▌慶北大農學誌(Agric. Rex. Bull. Kyungpook Natl. Univ.) 29(2011. 12) 29~35

투수계수로부터 입도분포 자료의 추정

은코모제피 템바 · 정상옥

경북대학교 농업토목공학과

Estimation of grain size data from the hydraulic conductivity

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Abstract

The relationship between hydrologic processes and scale is one of the more complex issues in surface water hydrology. Disturbances that change vegetation and/or soil properties have been known to subsequently alter the landscape. The primary objective of this study was to estimate the grain size of soils with different properties from the hydraulic conductivity using pedotransfer functions. The double ring infiltrometer method was used to measure the vertical hydraulic conductivity of three soils under different soil planar surface treatments. Seven selected pedotransfer functions were used to estimate percentile diameters and the reduction in infiltration caused by compaction was misconstrued as caused by changes in percentile diameter. Results showed that compaction on the sandy loamy foot paths reduced the hydraulic conductivity by about 50%. The study showed that perceptual models of infiltration processes and appreciation of scale problems in modeling are far more sophisticated than normally presented in texts. Hydraulic measurement methods are still relevant and will provide significant information of grain size of the soils.

Key words : grain size, hydraulic conductivity, soil compaction, pedotransfer function

Ⅰ. Introduction

Increasing infrastructural development has led to a quantifiable decrease in the area available to storm water for infiltration. Instead of returning to the soil through infiltration, storm water alters the hydrologic cycle by flowing over impervious areas such as parking lots, rooftops, greenhouses and roadways. Shallow impoundments are therefore introduced to reduce post-development runoff volumes and peak flow rates to pre-construction levels, while simultaneously increasing recharge (Braga et al., 2007). The design, construction, and operation of these infiltration basins to present time has not been standardized due to a lack of clear understanding of the infiltration processes that occur in these structures.

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(Received November 21. 2011; Examined December 8, 2011; Accepted December 17, 2011)

Robert E. Horton is best known as the originator of the infiltration excess overland flow concept for storm hydrograph analysis and prediction, which in conjunction with the unit hydrograph concept, provided the foundation for engineering hydrology for several decades (Beven, 2004). Transmissivity, hydraulic conductivity, and storativity are important parameters for developing local and regional ground water resources (Mace et al., 1999). Infiltration models often rely on an effective hydraulic conductivity (also known as the coefficient of permeability) which can be determined in the field from rainfall simulation experiments on small plots (Langhans et al., 2011).

The main factors influencing the infiltration capacity of various media have been investigated experimentally. Results from these studies indicate that the infiltration capacity is influenced by physical properties of soil such as soil texture, soil density and soil moisture and residue cover, water depth on soil surface and rainfall intensity. Li and Fan (2009) found that the soil density had the largest influence, the soil texture the second and water depth on soil surface the least to the accumulated infiltration. In another study, when the climate and soil type were the same, the soil texture and coarse root mass, but not aboveground biomass, were correlated with infiltration capacity (Thompson et al., 2010).

Review of relevant literature shows that there is widespread recognition that important interactions and feedbacks occur between vegetation, runoff, infiltration and soil properties over a range of scales. And also information on the control mechanisms of water infiltration is available. In general, it is proposed that disturbances that change vegetation and/or soil properties can trigger persisting alterations in soil hydrology and eventually change a functional landscape that efficiently captures, retains, and utilizes water and nutrients into a dysfunctional one that no longer can efficiently capture these resources (Chartier et al., 2011).

However, the relationship between hydrologic processes and scale is one of the more complex issues in surface water hydrology. The measurement of the infiltration process and quantification of its spatial variability is difficult due to inherent differences with the measurement methods and the scales at which they are applied (Paige and Stone, 2003). To lessen the burden, indirect methods such as pedotransfer functions have been developed based on multiple linear regression and neural network model in order to estimate saturated hydraulic conductivity from readily available soil properties (Ghanbarian-Alavijeh et al., 2010). Computer programs use a variety of equations including the Green and Ampt, Fletcher, and Fok and Hansen equations. Calculations can be based on hydraulic methods using Darcy’s law or correlation methods. Present study will focus on seven commonly used correlation formulas. These formulas are easily incorporated into software that will calculate and plot particle size accuumulation curve. And then, the estimated hydraulic conductivity of a soil layer could be calculated. The derived modified equations from these computer programs are usually tested on sample sites on which the infiltration and soil properties will have been measured.

The primary objective of this study was to estimate the grain size of soils with different properties from the measured hydraulic conductivity using pedotransfer functions. The grading characteristics are required in the design of infiltration basins or envelop material where the desired hydraulic conductivity is known. The double ring infiltrometer method is used to measure the vertical hydraulic conductivity on three planar soil surfaces with different properties.

II. Materials and methods

1. Experimental area

An area on the Kyungpook National University Campus in the northern part of Daegu (128.583 E 35.917

N; elevation: 107m) was used to conduct double ring infiltrometer tests. The soil was tilled, levelled and allowed to settle for several months and was covered by lawn and weeds. Tests were carried out on 3 types of land uses which were classified as area with grass cover (A) the pathway (B) and pit sand (C) where weeds were allowed to grow. Soils at A and B points were sandy loams and soil at C was sand from the feel tests.

2. Pedotransfer functions

Seven different equations given below can be used to determine the hydraulic conductivity from grain size data from sieve analysis as described in Carlson (2007) and Barry et al. (2010)

Hazen Formula	$K = \frac{g}{v} 6 \times 10^{-4} [1 + 10(n - 0.26)] d_{10}^{2}$	(1)
Sauerbrei Formula	$K = 3.49 n^{3} (1 - n)^{-2} t d_{17}^{2}$	(2)
Kozeny Formula	$K = 5400 n^{3} (1 - n)^{-2} d_{10}^{2}$	(3)
USBR Formula	$K = 0.36 d_{20}^{2.3}$	(4)
Pavchich Formula	$K = t d_{17}^{2}$	(5)
Slitcher Formula	$K = 4960 n^{3.287} d_{10}^{2}$	(6)
Terzaghi Formula	$K = \frac{g}{v} R (n - 0.13)^{2} (1 - n)^{-\frac{1}{3}} d_{10}^{2}$	(7)

where K is the hydraulic conductivity (m/day), g is the acceleration of gravity, ν is the kinematic viscosity at water temperature of 30℃, R is an empirical coefficient dependent on nature of grain surface, n is the porosity, d_{10}, d_{17}, d_{20} are the of grain diameters in the 10^{th}, 17^{th}, 20^{th} percentiles (mm), and t is a temperature correction factor which is 1.313 for a water temperature of 30℃.

Although most formulas were developed 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, they are frequently used to estimate the permeability of in situ soil (Carrier, 2003). In most studies, porosity values are obtained as a characteristic of the soil type and generally ranges from 0.38-0.44 (MDSNR, 2005 and EVS, 2011) and an average value of 0.4 was used in this study.

3. Apparatus and design

Single or double ring infiltrometers can be used to estimate the infiltration capacity and the vertical hydraulic conductivity. Single ring infiltrometers however, tend to overestimate vertical infiltration rates. This has been attributed to the fact that the flow of water beneath the cylinder diverges laterally due to capillary forces within the soil, resulting in a greater infiltration rates than the actual vertical infiltration. Double-ring infiltrometers minimize the error associated with the single ring method because the water level in the outer ring forces vertical infiltration of water in the inner ring (Gregory et al., 2005). The double ring infiltrometer used in this study consisted of two metal cylinders (30cm and 70cm diameter) that were partially driven into the soil. The inner and outer rings were filled with water, and the rate at which the water in the inner ring moved into the soil was measured. The falling head operational technique was employed in this study. In the falling head method, the sample is first saturated and the water is allowed to flow through the soil without maintaining a constant pressure head. It was assumed that when the rate became constant the saturated infiltration rate for the particular soil had been reached.

III. Results and Discussion

1. Measured infiltration data

The measured final infiltration rates into the soil ranged from 1.7 to 3.8 m day^{-1} over all sites as shown in Table 1. These rates are representative of moderately compacted fine sandy loamy soils as in other studies by Langhan et al. (2011) and Braga et al. (2007), etc. Site C (sand pit) had the highest infiltration rate while site B (foot path) lowest. The sites A and B had the same soil type, but the surface at B however, was compacted as a result of shortcut foot paths. Though site B was used as a pathway it showed a relatively high infiltration rate because of the thriving vegetation. Compaction by human walks could reduce the infiltration rate of a sandy loamy soil by about half as shown in Table 1.

Figure 1 shows plots of the infiltration rate against time. Site B has a very low infiltration rate thereby possesses much lower infiltration capacity. Site C had much higher initial infiltration rates than recorded because the water quickly sank before the experimenter could record and refill the rings.

Table 1. Measured final infiltration rate (m day^{-1})

Test no.	Site A	Site B	Site C
Soil texture	Sandy loam	Sandy loam	Sand
1	2.592	1.656	3.792
2	3.456	1.872	-
3	3.072	1.488	-
Mean	3.048	1.680	3.792

2. Pedotransfer functions

Table 2 shows the results of the 7 selected pedotransfer functions where the final infiltration rate was taken as hydraulic conductivity. The functions gave different values of d_{10} that range from 0.009mm to 0.111mm for the three sites.

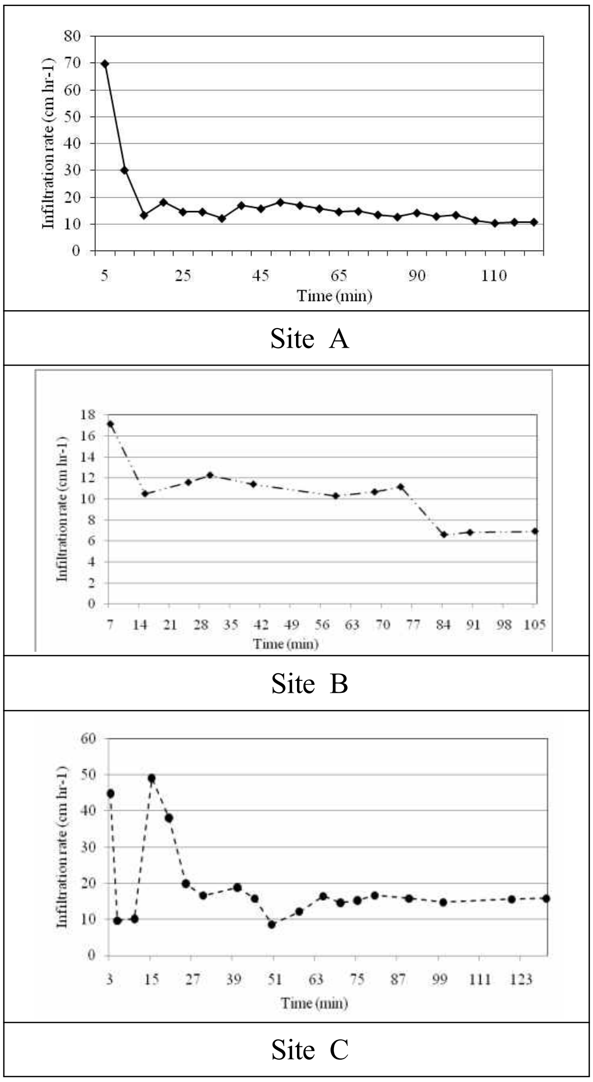

Fig. 1. Plots of the infiltration rate with time

Pathway compaction changes the porosity of the thin upper soil layer. The porosity is an input in most of the infiltration equations. However, still most pedotransfer functions refer soil porosity and K to a characteristic of the pore size distribution, grain size distribution, soil texture or soil mapping units

Table 2. Estimated percentile diameters of soil from correlation methods.

Site	Measured K(m d^{-1})	d_{20} (mm)	d_{10} (mm)				d_{17} (mm)	
		USBR	Kozeny	Slitcher	Terzaghi	Hazen	Pavchich	Sauerbrei
A	3.05	2.53	0.056	0.111	0.019	0.013	1.52	1.93
B	1.68	1.95	0.042	0.083	0.014	0.009	1.13	1.43
C	3.80	2.78	0.063	0.125	0.021	0.015	1.70	2.16

(Oosterbaan and Nijland, 1994). Previous studies have found that some pedotransfer methods over estimate whilst others under estimate the hydraulic conductivity computed from percentile diameters (Mbonimpa et al., 2002; Odong, 2007 Carrier, 2003). Hazen formula gave the best hydraulic conductivity estimation among the formulas despite its simplicity and ease of memorization (Odong, 2007 Cronican and Gribb, 2004). Similarly, the Slitcher under estimated the hydraulic conductivity from grain size (Odong, 2007).

Despite varying predicted diameters, all functions could be used to predict that the sandy soil (site C) had larger percentile diameters than the loamy sandy soil (site A and B). This could be attributed to the fact that in soils which have no systematic continuous pores, the soil permeability is related to the grain-size distribution.

Based on these results, the raw form of these functions cannot be used in land drainage designs because the homogeneous, isotropic, purely-granular soils to which they apply are rare. Mathematical models of hydrologic and agricultural systems require knowledge of the inter-relationships between numerous factors such as the soil moisture content, soil water pressure and unsaturated hydraulic conductivity (Kumar and Mittal, 2008). The inclusion of the specific surface ratio, the actual porosity, and shape factors for the particles and the voids would give better results (Oosterbaan and Nijland, 1994). The pore size distribution, the regularity of the pores, and their continuity has a great influence on the soil's K values. Nevertheless, the study and characterization of the porosity aiming at an assessment of the K values does not seem to be sufficiently advanced to be practical on a large scale.

3. Limitations of the infiltrometer method

The double ring infiltrometer method is associated with disadvantages that could lead to the inaccuracy of results as given in Smedema et al. (2004), i.e.

- Is inaccurate in swelling soils
- The final infiltration rate only approximates the saturation hydraulic conductivity.
- A number of replicates have to be undertaken due to soil variability
- The disturbance of soil when driving the infiltrometer ring into the soil
- Erroneous results.

Given this possible sources of inaccuracy in the measurement of K, more replications will reduce the error. This is difficult because the method is time consuming and very laborious.

IV. Conclusions

In this study, the results from the double ring infiltrometer measurements illustrated the variability of infiltration rates at the 3 sites. Pedotransfer functions were used to estimate the grain size distribution of soils with different properties from the measured hydraulic conductivity. It was shown that compaction as a result of the formation of foot paths will significantly affect the infiltration rate. However, it is evident from the results that the correlation methods are designed for specific soils and that the merits of one method over another would be application dependent. Although hydraulic measurements are expensive, time consuming, and laborious, but significant amount of information can be obtained from these measurements in terms of the infiltration and runoff. Further research with the aim of improving concepts of infiltration capacity and the performance of runoff and erosion models could focus on the interaction of soil properties, sedimentary seal, preferential flow, inundation and rainfall intensity. Stakeholders interested in sustaining the long term productivity of the soil and vegetation resources will be able to minimize runoff and soil loss thereby increasing infiltration and biomass.

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