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Double-Ring Infiltrometer for *In-Situ* Permeability Determination of Dam Material

Hans Rönnqvist

RQV Teknik AB, Hudiksvall, Sweden
Email: hans.ronnqvist@rqv.se

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Abstract

Three types of natural soils are studied in this paper: 1) a postglacial silt, 2) a glacial till, and 3) a postglacial sand. The former two are soils from embankment dam sites in Sweden, and the latter is a soil from a natural deposit situated in the Swedish east coastal region. *In situ* Double-ring infiltrometer (DRI) tests are compared with laboratory constant-head permeability determinations. This study shows that the DRI tests conducted on sandy-silty soils are within sufficient range to the laboratory results, to suggest that *in situ* near-saturated infiltration capacity may be used as a field estimate of hydraulic conductivity (permeability) for this range of soils. *In situ* infiltrometer testing may be the better alternative when there is difficulty in achieving representative field conditions in a laboratory setting, e.g., for widely graded soils such as glacial tills.

Keywords

Double-Ring Infiltrometer, DRI, Hydraulic Conductivity, Permeability, Infiltration Rate, Postglacial, Silt, Sand, Glacial, Till

1. Introduction

"Infiltration is the process of water penetrating from the ground surface into the soil" [1]. Infiltration may occur at different rates depending on soil type, and it can also vary within a single soil [2]. This variation is due to spatial difference that introduces inhomogeneities, such as local water content (ω, %) variations within the soil itself, and soil strata anomalies, and the rate at which the soil is infiltrated is influenced by many factors, e.g., porosity ($\varnothing$, %) and hydraulic conductivity (k, m/s) [1]. The infiltration rate (f, m/s), when it has reached a constant rate, is related to the infiltration capacity (f_t, m/s). In turn, although the infiltration capacity does not directly relate to the hydraulic conductivity [3], it may provide an estimate during near-saturated conditions [4].

Hydraulic conductivity, interchangeably termed permeability in the rest of this paper (although "permeability coefficient" would be the more correct synonym for hydraulic conductivity), is a key parameter in geotechnics, especially so in dam engineering, due to the importance of knowing the function of the dam zone material, e.g., the core, the filter or soil foundation, and the drainage features. Measurement of hydraulic conductivity is part of routine testing in a geotechnical laboratory, but it may be a time-consuming process due to soil-sampling, sample processing and testing. Furthermore, obtaining an undisturbed field sample and relocating it to the laboratory may be too impractical [5]. Thus, the validity of laboratory tests may be questioned when field conditions are difficult to duplicate. A simple instrument for field measurements of the infiltration of soil is the Double-ring infiltrometer, DRI [4] [5]. The use of DRI is a standard field-test method [3], the most commonly used practice [5]. Other field methods for measuring permeability include Single-ring infiltrometers, pump tests and bore-hole tests [5].

This paper investigates the use of the DRI by evaluating soils from three sites in Sweden. By comparing DRI data to laboratory determinations of hydraulic conductivity, the results show that the near-saturated infiltration capacity of sandy-silty materials is within sufficient correlation with results from constant-head laboratory tests to suggest that the DRI is an acceptable instrument for *in situ* permeability estimations for this range of soils.

2. Infiltration and Hydraulic Conductivity

The intensity of water penetrating a soil is called the infiltration rate (volume of water per surface area and per unit time), and when it reaches a constant value at near-saturation, it yields the infiltration capacity [4] [6]. Potential energy differences (gravitational and pressure) influence water to flow in certain directions and at certain speeds, but the rate of flow is also determined by the hydraulic conductivity (k, m/s) of the soil [1] [7]. The hydraulic conductivity is a soil's capacity to transmit water through its interconnected pores, and the highest level of hydraulic conductivity is reached at saturation, *i.e.*, the saturated hydraulic conductivity (k_{sat}, m/s). Reference [1] indicated that for unsaturated soil, the hydraulic conductivity is approximately half that of the saturated conductivity, and reference [5] stated it to a maximum of 70%. The infiltration rate, on the other hand, decreases over time during infiltration (and saturation); it varies from an initial high rate (due to matrix suction from the dry soil) to a constant rate at near-saturation, *i.e.*, at the infiltration capacity [4].

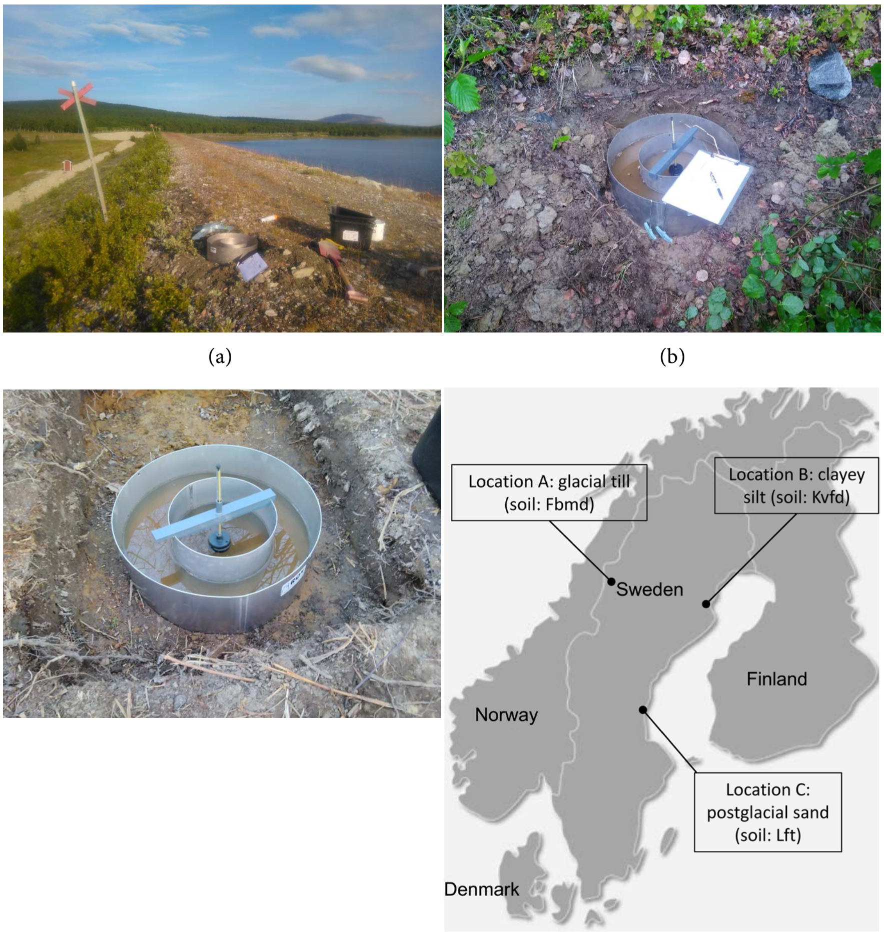
The infiltration rate and the hydraulic conductivity cannot be directly related [3]. In fact, the hydraulic boundary conditions must be known in order to make an equation; however, for near-saturated conditions and one-dimensional vertical flow, the infiltration capacity provides a reasonable estimate of the permeability, as will be shown in the following sections. Examples of empirical infiltration data (constant infiltration rates, *i.e.*, infiltration capacities or near-saturated hydraulic conductivity) are in the range of 10^{-5} m/s for sand and 10^{-7} m/s for clay [1].

3. Method

3.1. Soils and Study Areas

The test sites are located in the northern part of Sweden (in the province of Norrland) (**Figure 1(d)**). Location A, in the Swedish mountains, is an area typically characterized of moraine formations and post-glacial weathered soils [8]. Here, a glacial till (denoted "Fbmd 17/0.5" in **Figure 2**) was tested on the crest of an embankment dam (**Figure 1(a)**). The first number indicates fines content, and the second number indicates clay content, thus, the soil Fbmd17/0.5 has 17% fines content (full sample, no scalping, % < 0.063 mm and particle density 2.70 Mg/m^3) and it has negligible clay content, ca 0.5% (**Table 1**).

At location B (**Figure 1(b)**), in the northern coastal region of Sweden, the infiltrometer test was conducted on a foundation material of silt at a homogenous



(a) (b)

(c) (d)

Figure 1. Study areas: (a) Dam crest (glacial till), (b) Dam foundation (postglacial silt), (c) Natural deposit (postglacial sand), and (d) Map location.

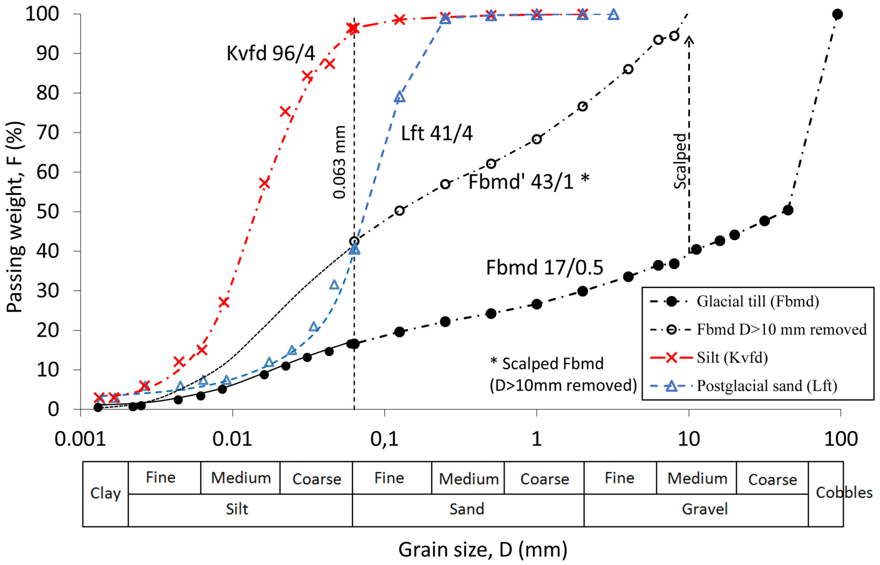


Figure 2. Particle size distributions of the tested soils.

Table 1. Geotechnical data of studied soils.

Parameter	Lft 41/4	Kvfd 96/4	Fbmd 17/0.5^a	Fbmd' 43/1^b
ρ_s (<0.063 mm, Mg/m^3)	2.61	2.68	2.70	2.70
D_{10} (mm)	0.016	0.0045	0.02	0.008
Fines content (% < 0.063 mm)	41	96	17	43
Clay content (% < 0.002 mm)	4	4	0.5	1
γ(bulk)/γ(dry) unit weight (kN/m^3)	18.8/14.8^c	-	-	-

^{a}Full sample. ^{b}Scalped gradation, $D > 10$ mm removed. ^{c}See [9] for data.

embankment dam. The soil (96% fines, 4% clay, particle density 2.68 Mg/m^3, see **Table 1**), denoted "Kvfd 96/4" in **Figure 2**, is a postglacial sediment deposited from glacial melt and once located below the highest shore line; it was thus post-glacially reworked by wave-washing [8].

Location C, a natural deposit situated in the coastal region of Sweden below the highest shoreline (**Figure 1(c)**), comprises postglacial sand (denoted "Lft 41/4" in **Figure 2**). This formation is described in [9], and it confirms that glacial clay usually sits underneath such postglacial sand [8]. The soil "Lft 41/4" exhibits 41% fines content (<0.063 mm, particle density 2.61 Mg/m^3), 4% clay, and a dry/bulk density of 14.8/18.8 kN/m^3 (**Table 1**).

3.2. The Double-Ring Infiltrometer

An "infiltrometer is a device for measuring the rate of entry of liquid into a porous body" [3]. In soils, the DRI is a commonly used instrument (**Figures**

1(a)-(c) show field photos of it in use), and reference [5] reports that the DRI gives fairly accurate estimates of surface permeability. The methodology is described in ASTM D3385 [3]. The DRI consists of two open stainless-steel cylinders, of which one is placed inside the other. The inner and outer rings are 280 mm and 530 mm in diameter, respectively.

By partially driving these into the soil and filling the rings with water, an above-ground reservoir is thus formed that is directly located above the set of soil that is being tested. The outer ring limits the lateral spread of water after infiltration so that one-dimensional, vertical flow is promoted beneath the inner ring [3]. This is indicated by the infiltration rate obtained with the DRI which typically is about 80% of the rate of the single-ring that allows horizontal infiltration [5].

Once the rings are filled, the water level is recorded by a float device in the inner ring at regular times as it recedes. When the steady-state is reached, the infiltration rate is determined. The DRI is particularly applicable to uniform fine-grained soils [3], but restrictions for use make it unsuitable for soils with excessive plasticity and high resistance to ring penetration (or dry and stiff soils that may fracture), or very pervious ($k > 10^{-4}$ m/s) or impervious ($k < 10^{-8}$ m/s) soils [3]. Furthermore, evaporation may affect the results if the infiltration is too slow, which requires a covered version of the DRI to reduce the evaporation effects [5].

3.3. The Constant-Head Seepage Cell

The hydraulic conductivity of the soils was determined in a laboratory setting using a constant-head permeability seepage cell (*i.e.*, permeameter) with a diameter of 114 mm. This is a Perspex permeability cell that mounts on an aluminum base and top with pressure points at different levels that connect to a manometer stand. The maximum particle size in permeameters, in order to avoid these particles affecting the seepage flow, should be limited to approximately 1/10 of the cell diameter [10]. Thus, particle sizes > 10 mm were removed from the soil Fbmd' 43/1, resulting in the scalped gradation in **Figure 2**.

The effect of excluding larger-sized particles is discussed in the following sections. Non-deaired tap water was used during the constant-head tests. The hydraulic conductivities were determined with hydraulic gradients ranging from approximately 1 to 3 for the Lft 41/4 soil, from 2 to 9 for the Kvfd 96/4 soil, and from 2 to 6 for the scalped Fbmd' 43/1 soil, as described in **Table 2**. The reported hydraulic conductivity for each soil was thereafter taken to be the average from these individual soil tests.

4. Results and Discussion

Figure 2 shows the particle size distributions (psd:s) of the tested soils and the geotechnical characteristics are given in **Table 1**. The widely graded gradation of the glacial till, Fbmd 17/0.5, required scalping of the 10-mm grain size (hence,

Table 2. Constant-head permeability test conditions.

Parameter	Lft 41/4	Kvfd 96/4	Fbmd' 43/1 [a]
Hydraulic gradient, i	1.3; 2.6	2.6; 5.4; 9.2	2.3; 3.1; 6.3
Water temp., t (˚C).	17.3; 20.0	17.3; 19.2; 22.5	21.6, 20.7; 19.2
Seepage flow, q ($\times 10^{-8}$ m^3/s)	0.80; 1.58	0.21; 0.38; 0,55	0.32; 0.65; 1.09
Hydraulic conductivity, k ($\times 10^{-7}$ m/s)	5.95; 5.90	0.81; 0.69; 0.58	1.38; 2.07; 1.69

[a] Scalped gradation, $D > 10$ mm removed.

minus 10 mm gradation, *i.e.*, Fbmd' 43/1). This resulted in an increase in fines content from 17% to 43%. The laboratory determination of the permeability of the scalped gradation is thus 1.7×10^{-7} m/s and the in situ infiltration capacity (near-saturated hydraulic conductivity) is 17×10^{-7} m/s, a difference of factor 10 due to scalping (**Table 3**, **Figure 3(a)** and **Figure 3(b)**).

Scalping gradations to suit laboratory equipment results in an increase in fines content (**Figure 2**) that will cause an underestimation of *in situ* "actual" permeability. This is rectified either by accommodating the permeameter to the field conditions (to fit otherwise excessive particle sizes) or conducting an in situ test. In fact, DRI testing may be the more suitable method; however, for important decisions, standardized laboratory testing is advised.

In terms of the postglacial sand (Lft 41/4) the DRI test yielded a 27% overestimation of the permeability (saturated infiltration capacity) compared to the laboratory determination (**Table 3**; **Figure 3(a)**; **Figure 3(b)**) (*i.e.*, 7.5×10^{-7} and 5.9×10^{-7} m/s, respectively), and for the postglacial silt (Kvfd 96/4) the DRI gave a value that were 10% under (0.6×10^{-7} compared to 0.69×10^{-7} m/s). Although revealing some discrepancies, the test methods show acceptable agreement between laboratory determinations and in situ DRI tests. Thus, the near-saturated infiltration rate is related to infiltration capacity, which, under certain conditions, may serve as a field estimate for permeability (hydraulic conductivity). Reference [5] found that the DRI gives approximately 41% lower permeabilities than in a laboratory falling-head test under saturated and de-aired water conditions.

Empirical criteria used to estimate hydraulic conductivity from particle size distribution are usually limited to sand-sized fractions [11]. The most commonly used criterion is Hazen's formula:

$$k = C \times D_{10}^2 \tag{1}$$

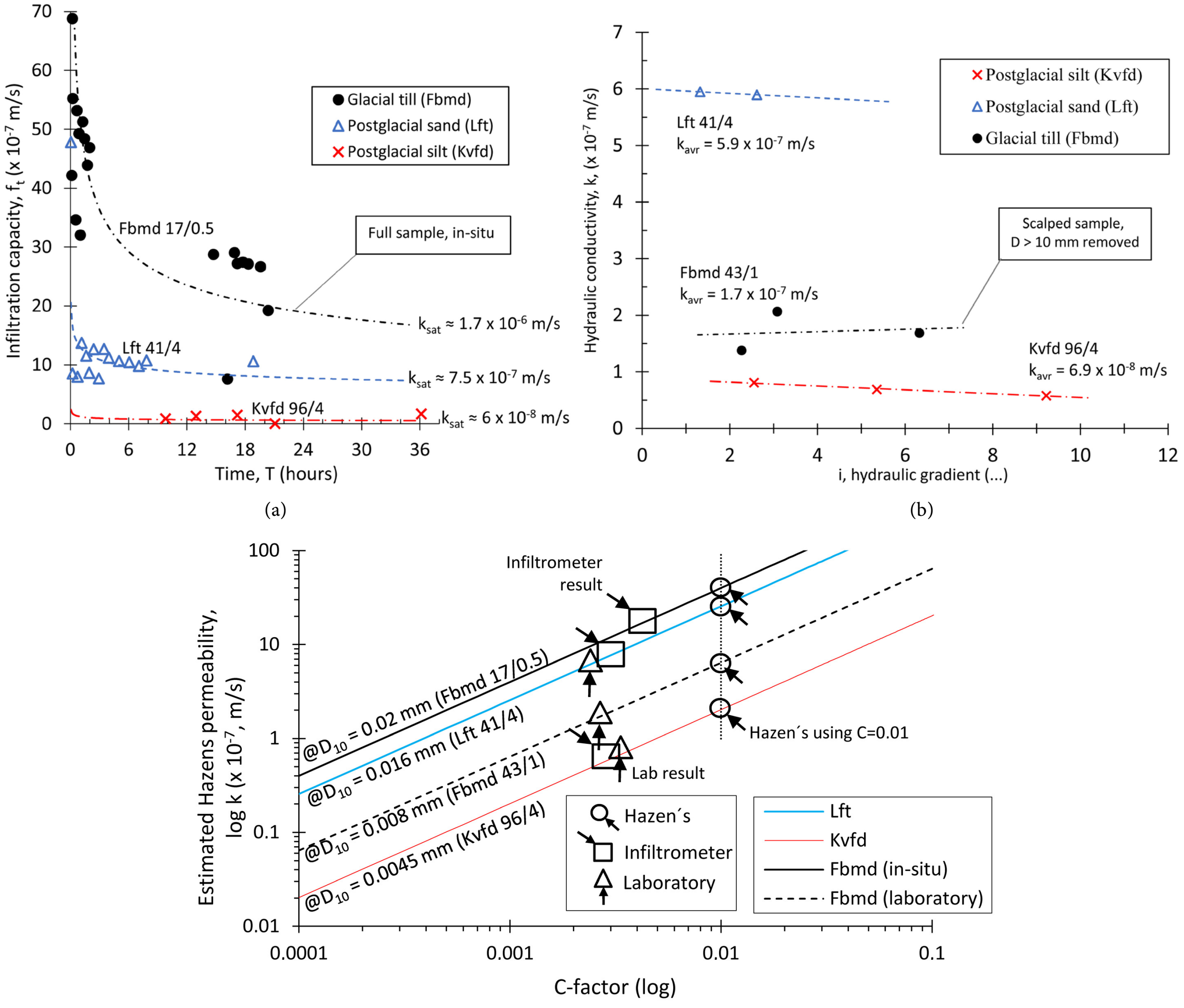
where C is a constant (factor, usually 0.01), D_{10} is the effective grain size (in mm), and k is the hydraulic conductivity (in m/sec). The formula was developed for uniform clean sands with less than 5% < 0.075 mm and 0.1 mm < D_{10} <3.0 mm, but even within these limits, the C-factor varied between 0.004 and 0.015 [11].

Using Hazen's empirical formula (with the characteristics listed in **Table 1**)

Table 3. Permeability determinations of studied soils.

Method	Lft 41/4	Kvfd 96/4	Fbmd 17/0.5[a]	Fbmd' 43/1[b]
Constant head seepage cell, k_{lab} ($\times 10^{-7}$ m/s)	$k_{lab} = 5.93$	$k_{lab} = 0.69$	-	$k_{lab} = 1.71$ (scalped sample)
Double-ring infiltrometer infiltration capacity, f_t "permeability" $k_{in\ situ}$ ($\times 10^{-7}$ m/s)	$k_{in\ situ} \approx 7.5$ (+27% of k_{lab})	$k_{in\ situ} \approx 0.6$ (−10% of k_{lab})	$k_{in\ situ} \approx 17$ (full sample)	-
Hazen's formula, Equation (1) empirical permeability, k_{est} ($\times 10^{-7}$ m/s).	$k_{est} = 25.6$ @ C=0.01; $D_{10} = 0.016$ (+430% of k_{lab})	$k_{est} = 2.0$ @ C = 0.01; $D_{10} = 0.0045$ (+290% of k_{lab})	$k_{est} = 40$ @ C = 0.01; $D_{10} = 0.02$	$k_{est} = 6.4$ @ C = 0.01; $D_{10} = 0.008$ (+376% of k_{lab})

[a]Full sample. [b]Scalped gradation, D_{10} > removed.



(a)

(b)

(c)

Figure 3. Infiltration and permeability results from: (a) infiltration curve measured in situ by DRI, (b) hydraulic conductivity determined by a constant-head laboratory permeameter, and (c) estimates using grain-size correlation (the Hazen's formula).

will result in consistently overestimating the permeability of the studied soils compared to the laboratory determinations (**Table 2**; **Figure 3(c)**).

However, clearly, none of the soils are strictly within the range of gradations tested by Hazen. This is a fact noticeable by the discrepancy between C-factors that are needed to achieve permeabilities in agreement with test results (ranging from 0.0024 to 0.0043) compared to what is typically used when applying the formula (usually 0.01) (**Figure 3(c)**).

Thus, the soils evaluated herein are strictly speaking outside the extent of the method data. Nevertheless, caution should be used when estimating permeability from grain-size correlations [5].

5. Conclusions

By studying the field measurements using a Double-ring infiltrometer (DRI) and the laboratory determination of three different soil's permeabilities (hydraulic conductivity, k), this paper shows that for sandy-silty soils:

1) The Double-ring infiltrometer (DRI) yields near-saturated infiltration capacity results that are within 30% of the laboratory (constant-head test) hydraulic conductivities.

2) The correlation between the DRI and the Constant-head test is sufficiently close to suggest that near-saturated infiltration capacity may be used as a field estimation of hydraulic conductivity (permeability) for this range of soils.

3) Applying empirical grain-size correlations (herein referred to as the Hazen formula) resulted in a 3 to 4 times overestimation of the hydraulic conductivity compared to laboratory and field determinations.

4) *In situ* DRI testing may be a more suitable method to use if field conditions are difficult to achieve in a laboratory setting (e.g., widely graded soils such as glacial till).

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Notation and Nomenclature

f	Infiltration rate, m/s.
f_t	Infiltration capacity, m/s
k	Hydraulic conductivity, m/s.
k_{sat}	Hydraulic conductivity at saturation, m/s.
C	Factor, Hazen's formula.
D	Grain size, mm.
D_{10}	Effective grain size, mm, Hazen's formula.
F	Passing weight, %.
T	Time, h.
t	Temperature, water, ˚C.
q	Seepage flow, m^3/s.
ω	Water content, %, = m_w/m_s.
i	Hydraulic gradient, (…).
Ø	Porosity, %, = V_v/V.
γ(bulk)	Bulk unit weight, kN/m^3, = $\rho \times g = m/V \times \mathrm{g}$.
γ(dry)	Dry unit weight, kN/m^3, = $\rho_{dry} \times g = \mathrm{m_s}/V \times \mathrm{g}$.
g	Standard gravity, = 9.8 m/s^2.
ρ_s	Particle density, Mg/m^3, = m_s/Vs.
DRI	Double-ring infiltrometer