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Variation of permeability with porous media: An overview

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ABSTRACT- Permeability is an important engineering property of soils and its knowledge is essential in number of water resource and geotechnical engineering problems such as seepage and design of filters in hydraulic structures, water and sewage treatment plants and settlement of structures. Enormous work has been done to understand the effect of various factors affecting permeability and numerous relations have been given from time to time to relate permeability with these factors and parameters. In this present work, variation of permeability with change in shape and size of porous media is presented. First of all the material is separated into five different shapes by visual examination. Five well defined shapes were chosen for the present study. The shapes were classified on the basis of elongation ratio, flatness ratio, sphericity and shape factor. The shape parameters for these well examined shapes were calculated. The "three dimensions of the particle that are necessary for determination of shape parameters are the longest dimension (dl), intermediate dimension (di), and shortest dimension" (ds). These "three dimensions along with the volume of circumscribing sphere, corresponding to the longest dimension of the particle were used to calculate" the shape parameters that are necessary to quantify the shape. After the sorting of the shape, they were sieved through a set of IS recommended sieves into different sizes. Sizes passing through a particular size and retained on adjacent lower sized sieve were given the name of the sieve through which they passed. Sieve analysis is necessary not only for sorting of the material but also for the calculation of gradation parameters whose effect on permeability will be studied.

KEYWORD- Permeability, Media, Soil, Material, Parameters.

I. INTRODUCTION

Soil, being particulate in nature, has many void spaces between the particles because of the discrete nature of the individual particles. The "discrete particles that make up soil are not strongly bonded together in the way that the crystals of a metal are, and hence the soil particles are relatively free to move with respect to one another". The soil particles are solid and cannot move relative to each other as easily as the elements in a fluid. This particulate and "hence porous nature of soil imparts many important engineering characteristic to soil, and permeability or hydraulic conductivity is one of them. Permeability, also known as hydraulic conductivity, is the property that represents the ease with which water flows through the porous media". It is an important property and its evaluation is required for many civil engineering problems such as seepage through dams, piping under embankments, groundwater hydrology, filter beds for water supplies and municipal sewer systems, irrigation and drainage problems, petroleum engineering, geotechnical engineering and agricultural engineering. "The rate of settlement of saturated soils under load, the stability of slop and retaining structures, the design of filters made of soil, and the design of earth dams are some of the examples of applications of permeability" in geotechnical engineering [21]. After the selection of the shapes and sizes, laboratory tests were done. Four types of tests namely A, B, C, and D were carried out. Selection of "primary assembly sphere sizes S1, S2 and S3 and intervening sphere of size S4" was done according to the model of packing [8]. The percentage by weight of different sizes S1, S2. S3 and S4 were taken according to the model [8]. Finally the four test types were done by constant head permeability method in the laboratory. "Darcy's was employed to calculate the permeabilities and they were standardized to a temperature of 20 °C". The laboratory calculated permeabilities were related to the different gradation parameter like "d_{10}, Cc and Cu and shape parameters like sphericity (ψ) and shape factor (F)".

II. OBJECTIVES

The main objective of the present studies are:

- To study the variation of permeability with the gradation parameters.
- To study the variation of permeability with the shape parameters.

A. Varied Perceptions on Permeability

The work carried out by some of the well renowned researchers in this field has been put in chronological order.

DARCY (1856) "Henry Philibert Gaspard Darcy, in a report on the construction of the Dijon, France, municipal water system, published a relationship for the flow rate of water in sand filters. In terms only slightly different from his own, Darcy's law" was given as;

$$Q = \frac{kA\Delta h}{\Delta x}$$

"where, Q is the volume flow rate, A is the area of porous media normal to the flow, k is the hydraulic conductivity, Δx is the length of the flow path, Δh is head loss over length Δx".

HAZEN (1892) - Hazen developed the following "empirical formula for predicting the permeability or hydraulic conductivity" of saturated sands;

$$k = \frac{g}{\mu} * 6 \times 10^{-4}[1 + 10(n - 0.26)]d_{10}^2$$

where, "k is permeability cm/s, g = acceleration due to gravity, n = porosity, μ = dynamic viscosity, d10 is particle size for which 10% of the soil is finer" (cm).
The most commonly used form of Hazen equation is

$$k = C_H\, d_{10}^2$$

where, "CH is Hazen's coefficient and the value of CH" ranges from l to 1,000.

Although Hazen developed his formula for the design of sand filters for water purification i.e., loose, clean sands with a coefficient of uniformity d_{60}/d_{10} less than about 2, it is frequently used to estimate the permeability of in situ soil [21].

The "advantage of Hazen's formula is that d_{10} from a large number of samples at a given site can be quickly and easily determined to compute permeability. This helps in evaluating the variability of permeability at a given site in a quick and cost effective manner".

Kozeny-Carman - "Kozeny (1927) and Carman (1938, 1956) [5] developed the following semiempirical, semi theoretical formula for predicting the permeability of porous media;

$$k = \frac{g}{\mu} * 8 \times 10^{-3}\left[\frac{n^3}{(1-n)^2}\right] d_{10}^2 \quad 2.4$$

Although "Kozeny-Carman formula is known to be more accurate than the Hazen formulae, it is hardly used. The explanation for this paradox is at least twofold: First, most geotechnical engineers do not regularly measure specific surface area and, thus, they are not used to it". Second, hardly any of the geotechnical textbooks explain, "that So can be simply estimated from the particle size distribution curves".
Terzaghi and Peck (1964) - "Terzaghi and Peck [21] developed the following empirical equation for predicting permeability of course grained" sands;

$$k = \frac{g}{\nu} C_t \left(\frac{n - 0.13}{\sqrt[3]{1-n}}\right)^2 d_{10}^2$$

where, k = permeability (cm/s), g = the acceleration due to gravity (cm/s^2), ν = kinematic viscosity (mm^2/s), C_t = sorting coefficient, ranging from 6.1x10^{-3} to 10.7x10^{-3}, n = porosity, d10 is particle size for which 10% of the soil is finer (mm).

Kenney (1984)- Kenney et al. [9] "proposed the following equation for estimating permeability using only a single point from the grain size distribution curve" of the soil;

$$k = 0.005\, d_5^2 \quad 2.6$$

where, "k = permeability (cm/day), d5 is particle size for which 10% of the soil" is finer (mm).

Vukovic and Soro (1992)- Vukovic and Soro [22] summarized "several empirical methods from former studies" and presented a general formula;

$$k = \frac{g}{v} Cf(n) d_e^2 \quad 2.7$$

where "k = hydraulic conductivity; g = acceleration due to gravity; v = kinematic viscosity ; C = sorting coefficient; f(n) = porosity function, and de = effective grain diameter". The values of "C, f (n) and d_e are dependent on the different methods used in the grain-size analysis".

"According to Vukovic and Soro, porosity (n) may be derived from the empirical relationship with the coefficient of grain uniformity" Cu as follows:

$$n = 0.255\,(1 + 0.83C_u) \quad 2.8$$

Alyamani and Sen. (1993) - Alyamani and Sen [l] conducted "the field work at several locations of Kingdom of Saudi Arabia and proposed the following equation" for well-graded soils. The formulae is;

$$k = 1300\,[I_o + 0.025\,(d_{50} - d_{10})]$$

where k = permeability (m/day), Io = the x intercept of the slope of the line formed by d_{50} and d_{10} of the grain-size distribution curve (mm), d_{50} = grain size corresponding to 50% by weight passing (mm), d_{10} = grain size corresponding to 10% by weight passing (mm).

III. METHODOLOGY

A. Shape Parameters

Researchers "have distinguished between different aspects that constitute porous media geometry and have found that the particle geometry can be fully expressed in terms of three independent properties: form, angularity or roundness, and surface texture" [3]. A "schematic diagram that illustrates the differences between these properties is shown in Fig.3". Form, the "first-order property, reflects variations in the proportions of a particle". "Angularity, the second-order property, reflects variations at the corners, that is, variations superimposed on shape. Surface texture is used to describe the surface irregularity at a scale that is too small to affect the overall shape Fig. No. 3". These three "properties can be distinguished because of their different scales with respect to particle size, and this feature can also be used to order them". Any of "these properties can vary widely without necessarily affecting the other two properties".

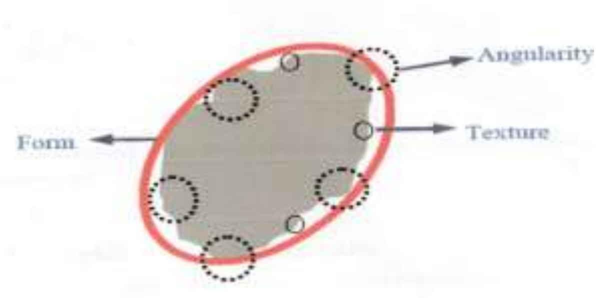

Figure 1: Components of Aggregate Shape Properties: Form, Angularity and Texture [15]

There are many "methods of finding permeability of porous media. Some of the methods are applicable in field whereas others are used in laboratory". The methods used in lab are (a) Constant head and (b) Variable head methods. The falling head method is used to measure the permeability of soils of the order of 1cm/sec. In the constant head method, permeability values from l cm/s to higher order can be measured easily. This type of test is suitable for coarse grained pervious soils where the quantity of flow is measurable in a reasonable time. Keeping in view the nature of material used in the present study, constant head experiments were carried in the laboratory. To find "the behavior of permeability with respect to varying effective pore channel for different primary assembly ratio of granular material with intervening size were carried out". The experimental set up, materials used and experimental procedure adopted are described in the following sections.

B. Experimental Set Up

The constant head permeameter used for carrying out these tests had following features:

- **Main cylinder:** "Main cylinder was made of steel having 25 cm diameter and length 60 cm excluding hopper base. It had a flange type opening resting on stand".
- **Hopper base:** "A hopper type base of diameter 8 cm was provided at the outlet of main cylinder".
- **Top flange:** "Top flange made of steel and carrying inlet pipe, two air valves and pressure gauge was connected to flange openi ng of main cylinder with the help of nuts and bolts". A rubber washer was used to make the arrangement water tight.
- **Air valves:** "Two air valves were provided at the top flange to release the air entrapped inside the body of main cylinder".
- **Pressure gauge:** "It was also provided at the top flange to record the pressure inside the cylinder".
- **Grid of rods:** "A grid of rods at 5 cm interval was provided at the bottom of main cylinder for supporting the wire mesh of different opening sizes".
- **Stand:** "Stand made of angle iron was used to hold the main cylinder in position".
- **Flexible pipe:** "Flexible pipe of (3.75 cm dia.) was connected to hopper base with suitable arrangement so that it could be adjusted to desired height to measure the outflow".
- **Measuring tank:** "A graduated steel tank of 94670 cm^3 capacity was used to measure the flow of water". Water from the tank was allowed to go into the cement concrete sump provided under ground in the laboratory.

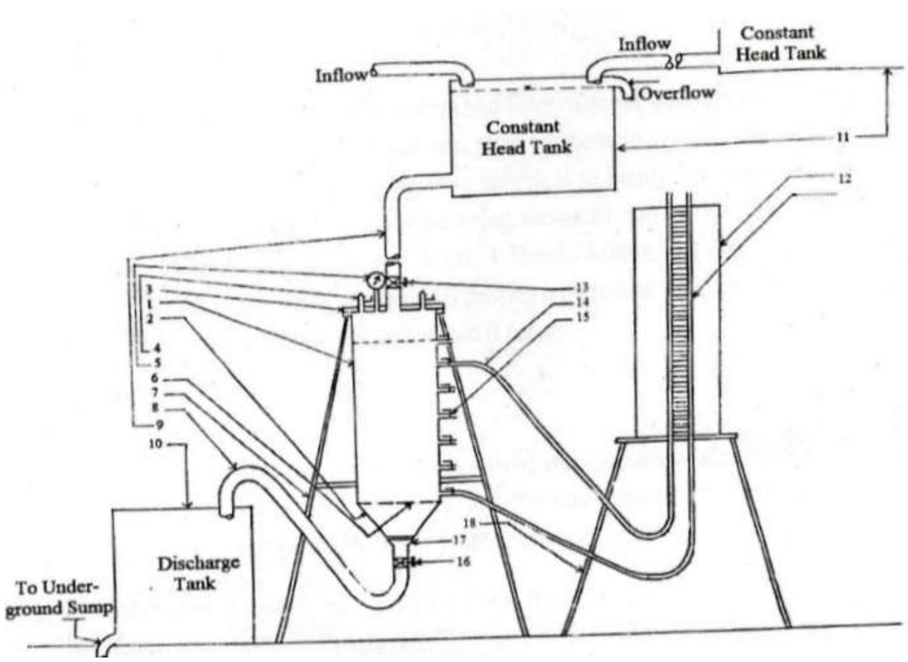

Figure 2: Apparatus used for determination of permeability

- **Constant head tank:** "This tank was situated at a height which could provide a constant head of 4.50m". Besides the direct supply of water from outside, the main source of water supply to this tank was an overhead tank (outside the laboratory) having "a capacity of 1.75 lakh liters". Water from the underground cement concrete sump was recycled into the overhead tank by means of a pump.
- **Staff Rod:** "A wooden staff rod of about 3 m length and 10 cm width having a cm scale fixed on it at the center graduated to measure a least count of 5mm".
- **Pinch cocks:** "Seven brass pinch cocks in a row were used as piezometer taps facilitating the closure and resumption of supply to the piezometers".
- **Piezometer tubing's:** "Rubber tubing's were used to connect the pinch cocks and calculate the heads available at the pinch cock levels".
- **Stop cocks (regulatory valves):** "Regulatory valves were provided near the inlet and outlet of main cylinder to adjust the flow of water through main cylinder".
- **Flange reducer and flexible pipe arrangement:** "The flange of hopper was connected to flange reducer and flexible pipe of 3.75cm dia. arrangement with the help of nuts and bolts and a rubber washer was used in between to make the assembly water tight".
- **Stand:** "An iron stand was provided to which the staff rod was attached for obtaining the heads present at various pinch cock levels".

C. Material

For the purpose of present study "the filter base and filter material were obtained from bed of river Sindh

Nallah at Ganderbal Srinagar and sites adjacent to river course”. The particle shapes of river bed material were ranging from spherical to highly irregular. The materials were grouped in the following standard sizes “using sieves: 50 mm, 40 mm, 31.5mm, 25mm, 20mm, 16mm, l2.5mm, 10mm, 8mm, 6.3mm, 4.75mm, 4.0mm, 3.4mm, 2.8mm, 2.4mm, 2mm, 1.7mm, l.4mm and l.0mm”. The material passing a particular sieve and retained on next sieve was given the name of sieve through which it passed.

D. Test Procedure

- **Step 1.** “The top flange of main cylinder was removed and cylinder was cleaned from inside. Then a wire mesh of opening size from 1 mm to 8mm was placed on the bottom grid of the cylinder to prevent the movement of material into the hopper base”.
- **Step 2.** “The weights of selected particles for a test specimen were then taken separately as described above. Each size of particles was then divided into ten equal parts by weight”.
- **Step 3.** “ One part from each of the three primary assembly sizes were mixed together thoroughly and poured into main cylinder in such a way as to ensure uniform mixing of primary assembly sizes”. Then the mass was compacted by blows by the wooden mallet. The materials were placed in dry.
- **Step 4. “**The intervening size material was taken in accordance and was divided into 10 equal parts by weight and was placed after each layer is compacted”. For the last two layers “ a circumferential layer of fine material was placed to minimize the uneven void formation at the material and permeameter interface”. The material was slightly finer than the *S*4 and coarser than *S*7.
- **Step 5.** “After placing the whole material into cylinder a wire mesh of 2mm and l0mm opening was placed at the top of it and pea gravel was placed over this mesh to prevent the direct impact of inflowing water on the mass”.
- **Step 6.** “The top flange was placed on the cylinder with washer in between and tightened to make it air tight”.
- **Step 7.** “The hopper base was connected to one end of a flexible pipe through flange, reduced arrangement and the other end placed in position over measuring tank by the help of clips”.
- **Step 8.** “Water under a constant head was made to pass through the main cylinder by regulating the valve at entrance and exit of the cylinder”. Air valves were kept open for *10 minutes to release the entrapped* air inside the cylinder. Initially discharge through cylinder was kept at maximum and was reduced step by step to give reading.
- **Step 9.** “Seven pinch cocks were numbered as *P1, P2, P3, P4, P5, P6,* and *P7* from the top of the cylinder”. Then tubes were connected to them to give the water levels in the tubes which are the heads or piezometric heads and were recorded as $h_1, h_2, h_3, h_4, h_5, h_6$, and h_7 for $P_1, P_2, P_3, P_4, P_5, P_6$, and P_7 respectively.
- **Step 10.** “The outlet valve of discharge tank was closed and the time taken by water to fill it was noted with the help of stopwatch”. Knowing the cross sectional area and the depth of water to be tilled flow rate is calculated.
- **Step 11.** “Above step was repeated for three different discharges”.
- **Step 12.** “The temperature of flowing water was noted to get permeability and standard temperature of 20°C”.

E. Calculation of Gradation and Shape Parameters

Thirty particles were selected randomly for each shape and size. Their “longest dimension (dl), intermediate dimension (di), and shortest dimension” (ds)were taken with a vernier calliper. The main gradation parameters that have been studied are, d10, d30, d60, Cc and Cu. These are obtained after the material of a particular shape has been sieved. The main shape parameters that were calculated include elongation ratio, flatness ratio, sphericity and shape factor by the formulas already mentioned in section 2.6. For calculation of sphericity, volume of particle was measured by immersing it in a measuring cylinder. “After the calculation of shape parameters the gradation parameters are calculated. Five well defined shapes were selected after thorough visual examination”. These are spherical, elliptical, blade, angular and sub angular. Sub angular was used for validation after other four were tested and used to get the various relations. The five selected shapes are shown in the next Figure 11.

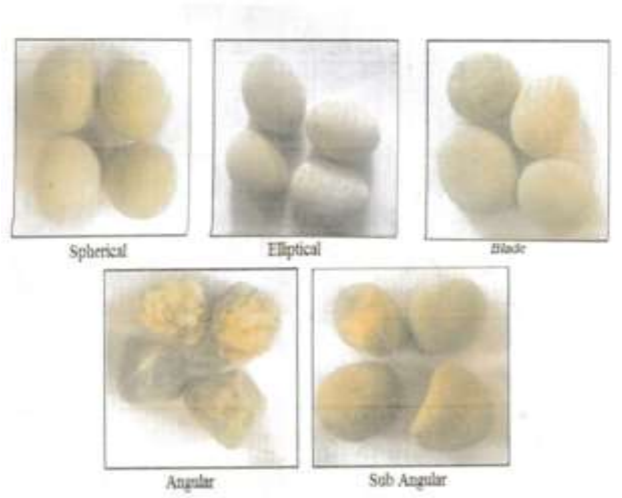

Figure 3: A view of five selected shape

Table No. 1: Gradation parameters for all four test types

Test type	S_1, S_2, S_3(mm)	S_4(mm)	d_{10} (mm)	d_{30} (mm)	d_{60}(mm)	*Cc*	*Cu*
A	12.5	1.875	1.775	10.054	10.598	1.203	1.022
A	16	2.4	2.250	12.576	13.337	1.227	1.024
A	20	3	3.025	16.087	16.957	1.203	1.022
A	25	3.75	3.550	20. 109	21.196	1.203	1.022
A	31.5	4.725	4.469	25.141	26.554	1.2 11	1.022
A	40	6	5.719	31.685	33.533	1 .219	1.023
A	50	7.5	7.550	40.217	42.391	1.203	1.022
B	12.5: 20: 25	2.75	10.192	12.115	19.467	2.248	1.352
B	16:25:31.5	3.52	12.769	15.462	24.333	2.255	1.300
B	20:31.5: 40	4.4	16.308	19.385	30.633	2.236	1.329
B	25: 40:50	5.5	20. 385	24.23 1	38.867	2.248	1.349
B	25: 40: 50	5.5	10.833	20.345	32.093	3.419	0.840
C	12.5: 25: 40	3.225	13.667	25.448	40.698	3.403	0.859
C	16: 31.5: 50	4.128	10.833	20.345	40.698	4.293	1.065
D	12.5: 25: 50	3.438	10.833	20.345	32.093	3.419	0.840

F. Calculation of Permeabilities

Permeability tests of all test types were carried out for all the four shapes. More than 70 permeability tests have carried out. The permeabilities were calculated at four different discharges and the average results are put in this work. The permeabilities were calculated at different temperature and "have been standardized to 20 °C to neglect the permeant effect". The permeabilities were calculated by using Darcy's law:

$$q = k\,i\,A$$

Flow is said to be laminar if permeability remains constant with increase in hydraulic gradient. Also "Darcy's law holds good as long as 30% of material is below 2.54cm which is hardly neglected in our study". The permeabilities of four shapes are shown in table 2.

Table No. 2: Effective pore size and corresponding permeabilities for all test types and shapes

Test type	S_1, S_2, S_3 (mm)	S_4(mm)	d^*(mm)	Spherical	Elliptical	Blade	Angular
A	12.5	1.875	0.81	2.72	2.40	2.28	2.03
A	16	2.4	1.08	3.25	2.78	2.59	2.29
A	20	3	1.31	3.65	3.53	3.41	3.19
A	25	3.75	1.575	4.13	3.95	3.87	3.58
A	31.5	4.725	2. 16	7.64	6.83	5.95	4.08
A	40	6	2.5	8.58	7.85	6.77	5.06
A	50	7.5	3. 16	19.53	17.5	14.31	10.21
B	12.5:20:25	2.75	1.09	2.61	2.47	2.23	1.89
B	16:25:31.5	3.52	1.30	3.52	3.26	2.93	2.58
B	20:31.5:40	4.4	1.80	5.70	5.17	4.27	3.47
B	25:40:50	5.5	2.17	7.57	6.93	5.73	4.46
c	12.5:25:40	3.225	1.26	3.09	2.91	2.9 1	2.59
c	16:31.5:50	4.128	1.71	4.23	3.85	3.42	2.81
D	12.5:25:50	3.438	1.28	3.51	3.41	3.28	3.04

IV. RESULTS & DISCUSSION

From the test results of test type A, B and C for particular shape, it was confirmed that the effect of gradation is small and has been neglected. This is evident from permeability and Cc graph. "Variation of permeability with d10 follows the power law which is in conformity with the work of many researchers like Hazen, Taylor, Shepherd, Kozney- Karman and Terzaghi". From the results it can be clearly seen that the d* and the shape parameters fully determine "the permeability of the porous media. d* is the smallest void present and hence controls the permeability of the porous media". This d* corresponds to S7 of the porous media according to theoretical model used and results in increases in permeability of porous media as it increases. Increase in sphericity and shape factor increases the permeability. This is confirmed from the permeability, d* and shape parameter relations which hold good for any gradation, size and shape.

V. CONCLUSION

There are many “methods of finding permeability of porous media. Some of the methods are applicable in field whereas others are used in laboratory”. The methods used in lab are (a) Constant head and (b) Variable head methods. The falling head method is used to measure the permeability of soils of the order of I cm/sec. In the constant head method, permeability values from lcm/s to higher order can be measured easily. This type of test is suitable for coarse grained pervious soils where the quantity of flow is measurable in a reasonable time. Keeping in view the nature of material used in the present study, constant head experiments were carried in the laboratory. To find “the behavior of permeability with respect to varying effective pore channel for different primary assembly ratio of granular material with intervening size were carried out”. The experimental set up, materials used and experimental procedure adopted are described in the following sections. None of the mentioned equations presented above considers neither the effect of the entire grain size distribution on the permeability nor the shape parameters. “Since grain size distribution controls the nature of interconnections between pores, the entire grain size distribution, rather than a single point on the grain size distribution curve, needs to be considered to reliably estimate the permeability of granular soils”. It is clear that almost all researchers have put forward power relationship between permeability and effective size or diameter, which is mostly d10. Furthermore, “none of the previously developed equations considers the effect of density of porous media on permeability which hardly is considered as most of porous media are compacted to about 90%” naturally.

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