# Field techniques for measuring field saturated and unsaturated hydraulic conductivity using soil moisture profile in a final disposal site

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## ABSTRACT

A new field experimental method of determining the hydraulic conductivity of unsaturated soils in the near surface of homogeneous sandy soils is proposed. Firstly a ponded single-ring infiltrometer technique, such as the Guelph Pressure Infiltrometer method was performed to determine the field-saturated hydraulic conductivity of soil. Secondly the instantaneous profile method with the unit hydraulic gradient assumption was applied to determine the unsaturated hydraulic conductivity of soil during drainage test. The vertical soil moisture profiles during the permeability tests were measured by a portable soil moisture device. The advantage of our proposed method is to measure the field-saturated and the unsaturated hydraulic conductivity of soil continuously by quite simple in-situ permeability tests with soil moisture profiles. The utility of our proposed method is demonstrated by using a numerical example of sandy soil and experimental data of the waste disposal site.

## KEYWORDS

hydraulic conductivity, in-situ permeability test, soil moisture profile, unsaturated soils

## INTRODUCTION

It is well noticed that in-situ measurement and evaluation of the soil hydraulic properties are essential to practical and accurate prediction of water movement in unsaturated soils such as natural slope, embankment, landfill and agricultural field. The hydraulic properties consist of the saturated hydraulic conductivity, the unsaturated hydraulic conductivity and the soil water characteristic curve. The hydraulic conductivity of unsaturated soils should be measured in the filed. Because air bubbles are usually entrapped in porous media when they are saturated by infiltrating water, the saturated hydraulic conductivity measured in unsaturated soil is lower than the truly saturated hydraulic conductivity measured by laboratory experiments and is often referred to as a field-saturated hydraulic conductivity. Field methods for determining the hydraulic conductivity of unsaturated soils include infiltration tests and instantaneous profile methods for near-surface application. For deeper soils, cone penetrometer methods can be applied. Disadvantages of these methods include the relatively high cost and complexity of the instruction and the long time period required for data collection.

In this study a new field experimental method of determining the hydraulic conductivity in the near surface of unsaturated homogeneous sandy soils is proposed. In this method, a ponded single-ring infiltrometer technique, such as the Guelph Pressure Infiltrometer (GPI) method, which was developed by Reynolds and Elrick (1990), is employed to measure the field-saturated hydraulic conductivity of sandy soils. The GPI method is classified into a constant-head infiltration method and provides a simple in-situ permeability test. Firstly the GPI method is performed to determine the field-saturated hydraulic conductivity. Our proposed test procedure of the GPI method is extended so that it determines soil moisture profiles with time beneath the plot by a portable soil moisture device. Secondly the instantaneous profile (IP) method, apparently first developed by Richards and Weeks (1953) was applied to determine the unsaturated hydraulic conductivity as a function of volumetric water content during drainage after the GPI method. The vertical soil moisture profiles during the drainage test were measured by using a portable device for collecting soil water content from multiple depths. The unit gradient 1.0 assumption was applied to calculate the unsaturated hydraulic conductivity. The advantage of the proposed method is that it allows measurements of the field-saturated and the unsaturated hydraulic conductivity of unsaturated soils continuously by using quite simple in-situ permeability tests. The utility of our proposed method is demonstrated by using a numerical example of sandy soil and experimental data of the top soil cover in the waste disposal site.

## MATERIALS AND METHODS

### 1. In-situ permeability test apparatus

Our proposed in-situ permeability test apparatus consists of a single steel ring with a radius *a* inserted into the soil to depth *d*, a water supply tube, a water reservoir tank and a portable soil moisture probe, Profile Probe type PR1 (Delta-T Devices Ltd.) for collecting soil water content from multiple depths as shown in **Fig.1**. The position of an air tube controls the constant head of water *H* applied on the soil surface within the steel ring.

A soil moisture probe was installed at center of the steel ring to depth *L*. It is designed to obtain volumetric water content measurements at 4 different depths within a vertical soil profile. The vertical soil sampling volume is within +5cm and -5cm of the each sensing depth. On-site data logger is connected to the soil moisture probe for automatic monitoring and transient data collection.

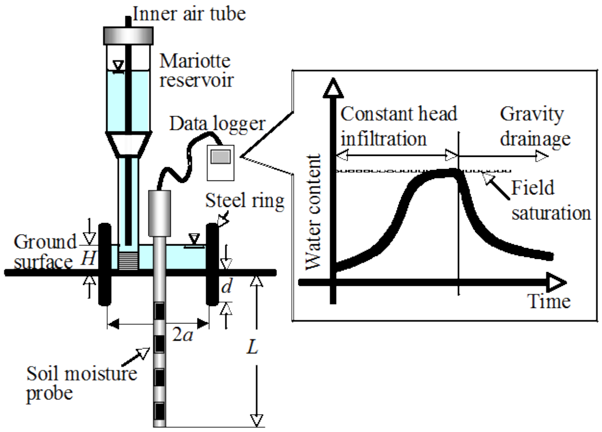


Fig.1 Schematic diagram of proposed in-situ permeability test apparatus

## 2. Constant-head infiltration test using GPI method

A constant-head infiltration test is performed to determine the field-saturated hydraulic conductivity of soil. The steady-state infiltration rate $Q_s$ measured during the constant-head infiltration from the single-ring into the soil reaches a quasi-steady state is required in the GPI method. The volumetric water content with time monitored by the soil moisture probe are used as indicator that the soil is field saturated. Then the value of the field-saturated hydraulic conductivity of soil, $K_{fs}$ is calculated by the following equation (Reynolds and Elrick, 1990; Elrick and Reynolds, 1992):

$$K_{fs} = \frac{\alpha^* G Q_s}{a\alpha^* H + a + G\alpha^* \pi a^2} \quad \cdots \quad (1)$$

where $G$ is a dimensionless shape factor, which takes account for the geometry of the infiltration surface within the ring. $G$ is given by

$$G = 0.316\frac{d}{a} + 0.184 \quad \cdots \quad (2)$$

In **Eq. (1)**, $\alpha^*$ is a power describing an exponential relationship of unsaturated hydraulic conductivity with negative pressure head of soil, and is interpreted as an index of texture/structure component of soil capillarity. The GPI method requires that $\alpha^*$ be site-estimated by simple observation of soil. Values of $\alpha^*$ for various soil textures and structures are recommended by Elrick and Reynolds (1992).

## 3. Gravity drainage test using IP method

A gravity drainage test using the IP method is performed to determine the unsaturated hydraulic conductivity of soil after the field-saturated hydraulic conductivity has been calculated by using the GPI method. Field application of the IP method is similar to that used in the laboratory. Steady state infiltration is indicated by constant readings on the soil moisture probe or the water reservoir tank of proposed infiltration test. The water flux across the ground surface is then shut off. The soil surface of the single-ring in the plot can be covered with plastic sheets to prevent evaporation. The only subsequent process, which occurs within the soil column, is a downward seepage of water. During the subsequent unsteady-state process, the pore water pressures and water contents are measured. The transient data are used to calculate the unsaturated hydraulic conductivity of soil, $K_{unsat}$ at some depth below the top of the soil profile $z_1$, according to the following equation:

$$K_{unsat} = \frac{\int_0^{z_1} \frac{\partial \theta}{\partial t} dz}{\frac{\partial h}{\partial z} + 1} \quad \cdots \quad (3)$$

where $h$ is the pressure head, $t$ is the elapsed time, $\theta$ is the volumetric water content profile as a function of depth, $z$.

The denominator of **Eq. (3)** shows the hydraulic gradient at a specific depth for a particular elapsed time computed from slope of the hydraulic head profile at that depth. The numerator of **Eq. (3)** shows the volume of water in the soil between the ground surface and a depth, $z$. At discrete depths, simultaneously, the hydraulic gradient is calculated from tensiometric data, and the rate of change in water content is calculated from the slope of the water content versus time.

The hydraulic conductivity calculated from **Eq. (3)** is associated with the mean water content at a particular depth. The analysis progresses from wet to dry conditions to obtain discrete values of hydraulic conductivity over a range of saturations. The drainage monitoring continues until the rate of decrease in water content is insignificant. Although, tensiometers are usually used to compute the hydraulic gradient, their installations are often difficult. However, in practice the hydraulic gradient is usually near 1.0 so that the determination of pressure head is not always critical to the analysis, at least in relatively uniform sandy soils. In this study, the unit gradient assumption was applied to the IP method. If the gradient was assumed 1.0, consequently, the unsaturated hydraulic conductivity can be estimated from the volumetric water content profile alone from **Eq. (3)** easily.

The procedure of our proposed in-situ permeability tests is shown in **Fig. 2**.

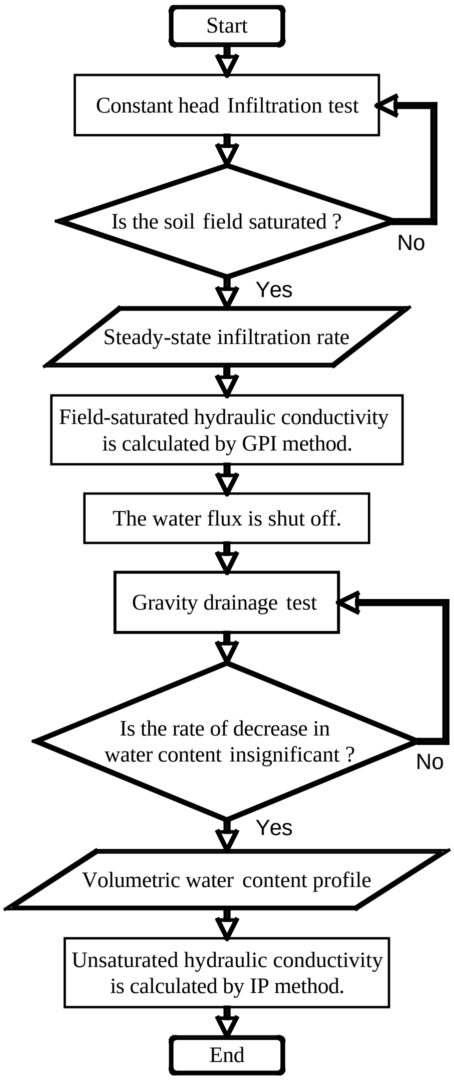


Fig.2 The procedure of proposed in-situ permeability tests

## 4. Numerical model of in-situ permeability test

To show a practicability of our proposed method, a numerical sandy soil model as shown in **Fig. 3** is selected and analyzed by the axisym-

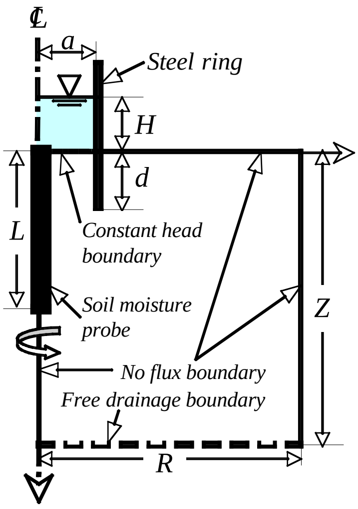


Fig.3 Axisymmetric soil region selected for seepage flow FEM

metric saturated-unsaturated transient seepage flow FEM (Rassam, et al., 2003). In **Fig. 3**, the radius of influence area $R$ is 300cm, and its thickness $Z$ is 300cm so that the flow out of the steel ring will not be affect significantly. The steel ring with $a$ = 7.9 cm is inserted to a depth $d$ = 5.0 cm. A soil moisture probe is installed at center of the single ring to depth $L$ = 51 cm. The volumetric water content is measured at depths 7cm, 17cm, 27cm, and 37cm under soil surface, respectively. Constant head $H$ = 5.0 cm was imposed on the soil surface within the ring for 60 minutes. An initial volumetric water content in the numerical sandy soil model was assumed to be 0.3.

The unsaturated soil hydraulic functions employed in the numerical model are described by van Genuchten (1980):

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[ \frac{1}{1+(\alpha h)^n} \right]^m \quad \cdots\cdots (4)$$

$$K(S_e) = K_s S_e^{0.5} \left[ 1 - \left(1 - S_e^{1/m}\right)^m \right]^2 \quad \cdots\cdots (5)$$

where $m = 1\text{-}1/n$, $S_e$ is the effective saturation, $\theta_s$ is the saturated water content, $\theta_r$ is the residual water content, $K_s$ is the saturated hydraulic conductivity, and $\alpha$, $n$ are the soil retention curve shape parameters (empirical parameters). These functions will be referred as VG model.

There are 5 unknown VG model parameters in **Eq. (4)** and **Eq. (5)**. In this study, $K_s = K_{fs} = 3.0\times10^{-3}$ cm/s, $\theta_s$ = 0.43, $\theta_r$ = 0.045, $\alpha$ = 0.145 cm$^{-1}$, and $n$ = 2.68 were given according to database of Hydrus-2D (Rassam, et al., 2003) for the sand.

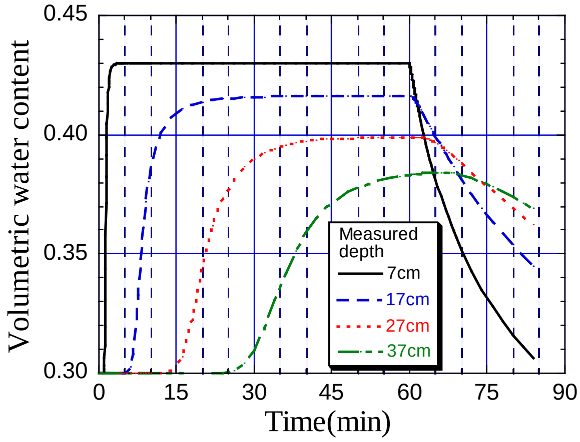


Fig. 4 Computed volumetric water contents

## RESULTS AND DISCUSSION

### 1. Numerical example of in-situ permeability test on sandy soil

**Fig. 4** shows the computed volumetric water content with time at 4 different measured depths of the soil moisture probe in the numerical example of in-situ permeability test on sandy soil. The volumetric water contents increased soon after the beginning of the stant-head infiltration and approached the con-

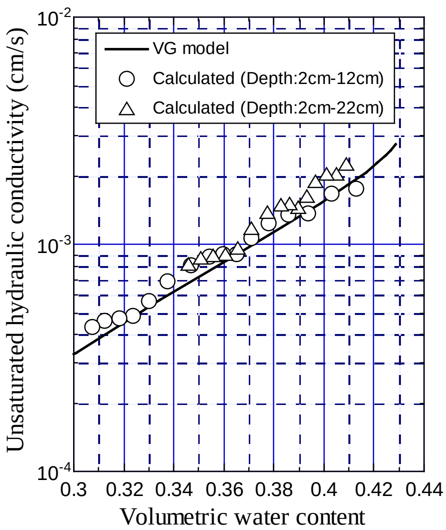


Fig.6 Unsaturated hydraulic conductivity calculated by the IP method (Numerical example)

stant value. The volumetric water contents measured at the depths 7cm and 17cm under soil surface have been reached to a saturated or near saturated steady-state condition. The IP method should be applied to obtain water content profiles at these depths, about 20cm under soil surface.

The hydraulic gradient until a specific depth 17cm under soil surface for an elapsed time can be computed from the slope of the hydraulic head profiles at that depth in **Fig. 5**. The hydraulic gradient changes by the depth and the elapsed time. They are distributed in 0.98 from 0.84. As a result of the numerical simulation, the hydraulic gradient can be assumed to 1.0 in relatively uniform and high permeable sandy soils.

**Fig. 6** presents the unsaturated hydraulic conductivity values as a function of volumetric water content calculated by the IP method with unit hydraulic gradient 1.0. The unsaturated hydraulic conductivity can be computed for the specific depth, 2cm to 12cm and 2cm to 22cm. A solid line in this figure shows VG model, which are given in the numerical sandy soil model. As seen in this figure, there is good agreement between calculated and given unsaturated hydraulic conductivities in the numerical sandy soil model. The unsaturated hydraulic conductivity calculated by the water content profile from the depth 2cm to 12cm is closer to given VG model than the depth 2cm to 22 cm. It is considered that these errors can be introduced by the difference in the degree of saturation at the beginning of the drainage test. It is desirable that the plot is inundated with water until the soil profile becomes filed-saturation under steady-state infiltration conditions.

## 2. Field example of in-situ permeability test on the waste disposal site

Our proposed in-situ permeability test was conducted for the top soil cover in the PIYUNGAN waste disposal site located in Yogyakarta, Indonesia. Two sites (site No.1 and No.2) were selected for in-situ permeability test. The infiltration test conditions were $a$ = 5.5cm, $d$ = 4.0cm (site No.1), $d$ = 5.0cm (site No.2), $H$ =5.0cm (site No.1), $H$ =3.0cm (site No.2) in **Fig. 1**. According to the soil condition, 0.15 (1/cm) was assumed as $\alpha^*$ in **Eq. (1)**. **Fig. 7** shows constant-head infiltration test using GPI method on the site No.1. Measured infiltration rate with time are shown in **Fig. 8**. The infiltration test was performed for 30minites. The field-saturated hydraulic conductivity of soil was measured by the GPI method to $1.54 \times 10^{-4}$ cm/s (site No.1) and $4.64 \times 10^{-4}$ cm/s (site No.2). GPI method offers a fast way for measuring the hydraulic conductivity and may be an interesting tool for low-cost mapping of the permeability of the unsaturated top soil cover in the waste disposal site.

## CONCLUSIONS AND PERSPECTIVES

In-situ permeability tests of determining the hydraulic conductivity in the near surface of unsaturated homogeneous sandy soils were proposed. Firstly the constant-head infiltration test was performed to determine the field-saturated hydraulic conductivity of soil. Secondly the instantaneous profile (IP) method with the unit gradient assumption was applied to determine the unsaturated hydraulic conductivity of soil. Its applicability was verified by using a numerical example of sandy soil and experimental data of the waste disposal site.

Fig. 7 Constant-head infiltration test using GPI method on the site No.1

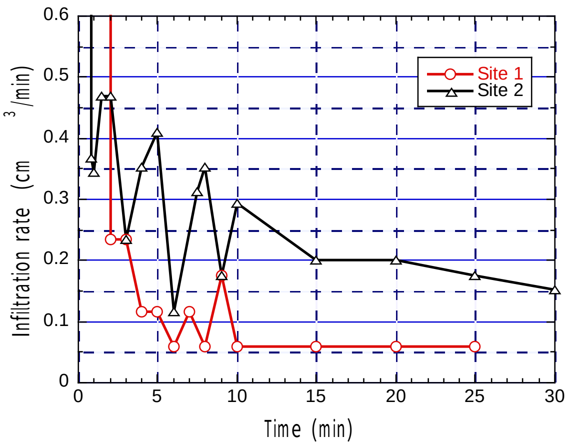


Fig. 8 Measured infiltration rate with time

The followings are remarked:

1) The constant-head infiltration test using the Guelph Pressure Infiltrometer (GPI) method was effectively applied to the sandy soil to determine the field-saturated hydraulic conductivity of soil. Our proposed test procedure of the GPI method was extended to measure the volumetric water content with time near the soil surface of the plot by using a portable soil moisture probe. The volumetric water contents monitored were used as indicator that the soil is field-saturated.

2) The IP method was applied to determine the unsaturated hydraulic conductivity of soil as a function of volumetric water content during drainage after the constant-head infiltration test. The vertical soil moisture profiles during the drainage test were measured by using a portable soil moisture probe from multiple depths. The unit gradient 1.0 was assumed to calculate the unsaturated hydraulic conductivity of sandy soils.

3) The proposed field experimental method can be an excellent practical in-situ permeability test because of its quite simple and speedy procedure to determine both the saturated and the unsaturated hydraulic conductivity of unsaturated soils continuously. The utility of our proposed method was demonstrated by using a numerical example of sandy soil. There was good agreement between calculated and given unsaturated hydraulic conductivities as a function of water content in the numerical sandy soil model.

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# Field techniques for measuring field saturated and unsaturated hydraulic conductivity using soil moisture profile in a final disposal site

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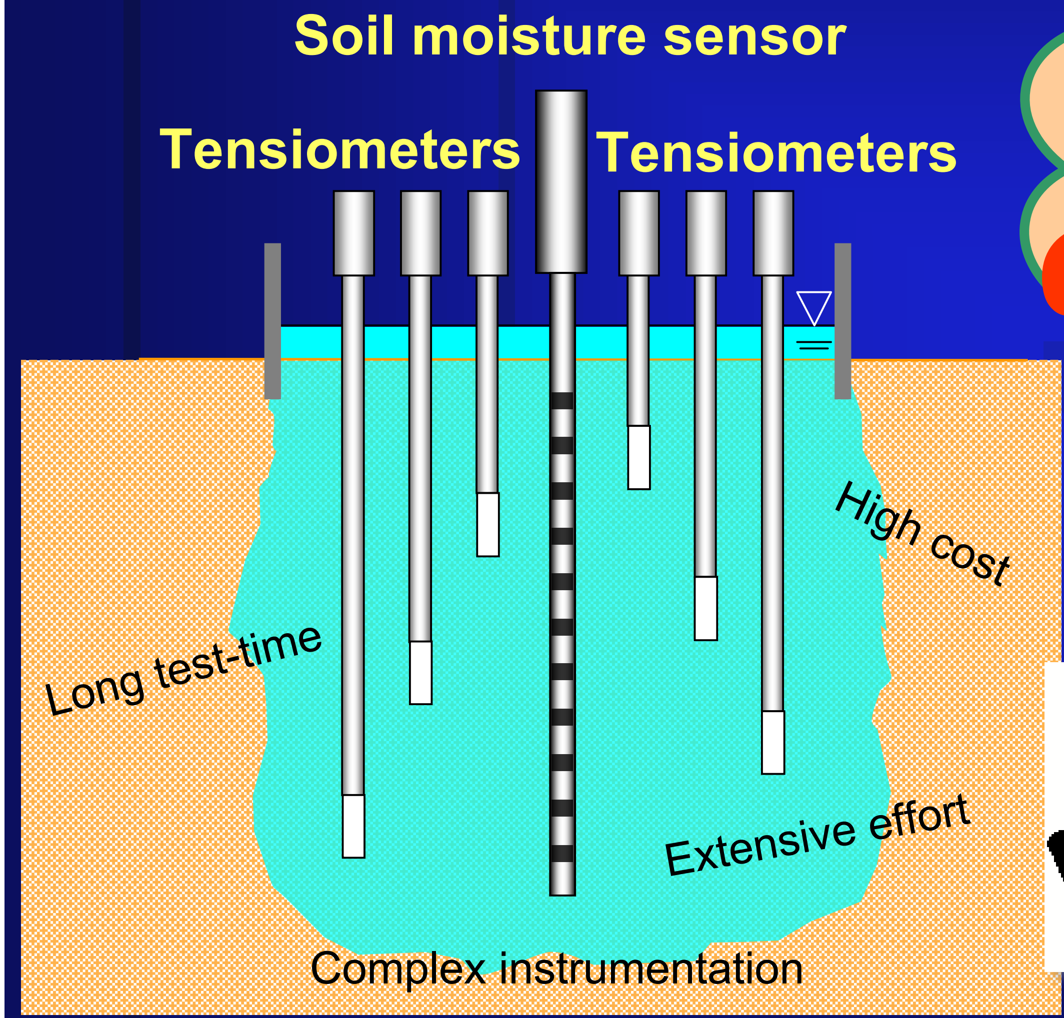
Gravity drainage test using instantaneous profile method with no tensiometers

Constant head single-ring infiltration test using Guelph pressure infiltrometer (Reynolds & Elrick 1990)

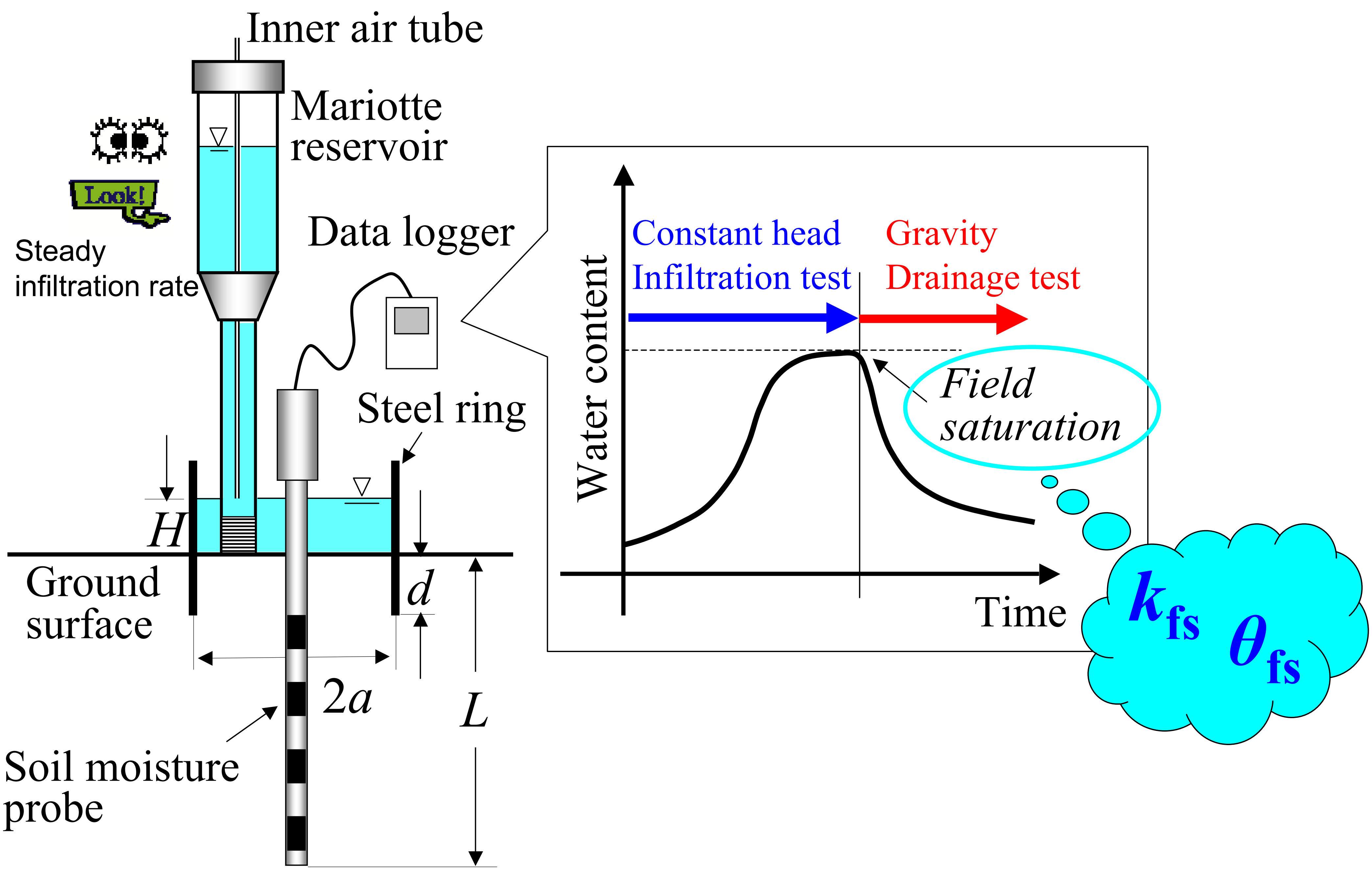
# How to measure hydraulic conductivity of unsaturated soils?




Field set-up for instantaneous profile method


**Next ?**

Constant head single-ring infiltration test
&
Gravity drainage test




Proposed in-situ permeability test based on single-ring infiltrometer

# Profile Probe type PR1/4 (Delta-T Devices Ltd.)

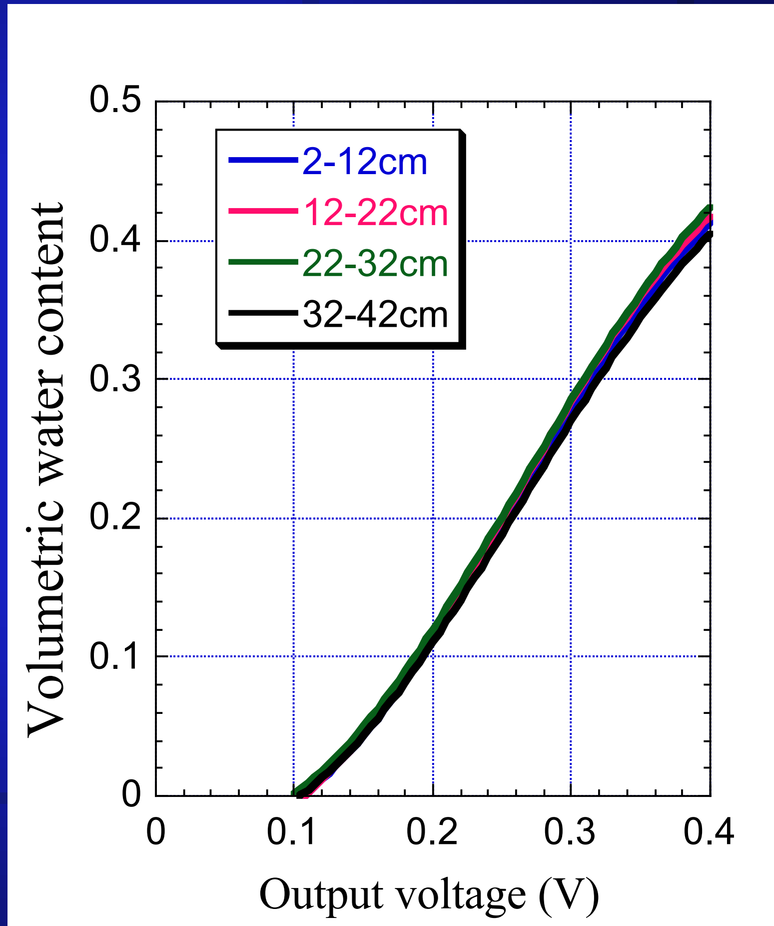
*±3% accuracy, with ±1% repeatability*

Measured soil volume

Sensor depths under soil surface (cm)


Pre-installed special access tube

On-site data logger




Calibration curves (for Tottori dune sand, Japan)

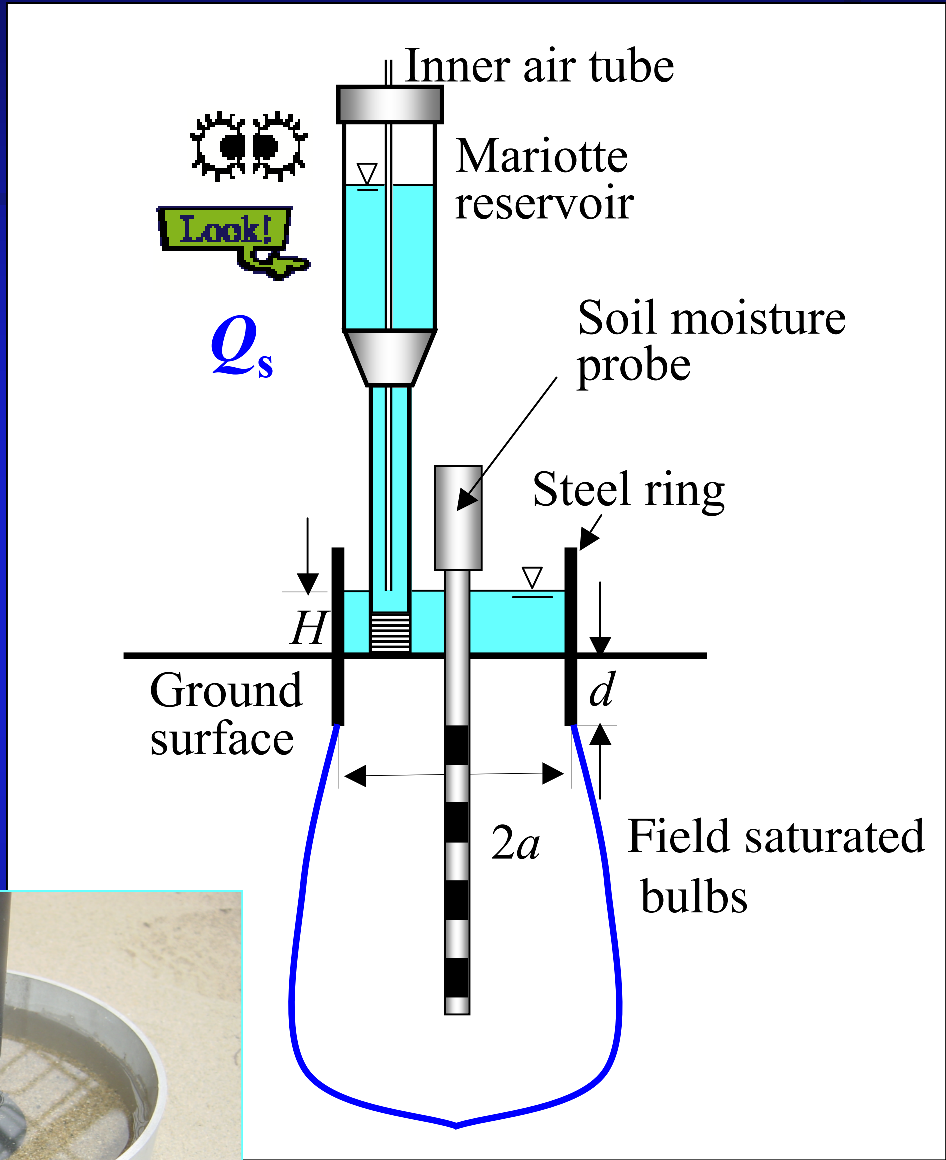
# *Field saturated hydraulic conductivity* $K_{fs}$

Guelph pressure infiltrometer method
(Reynolds & Elrick,1990)

$$K_{fs}=\frac{\alpha^{*}GQ_s}{a\alpha^{*}H+a+G\alpha^{*}\pi a^{2}}$$

$$G = 0.316\,d\,/\,a + 0.184$$

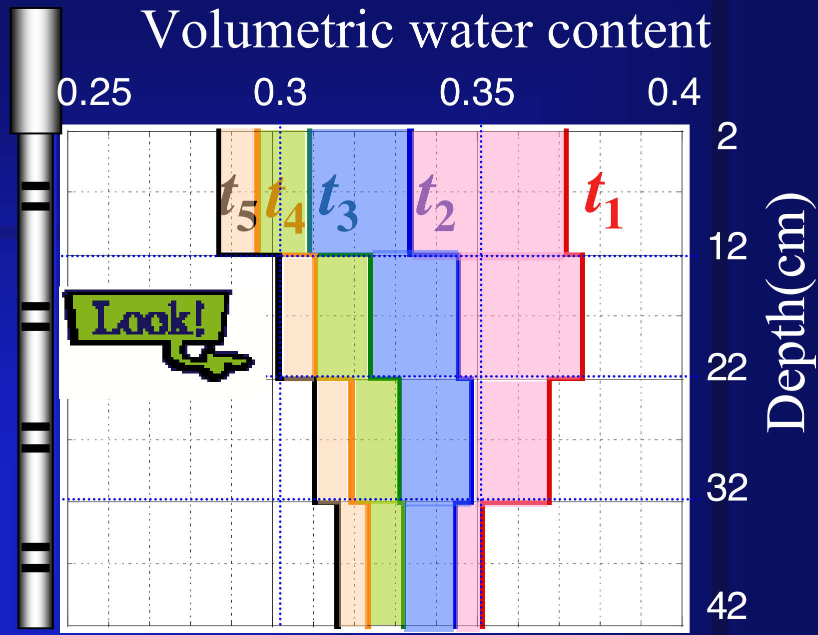
$Q_s$: steady infiltration rate, $G$: shape factor,
$H$:steady pressure head on the infiltration surface,
$\alpha^{*}$:soil texture/structure parameter;
( $0.12\text{cm}^{-1}$ is the first choice for most soils. )
$d$:depth of ring insertion into the soil,
$a$:inside radius of the ring





Constant head infiltration test

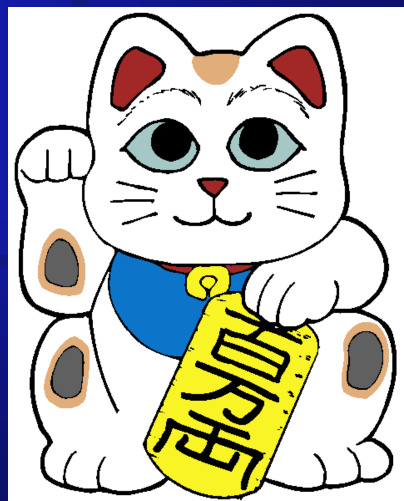
# Instantaneous Profile Method (Watson 1966)




**Vertical soil moisture profiles**

$$K(\theta) = \frac{\left(\int_0^z \frac{\partial \theta}{\partial t} dz\right)_{z,t}}{\left(\frac{\partial h}{\partial z} + 1\right)_{z,t}}$$

**No tensiometers !**



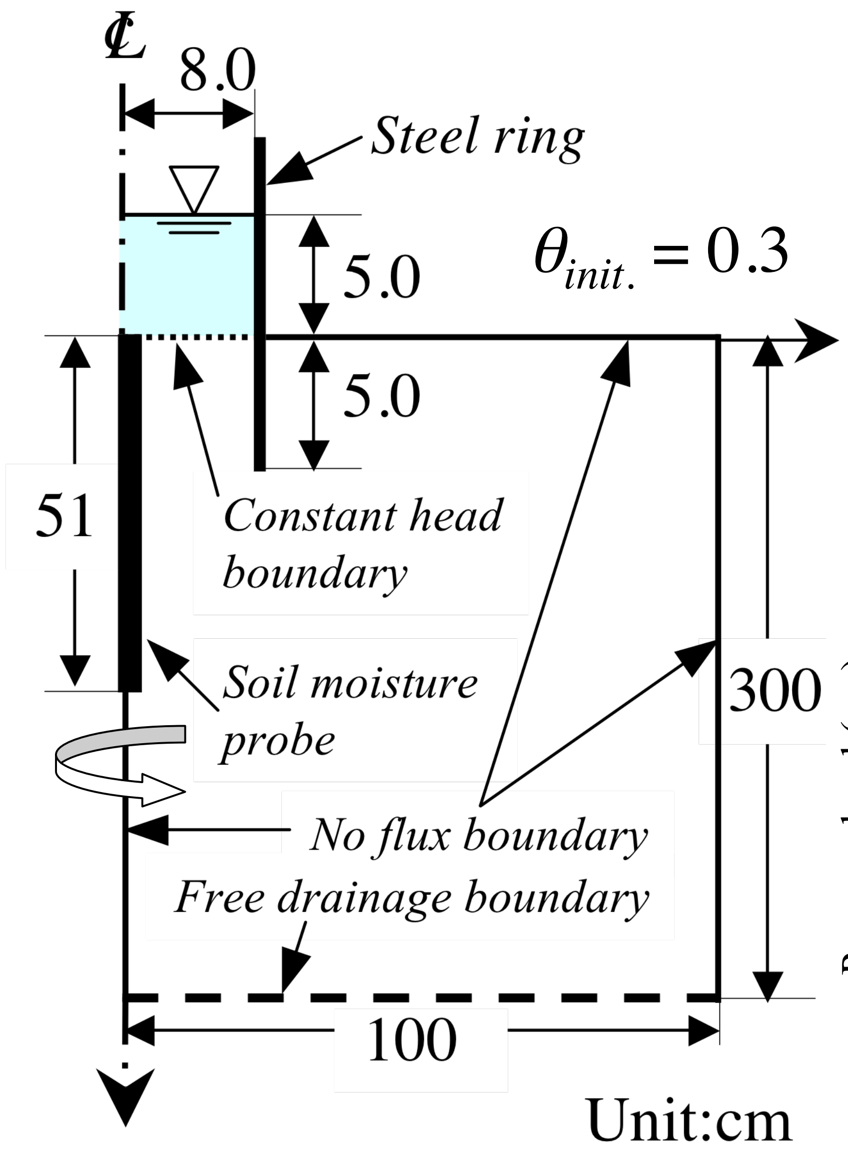
**Too happy!**

*In practice…*

**ASSUMPTION!**

The hydraulic gradient can be equal to 1.0 for gravity drainage in relatively uniform sandy soils.

# Numerical example




**Axisymmetric soil region**

***Saturated soil hydraulic property***

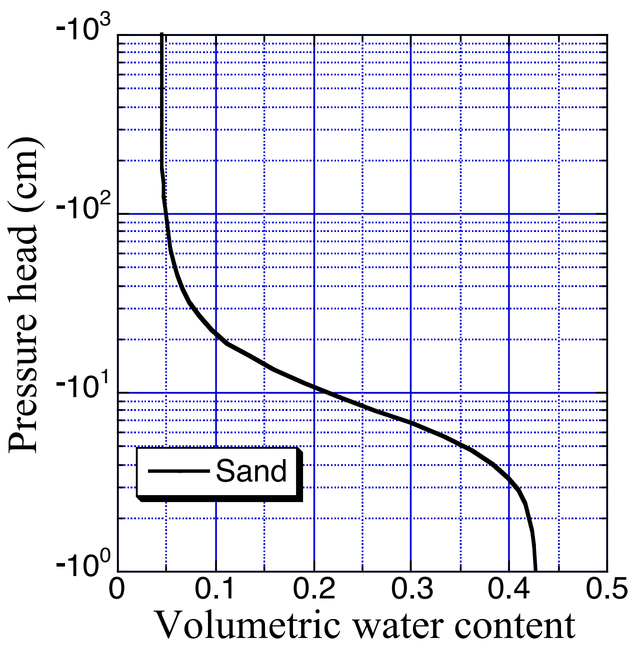
$K_{fs} = 3.0\times10^{-3}$ cm/s,

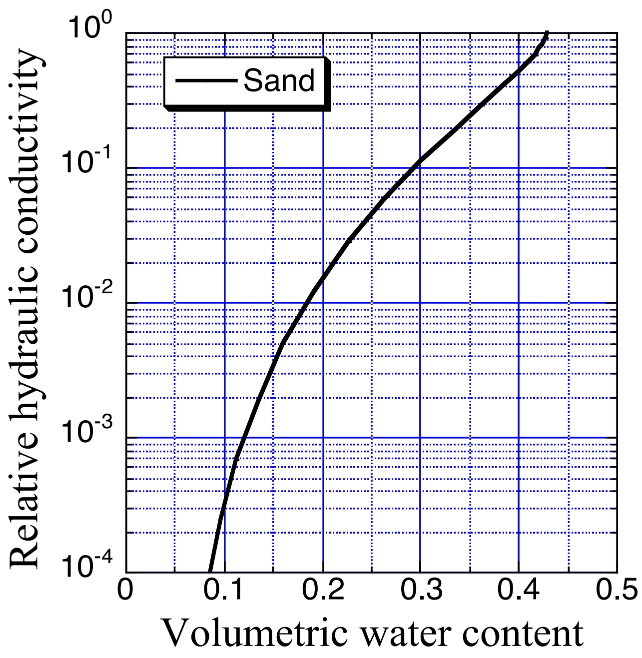
$\theta_s = 0.43$

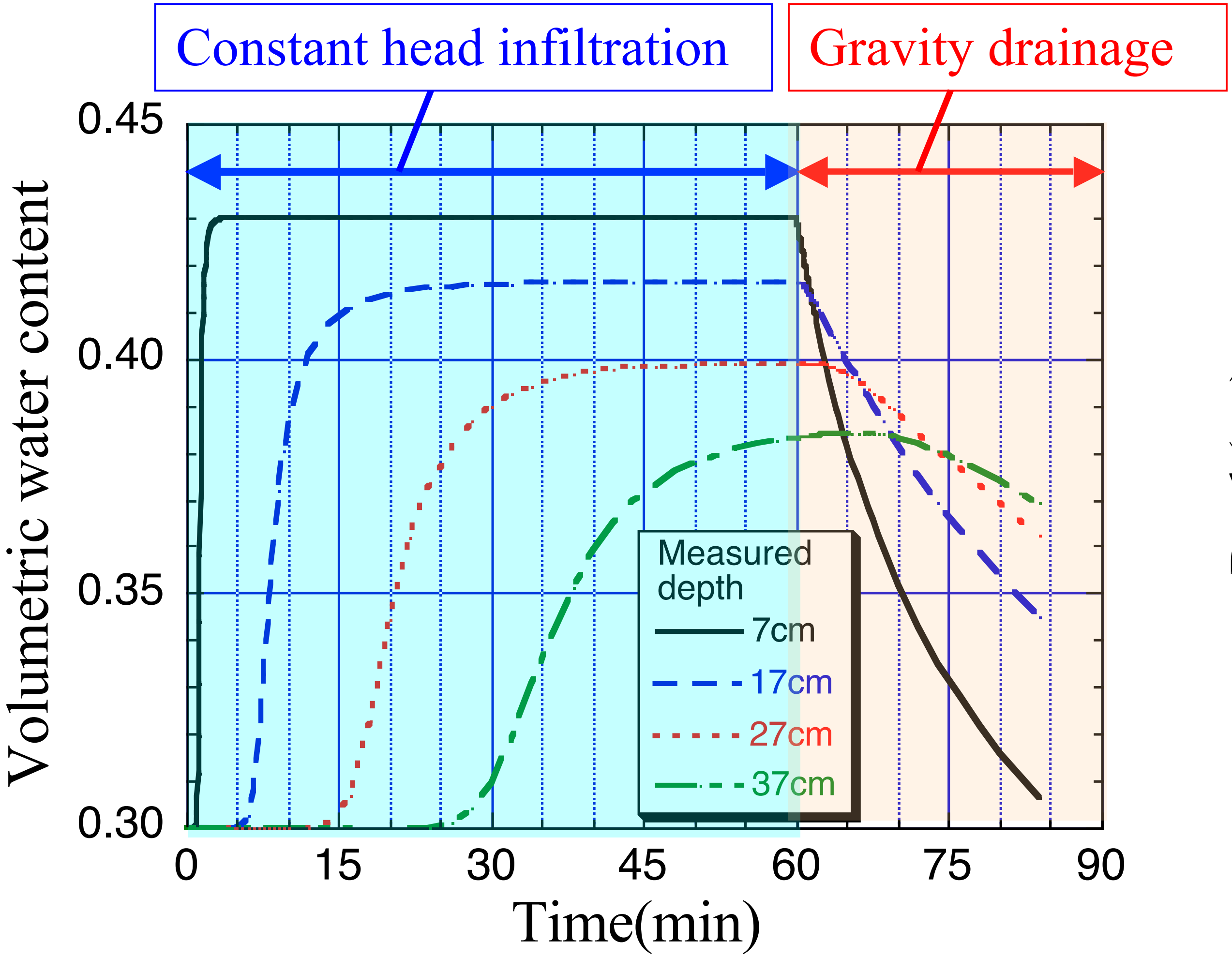
***Unsaturated soil hydraulic property***

van Genuchiten model (1980)

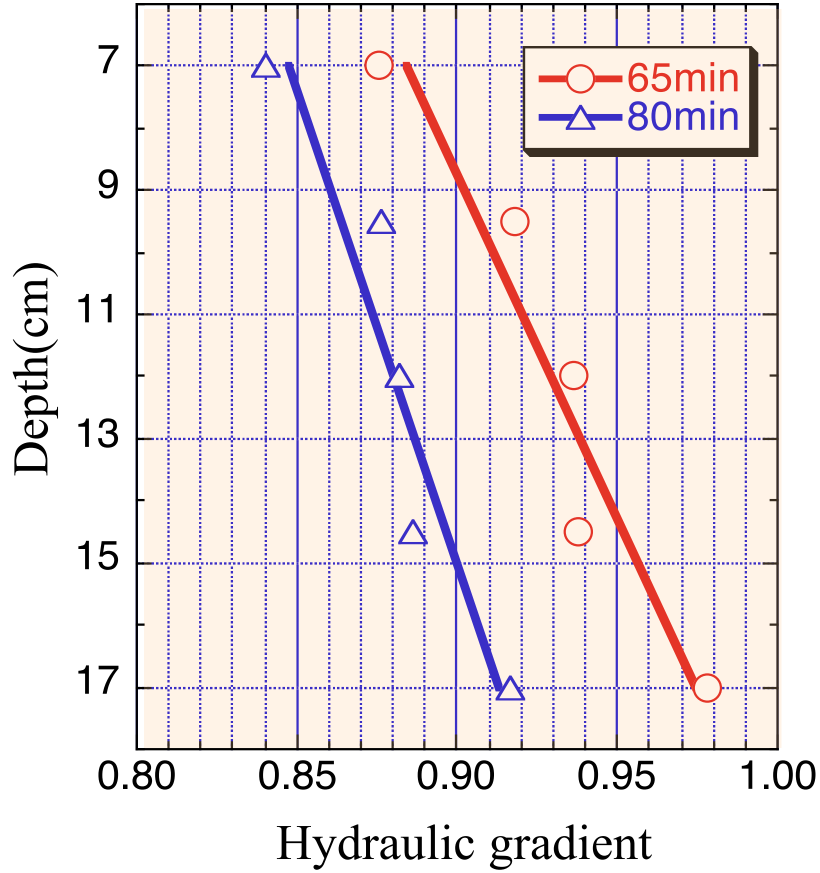
$\theta_r = 0.045,\ \alpha = 0.145\ \text{cm}^{-1},\ n = 2.68$



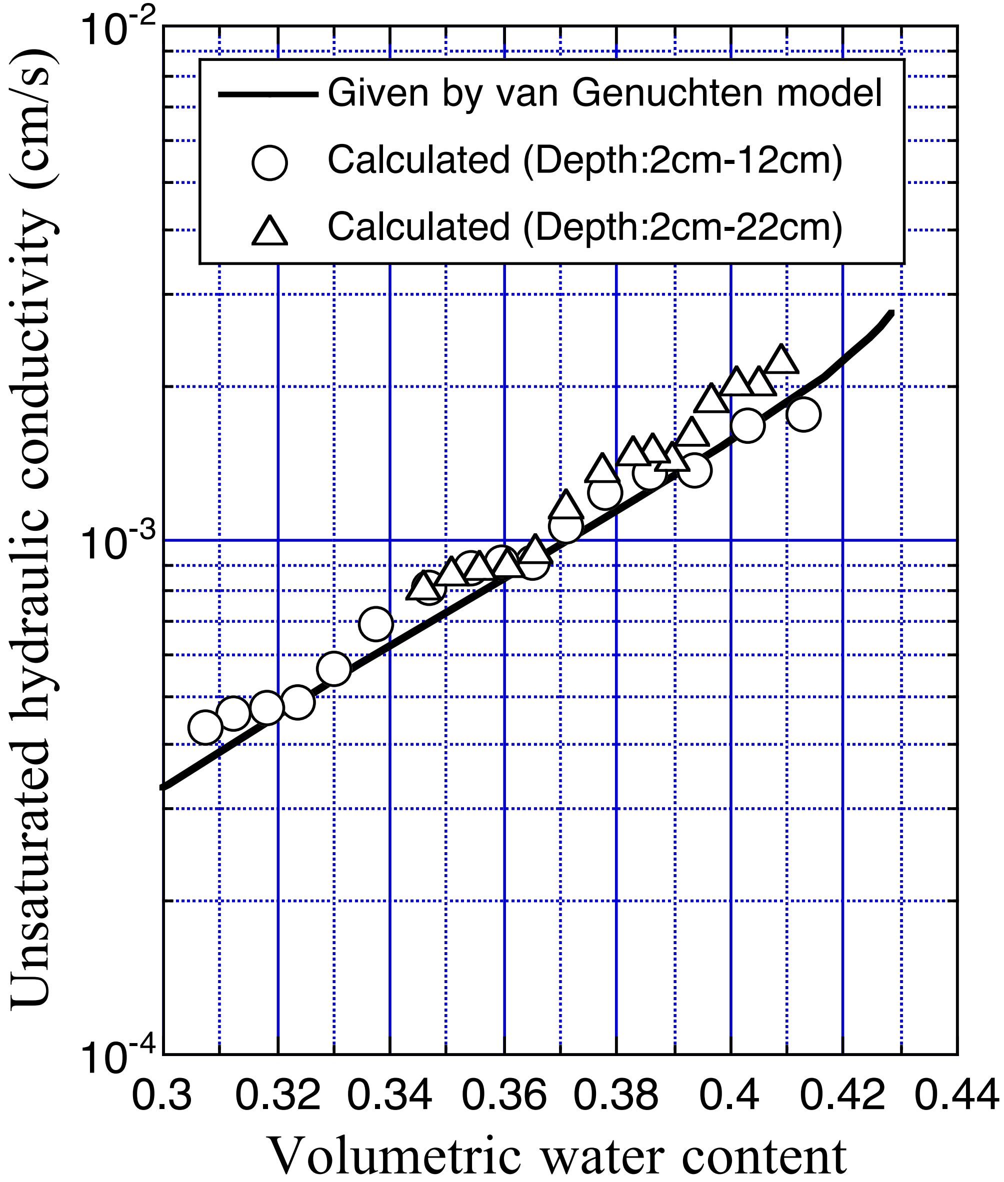






**Computed volumetric water contents with time**

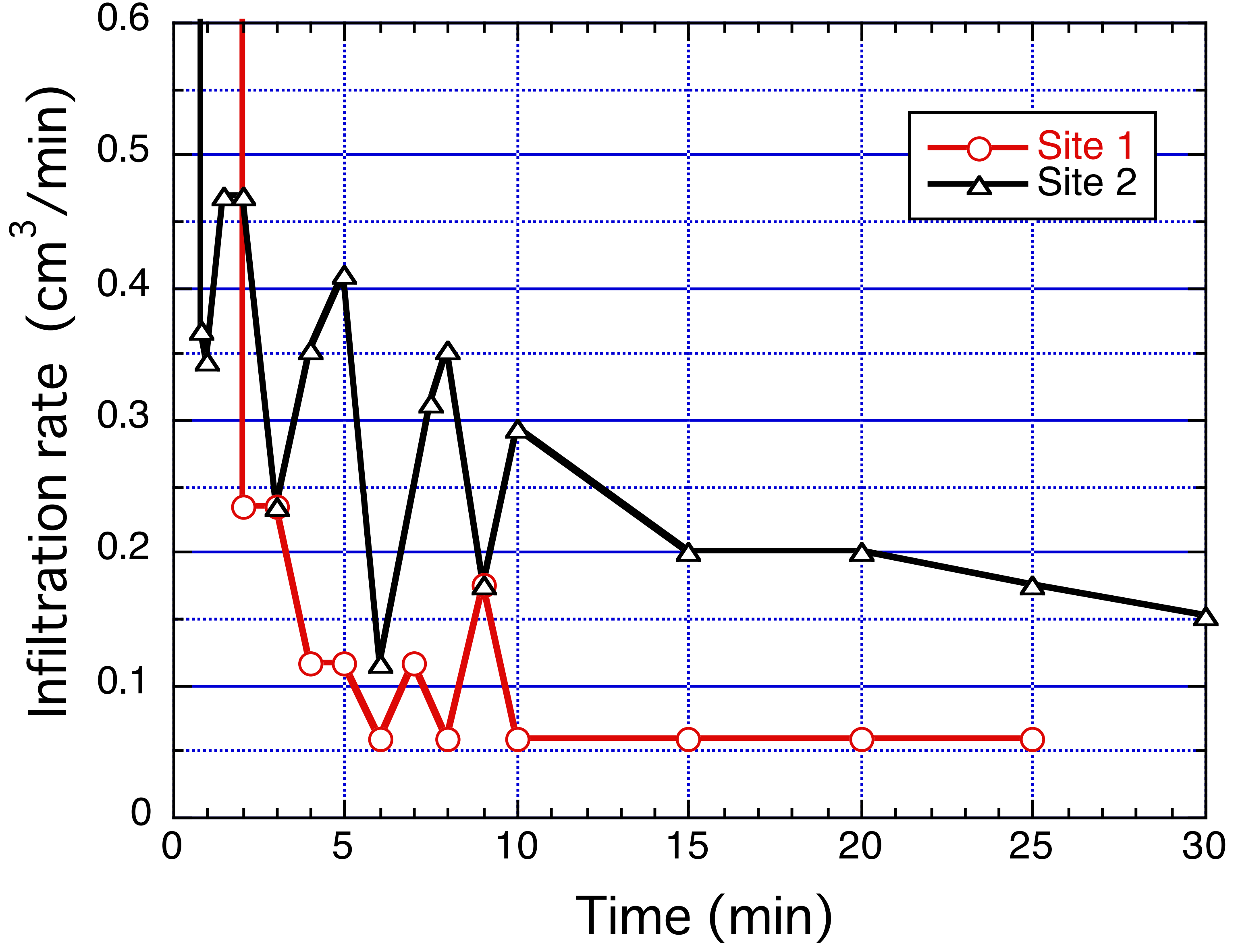



**Computed hydraulic gradient until depth 17cm under soil surface**




**Unsaturated hydraulic conductivity calculated by the instantaneous profile method (Numerical example)**

# Field measurements of field saturated hydraulic conductivity of the top soil cover in the PIYUNGAN waste disposal site in Yogyakarta, Indonesia




**Measured infiltration rate with time**

# Summary

Two simple in-situ permeability tests were proposed.

1. The constant-head infiltration test based on the Guelph pressure infiltrometer technique to determine the field-saturated hydraulic conductivity.

2. The instantaneous profile method with the unit hydraulic gradient assumption to calculate the unsaturated hydraulic conductivity.

Proposed method offers a fast way for measuring the hydraulic conductivity and may be an interesting tool for low-cost mapping of the permeability of top soil cover in the waste disposal site.