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The permeability of composite soils

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Abstract:	Many natural soils and artificial soils are composite soils formed of a range of particle sizes and types. These soils are often difficult to sample and test when following standard site investigation practice thus it is necessary to resort to empirical correlations, most of which were developed for either coarse-grained (e.g. clean sands) or fine-grained (e.g. pure clays) soils. The hydraulic conductivity of clean sands is a function of the void ratio and particle size distribution, and for clays, the clay type and void ratio. This suggests that the hydraulic conductivity of composite soils will be a function of these properties and the clay content. Composite soils formed of four clay minerals and two sands were consolidated from slurry to determine the variation of hydraulic conductivity with clay content, clay type and void ratio. With matrix dominated soils, soils that contain with more than 35% fines content, the flow is a function of the matrix void ratio and clay type; and, for clast dominated soils, soils that contain less than 20% fines content, the intergranular void ratio and particle size distribution. The behaviour of soils with a fines content between 20% and 35% depends on the confining pressure and density.

The permeability of composite soils

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ABSTRACT: Many natural soils and artificial soils are composite soils formed of a range of particle sizes and types. These soils are often difficult to sample and test when following standard site investigation practice thus it is necessary to resort to empirical correlations, most of which were developed for either coarse-grained (e.g. clean sands) or fine-grained (e.g. pure clays) soils. The hydraulic conductivity of clean sands is a function of the void ratio and particle size distribution, and for clays, the clay type and void ratio. This suggests that the hydraulic conductivity of composite soils will be a function of these properties and the clay content. Composite soils formed of four clay minerals and two sands were consolidated from slurry to determine the variation of hydraulic conductivity with clay content, clay type and void ratio. With matrix dominated soils, soils that contain with more than 35% fines content, the flow is a function of the matrix void ratio and clay type; and, for clast dominated soils, soils that contain less than 20% fines content, the intergranular void ratio and particle size distribution. The behaviour of soils with a fines content between 20% and 35% depends on the confining pressure and density.

KEYWORDS: composite soils, hydraulic conductivity, matrix void ratio, intergranular void ratio

1. INTRODUCTION

The classical approach to geotechnical engineering is to separate soils into two major groups; fine-grained soils are those soils that are formed of particles less than 0.063mm diameter and coarse-grained soils are formed of particles greater than 0.063 mm. In situ, most soils are formed of a range of particle sizes such that they are more correctly classed as composite or intermediate soils. BS6031:2009 suggests that composite soils are those that contain at least 10% of the secondary fraction. BS14688-1:2013 defines a composite fine soil as one in which the fines content determines the engineering behaviour. A composite coarse soil is one which contains fines but behaves as a coarse grained soil. In terms of engineered fills (BS6031:2009), soils that contain at least 15% fines are classed as cohesive soils and for the geotechnical design of cuttings and embankments, cohesive soils are defined as those containing at least 35% fines.

A significant difference between fine grained and coarse grained soils is the permeability which, expressed as the coefficient of hydraulic conductivity, ranges from (1×10^{-13} to 1×10^{-7} cm/sec) for fine grained soils to (1×10^{-8} to 0.01 cm/sec) for coarse grained soils. Stephenson et al (1988) suggests that there is a correlation between particle size distribution and hydraulic conductivity; most significantly a reduction of three orders of magnitude if the clay content exceeds 15% to 20%. This is consistent with the observations of Skempton (1985), Georgiannou et al (1990), Salgado et al (2000), and Vallejo and Mawby (2000) who suggested that a composite soil with more than 20% to 25% clay content behaves as a fine grained soil. Monkul and Ozden (2005) proposed a transition fines content of 20% to 34% when the intergranular void ratio of the composite soil is equal to the maximum void ratio of the host granular soil. The intergranular void ratio is the volume of voids and fine grains expressed as a percentage of the volume of coarse grains.

Given the difficulty of obtaining representative samples of composite soils, empirical correlations are often used to determine their characteristics. The permeability property, k_h, of clean sands was defined by Hazen (1892) as a function of the particle size distribution. Kozeny (1927), modified by Carman (1939), suggested that k_h depends on soil porosity, particle shape and size, and surface area. Estimates of flow in fine grained soils are usually based on empirical correlations with Atterberg limits, particle size and void ratio. Chapuis (2012) (Table 1) undertook a review of the characteristics of predictive methods to reach the conclusions that many methods are flawed because of errors in the experimental procedures but the methods attributed to Hazen (1892), Taylor (1948), Terzaghi (1925), and Shahabi et al. (1984) provide reliable predictions for coarse grained soils based on:-

$$k_h = A \frac{e_g^3}{1+e_g} \quad (1)$$

Where A is a constant, a function of the particle size distribution and, e_g, the global void ratio.

Chapuis (2012) concluded that regional correlations gave reasonable predictions for fine grained soils:-

$$log_{10} k_h = a + b\, log_{10} \left[\frac{e_g^3}{1+e_g} \frac{1}{I_L^2}\right] \quad (2)$$

Where a and b are constants, and I_L the liquid limit.

These predictive methods suggest that flow through composite soils will be a function of the void ratio, particle size and Atterberg limits. Flow in in coarse grained composite soils will depend on the intergranular void ratio; flow in fine grained composite soils will depend on the matrix void ratio.

It is possible to estimate k_h indirectly from oedometer tests using:-

$$k_h = c_v m_v \rho_w \quad (3)$$

Where c_v is the coefficient of consolidation and m_v the coefficient of volume compressibility. Tavenas et al. (1983) suggested that indirect assessments are unreliable because of the assumptions made in the analysis. Chapuis (2012) and Dafalla et al (2015) suggested that Equ (3) under predicts the hydraulic conductivity by two to three orders of magnitude. However, given the difficulty of determining k_h directly in composite soils, an indirect assessment was used to study the impact the characteristics of composite soils have upon k_h. A comparison with published correlations and values of k_h were used to assess the relevance of the estimate values. These are the aims of this paper.

2. GENERAL BEHAVIOUR OF COMPOSITE SOILS

A key to understanding the behaviour of saturated composite soils is the phase diagram formed of water, sands, and clays (Figure 1a). The global void ratio, e_g, is used to estimate consolidation characteristics of single size uniform grained soils. It may not be appropriate for composite soils as it does not take into account the influence of the matrix upon the permeability of sandy clays or the intergranular structure of clayey sands.

Mitchell (1976) introduced the concept of the matrix void ratio, e_m, which is function of the fine grained soil content within a composite soil. If the sand content in a soil is small (Figure 2a) the global behaviour of the soil will be controlled by the electrical chemical inter-particle forces existing between clay particles as the coarse grained particles may not be in contact with each other; that is the coarse grained particles are inactive. As the sand content increases, force chains start to develop between the coarse grained particles until the soil behaviour becomes dominated by the coarse grained particles (Figure 2d). Thus there is a transition zone, Figure 2c, when the soil has characteristics of both a fine grained and coarse grained soil. Therefore, for a fine grain dominated composite soil, it is the matrix void ratio and the properties of the fine grains that govern the behaviour of the composite soil. The matrix void ratio is:

$$e_m = \frac{V_v}{V_c} \quad (4)$$

Where V_v is the volume of voids and V_c the volume of clays. If e_g is known then:

$$e_m = \frac{e_g}{C_v} \qquad (5)$$

Where C_v is the volumetric fraction of dry solids occupied by the fine grains in the mixture. The mass fraction of clay C_m can be measured directly. The particle density can be used to convert C_m to C_v:

$$e_m = \frac{e_g}{\frac{G_T}{G_c} * C_m} \qquad (6)$$

Where G_T is the particle density of the composite soil; G_c is the particle density of the fine grained particles.

When the fine grained content is less than the transition fines content (typically 20% to 35%) (Figure 2d), the coarse grained fraction controls the behaviour of the soil with water and fine grained particles filling the voids between coarse grained particles and having a limited effect on the process of consolidation. The composite soil may behave in a similar manner to that of clean sand. In such a case, it is the intergranular void ratio, e_i, (Thevanayagam, 1998) that governs flow where:

$$e_i = \frac{V_v}{V_s} = \frac{V_w + V_c}{1 - V_c} \qquad (7)$$

This can be expressed in terms of e_g and clay content C_v:

$$e_i = \frac{e_g + C_v}{1 - C_v} \quad or \quad = \frac{e_g + \frac{G_T}{G_c} * (C_m)}{\frac{G_T}{G_s} * (1 - C_m)} \qquad (8)$$

The research programme set out to investigate the relation between the matrix and intergranular void ratios and the hydraulic conductivity of a range of composite soils.

3. EXPERIMENTAL PROGRAMME

3 .1 *Materials*

Investigation of the contribution a soil's composition makes to its consolidation properties is often based on artificial soils because the variability and fabric of natural soils will mask the intrinsic behaviour. Therefore, soils of known composition were prepared by mixing commercially produced clays with sands. The materials used in the study included four types of clays; kaolinite, bentonite, illite and sepiolite; and two uniform sands; medium and fine sands. Commercially available kaolin, polywhite E grade is one of the most common minerals found in natural clays (Grim, 1959) and has a consistent and uniform mineralogy with low organic content (Yukselen-Aksoy and Reddy, 2012). Bentonite CB (calcium type) was used because of its importance in civil engineering as it is a thixotropic, support and lubricant agent used in diaphragm walls and foundations, tunnelling, horizontal directional drilling and pipe jacking. Commercial illite clay with low plasticity and sepiolite, a highly porous clay mineral with low bulk density were also used giving a range of 40% to 120% for the liquid limit of the fine grained particles. The plasticity chart and the particle size distribution of the materials used are illustrated in Figure 3 and 4, respectively. The plasticity chart includes the T-line (Boulton and Paul, 1976), a line around which the limits of composite glacial soils tend to cluster. The composite soils in this study tended to migrate towards the T-line as the sand content increased. Note that in this study the limits were based on the whole sample rather than particles smaller than 425μm as specified in the test procedures.

3 .2 *Test equipment and procedures*

A rigid-wall consolidation cell was used to investigate the consolidation characteristics and to indirectly determine the coefficient of hydraulic conductivity of the composite soils. The standard consolidation cell was designed for testing natural homogeneous clays. It is recommended that the maximum particle size is 10% of the height of the sample but given the amount of sand (maximum 2mm diameter) present in the samples used in this research, a 20mm sample height was considered inappropriate. Further, to ensure saturated conditions, a slurry-like mixture was used to form the reconstituted samples, which meant a sample would undergo large volume changes under the initial loading. For these reasons, a new consolidation cell was designed.

The principles behind the design of the new consolidometer cell are similar to those prescribed in BS 1377-5:1990 and ASTM D2435 standards. The cell, shown in Figure 5, consists of a solid acrylic cylindrical cell (2) to contain and laterally restrain a soil specimen; a stainless steel base (6); bottom drainage systems (4); and a loading cap (1). The cell body is made of clear solid acrylic with 15mm wall thickness which can withstand soil pressures up to 1280kPa. An O-ring (5) sits between the cell base and the acrylic tube to ensure a complete seal during the operation. The cell was designed to sit in a standard oedometer test rig which restricted the outer diameter to 134mm and height 126mm. Drainage was allowed from top and bottom of a sample. The British standard recommends using a screen of filter papers between the specimen and the porous stones. Head (1982) stated that, when using such screen, fine soil grains can be enmeshed in the pores of the filter screen, leading to clogging and impeding the drainage of water. This can adversely affect the measurements. Thus, porous discs were used to transfer the applied stress to the sample and to provide a drainage path for the water.

The composite soils were prepared as slurry to ensure that they were fully saturated yet prevented segregation. A soil with varying coarse (sands) and fine (clays) grained fractions was mixed together dry for about half hour using a motorised rotary mixer. After that the dry soil mixture was blended to a slurry with tap water using an initial water content of up to 1.5 times the liquid limit to prevent segregation and be sufficiently viscous to allow air bubbles to be removed when the sample was vibrated during preparation. The internal surfaces of the cell were lubricated with a grease to reduce the side friction that may develop during the consolidation process. The slurry-like mixture was poured into the cell in layers up to the desired height. The cell was vibrated using a shaking table to eliminate any entrapped air and the sample sealed and stored overnight to ensure a homogenous sample. A loading cap with a porous disc was placed on top of the soil sample slurry. The assembled cell was centrally placed on the platform of the loading frame (Figure 6).

An initial stress of 2.5kPa used to consolidate the slurry to achieve a firm consistency. Thereafter, the applied stress was doubled at each increment. Each stress increment was maintained for a time periods ranging from 1 to 4 days based on the rate of consolidation, a function of the soil mix.

4. RESULTS AND DISCUSSION

The variation of k_h with effective stress, shown in Figure 7, confirms that, for composite soils, k_h is stress dependent and decreases with fine grained content. Figure 7 also suggests that a composite soil can exist in one of three states:- matrix dominated with fine grained content in excess of 30% to 40%; clast dominated with fine grained content less than 20%; and a transition zone with fine grained content between 20% and 30% or 40% depending on the confining stress and clay type. This is also consistent with those composite soils that exhibit plastic behaviour and those soils which are non-plastic. The data, replotted in Figure 8 using the matrix void ratio, shows that, for a fine grained content in excess of 30% the variation in hydraulic conductivity with effective stress, for a specific type of clay mineral, falls within a narrow band; that is, it is the matrix that dominates the permeability of the soil. This is consistent with the concept (Figures 2a and 2b) that flow is governed by the fine grained matrix with the coarse grained particles having little effect provided the coarse grained content is less than 30%. Figure 9 shows the transition fines content more clearly. k_h at a matrix void ratio of one is very nearly constant for all composite soils provided the fine grained content exceeds 30%.

Figure 8 shows that there is no correlation between hydraulic conductivity and matrix void ratio for non-plastic soils. Thevanayagam (1998) and others have suggested that the shear behaviour of clast dominated composite soils is a function of the intergranular void ratio. This also applies to hydraulic conductivity even though the intergranular void ratio includes the fine grained volume. The hydraulic conductivity of coarse grained soils is a function of d_{10} (Hazen, 1892) and the global void ratio (Equ 1) as shown in Figure 10a. A better fit to the data is given (Figure 10b) if the data for non-plastic soils are expressed in terms of d_{10} and e_i:

$$k_h = 2x10^{-4}\left[d_{10}^2\left(\frac{e_i^3}{1+e_i}\right)\right]^{0.885} \qquad (9)$$

k_h of fine grained soils depends on the liquid limit and global void ratio (Equ 2) as shown in Figure 11a. In the case of composite soils, k_h must depend on the percentage of fine grained particles and their type, which, collectively, can be expressed as the activity of the clay (A), and the matrix void ratio. This (Figure 11b) gives a better fit to the data as the results all fall within a band defined by:

$$k_h = 10^{-10}\left[\frac{1}{A^2}\frac{e_m^3}{1+e_m}\right]^{1.53} \qquad (10)$$

Figure 12 compares the particle size distribution of the soils reported in this paper and those of glacial soils, a form of composite soil, reported by Stephenson et al (1988). They can be grouped together according to their hydraulic conductivity and particle size into matrix dominated soils which have less than 65% coarse grained content and clast dominated soils with more 80% coarse gained content. The hydraulic conductivity for the former is given by Equ (10) (Table 2) and, for the latter, Equ (9), and are typically greater than 10^{-7} m/s for clast dominated soils and less than 10^{-9} m/s for matrix dominated soils. There is a transition zone between these two which depends on the soil density, fine grained type and confining pressure (Figure 7). Inspection of the data from Stephenson et al (1988) also shows that for soils with less than 10% clay content (Figure 13) and less than 75% coarse grained content, that is the fine grained content is predominantly silt, the hydraulic conductivity is the same as that for the transition zone which is typically between 10^{-7}m/s and 10^{-9}m/s.

5. CONCLUSIONS

This study of composite soils shows that they can be either matrix dominated soils in which the fine grained component dictates the engineering behaviour or clast dominated soils in which the coarse grained component dictates the engineering behaviour. There is a transitional behaviour between matrix dominated and clast dominated behaviour which occurs at between 20% and 35% coarse grained content depending on the confining stress and type of fine grained particles. In matrix dominated soils, the permeability is controlled by the characteristics of the fine grained component. The coarse grained content has little effect on the conductivity as the particles are randomly distributed through the fine grained matrix. As the fine grained content reduces, the number of active contacts between the coarse grained particles increases, leading to an increase in the size of pores contained within the soil matrix, thus increasing the permeability. This is the transition zone where the hydraulic conductivity starts to increase. With a further reduction in fine grained content, the hydraulic conductivity of the soil continues to increase until the flow is dominated by the characteristics of the coarse grained fabric as the influence of the fine grained content on the flow of water is small and can be ignored. The soil in this zone is non-plastic.

These results show that there is a relationship between hydraulic conductivity and void ratio (Table 2). For matrix dominated soils, the relationship is a function of clay type and matrix void ratio; for clast dominated soils, it is a function of particle size and intergranular void ratio. For design purposes, it is possible to use Figure 13 to estimate the coefficient of hydraulic conductivity.

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Notations

A	activity
C_m	mass fractions of fine grains (clay) in a mixture
c_v	coefficient of consolidation
C_v	volumetric fractions of fine grains (clay) in a mixture
d_{10}	effective diameter corresponding to 10% finer
e_g	global void ratio
e_i	intergranular void ratio
e_m	matrix void ratio
e_{max-s}	maximum void ratio of host coarser sand
G_c	particle density of clay
G_s	particle density of sand
G_T	global particle density of mixture
I_L	liquid limit
I_P	plastic limit
k_h	hydraulic conductivity
m_v	coefficient of volume compressibility
PI	plasticity index
V_c	volume of clay
V_s	volume of sand
V_v	volume of voids
V_w	volume of water
σ'_v	vertical effective stress

Table 1 Predictive methods of hydraulic conductivity (modified from Chapuis, 2012)

Table 2 Proposed predictive models for composite soils

Figure 1. Phase-diagrams of: (a) saturated composite soil; (b) matrix dominated soil; and (c) clast dominated soil.

Figure 2. The effect of sand content on composite soils

Figure 3. The plasticity chart for the composite soils showing the relationship of the limits to the T-line

Figure 4. Particle size distribution of; (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; and (f) medium sand-sepiolite mixtures

Figure 5. The consolidation cell

Figure 6. The test equipment showing the loading frame and consolidation cell

Figure 7. The variation of hydraulic conductivity with log effective stress for (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; (f) medium sand-sepiolite mixtures

Figure 8. The variation of hydraulic conductivity with matrix void ratio for: (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; (f) medium sand-sepiolite mixtures

Figure 9. The variation of hydraulic conductivity for a matrix void ratio of one for a composite soil with (a) fine grained content and (b) the hydraulic conductivity adjusted by the activity of the clay with fine grained content

Figure 10. The variation of hydraulic conductivity of clast dominated composite soils with (a) the global void ratio (Equ 1) and (b) the intergranular void ratio (Equ 9)

Figure 11. The variation of hydraulic conductivity of matrix dominated composite soils with (a) the global void ratio and liquid limit (Equ 2) and (b) the matrix void ratio and activity (Equ 10)

Figure 12 A comparison between the experimental observations of coefficient of hydraulic conductivity of composite soils and those reported by Stephenson et al (1988) for glacial soils

Figure 13 A relationship between the composition of composite soils and the coefficient of hydraulic conductivity showing that there are four distinct zones: matrix dominated soils, clast dominated soils, the transition between matrix and clast dominated soils, and soils that are predominantly formed of silt

Table 1: Predictive methods of hydraulic conductivity (modified from Chapuis, 2012)

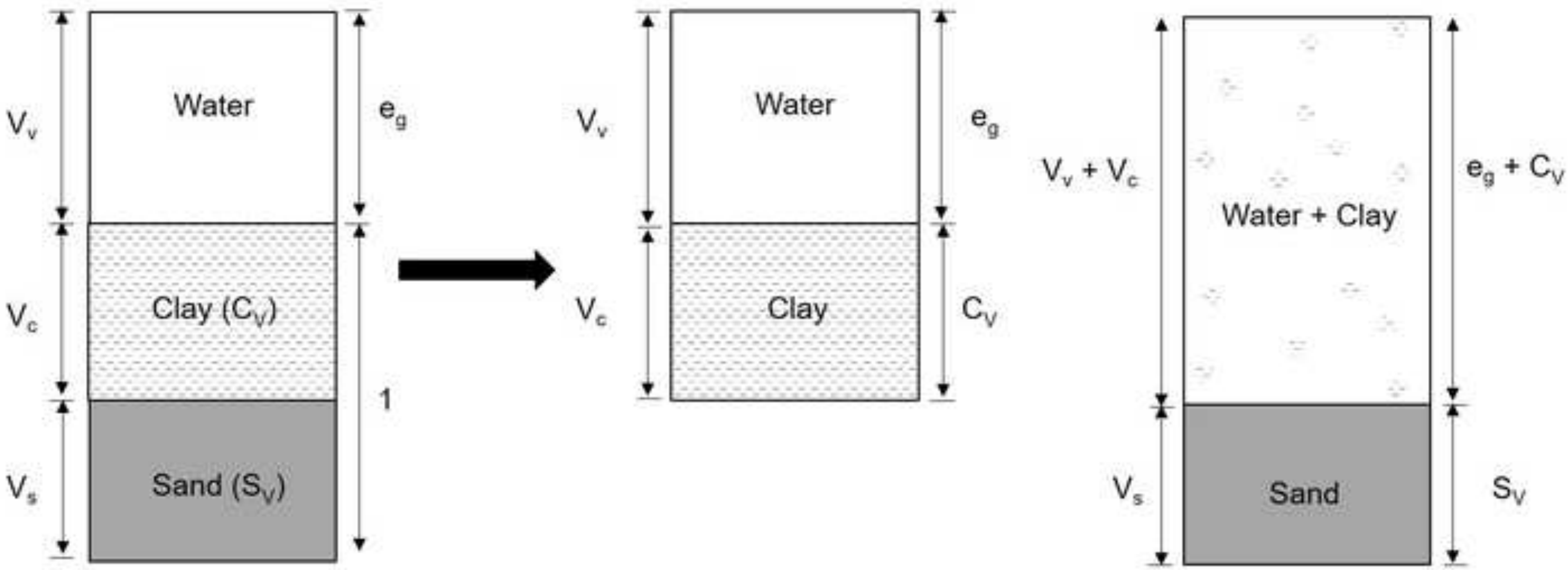
No	Author(s)	Year	Dependency of the predictive method			
			Type of soil	*PSD*	*n* or e_g	I_L, I_P, or P_I
1	Seelheim	1880	any soil	Yes	No	
2	Hazen	1892	Sand, gravel	Yes	$e=e_{max}$	
3	Slichter	1898	Spheres	No	Yes	
4	Terzaghi	1925	Sand	Yes	Yes	
5	Mavis and Wilsey	1936	Sand	Yes	Yes	
6	Tickell and Hiatt	1938	Sand	Yes	One value	
7	Krumbein and Monk	1942	Sand	Yes	No	
8	Craeger et al. N1	1947	Sand, gravel	Yes	No	
9	Taylor	1948	Sand, clay	No	Yes	
10	Loudon	1952	Any soil	No	Yes	
11	Kozeny	1953	Sand	Yes	Yes	
12	Wyllie and Gardner	1958a,b	Any soil	No	Yes	
13	Harleman	1963	Sand	Yes	No	
14	Beyer	1964	Sand	Yes	No	
15	Masch and Denny	1966	Sand	Yes	No	
16	Nishida and Nakagawa	1969	Clay	No	Yes	Yes
17	Wiebenga et al.	1970	Sand, silt	Yes	No	
18	Mesri and Olson N2	1971	Clay	No	Yes	
19	Beard and Weyl	1973	Sand	Yes	Yes	
20	Navfac DM7	1974	Sand, gravel	Yes	Yes	
21	Samarasinghe et al.	1982	Clay	No	Yes	Yes
22	Carrier and Beckman	1984	Clay	No	Yes	Yes
23	Summers and Weber	1984	Any soil	Yes	No	
24	Kenney et al.	1984	Sand	Yes	Yes	
25	Shahabi et al.	1984	Sand	Yes	Yes	
26	Kaubisch and Fischer	1985	Any soil	Yes	No	
27	Driscoll N3	1986	Gravel, sand	Yes	Yes	
28	Shepherd	1989	Sand, silt	Yes	No	
29	Uma et al.	1989	Sand	Yes	No	
30	Nagaraj et al.	1991	Clay	No	Yes	Yes
31	Vukovic and Soro N5	1992	Sand	Yes	Yes	
32	Kenney et al.	1992	Compacted sand-clay	No	No	No (k_B)
33	Alyamani and Sen	1993	Mostly sand	Yes	No	
34	Sperry and Pierce	1995	Granular	Yes	No	
35	Boadu	2000	Any soil	No	Yes	
36	Sivappulaiah et al.	2000	Clay-Sand	No	Yes	Yes
37	Mbonimpa et al.	2002	Any soil	Yes	Yes	Yes
38	Chapuis and Aubertin	2003	Any soil	Specific surface	Yes	No
39	Chapuis	2004b	Natural soils	Yes	Yes	
40	Berilgen et al.	2006	Clay	No	Yes	Yes
41	Chapuis et al.	2006	Compacted clay	Yes	Yes	
42	Ross et al.	2007	Any	No	Yes	
43	Mesri and Aljouni	2007	Peat	No	Yes	
44	Dolinar	2009	Clay	No	Yes	Yes
45	Sezer et al.	2009	Granular soil	No	Yes	
46	Arya et al. N6	2010	Golf sand	Yes	Yes	
47	Tripathi	2013	Bentonite, sand-bentonite	No	Yes	No

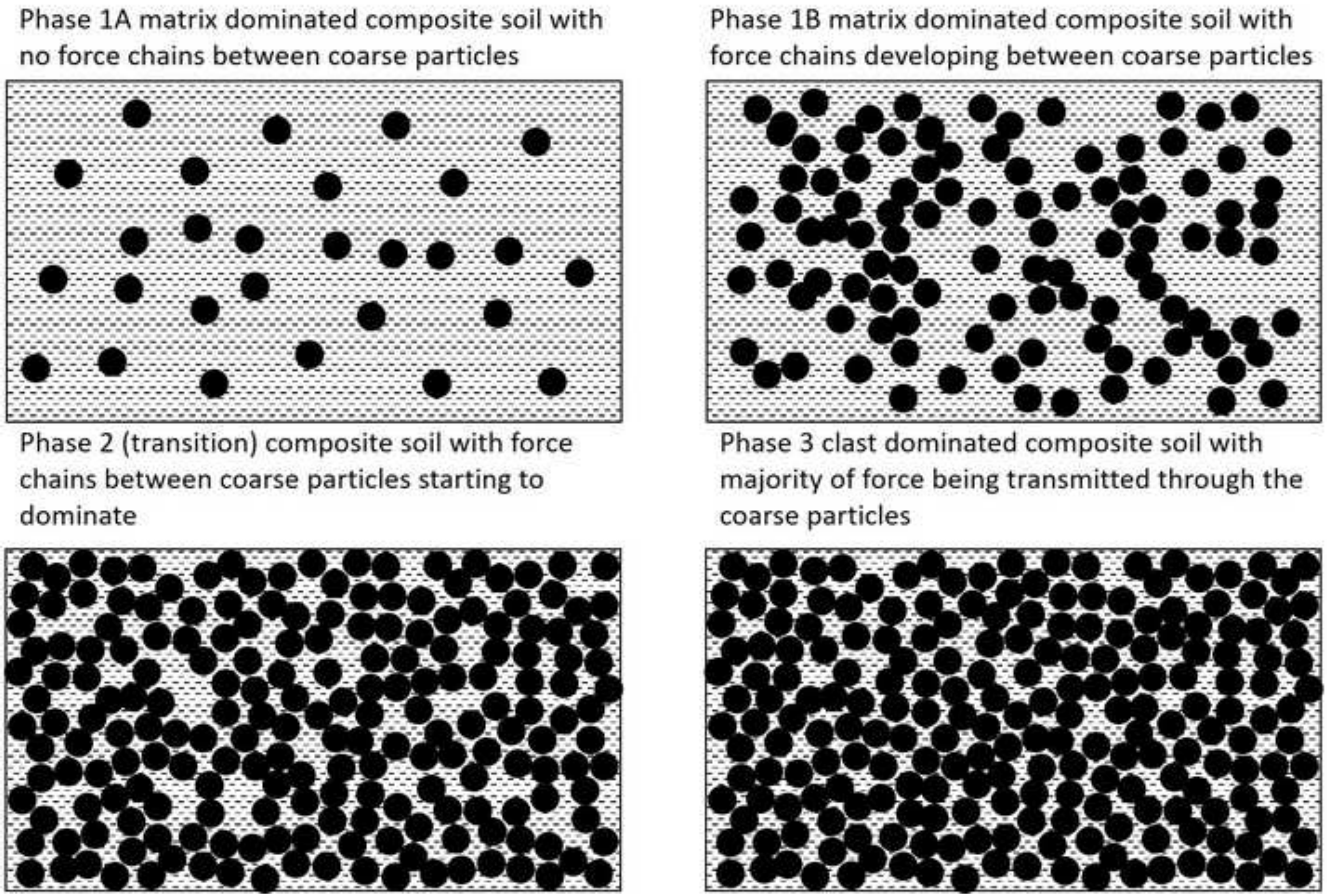
Table 2: Proposed predictive models for composite soils

Parameter	Equ.	Model form	Soil type
Coefficient of hydraulic conductivity (k_h)	9	$k_h = 2x10^{-4}\left[\frac{1}{d_{10}^2}\frac{e_i^3}{(1+e_i)}\right]^{0.885}$	Clast dominated soils
	10	$k_h = 10^{-10}\left[\frac{1}{A^2}\frac{e_m^3}{(1+e_m)}\right]^{1.531}$	Matrix dominated soils

Figure

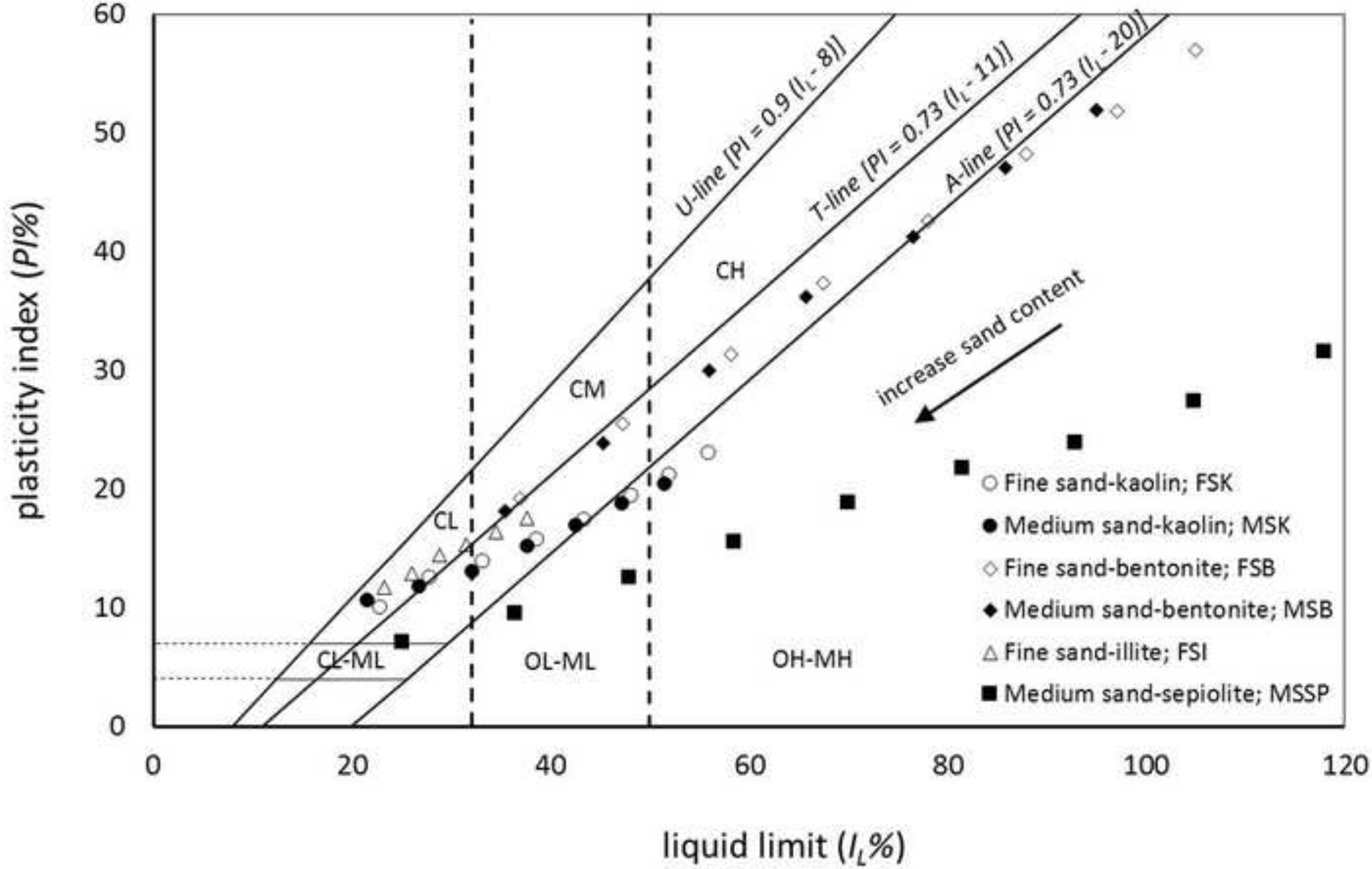
Click here to download Figure Fig 1.jpg




Phase 1A matrix dominated composite soil with no force chains between coarse particles
Phase 1B matrix dominated composite soil with force chains developing between coarse particles
Phase 2 (transition) composite soil with force chains between coarse particles starting to dominate
Phase 3 clast dominated composite soil with majority of force being transmitted through the coarse particles

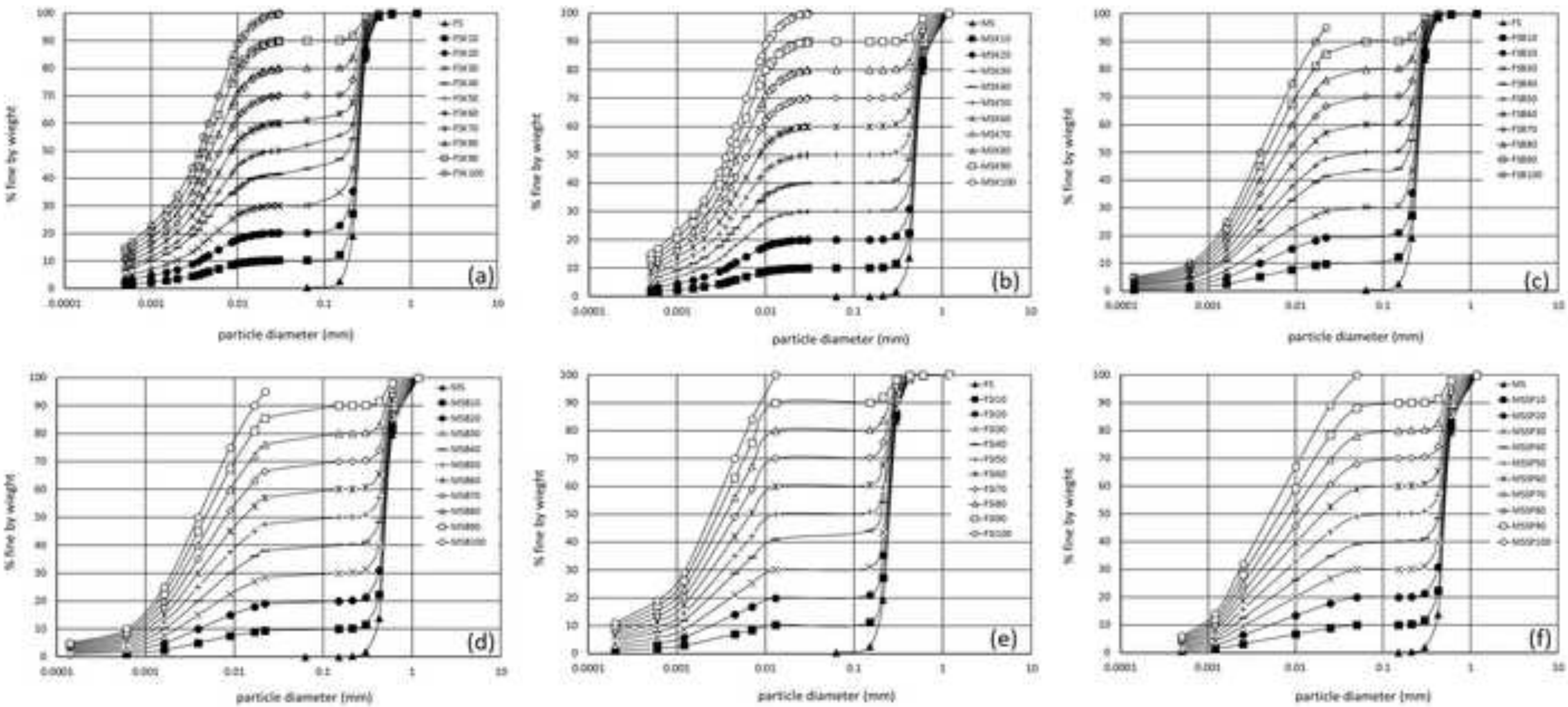
Figure

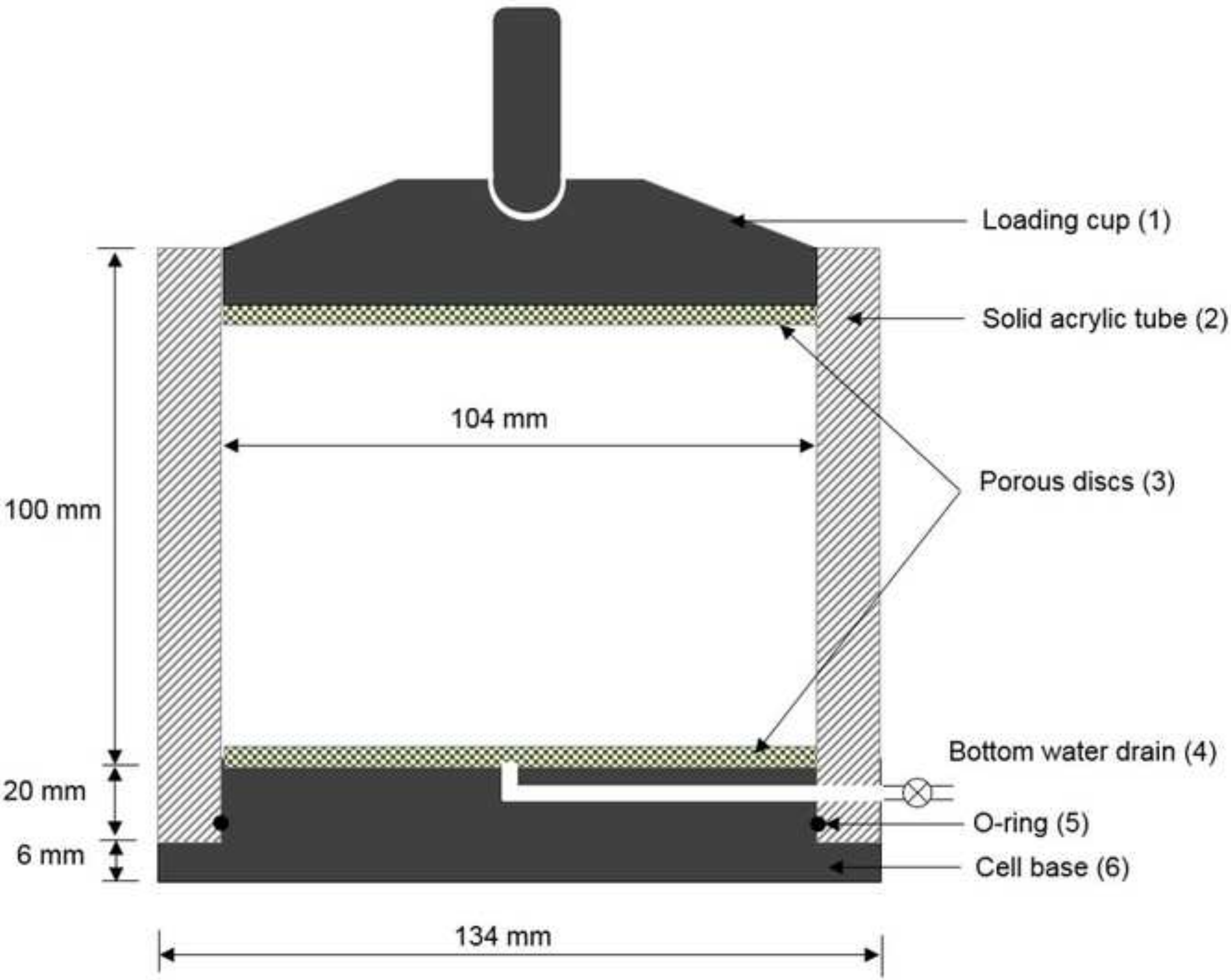
Click here to download Figure Fig 3.jpg



Figure

Click here to download Figure Fig 4.jpg

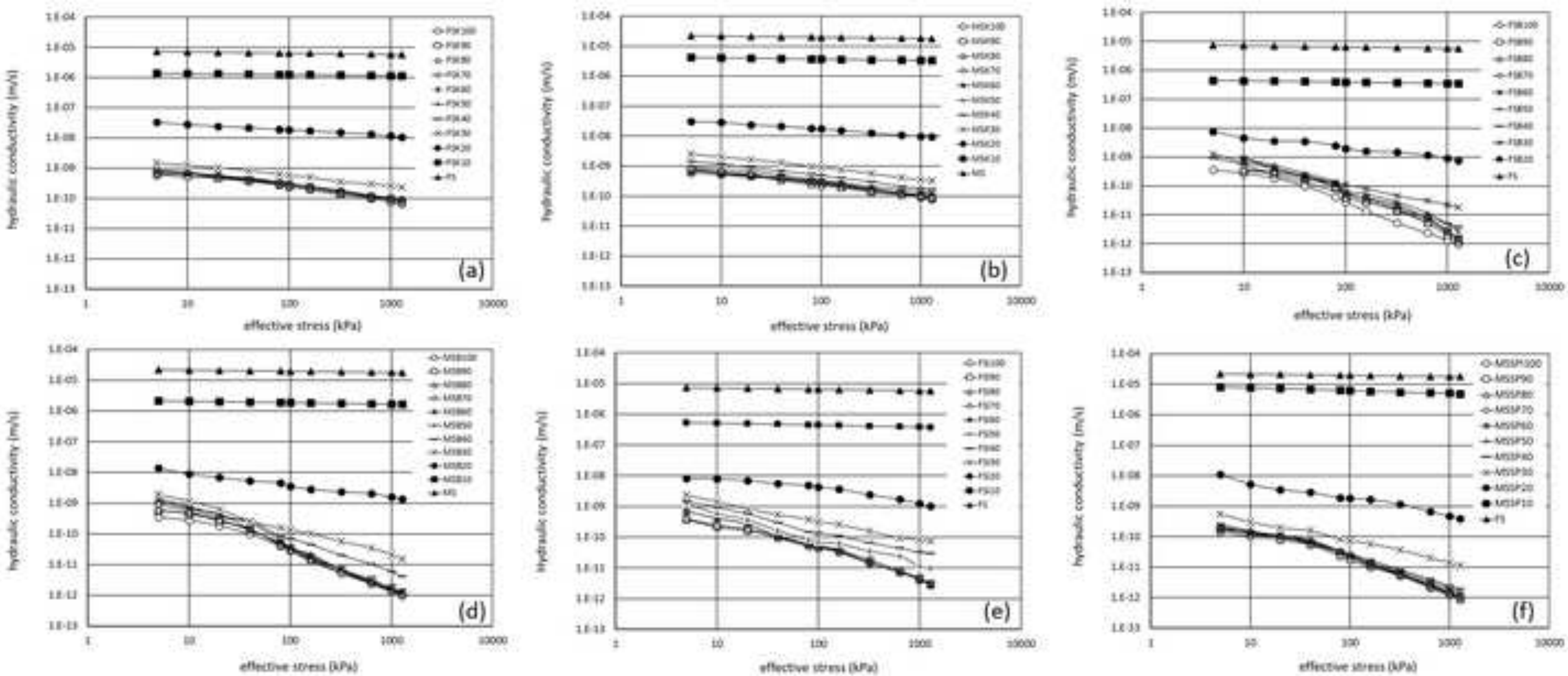


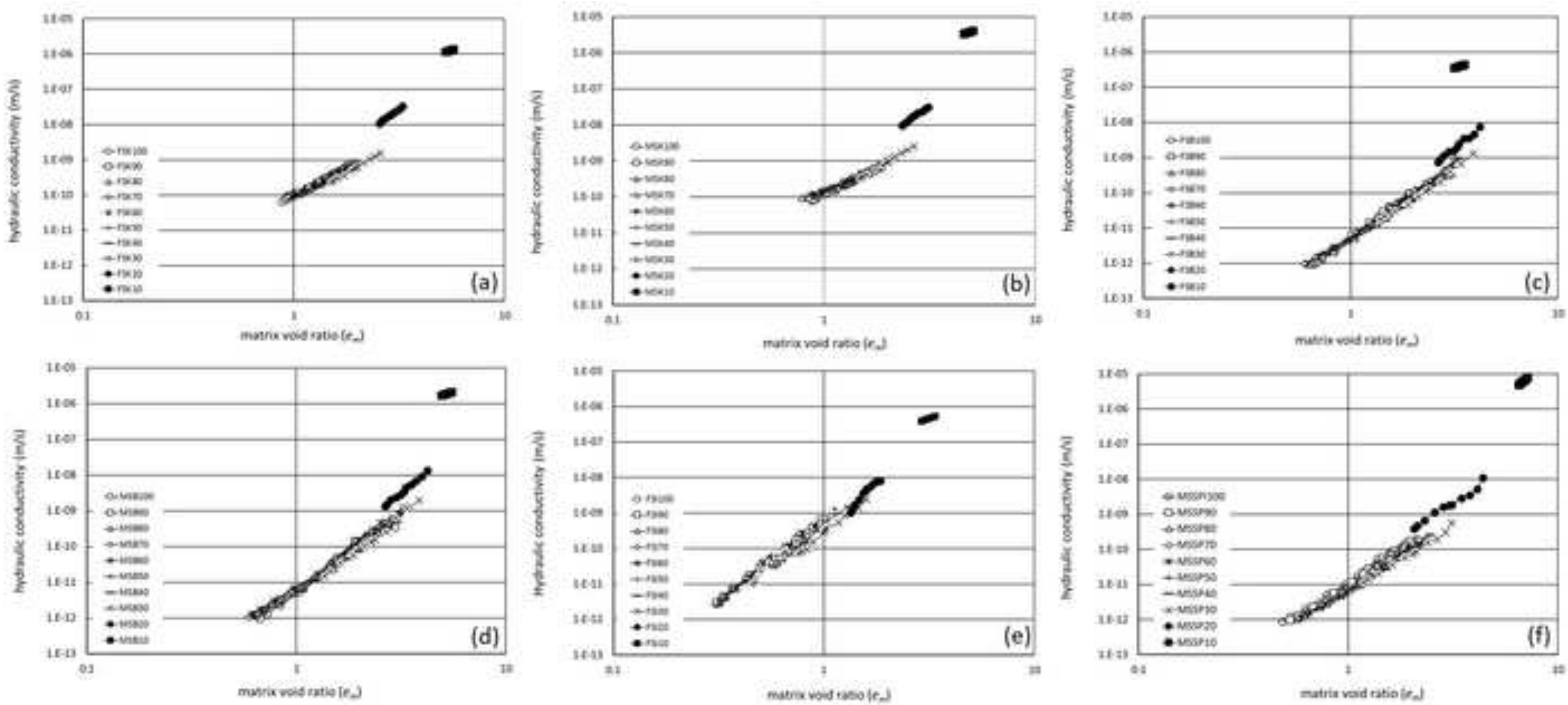

Loading cup (1)
Solid acrylic tube (2)
104 mm
100 mm
Porous discs (3)
Bottom water drain (4)
20 mm
O-ring (5)
6 mm
Cell base (6)
134 mm

Figure

Click here to download Figure Fig 6.jpg

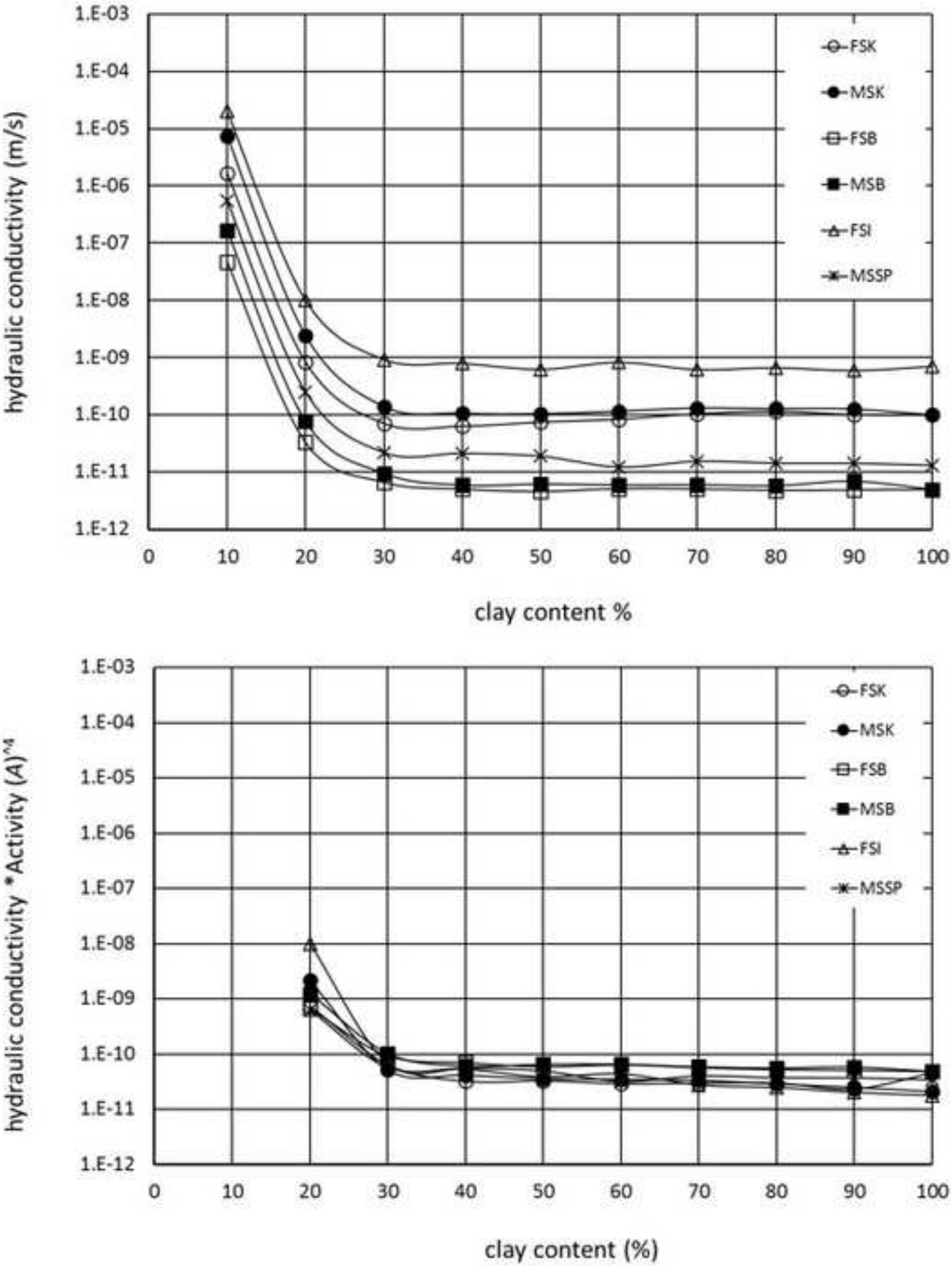
Figure Click here to download Figure Fig 7.jpg

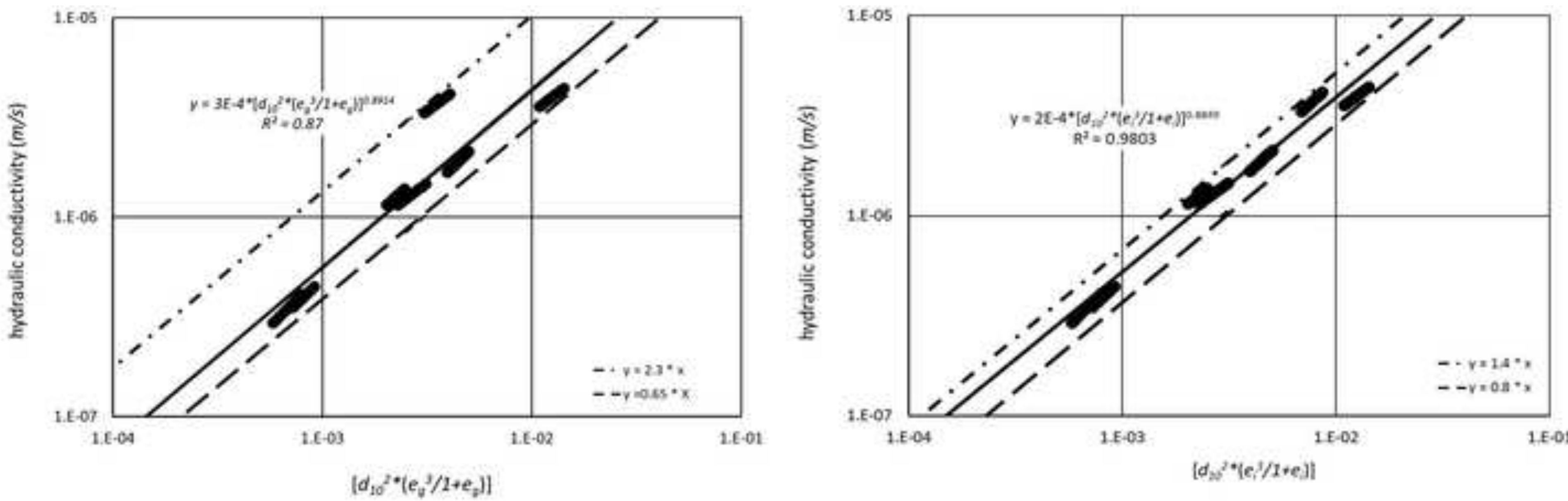


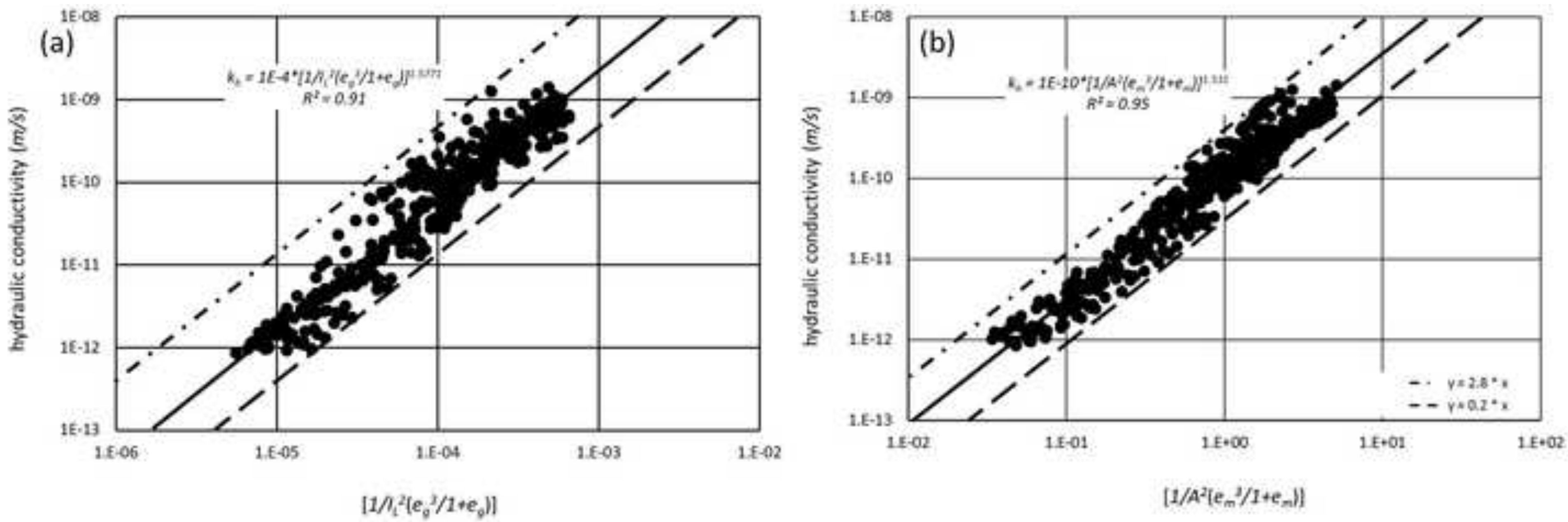

hydraulic conductivity (m/s)
matrix void ratio
(a)
(b)
(c)
(d)
(e)
(f)

Figure

Click here to download Figure Fig 9.jpg

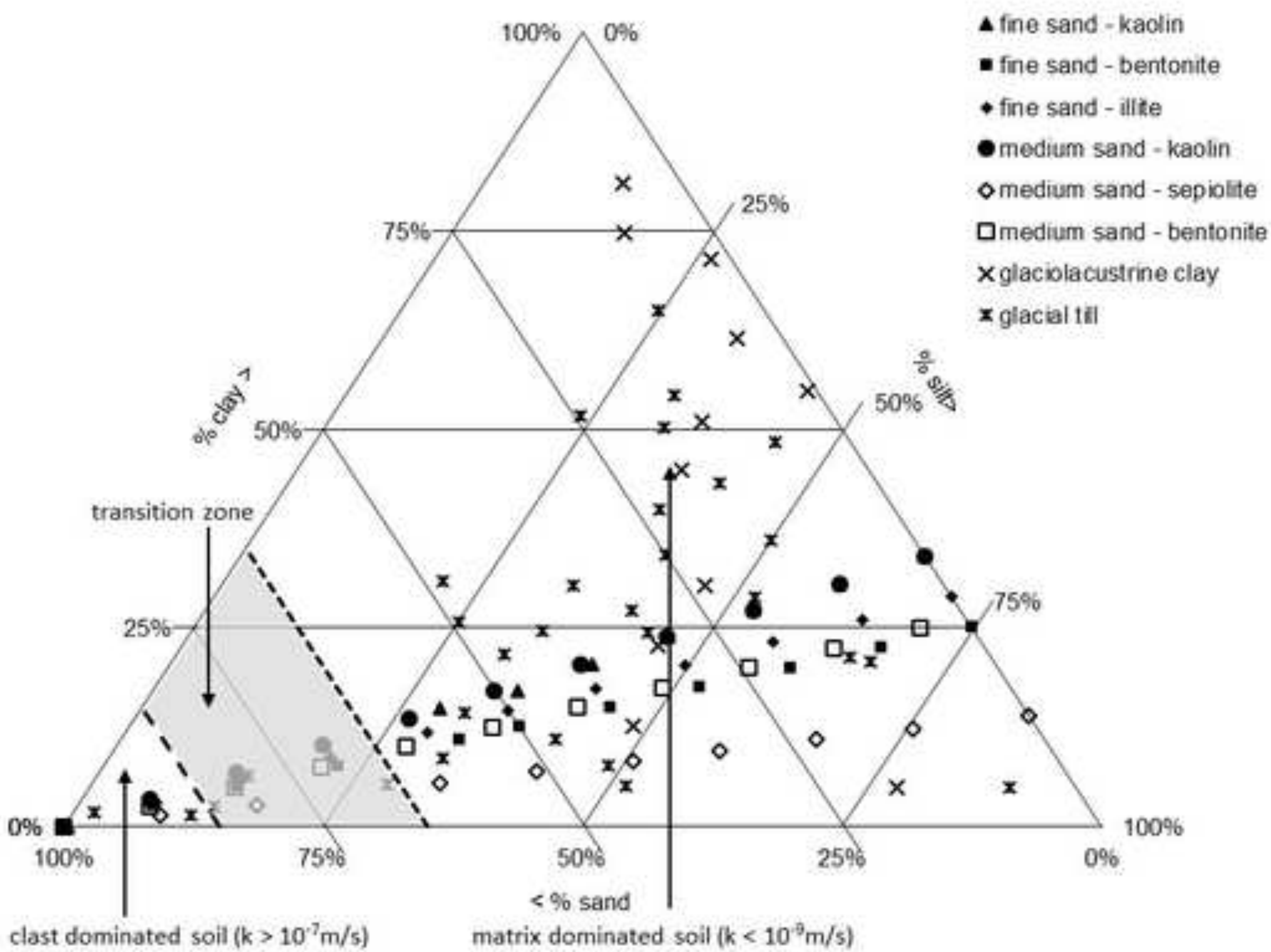


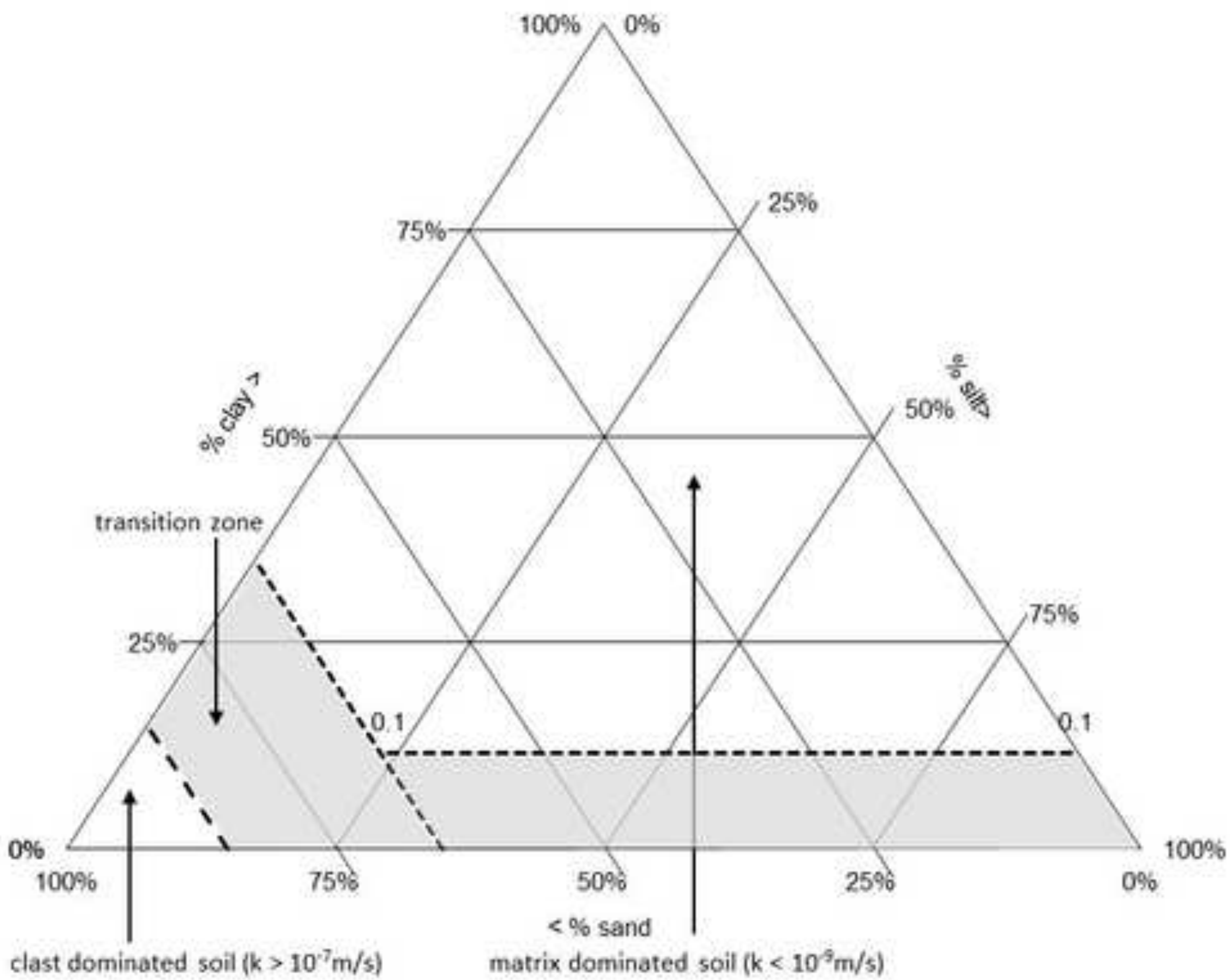

y = 3E-4*[d10^2*(eg^3/1+eg)]^0.8914
R^2 = 0.87
hydraulic conductivity (m/s)
1.E-05
1.E-06
1.E-07
1.E-04
1.E-03
1.E-02
1.E-01
y = 2.3 * x
y =0.65 * x
[d10^2*(eg^3/1+eg)]
y = 2E-4*[d10^2*(ei^3/1+ei)]
R^2 = 0.9803
hydraulic conductivity (m/s)
1.E-05
1.E-06
1.E-07
1.E-04
1.E-03
1.E-02
1.E-01
y = 1.4 * x
y = 0.8 * x
[d10^2*(ei^3/1+ei)]


(a)
(b)
hydraulic conductivity (m/s)
1E-08
1E-09
1E-10
1E-11
1E-12
1E-13
1.E-06
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
R² = 0.91
R² = 0.95
y = 2.8 * x
y = 0.2 * x

Figure

Click here to download Figure Fig 12.jpg




100%
0%
25%
75%
% clay >
% silt>
50%
50%
transition zone
25%
75%
0.1
0.1
0%
100%
100%
75%
50%
25%
0%
< % sand
clast dominated soil (k > 10⁻⁷m/s)
matrix dominated soil (k < 10⁻⁹m/s)