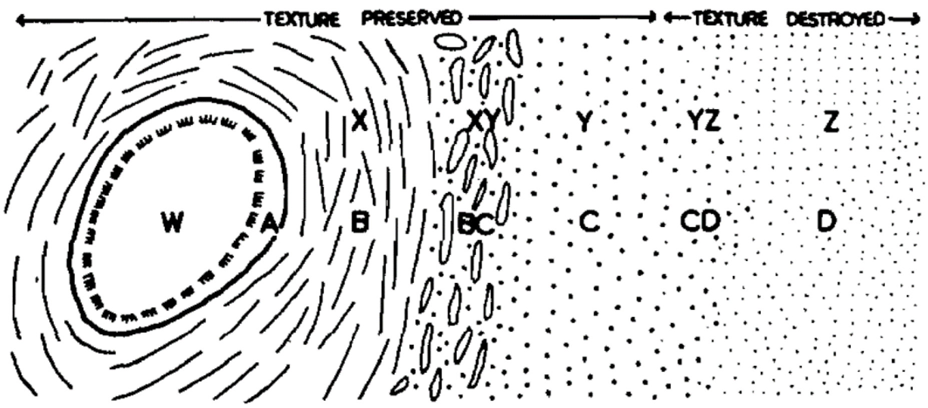


Figure 2.3 Spheroidal weathering surrounding a corestone (Ruxton and Berry, 1957)

Table 2.1 Stages of chemico-mineralogy change surrounding the corestone (Ruxton and Berry, 1957)

Chemico-mineralogical change	Effect	Symbol
Reddening and argillization.	Formation of reddish-brown silt and clay.	D
Complete decomposition of feldspars and biotite.	Formation of light-coloured kaolinitic debris.	C
Partial decomposition of feldspars and biotite	Formation of gruss.	B
Partial decomposition of biotite.	Formation of brown margin to joint block and corestones	A

Table 2.2 Stages of physical disintegration surrounding the corestone (Ruxton and Berry, 1957)

State of physical disintegration	Cause	Symbol
Differentiated debris	Further disaggregation, illuviation or eluviation.	Z
Residual debris	Disintegration and disaggregation.	Y
Gruss	Spheroidal scaling.	X
Corestone	Penetration of weathering agents' inward normal to open structure surfaces.	W

Through the reaction of spheroidal weathering, the process begins from a network of fractures and fissures surrounding the corestone surface (Ruxton and Berry, 1957). The presence of water that infiltrates along the fractures and fissures decomposes the main minerals such as plagioclase, K-feldspar and biotite between corestone and saprolites zone (Ruxton and Berry, 1957; Ollier, 1983; Fletcher *et al.*, 2006; Buss, 2006; Buss *et al.*, 2004, 2008). Simultaneously, the water penetrates into polygonal form surrounding the corestone and disintegrates the rock structure at the surrounding of the corestone to become soil (Ruxton and Berry, 1957). This process continuously occurs at the outer part of the corestone and gradually produces some concentric ellipsoidal and spherical shells of weathered rock with varying thickness ranging from 0.02 to 2.0 m (Ollier, 1971; Sarracino *et al*., 1987; Sarracino and Prasad, 1989; Turner *et al*., 2003; Fletcher *et al*., 2006; Buss *et al*., 2008). The result from spheroidal weathering on the rock producing some spheroids types which consist of (Sarracino and Prasad, 1989):

i. Unweathered cores,
ii. Partially decomposed and leached shells and
iii. Reprecipitated Fe-rich zones.

The formation of boulder due to spheroidal weathering reaction on a rock block can be seen in Figure 2.4 (Scholz, 1999; Thuro and Scholz, 2003). The spheroidal weathering reaction on a rock block comprises of several repeated processes, which begins at the outer part of the fresh rock block and at the end of the process; the whole of the fresh rock became sand or clay/silt (Scholz, 1999; Thuro and Scholz, 2003). The spheroidal weathering reaction attacks the outer part of the fresh rock to form a typically reddish-brown rust front. This reaction gradually moves from the outer part into the core of the rock block to form a zone of microscopic weathered granite (grade III). The presence of bleached light-brown to yellow-white zone at the outer part of the corestone denotes that the solid rock was decomposing to become soil (grade II to III).

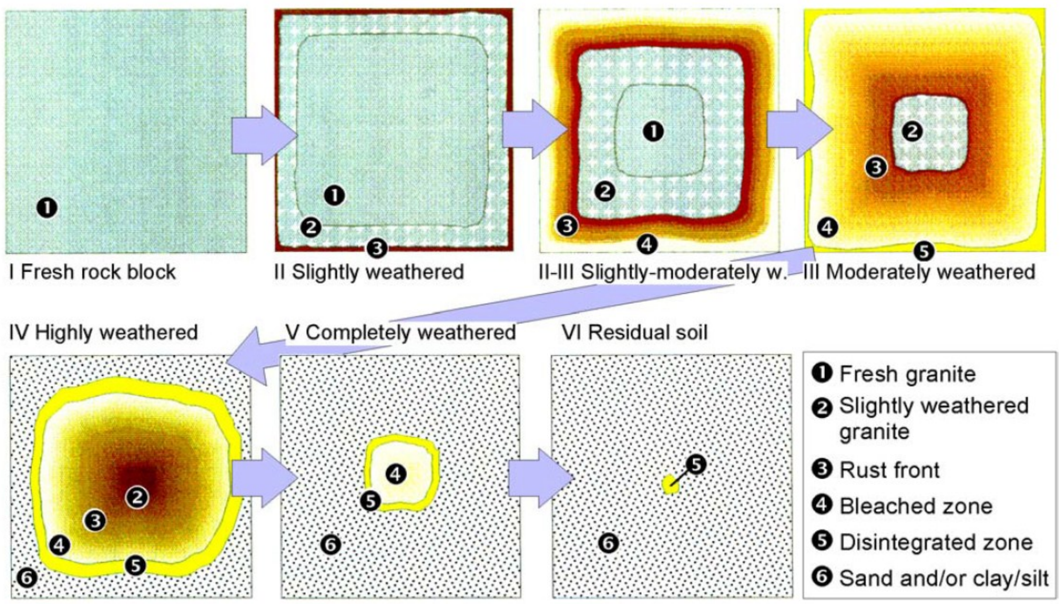


Figure 2.4 Grades of weathering in a Königshain granite block (Scholz, 1999)

The continuous process of spheroidal weathering was to shape the corestone to become spherical and reduce its volume (Sarracino and Prasad, 1989) as well as to increase the disintegrated zone at the surrounding of the corestone which comprises of decomposed clay and silt (Thuro and Scholz, 2003). The decomposed material at the surrounding of the corestone is the most dangerous material due to its low friction angle and tendency to shear along the existing discontinuities (Scholz, 1999; Thuro and Scholz, 2003). The end product of the spheroidal weathering is a mixture of sandy and/or clayey and silty material (Scholz, 1999).

2.6 Physical Characteristics of In Situ Boulder

This sub-chapter highlights the physical characteristics of boulder that is commonly used in engineering application and classification. There are four main physical characteristics of in situ boulder that have been reviewed, which are size, shape, material at the surrounding of the boulder or rindlets and saprolites zone where the in situ boulder is formed. These parameters are commonly used for prediction methods in the occurrence of boulder beneath the ground surface (Frank *et al*., 2000; Medley, 2002; Veneziano and Van Dyck, 2005; Jee and Ha, 2007; Felletti and Beretta, 2009) as well as weathering profile classification (Raj, 1985; Fookes, 1997; Tsidzi, 1997; Tuğrul and Gürpinar, 1997; Yang and Wu, 2006; Alavi *et al*., 2016) for geotechnical or geological engineering design (Irfan and Powell, 1985; Aydin, 2006; Arıkan *et al*., 2007; Ehlmann *et al*., 2008; Alejano *et al*., 2010; Arıkan and Aydin, 2012; Filbà *et al*., 2016).

2.6.1 Shape

In weathered rock masses, the in situ boulders can be found in variety of shapes and sizes. The shapes of the boulders are influenced by the discontinuities characteristics that are formed at the surrounding of the boulder in the rock mass

(Dearman, 1991; Palmström, 2001). In situ boulder can also be found in lozenge or flat shape, spherical to ellipsoidal or spheroidal shape and some of them are almost perfect spheres and/or cubic, but the corners and edges of the original blocks are rounded (Ruxton and Berry, 1957; Twidale, 1982, 1998; Shaw, 1997; Orso, 2014; Alavi *et al*., 2016).

In the engineering perspective, the boulder shape is commonly assumed as block or cubic shape due to the characteristics of discontinuities (Goodman and Shi, 1985; Maerz and Germain, 1996; Lu and Latham, 1999; Wang *et al*., 2003; Kalenchuk *et al*., 2006; Kim *et al*., 2007a; Stavropoulou, 2014). Some of the researchers assumed boulder to be in spherical shape (Tang and Quek, 1986; Medley, 2002) or cylindrical shape (Veneziano and Van Dyck, 2005) in order to easily predict the size. In fact, there is no specific shape of in situ boulder formed in weathered rock mass (Huddart *et al*., 1998; Kirschbaum *et al*., 2005). Some researchers had classified the shape of the boulder using several approaches for engineering purposes such as sphericity/angularity chart (Crofts, 1974), eigenshape analysis (MacLeod, 2002), shape index (Wang *et al*., 2003; Dunlop, 2006; Yang and Wu, 2006), digital shape visualisation (Stückrath *et al*., 2006) and block diagram (Feng *et al*., 2010). Unfortunately, the classification of boulder shape in different weathering zones is still not well understood.

2.6.2 Size

Various sizes of boulders can be found on the ground or in weathered rock mass. The occurrence of in situ boulders with various sizes in weathered rock mass are the result of discontinuities formation such as joint spacing, joint persistence, joint orientation, faults and bedding (Goodman and Shi, 1985; Maerz and Germain, 1996; Palmström, 2001, 2005; Kim *et al*., 2007b). On top of that, the size of in situ boulder embedded in weathered rock mass is difficult to be measured (Jee and Ha, 2007). However, it can still be done based on the long and short axis of the in situ boulder that are exposed to the ground surface due to evacuation and soil erosion

(Ditlevsen, 2005, 2006). The size of boulder can be described by its volume (Stückrath et al. 2006), in which the block volume of boulder can be estimated based on the interpretation of laser scanning result except for rounded or spheroidal boulder (Alejano *et al*., 2010).

The boulder size can be as small as 0.25 m or up to 20 m huge (Ruxton and Berry, 1957; Twidale, 1982). If the size of the boulder is large enough, it is classified as bornhardts or also known as bald domical hills with unknown size (Twidale, 1995, 1998; Bourne and Twidale, 2002). According to the classification of grain size criteria by New Zealand Geotechnical Society (2005), the particle size larger than 200 mm or 0.2 m is classified as boulder. In the engineering practice, the size of boulder is commonly classified to be more than 300 mm or 0.3 m (Boone *et al*., 1998; Poot *et al.*, 2000; Felletti and Beretta, 2009; Chandramohan, 2014). This measurement is always used to assess boulder size from borehole sample as carried out by previous researchers (Tang and Quek, 1986; Medley, 2002). In tropical weathered rock, there is no specific boulder size that had been classified (Raj, 1985; Komoo, 1985). In addition, the size of boulder in various weathering zones is not well understood and should be studied further.

2.6.3 Rindlets

Boulders are commonly found surrounded by several concentric sheets or layers of weathered rock (Ruxton and Berry, 1957; Ollier, 1971). The concentric sheets of weathered rock are identified as system of onion skin referring to the presence of concentric layers of weathered rock as thick as 3 to 50 cm surrounding the boulder with yellow-brownish colour (Braga *et al*., 2002; Turner *et al*., 2003; Buss *et al*., 2004; Fletcher *et al*., 2006; Chabaux *et al*., 2013). There are different names for the decomposed concentric layers of the boulder which includes concentric shells as called by most of the earlier researchers (Ruxton and Berry, 1957; Ollier, 1971; Sarracino *et al*., 1987; Sarracino and Prasad, 1989; Sørensen *et al*., 2003; Patino *et al*., 2003). Other names given for it are onion-skin layers

(Twidale, 1982) or spherical shell (Røyne *et al*., 2008; Jamtveit and Hammer, 2011). However, most recently, researchers classified the decomposed concentric sheets of weathered rock surrounding the corestone as rindlets (Turner *et al*., 2003; Fletcher *et al*., 2006; Buss *et al*., 2008; Brantley *et al*., 2011; Chabaux *et al*., 2013).

The terms rindlets was used by Turner *et al*. (2003) to describe the partially of weathered zone dominated by the weathering of plagioclase to kaolinite in Rio Icacos saprolite. Fletcher *et al*. (2006) used the term rindlets to refer to the alteration on the concentric fractures layers on the corestone outer surface that was found in Rio Icacos, Puerto Rico. Buss *et al.* (2008) used the term rindlets to describe the concentric layers with the thickness of 0.2 to 2 m formed around the corestone of quartz diorite bedrock. Similar to Brantley *et al*. (2011), the term rindlets adopted from Buss *et al.* (2008) was to define the onion skin-like shell that is formed around the corestone during spheroidal weathering as found at hill shale and Rio Blanco quartz diorite. The term rindlets as suggested by Turner *et al*. (2003) and used by Fletcher *et al*. (2006) and Buss *et al.* (2008) was used by Chabaux *et al*. (2013) to refer to concentric fracture shell with the thickness of 40 cm that was formed at the surrounding of the quartz diorite corestone found in tropical rain forest, Rio Icacos, Puerto Rico.

Rindlets that are commonly found consists of three to six concentric sheets of weathered rock surrounding the corestone (Ruxton and Berry, 1957; Turner *et al*., 2003; Fletcher *et al*., 2006; Buss *et al*., 2008; Brantley *et al*., 2011; Chabaux *et al*., 2013). The first layer located near the boulder is corestone-rindlets interface, which is then followed by rindlet zone (~0.2 to 2.0 m thick which ~2.5 cm each), rindlet-saprolite zone , protosaprolite layer (~ 7 cm) and saprolite zone (2-8 m thick) and the upper layer near the ground surface is soil with the thickness of 0.5 to 1 m thick (Fletcher *et al*., 2006; Buss *et al*., 2008; Brantley *et al*., 2011; Chabaux *et al*., 2013). Due to the development of cracks in rindlets layer, the thickness of the rindlets decreased with the increased of distance from corestone as shown in Figure 2.5 (Fletcher *et al*., 2006).

REFERENCES

Acworth, R.I., (1987). The Development of Crystalline Basement Aquifers in a Tropical Environment. *Quarterly Journal of Engineering Geology, London*, 20, pp.265–272.

Ahmad, F., Yahaya, A.S. & Farooqi, M.A., (2006). Characterization and Geotechnical Properties of Penang Residual Soils with Emphasis on Landslides. *American Journal of Environmental Sciences*, 2(4), pp.121–128.

Akin, M., (2009). A Quantitative Weathering Classification System for Yellow Travertines. *Environmental Earth Sciences*, 61(1), pp.47–61.

Akram, M. & Bakar, M., (2007). Correlation Between Uniaxial Compressive Strength and Point Load Index for Salt-Range Rocks. *Pakistan Journal of Engineering & Applied Sciences*, 1(50), pp.1–8.

Alavi, S.V.N.K.A., Edy Tonnizam, M., Komoo, I., & Kalatehjari, R., (2014a). A Typical Weathering Profile of Granitic Rock in Johor, Malaysia Based on Joint Characterization. *Arabian Journal of Geosciences*. pp. 1-11.

Alavi, S.V.N.K.A., Edy Tonnizam, M. & Komoo, I., (2014b). Dominant Weathering Profiles of Granite in Southern Peninsular Malaysia. *Engineering Geology*, 183, pp.208–215.

Alavi, S.V.N.K.A., Edy Tonnizam, M., Komoo, I., & Kalatehjari, R., (2014c). Assessment of Weathering Effects on Rock Mass Structure. *Jurnal Teknologi*, 1, pp.71–75.

Alavi, S.V.N.K.A., Tugrul, A., Gokceoglu, C. & Armaghani, D. J., (2016). Characteristics of Weathering Zones of Granitic Rocks in Malaysia For Geotechnical Engineering Design. *Engineering Geology*, 200(200), pp.94–103.

Alejano, L.R., Ordonez, C., Armesto, J., & Rivas, T., (2010). Assessment of the Instability Hazard of a Granite Boulder. *Natural Hazards*, 53(1), pp.77–95.

Alejano, L.R. & Carranza-Torres, C., (2011). An Empirical Approach for Estimating Shear Strength of Decomposed Granites in Galicia, Spain. *Engineering Geology*, 120(1-4), pp.91–102.

André, L., Rabemanana, V. & Vuataz, F.D., (2006). Influence of Water-Rock Interactions on Fracture Permeability of the Deep Reservoir at Soultz-Sous-Forêts, France. *Geothermics*, 35(5-6), pp.507–531.

Anon, (1981). Rock and Soil Description and Classification for Engineering Geological Mapping, Report by The International Association Of Engineering Geology Commission on Engineering Geological Mapping. *Bulletin of the*

International Association of Engineering Geology, 24, pp.235–74.

Arel, E. & Tugrul, A., (2001). Weathering and Its Relation to Geomechanical Properties of Cavusbasi Granitic Rocks in Northwestern Turkey. *Bulletin of Engineering Geology and the Environment*, 60(2), pp.123–133.

Arıkan, F. & Aydin, N., (2012). Influence of Weathering on the Engineering Properties of Dacites in Northeastern Turkey. *ISRN Soil Science*, 2012, pp.1–15.

Arıkan, F., Ulusay, R. & Aydın, N., (2007). Characterization of Weathered Acidic Volcanic Rocks and A Weathering Classification Based on a Rating System. *Bulletin of Engineering Geology and the Environment*, 66(4), pp.415–430.

ASTM C914, (2009). Standard Test Method For Bulk Density and Volume of Solid Refractories by Wax Immersion. *ASTM International, West Conshohocken, PA*, pp.3–5.

ASTM C97/C97M-09, (2009). Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone. *ASTM International, West Conshohocken, PA,*, pp.9–11.

ASTM D4220-95, (2007). Standard Practices for Preserving and Transporting Soil Samples. *ASTM International, West Conshohocken, PA*, 95(Reapproved 2007), pp.1–11.

ASTM STP479, (1970). Suggested Method of Test for Permeability of Undisturbed Soil or Rock Specimens. *Submitted by Holtz, W.G; ASTM International, West Conshohocken, PA*, pp.150–156.

Ayakwah, G.F., McLemore, V.T, Fakhimi, A., Viterbo., V.C., & Dickens, A.K., (2009). Effect of Weathering and Alteration on Point Load and Slake Durability Indices of Questa Mine Materials, New Maxico. *SME Annual Meeting, Mexico*.

Aydin, A., (2006). Stability of Saprolitic Slopes : Nature and Role of Field Scale Heterogeneities. *Natural Hazards and Earth System Sciences*, 6, pp.89–96.

Aydin, A. & Basu, A., (2005). The Schmidt Hammer in Rock Material Characterization. *Engineering Geology*, 81(1), pp.1–14.

Banks, D., Solbjorg, M.L. & Rohr-Torp, E., (1992). Permeability of Fracture Zones in A Precambrian Granite. *Quarterly Journal of Engineering Geology*, 25(4), pp.377–388.

Barata, F.E., (1969). Landslides in the Tropical Region of Rio De Janeiro. *Internat. Conf. Soil Mechanics and Foundation Engineering, 7th, Mexico City*, 2, pp.507–516.

Barton, N., (2013). Shear Strength Criteria for Rock, Rock Joints, Rockfill and Rock Masses: Problems and Some Solutions. *Journal of Rock Mechanics and Geotechnical Engineering*, 5(4), pp.249–261.

Barton, N., Bandis, S. & Bakhtar, K., (1985). Strength, Deformation and Conductivity Coupling of Rock Joints. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 22(3), pp.121–140.

Barton, N., Lien, R. & Lunde, J., (1974). Engineering Classification of Rock Masses for the Design of Tunnel Support. *Rock Mechanics*, 6(4), pp.189–236.

Basu, A. & Aydin, A., (2006). Predicting Uniaxial Compressive Strength by Point Load Test: Significance of Cone Penetration. *Rock Mechanics and Rock Engineering*, 39(5), pp.483–490.

Basu, A., Celestino, T.B. & Bortolucci, A.A., (2009). Evaluation of Rock Mechanical Behaviors Under Uniaxial Compression With Reference to Assessed Weathering Grades. *Rock Mechanics and Rock Engineering*, 42(1), pp.73–93.

Baumeister, J.L., (2012). Chemical Weathering of the Mafic Minerals Serpentine and Olivine in Natural Environments. *Master Thesis, University of Nevada*.

Baynes, F.J. & Dearman, W.R., (1978a). The Microfabric of A Chemically Weathered Granite. *Bulletin of the International Association of Engineering Geology*, 18, pp.91–100.

Baynes, F.J. & Dearman, W.R., (1978b). The Relationship Between the Microfabric and the Engineering Properties of Weathered Granite. *Bulletin of Engineering Geology*, 18, pp.191–197.

Baynes, F.J., Dearman, W.R. & Irfan, T.Y., (1978). Practical Assessment of Grade in A Weathered Granite. *Buletin of the International Association of Engineering Geology*, 18(1978), pp.101–109.

Begonha, A. & Braga, M.A.S., (2002). Weathering of the Oporto Granite : Geotechnical and Physical Properties. *Catena*, 49, pp.57–76.

Bieniawski, Z.T., (1993). Classification of Rock Masses for Engineering: The Rmr System and Future Trends. *Comprehensive rock engineering*, 3, pp.553–573.

Bieniawski, Z.T., (1990). Tunnel Design by Rock Mass Classification. *Technical Report; Army Corps Engineers*, GL-79-19.

Bierman, E.P.B., Brouwer, D.H. & van Hemmen, J.J., (1997). Measuring Crop Density: Comparison of Volumetry and Stereological Methods. *Bulletin of Environmental Contamination and Toxicology*, 58(6), pp.1006–1013.

Bisdom, E.B.A., (1967). Micromorphology of A Weathered Granite Near the Ria De Arosa (Nw Spain). *Leidse Geol. Meded. , Leyden*, 37, pp.33–67.

Boisen, B.P.A., (1977). Hand-Portable Point Load Tester for Field Measurements. *In Energy Resources and Excavation Technology. 18th U.S. Symposium on Rock Mechanics (Edited by Wang F. D. and Clark G. B.), Keystone, Colorado.*, pp.5C2–1–5C2–4.

Boone, S.J., Westland, J., Busbridge, J.R., & Garrod, B., (1998). Prediction Of Boulder Obstruction. *Tunnel and Metropolises, Negro Jr & Ferreira (eds)*, pp.817–822.

Borrelli, L., Perri, F., Critelli, S., & Gulla, G., (2014). Characterization of Granitoid and Gneissic Weathering Profiles of the Mucone River Basin (Calabria, Southern Italy). *Catena*, 113, pp.325–340.

Borrelli, L., Critelli, S., Gulla. G., & Muto, F., (2015). Weathering Grade and Geotectonics of the Western-Central Mucone River Basin (Calabria, Italy). *Journal of Maps*, 11(4), pp.606–624.

Borrelli, L., Coniglio, S., Critelli, S., La Barbera, A., & Gulla, G., (2016).

Weathering Grade in Granitoid Rocks: The San Giovanni in Fiore Area (Calabria, Italy). *Journal of Maps*, 12(2), pp.260–275.

Bourne, J.A. & Twidale, C.R., (2002). Morphology and Origin of Three Bornhardt Inselbergs Near Lake Johnston, Western Australia. *Journal of the Royal Society of Western Australia*, 85, pp.83–102.

Braga, S., Paquet, H. & Begonha, A., (2002). Weathering of Granites in a Temperate Climate (NW Portugal): Granitic Saprolites and Arenization. *Catena*, 49(1), pp.41–56.

Brantley, S.L., Buss, H., Lebedeva, M., Fletcher, R.C, & Ma, L., (2011). Investigating the Complex Interface Where Bedrock Transforms to Regolith. *Applied Geochemistry*, 26, pp.S12–S15.

Broch, E. & Franklin, J.A., (1972). The Point-Load Strength Test. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 9(6), pp.669–676.

Brown, E.T., (1981). Rock Characterizition, Testing and Monitoring. *ISRM suggested methods. Pergamon Press, NewYork*, p.211.

Buss, H.L., (2006). Biogeochemical Weathering of Iron-Silicate Minerals. *PhD Thesis, The Pennsylvania State University, College of Earth and Mineral Sciences*, (August).

Buss, H.L., Sak, P.B., Webb, S.M, & Brantley, S.L., (2008). Weathering of the Rio Blanco Quartz Diorite, Luquillo Mountains, Puerto Rico: Coupling Oxidation, Dissolution and Fracturing. *Geochimica et Cosmochimica Acta*, 72(18), pp.4488–4507.

Buss, H.L., White, A.F. & Brantley, S.L., (2004). Mineral Dissolution at the Granite–Saprolite Interface. *11th International Symposium on Water–Rock Interaction*, 11, pp.819–823.

Cai, M., Kaiser, P.K., Uno, H., Tasaka, Y., & Minami, M., (2004). Estimation of Rock Mass Deformation Modulus and Strength of Jointed Hard Rock Masses Using the GSI System. *International Journal of Rock Mechanics and Mining Sciences*, 41(1), pp.3–19.

Ceryan, S., (1999). Weathering and Classification of Harsit Granitoid and the Effect of Weathering on Engineering Properties. *Ph.D. Thesis Karadeniz Technical University, Trabzon, Turkey (in Turkish).*

Ceryan, S., Tudes, S. & Ceryan, N., (2007). A New Quantitative Weathering Classification for Igneous Rocks. *Environmental Geology*, 55(6), pp.1319–1336.

Ceryan, S., Tudes, S. & Ceryan, N., (2007). Influence of Weathering on the Engineering Properties of Harsit Granitic Rocks (NE Turkey). *Bulletin of Engineering Geology and the Environment*, 67(1), pp.97–104.

Chabaux, F., Blaes, E., Stille, P., di Chiara Roupert, R., Pelt, E., Dosseto, A., Ma, L., Buss, H.L., & Brantley, S.L., (2013). Regolith Formation Rate from U-Series Nuclides: Implications from the Study of A Spheroidal Weathering Profile in The Rio Icacos Watershed (Puerto Rico). *Geochimica et Cosmochimica Acta*, 100, pp.73–95.

Chandramohan, P. V., (2014). Pile Capacity in a Bouldery Stratum. In *Soil Behavior Fundamentals to Innovations in Geotechnical Engineering*. pp. 453–463.

Chigira, M., Mohamad, Z., Lim, C.S., & Komoo, I., (2011). Landslides in Weathered Granitic Rocks in Japan and Malaysia. *Bulletin of the Geological Society of Malaysia*, 57, pp.1–6.

Chiu, C.F. & Ng, C.W.W., (2014). Relationships Between Chemical Weathering Indices and Physical and Mechanical Properties of Decomposed Granite. *Engineering Geology*, 179, pp.76–89.

Choi, S.Y. & Park, H.D., (2004). Variation of Rock Quality Designation (RQD) With Scanline Orientation And Length: A Case Study in Korea. *International Journal of Rock Mechanics and Mining Sciences*, 41(2), pp.207–221.

Crawford, K.M., (2013). Determination of Bulk Density of Rock Core Using Standard Industry Methods. *Master Thesis, Michigan Technology University*.

Crofts, R.S., (1974). A Visual Measure of Shingle Particle Form for Use in the Field. *Journal of Sedimentary Research*, 44(3), pp.931–934.

de Almeida, J.A. & Kullberg, J.C., (2011). Rockfall Hazard and Risk Analysis for Monte Da Lua, Sintra, Portugal. *Natural Hazards*, 58(1), pp.289–310.

Dadey, K.A., Janecek, T. & Klaus, A., (1992). Dry-Bulk Density: Its Uses and Determination. *Proceedings of the Ocean Drilling Program, Scientific Results*, 126, pp.551–554.

Dearman, W.R., (1995). Description and Classification of Weathered Rocks for Engineering Purposes: The Background to the BS5930:1981 Proposals. *Quarterly Journal of Engineering Geology*, 28, pp.207–242.

Dearman, W.R., (1991). Engineering Geological Mapping. *Oxford: Butterworth-Heinemann (London and Boston)*, pp.367–378.

Dearman, W.R., (1974). Weathering Classification in the Characterisation of Rock For Engineering Purposes in British Practice. *Engineering Geology*, pp.33–42.

Dearman, W.R., (1976). Weathering Classification In The Characterisation of Rock: A Revision. *Bulletin of the International Association of Engineering Geology*, 14(1), pp.123–127.

Dearman, W.R., Baynes, F.J. & Irfan, T.Y., (1978). Engineering Grading of Weathered Granite. *Engineering Geology*, 12, pp.345–374.

Dearman, W.R. & Fookes, P.G., (1974). Engineering Geological Mapping for Civil Engineering Practice in the United Kingdom. *Engineering Geology*, 7, pp.223–256.

De Costa Nunes, A.J., (1969). Landslides in Soils of Decomposed Rocks Due to Intense Rainstorms. *Internat. Conf. Soil Me- chanics and Foundation Engineering, 7th, Mexico City , Proc.,*, 2, pp.547–554.

Deere, D.U., Merritt, A.H. & Coon, R.F., (1969). Engineering Classification of In-Situ Rock. *Technical Report No. AFWL-TR-67-144, Air Force Weapons Laboratory, New Mexico*.

Deere, D.U. & Miller, R.P., (1966). Engineering Classification and Index Properties for Intact Rock. *Technical Report, Air Force Weapons Laboratory*, 1, pp.65–116.

Dethier, D.P. & Bove, D.J., (2011). Mineralogic and Geochemical Changes from Alteration of Granitic Rocks, Boulder Creek Catchment, Colorado. *Vadose Zone Journal*, 10(3), p.858.

Dethier, D.P. & Lazarus, E.D., (2006). Geomorphic Inferences from Regolith Thickness, Chemical Denudation and Crn Erosion Rates Near the Glacial Limit, Boulder Creek Catchment and Vicinity. *Geomorphology*, 75(3-4), pp.384–399.

Devkota, K.C., Ham, J.-E. & Kim, G.W., (2009). Characteristics of Discontinuity Spacing of Yeongdeok Granite. *Geosciences Journal*, 13(2), pp.161–165.

Diamantis, K., Gartzos, E. & Migiros, G., (2009). Study on Uniaxial Compressive Strength, Point Load Strength Index, Dynamic And Physical Properties of Serpentinites From Central Greece: Test Results and Empirical Relations. *Engineering Geology*, 108(3-4), pp.199–207.

Ditlevsen, O., (2006). A Story About Distributions of Dimensions and Locations of Boulders. *Probabilistic Engineering Mechanics*, 21(1), pp.9–17.

Ditlevsen, O., (2005). A Story About Estimation of A Random Field of Boulders from Incomplete Seismic Measurements. *Probabilistic Engineering Mechanics*, 20(4), pp.342–354.

Dunlop, H., 2006. Rock Shape Characterization. *Computational Perception & Scene Analysis,* pp.1-12.

Durgin, P.B., (1977). Landslides and the Weathering of Granitic Rocks. *Geological Society of America*, 3, pp.127–131.

Edy Tonnizam, M., Md Isa, M.F., Mohd Amin, M.F., Komoo, I., Gofar, N., & Saad, R., (2011). Effect of Moisture Content on The Strength of Various Weathering Grades of Granite. *Electronic Journal of Geotechnical Engineering*, 16 H, pp.863–886.

Edy Tonnizam, M., Latifi, N., Arefnia, A., & Md Isa, M.F., (2015). Effects of Moisture Content on the Strength of Tropically Weathered Granite From Malaysia. *Bulletin of Engineering Geology and the Environment*. pp.1-22.

Edy Tonnizam, M., Saad, S. & Alavi, S.V.N.K.A., (2011). Durability Assessment of Weak Rock by Using Jar Slaking Test. *Electronic Journal of Geotechnical Engineering*, pp.1319–1335.

Eggleton, A. & Banfield, F., (1985). The Alteration of Granitic Biotite to Chlorite. *American Mineralogist*, 70, pp.902–910.

Ehlen, J., (1999). Fracture Characteristics in Weathered Granites. *Geomorphology*, 31(1-4), pp.29–45.

Ehlen, J., (2002). Some Effects of Weathering on Joints in Granitic Rocks. *Catena*, 49(1-2), pp.91–109.

Ehlmann, B.L., Viles, H.A. & Bourke, M.C., (2008). Quantitative Morphologic Analysis of Boulder Shape and Surface Texture to Infer Environmental History: A Case Study of Rock Breakdown at the Ephrata Fan, Channeled Scabland, Washington. *Journal of Geophysical Research: Earth Surface*, 113, pp.1–20.

Elliott, C.E., (2006). Physical Rock Weathering along the Victoria Land Coast , Antarctica. *PhD Thesis, University of Canterbury*.

Felletti, F. & Beretta, G.P., (2009). Expectation of Boulder Frequency when Tunneling in Glacial Till: A Statistical Approach Based on Transition Probability. *Engineering Geology*, 108(1-2), pp.43–53.

Feng, X.L., Li, D., Wang, L.G., Jing, Y.B., Xun, X.M., & Zeng, Q.T., (2010). A New Method of Block Shape Classification. *Science China Technological Sciences*, 54(1), pp.110–115.

Filbà, M., Salvany, J.M., Jubany, J., & Carrasco, L., (2016). Tunnel Boring Machine Collision With An Ancient Boulder Beach During the Excavation of the Barcelona City Subway L10 Line: A Case of Adverse Geology and Resulting Engineering Solutions. *Engineering Geology*, 200, pp.31–46.

Fletcher, R.C., Buss, H.L. & Brantley, S.L., (2006). A Spheroidal Weathering Model Coupling Porewater Chemistry to Soil Thicknesses During Steady-State Denudation. *Earth and Planetary Science Letters*, 244(1-2), pp.444–457.

Fonseca, A. V., (2003). Characterising and Deriving Engineering Properties of A Saprolitic Soil From Granite , Inn Porto. *Swets & Zeitlinger, Lisse*, pp.1341–1378.

Fookes, P.G., (1997). Tropical Residual Soils Geological Society Engineering Group Working Party Report. *Quarterly Journal of Engineering Geology and Hydrogeology; The Geological Society of London*, 23, pp.4–101.

Frank, G., Guy, E. & Daniels, J., (2000). The Use of Borehole Ground Penetrating Radar in Determining the Risk Associated with Boulder Occurrence. *North American Society for Trenchless Technology*, pp.39–48.

Franklin, J.A., Broch, E. & Walton, G., (1971). Logging the Mechanical Character of Rock. *Transactions of the Institution of Mining and Metallurgy*, 80(A), pp.1–9.

Franklin, J.A. & Chandra, A., (1972). The Slake-Durability Test. *International Journal of Rock Mechanics and Mineral Sciences,*, 9, pp.325–341.

Frederick, W. V., (2015). ORIENT 3.0.2. *Spherical Projection and Orientation Data Analysis Software User Manual.*, p.www.frederickvollmer.com.

Freire-Lista, D.M., Gomez-Villalba, L.S. & Fort, R., (2015). Microcracking of Granite Feldspar During Thermal Artificial Processes. *Periodico di Mineralogia*, 84(3A), pp.519–537.

Galvan, M., Preciado, J. & Seron, J., (2014). Correlation Between the Point Load Index, Is(50) and the Resistance to Unconfined Compression in Limestone from the Comunidad Valencia, Spain. *Acta Geotechnica Slovenica*, 2(50), pp.35–45.

Gamon, T.I., (1983). A Comparison of Existing Schemes for the Engineering Description and Classification of Weathered Rock in Hong Kong. *Engineering Geology*, (28), pp.225–232.

Ghani, A.A., Searle, M., Robb, L., & Chung, S.L., (2013). Transitional I S Type Characteristic in the Main Range Granite, Peninsular Malaysia. *Journal of Asian Earth Sciences*, 76, pp.225–240.

Ghobadi, M.H., (1994). Engineering Geologic Factors Influencing the Stability of

Slopes in The Northern Illawarra Region. *PhD Thesis, University of Wollongong*.

Ghosh, D.K. & Awasthi, D.D., (1990). Weathering Grade Classification of Lesser Himalayan Granites, Western India. *Bulletin of the International Association of Engineering Geology*, 42, pp.31–38.

Ghosh, D.K. & Srivastava, M., (1991). Point-Load Strength: An Index for Classification of Rock Material. *Bulletin of the International Association of Engineering Geology*, 24(44).

Goff, J., Weiss, R., Courtney, C.,& Dominey-Howes, D., (2010). Testing the Hypothesis for Tsunami Boulder Deposition from Suspension. *Marine Geology*, 277(1-4), pp.73–77.

Goodman, R.E., (1989). Introduction to Rock Mechanics, (2nd edition), *John Wiley and Sons, New York.*

Goodman, R.E., (1976). Methods of Geological Engineering in Discontinuous Rocks. *Library of Congress Cataloging in Publication Data*.

Goodman, R.E. & Shi, G., (1985). Block Theory and Its Application to Rock Engineering. *Englewood Cliffs, NJ: Prentice-Hall*.

Gordon, S.J. & Dorn, R.I., (2005). In Situ Weathering Rind Erosion. *Geomorphology*, 67, pp.97–113.

Goto, K., Chavanich, S.A., Imamura, F., Kunthasap, P., Matsui, T., Minoura, K., Sugawara, D., & Yanagisawa, H., (2007). Distribution, Origin and Transport Process of Boulders Deposited by the 2004 Indian Ocean Tsunami at Pakarang Cape, Thailand. *Sedimentary Geology*, 202(4), pp.821–837.

Gupta, A.S. & Seshagiri Rao, K., (1999). Weathering Effects on the Strength and Deformational Behaviour of Crystalline Rocks Under Uniaxial Compression State. *Engineering Geology*, 56(3), pp.257–274.

Gupta, A.S. & Seshagiri Rao, K., (2000). Weathering Effects on the Strength and Deformational Behaviour of Crystalline Rocks Under Uniaxial Compression State. *Engineering Geology*, 56(3-4), pp.257–274.

Gurocak, Z. & Kilic, R., (2005). Effect Of Weathering on the Geomechanical Properties of the Miocene Basalts in Malatya, Eastern Turkey. *Bulletin of Engineering Geology and the Environment*, 64(4), pp.373–381.

Hall, K., Thorn, C. & Sumner, P., (2012). On the Persistence of "Weathering." *Geomorphology*, 149-150, pp.1–10.

Hardy, M., (1992). X-Ray Diffraction Measurement of the Quartz Content of Clay and Silt Fractions in Soils. *Clay Minerals*, 27, pp.47–55.

Hatzor, Y.H. & Goodman, R.E., (1997). Three-Dimensional Back-Analysis of Saturated Rock Slopes in Discontinuous Rock—A Case Study. *Géotechnique*, 47(4), pp.817–839.

Havaej, M., Wolter, A. & Stead, D., (2015). The Possible Role of Brittle Rock Fracture in the 1963 Vajont Slide, Italy. *International Journal of Rock Mechanics and Mining Sciences*, 78, pp.319–330.

Head, K.H., (1998). Manual of Soil Laboratory Testing: Effective Stress Tests BS 1377:1990. *John Wiley & Sons Ltd.*, 3(2).

Heidari, M., Khanlari, G.R., Momeni, A.A., & Jafargholozadeh, H., (2011). The Relationship Between Geomechanical Properties and Weathering Indices of Granitic Rocks, Hamedan, Iran. *Geomechanics and Geoengineering*, 6(1), pp.59–68.

Heidari, M., Momeni, A.A. & Naseri, F., (2013). New Weathering Classifications for Granitic Rocks Based on Geomechanical Parameters. *Engineering Geology*, 166, pp.65–73.

Hencher, S.R. & Martin, R.P., (1982). The Description and Classification of Weathered Rocks in Hong Kong for Engineering Purposes. *Proceedings of 7th South-east Asian Geotechnical Conference. Hong Kong*, 1, pp.125–142.

Hoek, E., (1983). Strength of Jointed Rock Masses. *Geotechnique*, 33(3), pp.187–223.

Hoek, E., Kaiser, P.K. & Bawden, W.F., (1993). Support of Underground Excavation in Hard Rock. *Mining Research Directorate andUniversities Research Incentive*.

Hoek, E. & Londe, P., (1974). The Design of Rock Slopes and Foundations. *General report for Third Congress of the International Society for Rock Mechanics*.

Hoseinie, S.H., Aghababaei, H. & Pourrahimian, Y., (2008). Development of A New Classification System for Assessing of Rock Mass Drillability Index (RDi). *International Journal of Rock Mechanics and Mining Sciences*, 45(1), pp.1–10.

Hoseinie, S.H., Ataei, M. & Osanloo, M., (2009). A New Classification System for Evaluating Rock Penetrability. *International Journal of Rock Mechanics and Mining Sciences*, 46(8), pp.1329–1340.

Hossain, D., (1992). Prediction of Permeability of Fissured Tills. *Quarterly Journal of Engineering Geology and Hydrogeology*, 25(4), pp.331–342.

Howarth, D. & Rowlands, J., (1986). Development of an Index to Quantify Rock Texture for Qualitative Assessment of Intact Rock Properties. *Geotechnical Testing Journal*, 9(4), p.169.

Huat, B.B.K., Ali, F.H. & Rajoo, R.S.K., (2006). Stability Analysis and Stability Chart for Unsaturated Residual Soil Slope. *American Journal of Environmental Sciences*, 2(4), pp.154–156.

Huber, N.K., (1987). The Geologic Story of Yosemite National Park. *(No. 1595). USGPO,.*

Huddart, D., Bennett, M.R., Hambrey, M.J., Glasser, N.F., & Crowford, K., (1998). Origin of Well-Rounded Gravels in Glacial Deposits From Briggerhalvoya , Northwest Spitsbergen : Potential Problems Caused by Sediment Reworking in the Glacial Environment. *Norsk Polarinstitutt*, 17, pp.61–69.

Hutchinson, C.S., (1974). Laboratory Handbook of Petrographic Techniques. *Wiley, New York*.

Imamura, F., Goto, K. & Ohkubo, S., (2008). A Numerical Model for the Transport of A Boulder by Tsunami. *Journal of Geophysical Research: Oceans*, 113(1), pp.1–12.

Irfan, T.Y. & Dearman, W.R., (1978). Engineering Classification and Index Properties of A Weathered Granite. *Buletin of the International Association of Engineering Geology*, 17, pp.79–90.

Irfan, T.Y. & Powell, G.E., (1985). Engineering Geological Investigations for Pile Foundations on A Deeply Weathered Granitic Rock In Hong Kong. *Bulletin of the International Association of Engineering Geology - Bulletin de l'Association Internationale de Géologie de l'Ingénieur*, 32(1), pp.67–80.

ISRM, (2007). *The Complete ISRM Suggested Methods For Rock Characterization, Testing and Monitoring: 1974-2006* April 2007. R. Ulusay & J. A. Hudson, eds., Ankara, Turkey.

Jakubec, J., (2013). Role Of Defects in Rock Mass Classification. *Australian Centre for Geomechanics*, pp.1–8.

Jamtveit, B. & Hammer, Ø., (2011). Hierarchical Fracturing During Weathering and Serpentinisation. *Geomechanical Perspectives*, 1(3), pp.418–432.

Jee, W.W. & Ha, S.G., (2007). Feasible Boulder Treatment Methods for Soft Ground Shielded TBM. *Underground Space – the 4th Dimension of Metropolises*, pp.217–222.

Jiao, J.J., Wang, X.S. & Nandy, S., (2005). Confined Groundwater Zone and Slope Instability in Weathered Igneous Rocks in Hong Kong. *Engineering Geology*, 80(1-2), pp.71–92.

Kahraman, S., Gunaydin, O. & Fener, M., (2005). The Effect of Porosity on the Relation Between Uniaxial Compressive Strength and Point Load Index. *International Journal of Rock Mechanics and Mining Sciences*, 42(4), pp.584–589.

Kalenchuk, K.S., Diederichs, M.S. & McKinnon, S., (2006). Characterizing Block Geometry in Jointed Rockmasses. *International Journal of Rock Mechanics and Mining Sciences*, 43(8), pp.1212–1225.

Keykha, H.A., Yusof, Z.M. & Ali, T.A.M., (2011). Kinematic Analysis of Blocks in Tunnel on the Basis of Discontinuities. *Electronic Journal of Geotechnical Engineering*, 16, pp.513–520.

Khalily, M., Reza, G., Ghafoori, M., Khanehbad, M., & Dehghan, P., (2013). Durability Characterization of Abderaz Marly Limestone in the Kopet- Dagh Basin , NE of Iran. *International Journal of Emerging Technology and Advanced Engineering*, 3(5).

Khanlari, G.R., Heidari, M., Sepahigero, A.A., & Fereidooni, D., (2014). Quantification of Strength Anisotropy of Metamorphic Rocks of the Hamedan Province, Iran, as Determined from Cylindrical Punch, Point Load and Brazilian Tests. *Engineering Geology*, 169(August), pp.80–90.

Khanlari, G.R., Heidari, M. & Momeni, A.A., (2012). Assessment of Weathering Processes Effect on Engineering Properties of Alvand Granitic Rocks (West of Iran). *Environmental Earth Sciences*, 67(3), pp.713–725.

Kim, B.H., Cai, M., Kaiser, P.K., & Yang, H.S., (2007a). Estimation of Block Sizes for Rock Masses with Non-Persistent Joints. *Rock Mechanics and Rock Engineering*, 40(2), pp.169–192.

Kim, B.H., Kaiser, P.K. & Grasselli, G., (2007b). Influence of Persistence on Behaviour of Fractured Rock Masses. *Geological Society, London, Special Publications*, 284(September 2010), pp.161–173.

Kim, J., Jeong, S., Park, S., & Sharma, J., (2004). Influence of Rainfall-Induced Wetting on The Stability of Slopes in Weathered Soils. *Engineering Geology*, 75(3-4), pp.251–262.

Kim, S. & Park, H.D., (2003). The Relationship Between Physical and Chemical Weathering Indices of Granites Around Seoul, Korea. *Bulletin of Engineering Geology and the Environment*, 62(3), pp.207–212.

Kirschbaum, A., Martinez, E., Pettinari, G., & Herrero, S., (2005). Weathering Profiles in Granites, Sierra Norte (Co'rdoba, Argentina). *Journal of South American Earth Sciences*, 19(4), pp.479–493.

Koita, M., Jourde, H., Koffi, K.J.P., Silveira, K.S.D., & Biaou, A., (2013). Characterization of Weathering Profile in Granites and Volcanosedimentary Rocks in West Africa Under Humid Tropical Climate Conditions . Case of the Dimbokro Catchment (Ivory Coast). *Journal of Earth System and Science*, (3), pp.841–854.

Komoo, I., (1989). Engineering Properties of the Igneous Rocks in Peninsular Malaysia. *Proc. 6th Regional Conference on Geology, Mineral and Hydrocarbon Resources of Southeast Asia, Jakarta, Indonesia*, pp.445–458.

Komoo, I., (1985). Engineering Properties of Weathered Rock Profiles in Peninsular Malaysia. In *Proceedings of the eighth Southeast Asian conference geotechnical conference, Kuala Lumpur*. pp. 1: 3–81 – 3–86.

Komoo, I., (1995). Geologi Kejuruteraan Perspektif Rantau Tropika Lembab. *Syarahan Perdana,Universiti Kebangsaan Malaysia, Bangi, Selangor Malaysia*, pp.1–62.

Komoo, I., (1997). Slope Failure Disaster - A Malaysian Predicament. *In Proc. Int'l. Symp Eng. Ceology and the Environment, Athens: Balkema Rotterdam.*, pp.777–781.

Kumar, R., Suresh, N., Sangode, S.J., & Kumaravel., V., (2007). Evolution of the Quaternary Alluvial Fan System in the Himalayan Foreland Basin: Implications for Tectonic and Climatic Decoupling. *Quaternary International*, 159(1), pp.6–20.

Lachassagne, P., Wyns, R. & Dewandel, B., (2011). The Fracture Permeability of Hard Rock Aquifers is due neither to Tectonics, nor to Unloading, but to Weathering Processes. *Terra Nova*, 23(3), pp.145–161.

Lan, H.X., Hu, R.L., Yue, Z.Q., Lee, C.F., & Wang, S.J., (2003). Engineering and Geological Characteristics of Granite Weathering Profiles in South China. *Journal of Asian Earth Sciences*, 21(4), pp.353–364.

Lednicka, M. & Kalab, Z., (2012). Evaluation of Granite Weathering in the Jeronym Mine Using Non-Destructive Methods. *Acta Geodynamica et Geomaterialia*, 9(2), pp.211–220.

Leopold, L., (1970). An Improved Method for Size Distribution of Stream Bed Gravel. *Water Resources Research*, 6(5), pp.1357–1366.

Liang, M., Edy Tonnizam, M., Khun, M.C., & Alel, M.N.A., (2015). Estimating Uniaxial Compressive Strength of Tropically Weathered Sedimentary Rock Using Indirect Tests. *Jurnal Teknologi*, 3, pp.49–58.

Little, A.L., (1969). The Engineering Classification of Residual Tropical Soils. *in proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering Specialty Session on Engineering Properties of Lateritic Soils, Mexico*, 1(1), pp.1–10.

Liu, W., Liu, C., Brantley, S.L., Xu, Z., Zhao, T., Liu, T., Yu, C., Xue, D., Zhao, Z., Cui, L., Zhang, Z., Fan, B., & Gu, X., (2016). Deep Weathering along A Granite Ridgeline in A Subtropical Climate. *Chemical Geology*, 427, pp.17–34.

Lu, P. & Latham, J.P., (1999). Developments in the Assessment of In-situ Block Size Distributions of Rock Masses. *Rock Mechanics and Rock Engineering*, 32(1), pp.29–49.

Lumb, P., (1983). Engineering Properties of Fresh and Decomposed Igneous Rocks from Hong Kong. *Engineering Geology*, 19, pp.81–94.

MacLeod, N., (2002). Geometric Morphometrics and Geological Shape-Classification Systems. *Earth-Science Reviews*, 59(1-4), pp.27–47.

Maerz, N.H., Likos, W.J., Loehr, J.E., Ding, D., & Miller, A., (2010). Evaluating Properties of Weak Shales in Western Missouri. *American Rock Mechanics Association, 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, held in Salt Lake City, UT June 27–30, 2010.*

Maerz, N.H., (1996). Reconstructing 3-D Block Size Distributions from 2-D Measurements on Sections. In *Proceedings of the FRAGBLAST 5 Workshop on Measurement of Blast Fragmentation, Montreal, Quebec, Canada*. AA Balkema, pp. 39–43.

Maerz, N.H. & Germain, P., (1996). Block Size Determination Around Underground Openings Using Simulations. *Proceedings of the FRAGBLAST 5 Workshop on Measurement of Blast Fragmentation, Montreal, Quebec, Canada*, pp.215–223.

Marinos, V., Marinos, P. & Hoek, E., (2005). The Geological Strength Index: Applications and Limitations. *Bulletin of Engineering Geology and the Environment*, 64(1), pp.55–65.

Marques, E.A.G., Barroso, E.V., Menezes Filho, A.P., & Vargas, E.D.A, (2010). Weathering Zones on Metamorphic Rocks From Rio De Janeiro-Physical, Mineralogical and Geomechanical Characterization. *Engineering Geology*, 111(1-4), pp.1–18.

Matsuo, S., Nishida, K. & Sasaki, S., (1979). Physical Properties of Weathered Granite Soil Particles and Their Effect on Permeability. *Bioscienci Biotechnology Biochemistry*, 19(1), pp.13–22.

Matula, M., (1981). Rock and Soil Description and Classification for Engineering Geological Mapping Report by IAEG Comission on Engineering Geological Mapping. *Engineering Geology*, 24, pp.235–274.

Medley, E.W., (2002). Estimating Block Size Distributions of Melanges and Similar Block-in-Matrix Rocks (Bimrocks). *Proceedings of 5th North American Rock Mechanics Symposium (NARMS)*, pp.509–606.

Mert, E., (2014). An Artificial Neural Network Approach to Assess the Weathering Properties of Sancaktepe Granite. *Geotechnical and Geological Engineering*, 32(4), pp.1109–1121.

Mills, H.H. & Allison, J.B., (1995). Weathering Rinds and the Evolution of Piedmont Slopes in the Southern Blue Ridge Mountains. *The Journal of Geology*, 103(4), pp.379–394.

Mohamed, Z., Rafek, A.G. & Komoo, I., (2007). Characterization and Classification of the Physical Deterioration of Tropically Weathered Kenny Hill Rock for Civil Works. *Electron J Geotech Eng*, 12(A), p.16.

Mohd Amin, M.F. & Kassim, A., (2000). Description and Classification of Filled Joint in Granite - An Approach. *Geological Society of Malaysia*, 44(July), pp.45–54.

Mohd Taha, R. et al., (1998). Geotechnical Behaviour of a Malaysian Residual Granite Soil. *Pertanika journal of Sciences and Technology*, 7(2), pp.151–169.

Momeni, A.A., Khanlari, G.R., Heidari, M., Sepahi, A.A., & Bazvand, E., (2015). New Engineering Geological Weathering Classifications For Granitoid Rocks. *Engineering Geology*, 185, pp.43–51.

Moye, D.G., (1955). Engineering Geology for the Snowy Mountains Scheme. *Journal of the Institution of Engineers*, 27(10-11), pp.287–298.

Munsell, (2009). Geological Rock-Color Chart. *Munsell color, Geological Society of America (GSA) Rock-Color*.

Murphy, S.F., Brantley, S.L., Blum, A.E., White, A.F., & Dong, H., (1998). Chemical Weathering in a Tropical Watershed, Luquillo Mountains, Puerto Rico: II. Rate and Mechanism of Biotite Weathering. *Geochimica et Cosmochimica Acta*, 62(2), pp.227–243.

Nandasena, N.A.K. & Tanaka, N., (2013). Boulder Transport by High-Energy (Tsunamis): Model Development for Threshold Entrainment and Transport. *Research Report of Department of Civil and Environmental Engineering, Saitama Univ.*, 39(1), pp.1–12.

New Zealand Geotechnical Society, (2005). Field Description of Soil and Rock. *Guideline for the field classification and description of soil and rock for engineering purpose,*, (December).

Ngerebara, O.D. & Youdeowei, P., (2014). Correlation of Mechanical Properties of Some Rocks in South-Eastern Nigeria. *International Journal of Scientific and Research Publications*, 4(2), pp.2–7.

Nickmann, M., Spaun, G. & Thuro, K., (2006). Engineering Geological Classification of Weak Rocks. *The Geological Society of London*, (492), pp.1–9.

Noormets, R., Crook, K.A.W. & Felton, E.A., (2004). Sedimentology of Rocky Shorelines: 3. Hydrodynamics of Megaclast Emplacement and Transport on a Shore Platform, Oahu, Hawaii. *Sedimentary Geology*, 172(1-2), pp.41–65.

Northmore, K.J., Culshaw, M.G., Hobbs, P.R.N., Hallam, J.R., & Entwisle, D.C., (1992). Engineering Geology of Tropical Red Clay Soils. *ODA/BGS Programme of Research and Development in Developing Countries*, pp.1–88.

Nott, J., (2000). Records of Prehistoric Tsunamis from Boulder Deposits Evidence from Australia. *The International Journal of The Tsunami Society*, 18, pp.3–15.

Nott, J., (2003). Waves, Coastal Boulder Deposits and the Importance of the Pre-Transport Setting. *Earth and Planetary Science Letters*, 210(1-2), pp.269–276.

Nott, J. & Bryant, E., (2003). Extreme Marine Inundations (Tsunamis?) of Coastal Western Australia. *The Journal of Geology*, 111(6), pp.691–706.

Oliva, P., Viers, J. & Dupre, B., (2003). Chemical Weathering in Granitic Environments. *Chemical Geology*, 202(3-4), pp.225–256.

Ollier, C.D., (1971). Causes of Spheroidal Weathering. *Earth-Science Reviews*, 7(3), pp.127–141.

Ollier, C.D., (1967). Spheroidal Weathering, Exfoliation and Constant Volume Alteration. *Zeitschrift für Geomorphologie*, 11(1), pp.103–108.

Ollier, C.D., (1983). Weathering or Hydrothermal Alteration. *Catena*, 10(1967), pp.57–59.

Orso, J., (2014). Rock Size Distribution at Boulder Field in Alexandria , Pennsylvania. *The Juniata Journal of Geology*, 7, pp.1–5.

Ozturk, C.A. & Nasuf, E., (2013). Strength Classification of Rock Material Based on Textural Properties. *Tunnelling and Underground Space Technology*, 37, pp.45–54.

Palmström, A., (2000). Block Size and Block Size Distribution. *GeoEng2000 conference, Melbourne*, (November), pp.18–24.

Palmström, A., (2001). Chapter 2: In-Situ Characterization of Rocks. *Balkema Publisher (Editor: Sharma, V.M. & Saxena, K.R)*, pp.49–97.

Palmström, A., (2005). Measurements of and Correlations between Block Size and Rock Quality Designation (RQD). *Tunnelling and Underground Space Technology*, 20(4), pp.362–377.

Panthi, K.K., (2006). Analysis of Engineering Geological Uncertainties Related to Tunnelling In Himalayan Rock Mass Conditions. *PhD Thesis, Norwegian University of Science and Technology*.

Paris, R., Fournier, J., Poizot, E., Etienne, S., Morin, J., Lavigne, F., & Wassmer, P., (2010). Boulder and Fine Sediment Transport and Deposition by the 2004 Tsunami in Lhok Nga (Western Banda Aceh, Sumatra, Indonesia): A Coupled Offshore-Onshore Model. *Marine Geology*, 268(1-4), pp.43–54.

Paris, R., Wassmer, P., Sartohadi, J., Lavigne, F., Barthomeuf, B., Desgages, E., Grancher, D., Baumert, P., Vautier, F., Brunstein, D., & Gomez, C., (2009). Tsunamis as Geomorphic Crises: Lessons from the December 26, 2004 Tsunami in Lhok Nga, West Banda Aceh (Sumatra, Indonesia). *Geomorphology*, 104(1-2), pp.59–72.

Patino, L.C., Velbel, M.A., Price, J.R., & Wade, J.A., (2003). Trace Element

Mobility during Spheroidal Weathering of Basalts and Andesites in Hawaii and Guatemala. *Chemical Geology*, 202(3-4), pp.343–364.

Pettifer, G.S. & Fookes, P.G., (1994). A Revision of the Graphical Method for Assessing the Excavatability of Rock. *Quarterly Journal of Engineering Geology and Hydrogeology*, 27(2), pp.145–164.

Poot, S., Boone, S.J., Westland, J., & Pennington, B., (2000). Predicted Boulder Frequency Compared to Field Observation During Construction of Toronto's Sheppard Subway. In *Proceedings 16th Annual Conference of Tunneling Association of Canada–Montreal*. pp. 47–54.

Priest, S.D., (2004). Determination of Discontinuity Size Distributions from Scanline Data. *Experiments in Fluids*, 37(5), pp.347–368.

Priest, S.D., (1993). Discontinuity Analysis for Rock Engineering. *Springer Netherlands*.

Priest, S.D. & Hudson, J.A., (1976). Discontinuity Spacings in Rock. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, 13(5), pp.135–148.

Pye, K., (1986). Moneralogical and Textural Controls on the Weathering of Granitoid Rock. *Catena*, 13, pp.47–57.

Que, M. & Allen, A.R., (1996). Sericitization of Plagioclase in the Rosses Granite Complex, Co. Donegal, Ireland. *Mineralogical Magazine*, 60(December), pp.927–936.

Rahardjo, H., Aung, K.K., Leong, E.C., & Rezaur, R.B., (2004). Characteristics of Residual Soils in Singapore As Formed by Weathering. *Engineering Geology*, 73(1-2), pp.157–169.

Rahardjo, H., Rezaur, R.B. & Leong, E.C., (2009). Mechanism of Rainfall-Induced Slope Failures in Tropical Regions. In *The 1st Italian Workshop on Landslides. Napoli, Italy*. pp. 8–10.

Raj, J.K., (1985). Characterisation of the Weathering Profile Developed Over A Porphyritic Biotite Granite in Peninsular Malaysia. *Bulletin of the International Association of Engineering Geology*, 32, pp.121–129.

Raj, J.K., (1994). Characterisation of the Weathering Profile Developed Over An Amphibole Schist Bedrock in Peninsular Malaysia. *Bulletin of the Geological Society of Malaysia*, 35(JuLy), pp.135–144.

Rajah, S.S., Manikam, K., Ismail, N.M.Y., & Chung Sooi, K., (1982). Mineral Resources Map of Johor, Penisular Malaysia. *Director-General of Geological Survey*.

Røyne, A., Jamtveit, B., Mathiesen, J., & Malthe-Soressen, A., (2008). Controls on Rock Weathering Rates by Reaction-Induced Hierarchical Fracturing. *Earth and Planetary Science Letters*, 275(3-4), pp.364–369.

Ruxton, B.P. & Berry, L., (1957). Weathering of Granite and Associated Erosional Features in Hong Kong. *Bulletin of the Geological Society of America*, 68(10), pp.1263–1292.

Sadisun, I.A., Shimada, H., Ichinose, M., & Matsui, K., (2005). Study on the

Physical Disintegration Characteristics of Subang Claystone Subjected to a Modified Slaking Index Test. *Geotechnical and Geological Engineering*, 23(3), pp.199–218.

Sajid, M., Arif, M. & Muhammad, N., (2009). Petrographic Characteristics and Mechanical Properties of Rocks from Khagram-Razagram Area, Lower Dir, NWFP, Pakistan. *Journal of Himalayan Earth Sciences*, 42, pp.25–36.

Salah, H., Omar, M. & Shanableh, A., (2014). Estimating Unconfined Compressive Strength of Sedimentary Rocks in United Arab Emirates from Point Load Strength Index. *Journal of Applied Mathematics and Physics*, 02(06), pp.296–303.

Salih, A.G., (2012). Review on Granitic Residual Soils' Geotechnical Properties. *Ejge*, (2012), pp.2645–2658.

Saliu, M.A. & Lawal, A.I., (2014). Investigations of Weathering Effects on Engineering Properties of Supare Granite Gneiss. *Journal of Mining World Express*, 3, p.53.

Santi, P.M., (2006). Improving Jar Slake and Durability Test for Shales. *Environmental and Engineering Geoscience*, 12(1), pp.1–11.

Santi, P.M., (1998a). Improving Jar Slake and Durability Test for Shales. *Environmental and Engineering Geoscience*.

Santi, P.M., (1998b). Improving Jar Slake, Slake Index and Durability Tests for Shales. *Environmental and Engineering Geoscience*, IV(3), pp.385–396.

Santi, P.M. & Higgins, J.D., (1998). Methods for Predicting Shale Durability in the Field. *Geotechnical Testing Journal, Coden: GTJODJ*, 21(3), pp.195–202.

Sarracino, R. & Prasad, G., (1989). Investigation of Spheroidal Weathering and Twinning. *GeoJournal*, 19(1), pp.77–83.

Sarracino, R.S., Prasad, G. & Hoohlo, M., (1987). A Mathematical Model of Spheroidal Weathering. *Mathematical Geology*, 19(4), pp.269–289.

Sausse, J., Jacquot, E., Frizt, B., Leroy, J., & Lespinasse, M., (2001). Evolution of Crack Permeability During Fluid-Rock Interaction. Example of the Brézouard Granite (Vosges, France). *Tectonophysics*, 336(1-4), pp.199–214.

Scholz, M., (1999). Über die Verwitterung im Königshainer Granitmassiv und ihre Auswirkungen auf den Vortrieb beim Bau der Tunnelanlage Königshainer Berge. *Petrographische, fels- und bodenmechanische Untersuchungen. Diploma Thesis, Technical University of Munich*.

Schormair, N.I.K., Thuro, K. & Plinninger, R., (2006). The Influence of Anisotropy on Hard Rock Drilling and Cutting. *The Geological Society of London*, (491), pp.1–11.

Schulz, M.S. & White, A.F., (1999). Chemical Weathering in a Tropical Watershed, Luquillo Mountains, Puerto Rico III: Quartz Dissolution Rates. *Geochimica et Cosmochimica Acta*, 63(3-4), pp.337–350.

Schunnesson, H., (1996). RQD Predictions Based on Drill Performance Parameters. *Tunnelling and Underground Space Technology*, 11(3), pp.345–351.

Şen, Z. & Eissa, E.A., (1991). Volumetric Rock Quality Designation. *Journal of Geotechnical Engineering*, 117(9), pp.1331–1346.

Shaw, R., (1997). Variations in Sub-Tropical Deep Weathering Profiles Over the Kowloon Granite, Hong Kong. *Journal of the Geological Society*, 154(6), pp.1077–1085.

Singh, T.N., Kainthola, A. & Venkatesh, A., (2012). Correlation between Point Load Index and Uniaxial Compressive Strength for Different Rock Types. *Rock Mechanics and Rock Engineering*, 45(2), pp.259–264.

Singhal, B.B.S. & Gupta, R.P., (1999). Applied Hydrogeology of Fractured Rocks. *In Applied Hydrogeology of Fractured Rocks .Springer Netherlands.*

Singhal, B.B.S. & Gupta, R.P., (2010). Fractures and Discontinuities. In *In Applied Hydrogeology of Fractured Rocks .Springer Netherlands.*

Smith, B.J., (2009). Geomorphology of Desert Environments, Chapter 4 - Weathering Processes and Forms, *Geomorphology of Desert Environment,* pp. 69-100.

Sørensen, H., Bailey, J.C., Kogarko, L.N., Rose-Hansen, J., & Karup-Moller, S. (2003). Spheroidal Structures in Arfvedsonite Lujavrite, Ilímaussaq Alkaline Complex, South Greenland—An Example of Macro-Scale Liquid Immiscibility. *Lithos*, 70(1-2), pp.1–20.

Sousa, L.M.O. & Gonçalves, B.M.M., (2012). Differences in the Quality of Polishing Between Sound and Weathered Granites. *Environmental Earth Sciences*, 69(4), pp.1347–1359.

Stanley, J.D. & Victoria, L.S., (2006). Inconsistent Grain Roundness and Sphericity Trends and the Valley Wall Influx Factor: Between Alpine Source and Lake Shore, SE France. *Journal of Coastal Research*, 22(3), pp.547–560.

Stavropoulou, M., (2014). Discontinuity Frequency and Block Volume Distribution in Rock Masses. *International Journal of Rock Mechanics and Mining Sciences*, 65, pp.62–74.

Stoops, G. & Schaefer, C.E.G.R., (2010). Pedoplasmation: Formation of Soil Material. *In Stoops, G., Marce- lino, V. & Mees, F. (eds.), Interpretation of Micromorphological Features of Soils and Regoliths, Elsevier, Amsterdam,*, pp.69–79.

Strickland, T. & Korleski, C., (2007). Chapter 6: Drilling and Subsurface Sampling. In *Technical Guidance Manual for Ground Water Investigation, State of Ohio, Environmental Protection Agency, Division of Drinking and Ground Waters*. pp. 1–35.

Stückrath, T., Völker, G. & Meng, J., (2006). Classification of Shape and Underwater Motion Properties of Rock. *Third Chinese-German Joint Symposium on Coastal and Ocean Engineering, National Cheng Kung University, Tainan*.

Switzer, A.D. & Burston, J.M., (2010). Competing Mechanisms for Boulder Deposition on the Southeast Australian Coast. *Geomorphology*, 114(1-2), pp.42–54.

Tan, D.N.K., (1985). Geological Map of Peninsular Malaysia. *General Director of Minerals and Geosciences Department of Malaysia, Ministry of natural resources and the environment of Malaysia*, 8.

Tang, W. & Quek, S.T., (1986). Statistical Model of Boulder Size and Fraction. *Journal of Geotechnical Engineering*, 112(1), pp.79–90.

The Sunday Daily, 2013. Boulders Delay Car Park Project. *http://www.thesundaily.my/news/846005*, 2 October, p.28.

Thuro, K., Plinninger, R.J. & Spaun, G., (2002). Drilling, Blasting and Cutting–Is It Possible to Quantify Geological Parameters Relating to Excavatability? *In Engineering Geology for Developing Countries-Proceedings of 9th Congress of the International Association for Engineering Ge*, (September), pp.16–20.

Thuro, K. & Scholz, M., (2003). Deep Weathering and Alteration in Granites- A Product of Coupled Process. In *International Conference on Coupled T-H-M-C Processes in Geosystems: Fundamentals, Modeling, Experiments and Application (GeoProc 2003)*. pp. 13–15.

Tsidzi, K.E.N., (1991). Point Load - Uniaxial Compressive Strength Correlation. *International Congress on Rock Mechanics, 16–20 September*, (1979), pp.637–639.

Tsidzi, K.E.N., (1997). An Engineering Geological Approach to Road Cutting Slope Design in Ghana. *Geotechnical and Geological Engineering*, 15, pp.31–45.

Tugrul, A., (2004). The Effect of Weathering on Pore Geometry and Compressive Strength of Selected Rock Types From Turkey. *Engineering Geology*, 75(3-4), pp.215–227.

Tuğrul, A. & Gürpinar, O., (1997). A Proposed Weathering Classification For Basalts and Their Engineering Properties (Turkey). *Bulletin of the International Association of Engineering Geology - Bulletin de l'Association Internationale de Géologie de l'Ingénieur*, 55(1), pp.141–149.

Tugrul, A. & Zarif, I.H., (1999). Correlation of Mineralogical and Textural Characteristics With Engineering Properties of Selected Granitic Rocks From Turkey. *Engineering Geology*, 51(4), pp.303–317.

Turk, N. & Dearman, W.R., (1983). A Practical Classification of Rock for Engineering Purposes. *Engineering Geology*, 28, pp.161–167.

Turkington, A. V., Phillips, J.D. & Campbell, S.W., (2005). Weathering and Landscape Evolution. *Geomorphology*, 67, pp.1–6.

Turner, B.F., Stallard, R.F. & Brantley, S.L., (2003). Investigation of In Situ Weathering of Quartz Diorite Bedrock in the Rio Icacos Basin, Luquillo Experimental Forest, Puerto Rico. *Chemical Geology*, 202(3-4), pp.313–341.

Twidale, C.R., (1995). Bornhardts, Boulder and Inselbergs. *Caderno Lab. Xeoloxico de Laxe*, 20, pp.347–380.

Twidale, C.R., (1982). Chapter 4: Part II- Major Forms and Assembles, Boulders. In *Granite Landforms*. Amsterdam: Elsevier, pp. 89–123.

Twidale, C.R., (1986). Granite Landform Evolution : Factors and Implications. *Geologische Rundschau*, 75(3), pp.769–779.

Twidale, C.R., (1998). Granitic Bornhardts : Their Morphology , Characteristics and Origins. *Geological Society of Malaysia*, 42(December), pp.237–255.

Vahed, G., Husaini, O. & Bujang, K.H., (2009). A Study of the Weathering of the Seremban Granite. *EJGE, Electronic Journal of Geotechnical Engineering,*, 14.

Velde, B. & Meunier, A., (2008). *The Origin of Clay Minerals in Soils and Weathered Rocks*, Springer Berlin Heidelberg.

Veneziano, D. & Van Dyck, J., (2005). Statistics of Boulder Encounters during Shaft Excavation. *Rock Mechanics and Rock Engineering*, 39(4), pp.339–358.

Wadsworth, W.B. & Baird, A.K., (1989). Modal Analysis of Granitic Rocks by X-Ray Diffraction. *Canadian Minerologist*, 27, pp.323–341.

Wang, L.G., Yamashita, S., Sugimoto, F., Pan, C., & Tan, G., (2003). A Methodology for Predicting the In Situ Size and Shape Distribution of Rock Blocks. *Rock Mechanics and Rock Engineering*, 36(2), pp.121–142.

White, A.F., Blum, A.E., Schulz, M.S., Vivit, D.V., Stonestrome, D.A., Larsen, M., Murphy, S.F., & Eberl, D., (1998). Chemical Weathering in a Tropical Watershed, Luquillo Mountains, Puerto Rico: I. Long-Term Versus Short-Term Weathering Fluxes. *Geochimica et Cosmochimica Acta*, 62(2), pp.209–226.

White, A.F., Bullen, T.D., Schulz, M.S., Blum, A.E., Huntinhton, T.G., & Peter, N.E., (2001). Differential Rates of Feldspar Weathering in Granitic Regoliths. *Geochimica et Cosmochimica Acta*, 65(6), pp.847–869.

Wines, D.R. & Lilly, P.A., (2002). Measurement and Analysis of Rock Mass Discontinuity Spacing and Frequency in Part of the Fimiston Open Pit Operation in Kalgoorlie, Western Australia: A Case Study. *International Journal of Rock Mechanics and Mining Sciences*, 39(5), pp.589–602.

Yang, Z.Y. & Wu, T.J., (2006). An Index for Describing the Core-Stone Shape in Weathered Columnar Joints. *Geotechnical and Geological Engineering*, 24(5), pp.1349–1363.

Yarali, O. & Soyer, E., (2013). Assessment of Relationships Between Drilling Rate Index and Mechanical Properties of Rocks. *Tunnelling and Underground Space Technology*, 33, pp.46–53.

Zauyah, S., Schaefer, C.E.G.R. & Simas, F.N.B., (2011). Chapter 4: Saprolite, Interpretation of Micromorphological Features of Soils and Regoliths. In *Eurasian Soil Science*. Elsevier, pp. 824–828.

Zhao, J., Broms, B.B., Zhao, Y., & Choa, V., (1994). A Study of the Weathering of the Bukit Timah Granite Part B: Field and Laboratory Investigations. *Bulletin of the International Association of Engineering Geology*, 50, pp.105–111.

Zhao, J. & Lee, K.W., (1996). Construction and Utilization of Rock Caverns in Singapore: Part C: Planning and Location Selection. *Tunnelling and Underground Space Technology*, 11(1 SPEC. ISS.), pp.81–84.

Zuffa, G., (1985). Provenance of Arenites. In: NATO ASI Series. Series C: *Mathematical and Physical Sciences, Reidel, Dordrecht*, 148, pp.115–135.