DEVELOPMENT OF A NEW SAND PARTICLE CLUSTERING METHOD WITH RESPECT TO ITS STATIC AND DYNAMIC MORPHOLOGICAL AND STRUCTURAL CHARACTERISTICS

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ABSTRACT

Characteristics of particle morphology (size and shape) are key factors that govern the interparticle behaviour of granular soils. However, the current status of its fundamental research has not reach significant development for its inclusion in geotechnical modelling of granular materials. Particle morphology parameters were prioritised only in classifying the particle size and not particle shapes in current geotechnical standards. Therefore, this research is focused in establishing proper classification methods of particle shapes and comparing it with the classification of particle sizes on its importance of its impact on the interparticle behaviour of the soil. This was done using five strategically chosen sand samples of different morphologies tested under static and dynamic loading. A number of sand particles from each sample were first quantified to obtain their shapes using a digital microscope according to the shape parameters of sphericity (S), roundness (R) and regularity (ρ). To find a single representative establish value of the shape parameters, a new statistical approach using cluster analysis with the addition of probability distributions were introduced. From the particle size and the modelled values of the shape parameters, correlations were obtained from the results of the static and dynamic loading test. Direct shear test showed relationships that incorporates the critical state stress, the normal stress and the particle size and shape parameters of the samples which is significant in predicting the critical shear strength behaviour of the soil. Improvement of the classical modified Mohr-Coulomb shear strength expression was also obtained to take into account a factored dilatancy angle value that is dependent to the properties of particle morphology. Dynamic loading analysis showed that particle level interaction played an important role in affecting liquefaction potential characteristics, the resilient modulus, M_r, dynamic shear modulus, G, and damping ratio, D. These dynamic loading parameters were found to be intrinsically dependent on the effective size (D_{10}), S, R and ρ. The findings contributes in improving a novel fundamental understanding on the development of parametric correlations to provide good estimates of the static and dynamic strength behaviour of sands based on the new methods of particle morphology classification.

Keyword: Morphology, statistical modelling, shear strength, dilatancy, dynamic shear modulus, damping ratio.

ABSTRAK

Ciri-ciri morfologi zarah (saiz dan bentuk) adalah faktor utama yang mentadbir tingkah laku makro tanah berbutir. Walau bagaimanapun, kepentingan asasnya belum mencapai tahap pembangunan untuk pemodelan reka bentuk kelakuan bahan berbutir. Klasifikasi piawaian tanah hanya mempertimbangkan analisa saiz zarah tanah dan bukan bentuk zarah. Oleh itu, kajian ini bertumpu untuk mencari klasifikasi bentuk zarah yang betul dan membandingkan dengan klasifikasi size zarah dalam kepentinganya dalam tingkah laku anatar zarah. Kajian ini bertumpu meneroka interaksi tingkah laku zarah-zarah menggunakan lima sampel pasir yang dipilih secara strategik dengan mempunyai morfologi yang berbeza diuji dengan ciri-ciri ricih statik dan dinamik. Beberapa bentuk zarah pasir telah secara komprehensif diukur menggunakan imej yang diperolehi daripada mikroskop digital bedasarkan parameter bentuk *Sphericity* (S), *Roundness* (R) dan *Regularity* (ρ). Kaedah statistik baru seperti *cluster analysis* dan tabuaran keberangkalian telah diguna untuk menentukan bentuk zarah wakil sampel. Keputusan eksperimen dari ujian beban statik dan dinamik, dianalisis untuk mengkaji kesan morfologi zarah kepada kekuatan dan *dilatancy* ciri-ciri ricih. Daripada keputusan ujian ricih terus, hubungan kekuatan ricih kritikal (τ_{cr}) dengan saiz zarah dan bentuk parameter sampel pasir telah didapati untuk meramal kekuatan ricih kritikal kelakuan tanah. Kaedah Mohr-Coulomb untuk ungkapan kekuatan ricih yang mengambil kira *dilatancy* juga telah dibentangkan. Analisis pembebanan dinamik menunjukkan bahawa interaksi tahap zarah memainkan peranan penting kepada ciri *liqeufaction, resilient modulus,* M_r, *Dynamic shear modulus*, G, dan *damping ratio*, D. Parameter dinamik ini didapati bergantung kepada *effective size* (D_{10}), S, R dan ρ. Kajian ini menyumbang dalam meningkatkan pemahaman baru kepada pembangunan parameter berkorelasi yang melibatkan parameter utama untuk pengelasan tanah baru yang merangkumi morfologi zarah asas sabagai aplikasi kejuruteraan geoteknikal.

Kata Kunci: Morfologi, pemodelan statistik, kekuatan ricih, *dilatancy*, *dynamic shear modulus*, *damping ratio*.

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CHAPTER I

INTRODUCTION

1.1 Preamble

Soil mechanics/science is an academic discipline of prime civil engineering importance, particularly in foundation design and hazardous ground analysis. Soils differ from other engineering materials because of its morphological (size and shape) characteristics which require a distributed particulate mechanical approach.

This thesis explores the significance of these particle morphology characteristics by incorporating statistical modelling on particle shape analysis and how it can have an effect on the fundamental study of static and dynamic loading behaviour of granular soils. This can be reflected as granular soil materials such as that of sand consist of soil particles which has distinctively unique sedimentological characteristics. The uniqueness of these characteristics is due to the fact that sand particles feature a wide range of shape and size distributions, which solicit further research into the knowledge of the underlying geological principles and consequent influence on the geotechnical aspects of the soil. The principal geological feature of sands is that they are relatively young and are unconsolidated superficial deposits which have accumulated in the geological past (Archer, 1972). These geological deposits include marine beach deposits, lacustrine deposits, alluvial deposits, mountain slope solifluction wastes as well as those of the glacial deposits. The combination of the physical and mineralogical characteristics of the sand particles with the geological processes (weathering, erosion and deposition) of these deposits gives rise to the different shape and size (grading) distributions.

The interparticle reaction of sands (assumed cohesionless) relies heavily on its initial density, initial confining pressure and most importantly the interlocking structure of the particles. Eventually, these conditions will also contribute to the effect of the phenomenon of dilatancy, which is the ability of the soils to change in volume under shearing stresses. As a result, both the intergranular friction and dilatancy are likely to be affected by the morphological characteristics.

The fundamentals of laboratory soil testing are crucial in the understanding of the actual physical and mechanical behaviour of interparticulate medium. In the pre1990's, soil mechanics research was devoted to the determination on the behaviour of soil under static loading conditions and it is still currently being research intensively. However, the stress-strain relationship of a soil and its behaviour depends upon several factors and can differ in many ways when it is tested under dynamic loading conditions as compared to the case of static loading (Das,1993).

The behaviour of a soil under dynamic loading is very complex and governs the phenomenon called liquefaction which commonly occurs with sandy/silty soils. The repetitive loading on saturated granular soils causes the pore water pressure in the soil to increase and becomes greater than that of the stresses acting between the soils grains which keep them in contact with each other (Erten and Maher, 1994). This ultimately can cause the soil to lose its strength and lead to a potential structural failure within the soil-structure system. However, the author believes that the increases in pore water pressure might not be the sole criteria in liquefaction, but the size and shape of the granular soil particles will also influence the interparticle reactions.

The two prime parameters in dynamic testing of soil are the dynamic shear modulus and the damping ratio, which will vary with the morphology of the soil particles and the fabric (structural arrangement of the particles within the soil mass). Simony and Houlsby (2006) has shown that correlations exist between the gradations of sands with its shear strength and also their effect on dilatancy. However, less is known on the effects due to particle shapes. This thesis embarks the study on the characterisation of the morphological properties of sand samples through advanced statistical analysis and on the analysis of macroscale behaviour of the soil through various testing methods. This will provide a better understanding and a guideline to geotechnical engineers of the fundamental soil structure interaction when subjected to the application of static and dynamic stresses.

1.2 Problem statements as research drivers for the study

Sand is an important material used in a wide spectrum of industrial practices; for example it is used as principal raw materials (namely glass production), it's also used in agriculture and in land reclamation. The high demand and diminishing resources of sand deposits has even led to irresponsible acts of illegal mining. Some countries such as Sri Lanka, Philippines and even Malaysia are facing a scarcity of suitable sand for construction and now imposing fines and penalties for such irresponsible and indiscriminate acts (Ann, 2012). Therefore, it is important to properly characterise these sand materials to fully understand its behaviour so that it can be used to its optimum potential.

It has been well established that there are many correlations that involves particle size distribution parameters on the strength characteristics with silty sands under monotonic and cyclic loading (Yamamuro and Lade, 1998; Amini and Qi, 2000; Naeini, 2001; Naeini and Baziar, 2004; Sharafi and Baziar, 2010; Belkhatir et al., 2010). Size distribution of a soil mass has been an important basis of information in soil classification system and is adopted in various standards (BSCS, ASTM, and AASHTO), shape classification however has not been taken in these conventional soil classification systems. Therefore, as important as the effect of the particle size distribution on the interparticle reaction, there only very few established correlations with particle shape on the strength properties of granular materials.

This is due to the problem that appropriate classification based on standardized and cost effective techniques on the quantification of particle shapes is still lacking. Current imaging techniques such as the scanning electron microscope are expensive and time consuming that may not be suitable for routine measurement. There is also still no established particular representative shape variable that can identify key characteristics and distinguish one type of particle from another.

Understanding the behaviour of the soil and reducing the existing uncertainties in geotechnical engineering design subjected to both static and dynamic loading ultimately require the knowledge of characterising the morphological aspects of the soil. Dilatancy is another feature which plays a key role in every static soil structure response especially in soils denser than critical state (Brooke, 2008). It is said that size and shape distribution of the particles significantly influences the structural arrangement of a granular mass. As a result, the interparticle friction and dilatancy are likely to be affected by the particle size and shape distribution.

Structures constructed on granular soils are prone to face many ground related dynamic failures due to the repetitive (often cyclic) force that is applied rapidly (earthquakes, bomb blasts, operations of vibrating machinery, construction operations, mining, traffic, wind, tidal and wave actions). Understanding soil dynamics should not only be limited to the intensity or the frequency of the dynamic loading but consideration needs to be given also on the particle morphological factor which can influence in the dynamic loading parameters such as liquefaction, the dynamic shear modulus and damping ratio.

The accomplishment of this research hopes to introduce a new shape classification method for sand and how it can be compared with the established particle size classification in providing good estimates from prediction models that particle morphology can have a significant impact on the strength behaviour of the soil under static and dynamic loading characteristics.

1.3 Research objectives

Accordingly, the aim of this research is to develop a new approach of particle shape analysis and to compare it with the established particle size classification on its effect of a wide spectrum of static and dynamic shear strength characteristics for sand. For that purpose, the consequent objectives for this research are:

i) To characterise a chosen suite of tested soils and testing apparatus whether it is appropriate for the purpose in studying its particle size and shape parameters that could have an impact in the static and dynamic loading shear strength characteristic of the soil.

ii) To develop innovative experimental and new statistical analysis techniques of cluster analysis and probability distributions to quantify various aspects of particle shape parameters.

iii) To analyse the shear strength parameters and to find new relationships between shear strength and dilatancy characteristics based on the effect of particle size and shape parameters of sand.

iv) To determine the effect of the particle size and shape parameters of the sand samples on the dynamic modulus, as well as the damping ratio (D), which will be critically investigated based on different dynamic loading frequencies and to establish how these geotechnical parameters correlate.

1.4 Scope of research

In order to achieve the objectives of this research, sands acquired from 3 different origins were used. Firstly, sands from a sand quarry in Kahang, Johor Malaysia generally classified as Well Graded (SW) was used. Subsequent alteration through riffling from the SW sand was necessary to obtain two other different size distributions of uniformly graded (SPu_{Kahang}) and gap graded (SPg) sands. Secondly, sands originated from Leighton Buzzard, UK ($SPu_{L.\ Buzzard}$) was also used and it is documented as being uniformly graded sand and it has slightly rounded particle shapes. Thirdly, manufactured glass beads commercially known as Glass Ballotini was used. It is also classified to be uniformly graded but having perfectly rounded shapes. Sand was chosen because unlike gravel or clay, the particles are too big and too small respectively to be used for macroscale imaging analysis.

The particle size range is limited from fine to coarse grains with average diameters from 0.08 mm to 5 mm. Quantification of the particle shapes was done with an imaging tool called the digital microscope on a 100 particles from each sample. Based on the new methods of shape classification using cluster analysis with the addition probability distributions, the amount of particles quantified is deemed to be sufficient for the analysis of determining representative shape parameters.

Static loading characteristics was analysed using only the direct shear test with different relative densities (D_r) to find relationships of the structure, particle morphology and the strength characteristics. Dynamic loading analysis however was done using resilient modulus test, cyclic simple shear test and the cyclic triaxial test for the purpose of obtaining different frequencies and loading conditions. The sand samples for cyclic test were all tested under fully saturated conditions. It is also should be noted that consolidation on all test samples was limited to low levels (<100kPa) of normal (σ_N) and confining stresses (σ_3) to avoid particle crushing. All laboratory testing was done in RECESS, UTHM.

1.5 Expected contributions from the research

The research expects to present several benefits in a wide spectrum of geotechnical aspects. From the particle shape modelling analysis, a new established statistical quantification of particle shapes can provide suitable representative values for classification of particle shape parameters. Based on these established size and shape parameters, this research will help geotechnical engineers to have a better understanding on the fundamental relationships of soil classification encompassing both shape and size distributions of the particles with the shear strength characteristics. The correlations obtained can be a guideline in understanding and predicting design parameters under static and dynamic loading behaviour.

1.6 Thesis outline

A brief summary of each chapter is explained in this section so that the structure of the research can be easily understood and followed. Firstly, **Chapter I** describes the introduction of the research, the objectives, the scope of the study and the research's expected contributions to knowledge. **Chapter II** then reviews works from past research relating to the classification of the shape and size characteristics of sand particles and the behaviour of the soils mechanical properties. Most of the review presented are abstracted from previous researchers and are acknowledged as appropriate.

Contents in **Chapter III** describe the characterisation of the samples, sample preparations techniques and all the testing procedures. This chapter also discusses the implementation of the soil testing machines, its description and limitations. **Chapter IV** will provide detail descriptions of the results obtained from various classifications testing which includes the index properties test, particle size distribution curves, and presenting suitable methods of digital imaging. The development of cluster analysis and probability distribution for particle shape classification is presented.

Chapter V presents the critical analysis of a wide spectrum of test results from the static load shearing test. The strength behaviour of the samples was analysed and explained in detail. Incorporation of the size distribution and the modelled shape parameters with the friction angle and dilatancy parameters are presented. **Chapter VI** then discusses and establishes relationships of the various test properties from dynamic load testing of sand samples of different particles sizes and shape characteristics. The study thoroughly assesses the influence of particle morphology on the behaviour of resilient modulus, dynamic shear modulus and damping ratio. The other parameters such as the cyclic stress ratio, cyclic loading frequency, pore pressure response and cyclic deformation were also critically discussed.

Lastly, **Chapter VII** outlines the conclusion of the research and a summary of the key results and findings from the present work and detail recommendation for future works.

CHAPTER II

CRITICAL REVIEW OF PAST LITERATURE

2.1 Introduction

This chapter presents the author's critical review of past research relevant to this study. The macroscale behaviour of soil particles is very interesting and directing the engineering characteristics of the soil. Static testing on soil is a common practice in geotechnical engineering, but dynamic testing is more complex and is somewhat limited. During the past three decades, considerable progress has been made in the area of soil dynamics (Sitharam et al., 2004). Outcomes of such intensive research is gradually been applied in evaluation of the response of structures to dynamic stresses such as earthquakes, machine vibrations, wind, blasting, traffic loading, tidal waves and many others. Under these kinds of stress conditions, failure occurs when the strains become excessive, and this strain value depends on the soil properties.

Only sand is preferentially used in this research because of the various scales of particle shapes and sizes. In this chapter, properties of the sand based on particle size distributions and shapes are discussed in detail. It also reviews some correlations of the soil properties subjected to dynamic and static loading with particle morphology from past studies. This chapter critically reviews the literature on the following aspect relevant to:

- The genesis and morphology of sand
- Effect of particle size on the void ratio
- Characteristics of particle shape classification
- Correlation of particle morphology with shear strength

- Dilatancy of soil
- Dynamic characteristics of soil

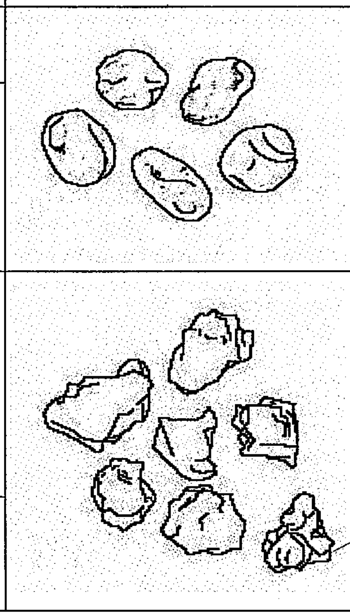
2.2 The genesis and morphology of sand

Sand naturally occurs as granular material composed usually of broken rock fragments and mineral particles. The composition of sand can be highly variable, depending on the parent rock source and surrounding conditions, but the most common constituent of sand in inland continental settings and non-tropical coastal settings are quartz and silicates. Quartz is also the most abundant mineral in the world, usually in one of the different forms (silicon dioxide, or SiO_2) (Urquhart, 1959).

The properties of sand largely depend on the rocks from which they are derived, however during the process of transportation and weathering especially by water prior to deposition, the weaker particles tend to be selectively removed by attrition making the resulting material to contain stronger aggregates than the parent rock when crushed (Harris et al., 1974). The coarsey fragmented particles will be deposited nearest to the source area and the finer materials are transported in suspension to longer distances before they are deposited (McLean and Gribble, 1979). Different shapes are imposed on the sand particles as a consequence of the prevailing transport mechanism such as fluvial, aeolian or glacial process. The continual process of the mechanism will eventually cause a certain amount of abrasion during the transport depending on the size and hardness of the grains and the violence of the impact of one against the other. **Table 2.1** explains the occurrence of obtaining different particle shapes based on its transport mechanism.

In accordance with the Unified Soil Classification System (USCS) under ASTM D2487, the grain size of sand would be in the range of 4.75 to 0.075mm. The British Soil Classification System (BSCS), in BS 5930: 1981 states that sand particles are between 0.060mm to 2mm. **Figure 2.1** shows the relationship between the USCS and the BSCS classification system where the shaded area clarifies the size range of the sands samples which is used in this research. Laboratory testing under the USCS standard shows that sand can be classified as coarse grained soil when less than 50% of the sample passes through the No. 200 sieve (0.075mm). Within this coarse grained group, sand can be indentified when more than 50% of the course grained soil passes through the No. 4 sieve (4.76mm).

Table 2.1: Description of the occurrence of particle shape based on its transportation mechanisms (after McLean and Gribble, 1979)

Type of shape	Image	Transport Mechanism	Explanation
Very spherical		High wind speeds	Usually occur in sand dunes due to higher wind speeds
Spherical		Wind	Achieved when the particles are blown by wind, because it is less viscous than water it can collide more energetically and violently to each other.
Angular		Water	Sand grains lack the necessary momentum when they collide under water to produce spherical particles. It is also due to the waters cushioning effect.
Very angular		Deposited from ice	Grains deposited from ice are normally more angular than those in river deposits.

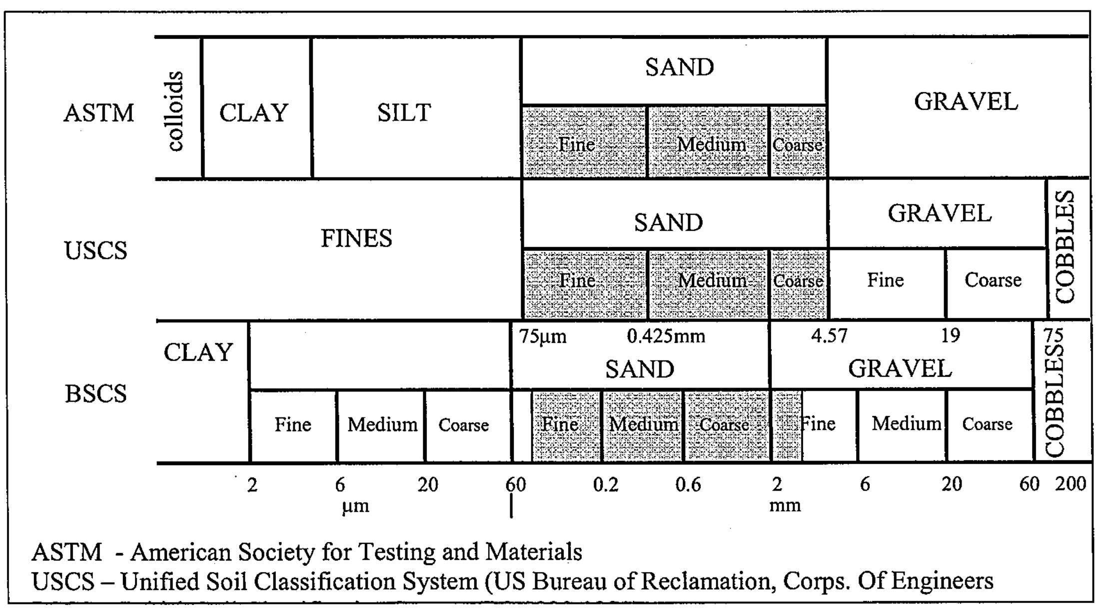


Figure 2.1: Comparison of soil classification systems (Note: Shaded grey areas are the classification range of the sands for this research)

Further classification enables proper identification of the existence of fines and silt content in the sand. According to BSCS, the sand samples used in this research contain fine gravel. It is therefore important to state clearly the standards used in classifying soils. Other conventional methods known as the triangular classification chart are also used as an alternative to compare soil types as shown in **Figure 2.2**. The triangular classification chart is not practically often used, but it can be very convenient in comparing clay-silt-sand mixtures (Lee et. al. 1983). Hence, the chart is a good indicator for soil mixtures.

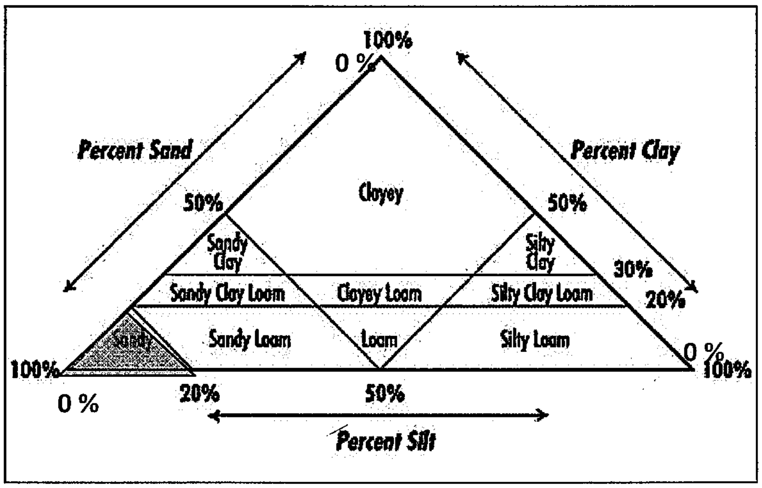


Figure 2.2: Triangular classification chart (Lee et. al., 1983) (Note: Shaded grey area is the classification range of the sands for this research)

2.3 Particle size analysis of sand and its effect on its physical properties

Particle size analysis is the determination of the distribution of size range of particles that is present in a soil mass. Two methods of classification tests are generally used which are the sieve analysis where it is only used for particle sizes larger than 0.075mm in diameter (i.e > silt size) and the hydrometer analysis for particle sizes smaller than 0.075mm in diameter (i.e < clay/silt size). Therefore, the sieve analysis method is appropriate for sand samples, although the hydrometer analysis would also be appropriate if there are significant amount of fines and silt contents in the sand (Refer to triangular classification chart, **Figure 2.2**).

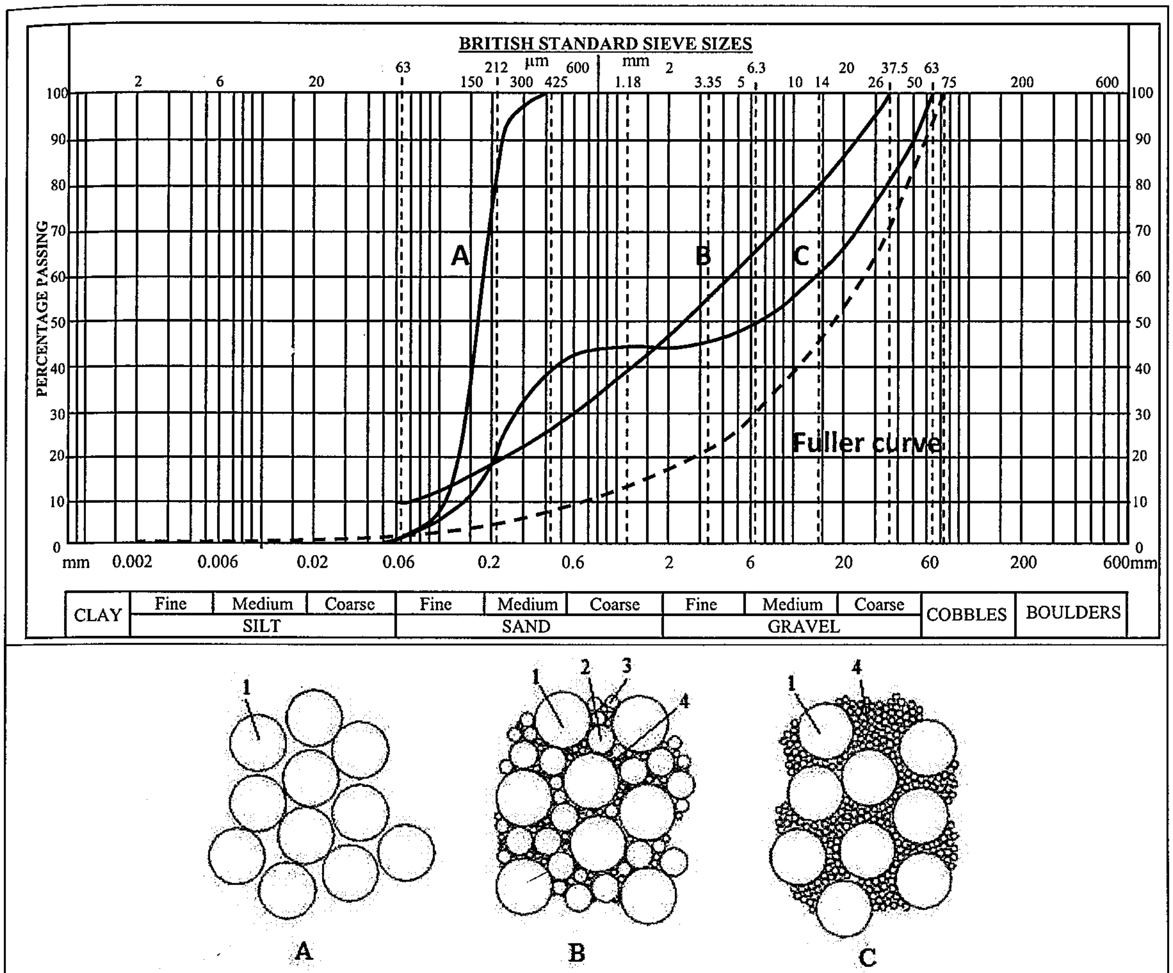
Sieve analysis results are generally presented in semilogarithmic plots and are known as particle size distribution curves (refer to **Figure 2.3**). The grading curves enable sand to be identified generally as being of three types, which are uniform sand, well graded sand and gap graded sand. The form of these distribution curves are analysed to present an important parameter called the uniformity coefficient (C_u), and it is defined in Equation 2.1. This expression is defined from the ratio of the diameter of the particle size at 60% finer (D_{60}) to the diameter of the particle size at 10% finer (D_{10}) by mass on the particle size distribution curve. D_{10} is also known as the effective size, however literature does not provide substantial evidence on why the effective size should be the size at 10% finer.

$$C_u = \frac{D_{60}}{D_{10}} \tag{2.1}$$

Another important parametric feature of size distribution is the coefficient of curvature/gradation C_z and it is defined in Equation 2.2 where D_{30} (particle size at 30% finer) is used in the evaluation of the equation.

$$C_z = \frac{D_{30}^2}{D_{10}D_{60}} \tag{2.2}$$

Figure 2.3 shows the semilogarithmic graph of the particle size distribution curves of sand and gravel mixtures adopted form Head (1992) and the summary of its particle size parameters. Illustrations of the particle sizes were shown in the figure which distinguished between the types of size distribution characteristics. The numberings indicates the scale of the size of the particles relative to one another. As an example, well graded sand consist particles of a wide range of sizes, whereas uniformly graded sand has most of its particles at about the same size. Gap graded sand shows that there is an excess or deficiency of certain particle sizes that has at least one particle size missing, and in natural soils the deficiency usually occurs in the coarse sand-fine gravel range. The dashed curved line called the Fuller Curve in the graph as presented by head (1992) represents a theoretical grading of a material where the particles are fit together in the densest most possible state of packing. In this idealised material the largest particles just touches each other, while there are enough intermediate size of particles to occupy the voids between the largest without holding them apart. The smaller particles then tend to occupy the voids between intermediate sizes, and so on.



Note: The numbers indicates the scale of the particles

Parameters	A	B	C	Fuller Curve
D_{10}	0.092	0.07	0.1	0.6
C_u	1.74	64.29	203	45
C_z	0.679	1.143	0.064	0.8

Figure 2.3: Particle size distribution curves presented in a semilogarithmic graph and illustrations of the particle sizes for (A) uniformly graded sand, (B) well graded sandy gravel and (C) Gap graded sandy gravel (modified from Head, 1992)

Detailed summary of these particle size distribution characteristics are given in **Table 2.2** to distinguish between its grading classification types. According to Head (1992) which he described based on BS1377:1990, it appears that gap graded sands is not classified by the determination of both the parameters of C_u and C_z but by the pattern of its particle size distribution curve. However, gap graded sands commonly tend to have very large values of uniformity coefficient (C_u).

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