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Relationship between hydraulic conductivity and formation factor of coarse-grained soils as a function of particle size

H. Choo [a], J. Kim [a], W. Lee [a], C. Lee [b,*]

[a] School of Civil, Environmental, and Architectural Engineering, Korea University, Anam-dong 5-ga, Seoul 136-713, South Korea
[b] Department of Marine and Civil Engineering, Chonnam National University, Yeosu 550-749, South Korea

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ABSTRACT

This theoretical and experimental study investigates the variations of both the hydraulic conductivity and the electrical conductivity of coarse-grained soils as a function of pore water conductivity, porosity, and median particle size, with the ultimate goal of developing the relationship between the hydraulic conductivity (K) and the formation factor (F) in coarse-grained soils as a function of particle size. To monitor the variations of both the hydraulic conductivity and electrical conductivity (formation factor) of six sands with varying particle sizes, a series of hydraulic conductivity tests were conducted using a modified constant head permeameter equipped with a four electrode resistivity probe. It is demonstrated that K of the tested coarse-grained soils is mainly determined by the porosity and particle size. In contrast, the effect of particle size on the measured electrical conductivity (or F) is negligible, and the variation of F of the tested soils is mainly determined by porosity. Because the porosity may act as a connecting characteristic between K and F, the relation between them in coarse-grained soils can be expressed as a function of particle size. Finally, simple charts are developed for estimating the hydraulic conductivity of coarse-grained soils from the measured particle sizes and formations factors.

1. Introduction

The reliable estimation of hydraulic conductivity (K) in a porous media is a very important task in many areas of engineering, soil science, and industry because hydraulic conductivity is an essential property describing the ability of soils to conduct fluid through the pore space between soil particles (Alyamani and Sen, 1993; Costa, 2006; Mitchell and Soga, 2005). The K of soils has been measured in the field using various hydrogeological methods, including ring infiltrometers, two- or four-well methods, constant or falling head permeameters, and other methods (Daniel, 1989; Lee et al., 1985). However, these methods are laborious and expensive. Furthermore, the measured K resulting from these hydrogeological methods represents the average of a large volume of tested areas (Khalil and Santos, 2009; Sikandar and Christen, 2012; Slater and Lesmes, 2002). Consequently, the estimation of K using geophysical methods (i.e., electrical conductivity measurement) has attracted the attention of many researchers because the measurements of electrical properties of soils are nondestructive, continuous, reliable, and relatively inexpensive (Gomez et al., 2010; Kelly and Frohlich, 1985; Khalil and Santos, 2009; Mazac et al., 1985; Sikandar and Christen, 2012; Slater and Lesmes, 2002; Urish, 1981; Worthington, 1997). In particular, these previous studies demonstrated that there is a strong correlation between K and the formation factor F ($F = \sigma_w / \sigma_{mix}$, where σ_w = pore water conductivity and σ_{mix} = electrical conductivity of media) for coarse-grained soils because both hydraulic and electrical conductions in coarse-grained soils mainly occur through the pore space between soil particles (Milsch et al., 2008).

Previous empirical relations between K and F showed debatable results, with some investigations reporting a direct relationship between those two (Kelly and Frohlich, 1985; Perdomo et al., 2014; Sikandar and Christen, 2012; Urish, 1981), but the others showing an inverse relationship (Archie, 1942; Frohlich et al., 1996; Gomez et al., 2010; Heigold et al., 1979; Milsch et al., 2008). These previous empirical relations between K and F were generally derived for local field conditions; therefore, each relation may be site-specific, resulting in debatable (or at least inconsistent) results. In contrast, previous studies using controlled laboratory tests with theoretical background showed that the relation between K and F can be either direct or inverse according to the results of the electrical property measurements (Khalil and Santos, 2009; Mazac et al., 1985; Worthington, 1997). When the measured electrical conductivity (or resistivity) can be captured by Archie's equation (a decrease of electrical conductivity with a decrease in porosity), the relationship between K and F is inverse, while the relationship is direct in cases where the result is a non-Archie type.

Additionally, previous empirical relations generally didn't consider the impact of particle size on the relation between K and F. In theory, the K of soils is determined by the pore size and the distribution of pore space. However, both parameters are not easy to measure;

* Corresponding author.
E-mail addresses: choohw@gmail.com (H. Choo), ksmart@korea.ac.kr (J. Kim), woojin@korea.ac.kr (W. Lee), changho@jnu.ac.kr (C. Lee).

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Table 1
Exponent m in Archie's equation for coarse-grained soils.

m	Description	Reference
1.3	Unconsolidated sand	Archie (1942)
1.5	Marine sand	Taylor-Smith (1972)
1.4–1.66	Quartz and dolomite sand	Barnes et al. (1972)
1.52–1.58	Natural quartz sand	Windle and Wroth (1975)
1.40–1.52	Rounded and shaley sands	Jackson et al. (1978)
1.45	Crushed sand	Kim et al. (2011)

Note: Archie's equation = Eqs. (10) or (11).

therefore, the K of coarse-grained soils is generally estimated using the easy measurable soil particle characteristics, including particle size, packing density, uniformity coefficient, and particle shape (Bear, 1988; Budhu, 2008; Chapuis, 2004; Chapuis, 2012; Taylor, 1948). Note that the particle size captures the pore size, and the others capture the distribution of pore space. Because the porosity directly reflects the packing density of soils, along with the information of the coefficient of uniformity and particle shape (Mitchell and Soga, 2005; Youd, 1973), many previous K estimating formulas were expressed as the function of the particle size and porosity of coarse-grained soils (a summary of previous K estimating formulas can be found in Chapuis (2012)). In contrast, F in coarse-grained soils is not affected by particle size, and is typically a function of porosity only (Archie, 1942; Choo and Burns, 2014; Klein and Santamarina, 2003). Therefore, a link between K and F in coarse-grained soils should be a function of particle size.

The present investigation aims at developing the relationship between K and F in coarse-grained soils as a function of particle size. Previous hydraulic and electrical conductivity formulas were reviewed to find a physical mechanism controlling the relationship between K and F. In addition, a series of hydraulic conductivity tests for six sands with varying particle sizes were conducted using a modified constant head permeameter equipped with four electrode resistivity probe.

2. Theoretical framework

2.1. Hydraulic conductivity

In this study, the relationship between K and F is developed using the porosity as the medium connecting them each other, which will be shown in the later part of this study. Therefore, among the various K estimating formulas (Chapuis, 2012), the following paragraphs review the Kozeny–Carman and modified Hazen formulas because both are used extensively and are the function of particle size and porosity.

The Kozeny–Carman formula (K-C formula), which links fluid resistance and porous media properties, is the most frequently quoted hydraulic conductivity equation for coarse-grained soils because it includes the effect of fluid properties (unit weight of fluid, fluid viscosity), geometrical properties of soils (shape factor, specific surface,

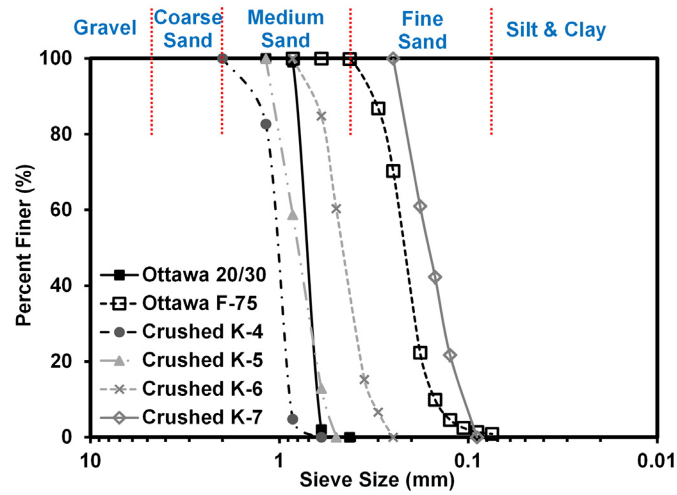

Fig. 1. Particle size distributions of the tested materials. Information of soil classification according to the USCS is also included in above figure.

tortuosity, porosity), and an external property (saturation) (Bear, 1988; Carrier, 2003; Chapuis and Aubertin, 2003; Freeze and Cherry, 1979):

$$K = \frac{\gamma_w}{\mu} \cdot \frac{1}{C_S \cdot S_0{}^2 \cdot T^2} \cdot \frac{n^3}{(1-n)^2} \cdot S^3 \tag{1}$$

where γ_w = unit weight of fluid (kN/m^3); μ = viscosity of fluid (N·s/m^2); C_s = channel shape factor; S_0 = volume-based specific surface (m^{-1}); T = tortuosity; n = porosity; and S = degree of saturation.

Among the variables in Eq. (1), the estimation of the volume-based specific surface (S_0) is the most challenging. For mono-sized spherical particles, S_0 (area/volume) = 6/sphere diameter. However, real coarse-grained soils have varying particle shapes and particle size distributions. Consequently, previous researchers estimated S_0 using an equivalent particle size (D_{eq}) and a particle shape factor (SF) (Carrier, 2003; Chapuis and Aubertin, 2003). Additionally, C_s and T are known to influence each other (i.e., inverse relationship), which results in $C_s \cdot T^2 \approx 5$ (valid for sand and silt) (Bear, 1988; Carrier, 2003). Therefore, under the assumption of fully saturated conditions (i.e., S in Eq. (1) = 1), Eq. (1) can be written as:

$$K = \frac{\gamma_w}{5 \cdot \mu} \cdot \left(\frac{D_{eq}}{SF}\right)^2 \cdot \frac{n^3}{(1-n)^2} \tag{2}$$

where SF = particle shape factor (round particles: 6.0–6.6; angular particles: 7.7–8.4) (Carrier, 2003; Freeze and Cherry, 1979; Loudon, 1952);

Table 2
Material properties.

Properties	Ottawa 20/30	Ottawa F-75	Crushed K-4	Crushed K-5	Crushed K-6	Crushed K-7	Method
D_{60}	0.740	0.233	1.053	0.858	0.500	0.180	ASTM D422
D_{50}	0.720	0.217	1.010	0.798	0.467	0.163	ASTM D422
D_{10}	0.620	0.150	0.885	0.584	0.330	0.106	ASTM D422
D_{eq}	0.687	0.206	1.010	0.754	0.436	0.150	Eq. (3)
C_u	1.194	1.553	1.190	1.469	1.515	1.698	ASTM D422
G_s	2.65	2.65	2.65	2.65	2.65	2.65	ASTM D854
e_{max} (n_{max})	0.742 (0.426)	0.813 (0.448)	1.077 (0.519)	1.071 (0.517)	1.035 (0.509)	1.041 (0.510)	ASTM D4253
e_{min} (n_{min})	0.502 (0.334)	0.540 (0.351)	0.707 (0.414)	0.688 (0.408)	0.656 (0.396)	0.600 (0.375)	ASTM D4254
R	0.90	0.75	0.20	0.18	0.17	0.20	Wadell (1935)

Note: D_{60} = particle size corresponding to 60% of the sample passing by weight; D_{50} = median particle size (50% passing); D_{10} = effective particle size (10% passing); D_{eq} = equivalent particle size; C_u = uniformity coefficient; G_s = specific gravity; e_{max} = maximum void ratio; e_{min} = minimum void ratio; n_{max} = maximum porosity; n_{min} = minimum porosity; R = roundness.