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Evaluation of PSD Models for the Estimation of Hydraulic Conductivity for Different Soil Textural Classes

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***Abstract*—**The Hydraulic conductivity (K) of soil, is an important parameter that is used to predict the movement of water and the dissolved contaminants, if any, through it. It can be determined through different in-situ and lab methods; however, it can also be determined easily, using the PSD models or empirical equations developed for this purpose. These equations specifically utilize the particle size distribution (PSD) data of the soil, as movement of water, and hence the hydraulic conductivity depends upon the types and sizes of the soil particles. Most of these equations have been developed for the coarse-grained soil only like the sand and gravel, and some of them only consider the fine-textured soil. In actual condition, soil is not present only as the sand or gravel or as fine-textured only but is the combination of three important particles, which are sand, silt, and clay, due to which the permeability of the soil is affected. This research work is based on the hypothesis that the formulas developed for the estimation of K, the hydraulic conductivity of the soil, may not work properly due to the presence of other particles. For this, different empirical models were considered for only four textural classes of the soil i.e., sand, loamy sand, sandy loam, and silt loam. It was found that as the number of fine particles increases in the sand the formulas do not give a good estimate of the K value.

***Keywords*—** hydraulic conductivity, PSD model, effective size, soil texture.

I. Introduction

Soil is naturally a disperse, polyphasic, porous, and a diverse system. Innumerable discrete mineral particles of various sizes and composition naturally combine to make up the soil matrix [1]. These particles can be separated into groups to classify the soil in terms of relative proportions of its particle-size. The soil water filling the voids between the soil particles partially or completely makes its liquid phase, While the soil air or entrapped gases filling the soil voids, which are not occupied by soil water, is termed as the gaseous phase or the vapor phase [2]. The occurrence and movement of groundwater depends upon the porous media when it is completely saturated. As all the soils are permeable, water flows freely through their interconnected pores, even though it may be at a very slow rate in some soils [3]. The hydraulic conductivity (K) value is the key to the solution of several geotechnical engineering and hydrological problems like the modeling of underground flow of water, determination of the hydraulic properties of leachate water in waste disposal areas, calculation of the compressibility, and much more [4].

The 'K' value can be found by hydraulic methods or the correlation methods. The hydraulic methods can either be the field methods or the laboratory methods, while the correlation methods are based on relationships between hydraulic conductivity value and easily determining soil properties like texture, bulk density, etc., [5].

Different techniques are applied to find the K¬-value of the soil by field methods, depending upon the situation. For rapid testing, the small-scale methods are designed while the large-scale methods are used to get a representative K-value of soil body that is of a larger scale. Constant head and Falling head permeameter methods are based on Darcy's law of hydraulic conductivity to determine the K value in the laboratory of coarse and fine-grained soil, respectively [6].

Owing to the difficulties in the determination of the K value in the field and the laboratory different empirical formulas have been developed for the estimation of the K value Some of these are purely the PSD models as they consider the data of the particle-size distribution only, while other are the pedotransfer functions (PTFs) which not only consider some data of the PSD but also take into account some other properties of soil [7]. Where the permeability data is scarce and the region is comprised of a variety of soils making the direct measurements impractical for larger-scale studies, then these interrelationships can be useful and economically feasible for the estimation of K¬ values [8]. The determination of a relation between Ks and soil PSD data is dependent on the selection of a representative grain-size or particle size diameter, dn [9]. Later on, it was further concluded that the diameter of the pores also plays a more significant role in the estimation of K but their determination is a cumbersome job, therefore, the estimation of the hydraulic conductivity is mostly based on the particle size distribution (or PSD), which can be determine easily [10].

It was observed by the researchers that soil water retention characteristics are dependent upon the percentage of the soil particles i.e., sand, silt, and clay, the quantity of the organic matter, and the bulk density of the soils [11]. Mishra et. al. (1989), reported that as compared to the dynamic hydraulic data, the soil textural data can be a good alternative for estimating soil properties. It was further concluded that the ability of the PSD models to predict the hydraulic conductivity of the soil, was affected by the soil texture, which was generally neglected in those models [12].

The study objective was to check the effects of soil texture on the efficiency of some well-known PSD Models.

II. MATERIALS AND METHODS

In this study, 25 sets of soil samples were collected to evaluate the PSD models. The samples selected had a high proportion of sand particles as the PSD models selected for this research work were developed for the sand texture. The texture of the soil samples was tested according to the USDA soil classification system, these belonged to sand, loamy sand, sandy loam, and silt loam textural classes. Standard methods were applied for the investigation of saturated hydraulic conductivity (K) in the laboratory, and to determine the particle size distribution (PSD) of these samples.

TABLE 1: LIST OF THE EQUATIONS USED TO ESTIMATE THE HYDRAULIC CONDUCTIVITY OF THE SOIL (K)

Equation/Researcher Name	Type	Equation	Reference
Hazen (1893)	Quadratic	$K = \frac{g}{\upsilon} C_h f(n) d_{10}^2$ $K = c d_{10}^2$	Sezer et al. (2009)
Slitcher (1899)	Rational	$K = 0.01 \frac{g}{\upsilon} n^{3.287} d_{10}^2$	Sezer et al. (2009)
Beyer (1998)	Logarithmic	$K = 6 \times 10^{-4} \times \frac{g}{\upsilon} \log \frac{500}{C_u} \times d_{10}{}^2$	Rosas et al. (2014)
Alyamini and Sen (1993)	Quadratic	$K = 1300 \left[I_o + 0.025 \left(d_{50} - d_{10} \right) \right]^2$	Alyamini and Sen, (1993).
Kozeny (1953)	Functional	$K = 8.3 \times 10^{-4} \frac{g}{\upsilon} \frac{n^3}{(1-n)^2} d_{10}^2$	Sezer et al. (2009)
Gustafson (1984)	Functional	$K = 10.2 \times 10^6 \times \frac{(0.8 \times \frac{1}{2 \times \ln(C_u)} - \frac{1}{(C_u)^2 - 1})^3}{1 + (0.8 \times \frac{1}{2 \times \ln(C_u)} - \frac{1}{(C_u)^2 - 1})^3} \times \frac{1}{(\frac{1.3}{\log_{10} C_u} \times \frac{C_u^2 - 1}{C_u^{1.8}})^2} \times \left(\frac{d_{10}}{1000} \right)^2$	Svensson, (2014)

The PSD data was used to determine different soil parameters like, the grain diameters (mm) of which 10%, 30%, 50%, and 60% of all soil particles are finer by weight i.e., d10, d30, d50, and d60, respectively, also the coefficient of uniformity (Cu) of the soil. The soil porosity (η) and the bulk density (ρb) data were calculated using the general formulas proposed by Vukovic and Soro (1992). The mean values of all these soil properties are summarized in Table 1. It was clear that the most abundant particle of these soil samples was sand.

The data obtained by the soil tests were utilized in already developed empirical formulae and PSD models, given in Table 1, for estimating the K values, and the results were compared with experimental methods. The missing data like the porosity and bulk density of the soil, which are required in some equations were determined by using the general equation presented by Vukovic and Soro (1992).

TABLE 2: MEAN VALUES OF THE PARAMETERS OF THE SOIL USED IN THIS STUDY

Soil Class	Parameters										
	d_{10} (mm)	d_{30} (mm)	d_{50} (mm)	d_{60} (mm)	C_u	ρ_b (g/cm^3)	H	%Sand	%Silt	%Clay	K (cm/s)
Sand	0.202	0.300	0.487	0.483	2.51	1.66	0.37	89	7	4	$3.78*10^{-02}$
Loamy Sand	0.094	0.194	0.292	0.351	4.12	1.65	0.38	78	15	7	$4.44*10^{-03}$
Sandy Loam	0.042	0.115	0.179	0.232	8.53	1.75	0.34	68	25	7	$4.84*10^{-04}$
Silt Loam	0.015	0.073	0.222	0.333	20.13	1.88	0.29	32	58	10	$7.81*10^{-05}$

III. RESULTS AND DISCUSSION

In the original Hazen equation (Table 1), the constant c varies from 1 to 1.5, for the research work it was considered to be 1.25, and it was observed that the Hazen equation give a good result for the sand class but for the other three classes the estimated value of K by this equation was not satisfactory. The Slitcher equation cannot predict the K-value for medium-grained soils but overall, the result was satisfactory. The overall result by the Breyer equation was satisfactory but for the separate classes, it was not good in the estimation of the soil classes with a larger percentage of fine particles. The Alyamani and Sen equation was developed while testing the sandy soils therefore it was good in estimating the K-value of the sand and loamy sand, but as it incorporates the d50 value therefore as compared to the three classes, its prediction was relatively better for the other two classes as well. It was observed that the result of the Kozeny equation was similar to the Slitcher equation. The Gustafson equation also held good for the prediction of coarse-grained soils. Table 3 gives a clear picture of the r-square value of these equations.

TABLE 3: MEAN VALUES OF THE PARAMETERS OF THE SOIL USED IN THIS STUDY

Equation	R^2 for Sand	R^2 for Loamy Sand	R^2 for Sandy Loam	R^2 for Silt Loam	R^2 for types of soils combined
Hazen Original	0.71	0.63	0.0007	0.0077	0.72
Slichter	0.68	0.68	0.010	0.001	0.88
Beyer	0.74	0.60	0.004	0.010	0.70
Alyamini and Sén	0.78	0.62	0.013	0.140	0.78
Kozeny	0.67	0.69	0.014	0.014	0.60
Gustafson	0.74	0.42	0.004	0.001	0.82

CONCUSLION

It was concluded that the empirical equations which had been developed for the estimation of K generally considering the effective diameter along with other properties of soil predicted well about the saturated hydraulic conductivity of the soil having a larger amount of sand. Moreover, it was found that besides the Slitcher equation, the Gustafson equation also predicted well about the K value of the soil with an R-square value of 0.82, the reason was that, that the equation took use of the coefficient of uniformity of the soil (Cu). It was also observed that these models do not hold good for every texture of the soil, even if there is not a very large deviation of percentages of particles. It is therefore recommended to develop an equation which can be used for different soil classes with a wide range of percentage of the particles.

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