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Correlation of the hydraulic conductivity of fine-grained soils with water content ratio using a database

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ABSTRACT: The saturated hydraulic conductivity of fine-grained soils is of great importance as it is directly linked to many fundamental calculations in geotechnical engineering. In this paper various models to predict saturated hydraulic conductivity using simple soil parameters are reviewed. A simplified semi-empirical prediction equation using water content ratio (w/w_L) as the predictor of saturated hydraulic conductivity is calibrated using a large database called FG/KSAT-1358 (n >1300) of saturated hydraulic conductivity (k_{sat}) measurements on fine-grained materials. The regression equation can predict the saturated hydraulic conductivity of the measurements included in the database to within plus or minus an order of magnitude around 90% of the time. To study other factors which may affect the values of k_{sat}, the database was then subdivided according to liquid limit level; silt or clay classification; hydraulic conductivity test method and sample condition. Some variations in the regression equations for each of the aforementioned subsets are observed but the effect on the value of the exponent in the derived power-law relationships is relatively minor.

Author Keywords: Saturated Hydraulic Conductivity; Water Content; Liquid Limit; Water Content Ratio; Database

ICE Keywords: Geotechnical Engineering; Porous-media characterisation and Statistical Analysis.

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INTRODUCTION

Reliable a-priori assessments of the saturated hydraulic conductivity (k_{sat}) of fine-grained soils are useful for geotechnical and geoenvironmental engineers. The saturated hydraulic conductivity is directly linked to seepage and consolidation characteristics for clays and silts (Pane et al., 1983; Tavenas et al., 1983a, 1983b; Leroueil et al., 1990; Chapuis, 2012). Fine-grained soils are often used in the construction of geo-structures such as waste disposal facilities (Benson and Trast, 1995; Terzaghi et al. 1996; Bannour et al. 2016; O'Kelly, 2016), road slopes and embankments (Walker and Raymond, 1968), and earth dams (Terzaghi et al. 1996) and the need to model the flow of water through such structures is required for assessing serviceability and stability. For landfill applications the k_{sat} of the clay liner is often the 'governing parameter' (e.g., Amadi and Alih 2017). Saturated hydraulic conductivity is also important in the assessment of slope stability (e.g., Hamm et al. 2006).

This paper presents a simple prediction model for saturated hydraulic conductivity calibrated with a large database (n >1300) of laboratory tests (FG/KSAT-1358) on a wide variety of fine-grained soils. Use of geo-databases to develop 'transformation models' for a-priori estimation of soil parameters is valuable in geotechnical and geoenvironmental engineering (cf. Kulhawy and Mayne (1990); Phoon and Kulhawy (1999a, 1999b) and Ching et al. (2017)). It should be noted that to predict the hydraulic conductivity of 'unsaturated' fine-grained materials alternative approaches are needed (see e.g., the papers of Mualem (1976), Olson and Daniel (1981), Santoso et al. (2011), Dong et al. (2018)). Also, composite soils (including sands) (e.g., Al-Moadhen et al. 2018) and modified soils (e.g., Azad et al. 2015) are beyond the scope of this work and such data is not included in the database presented in this paper.

LITERATURE REVIEW

Chapuis (2012) comprehensively reviewed various empirical and semi-empirical approaches for predicting hydraulic conductivity of soils. The ‘Kozeny-Carman’ equation (Kozeny, 1927; Carman, 1937, 1939) is a commonly used semi-empirical approach, which relates the hydraulic conductivity k (Length (L).Time $(T)^{-1}$) to the specific surface (S_S) and a void ratio function $e^3/(1+e)$. Eq. (1) is the form of the ‘Kozeny-Carman’ equation shown in Chapuis and Aubertin (2003):

$$k = C\frac{g}{\mu_w \rho_w}\frac{e^3}{{S_S}^2{D_R}^2(1+e)} \tag{1}$$

where C is a constant, g is the gravitational acceleration, μ_w is the dynamic viscosity of the permeant, ρ_w is the density of the permeant (e.g. water), e is the void ratio, and D_R is the specific weight of the solid material. Variants of Eq. (1) have been used to predict the saturated hydraulic conductivity of soils (e.g., Mbonimpa et al. 2002; Chapuis and Aubertin, 2003; Sanzeni et al. 2013 and Ren et al. 2016 and Ren and Santamarina 2018).

Carrier and Beckman (1984) indicate that for remoulded clays, the hydraulic conductivity can be correlated with w_P, I_P and e, via:

$$k_{sat}(m/s) = \mu\frac{(e-\delta)^{\nu}}{1+e} \tag{2}$$

where $\mu = (0.389/w_P)^{4.29}$, $\delta = 0.027(w_P - 0.242I_P)$, $\nu = 4.29$, w_P is the plasticity limit, I_P is the plasticity index. Eq. (2) requires a variable exponent on the void ratio (e).

Specific Surface

Sanzeni et al. (2013) explain that the success of the use of variants of Eq. (1) for prediction of k_{sat} relies on a good estimate or proxy for specific surface being available. Past studies (e.g., Farrar and Coleman, 1967; Sridharan et al., 1988; Muhunthan, 1991) show that specific surface S_S and liquid limits w_L are correlated for a variety of plastic soil. Chapuis and Aubertin (2003) derived a linear relationship between $1/S_S$ and $1/w_L$ (Eq. (3)) for different types of clays using a gathered database from five publications (De Bruyn et al., 1957; Farrar and Coleman. 1967; Locat et al., 1984; and Sridharan et al. 1986b, 1988):

$$\frac{1}{S_S\,(m^2/g)} = 1.3513\left(\frac{1}{w_L}\right) - 0.0089 \tag{3}$$

By replacing S_S with w_L in the 'Kozeny-Carman' equation, Chapuis (2012) suggested that the saturated hydraulic conductivity k_{sat} may be correlated to $e^3/[w_L^2(1+e)]$. Chapuis (2012) developed a correlation based on data from Quebec Champlain Sea clay:

$$k_{sat} = 6.68 \times 10^{-6}\left[\frac{e^3}{(1+e)(w_L{}^{-1}+z)^2}\right]^{1.339} \qquad R^2 = 0.81 \tag{4}$$

Where $z = 0.00836$ determined by the least squares method using experimental data for the specific clay studied i.e. Quebec Champlain Sea clay.

By using w_L (for fine-grained soils) and cumulative grain size distribution (for sandy soils) to estimate the S_S, Ren and Santamarina (2018) developed a hydraulic conductivity prediction model (Eq. (5)) for a wide range of sediments calibrated using a laboratory database.

$$\frac{k}{cm/s} = 10^{-5}\left(\frac{S_S}{m^2/g}\right)^{-2} e^{\beta} \tag{5}$$

As reported by Ren and Santamarina (2018), the predicted values using Eq. (5) mostly fall within $k_{measured}/5 \leq k_{predict} \leq 5k_{measured}$ range based on their database. Ren and Santamarina (2018) used a correlation between S_S and w_L to derive missing values of S_S in their database. It is worth noting that, significant scatter below $k_{measured} < 10^{-5}$cm/s (the clay/ silt material region) can be observed on the predicted versus measured plot – wider than the general range $k_{measured}/5 \leq k_{predict} \leq 5k_{measured}$ quoted. This paper focuses on clay and silt soils with k_{sat} generally less than 10^{-5}cm/s.

Shrinkage Limit

Sridharan and Nagaraj (2005) found that the shrinkage limit (w_s) is also important for prediction of hydraulic conductivity of remoulded fine-grained soils as well as the w_L when developing the following equation:

$$k = \alpha\left[\frac{e^x}{1+e}\right] \tag{6}$$

where $x = 4$ based on the regression analysis and $C = 2.5\times10^{-4}(w_L\text{-}w_S)^{-3.69}$. However despite being a key soil mechanics parameter (e.g., Hobbs et al. 2018), w_s is not as often measured as the w_L during routine field and laboratory investigations and therefore could not be used in the analysis in this paper (it was rarely reported in the examined publications).

Void Ratio Function

Various studies have used a simple power - law correlation (e.g., Eq. (7)) for hydraulic conductivity of soils (e.g., Mesri and Olson, 1971b; Samarasinghe et al., 1982; Al-Tabbaa and Wood, 1987; Dolinar, 2009).

$$k = ae^b \tag{7}$$

Where a and b are regression constants.

Vardanega et al. (2017) using small database (n = 119) of falling and constant head hydraulic conductivity test results showed for hydraulic conductivity prediction of single type clay Eq. (7) was statistically acceptable. Vardanega et al. (2017) showed that the exponent b varied from 1.53 to 5.32 for 10 different types of soils.

Water content ratio

The e/e_L ratio (or as w/w_L ratio) is also used in many soil behaviour correlations: e.g., Nagaraj and Murthy (1986) for clay compressibility; Griffiths and Joshi (1988) for clay cementation; and for modelling undrained shear strength variation of fine-grained soils (Kuriakose et al. 2017 and Spagnoli and Feinendegen 2017). Nagaraj et al. (1993, 1994) proposed Eqs. ((8) and (9)) to predict hydraulic conductivity prediction for fine-grained soils by introducing the voids ratio at liquid limit (e_L) as a normaliser of e. This approach is elegant as e_L which can be reduced to w_L (as shown previously) is a good predictor of specific surface for fine-grained soils.

$$\frac{e}{e_L} = 2.38 + 0.233 \log k \qquad \text{(normally consolidated materials)} \tag{8}$$

$$\frac{e}{e_L} = 2.162 + 0.195 \log k \qquad \text{(over consolidated materials)} \tag{9}$$

While not stated explicitly in Nagaraj et al. (1993, 1994) for Eqs. ((8) and (9)) as shown here k is in cm/s (as also stated in Sridharan and Nagaraj (2005) and Chaupis (2012)) when discussing Eq. (8). Sivapullaiah et al. (2000) also used the e/e_L ratio when investigating various function predicting hydraulic conductivity of soils. Mbonimpa et al (2002) also show that e/e_L (w/w_L) correlated with k_{sat} based on a database (n=342) (given here as Eq. (10)) using data from six publications (Raymond 1966; Al-Tabbaa and Wood 1987; Tan 1989; Leroueil et al. 1990; Nagaraj et al. 1994 and Sivapullaiah et al. 2000) with prediction bounds of approximately 0.2 to 5 times the measured value. This paper aims to calibrate an equation for k_{sat} using w/w_L using a much larger database. Eq. (10) was generated partly using all the data in Sivapullaiah et al. (2000) which included tests on soil mixtures containing sand. In this paper the data used is for soils classified as fine-grained.

$$k\ (cm/s) = 7 \times 10^{-8} \left(\frac{e}{e_L}\right)^{3.15} \qquad n = 342 \qquad (10)$$

DATABASE

The database comprises over 1300 experimental values of k_{sat} on over 130 different types of clay samples sourced from over 30 publications. The database includes the data sources examined in Vardanega et al. (2017) with the data from Chung et al. (2002) excluded due to the lack of relevant information on w_L. Table 1 summarises the key information relating to the sources used to generate the database. The following hydraulic conductivity test methods are represented in the database: *constant head test*, *falling head test*, *flow pump test* and *consolidation test*. Hydraulic conductivity anisotropy is beyond the scope of this paper, and the hydraulic conductivity measurements aggregated in this database were all measured vertically. Only test results of saturated hydraulic conductivity k_{sat} measured with water as the permeant were included in the database. The database comprises tests conducted on both samples derived from natural soils and artificially fabricated ‘laboratory soils’. As the natural soils generally contain some percentage of coarse material, soil mixtures with less than 50% coarse particles (d > 75µm) and a measured plasticity limit have been classified as fine-grained materials and thus included in the database. For the 'laboratory soils' only tests on samples made from pure clay have been included.

Temperature effects

Due to the lack of available test temperature information from most sources (cf. Table 1), the collected k_{sat} could not be corrected to the intrinsic permeability K. Given the k_{sat} measurements in the database are laboratory measurements it is assumed that the test temperature (where not quoted) was not significantly different between different laboratories. It is acknowledged that some of the scatter in the correlations shown in this paper is possibly due to temperature effects.

Soil classification

The Atterberg limits of the collected data are plotted on a Casagrande chart in Fig. 1 (chart design based on ASTM (2017)). Using the classification framework given in ASTM (2017), the database consists of 31% lean clay ($w_L < 50$, $I_P > 7$ and plots on or above "A" line as shown in Fig. 1), 5% silts ($w_L < 50$, $I_P < 4$ or plots below "A" line), 38% fat clay ($w_L \geq 50$, I_P plots on or above "A" line), 20% elastic silts ($w_L \geq 50$, I_P plots below "A"line), 1 sample was classified as clayey sand and 75 samples were without I_P or Unified Soil Classification System (USCS) information, thus were left unclassified.

Table 1: Summary of the database

Sources[a]	Materials	n	e range	k_{sat} (m/s) range	k test method	Test T. (℃)	w_L	I_P	Atterberg limits test method[b]	Clay fraction (<2μm)	G_S	USCS[c]	Remarks
Raymond (1966)	Bentonite, Don valley clay, New Liskeard clay, Leda clay	123	0.51-2.30	1.49×10^{-12}-3.56×10^{-9}	Consolidation test, Falling head test	-	33.4-118	17.1-72.2	-	28%-83%	-	CL, CH	
Walker and Raymond (1968)[d]	Leda clay	8	0.83-1.47	8.11×10^{-11}-9.16×10^{-10}	Falling head test	-	36	13	-	57%		CL	The Atterberg limits and clay fraction are rough estimation based on averaged values from previous studies.
Mesri and Olson (1971a)	Calcium montmorillonite	71	1.08-6.11	1.99×10^{-13}-4.39×10^{-9}	Consolidation test	-	189-220	157-187	ASTM	-	2.8	CH	
Mesri and Olson (1971b)	Kaolinite	19	0.87-2.24	1.49×10^{-10}-2.14×10^{-8}	Consolidation test	-	45	16	-	47%	2.65	ML	See note f
Salem and Krizek (1973)	Dredging slurries	22	0.55-2.15	1.30×10^{-11}-1.42×10^{-9}	Consolidation test	-	61, 71	30, 44	-	30%, 40%		CH, MH	
Bartos (1977)	Dredged materials	5	0.87-1.12	4×10^{-11}-2.9×10^{-10}	Consolidation test	Usually 20	42-129	19-97	-	13-58%		CH, CL, SC	
Chamberlain and Gow (1979)	CRREL clay, Morin clay, Ellsworth clay	63	0.65-1.87	1.96×10^{-10}-4.29×10^{-6}	Falling head test	≈ 22	26-45	5- 20	-	-	2.66-2.77	ML, CL	Including 29 frozen and thawed samples.
Samarasinghe et al. (1982)	Greyish clay	12	0.32-0.57	1.75×10^{-11}-4.79×10^{-10}	Flow pump test	-	27	14	-	-	-	CL	
Pane et al. (1983)	Kaolinite	37	1.00-3.55	8.23×10^{-10}-2.15×10^{-7}	Falling head test, flow pump	-	53.6	21.7	-	-	2.66	MH	

					test							
Tavenas et al. (1983b)**d**	Natural soil	27	0.84-2.48	3.13×10^{-10}-5.11×10^{-9}	Constant head test	21±0.5	34-65	15-39	-	54.5%-81%		CH, CL	
Tavenas et al. (1983a)**d**	Louiseville clay	5	1.27-2.19	1.67×10^{-10}-1.45×10^{-9}	Falling head test	-	62	37	-	85%	-	CH	
Sridharan et al. (1986a)	Bentonite	44	0.81-7.48	8.72×10^{-13}-1.73×10^{-10}	Consolidation test	20	108-675	47.5-625.9	Casagrande method	-	2.59 - 2.81	CH, MH	
Al-Tabbaa and Wood (1987)	Speswhite kaolin	33	0.96-2.21	4.55×10^{-10}-6.00×10^{-9}	Falling head test	-	69	31	-	80%		MH	
Tan (1989)	Silty marine clay, marine clay	13	1.08-2.25	7.84×10^{-11}-1.10×10^{-9}	Falling head test	-	80, 108	54, 78	-		2.65, 2.7	CH	*e* adopted here is the averaged value.
Chandler et al. (1990)**d**	London clay	11	0.68-0.87	5.28×10^{-12}-2.3×10^{-11}	Constant head test	20	85	59	BSI 1377 (1975)	66%	2.72	CH	
Leroueil et al. (1990)**d**	Louiseville clay, St Esprit clay, Backebol clay, Matagami A, Matagami B	33	0.93-2.37	8.69×10^{-11}-2.51×10^{-9}	Constant head test, falling head test	-	41-88	19-56	-	55-80%		CL, CH	
Towhata et al. (1993)	MC clay, bentonite	16	0.81-8.57	1.44×10^{-13}-2.09×10^{-9}	Consolidation test	20	70, 450	29, 421	-	-	2.75, 2.78	CH, MH	Including only test results at 20°C.
Nagaraj et al. (1993)	Black cotton soil, brown soil, red soil, bentonite	23	0.57-7.048	1.15×10^{-11}-1.83×10^{-9}	Falling head test	-	50-300	23-230	-	-	2.65, 2.8	MH, CH	-
Nagaraj et al. (1994)	Black cotton, soil, brown soil, red soil, marine soil	70	0.56-2.37	9.19×10^{-12}-1.82×10^{-9}	Falling head test	-	50-106	23-59	-	-	2.64 - 2.67	MH, CH	-
Benson and Trast(1995)	Mine spoil, loess, glacial till, marine sediment, alluvial, glacio-	190	0.29-1.38	9×10^{-12}-7.5×10^{-6}	Falling head test	-	24-70	11-46	ASTM D4318 (version unspecified)	16-65%	2.68 - 2.9	CL, CH	*e* is calculated based on the reported dry unit weight γ_d and specific gravity *Gs*.

	lacustrine											
Siddique and Safiullah (1995)	Dhaka clay	11	0.51-0.97	7.30×10^{-11}-9.72×10^{-10}	Constant head test, consolidation test		40	20	-	22%	2.68	CL	
Dewhurst et al. (1996)	Marine clay	12	0.19-0.94	2.99×10^{-12}-1.98×10^{-10}	Flow pump test	-	58	32	-	-	2.68	CH	
Pane and Schiffman (1997)	Speswhite kaolin	8	1.29-4.13	8.98×10^{-10}-1.05×10^{-7}	Flow pump test	22± 0.5	53	21	-	75%	2.6	MH	
Clennell et al. (1999)	Silty clay, speswhite kaolin, Ca-montmorillonite, natural clay	39	0.32-2.53	4.45×10^{-13}-4.34×10^{-9}	Flow pump test	-	55-120	31-34	-	-	2.61 - 2.69	CH, MH	
Sivapullaiah et al. (2000)	Bentonite, silt, silt and bentonite mixtures	102	0.61-5.98	1.27×10^{-12}-3.46×10^{-8}	Consolidation test	-	35-344	-	Cone penetration method	8%-100%	-	-	
Lekha et al. (2003)	Local IIT clay, calcium bentonite	12	0.48-1.84	3.20×10^{-11}-1.23×10^{-9}	Falling head test	-	47, 97	-	-	-		CL, MH	
Sridharan and Nagaraj (2005)	Red earth, silty soil, kaolinite, Cochin clay, brown soil, illitic soil	63	0.53-1.84	1.20×10^{-11}-6.89×10^{-8}	Falling head test	20± 1	37-73.4	9.5-26.4	BSI 1377 (1990) cone penetrometer method	5%- 35%	2.58 - 2.7	CL, ML, MH	
Shafiee (2008)	Illite, montmorillonite	6	0.28-0.59	6.60×10^{-9}-1.07×10^{-6}	Constant head test	22± 0.5	29.5, 69	20, 31	-	-	2.72 , 2.74	CL, MH	Not included in the analysis of Equation 12 and after, as the data points are potentially outliers.
Dolinar (2009)	Crystalized kaolinite, Ca-montmorillonite, Kaolinite&	25	0.86-2.5	1.6×10^{-10}-4.95×10^{-9}	Falling head test	20	40.1-129	25.9-39.5	-	-	-	ML, MH	

	Ca-montmorillonite mixture										
Horpibulsuk et al. (2011)	Kaolin, bentonite, Bangkok clay	79	0.63-3.58	1.30×10^{-12}-9.22×10^{-10}	Consolidation test	23	54-131	28-105	Casagrande method	-	2.63 - 2.66	CH
Adams et al. (2013)	Boston blue clay	11	0.58-0.97	3.57×10^{-11}-5.52×10^{-10}	Constant head test	26± 0.1	46	23	-	53%	2.78	CL
Kim et al. (2013)[d]	Marine sediments	43	0.59-1.95	1.31×10^{-11}-8.52×10^{-9}	Consolidation test	-	38.8-77	11.2-28	ASTM D4318 (version unspecified) Casagrande method	-	2.45 - 2.74	ML, MH
Sanzeni et al. (2013)[e]	Fine grained soil	122	0.33-1.21	1.2×10^{-11}-1.52×10^{-6}	Constant head test, consolidation test, falling head test	-	22-71	5- 46	ASTM D4318 (2010)	-	-	CL, ML, CH, MH
Total		1358	0.19-8.57	1.44×10^{-13}-7.5×10^{-6}			22-675	5-625.9		5%- 85%	2.09 - 2.9	

Note

[a] Data by Walker and Raymond (1968), Pane et al. (1983), Al-Tabbaa and Wood (1987), Leroueil et al. (1990) and Lekha et al. (2003) were also used by Vardanega et al. (2017). Data by Mesri and Olson (1971a), Horpibulsuk et al. (2011), Raymond (1966), Siddique and Safiullah (1995), Tavenas et al. (1983a, 1983b), Dolinar (2009), Sanzeni et al. (2013), Kim et al. (2013), Sridharan and Nagaraj (2005) and Sivapullaiah et al. (2000) were also used in the database of Ren and Santamarina (2018). Data by Raymond (1966), Al-Tabbaa and Wood (1987), Tan (1989), Leroueil et al. (1990), Nagaraj et al. (1994) and Sivapullaiah et al. (2000) were also used by Mbonimpa et al. (2002). Note: hydraulic conductivity data without corresponding Atterberg limits were not included in this database, and hydraulic conductivity data of the flow-pump tests in the study by Pane et al. (1983) were also added in this study;

[b] For the publications specified, some used the fall-cone test, while some used the Casagrande method in w_L measurement. O'Kelly et al. (2018) showed that the test values tend to be similar up to w_L equal to 120%;

[c] CH, fat clay; CL, lean clay; MH, elastic silts; ML, silts; SC, clayey sand (abbreviations follow ASTM (2017));

[d] Provided test results on undisturbed samples;

[e] The exact sample states are not specified;

[f] Only the kaolinite data was included in the database range of liquid limit values reported was considered sufficiently narrow to justify using average values of the Atterberg limits in the analysis;

CRREL, Cold Regions Research and Engineering Laboratory, USCS, Unified Soil Classification System

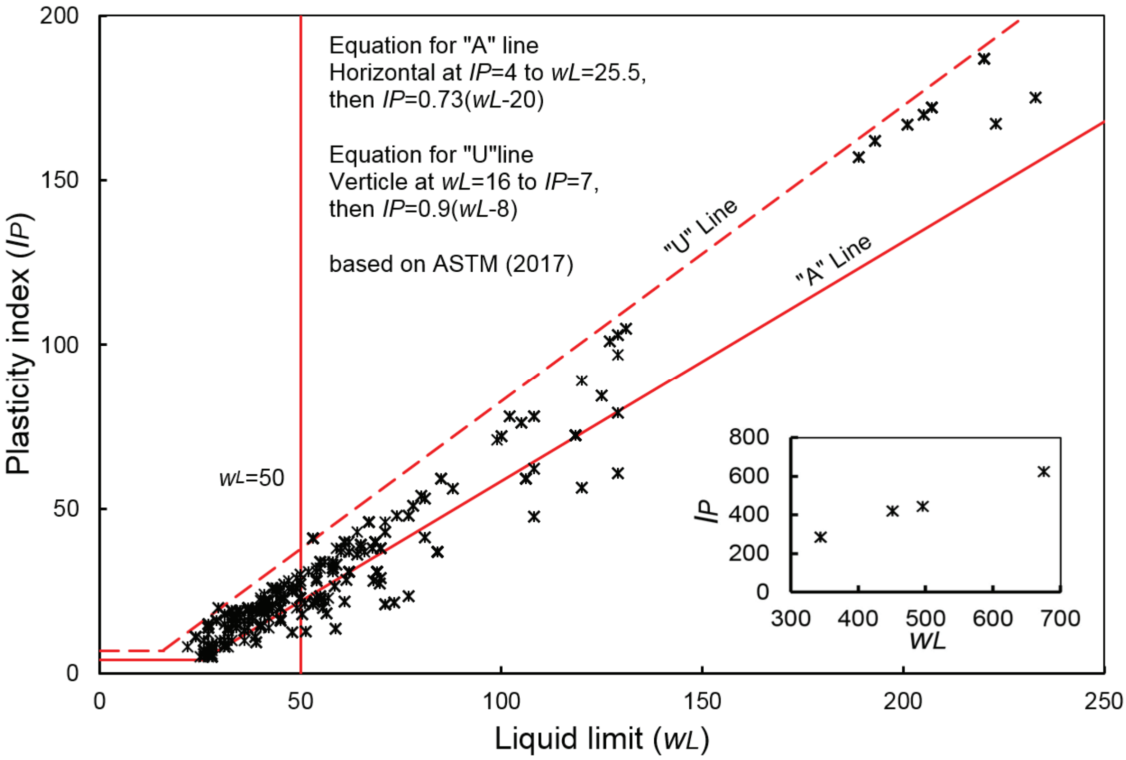


Figure 1: Database soils plotted on a Casagrande chart (73% clays and 27% silts) (chart design based on ASTM (2017))

ANALYSIS

Statistical measures

The coefficient of determination (R^2) is given for the correlations in this paper. For example an R^2 of 0.50 suggests that it explains 50% of the variability of the data (see Montgomery et al. 2007 p.294). When performing correlation analyses, computing only the coefficient of determination (R^2) does not allow for adequate justification of the strength of a correlation (Kulhawy and Mayne 1990). In the correlation analyses in this paper the R^2, number of datapoints (n) and the standard error (SE) are quoted following the approach shown in Kulhawy and Mayne (1990). Quoting the *SE* (sometimes referred to as the standard deviation) is important as it gives a measure of the 'transformation uncertainty' of the correlations (see Phoon and Kulhawy 1999a and 1999b). In addition the p-value of the correlation is quoted which is the probability that one would say that no correlation exists (i.e. rejection of the null hypothesis) as well as the relative deviation, RD ($RD = 100\sqrt{(1-R^2)}$) which gives the percentage of error about the fitted line versus a horizontal fit (average value) (see Waters and Vardanega, 2009).

Regression analyses

The available $1/S_S$ values from the database were plotted against $1/w_L$ in Fig. 2, and Eq. (11) was produced.

$$\frac{1}{S_S}\left(\frac{\text{kg}}{m^2}\right) = 0.0036\left(\frac{1}{w_L}\right) - 0.000018$$

$$[\,R^2 = 0.84,\ n = 29,\ SE = 0.0000097,\ p < 0.0001] \qquad (11)$$

Eq. (11) along with Eq. (3), further confirms that w_L can be used as a substitute for S_S.

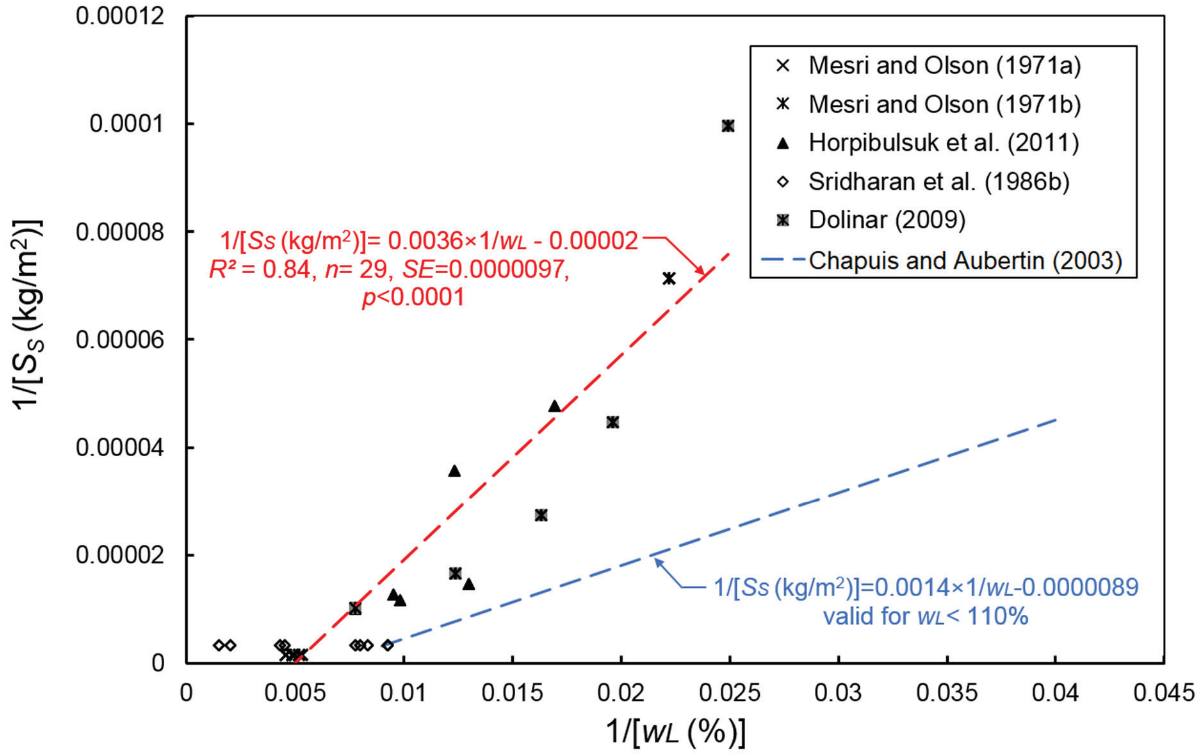
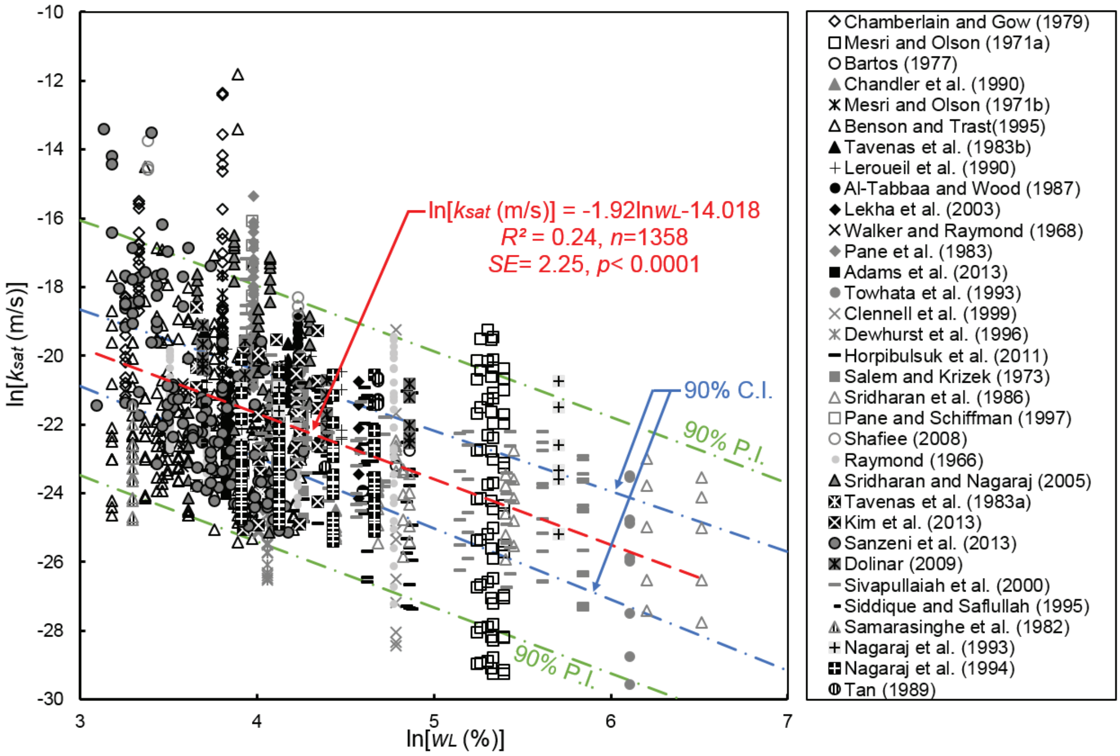
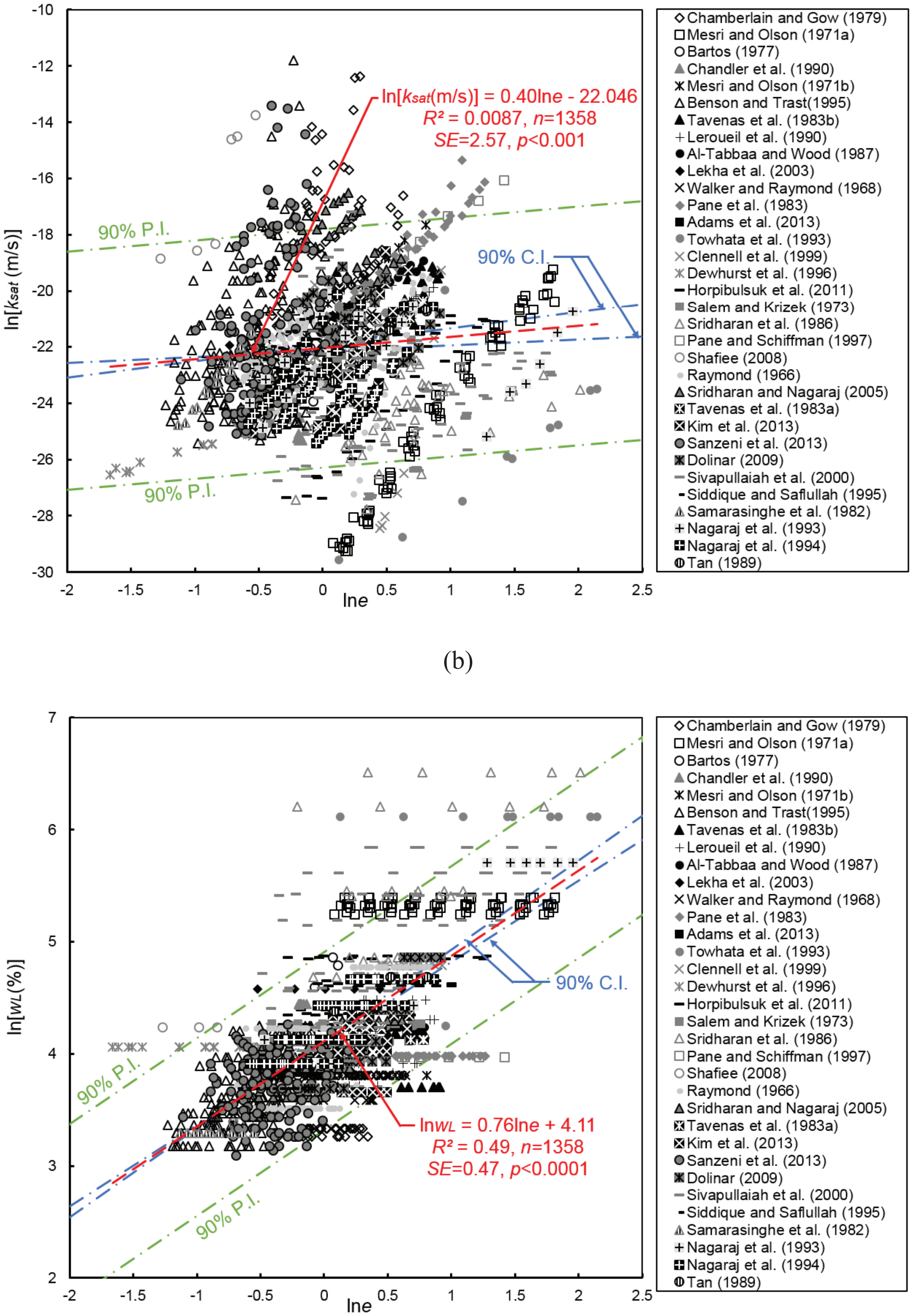


Figure 2: $1/S_S$ plotted against $1/w_L$ (Equation 3 also shown for comparison; Ss information for Sridharan et al. (1986b) is given in Sridharan and Choudhary (2008); note: the trend line from the paper by Chapuis and Aubertin (2003) is based on a separate soil database)

Figs (3a and 3b) show that when considering the entire database (n>1300) w_L and e are poor predictors of k_{sat}. However, Fig. 3b shows visually that k_{sat} is related to e for individual test series and strong correlations for individual soils are present (see Table S1). Table S1 shows that for most single soil types, a reliable power correlation exists between k and e. Compared to the regression results between k and $e^3/(1+e)$, the regression results between k and e generally yields similar R^2 value (average difference in R^2 is 0.001 and 0.24% for RD) for each single soil type. In this paper, e will be used in lieu of $e^3/(1+e)$ for developing the correlation used to predict saturated hydraulic conductivity.



(a)



(b)

(c)

Figure 3: (a) lnk_{sat} plotted against lnw_L; (b) lnk_{sat} plotted against ln$e$; (c) lnw_L plotted against ln$e$

Some covariance between w_L and e in the collected database is observed (see Fig. 3c). However, the void ratio e and liquidity index w_L can be measured independently of each other and so regression analyses using both are justified. Fig. 4 shows that the 'a' from Eq. (7) ($k=ae^b$) is strongly correlated to w_L thus demonstrating that w_L is an effective normaliser for w. The multiple linear regression of k_{sat} with both e and w_L gives the following equation:

$$\ln[k_{sat}(m/s)] = 3.78\ln[e] - 4.33\ln[w_L] - 4.27$$

$$[R^2 = 0.64,\ n = 1352,\ SE = 1.54,\ p < 0.0001] \tag{12a}$$

which can be re-arranged to:

$$k_{sat}(m/s) = 0.014e^{3.78}{w_L}^{-4.33} \tag{12b}$$

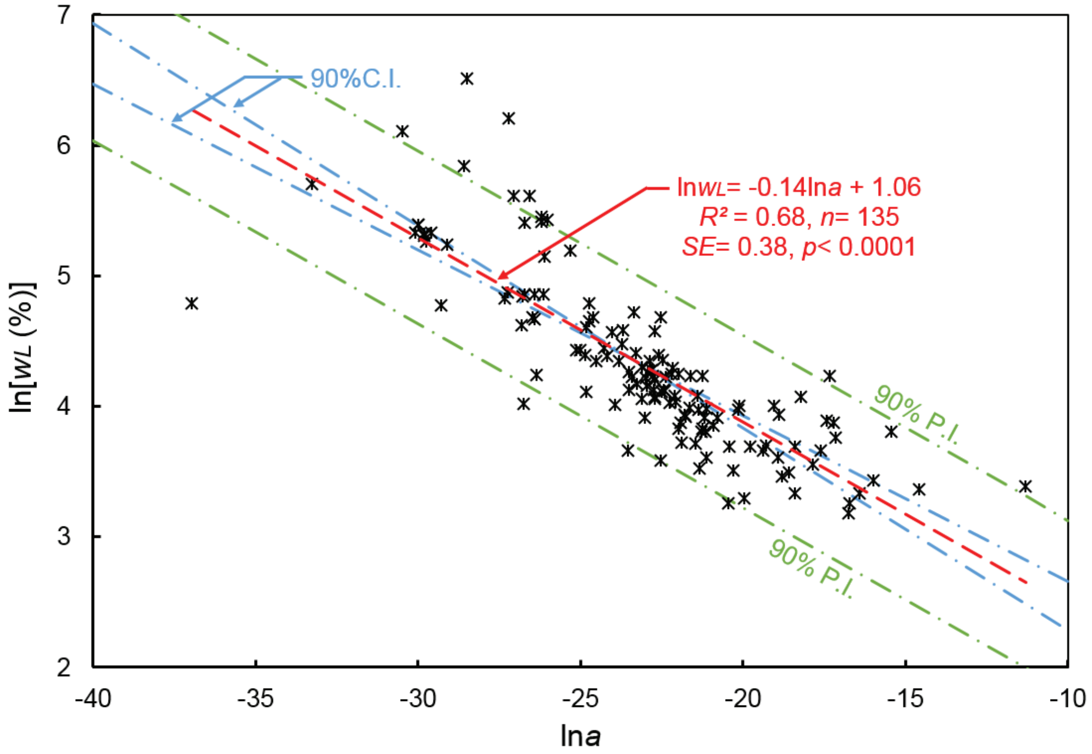


Figure 4: $\ln w_L$ plotted against $\ln a$

The six data points from Shafiee (2008) were excluded from the regression as examination of these data is at least 2 magnitudes higher than for similar materials of the same consolidation states (e.g. Mesri and Olson, 1971a; Clennell et al., 1999; Sridharan and Nagaraj, 2005; Dolinar, 2009; and Adams et al., 2013) these data are shown on Figs S1 and S2 for reference.

Fig. 5 presents the k_{sat}-measured versus k_{sat}-predicted plot based on Eq. (12b) which shows that 10% of the total points fall out of the 'y=0.1x' and 'y=10x' range, 56% of the data points plot below the line of equality (44% above). Eq. (12b) generally gives a prediction of k_{sat} between 0.1 to 10 times of the measured value and tends to give slightly overpredicted results. However, given the exponent on e and w_L^{-1} is similar, Eq. (12b) could be simplified by setting the exponents to equal numerical values:

$$\ln\left[k_{sat}(m/s)\right] = 4.13\ln[e/w_L] - 5.12$$

$$[R^2 = 0.62,\ n = 1352,\ SE = 1.57,\ p < 0.0001] \qquad (13a)$$

which can be re-arranged to:

$$k_{sat}(m/s) = 0.0060(e/w_L)^{4.13} \qquad (13b)$$

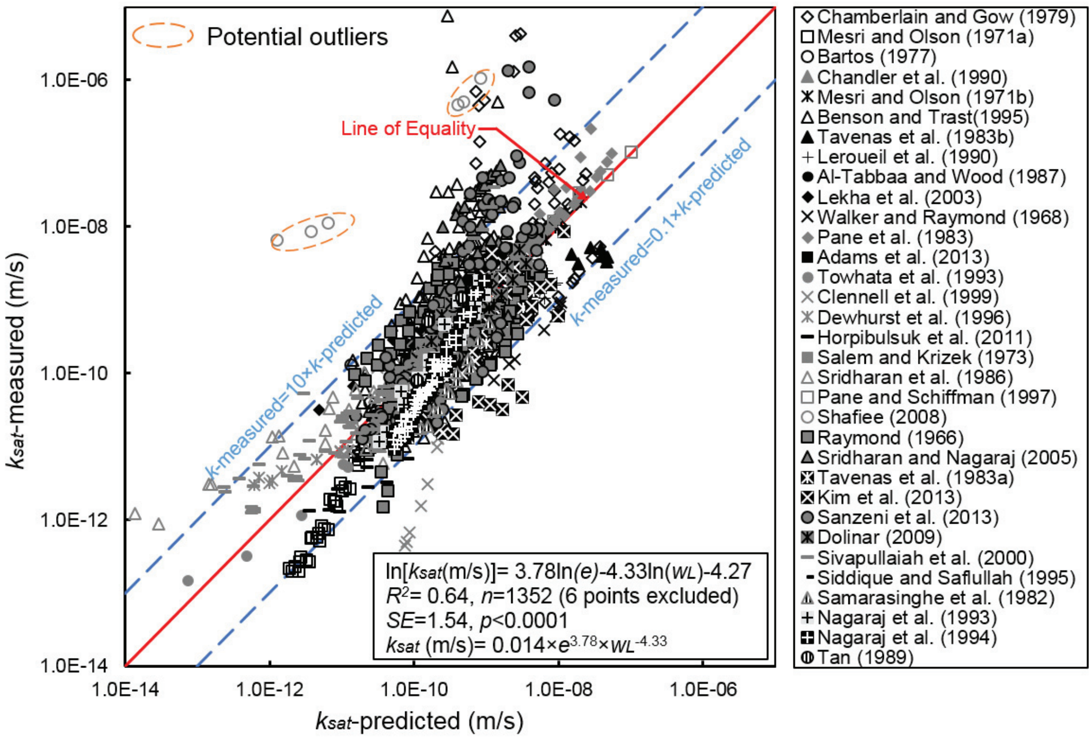


Figure 5: k_{sat}-measured plotted against k_{sat}-predicted (Eq. (12))

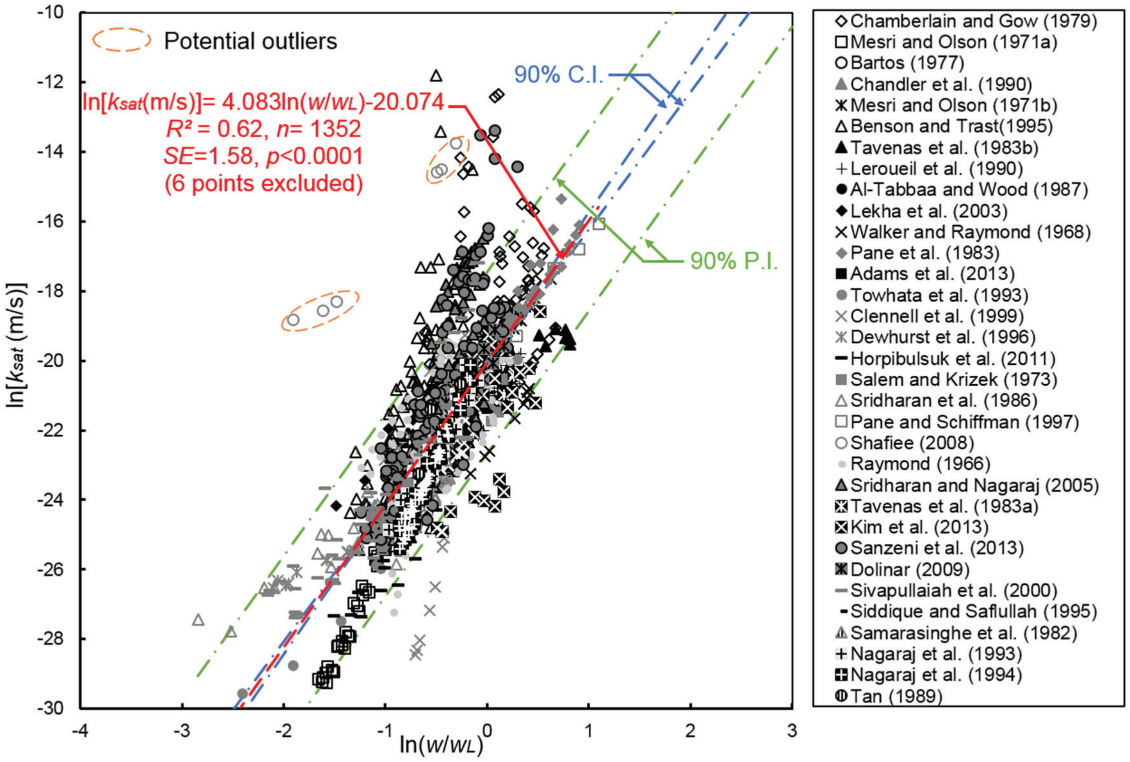


Figure 6: lnk_{sat} plotted against ln(w/w_L)

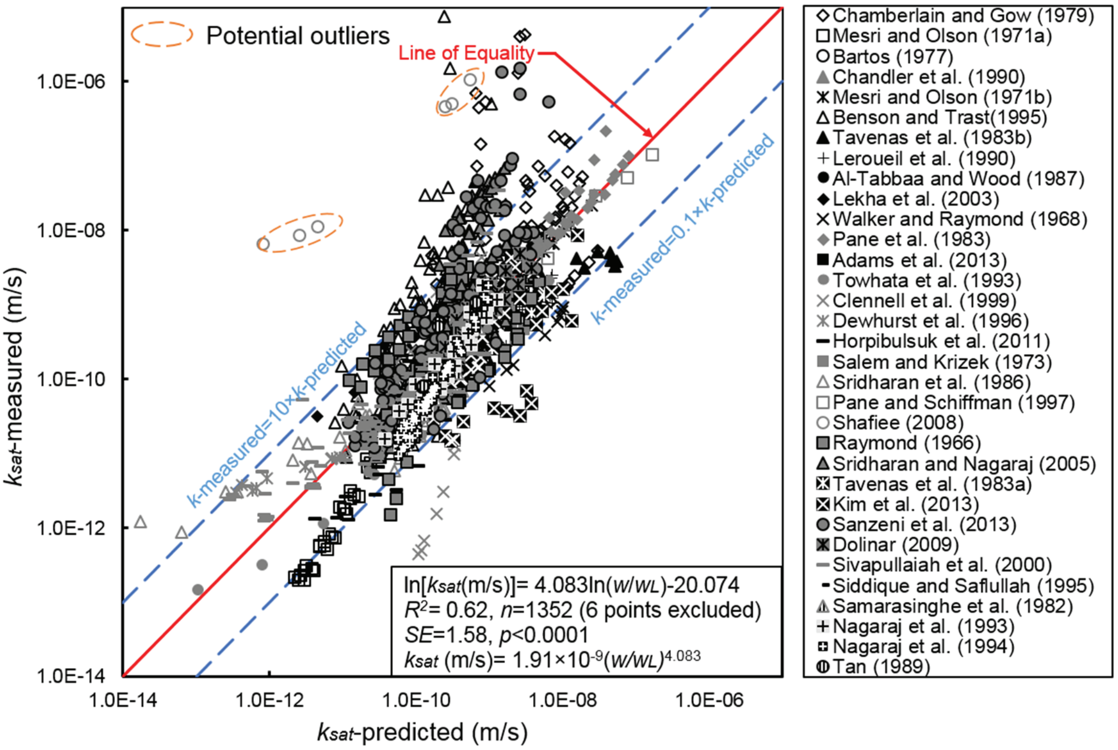


Figure 7: k_{sat}-measured plotted against k_{sat}-predicted (Eq. (14))

The reported specific gravity (G_S) values in the database ranges from 2.09 to 2.90, the void ratio e might be further reduced to the saturated water content (w) expressed as a percentage so that $w/w_L(\%) = e/e_L$. Fig. 6 shows the correlations between lnk_{sat} and ln(w/w_L), which can be re-arranged and gives:

$$\ln\left[k_{sat}(m/s)\right] = 4.083\ln\left[w/w_L\right)] - 20.074$$

$$[R^2 = 0.62,\ n = 1352,\ SE = 1.58,\ p < 0.0001] \tag{14a}$$

which can be re-arranged to:

$$k_{sat}(m/s) = 1.91 \times 10^{-9}(w/w_L)^{4.083} \tag{14b}$$

For the data sources where G_S was not explicitly quoted, the average G_S value 2.701 (n = 860) based on the entire database were used to calculate w.

Eq. (14b) uses w/w_L, which is equivalent to the e/e_L ratio given in Nagaraj et al. (1993, 1994) (see Fig. 6) and present a simplified method to make a-priori prediction of k_{sat}. The k_{sat}-measured versus k_{sat}-predicted plot (see Fig. 7) shows that Eq. (14b) generally allows for the prediction of k_{sat} between 0.1 to 10 times of the measured value (plus or minus an order of magnitude) (89% of the total points fall within this range) and tends to give slightly overpredicted results (59% plot below the line of equality and 41% above). Eq. (14b) is compared with the correlations from Nagaraj et al. (1993) (Eq. (8)), Nagaraj et al. (1994) (Eq. (9)) and Mbonimpa et al. (2002) (Eq. (10)) in Fig. 8 for comparison.

Influence of Atterberg limits

The database is classified into samples with high liquidity ($w_L \geq 50\%$) and low liquidity ($w_L < 50\%$). Fig. 9 presents the relationship between lnk_{sat} and ln(w/w_L) for each subset. The equations obtained from regression analysis and corresponding prediction results are summarized in Table 2 (see Figs S3-S4 for the predicted versus measured plots). The exponent in the regression equation does not vary considerably within different subsets (3.70 versus 3.95), with around 90% of the predicted values falling within the y= 0.1x and y= 10x

bounds. Both subsets generally give a prediction of k_{sat} within 0.1 to 10 times accuracy. Compare to the low liquidity sub-dataset ($w_L < 50\%$), the sub-dataset with $w_L > 50$ has more reliable (93% within the range), and unbiased (52% overpredicted, 48% underpredicted) predictions of k_{sat} with its regressed prediction model.

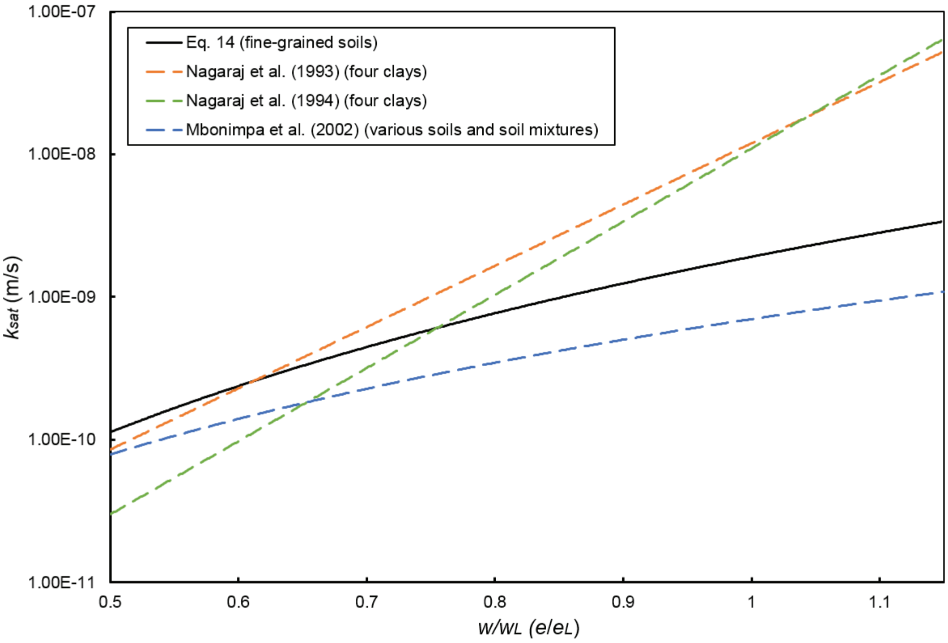


Figure 8: Comparison with previous correlations

Fig. 10 shows the correlations between $\ln k_{sat}$ and $\ln(w/w_L)$ for data subsets "above A line" (clayey soil) and "below A line" (silty soil) respectively. For the database presented in this paper 75 samples did not have I_P or USCS information available and therefore were not included in this part of the analysis. Table 3 summarizes the linear regression results and the corresponding prediction outcomes for both data subsets (see Figs S5-S6 for the predicted versus measured plots). The regression equations of both sub-datasets are similar to the regressed results of the total database (Eq. (14b)). Both sub-datasets provide a prediction of k_{sat} mostly within 0.1 to 10 times accuracy, while the "above A line" (clayey soil) sub-dataset comes with a higher percentage of datapoints (89%) fall within $y = 0.1x$ to $y = 10x$ range and while the "below A line" (silty soil) sub-dataset gives a more symmetrical prediction (57% overpredicted; 43% underpredicted) using the regression equation.

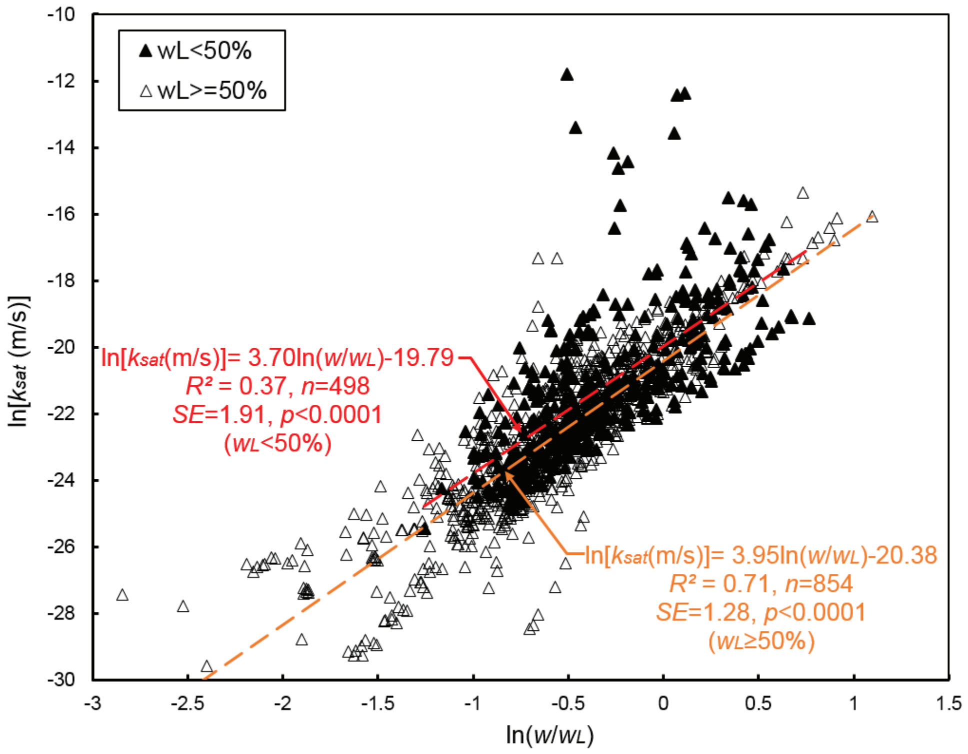


Figure 9: lnk_{sat} plotted against ln(w/w_L) with soil classified by w_L

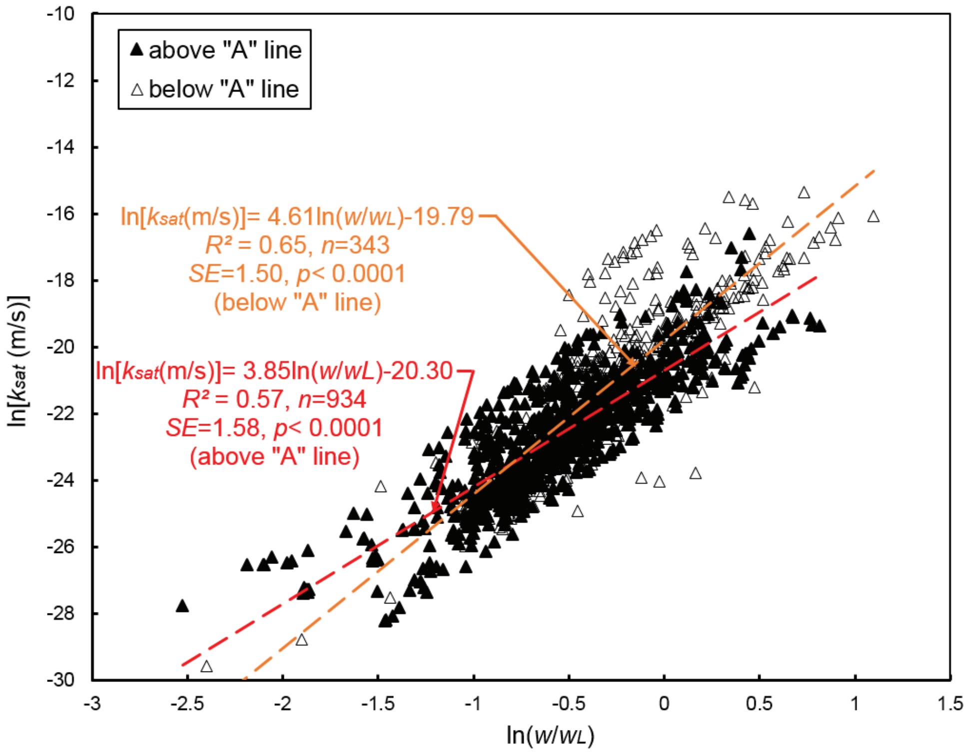


Figure 10: lnk_{sat} plotted against ln(w/w_L) with soil classified by location on the Casagrande chart with respect to the location of the A-line

Influence of permeability test method

As listed in table 1, four different types of hydraulic conductivity measurement approaches are involved in the analysed database. The database is further subdivided based on the reported k test methods to examine the potential effect brought by k test approaches. The $\ln k_{sat}$ versus $\ln(w/w_L)$ of four data subsets individually are presented in Fig. 11. Table 4 summarized the analysis results of each data subset (see Figs S7-S10 for the measured versus predicted plots). The exponent in the regressed equation does not fluctuate much within different sub data-sets, and all four sub-datasets provide predictions of k_{sat} mostly within 0.1 to 10 times of the measured k_{sat}, the 'consolidation test' subdataset has the most data points (93%) fall within the $y= 0.1x$ to $y=10x$ range and also gives the most unbiased prediction results with its regressed equation among four data subsets.

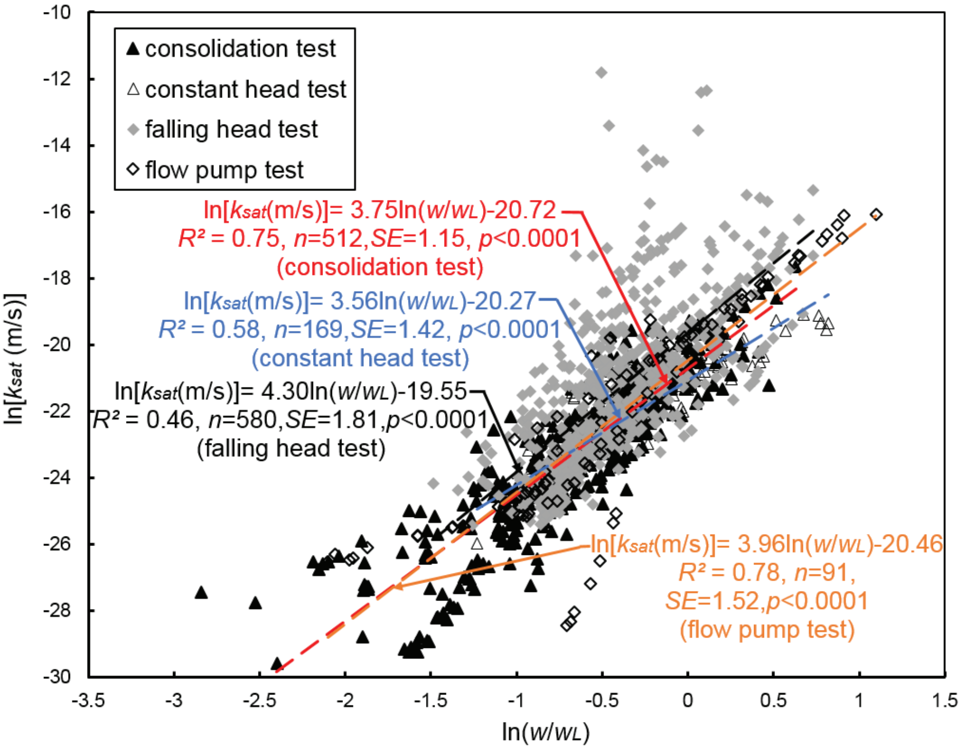


Figure 11: $\ln k_{sat}$ plotted against $\ln(w/w_L)$ with soil classified by k test methods

Influence of test sample states

Finally, the saturated hydraulic conductivity results in the database were subdivided on the basis of samples whose state was able to be classed as “undisturbed” or “disturbed” (i.e. those where natural structure, water content and or stress-level were changed during testing from the in-situ conditions). The bulk of the database was classified as “disturbed”, while the test results reported in Walker and Raymond (1986), Tavenas et al. (1983a, 1983b), Chandler et al. (1990), Leroueil et al. (1990) and Kim et al. (2013) were identified as “undisturbed”. Noted that the sample states in Sanzeni et al. (2013) (n = 122) were not clearly specified, therefore, these 122 datapoints were not included in either the “disturbed” or “undisturbed” subsets. The correlations between lnk_{sat} and ln(w/w_L) for both disturbed and undisturbed data subsets are presented in Fig. 12. Table 5 shows the regression equation and analyses results for both data subsets (see Figs S11-S12 for the corresponding measured versus predicted plots). Both sub-datasets provide a prediction of k_{sat} mostly within 0.1 to 10 times accuracy, while the regression equation of “undisturbed” data subset gives a better prediction with higher percentage of data points (97%) plot within the y= 0.1x to y=10x range. The difference in the correlations in these two subsets is more noticeable than the previous sub-sets with the exponent being considerably lower for undisturbed soils.

CONCLUDING REMARKS

A large database FG/KSAT-1358 (n>1300) of saturated hydraulic conductivity measurements on fine-grained materials have been gathered, a simplified prediction equation was proposed (see Eq. (14b)). Using the data from soil database, it is shown that both e and $e^3/(1+e)$ both statistically predict k, the variable in the obtained R^2 is shown to be minor. Use of the water content ratio (w/w_L) is theoretically justified as w is an acceptable surrogate for e and w_L is an acceptable surrogate for S_S, which are two key factors of the 'Kozeny-Carman' equation. This approach has been successfully used by the past researchers with smaller datasets.

The prediction equation gives a good prediction of hydraulic conductivity mostly within 0.1 to 10 times ranges for the whole database. Splitting the database by w_L level, clay/silts, k test methods, and the states of test sample shown minor variation on the regressed equation with the exponent of w/w_L usually around 4. Therefore, Eq. (14b) offers a theoretically sound, semi-empirical approach to predict k_{sat} for fine-grained soils.

$$k_{sat}(m/s) = 1.91 \times 10^{-9}(w/w_L)^{4.083} \qquad \text{(14b) bis}$$

The accuracy of Eq. (14b) would be improved with a database that allowed for the correction of all k_{sat} values to a set temperature: some of the scatter in the database is probably due to some variation in test temperature. While the prediction bounds for Eq. (14b) are wider than those from Nagaraj et al. (1993, 1994) and Mbonimpa et al (2002) it should be noted that Eq. (14) has been calibrated by a much larger database of over 1300 k_{sat} measurements.

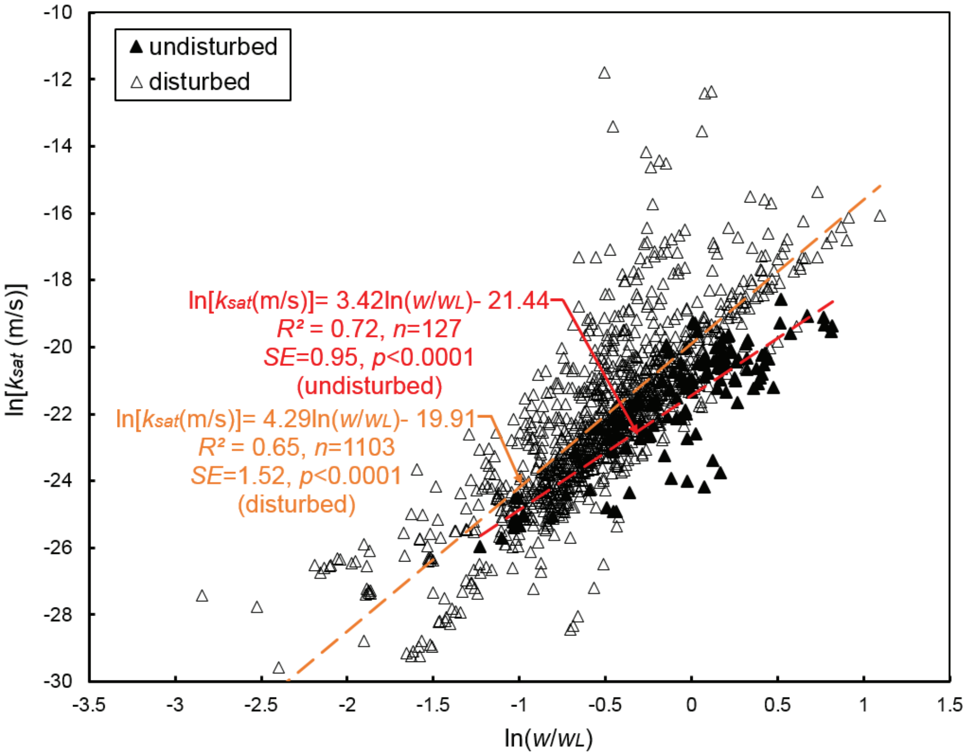


Figure 12: lnk_{sat} plotted against ln(w/w_L) with soil classified by test sample states

Data Availability Statement

This study has not generated new experimental data.

Acknowledgements

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Table 2: Analysis results of data subset classified by w_L level

Classification	***n***	**Regressed equation**	***R²***	***SE***	**Between y=0.1x and y=10x**	**Over-predict**	**Under-predict**	**Re-arranged equation**
$w_L < 50$	498	$\ln[k_{sat}(\mathrm{m/s})] = 3.70\ln(w/w_L) - 19.79$	0.37	1.91	82%	62%	38%	$k_{sat}(m/s) = 2.54 \times 10^{-9}(w/w_L)^{3.70}$
$w_L > 50$	854	$\ln[k_{sat}(\mathrm{m/s})] = 3.95\ln(w/w_L) - 20.38$	0.71	1.28	93%	52%	48 %	$k_{sat}(m/s) = 1.41 \times 10^{-9}(w/w_L)^{3.95}$
Total	1352							

Table 3: Analysis results of data subset classified by location relative to the A line: IP = 0.73(wL-20)

Classification	***n***	**Regressed equation**	***R²***	***SE***	**Between y=0.1x and y=10x**	**Over-predict**	**Under-predict**	**Re-arranged equation**
above A line	934	$\ln k_{sat}(\mathrm{m/s}) = 3.85\ln[(w/w_L)] - 20.30$	0.57	1.58	89%	61%	39%	$k_{sat}(m/s) = 1.53 \times 10^{-9}(w/w_L)^{3.85}$
below A line	343	$\ln k_{sat}(\mathrm{m/s}) = 4.61\ln[(w/w_L)] - 19.79$	0.65	1.50	87%	57%	43 %	$k_{sat}(m/s) = 2.54 \times 10^{-9}(w/w_L)^{4.61}$
Total	1277							

Table 4: Analysis results of data subset classified by ksat test method

Classification	***n***	**Regressed equation**	***R²***	***SE***	**Between y=0.1x and y=10x**	**Over-predict**	**Under-predict**	**Re-arranged equation**
Falling head	580	$\ln[k_{sat}(\mathrm{m/s})] = 4.30\ln(w/w_L) - 19.55$	0.46	1.81	86%	59%	41%	$k_{sat}(m/s) = 3.23 \times 10^{-9}(w/w_L)^{4.30}$
Constant head	169	$\ln[k_{sat}(\mathrm{m/s})] = 3.56\ln(w/w_L) - 20.27$	0.58	1.42	90%	63%	37 %	$k_{sat}(m/s) = 1.57 \times 10^{-9}(w/w_L)^{3.56}$
Consolidation	512	$\ln[k_{sat}(\mathrm{m/s})] = 3.75\ln(w/w_L) - 20.72$	0.75	1.15	93%	45%	55%	$k_{sat}(m/s) = 1.00 \times 10^{-9}(w/w_L)^{3.75}$
Flow pump	91	$\ln[k_{sat}(\mathrm{m/s})] = 3.96\ln(w/w_L) - 20.46$	0.78	1.52	89%	42%	58%	$k_{sat}(m/s) = 1.30 \times 10^{-9}(w/w_L)^{3.96}$
Total	1352							

Table 5: Analysis results of data subset classified by states of test samples

Classification	***n***	**Regressed equation**	***R²***	***SE***	**Between y=0.1x and y=10x**	**Over-predict**	**Under-predict**	**Re-arranged equation**
Disturbed	1103	$\ln[k_{sat}(\mathrm{m/s})] = 4.29\ln(w/w_L) - 19.91$	0.65	1.52	91%	61%	39%	$k_{sat}(m/s) = 2.26 \times 10^{-9}(w/w_L)^{4.29}$
Undisturbed	127	$\ln[k_{sat}(\mathrm{m/s})] = 3.42\ln(w/w_L) - 21.44$	0.72	0.95	97%	48%	53%	$k_{sat}(m/s) = 4.88 \times 10^{-10}(w/w_L)^{3.42}$
Total	1230							

Notation list

The following notation is used in this paper (units shown in brackets)

a = a Regression constant;

b = a Regression constant;

C = Constant;

$C.I.$ = Confidence interval;

d= Particle size;

D_R = Specific weight of solid;

e = Void ratio;

e_L = Void ratio at liquid limit;

g = Gravitational acceleration (Length.Time^{-2});

G_S = Specific gravity;

I_P = Plasticity index; %

k = Hydraulic conductivity (Length.Time^{-1});

k_{sat} = Saturated hydraulic conductivity (Length.Time^{-1});

L = Length;

n = Number of data points;

$P.I.$ = Prediction interval;

R^2 = Coefficient of determination;

RD = Relative deviation ($RD = 100\sqrt{(1-R^2)}$);

SC = Clayey sand;

SE= Standard error;

S_S = Specific surface area (Length^2.Mass^{-1});

T= Time;

w = Water content; %

w_L = Liquid limit; %

w_P = Plastic limit; %

w_S = Shrinkage limit; %

z = a regression model parameter;

α = a regression constant;

β = an exponent;

δ = a coefficient;

μ = a coefficient;

μ_w = Dynamic viscosity of the permeant (Mass.Time^{-1}. Length^{-1});

v = an exponent;

ρ_w = Density of the permeant (Mass. Length^{-3}).

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