Characterization of Particle Size Distribution in Expansive Soils using Logarithmic Density Distribution

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Abstract

*Particles size distribution(PSD) is a mathematical function that defines the relative amount, typically by mass, of particles present according to size. Geotechnically, particle size analysis is required torelate soil texture to soil performance or behavior. The objective of this paper is to use a logarithmic scale for particle size to get accurate grain size information for sediment distribution.*Through accurate*determination of grain size, it is possible to examine the influence of particle-size on swelling potential of the soil because chemical composition of sedimentthat relates to swell varies with grain size. Soil samples used in this study were retrieved from open pits in an area which falls within the*expansive soil zone *in the Coast Region of Tanzania. The standard analyses used included sedimentation using a hydrometer or pipette method for clay- and silt-sized particles and sieve analysis for sand. For the fact that particle distribution spans over several orders of magnitudes, a* base*two*logarithmic scale*for the x-axis and a linear scale for the y-axis was used to plot the grain size distribution. The* Particle size distribution was supplemented with the free swell tests and Atterbarg Limitsin order to collate Particle size distribution and swell potential. *The results showed that the soils have highest sand fractions followed by notable proportion of fines and a small amount of gravel. Ironically, the soils exhibit high swell potential albeit predominance of sand. It implies that expansive character might not be limited to pure clay soils. Hypothetically, sandstones formed by the consolidation of sediments of an expansive nature are likely to have the characteristic to expand.*

Keywords: *Expansive soils, Particle size, Particle size distribution (PSD), andBase two logarithmic*

I. INRODUCTION

The inherent swelling potential of soil is directly related to the total amount of clay-mineral particles (particles that are <2 μ m in diameter) in it. The swelling potential and swell pressures generated by the swelling of the expansive soil are to a large degree, functions of the combined inherent swelling capacities of all of its clay-mineral components ([7], [15], [16], [22], [24], [26]). The swelling pressureandswelling potential increase with an increase in clay minerals and decreaseas silt, sand, and other non-clay materials increase ([1], [13], [18], [20]). Therefore, separation of sand fractions from silt and clay fractions in the soil may be more important in the study of inherent compositional characteristics of expansivesoils. Soil separation by sieve analysis is a practice or procedure used to assess the particle size distribution(also called gradation).Indeed, soil particle size distribution (PSD)is known to be acritical parameter towardspreliminary understanding of physical and mechanical behavior of soil in many geotechnical applications ([8]). Moreover, particle size distributions of soil mineral separates are critical for getting hold of many soil properties such as water holding capacity, rate of movement of water through the soil, kind of structure of soil, bulk density and consistency of soil. The procedure of determining the size distribution of mineral particles in the soil is called particle size analysis or mechanical analysis of the soil.

The first stage of the analysis is to separatesand fractions from silt and clay fractionsthrough sieve analysis ([12],[25]). However, before the mineral soil can be sieved, aggregates and organic matter must be broken down and removed. Furthermore, the silt and clay fractions cannot be distinguished from one another by sieveanalysis but rather by sedimentation analysis, which is based upon the fact that larger particles settle faster through water than smaller ones. Therefore, for a suspension made up of clay and silt, the silt settles out first and clays settles last, thus by measuring the sedimentation velocity at which the suspension as a whole settles out, it is possible to measure the size, weight or density of the particle ([5], [9], [10],

[23]).The results of the particle size analysis assist in the soil-classification processes.

Classification of soils for engineering purpose depends very much on the system used. In this study, use is made of the two systems found in [4] and [28]. The grain size and grain size distribution are according to [28], while the wet sieve is according to [4]. That means the distribution of particle sizes larger than 0.002 mm is determined by dry sieve, while a sedimentation process using a hydrometer determines the distribution of particle sizes smaller than 0.002 mm (Fig.1). For both systems, a cumulative frequency distribution graph is plotted for each sample to characterize the relative number of particles within each range of diameter.The graphs are cumulative percent frequency distribution curves, which represent the cumulative weight percent by particle size of the sample. In one of the curves (cumulative weight percent passing), the fraction that is finer than each subsequent grain size is shown. In the other curve (cumulative weight percent retained) the fraction that is coarser than each subsequent grain size is shown. Essentially, for each grain size, the curve indicates how much of the sample is finer or coarser

Particle size distribution in base two logarithmic

In expansive soils, particle diameters typically span many orders of magnitude for natural sediments, thus the best way to conveniently describe wide ranging data set in sediment distribution is the use of base two logarithmic ϕ (phi) scale which allows grain-size data to be expressed in unit of equal values. Logarithmic phi values (in base two) are calculated from particle diameter size measures in millimetres as follows ([21]).

$$\phi = -\log_2 d = -\left(\frac{\log_{10} d}{\log_{10} 2}\right) \qquad (1)$$

where ϕ = particle size in ϕ units and d = diameter of particle in mm

The end result is the preparation of particle size distribution curves for soils called cumulative weight percent curves. The cumulative percent frequency distribution curves represent the cumulative-percent mass of each fraction with respect to the total mass of the sample versus the grain-size in mm or phi. Generally, the curves reveal how much of the sample is finer or coarser.

The particle size location and variability can be characterized statistically in terms of mean (average size), standard deviation (the spread/sorting of the sizes around the average), skewness (the degree of asymmetry of the grain sizes around their mean) and kurtosis (degree of the peakedness or flatness of the grains relative to the average) as shown in equations (2) to (14) ([19]). The average grainsizes are measured by mode,mediansize or mean size distribution. The mode or modal diameter (ϕ_o)refers to the most frequently occurring particle size in a population ofgrains that corresponds to the diameter represented by thepeakof afrequency curve or steepest point (inflection point) on the cumulative curve. Themedian (ϕ_d) size represents the midpoint of thegrain-size distribution and corresponds to the 50% percentile diameter (i.e.50% of the total frequency) on the cumulative curve. Themeansize (ϕ_m) is the arithmeticaverageof all the particle sizes in a sample. ϕ_m .

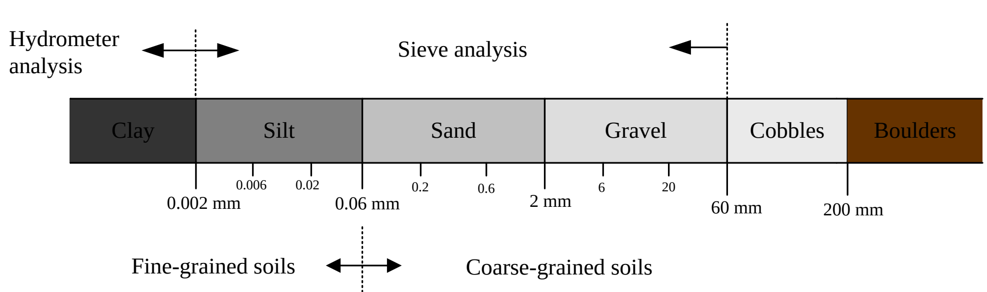


Fig.1: Grain size distribution for dry and wet sieve analysis.

The standard deviation is a measure of uniformity or sorting of the sediment represented by a disaggregated sample. Skewness is a measure of the symmetry, or more precisely, the lack of symmetry of the grain size distribution about the mean with a maximum possible value of +1 and a minimum possible value of -1. A positive value of skewness indicates that the distribution has a larger proportion of fine grains and a negative skewness indicates the distribution has a large proportion ofcoarse. A skewness close to zero indicates that the distribution is very symmetrical and themean, median, and mode allfallat the same point. Kurtosis is a measure of the degree of "peakedness/sharpness" or "flatness" of the grain size distribution compared to the normal distribution. Three types of kurtosis that a distribution might display are leptokurtic (relatively peaked distribution; K >1), mesokurtic (normal distribution; K = 1), and platykurtic (relatively flat distribution; K < 1).

$$x_{avg} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (2)$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_{avg})^2}{n-1}} = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - n(x_{avg})^2}{(n-1)}} = \sqrt{\frac{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}{n(n-1)}} \qquad (3)$$

$$\text{C.V} = s/x_{avg} \qquad (4)$$

Skewness(*Skew(X)*)=

$$\frac{n}{(n-1)(n-2)}\sum_{i=1}^{n}\left(\frac{x_i - x_{avg}}{s}\right)^3 \qquad (5)$$

Kurtosis (*kurt(X)*) =

$$\left\{\frac{n(n+1)}{(n-1)(n-2)(n-3)}\sum_{i=1}^{n}\left(\frac{x_i - x_{avg}}{s}\right)^4\right\} - \frac{3(n-1)^2}{(n-2)(n-3)} \qquad (6)$$

where n = number of occurrence

x_i = mid point of each class interval in metric

x_{avg} = mean grain size

s = standard deviation

C.V = coefficient of variation (uniformity of distribution)

According to [3] the alternative to the above statistical formulae is given by Folk and Ward in 1957 in (original) graphical measures in phi (Table I) as follows:

$$\phi_m = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \qquad (7)$$

$$s = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \qquad (8)$$

Skewness (Sk) =

$$\frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)} \qquad (9)$$

$$\text{Kurtosis (K)} = \frac{\phi_{95} - \phi_5}{244(\phi_{75} - \phi_{25})} \qquad (10)$$

where ϕ_x = the grain diameter in phi units at the cumulative percentile value of x

ϕ_m = mean grain size

The modification of the above measures is given in metric in Table II ([3]) as follows:

$$P_m = \exp\frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3} \qquad (11)$$

$$s = \exp\left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6.6}\right) \qquad (12)$$

Skewness(Sk) =

$$\frac{\ln P_{16} + \ln P_{84} - 2\ln P_{50}}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2\ln P_{50}}{2(\ln P_{25} - \ln P_5)} \qquad (13)$$

$$\text{Kurtosis (K)} = \frac{\ln P_5 - \ln P_{95}}{244(\phi_{25} - \phi_{75})} \qquad (14)$$

where P_x is the grain diameter and P_m is the mean in metric units

I. **TABLE I:** Description of limits of distribution of values – logarithmic (origin) graphical measures ([21]).

Mean in phi		Standard deviation in phi		Skewness		Kurtosis	
-12 to -8	boulder	under .35	very well sorted	from +1.00 to +0.30	strongly fine skewed	under 0.67	very platykurtic
-8 to -6	cobble	0.35-0.50	well sorted	from +0.30 to +0.10	fine skewed	0.67-0.90	platykurtic
-6 to -2	pebble	0.50-0.71	moderately well sorted	from +0.10 to -0.10	near symmetrical	0.90-1.11	mesokurtic
-2 to -1	granular	0.71-1.0	moderately sorted	from -0.10 to -0.30	coarse skewed	1.11-1.50	leptokurtic
-1 to 0.0	very coarse	1.0-2.0	poorly sorted	from -0.30 to -1.00	strongly coarse	1.50-3.00	very leptokurtic

	grained				skewed		
0.0 to 1.0	coarse grained	2.0-4.0	very poorly sorted	-	-	over 3.00	extremely leptokurtic
1.0 to 2.0	medium grained	over 4.0	extremely poorly sorted	-	-	-	-
2.0 to 3.0	fine grained	-	-	-	-	-	-
3.0 to 4.0	very fine grained	-	-	-	-	-	-
5.0 to 6.0	medium silt	-	-	-	-	-	-
6.0 to 7.0	fine silt	-	-	-	-	-	-
7.0 to 8.0	very fine silt	-	-	-	-	-	-
>8.0	clay	-	-	-	-	-	-

II. **TABLEII:** Description of limits of distribution of values – geometric (modified) graphical measures in metric ([3]).

Standard deviation		Skewness		Kurtosis	
<1.27	very well sorted	from -0.3 to -1.0	very fine skewed	< 0.67	very platykurtic
1.27 – 1.41	well sorted	from -0.1 to -0.3	fine skewed	0.67-0.90	platykurtic
1.41 –1.62	moderately well sorted	from -0.1 to +0.1	near symmetrical	0.90-1.11	mesokurtic
1.62-2.0	moderately sorted	from 0.1 to 0.3	coarse skewed	1.11-1.50	leptokurtic
2.0-4.0	poorly sorted	from +0.3 to +1.0	very coarse skewed	1.50-3.00	very leptokurtic
4.0-16.0	very poorly sorted	-	-	> 3.00	extremely leptokurtic
> 16.0	extremely poorly sorted	-	-	-	-

I. MATERIALS AND METHODS

A. *Study site*

The study area (Kibaha) is a township located in eastern Tanzania, about 40 km west of Dar es Salaam (the commercial capital city of Tanzania), along the Dar Es Salaam-Morogoro highway. It's positioned at an altitude of about 155 m above sea level and located approximately by geographic latitude and longitude of 06º46'S and 38º55'E respectively. It is within the coastal belt where plastic clay soil is predominant.

The geology of the catchment is complex ([14]): it comprises a complex autochthonousand allochthonous sequence of late mesozoic and early cenozoic sediments. The indigenous and non-indigenous sediment fillings are composed of lacustrine, fluviatile, residual, pluvial and alluvial deposits that include micaceous materials (micaceousschists, clay shale, siltstones, silty mudstones etc), calcareous sandstones, limestones, marine marls, shells, organic materials and conglomerates. By the processes of chemical and physical weathering, these conglomerates converted to soils rich in clay. Typically, the deposits are reddish brown, grey brown and grey in colour. Generally, soils tend to be sandy clay, although deposits of terrace gravels, marine clays and fossiliferous shells are common locally. The underlying basement consists of the crystalline and metamorphic rocks of the Mozambique orogenic belt ([17]). Largely, the soils reflect the geology and climatic conditions of the area.

In general, the mesozoic and cenozoic sediments of coastal marine belt contain significant amount of the active clay minerals (montmorillonite), the most troublesome expansive clay mineral. Montmorillonite is remarkable for its very small fine particles which may be considered small colloid with dimensions as small as a few tens of Angstrom units. The small non-scale fine particles are agglomerated due to surface attraction of one particle to another. Since montmorillonite minerals are very fine with large specific surface areas, their presence contributes to high degree of expansiveness of soil. Usually, the degree of expansiveness is proportional to the amount of montmorillonite or other expansive clay minerals present in the soil.

B. Soil sampling and analysis

The expansive soilsamples used in this study were retrieved from open pits near Tumbi Catholic Church in Kibaha Town, Coast Region, Tanzania.The retrieved samples were carefully packed in thick polyethylene bags, sealed with tape, logged and transported to thesoil laboratory at the Dar es Salaam Institute of Technology (DIT). At the laboratory, the samples were air-dried, gently crushed, and then dry-sieved using a 2-mm mesh to remove coarse fragments. The samples were then treatedwith an excess of 30% hydrogen peroxide to remove the organicmaterials. Thereafter, the grading analyses were performed using both standard wet-sieve (sedimentation technique) and hydrometer methods. To carry out the two methods, the samples were first washed through 0.063mm sieve, thus the soil passing the sieve was allowed to stand overnight and the suspension was then tested using sedimentation technique (hydrometer). The sedimentation technique is based on an application of Stokes'law to a soil/water suspension and periodic measurement of the density of the suspension. The soil that remained in the sieve was oven dried and subjected to dry sieve in accordance with [4]Methods of test for soils for civil engineering purposes.

C. Dry Sieve Analysis.

Particle size (sieve analysis) carried out for soil classification in accordance with [4]Methods of test for soils for civil engineering purposes allowed the sample retained on the sieve 0.063mm to run run through a standard set of sieves on a mechanical sieve shaker. This partitioned the sample into various grain sizes that allowed presentation of the grain size distribution shown in Table III. The particle size distribution was carried out together with the Atterberg limits (liquid, plastic and shrinkage limits) and hydrometer tests according to the guidelines provided in [4], clause 9.5, density determination based on the standard method for measuring particle density according to [4] clause 7, swell potential, free swell according to [11]and oedometer tests were performed.

D. Wet sieve and hydrometer test

Wet sieving and hydrometer tests were performed to obtain the grain size distribution of fine particles. As it has been pointed out before, the tests were performed according to the guidelines given in [4] Part 2, clauses 9.2 & 9.5.

The representative test samples were crushed, placed in an evaporating dish and dried overnight in an oven maintained at 105-110°C. The cool dried samples were weighed to the nearest 0.01 g and sieved through a 20 mm sieve. A mass of 2 kg of particles finer than 20 mm was taken to form a number of portions. A portion of 40 g soil was spread in a tray and treated with distilled water and a dispersant solution of 2 g/l sodium hexametaphosphate (known commercially as Calgon) to make 1000 ml. The mixture was stirred for 1 hour to break down and separate clay particles. The soil in small batches was separated into coarser and finer portions by washing it through the 63 µm sieve. The > 63 µm portions were oven dried at 105-110°C and sieved through standard mesh sizes between 20 mm and 63 µm using the dry sieve procedure. The weight retained on each sieve was noted.

The <63 µm portion was mixed with water in a 1000 ml sedimentation cylinder, thoroughly stirred, allowed to settle for about five minutes prior to the decantation of the suspension. The test is an application of Stoke’s law (larger particles fall more quickly in a suspending fluid, while finer particles remain in suspension longer). The reading on the hydrometer determines the amount of that size, while the time at which the hydrometer readings are taken determines the size of particle remaining in suspension. The process was repeated several times to separate particles of different size from each other in the mixed suspension.

E. Free Swell test and Atterberg Limits

In order to determine the correlation between particle size distribution and potential expansion,Atterberg limits (liquid, plastic and shrinkage limits) followed the guidelines provided in [4], clause 9.5. The swelling index tests that point out the potential expansiveness of soils were performed according to [11] by slowly pouring 10 cm^3 of dry soil passing the 0.42 mm sieve into a graduated cylinder filled with distilled water and left there overnight to freely swell (increase in volume to full swell) to reach equilibrium after 24 hours. The free swell is defined as the ratio of the increase in volume of the soil from a loose dry powder form to the equilibrium sediment when it is poured into water, expressed as the percentage of the original volume. Soils with free swell less than 50% are not likely to show expansive property, while soils with free swell in excess of 50 percent could present swell problems.

Values of 100% or more are associated with clay which could swell considerably, especially under light loadings.

The percent of free swell is expressed in equation (15) as:

Free swell percent = $\Delta V/V*100\%$ ____________(15)

where $\Delta V = V_s - V$= change in initial volume (V) of a specimen and

V = initial volume (10 mm^3) of the specimen

V_s = final volume of the specimen

II. RESULTS

The results of three samples (RC1, RC2 and RB) from a depth of 1 m of each peat are presented in Tables III&IVand Fig.2. According to [6], soils containing appreciable quantities of colloidal particles (less than 0.001 mm in diameter) greater than 28% have very high degree of expansion. Soils containing 23% – 15% have medium to high degree of expansion while those containing colloidal particles less than 15% have low degree of expansion. The soils under consideration have very high degree of expansion.

The Particle size distribution was supplement with the free swell tests according to [11]. The test results yielded free swell values between 100% and 150% (Table 3). The results were prima facie evidence that the soils are associated with clay, which could swell considerably when wetted. The soils proved to have the ability to absorb and retain a great deal of water and undergo significant volumetric changes with moisture fluctuations (i.e. clay having high to very high swelling-shrinkage potential)

III. TABLEIII: Physical properties of Kibaha clay samples at the regional office block (RB) and Roman Catholic Church (RC).

Sample No:	Depth (m)	Grain size (%) Gravels	Sand	Fines	Atterberg's limits (%) LL	PL	PI	SL	Clay content % (<2μm)	Free swell (%)	Activity Eqn. 2.17
RC1	0.6	11	50	39	64	21	43	12.5	34	150	1.5
	1.0	14	51	35	63	24	39	13.3	30	130	1.6
	2.0	16	51	33	54	23	31	14.2	29	100	1.3
	3.0	5	59	36	59	22	37	14.0	33	130	1.4
RC2	1.0	9	42	49	69	23	46	11.1	29	140	2.0
	2.0	12	63	24	61	30	31	16.6	22	100	1.8
	3.0	1	67	32	69	23	46	13.6	27	100	2.0
RB	1.0	2	55	44	51	21	30	16.5	39	130	0.9
	2.0	1	60	39	51	15	36	15.0	35	120	1.2
	3.0	3	52	44	49	23	26	15.1	34	140	0.9
Mean		7.4	55.0	37.5	59.0	22.5	36.9	14.2	31.2	124.0	1.46
St. Error		1.8	2.3	2.3	2.4	1.2	2.2	0.5	1.5	5.8	0.13
STD		5.7	7.3	7.1	7.4	3.7	6.8	1.7	4.8	18.4	0.40
Kurtosis		-1.8	-0.2	0.2	-1.5	3.4	-1.4	-0.1	0.4	-1.3	-1.05
Skewness		0.2	-0.0	-0.2	0.0	0.0	0.1	-0.2	-0.4	-0.3	0.02
Min.		1.0	42	24	49.0	15.0	27.0	11.1	22.0	100.0	0.88
Max.		16	67	49	69.0	30.0	47.0	16.6	39.0	150.0	2.05

IV: TABLEIV: Hydrometer results for samples RC1, RC2 and RB.

RC1 Particle diameter (D micro-mm)	% finer than D	RC2 Particle diameter (D micro-mm)	% finer than D	RB Particle diameter (D micro-mm)	% finer than D
0.0630	42	0.0649	35	0.06202	45
0.0449	40	0.0459	35	0.04420	43
0.0317	40	0.0327	34	0.03149	42
0.0226	39	0.0231	34	0.02227	42
0.0161	37	0.0163	34	0.01575	42
0.0118	35	0.0119	34	0.01150	42
0.0084	35	0.0084	34	0.00813	42

0.0060	34	0.0060	34	0.00579	40
0.0042	34	0.0042	32	0.00410	40
0.0030	31	0.0030	31	0.00292	39
0.00124	29	0.00125	27	0.00120	37

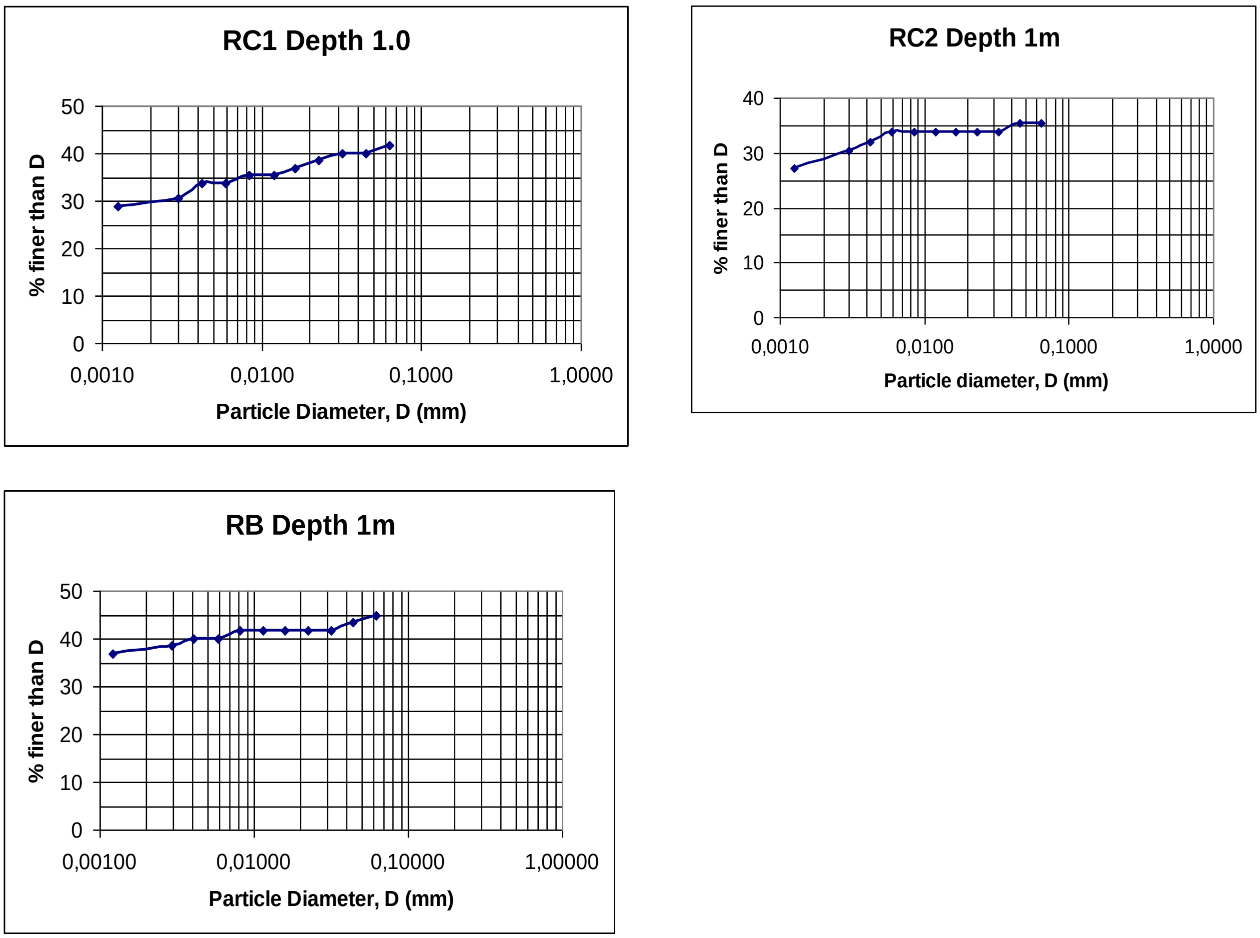


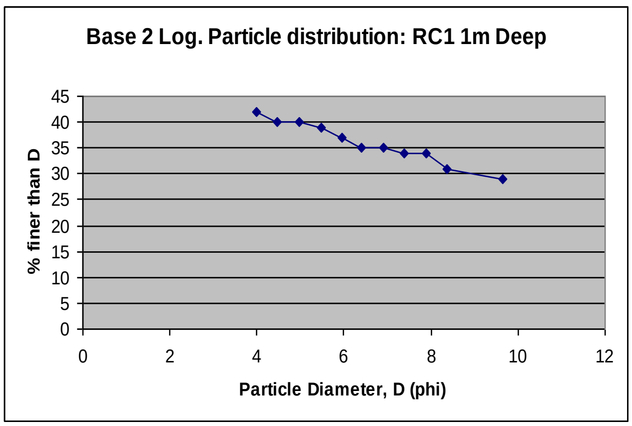
Fig.2: Hydrometer results for samples RC1, RC2 and RB from 1 metre deep.

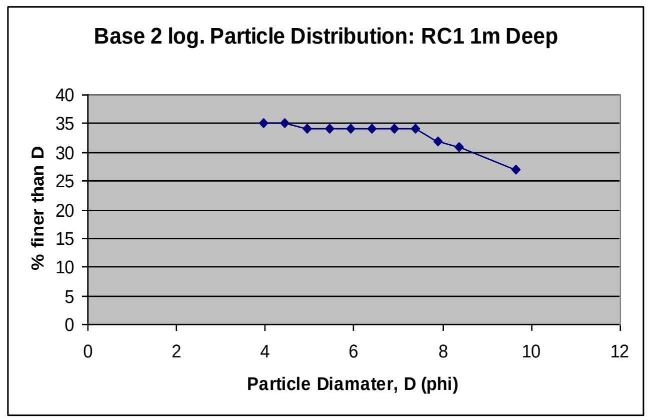
The logarithmic (origin) graphical measures for three samples from a depth of 1 m from each trial pit were calculated according to equation (1) and the results are presented in Fig. 3.

Particles size distribution tests indicated that the soils have highest sand fractions followed by notable proportion of fines and a small amount of gravel (Fig. 3). Ironically, the soils exhibit high swell potential albeit predominance of sand. It implies that expansive character might not be limited to pure clay soils. Hypothetically, sandstones formed by the consolidation of sediments of an expansive nature are likely to have the characteristic to expand.

For the 3 pits, the mean was between 0.0 phi and 1.0 phi, the standard deviation was under 0.5 phi, the skewness ranged from -0.1 to 0.1 and the kurtosis was under 0.67 (equations 5 to 14). Therefore, the soils are coarse grained, very well sorted, nearly symmetry and very platykurtic (Tables 1 & 2).

The coarse grains reflect the presence of terrace gravel deposits and high proportion of sands in the soils. This system allows interpretation of many geological engineering soils rather than geotechnical interpretation. However, the system is in total agreement with [2]: clause 13.1 that the soil is coarse grained if it contains less than 50% fines.





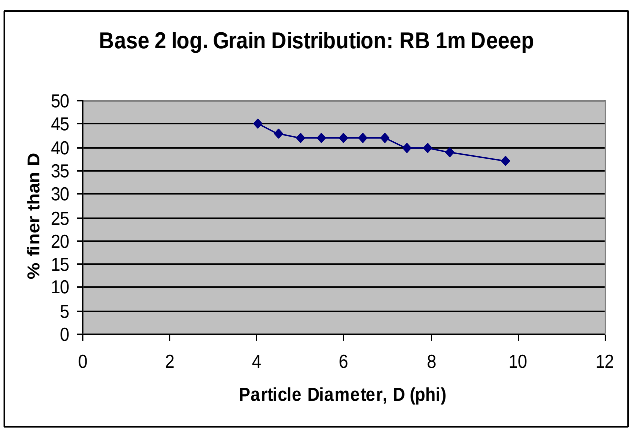


Fig. 3: Base two logarithmic particle size distribution curves for 3 samples.

IV. CONCLUSIONS

In this study the base two logarithmic ϕ (phi) scaleshas been used to represent grain size information for Particle size distribution(PSD). Sieve size analysis was performed on expansive soil samples and the cumulative distribution curves that represent the cumulative weight percent by particle size of the sample werecreated from the analysis data. Indeed the logarithmic scale for particle size has been used to get accurate grain size information for sediment distribution. How much of the sample was finer or coarser has been clearly shown in the cumulative distribution curves.The accurate completion of the sieve-analysis test produced the percentage of different grain sizescontained within a soil that are related to the swelling potential of the soil because swelling potential increases withincreasing fines content. The results showed that the soils have highest sand fractions followed by notable proportion of fines and a small amount of gravel. Ironically, the soils exhibitpronouncedswelling-shrinkingbehavior as well ashighplasticity and cohesionalbeit predominance of sand ([14]). It implies that expansive character might not be limited to pure clay soils but also to clay/silt/sand mix. Hypothetically, sandstones formed by the consolidation of arenaceous and argillaceoussediments of expansive nature are likely to have the characteristic to expand.

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