

## CHARACTERISTICS OF BOULDERS FORMED IN TROPICAL WEATHERED GRANITE: A REVIEW

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### Article history

Received

18 January 2016

Received in revised form

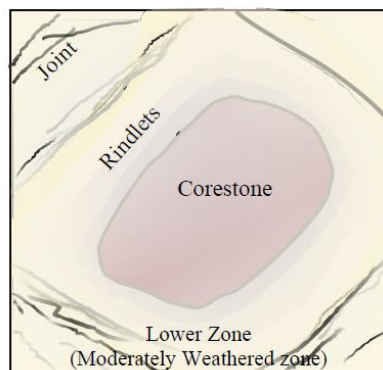
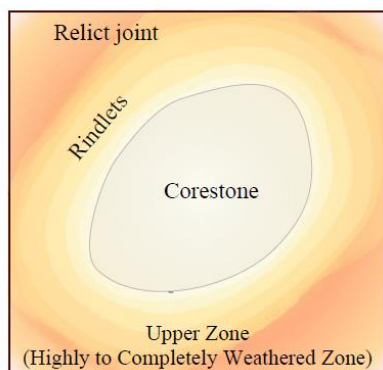
8 March 2016

Accepted

18 March 2016

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### Graphical abstract



### Abstract

Boulder is well known as one of the obstruction material and problematic to the underground excavations and constructions. Although the presence of boulder in weathered rock mass was revealed and reported by many researchers, but the occurrence and physical characteristics of boulders in weathering profile are still not clearly understood. This paper attempts to revise the issues and characteristics of boulder formed in weathered granite which include the formation, distribution, properties and location of boulders found in tropical weathering profile. As a weathering product, boulder is dominantly found in moderately to completely weathered zone of rock mass (Grade III to V). Boulder consists of corestone Grade I or II and surrounded by some concentric sheet of weathered rock Grade III to V or rindlets which formed due the reaction of spheroidal weathering. The rindlets with thickness ranges 0.2 mm to 2.0 m is the zone of decomposition and dissolution of biotite and feldspar that gradually transforming to saprolite. This information is useful to geotechnical engineers and researchers for engineering purposes and weathering zone classification especially in underground excavation and structure design.

Keywords: Boulder; formation; physical characteristics; weathered rock mass

### Abstrak

Batu tongkol terkenal sebagai salah satu bahan halangan dan bermasalah kepada penggalian bawah tanah dan pembinaan. Walaupun kehadiran batu tongkol di dalam jasad batuan terluhawa telah didedahkan dan dilaporkan oleh ramai penyelidik, tetapi kejadian dan ciri-ciri fizikal batu tongkol dalam profil batuan terluhawa masih kurang difahami. Kajian ini cuba untuk menyemak semula isu-isu dan ciri-ciri batuan batu tongkol dan lokasi batuan yang terdapat dalam profil luluhawa tropika. Sebagai satu produk luluhawa, batu tongkol secara dominannya ditemui di zon sederhana hingga ke zon sangat terluhawa (Gred III hingga V). Batu tongkol terdiri daripada batuan teras Gred I atau II dan dikelilingi oleh beberapa kepingan batuan luluhawa sepusat Gred III hingga V atau 'rindlets' yang terbentuk akibat reaksi luluhawa berbentuk sfera. 'Rindlets' dengan ketebalan 0.2 mm hingga 2.0 m adalah zon penguraian dan pembubaran biotit dan feldspar yang berubah perlahan-lahan menjadi 'saprolite'. Maklumat ini amat berguna kepada jurutera geoteknik dan penyelidik untuk tujuan kejuruteraan dan klasifikasi zon luluhawa terutama dalam penggalian bawah tanah serta reka bentuk struktur.

Kata kunci: Batu tongkol; pembentukan; ciri-ciri fizikal; jisim batuan terluhawa

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## 1.0 INTRODUCTION

The knowledge on the weathering profile of rock mass has been studied by many previous researchers to understand the characteristics and classification of weathered rock mass. The weathering occurs due to the water infiltration deep into bedrock zone via open spaces such as soil stratum, relict joints, rock fractures and joints [1-5]. This process is gradually decomposing and disintegrating the massive rock and forming thick stratum of soil and fractured rocks [6-9]. This sequence reaction is commonly known as deep weathering process [5,10]. The deep weathering profile is a common phenomenon in wet tropical region [11,12]. The continuous reaction of the deep weathering under soil surface on the fractured rock and rock blocks finally creates some concentric fractures on the rock block and then progressively altering the rock to become spherical or rounded shape known as boulder [5,13,14].

In underground exploration works, the presence of boulder is often disturbing the tunnelling, excavation and borehole works [15-20]. This problems are commonly leads to the projects delayed and increased the unexpected cost [15, 18, 20]. Not only problematic to the underground excavation, but the stability or failure of slopes are also commonly related to the heterogeneous zone that is dominated by the presence of boulder [11, 21, 22]. Furthermore, the presence of boulder beneath ground level is difficult to be predicted especially based on Rock Quality Designation (RQD) method from borehole data [15, 23-25]. Although it can be predicted by using geophysical technique, but the cost of work is very expensive, take long time and require combination of more than two methods to obtain reliable results [15, 26].

Therefore, this review will develop a clear fundamental understanding on the natures of the boulder in weathered rock mass in wet tropical region. This information is believed useful for engineering purposes especially in underground and structure design.

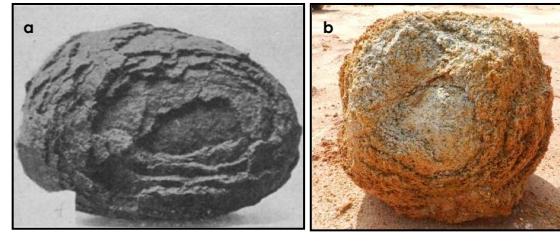
## 2.0 DEFINITION OF BOULDER

There are various definitions of boulder in different field studies. In geological and geomorphological study, the "boulder" or boulder was identified as a corestone that possess various sizes and shapes, and surrounded by concentric shell or sheets or layers of rock due to the spheroidal weathering reaction such as spalling, chemical exfoliation, disintegration and fracturing [14, 27-30] (Figure 1).

In the study of chemical geology, the boulder is refer to the corestone that is formed by the reaction of spheroidal weathering on fractured bedrock, and surrounded by some concentric of weathered rock known as rindlet [2, 31-34].

From engineer's point of view, the boulder is defined as an obstruction material for underground

excavations which possess various shapes of spherical and size larger than 0.3 m and located at the unpredictable locations in the weathering profile [15-20].



**Figure 1** An exfoliated "boulder" or boulder; a) Bentonite boulder found at California Coast Range, near San Luis Obispo [27], b) Granite boulder found at Batu Pahat, West of Johor, Southwest of Peninsular Malaysia

According to the definitions that were made by the previous researchers, it can be concluded that the boulder rock is one of the weathered product consist of corestone that surrounded by some concentric sheets of weathered. It is formed by the reaction of spheroidal weathering and its presence in weathering profile can causing problems to the civil engineering works.

## 3.0 BOULDER'S FORMATION

In humid tropics, deep weathering is one of the triggering factors to the creation of the boulder through the joints in the bedrock surface. The deep weathering can occur as deep as thickness of up to 100 m from ground level and up to 10 m to 30 m deep for granitic weathered rock [4,12, 35-37].

The presences of water become triggering factor to the weathering reaction in the rock mass [1, 5, 38]. Additionally, the presence of discontinuities in the rock mass provide avenues for water to attack the rock and proceed the weathering process in the rock mass to form rock blocks [29]. This process obviously indicates that the presence of the mutual intersection of discontinuity with different spacing and orientation characteristics in the rock mass become one of the primary factor to the formation of individual rock block [25, 39-43]. This rock block commonly interlock and possesses angular edges and corners on the outer surface [29, 44-47].

The continuous spheroidal weathering at steady-state denudation transformed the angular rock block to become spherical or rounded shape [14, 28, 30, 48]. In addition, the angular surfaces of rock block exposes a greater surface area to weather faster than the flat surfaces to become rounded or spherical boulder [48-50]. The spheroidal weathering reaction at the surrounding of the rock block are inclusive the chemical decomposition and physical disintegration such as exfoliation, flaking, spalling and fracturing [13,14, 28, 30, 48, 49, 52]. The chemical

change and physical disintegration in the spheroidal weathering are the most vital processes types to the formation of rounded boulder [28].

The spheroidal weathering reaction at the surrounding involve both of chemical changes and physical disintegration [48]. The process stages can be summarised as shown in Figure 2, Table 1 and Table 2 [48]. Through the reaction of spheroidal weathering, the process is begin from a network of fractures and fissures surrounding the corestone surface. The presence of water that infiltrate along the fractures and fissures was decomposing the main minerals such as plagioclase feldspar and biotite between corestone and the outer layer of the boulder[31, 48, 53].

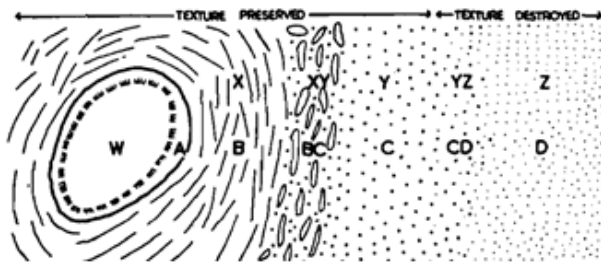


Figure 2 Spheroidal weathering surrounding a corestone [48]

Table 1 Stages of chemico-mineralogy change surrounding the corestone (Modified from [48])

Chemico-mineralogical change	Effect	Symbol
Reddening and argillization Complete	Formation of reddish-brown silt and clay	D
Partial 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 Stages of physical disintegration surrounding the corestone (Modified from [48])

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

Simultaneously, the water penetrates into the polygonal form surrounding the corestone and disintegrating the rock structure at the surrounding of the corestone to become soil [48]. This process continuously occurs at the outer part of the corestone and gradually producing some concentric

ellipsoidal and spherical shells of weathered rock with thickness 0.02 to 2.0 m [14, 30]. The result from spheroidal weathering on a rock producing some spheroids types: (1) unweathered cores, (2) partially decomposed and leached shells, and (3) reprecipitated Fe-rich zones [14].

The formation of boulder due to the spheroidal weathering reaction comprise several repeated processes. It 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. 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 presences of bleached light-brown to yellow-white zone at the outer part of the corestone denote that the solid rock was decomposing to become soil (Grade II to III). The continuous process of spheroidal weathering was shaping the corestone to become spherical and reducing the corestone volume[14]; and increase the disintegrated zone at the surrounding of the corestone which comprises of decomposes clay and silt[55]. The decomposed material at the surrounding of the corestone is the most dangerous material because of the low friction angle and tendency to shear along existing discontinuities [54, 55]. The end product of the spheroidal weathering is a mixture of sandy and/or clayey and silty material.

According to the formation of the boulder in the weathered rock mass, it can be concluded that at the early stage, the boulder formed as an individual block due to the presence of discontinuity intersection with different spacing and direction in rock mass. Due to the disintegration and decomposition process during spheroidal weathering reaction, the rock block was altered physically and chemically to become a boulder with rounded or spherical shapes.

## 4.0 PHYSICAL CHARACTERISTICS OF BOULDER

There are three main physical characteristics of boulder that will review in this sub-chapter: size, shape, and concentric sheets of weathered material at the surrounding of the boulder known as rindlets. All these parameters are also known as boulder morphology[56].

### 4.1 Size

There are various sizes of boulders that can be found on the ground or beneath the ground level. The various sizes of the boulder are due to the pattern of the discontinuities that present in the rock mass such as joint spacing, joint persistence, joint orientation, faults, bedding [25, 42, 57-59]. However, it is difficult

to be measured especially for those embedded in the ground surface[26].

The boulder size can be small as 25 cm or up to 23 m huge as found in the Devil's Marbles in the central part of the Northern Territory[29]. If the size of the boulder is large enough, it is classified as bornhardts or known as bald domical hills with unknown size[60–62]. In tropically weathered rock, the boulder size can be found more than 0.3 m [48, 63–65].

According to the classification of grain size criteria by New Zealand Geotechnical Society, the particle size larger than 200 mm or 0.2 m was classified as boulder[66]. However in the engineering practice, the size of boulder commonly classified more than 300 mm or 0.3 m [15,18,19]. This measurement commonly used for assessment of boulder size from borehole sample as carried out by some previous researchers [20,17].

## 4.2 Shape

In weathered rock masses, boulders can be found formed in variety of shapes and sizes. The shapes of the boulders are related to the discontinuities properties that present in the rock mass [67]. Boulder can 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 being rounded [29, 48, 63, 64, 68].

In engineering analysis, the boulder shape is commonly assumed as block shape due to the characteristics of discontinuities [39–42, 57, 58, 69] and some of them assume boulder as a spherical shape [20, 17] in order to make the size prediction easier. Due to the importance of boulder shape in engineering application, there are some researchers have classify the shape of the boulder by using several approaches such as chart [70], diagram [71], index properties [72, 73], and computer simulation [40, 74, 75].

## 4.3 Rindlets

Boulders are commonly found surrounded by several concentric sheets or layers of weathered rock[28]. Some of the reseachers characterized the concentric sheets of weathered rock as system of onion skin referring to the presence of concentric layers of weathered rock as thick as 3 to 50 cm thick surrounding the boulder with yellow-brownish colour [32–34, 64, 76, 77].

There are various names for the decomposed concentric layers of the boulder. Most of researchers called it as concentric shells [14, 27, 28, 30, 48, 78, 79] Some of researchers called it as onion-skin layers [29 33] or spherical shell [49, 47]. However a few last years, most of the researchers called the decomposed concentric sheets of weathered rock surrounding the corestone as rindlets [2, 31, 32, 77].

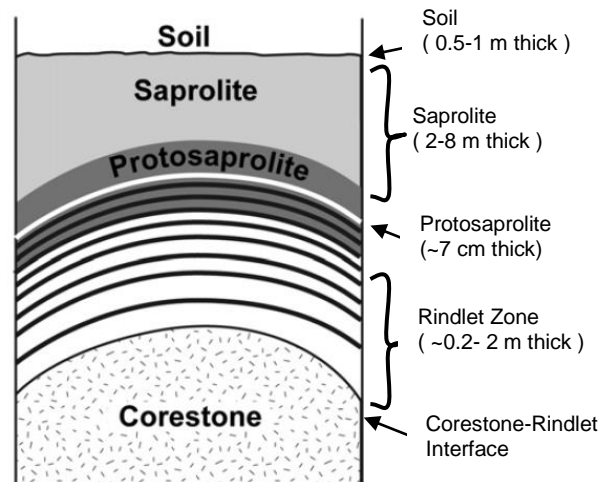
The terms rindlets was used by Turner *et al.* [33] to describe the partially of weathered zone dominated

by weathering of plagioclase to kaolinite in Rio Icacos saprolite. Fletcher *et al.* [32] used the term rindlets to refer the alteration on the concentric fractures layers on the corestone outer surface that found in Rio Icacos. While Buss *et al.*[31]used the term rindlets to describe the concentric layers with thickness 0.2 to 2 m thick that formed around the corestone that found in quartz diorite bedrock. Similar to Brantley *et al.*[2], the term rindlets adopted from Buss *et al.* [31] is to define the onion skin-like shell that formed around the corestone during spheroidal weathering as found at hill shale and at Rio Blanco quartz diorite. The term rindlets as suggested by Turner *et al.* [33], Fletcher *et al.* [32] and Buss *et al.*[31] was used by Chabaux *et al.* [77] to refer the concentric fracture shell with thickness ~ 40cm that found surrounding the corestone of quartz diorite that found in tropical rain forest, Rio Icacos.

Rindlets commonly found consists of three to six concentric sheet of weathered rock surrounding the corestone [2, 31–33, 64, 77]. The first layers located near the boulder is corestone-rindlets interface, then followed by rindlet zone (~0.2-2 m thick which ~2.5 cm each), rindlet-saprolite zone, protosaprolite layer and saprolite zone (2-8 m thick) and the upper layer near the ground surface is soil (0.5 to 1 m thick) (Figure 3) [2, 31, 32, 77].

## 5.0 PROFILE FEATURES AND DISTRIBUTION OF BOULDER IN WEATHERING PROFILE

As one of the weathering products, boulder can be found embedded in sedimentary deposits [20], glacial tills deposits [15, 80], and at the upper zone near the ground surface which commonly encountered during tunneling, borehole drilling or underground excavation [15, 20, 18, 48]. The presence of boulder in weathered rock mass can be seen from the excavated cliff, cut slope, and soil excavation for underground construction[9,12,48,81].



**Figure 3** Corestone with five layers of rindlets, corestone-rindlets interface, rindlet zone, rindlet-saprolite interface,

protosaprolite and saprolite layer (Modified from [31] and [33])

The distributions of boulder in weathered rock mass were reported by several previous researchers in their weathering mass classification. The earlier study has revealed the occurrence of boulder in weathered rock mass are dominantly embedded in the decomposed zone at the lower part (zone III), but the presence of the boulder at the upper zone (zone II) near the ground surface is occasionally found [48]. In the lower part (zone III), boulder were formed in the disintegrated material such as gruss and subordinate residual debris which mostly retains some visible orthoclase and biotite. At this zone, boulders were found in rectangular or locked forms. At the upper part (zone II), there are two zones identified: zone IIa and IIb. Zone IIa was identified based on the presence of boulder which the boulders are rare to be found or almost absent which their presence less than 10 %. For zone IIb, the presences of boulder are between 10 to 50 %. In zone II, boulders were found in form of rounded and floating freely in geologic medium.

There are two types of boulder which embedded separately in weathering zone: 1) partly weathered core boulder, 2) unweathered core boulder (Figure 11) [82]. The unweathered to partly weathered core boulders were dominantly found in morphological horizon IID which located 33.12 m to 49.20 m from ground surface. In the morphological horizon IIC at depth 24.84 m to 33.12 m from ground surface, the unweathered boulders were found unweathered at the core but show some weathered material with concentric outer layer. The partly weathered boulders that present in the IIC horizon show similar features as the boulders that found in morphological horizon IIA. In morphological horizon IIB, the partly weathered core boulders that found in this zone similar stage of weathering as those found in morphological horizon IIA. The partly weathered core boulders that found in morphological horizon IIA show that the boulders are moderately weathered with concentric outer layers of highly to completely of weathered bedrock material.

The occurrence of boulder in weathered rock mass can be an indicator to the weathering profile classification. Based on the weathering classification by Moye [83], previous study reported that there are two types of weathering profile in the granite namely type-A and type-B [12]. Both of these types are quite similar but the significant difference is the occurrence of boulders in Grade III, IV and V. The formation of boulders in type-A is commonly encountered in highly weathered (Grade IV) and completely weathered (Grade V) at depth of 25 m to 40 m, but not available in Grade III due to high discontinuities densities and higher weathering grade. However in

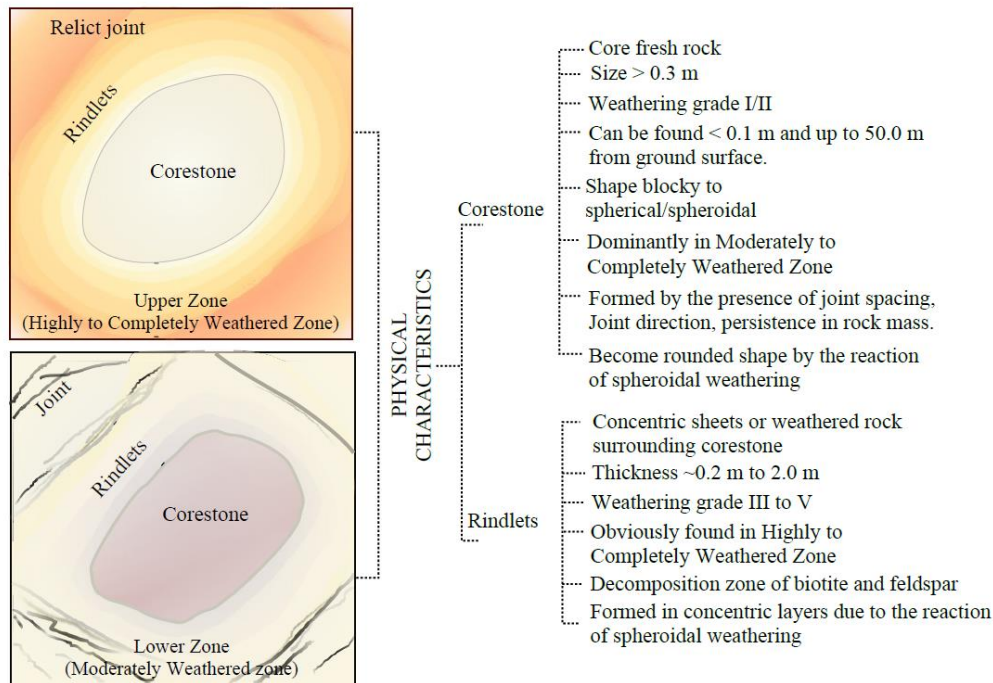
type-B, boulders can be found in weathered granitic area as deep as 10 m to 50 m under soil stratum in moderately weathered, (Grade III) to completely weathered, (Grade V) but the most occurrence of boulders are located in Grade III [12].

The depth and distribution of boulder in weathering profile sometimes are quite difficult to be predicted. Previous researchers described the profiling of weathered basalts in order to classify and identify the distribution of boulders and the weathered material [81]. The large boulder with weathering Grade II can be found at 1 to 30 m from the ground surface. Such boulder mostly formed in faintly to moderately weathered rock in slightly weathered zone (Grade II). For boulder with classified as weathering Grade III, it can be found at 0.1 to 20 m from ground surface. The boulders are commonly found embedded in highly to completely weathered rock in moderately weathered zone (Grade III) [81].

There are some researcher described the distribution of boulder in the weathering profile over massive crystalline rock in a tropical environment [84]. The description is adapted and adopted from previous weathering classification scheme [8, 85] and adapted to local condition which is similar to weathering profile in Ghana. The weathering profile is divided into three different horizons profile namely: (1) upper horizon of residual soil (predominantly lateritic); (2) Middle horizon of moderately to completely weathered rock (saprolite); and (3) Lower horizon of fresh or slightly weathered rock (bedrock). Based on the schematic tropical weathering profile, boulders are commonly found in saprolite zone (moderately to highly weathered) especially in weathering Grade III (moderately weathered rock) which has 10 % to 35 % degree of weathering. There are no boulders found in predominantly lateritic or residual soil (weathering Grade VI) which consists of 100% weathered rock.

Recent study has classified the mass weathering profile in tropical weathered granite into four dominant types [9]. The classification was take account the characteristics of joints, topography condition and the boulder appearance in the weathered rock mass. According to the study, the boulders with diameter up to 2 m huge present in the highly weathered zone with zone thickness 1.5 m to 6,5 m from the ground surface. The mass weathering classification indicated that the presence of boulder in the mass weathering profile became one of the primary features to the classification.

The physical characteristics and distribution of boulder in weathered rock mass can be summarized as shown in Figure 6. The summary including the physical characteristics of corestone and rindlets in moderately to completely weathered zone.



**Figure 4** Summarization of the occurrence and characteristics boulder in tropical weathered rock mass

## 6.0 CONCLUSION

The occurrence and characteristics of boulder in weathered rock mass was reviewed in terms of definitions, the formation of the boulder in weathered rock mass, the physical characteristics of the boulder including the size, shape and rindlets and the profile features and distribution in weathering profile.

On the basis of the review that have been made, boulder in weathered rock mass can be summarized as a fresh core rock with blocky or spherically shape and possess engineering size more than 0.3 m, experiencing decomposition and disintegration at the outer part of the core via the reaction of spheroidal weathering to form concentric sheet of weathered rock or rindlets with thickness ~0.2 m and up to ~2 m thick. The boulders are dominantly found at the upper zone near the ground surface especially in moderately to completely weathered zone (Grade III to V). Blocky boulder or rock block commonly located at the lower zone (moderately weathered zone). There are rare or no boulder found in the residual soil (weathering zone VI).

This review indicate that the boulder comprise of two main part or zones: (1) corestone, which normally located at the center of the boulder and classified as fresh rock with weathering Grade I. At this zone, biotite is slightly decomposed. (2) Rindlets, the concentric layer of weathered rock which commonly known as onion-skin or spheroidal shell. Also known as gruss where it consist of porous material and the zone where the feldspars and biotite are partially decomposed. The rindlets zone comprise of several

thin layers with thickness of each layer ~2.5 cm and the total thickness of the rindlets zone can be reach as thick as ~ 2.0 m (Figure 16). Saprolites which is commonly known as residual debris where the feldspars and biotite are completely decomposed. It is partly of material in moderately to completely weathered zone.

As a conclusion, although the boulder could be recognised as one of the problematic material to the civil engineering works, but it can be defined as a unique weathered product that possess unique physical characteristics. The characteristics of size, shape, material surrounding the boulder and the distribution of boulder in weathered rock mass probably can be used as one of the parameters in civil engineering design.

## Acknowledgement

Authors are grateful to the Ministry of Higher Education (MOHE) for the Fundamental Research Grant Scheme, Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia and Department of Infrastructure and Geomatics, Universiti Tun Hussein Onn Malaysia.

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