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Research Article

Comparative Evaluation of Three Methods of Saturated Hydraulic Conductivity Measurement of Soils

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ABSTRACT

For successful soil and water management practices, knowledge of saturated hydraulic conductivity (K_s) is essential. Positive-head tension infiltrometer (TI) and single-ring pressure infiltrometer (PI) methods have potential for measuring K_s. However, these methods are not widely tested and compared with commonly used methods. The TI, PI, and classical undisturbed soil core (SC) methods for measuring K_s were compared on three soils (sandy loam, clay loam, and clay) under three land use managements (conventional tillage, CT; no-tillage, NT; and native vegetation, NV). Only four out of the 27 combinations were significantly ($p<0.05$) correlated. The TI method yielded lower K_s values under high-permeability conditions ($K_s \geq 1.2 \times 10^{-4}$ m s^{-1}) relative to other methods, as evidenced by lower geometric mean K_s (K_{gm}), lower maximum K_s (K_{max}), and lower minimum K_s (K_{min}) values. In the SC method, the cores (0.1 m diameter and 0.1 m long) might have been too small to yield representative estimates of K_s in the clay and in the NT and NV managements of the sandy loam and clay loam soils. Erratic K_{max} and K_{min} values, along with high CVs, suggest that the 0.1 m diameter PI ring may have been too small to adequately sample the clay soil under CT and NT management. The K_s values were highly sensitive to even relatively small differences in sample size, pore geometry and soil structure.

Key words: Infiltration, Permeability, Hydraulic conductivity, Sorptivity, Tillage

Introduction

Saturated hydraulic conductivity (K_s) is a key soil property that influences physical, chemical and biological processes in soil. Information on K_s is essential in water-solute transport models (van Dam *et al.*, 1997), and in soil physical quality evaluation (Buczko *et al.*, 2006). It is also an important soil characteristic in the design and performance assessment of irrigation and drainage systems, waste water irrigation (Ward and Morrison, 1984), and many other agricultural, geotechnical, and environmental structures.

Several methods have been developed over time for measurement of K_s in the field and laboratory (Klute and Dirksen, 1986; Iwanek, 2008). Most of these methods often yield dissimilar K_s values mainly due to sensitivity of K_s to sample size and collection procedures, flow geometry and various soil physical and hydrological characteristics (Bouma, 1983). Therefore, many of the methods are neither appropriate nor uniformly accurate for all applications, soil types or soil conditions (Bouma,

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1983). For obtaining the most accurate K_s values, methods should be implied carefully.

Tension infiltrometer (TI) method (Perroux and White, 1988; Reynolds and Elrick, 1991), due to its simple and rapid nature, has gained popularity during last two decades for *in-situ* measurement of near-saturated and saturated soil hydraulic conductivity (Mohanty *et al.*, 1998). However, K_s through TI method has serious difficulty in ensuring perfect hydraulic contact between the infiltrometer and the soil (Perroux and White, 1988) and can introduce flow impedance effects particularly at the high infiltration rates (Reynolds and Zebchuk, 1996). Further, the classical TI theory, which is based on the Wooding (1968) and the Philip (1969) infiltration analyses, does not apply to the ponded infiltration conditions necessary for measuring K_s (Reynolds and Elrick, 1991; Reynolds and Zebchuk, 1996).

To overcome the problem of hydraulic contact, Reynolds and Zebchuk (1996) have developed an approximate steady flow–shallow ponded head analysis for the TI, as well as procedures for accounting for flow impedance by the contact medium. Laboratory and numerical simulation tests (Reynolds and Zebchuk, 1996) indicated that these innovations are accurate and can be successfully used. For applying Wooding (1968) and Philip (1969) infiltration analyses under ponded conditions, extrapolation from negative to zero pressure head using an assumed hydraulic conductivity–pressure head relationship *viz*., empirical functions of Gardner (1958) and van Genuchten (1980) (Messing and Jarvis, 1993; Jarvis and Messing, 1995) may be a better alternative. However, the accuracy of the hydraulic conductivity-pressure head relationship decides the accuracy of such a procedure. The accuracy of the relationship varies with soil texture and structure at each measurement site (Messing and Jarvis, 1993).

Pressure infiltrometer (PI) method, which is a single-ring, steady-flow technique, is also being used for *in-situ* determination of K_s (Reynolds, 1993a). Besides being simple and rapid, PI method does not pose the problem of hydraulic contact and applicability of infiltration analyses. Despite its suitability in determining *in-situ* K_s, it has received limited attention compared with the other methods.

Soil core (SC) method is one of the classical techniques for measuring K_s and involves direct application of Darcy's Law (Klute and Dirksen, 1986). Like PI, the SC method has limitations related to small or inadequate sample size, soil disturbance during collection and possible short circuit flow through macropores or along the core wall (Bouma, 1980). However, this remains one of the most popular means for measuring K_s, and often used as a benchmark for evaluating other methods.

The objectives of this study were to (i) compare the TI and PI methods with SC method for measuring K_s and (ii) obtain information suggesting soil textural and structural conditions for which each of these methods might not result in representative estimates of K_s of these soils.

Materials and Methods

Three field sites with sandy loam, clay loam and clay texture (0-50 cm) were selected from the experimental site of Jahami in Ganjam district of Odisha, India. Basic properties of these soils are presented in Table 1. At each site, adjacent plots with three crop management practices *i.e.*, conventional tillage (CT), and no tillage (NT) cropping, and uncultivated native vegetation (NV) were selected for K_s measurements. The CT consisted of moldboard ploughing in the month of May, followed by discing and harrowing immediately before planting. The NT site had only no-till seed-drill. The uncultivated native vegetation (NV) site had deciduous trees and grasses. The CT and NT plots were well established at each field site and the NV plots had not been cropped or cultivated in the living memory. For the last 20 years, the cultivated sites were under rice-vegetable rotation. The K_s measurements were carried-out in non-traffic crop inter-rows.

A Mariotte-based apparatus and multiple head–single disc procedures (Reynolds, 1993a; Reynolds and Elrick, 1991; Reynolds and

Table 1. Basic properties of the selected soils

Texture	Soil classification	Sand	Silt	Clay	Clay mineralogy (%)		pH	EC	$CaCO_3$	Organic carbon
			%		Expanding	Non-expanding		dS m^{-1}	%	g kg^{-1}
Sandy loam	Lithic Ustorthent	62.6	22.4	15.0	02	98	7.87	0.79	0.96	3.2
Clay loam	Vertic Haplustept	40.5	23.8	35.7	18	82	8.19	0.54	3.32	4.2
Clay	Typic Haplustert	23.5	21.2	55.3	73	27	7.98	0.68	2.75	6.4

Zebchuk, 1996) were used in estimating K_s by TI method (Fig. 1). Hydraulic contact between the TI membrane and the soil was secured through a 0.01 m thick glass bead material, held in place by a 0.25 m diameter retaining ring. A nylon guard cloth (53 µm equivalent pore size) was placed between the soil and the contact material to prevent slumping of the air-dry contact material into soil cracks and macropores during its initial placement and when $h \leq 0$. Pressure heads of ≈ -0.15, -0.10, -0.05, -0.03, -0.01, 0, +0.01, and +0.02 m of water were established in ascending order on the soil surface, and the corresponding quasi-steady flow rates were measured as

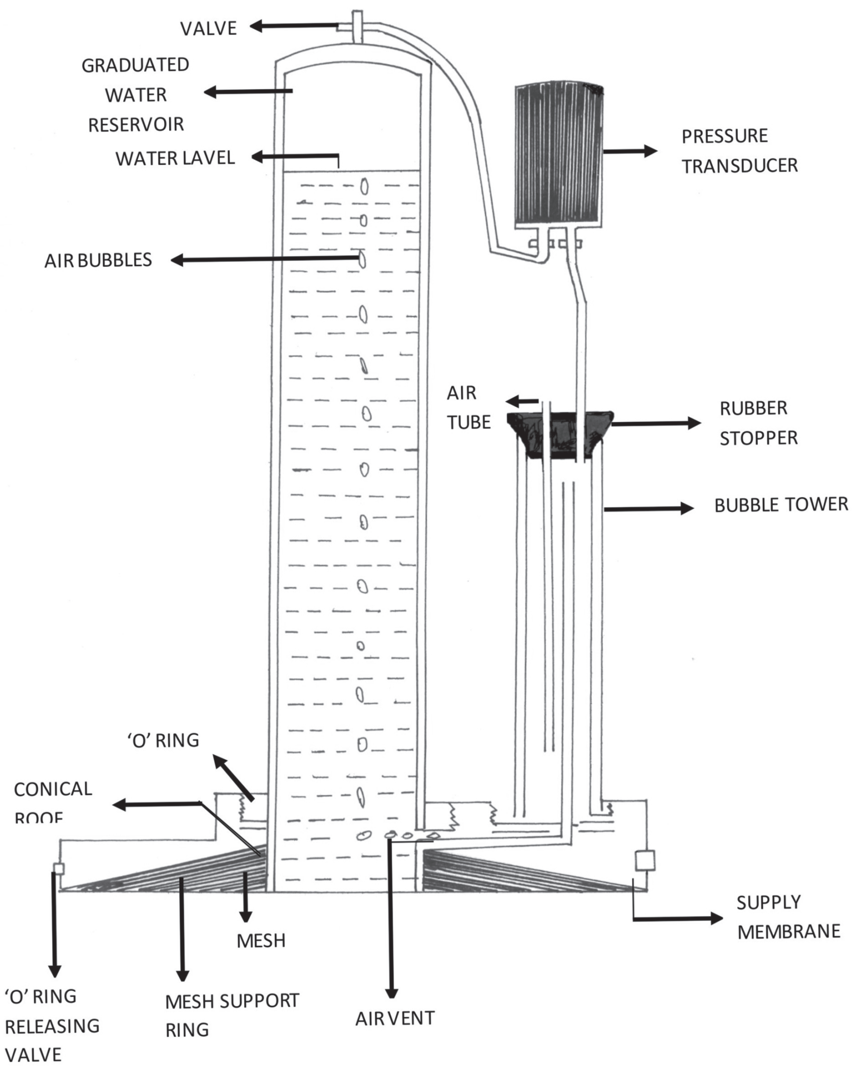

Fig. 1. The experimental sketch of Tension Infiltrometer

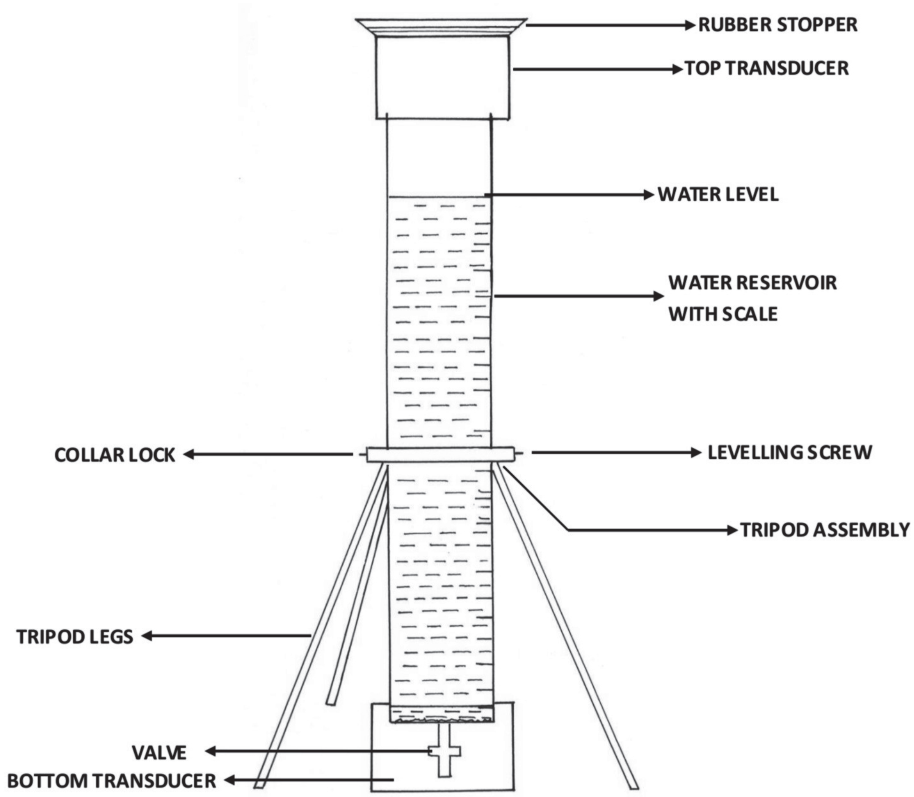

Fig. 2. The experimental sketch of Pressure Infiltrometer

described in Reynolds and Zebchuk (1996). Flow rates were deemed quasi-steady when the rate of fall of the water level in the TI reservoir was constant for at least 10 min. The K_s was determined at two positive h values (0.01, 0.02 m).

The apparatus and procedures described by Reynolds (1993b) were used to obtain K_s estimates by PI method (Fig. 2). A stainless steel ring (0.10 m each of diameter and length, 2.5 mm wall thickness) was fully inserted into the soil, and the Mariotte reservoir along with PI base-plate was attached. No contact material or guard cloth was placed on the soil surface. The set pressure heads varied between 0.08 and 0.14 m for the first head, and between 0.21 and 0.42 m for the second head. Lower heads were set for faster flow rates to reduce water consumption. In PI estimates of K_s, the flow rates were also considered quasi-steady when the rate of fall of water level in the reservoir was constant for at least 10 min. The single-head or multiple-head procedures described in Reynolds (1993b) were followed. The experimental sketch of the PI is described in Fig. 2.

The same stainless steel rings used in the PI method were extracted with undisturbed soil cores. The cores were saturated and the K_s was determined by constant-head method (Klute and Dirksen, 1986) at 25°C (Fig. 3).

For *in-situ* measurements of K_s, approximately 1m x 1 m area was selected at each of the three sites and management systems. The area was covered with metal sheets to get the tent effect for avoiding day-time evaporation and evening condensation. The measurements were taken during the month of May.

At each site, the K_s measurement had the following steps:

(i) The TI method applied on a relatively level spot within the sheet metal frame where local surface irregularities were ±5 mm or less. The soil surface was not scraped, leveled, brushed, or evacuated before installation of the retaining ring, guard cloth and contact

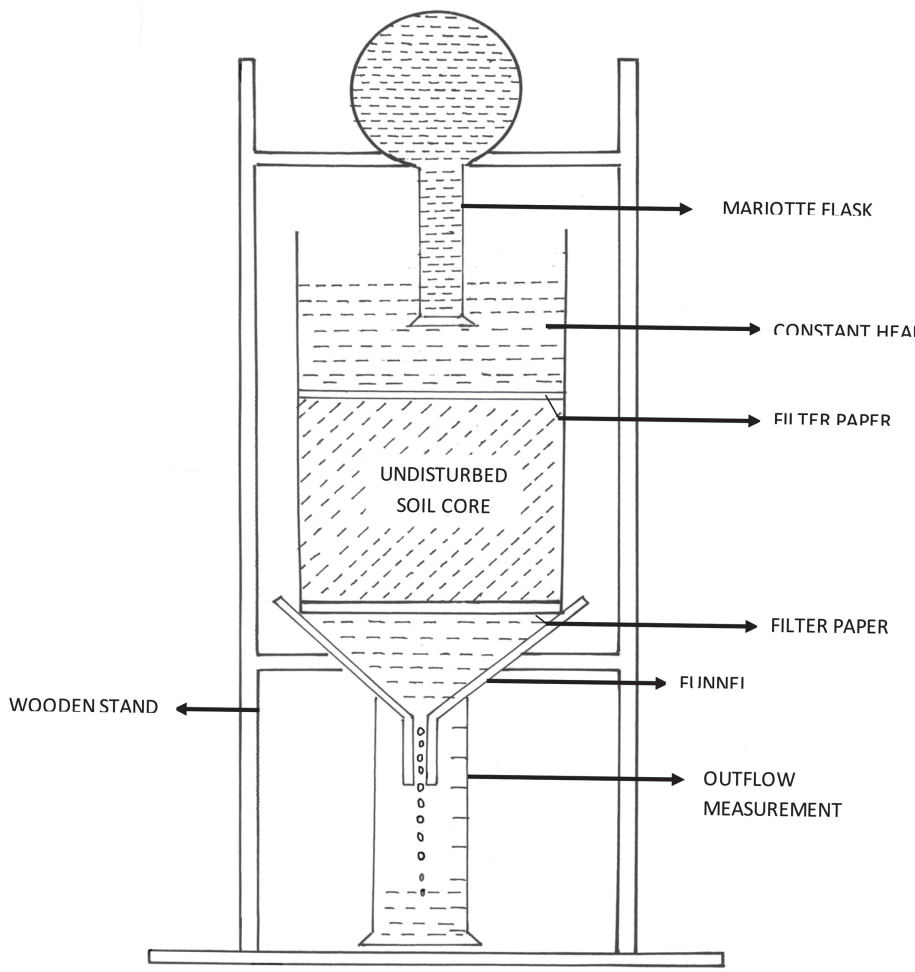

Fig. 3. The experimental sketch of the SC method

material. These installations were removed after completing the measurements and the frame recovered with plywood.

(ii) After a 2- to 5-d drainage period, the plywood cover was removed from the frame and the PI method applied on the TI infiltration surface (*i.e.*, within the wetted circle left by the TI measurement). The PI ring was left in place after the measurements were completed. The frame was then recovered with plywood.

(iii) After a 1- to 5-d drainage period, the plywood cover was again removed and the PI ring extracted as an undisturbed soil core. The core was analyzed in the laboratory using the SC method.

The K_s measurements were replicated 7-12 times with each method (TI, PI, SC) on each land management practice (CT, NT, NV) at each field site, resulting into a total of 267 measurements.

The *Ks* values from the three methods were compared on the basis of their mean, maximum and minimum values, coefficient of variation, and the Pearson correlation coefficient. Log-normal statistical distributions were assumed, as is common for *in-situ* and undisturbed core measures of K_s reported by Warrick and Nielsen (1980). The K_s data were consequently log(ln)-transformed before statistical comparison; geometric means were calculated rather than the arithmetic means; and the coefficient of variation was calculated using an appropriate log-normal relationship (Hastings and Peacock, 1975). Correlations among the methods were conducted on a site-by-site basis within each land management practice and field sites (27 separate correlations) using the log-transformed K_s values. The terms K_{gm}, K_{max}, and K_{min} were used to represent the geometric mean, the maximum and the minimum K_s values, and CV for coefficient of variation.

Results and Discussion

The TI and PI methods go through an initial transient phase, and the accuracy of the K_s depends on the degree to which quasi-steady flow is achieved. We used Philip (1986) t_{grav} calculation to assess the degree of quasi-steady flow as:

$$t_{grav} = \left(\frac{S}{K_s}\right)^2$$

where S (m s$^{-1/2}$) is sorptivity.

The measured equilibration times were highly variable for both the methods, with CVs varying 20-60% at each pressure head. The TI required 10-20 min to equilibrate at each of the two pressure heads, whereas the PI required 18-29 min at the first and 16-22 min at the second head. The estimated t_{grav} for the TI and PI method was 17.2 ± 11.5 and 14.7 ± 14.2 min, respectively.

Out of the 27 correlations between K_s values, only 4 were significant at $P<0.05$; one negative and the other 3 were positive (italicized values in Table 2). Although frequent statistical equivalence of K_{gm} values was evident, the general lack of correlation has been seen (Table 3). In addition, correlations between the PI and SC methods in sandy loam soil were found non-significant (Table 2).

Poor correlation between TI and the other two methods might be attributed to sample size and/or flow geometry and/or soil disturbance. The TI infiltrates through a much larger soil area (approximately 50000 mm^2) than the PI and SC methods (7800 mm^2), and may therefore sample more macropores and other soil heterogeneities. Flow is three-dimensional in the TI method, as opposed to (predominantly) one-dimensional in the PI and SC methods, which may possibly affect K_s results if macropores, etc. have induced substantial vertical-horizontal anisotropy into the infiltration process. Insertion of the ring for the PI and SC methods also might also have caused varying degrees of artifacts such as soil crack creation, which would not occur for the TI method.

Both PI and SC methods had the same sample size, flow geometry, and sample collection technique. Virtually the same soil volumes were sampled by these two methods, since the SC cores were obtained by extracting the PI rings and their contained soil. Yet, there was poor correlation between PI and SC methods, which was difficult to explain.

Table 2. Site-wise Pearson correlation coefficients (r value) plus statistical significance (p value) among the tension infiltrometer (TI), pressure infiltrometer (PI), and intact soil core (SC) methods for measuring K_s (N = 7 to12). Correlations performed using the log-transformed K_s data. Italicized P values are <0.05

Soil management	Methods	Sandy loam		Clay loam		Clay	
	comparison	r value	p value	r value	p value	r value	p value
Conventional tillage	SC vs. TI	+0.2585	0.6934	-0.3427	0.2381	-0.6900	***0.0511***
	SC vs. PI	+0.4679	0.2744	-0.3069	0.3280	+0.3012	0.7415
	PI vs. TI	+0.4706	0.2970	+1.0290	***0.0045***	+0.1569	0.9490
No tillage	SC vs. TI	+0.0592	0.8543	+0.9081	***0.0174***	+0.7581	0.0951
	SC vs. PI	-0.0293	0.6570	+0.6477	0.1588	+0.7643	0.0910
	PI vs. TI	+0.1541	0.9257	+0.2464	0.7566	+0.9862	***0.0159***
Native vegetation	SC vs. TI	+0.4318	0.3577	+0.7036	0.1423	+0.0560	0.8631
	SC vs. PI	+0.3663	0.4482	+0.5779	0.2000	+0.4678	0.3695
	PI vs. TI	+0.3388	0.5261	+0.7126	0.1348	+0.4636	0.3758

The general lack of statistical correlation (Table 2), despite frequent statistical equivalence of K_{gm} values (Table 3), might also be due to the lack of trend in the data. The general lack of statistically significant correlation or even trends amongst various methods is also reported by Bouma (1980) and Bouma (1983), explaining that K_s is extremely sensitive to even relatively small differences in sample size, flow geometry, and soil structure.

The TI method resulted in a significantly lower K_{gm} (P<0.05), as well as lower K_{max} and K_{min} values, when K_{gm} by the other methods was greater than about 1.2 x 10^{-4} m s^{-1} (Table 3). For lower permeabilities (*i.e.*, K_s ≤1.2 x 10^{-4} ms^{-1}), the TI method yielded K_{gm}, K_{max}, and K_{min} values which were comparable with one or both of the other methods. This suggests that either the TI method underestimated K_s under high permeability conditions (*i.e.*, *Ks* > 1.2 x 10^{-4} ms^{-1}), or the other two methods overestimated the K_s. Such underestimation by the TI method might be due to restriction at high flow by the Mariotte air and/or water supply tubes; impedance by the TI membrane and/or guard cloth and/or contact material; inaccuracy in the positive-head method for K_s calculation; three-dimensional vs. one-dimensional flow geometry effects; or restricted operation of surface-vented macropores, cracks, or other preferential flow zones under the TI infiltration surface.

Inaccuracy in the K_s calculation cannot be a reason for underestimation because the method was developed especially for small ponded head conditions in the TI. Also the method was established in a numerical simulation study (Reynolds and Zebchuk, 1996) to be accurate within ±10% for K_s ranging from 10^{-4} to 10^{-8} ms^{-1}. The K_s determined by this procedure were consistently greater than the K_s obtained by extrapolation from slightly negative pressure heads using the Gardner (1958) exponential $K(h)$ relationship (*e.g.*, Messing and Jarvis, 1993; Jarvis and Messing, 1995).

Surface cracks, restricted operation of surface-vented macro-pores, and preferential-flow zones under the TI could also cause underestimation in K_s. The TI generally produces a known positive pressure head at the contact material–soil interface (Reynolds and Zebchuk, 1996), it may still be possible for small, isolated areas at the interface to have a lower pressure head directly above the preferential-flow zones. Such localized areas of reduced pressure head would be caused by hydraulic head loss through the contact material (impedance) as a result of a very rapid flow through the preferential-flow zones. If the head loss was sufficient to cause the pressure head immediately above the preferential-flow zone to be reduced substantially from the value set by the TI, this would in turn reduce the flow through the preferential-flow zone relative to what would otherwise occur if no contact material was present. Mohanty *et al*. (1996) demonstrated that preferential-flow zones, particularly surface-vented macropores and cracks, occupying as little as 3% of the infiltration surface can conduct as much as 90% of the measured flow, when even a few preferential-flow zones with restricted flow may be sufficient to cause a substantial reduction in measured flow rate with significantly lower estimate of K_s.

In the sandy loam and clay loam soils, the K_{gm} values from the SC and PI methods were similar but higher than those from the TI method (Table 3). However in the clay soil, the SC method produced both higher and lower K_{gm} values. In addition, the SC method often produced the largest K_{max}, K_{min}, and CV among the three methods, regardless of soil type and especially in the NT and NV managements (Table 3). The higher values of K_{gm}, K_{max}, and K_{min} might reflect rapid pipe-flow through worm holes, old root channels, and cracks that extend all the way through the cores. The lower K_{gm} and K_{min} values in the CT management of the clay soil might have been resulted due to slow flow after swelling-induced closure of shrinkage cracks during core saturation as observed by Jarvis and Messing (1995).

In the clay soil, K_{gm}, K_{max}, and K_{min} values did not show any specific trend (Table 3). Such high–low behavior of the K_{gm}, K_{max}, and K_{min} in clay soil suggests that the SC cores (0.10-m diam. x

Table 3. Comparison of K_s measurements obtained using the tension infiltrometer (TI), pressure infiltrometer (PI), and intact soil core (SC) methods (K_{gm}, K_{max} and K_{min} are the geometric mean, maximum and minimum K_s values; CV is coefficient of variation)

Methods	Conventional tillage					No tillage					Native vegetation				
	N	K_{gm}	K_{max}	K_{min}	CV%	*N*	K_{gm}	K_{max}	K_{min}	CV%	*N*	K_{gm}	K_{max}	K_{min}	CV
		—— × 10^{-4} m s^{-1}——					—— × 10^{-4} m s^{-1}——					—— × 10^{-4} m s^{-1}——			%
							Sandy loam								
TI	11	2.895_b	6.955	1.384	55.0	11	2.833_b	6.545	2.536	59.5	10	4.000_b	3.590	2.540	49.6
PI	11	9.225_a	17.975	3.214	46.5	12	5.623_a	11.165	2.966	70.3	11	23.560_a	36.360	8.680	54.3
SC	12	7.735_a	16.625	3.924	44.0	11	8.403_a	39.935	4.676	85.9	12	23.480_a	56.710	6.050	92.0
							Clay loam								
TI	11	1.325_a	7.865	0.294	159.3	9	4.463_a	17.215	3.746	80.4	10	6.400_b	7.390	2.370	93.9
PI	9	1.245_a	4.515	0.374	97.2	11	7.163_a	16.925	3.096	91.7	10	25.690_a	79.000	13.760	60.3
SC	10	0.915_a	6.695	0.264	214.0	8	3.643_a	35.535	1.536	357.1	9	34.270_a	85.610	10.120	80.8
							Clay								
TI	9	0.795_a	2.265	0.704	39.9	10	2.593_{ab}	6.335	2.306	75.0	8	8.200_b	9.680	3.520	80.0
PI	10	0.103_{ab}	1.205	0.133	357.8	11	2.153_b	127.485	1.384	124.6	10	9.110_b	15.710	5.130	49.8
SC	7	0.015_b	4.465	0.135	48.0	8	13.893_a	69.935	2.816	218.8	9	27.080_a	75.610	12.360	77.5

N = Number of measurements

Mean values within a column and soil type followed by the same letter are not significantly different at $P < 0.05$

0.10-m length) were possibly not adequate to sample this soil. This is perhaps not surprising, given that the clay soil had large proportions of swelling-type clay minerals (Table 1). Bouma (1983) recommended that detached soil samples should be large enough to contain at least 20 soil peds, which implies that cores from the clay soil needed to be at least twice the size used here (*i.e.*, 0.20-m diam. x 0.20-m length). Some of the researchers (Wu *et al.*, 1992) obtained representative *Ks* results in structured clay and macro-porous loam soils using intact soil cores that were 0.30 m in diameter and 0.25 to 0.30 m in length. The SC method yielded consistently higher K_{max} values than the other two methods for NT and NV managements of the sandy loam and clay loam soils (Table 3). These high K_{max} values might was the result of rapid pipe-flow through worm holes and old root channels, which extend through the entire length of the core. The K_s obtained across the management practices did not show the significant impact of management on its determination. However, changes in *Ks* due to surface manipulation in conventional tillage and soil structure stabilization in NV were in proportion with the soil disturbances in respective management practices.

The K_{gm} values obtained by the PI method were statistically at par with one or both of the other methods in all soil types and land management combinations (Table 3). The K_{max}, K_{min}, and CV values from the PI method were also comparable to those from one or both the other methods. Possible reasons for the high level of internal consistency relative to the other methods are (i) lack of membrane, contact material, or guard cloth to cause possible flow impedance effects; (ii) reduced impact of soil swelling because the relatively rapid PI measurements (30–50 min duration), completed before substantial swelling could occur; and (iii) reduced effect of pipe-flow through macropores because the soil core remains attached to the underlying soil profile. It is noted, however, that the PI method produced erratic K_{max} and K_{min} values, as well as high CV for the CT and NT managements in the cracking clay. As with the SC method, this may be suggested that the soil volume sampled by the PI method was too small for the structural conditions in the CT and NT managements on the clay loam soil. Another possibility might be air entrapment effects caused by rapid wetting of the soil within the confines of the PI ring.

Conclusions

The TI, PI, and SC methods tested in this study yielded different measures of K_s under CT, NT and NV managements. No consistency or pattern among the K_{gm}, K_{max}, K_{min}, and CV values was observed for the three methods. The TI produced the most representative estimates of K_s in the CT and NT managements of the cracking clay. Different management practices did not influence K_s values significantly and the changes in K_s were in proportion with the structural disturbances due to tillage or vegetation. Results suggest that TI method cannot be used in highly permeable soils, but can be successfully used in low and moderately permeable soils. PI method can be used in all soil types with certain precautions.

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