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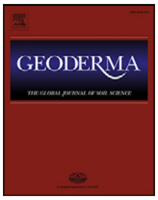

Characterizing the spatial variability of the hydraulic conductivity of reclamation soils using air permeability

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ABSTRACT

The saturated hydraulic conductivity (K_s) is a key property in the design of reclamation soils, influencing key aspects of the water balance including infiltration and net percolation. The conventional field method of measuring K_s for reclamation soils has been the use of water infiltration tests such as the Guelph permeameter (GP). However, the time required to conduct a large number of water infiltration tests can make it difficult to obtain a sufficiently large dataset to define the spatial variability of the large areas associated with mine site reclamation. The objectives of this study were: (1) to compare the K_s estimated from air permeability measurements with those measured using a GP and (2) to use air permeability measurements to characterize spatial variations of K_s for two reclamation sites, one on a lean oil sands dump at the Aurora oil sands mine in Northern Alberta, and a second on a waste rock storage area at the Key Lake Uranium Mine in Northern Saskatchewan. The results indicated that the K_s values estimated from air permeability measurements were similar to those measured using a GP if the air permeability measurements were adjusted for differences between in situ water contents and field capacity water contents. The probability distributions of K_s values obtained from both measurement methods were also found to be similar at a 0.01 level of confidence. Geostatistical analysis revealed a weak spatial dependency in K_s values, with an effective range of 158 m for the Aurora site and a non-significant spatial structure for K_s at the Key Lake mine site. This paper provides a practical example of how air permeability measurements combined with a limited program of GP testing can be used to characterize spatial variability of K_s on reclamation soils.

1. Introduction

Soil cover systems are used extensively to reclaim mine waste such as overburden, tailings or waste rock. The saturated hydraulic conductivity (K_s, m s^{-1}) is a key property governing the performance of these covers in that it influences key aspects of the water balance including infiltration and net percolation. In many cases, in situ testing is required to both characterize the cover soil and to evaluate the spatial distribution of K_s following construction of the reclamation cover. The hydraulic properties of reclamation soil covers can also evolve over time as a result of changes in secondary structure brought about by processes such as freeze–thaw or wet–dry cycles, or bioturbation processes caused by rooting or burrowing animals. All of these processes can lead to the formation of macropores and fractures, which increase the hydraulic conductivity over time (Meiers et al., 2011). Therefore, accurate knowledge of K_s and its spatial variability is important for understanding the hydrology of reclamation covers, and provides key parameters for water balance and solute transport models (Swanson et al., 2003; Huang et al., 2015a).

One of the common methods of measuring the K_s in situ is the Guelph permeameter (GP). This method has been shown to provide a valuable estimate of K_s (Reynolds and Elrick, 1986; Meiers et al., 2011); however, the GP method is time consuming and labor intensive (Reynolds and Elrick, 1986; Meiers, 2002). This makes it challenging to use this method to acquire sufficient test data to interpret spatial variability in K_s over the large areas involved in mine site reclamation.

The value of K_s can be estimated from field measurements of air conductivity (K_a, m s^{-1}) using the following equations as shown by Loll et al. (1999), Iversen et al. (2001), Wells et al. (2006), Chief et al. (2008), Rodger and Barbour (2008), Huang et al. (2015b) and others:

$$K_a = k_a \rho_a g / \mu_a \tag{1}$$

$$K_s = k_w \rho_w g / \mu_w \tag{2}$$

where k is the intrinsic permeability [m^2], ρ is the fluid density [kg m^{-3}], g is the gravitational constant [m s^{-2}], μ is the dynamic viscosity of fluid [kg (m · s)$^{-1}$], and subscripts a and w refer to air and water, respectively.

Theoretically, the intrinsic permeability of a porous media, as estimated from measurements using water or air, should be the same (i.e.

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k_a is equal to k_w) if the media is considered to be inert and the testing is done at identical fluid contents of the respective phases (Wells et al., 2007). However; in practice, there are factors that may result in different values for the intrinsic permeability as measured by air and water. The volume of the soil may change (e.g. shrinkage or swelling) due to the introduction of air or water which can lead to a change in the pore-structure within the soil (Bear, 1972). This can include changes in the water chemistry during GP testing which can lead to particle dispersion or changes in soil structure (Quirk, 1986). The flow of air may not represent the viscous, laminar flow of water due to slippage along solid boundaries or the development of turbulent flow, and in the case of water flow, there may be entrapped air within the soil which blocks water movement through all of the pores (Iversen et al., 2003; Huang et al., 2015b). Despite these problems, the k_a measured at or near field capacity has been shown to provide a useful estimate of K_s, since the air flow (in a dry soil) and water flow (in a saturated soil) are dominated by the pore distribution and structure associated with the largest pore sizes (Watson and Luxmoore, 1986; Kelln et al., 2009). For example, Riley and Ekeberg (1989), Blackwell et al. (1990), Loll et al. (1999) and Iversen et al. (2001) have successfully predicted K_s using the measurements of K_a at a soil water suction of 50 cm or 100 cm H_2O in undistributed soil cores.

The measurement of the K_a is rapid and easy and has proven useful to characterize the spatial variability of K_s in natural soils. Loll et al. (1999) used the stochastic analyses of field scale infiltration and ponding during a rainstorm event to evaluate the accuracy and usefulness of the spatial variability of K_s values as estimated from K_a measurements. Their results showed that bias appeared between the predicted and measured values, but much less than the sampling uncertainty associated with the estimation of spatial variability in K_s values from a limited number of samples. Iversen et al. (2003) developed a portable air permeameter (AP) to measure the K_a in order to characterize the spatial variability of K_s at five field sites, and their results indicated that three out of five sites showed a spatial correlation to K_s, with correlation distances as low as 30 m and higher than 120 m. Wells et al. (2007) used K_a measurements to estimate the K_s values for 5 granular soils covering a wide range of hydraulic conductivity, and found that the indirect estimations of K_s from K_a measurements were in close agreement with values determined using the constant head permeameter. Previous researchers have shown that AP techniques are particularly suited to sandy or structured natural soils where bulk water movement under gravity is dictated by the distribution of macropores (Wells et al., 2007; Iversen et al., 2001).

A relatively large set of literature has described the spatial variability of K_s for natural soils (Mohanty et al., 1994; Buttlea and Houseb, 1997; Regalado and Muñoz-Carpena, 2004; Gupta et al., 2006); however, similar literature for the spatial variability for constructed reclamation soils is lacking. Gwenzi et al. (2011) measured K_s for a sand cover at an Australian Kwinana Bauxite residual disposal area using the Philip–Dune permeameter (Muñoz-Carpena et al., 2002) and GP and evaluated the spatial variability of K_s using univariate and geostatistical analyses. Their results indicated that the K_s values of the soil cover were very high and ranged from 7×10^{-05} to 2×10^{-03} m s^{-1}, exceeding the values for natural sandy soils by several orders of magnitude. Geostatistical analyses revealed a spatial structure in lateral and vertical K_s data with a correlation range of 8 m and 0.4 m, respectively. Huang et al. (2015b) compared K_a measurements to GP measurements of K_s for three types of reclamation soils at oil sands mines near Fort McMurray, Alberta, Canada. The results highlighted that the values of K_s estimated from measured K_a values were higher than the values of K_s measured directly using the GP. This was assumed to be due to swelling of the clay rich soils or due to air-entrapment during GP measurements. Somewhat surprisingly, although the magnitude of K_s was overestimated, the variability of K_s was captured by the AP measurements.

The objectives of this study were: (1) to compare the K_s estimated from AP measurements with those measured using a GP and (2) to use AP measurements to characterize spatial variations of K_s for two reclamation sites, one on a lean oil sands dump at the Aurora oil sands mine in Northern Alberta, and the second on a waste rock dump at the Key Lake Uranium Mine in Northern Saskatchewan.

2. Materials and methods

2.1. Study sites

The locations of the two study sites are shown in Fig. 1. The first site is relatively flat with an average grade of approximately 1.6% located at a lean oil sands (LOS) dump at the Aurora oil sands mine operated by Syncrude Canada Limited in Northern Alberta. This site consists of 36 prototype watersheds constructed on a LOS overburden dump. AP and GP methods were utilized to characterize the overburden LOS. This material consisted of 2.7% bitumen and 97.3% mineral sandy loam, with mean particle sizes of clay, silt, and sand of 12.2%, 30.3%, and 57.6%, respectively.

The second site is located at a waste rock dump at the Key Lake Uranium Mine operated by Cameco Corporation in Northern Saskatchewan. This site consists of a plateau cover constructed with glacial till (pink till), and a sloped (4H:1V) cover constructed with a second glacial till (brown till) (Fig. 1). The mean clay, silt, and sand size fractions of the pink till were 5.8%, 8.4%, and 85.8%, respectively, while that of the brown till were 1.6%, 19.8%, and 78.6%, respectively (Zettl et al., 2014).

2.2. Field measurements

The AP tests were undertaken using an AP modified from a design developed at the University of Saskatchewan by Rodger (2007) and described by Rodger and Barbour (2008) and Huang et al. (2015b). The test procedure involved insertion of a 15 cm diameter steel tube to a depth of 10 cm. The soil sample size of the AP measurements was 1766 cm^3. The top of the tube was sealed and a series of constant airflow rates was applied to the top of the soil through this tube while the pressure within the head space was measured by a pressure transducer (Cole Parmer Instrument Company). A minimum of three different air-flow rates (for example 0, 5, 10, 15 and 20 L/min) were applied at each test location using a flow controller (OMEGA Engineering Inc.), and the corresponding equilibrium pressures at each flow rate were recorded. The linearity between the air-flow and pressure was checked. When the portable AP was fully functional, one test could be completed in 20 to 30 min including set up, measuring, soil sampling and moving to a new site.

The locations for the AP tests were selected randomly over the areas. A total of 145 locations were measured at the Aurora site, while 32 locations were measured at the Key Lake mine (24 measurements for pink till and 8 measurements for brown till) (Zettl et al., 2014). Upon completion of each measurement, a soil sample was collected from the top 10 cm of soil within the tube. This sample was analyzed for gravimetric water content and particle size distribution (PSD).

A program of paired GP and AP tests was conducted to evaluate the AP method. The GP tests were undertaken at 42 locations for the Aurora site and 10 locations for the Key Lake mine (5 locations for each soil, Fig. 1), these locations were selected randomly from the AP test locations (Zettl et al., 2013, 2014; O'Kane Consultants Inc., 2013, 2014). A Model 28001K1 Guelph permeameter constant head-device (ASTM, 2005 D2434-68), fitted with a Pressure Infiltrometer Adapter kit was utilized for all location measurements done by O'Kane Consultants Inc. The measurements were conducted as recommended in the manufacturer manual (Soilmoisture Equipment Corporation). The 20 cm diameter ring was pounded in (bigger diameter than tube above) to make a seal between the ground and ring thus making the test possible without augering a hole. After the ring had been successfully installed, the reservoir assembly was fitted to the ring and filled with water. Once set, the air tube was raised to establish the head height and start the test. A