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Correlation of Hydraulic Conductivity with Grain size Distribution Parameters

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Abstract: Hydraulic conductivity is a soil characteristic which plays an important role in geotechnical and water resources projects making its determination an important task. Most convenient method to accomplish this task is by using empirical relationships correlating hydraulic conductivity with various properties of porous media.This study aims at the development of regression models to predict Hydraulic conductivity of sandy soils by incorporating two grain size distribution parameters which are the representative grain size and standard deviation of Grain size distribution. Linear and nonlinear regression models were developed and compared with already established empirical formulae.

Keywords: *Correlation, Least Square Regression Method, Hydraulic conductivity, Grain Size, Grain Size Distribution, Standard Deviation of Grain Size Distribution*

1. Introduction

Hydraulic conductivity is an important physical property of the soil, which represents the ease with which water flows through porous media. Determination of hydraulic conductivity is an important factor for various water resources and geotechnical projects and can be ascertained by field tests, permeameter tests or by empirical relationships. The Field method called pumping tests requires expensive machines. The permeameter tests are performed in laboratories and require time and sophisticated equipment. Empirical formulae are the correlations between hydraulic conductivity and various parameters affecting it. These empirical relationships are developed by statistical analysis of experimental data. This is the easiest and quickest method.

The objective of this study is to develop new statistical models to predict hydraulic conductivity using grain size distribution parameters. Although with hydromechanics point of view, pore size distribution is a better parameter, but determining the pore size distribution is very difficult task, hence it is substituted by easy to determine grain size distribution parameters. Representative grain size (d) and standard deviation (σ) are the two grain size distribution parameters selected for developing regression model.

2. Previous Work

Hazen [1] developed the following correlation for uniform sands

$$K=c.d_{10}^{2}$$

Where K is the hydraulic conductivity in gallon per feet^2 per day, c is a constant and d_{10} is the effective grain size in mm.

Uma et al. [2] also developed a correlation similar to that of Hazen and incorporated the effect of consolidation and cementation in their study.

$$K=c.d_{10}^{2}$$

Where K is the hydraulic conductivity in cm/sec, c is a constant with value of 6 and 3.8 for consolidated and unconsolidated aquifers respectively, d_{10} is the effective grain size in cm.

Shepherd [3] extended the Hazen's research and proposed the following expression

$$K=cd_{50}^{1.65-1.85}$$

Where K is the hydraulic conductivity in gallon per feet^2 per day, c is constant which varies from 800 to 300000, d_{50} is the mean grain size.

Alyamani and Sen [4] proposed the following expression.

$$K=1300(I_o + 0.025(d_{50}-d_{10}))^2$$

Where K is the hydraulic conductivity in m/day, d_{10} and d_{50} are the effective and mean grain sizes respectively in mm, I_o is the slope of the line joining d_{10} and d_{50}.

Salarashayeri & Siosemarde [5] proposed a linear relationship as given below

$$K=10.06 + 118.54(d_{10}) -12.50(d_{50}) - 7.32(d_{50})$$

Where K is the hydraulic conductivity in cm/sec, d_{10} is the effective grain size in mm, d_{50} is the mean grain size in mm and d_{60} is the grain size (in mm) to which 60% of the soil mass is finer by weight.

Most of the research work focused on correlating hydraulic conductivity with only different grain sizes while the standard deviation (σ) is also an important factor which affects hydraulic conductivity as pointed out by Muskat and Wyckoff [6] and Bear [7] .This study included standard deviation along with representative grain size as parameters to develop regression models.

3. Methodology:

Twenty one soil samples were collected from borehole site at Dera Bassi, Punjab. Hydraulic tests such as constant head permeability tests were performed on these samples in irrigation and hydraulics laboratory of PEC University of Technology, Chandigarh. Details of the different tests conducted on soil samples are given in the next section.

3.1 Sieve Analysis

Sieve analysis was performed on soil samples and grain size distribution curve was plotted in SigmaPlot version 12.5.The sizes such as d_{10}, d_{30}, d_{50} and d_{60} were determined for each sample from their respective grain size distribution curve. Grain size distribution curves of all samples are shown in Figure 1.

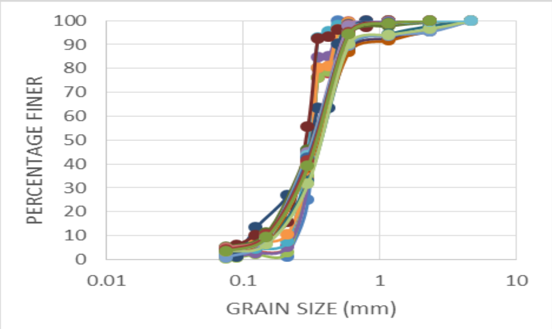

Figure 1: *Grain Size Distribution Curve of Samples*

d_{10} (mm), d_{30} (mm), d_{50} (mm) and d_{60} (mm) are summarized in Table 1.

Table 1: *Summary of statistics of d_{10}, d_{30}, d_{50} and d_{60}*

Statistics	d_{10}	d_{30}	d_{50}	d_{60}
Mean	0.178	0.266	0.333	0.361
Minimum	0.113	0.234	0.313	0.316
Maximum	0.259	0.307	0.326	0.413

Standard deviation (σ) was determined using following expression as given by Garde and Ranga Raju [8]

$$\sigma = \sqrt{\sum_{i=1}^{n} \Sigma (d_i - d_{50})^2 f_i}$$

Where d_i is the arithmetic mean of adjacent sieves, d_{50} is the mean grain size and f_i is the proportion of material retained between adjacent sieves.

σ (mm) and saturated hydraulic conductivity, K (mm/sec) for 21 samples are summarized in Table 2.

Table 2: *Summary of statistics of σ(mm) and saturated hydraulic conductivity (K in mm/sec)*

Statistics	σ	K
Mean	0.679	0.0804
Minimum	0.069	0.01233
Maximum	3.286	0.5500

3.2 Specific Gravity Test

The specific gravity of soil samples was measured by pycnometer method.

3.3 Constant Head Permeability Test

Experimental setup of constant head permeability test is shown in Figure 2. The main permeameter section consisted of a 101.6 mm internal diameter galvanized iron tube with a total length of 1006 mm and a test length of 46 cm.

All the hydraulic conductivity tests were performed at 40% porosity. The weight of the soil to be filled in permeameter was determined by the following equation

$$W_S = (1-n)V_T G_S \gamma_w$$

Where W_S is the weight of the material filled in permeameter, n is porosity taken as 0.4.V_T is the volume of the tube.G_S is the specific gravity of material and γ_w is the unit weight of water

Permeameter was connected to water supply and left for 24 hours to make the material saturated. The discharge was calculated by the volumetric method and hydraulic conductivity was calculated by Darcy's law.

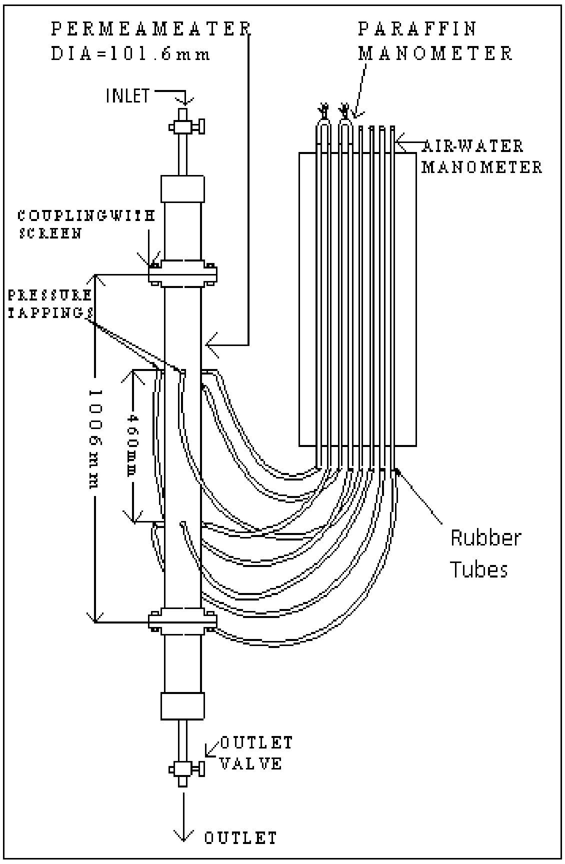

Figure 2: *Laboratory Setup of Constant Head Permeameter test*

Reynold's number and friction factor were calculated and plotted on log-log graph paper to validate the laminar flow conditions as shown in figure 3.

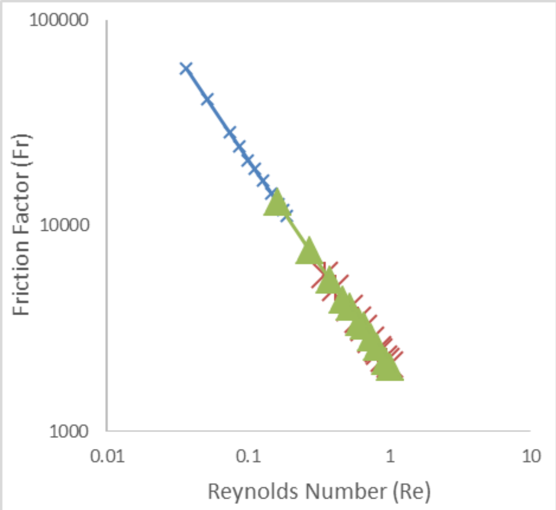

***Figure 3:** Plot of Friction Factor (F_r) Versus Reynolds Number (R_e)*

3.4 Statistical Analysis

The data collected was analysed using statistical approach and Least square regression analysis was performed using Minitab version.17 to develop linear and nonlinear equations. General equation of a regression model is given by the following expression

$$\hat{K_i} = \beta_0 + \beta_1 f(d) + \beta_2 g(\sigma)$$

Where f (d) and g (σ) are the functions of representative grain size and standard deviation respectively.

β_0, β_1 and β_2 are regression coefficients obtained by solving equations obtained by the condition given below

$$\frac{\partial(SSE)}{\partial \beta_i} = 0$$

These equations were compared on the basis of two statistical parameters.

First statistical parameter is the coefficient of determination (R^2) given by Walpole et al. [9] equation below.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(K_i - \hat{K_i})^2}{\sum_{i=1}^{n}(K_i - \bar{K})^2}$$

Where K_i is the hydraulic conductivity test data, $\bar{K}$ is the mean of hydraulic conductivity test data, $\hat{K_i}$ hydraulic conductivity obtained from the regression model, and n is the number of data.

Its value lies between zero and unity. A greater value of R^2 indicates a better fit of the data.

Second statistical parameter is the sum of squares of error (SSE), given by the following equation

$$SSE = \sum_{i=1}^{n}(K_i - \hat{K_i})^2$$

A lower value of SSE indicates a better model.

Various linear and nonlinear regression models were developed which were compared on the basis of above statistical parameters. Best of these models in terms of statistical parameters are given in next section.

4. Results of Regression Analysis

Regression models developed through least square regression analysis of 21 samples are given in table 3.

***Table 3:** Models developed through least square regression analysis*

No.	Equation
1	$K=-0.34 + 2.43d_{10} - 0.018\sigma$
2	$K=-0.27+ 2.42d_{10} - 0.205d_{50} - 0.016\sigma$
3	$K=-0.30+2.13d_{10} + 0.43d_{30} - 0.19d_{60} -0.014\sigma$
4	$K=-0.13+ 6.64d_{10}^2 - 0.004\sigma^2$
5	$K=-0.11+ 6.61d_{10}^2 - 0.19d_{50}^2 - 0.0037\sigma^2$
6	$K=42.46\, d_{10}^{4.189}\sigma^{-0.233}$

SSE and R^2 for these equations are given in table 4

***Table 4:** R^2 and SSE for regression models*

Equation No.	SSE	R^2
1	0.1024	0.6773
2	0.1020	0.6785
3	0.1018	0.6790
4	0.0877	0.7236
5	0.0875	0.7241
6	0.0801	0.7959

5. Comparison with Already Established Models

Hydraulic conductivity predicted by developed model (Eq. 6) and already established empirical equations were compared with experimentally observed values for 10 samples. Results of these comparisons are shown in Table5.

***Table 5:** Comparison of different methods for computing Hydraulic Conductivity (in mm/sec)*

Sample No.	Experimentally Observed Value	Predicted Values of hydraulic conductivity (mm/sec) by different models					
		Present model (Eq.6)	Hazen's Model	Uma's Model	Shepard's Model	Alyamani's model	Salarashayeri's Model
1	0.0193	0.019	0.059	0.354	0.076	0.768	0.375
2	0.0124	0.015	0.020	0.121	0.075	0.159	0.235
3	0.0129	0.015	0.025	0.154	0.080	0.226	0.257
4	0.0324	0.028	0.034	0.206	0.099	0.311	0.282
5	0.0129	0.018	0.021	0.127	0.082	0.162	0.236
6	0.0137	0.020	0.022	0.133	0.082	0.174	0.241

7	0.0176	0.024	0.024	0.144	0.086	0.192	0.247
8	0.0132	0.021	0.023	0.141	0.078	0.200	0.249
9	0.0325	0.028	0.028	0.172	0.098	0.233	0.260
10	0.0268	0.018	0.028	0.168	0.088	0.242	0.262

6. Conclusion

On the basis of the values of SSE and R^2, it can be concluded that Equation No.6 is the best regression model. This model shows that hydraulic conductivity has a positive correlation with effective grain size and negative correlation with the standard deviation.

Comparison between predicted values of hydraulic conductivity by developed model (Eq. 6) and already established empirical equations shows that the developed model is giving better results to predict hydraulic conductivity of sands.

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