INTERNATIONAL SEMINAR ON APPLICATION OF ADVANCED TECHNOLOGY IN SLOPE ENGINEERING

@ Hanoi University of Mining and Geology, Hanoi, Vietnam

7 January 2025

A consideration of evaporation properties in unsaturated sandy soil based on soil water characteristic curve and unsaturated hydraulic conductivity

Yamaguchi University ○ ***Yuta Jikuya***, *Motoyuki Suzuki*

Kagoshima University *Kazunari Sako*

Ritsumeikan University *Shinichi Ito*

Overview

1. **Introduction to the background**
   - … How to assess the risk of rainfall-induced slope failure?
   - … What are the unsaturated evaporation properties?
2. **Description of measurement methods for the water retention, seepage, and evaporation properties**
   - … Previous methods for measuring these three properties
   - … Proposed method that can measure these three properties simultaneously
3. **Discussion based on the measurement results**
   - … Validity of the simultaneous measurement method
   - … Trends in the evaporation properties
4. **Conclusions and remaining questions**

Background: Rainfall-induced slope failure

In Japan, various slope failures due to heavy rainfall occur frequently during the rainy and typhoon seasons.

Natural disaster warnings
Traffic restrictions

Issuance of these warnings
… Timings are determined based on rainfall intensity.

Cancellation of these warnings
… Timings are difficult to determine.

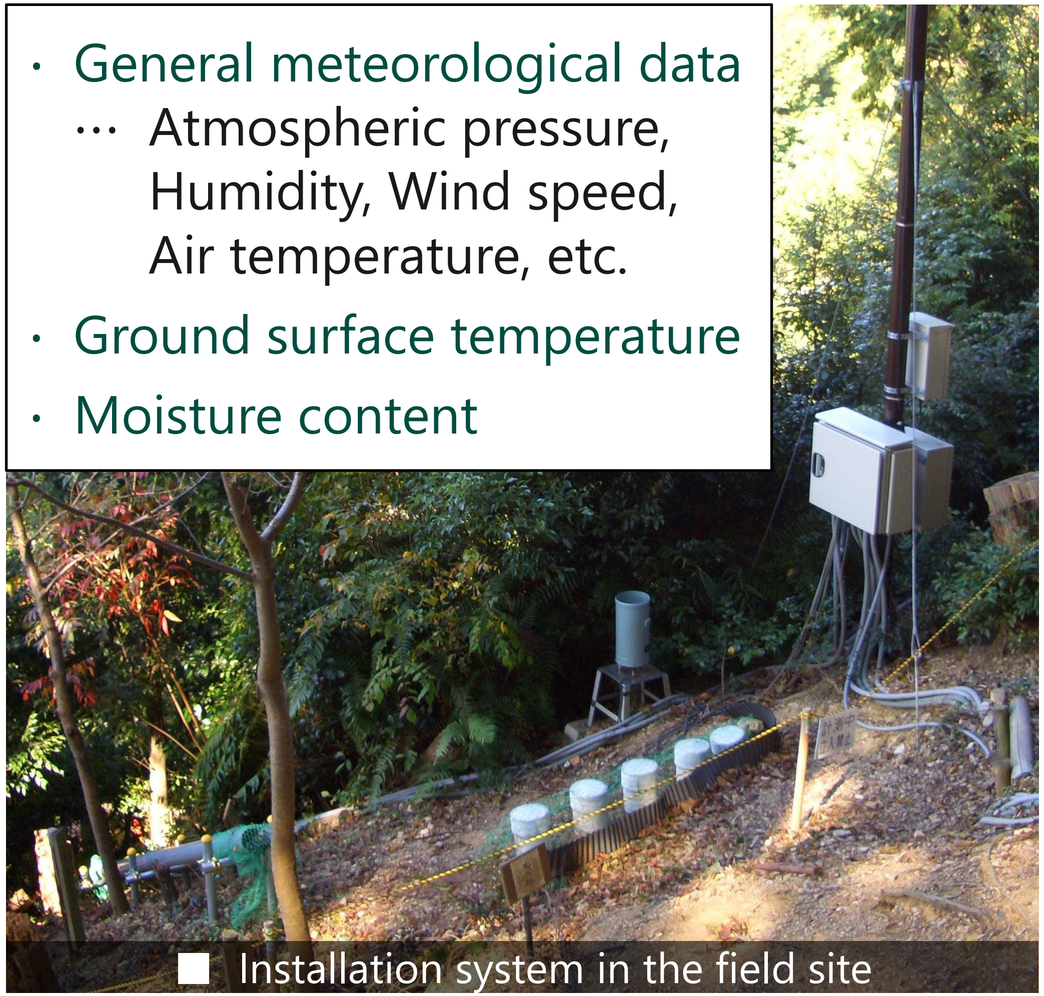
■ Slope failure at Kagoshima Prefecture (4 July 2019)

To determine the timings of the cancellation, It is necessary to comprehend the slope stability over time after a rainfall event.

Background: Method for slope stability assessments

Real-time monitoring

- General meteorological data
  … Atmospheric pressure, Humidity, Wind speed, Air temperature, etc.
- Ground surface temperature
- Moisture content

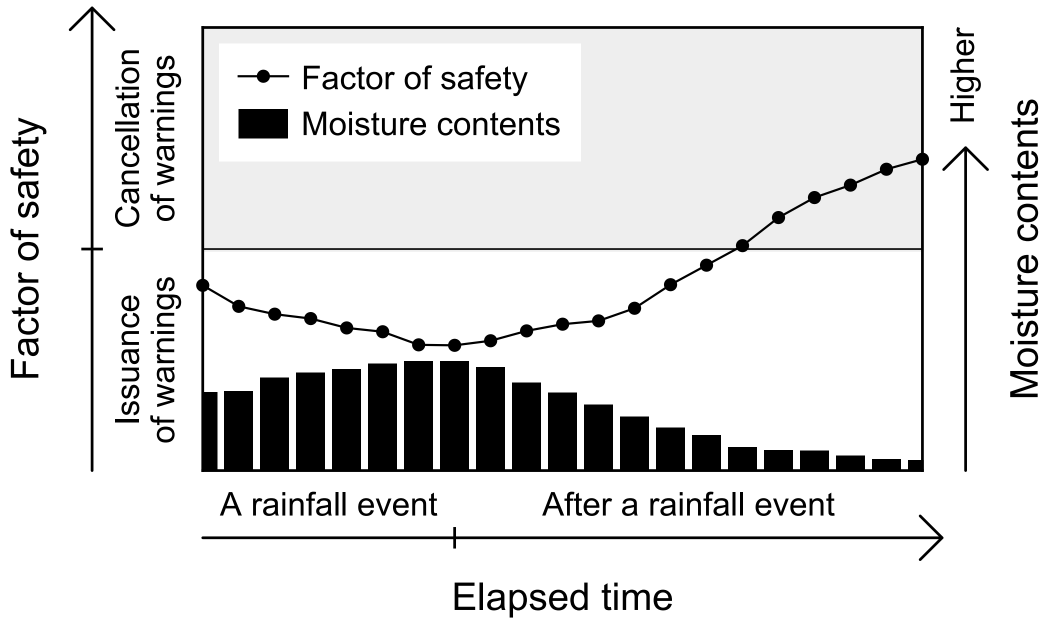


■ Installation system in the field site

Numerical simulations

☑ Saturated-unsaturated seepage analysis

☐ Slope stability analysis



■ Schema of time-series variation in factor of safety on slope failure (Left-axis) and moisture contents (Right-axis)

Background: Saturated-unsaturated seepage analysis

Richards' equation

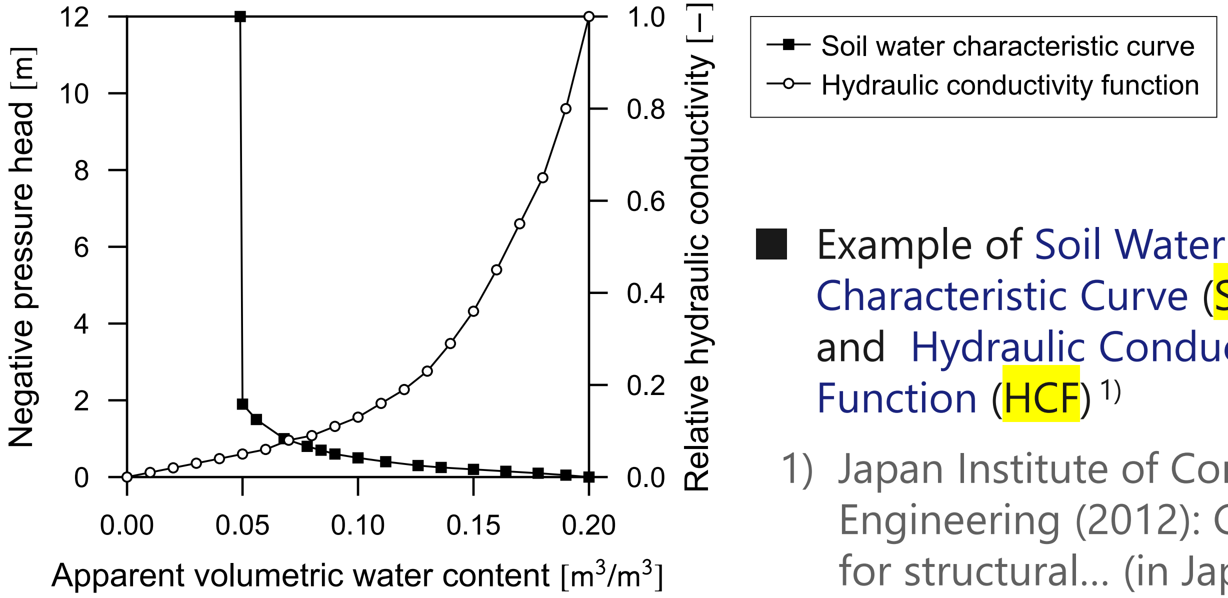
$$\left(\frac{\partial\theta}{\partial h}+\alpha\cdot S_{\mathrm{s}}\right)\frac{\partial h}{\partial t}=\frac{\partial}{\partial x_i}\left[k\frac{\partial(h+z)}{\partial x_i}\right]$$

Where

t : Time,
x_i : Coordinate (x, y, z),
h : Pressure head,
k : Hydraulic conductivity,
θ : Volumetric water content,
S_s : Specific storage,
α : 1 in saturated conditions,
0 in unsaturated conditions.

Boundary conditions

☐ During rainfall: Amount of rainfall
☑ After rainfall : Amount of evaporation



■ Example of Soil Water Characteristic Curve (SWCC) and Hydraulic Conductivity Function (HCF) [1)]

1) Japan Institute of Construction Engineering (2012): Guideline for structural... (in Japanese).

For the estimation of slope stability after a rainfall event, it is essential to obtain the amount of evaporation.

Background: Method of obtaining evaporation

Bulk method (β-method)

- The amount of evaporation per unit time and unit area, E can be estimated from general meteorological data and the ground surface temperature T_s (Table below).

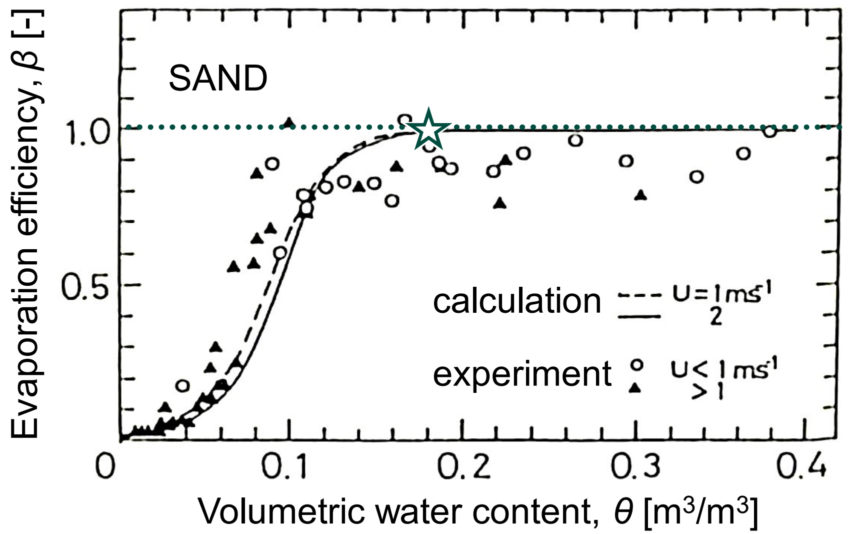
$$E = \rho \cdot g_a \cdot \beta \left[q_{sat}(T_s) - q \right]$$

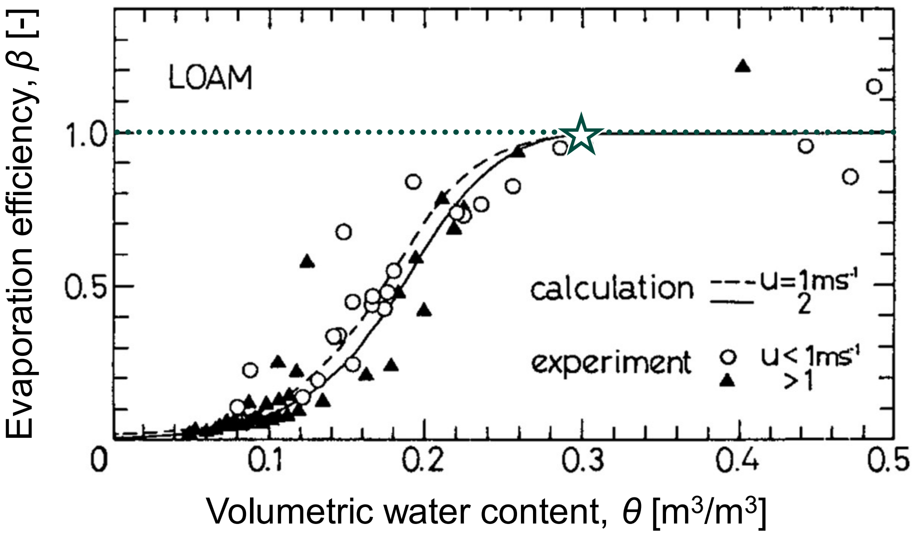
Parameters				Observation data			
ρ	:	Air density	$[\mathrm{kg\ m^{-3}}]$	P	:	Atmospheric pressure	[hPa]
				h_r	:	Relative humidity	[%]
				T_a	:	Air temperature	[℃]
q_{sat}	:	Saturation specific humidity	$[\mathrm{kg\ kg^{-1}}]$	P	:	Atmospheric pressure	[hPa]
				T_s	:	Ground surface temperature	[℃]
q	:	Specific humidity of the air	$[\mathrm{kg\ kg^{-1}}]$	P	:	Atmospheric pressure	[hPa]
				h_r	:	Relative humidity	[%]
				T_a	:	Air temperature	[℃]
g_a	:	Exchange speed	$[\mathrm{m\ s^{-1}}]$	Calculated from the laboratory experiments.			
β	:	Evaporation efficiency	[–]				

Background: Evaporation properties in unsaturated soil

Evaporation efficiency β (namely, evaporation properties)

- β expresses the ease with which evaporation from the ground surface occurs.
- β has a value between 0 and 1.0 depending on the Volumetric Water Content θ (VWC) (e.g., $\beta = 0$ under dry conditions and $\beta = 1.0$ under saturated conditions).





- θ and β relations[2)] (corrected with additions)

2) Kondo, J. ... (1990): A parameterization of evaporation from bare soil... .

The boundary moisture content when β begins to decrease, is affected by the soil conditions (soil type and compaction).

Purpose and structure

No studies have focused on the relationship of the boundary moisture content to the water retention (SWCC) and seepage properties (HCF).

Purpose: To discuss the evaporation efficiency functions based on the SWCC and HCF obtained from identical specimens.

1) A method for the simultaneous measurement of the SWCC, HCF, and evaporation efficiency function (θ and β relation) is developed.

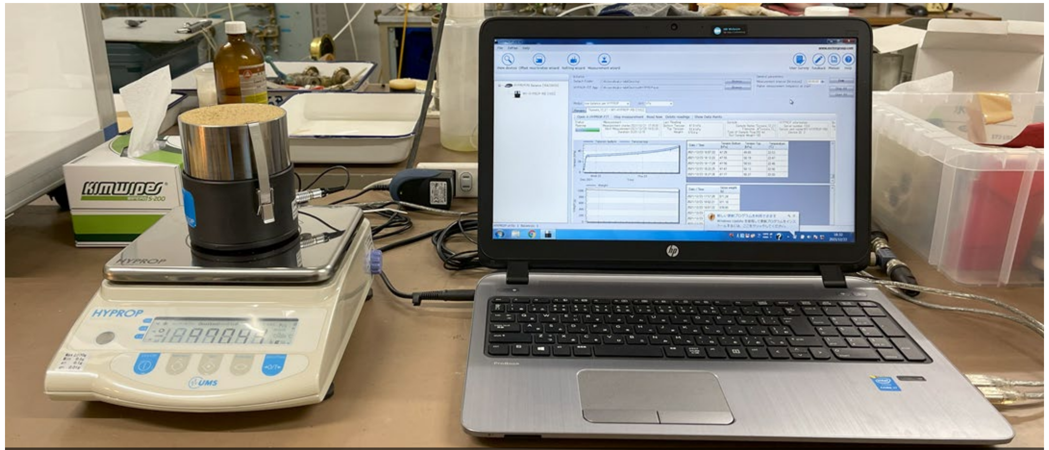
   … Its feasibility is confirmed based on the measurement results using sandy and volcanic sandy soil.

2) The trends in the θ and β relation are discussed in relation to the SWCC and HCF obtained from identical specimens.

   … VWCs are investigated at the time β begins to decrease.

Measurement methods: Previous methods

Simplified evaporation method (HM)



■ Measurement by HM

Measurement Items

- ☐ Evaporation (soil surface)
- ☐ Matric suction at two points in the soil

Results obtained

… SWCC (water retention properties)

… HCF (seepage properties)

Laboratory experiment to measure β (EM)

■ Measurement by EM

Measurement Items

- ☐ Evaporation (soil and water surfaces)
- ☐ Surface temperatures
- ☐ Meteorological data

Results obtained

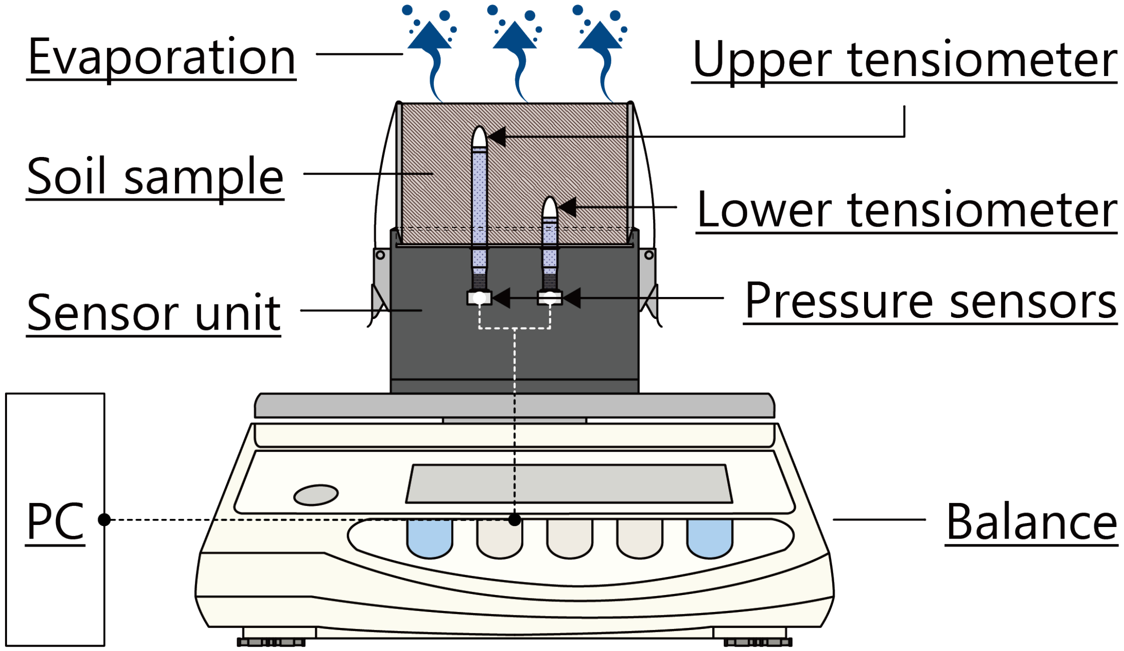
… θ and β relation
(evaporation properties)

Measurement methods: HM (HYPROP device)

Simplified evaporation method (Schindler, U., 1980)

- HM can simultaneously measure SWCC and HCF using an evaporation experiment.
- HYPROP device (METER Group, Inc., USA) used in this study is based on the theory of HM.

… **Two tensiometers**: Matric suction at two points in the soil (up to approximately 200 kPa)
… **Electronic balance**: Specimen weight (minimum weight: 0.01 g)



■ Schema of HYPROP device

Specimen dimensions

… Diameter: 8.0 cm
… Height : 5.0 cm

Tensiometer installation locations

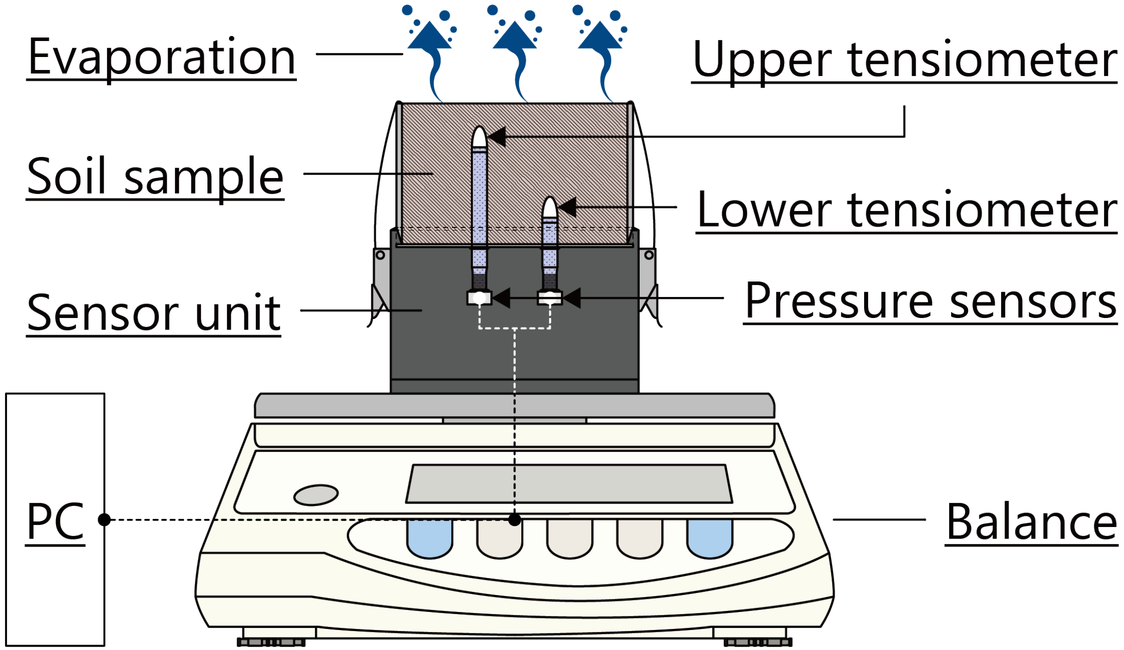
… Upper: 1/4 depth of the specimen
… Lower: 3/4 depth of the specimen

Measurement methods: HM (HYPROP device)

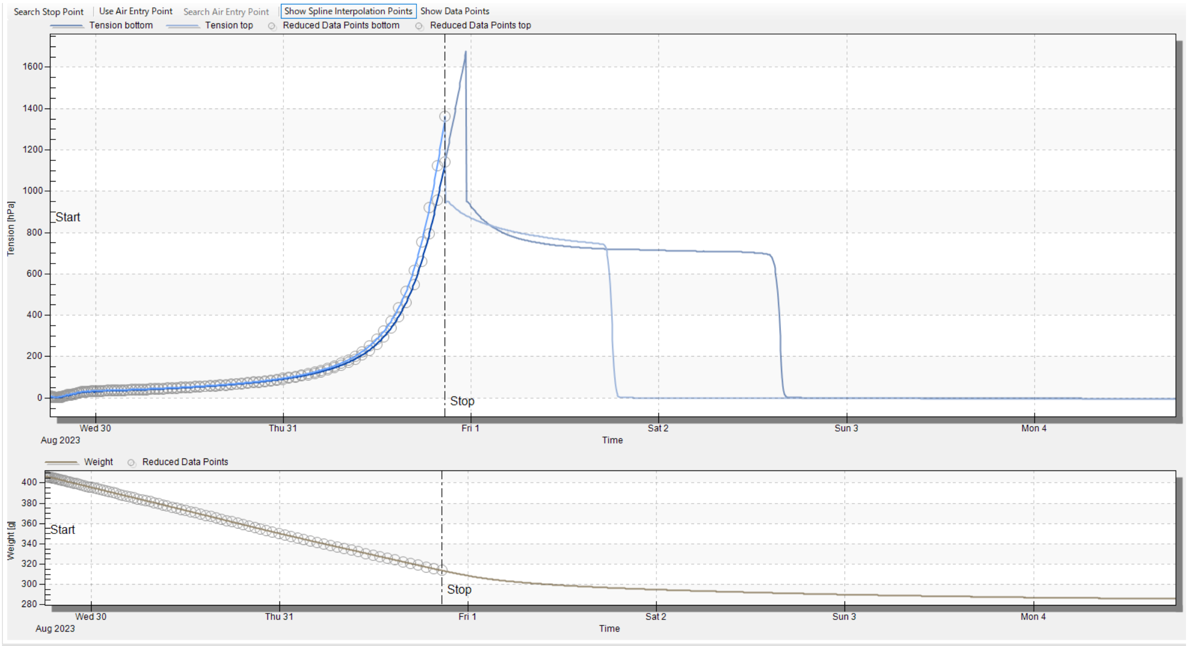
Simplified evaporation method (Schindler, U., 1980)

- HM can simultaneously measure SWCC and HCF using an evaporation experiment.
- HYPROP device (METER Group, Inc., USA) used in this study is based on the theory of HM.

… **Two tensiometers**: Matric suction at two points in the soil (up to approximately 200 kPa)
… **Electronic balance**: Specimen weight (minimum weight: 0.01 g)



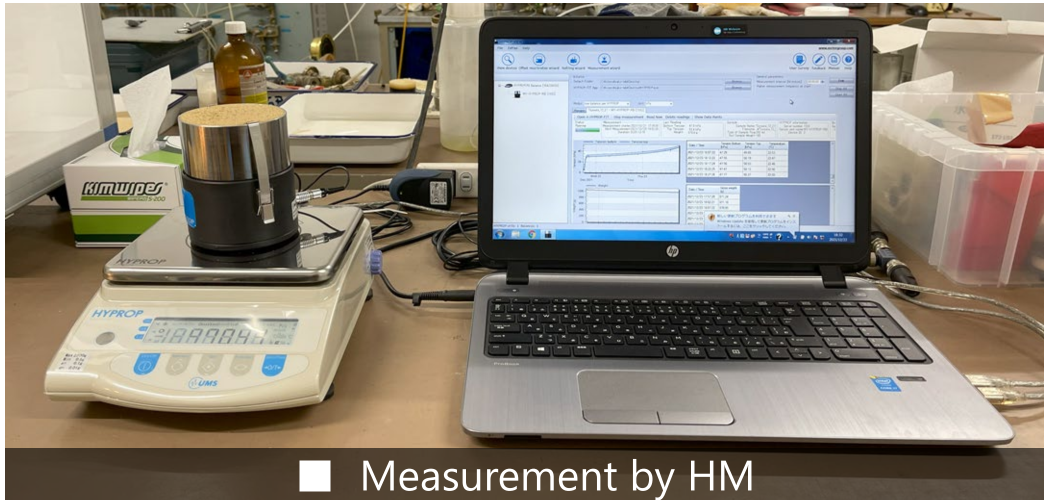
■ Schema of HYPROP device



■ Example of measurement results of matric suction (Above) and specimen weight (Below)

Measurement methods: Previous methods

Simplified evaporation method (HM)



■ Measurement by HM

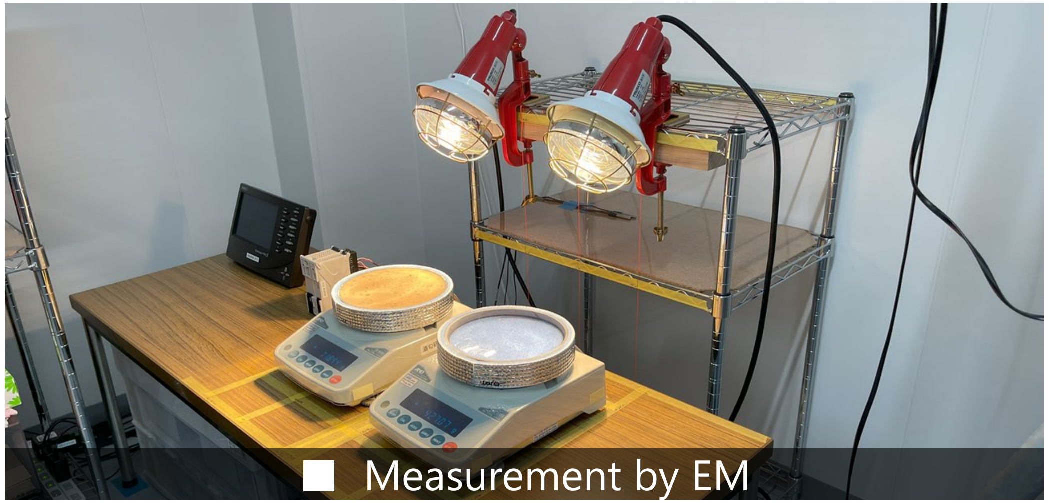
Measurement Items

- ☐ Evaporation (soil surface)
- ☐ Matric suction at two points in the soil

Results obtained

… SWCC (water retention properties)
… HCF (seepage properties)

Laboratory experiment to measure β (EM)



■ Measurement by EM

Measurement Items

- ☐ Evaporation (soil and water surfaces)
- ☐ Surface temperatures
- ☐ Meteorological data

Results obtained

… θ and β relation (evaporation properties)

Measurement methods: EM

Start

Meteorological monitoring

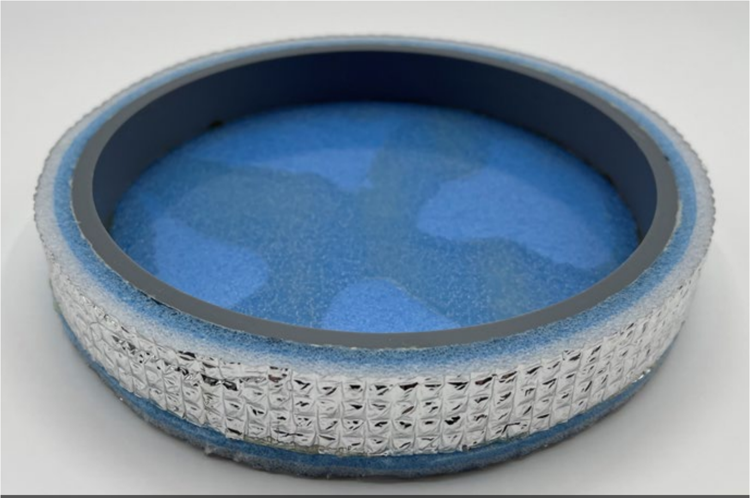
- Monitoring | Air temperature: T_a
  | Atmospheric pressure: P
  | Relative humidity: h_r
  | Wind speed: U

Water tank experiment

- Measurement | Surface temperature: T_{ws}
  | Evaporation: E_{water}
- Condition | Evaporation efficiency: $\beta = 1$
  (with saturated surface)

Soil tank experiment

- Measurement | Surface temperature: T_{ss}
  | Evaporation: E_{soil}
  | Volumetric water content: θ
  (by weighing soil tank)



■ Cylindrical container

Specimen dimensions

… Diameter: 12.65 cm
… Height : 2.0 cm

Soil and water tank experiments

Measurement Items

- ☐ Evaporation (soil and water surfaces)
  … Electronic balance (minimum weight: 0.01 g)
- ☐ Surface temperatures
  … Infrared thermometers (resolution: 0.1 ℃)
- ☐ Meteorological data

Heat supply to surfaces by radiation

- ☐ Floodlights (180 W)

Measurement methods: EM

Start

Meteorological monitoring

- Monitoring | Air temperature: T_a
  | Atmospheric pressure: P
  | Relative humidity: h_r
  | Wind speed: U

Water tank experiment

- Measurement | Surface temperature: T_{ws}
  | Evaporation: E_{water}
- Condition | Evaporation efficiency: $\beta = 1$ (with saturated surface)

Soil tank experiment

- Measurement | Surface temperature: T_{ss}
  | Evaporation: E_{soil}
  | Volumetric water content: θ (by weighing soil tank)

Natural convection ?

$U < 0.3$ [m/s]

$T_{ws;ss} - T_a > 0.5$ [℃]

No / Yes

Bulk formula（water tank）

$$E = \rho g_a \beta [q_{sat}(T_s) - q]$$

- Parameter | $T_s = T_{ws}$, $\beta = 1$
- Calculation | Exchange speed on the water tank: $g_{a,water}$

Correction of exchange speed

$$g_{a,soil} = \left(\frac{\zeta_{water}}{\zeta_{soil,sat}}\right)^{1/3} \cdot g_{a,water}$$

- Parameter | Volumetric heat capacity: ζ
- Calculation | Exchange speed on the soil tank: $g_{a,soil}$

Bulk formula（soil tank）

$$E = \rho g_a \beta [q_{sat}(T_s) - q]$$

- Parameter | $T_s = T_{ss}$
- Calculation | Evaporation efficiency: β

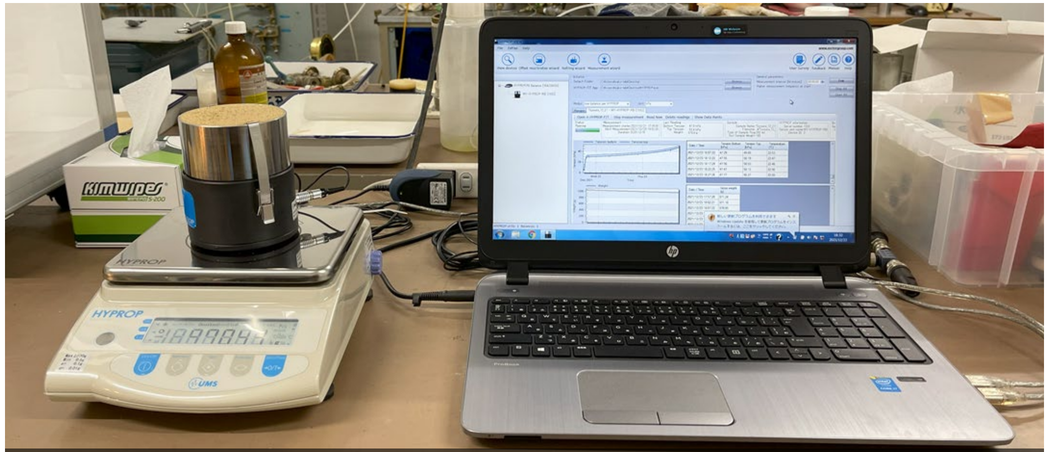
Derivation | $\theta - \beta$ relation

The calculation method considering the difference in heat capacity between soil and water (Jikuya et al., 2024)

⋯ Where ζ: Volumetric heat capacity [$\mathrm{J\ m^{-3}\ K^{-1}}$]
($\zeta_{soil,sat} = 3.1 \times 10^{-3}$, $\zeta_{water} = 4.2 \times 10^{-3}$).

Measurement methods: Previous methods

Simplified evaporation method (HM)



■ Measurement by HM

Measurement Items

- ☑ Evaporation (soil surface)
- ☐ Matric suction at two points in the soil

Results obtained

… SWCC (water retention properties)
… HCF (seepage properties)

Laboratory experiment to measure β (EM)

■ Measurement by EM

Measurement Items

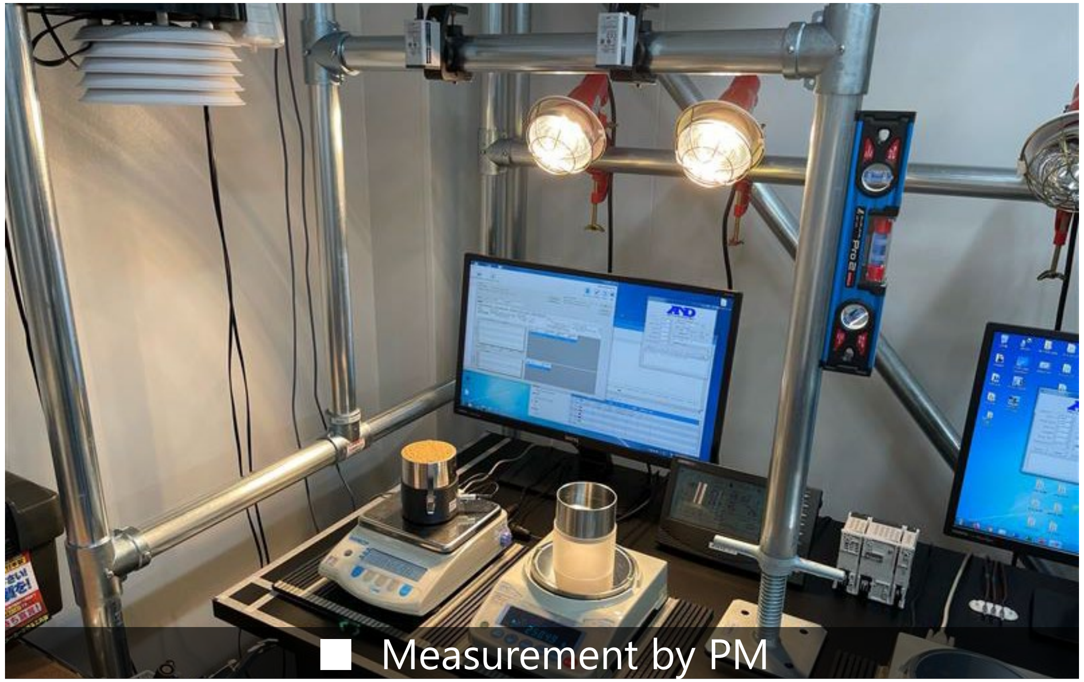
- ☑ Evaporation (soil and water surfaces)
- ☐ Surface temperatures
- ☐ Meteorological data

Results obtained

… θ and β relation (evaporation properties)

Measurement methods: Proposed method

Simultaneous measurement method (PM)



Measurement Items

- ☑ Evaporation (soil and water surfaces)
- ☐ Matric suction at two points in the soil
- ☐ Surface temperatures
- ☐ Meteorological data

Results obtained

- … SWCC (water retention properties)
- … HCF (seepage properties)
- … θ and β relation (evaporation properties)

Matters for consideration

HM→PM) What is the effect of the heat supply to the HYPROP device?

EM →PM) What is the effect of the difference in the specimen dimensions?

Measurement conditions

■ Measurement conditions and physical properties of the soil samples (the measurements were all taken on different days)

Measurement theory	HM		EM		PM	
Heat supply	×		○		○	
Specimen dimensions	$\varphi 8.0 \times 5.0$ cm		$\varphi 12.65 \times 2.0$ cm		$\varphi 8.0 \times 5.0$ cm	
Soil samples	**Toyoura** sand (sandy soil, with a soil particle density of 2.640 $\mathrm{Mg\ m^{-3}}$) **Higashimata** soil (volcanic sandy soil, with a soil particle density of 2.514 $\mathrm{Mg\ m^{-3}}$)					
	Toyoura	Higashimata	Toyoura	Higashimata	Toyoura	Higashimata
Void ratios e	0.750	1.147	0.750	1.197	0.759	1.220
Initial degree of saturation $S_{r,0}$ [%]	87.66	84.92	58.67	58.19	89.49	89.60

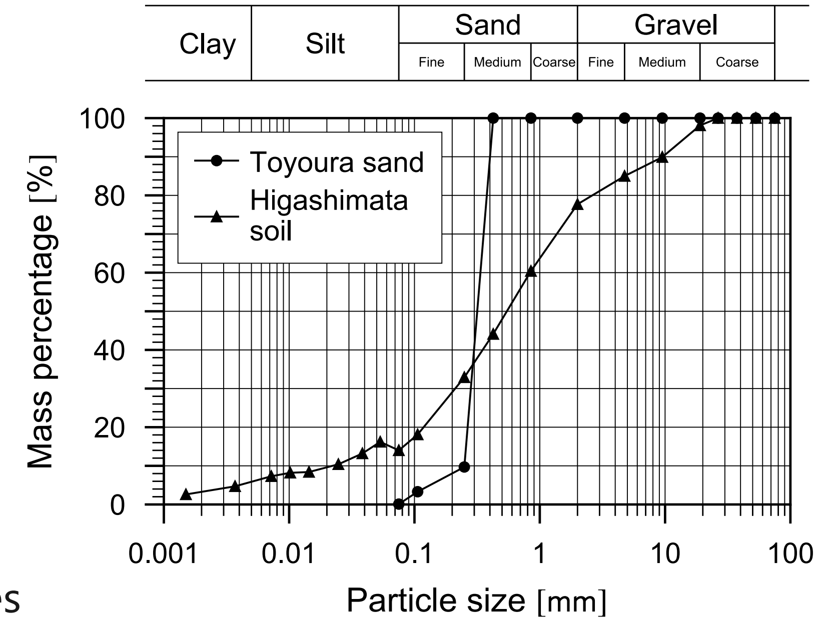
Measurement periods:

SWCC and HCF) Until cavitation occurred inside one of the tensiometers

θ and β relation) Until the weight changes became marginal

Measurement intervals: 30 minutes

※ The water tank was refilled with distilled water at approximately daily intervals

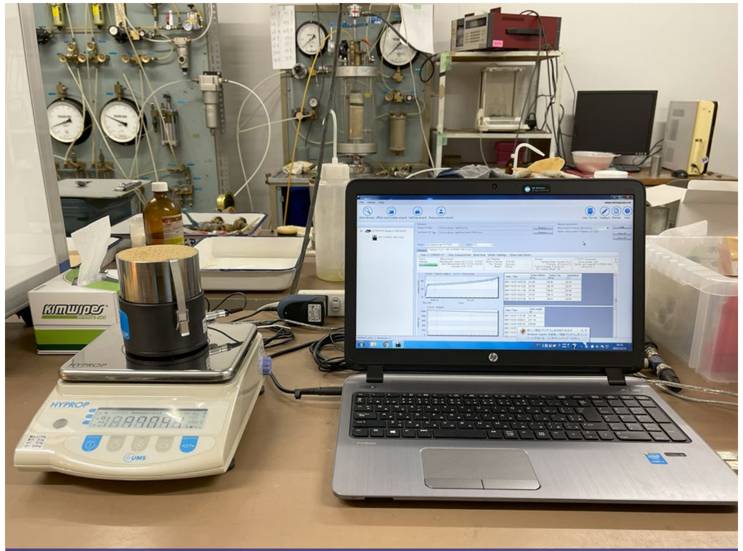


■ Grain size distribution curves

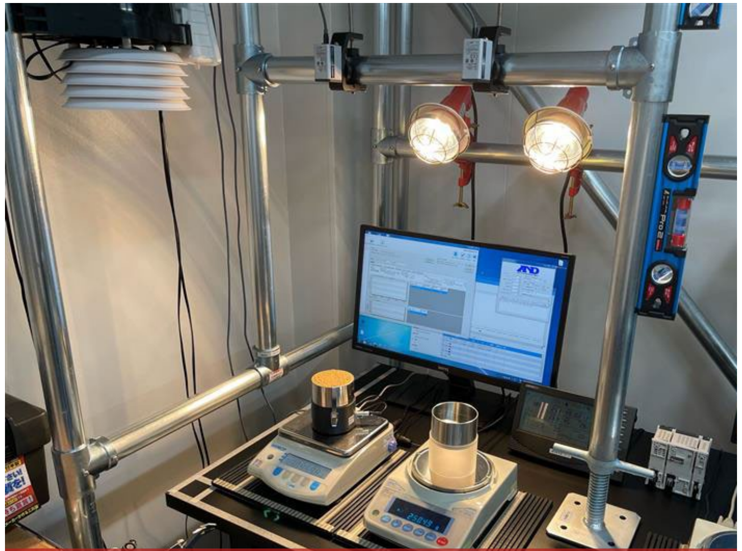
Measurement conditions

■ Measurement conditions and physical properties of the soil samples (the measurements were all taken on different days)

Measurement theory	HM		EM		PM	
Heat supply	×		○		○	
Specimen dimensions	$\varphi 8.0 \times 5.0$ cm		$\varphi 12.65 \times 2.0$ cm		$\varphi 8.0 \times 5.0$ cm	
Soil samples	**Toyoura** sand (sandy soil, with a soil particle density of 2.640 $\mathrm{Mg\ m^{-3}}$) **Higashimata** soil (volcanic sandy soil, with a soil particle density of 2.514 $\mathrm{Mg\ m^{-3}}$)					
	Toyoura	Higashimata	Toyoura	Higashimata	Toyoura	Higashimata
Void ratios e	0.750	1.147	0.750	1.197	0.759	1.220
Initial degree of saturation $S_{r,0}$ [%]	87.66	84.92	58.67	58.19	89.49	89.60

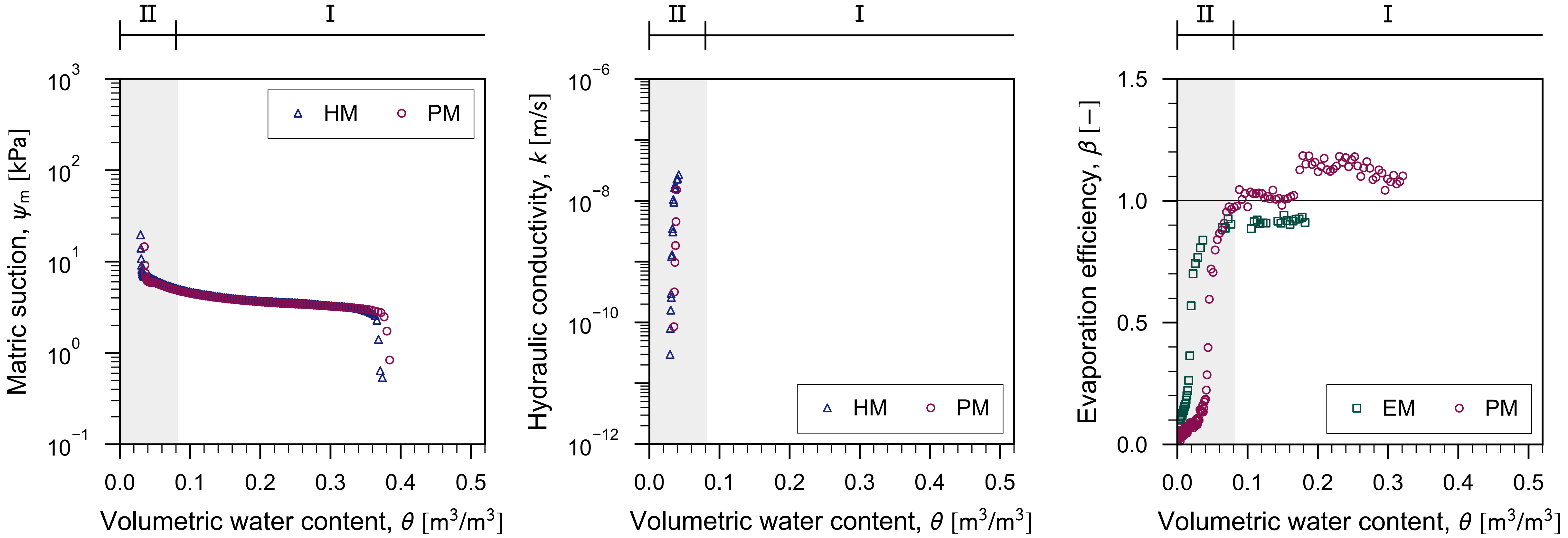

HM


EM


PM

Measurement results: Ranges of I to II

SWCC — HCF — θ and β relation

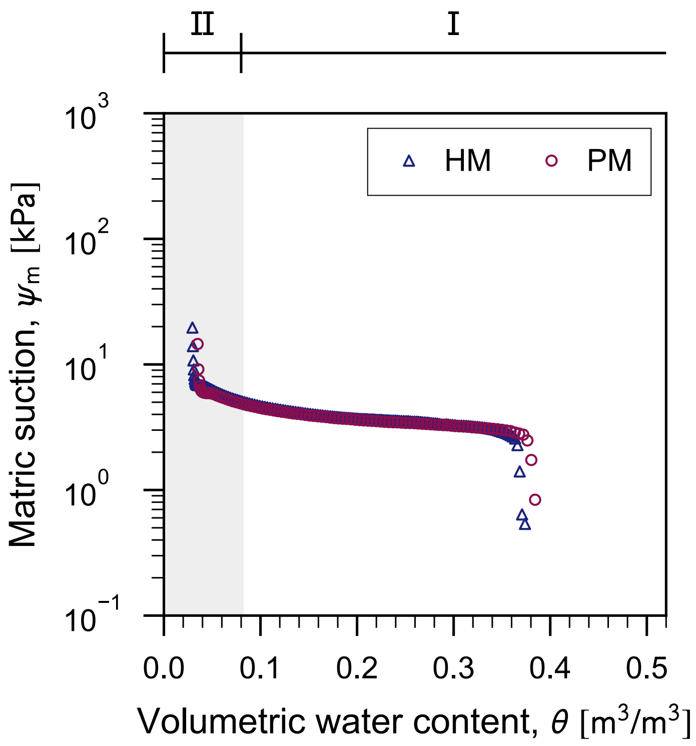


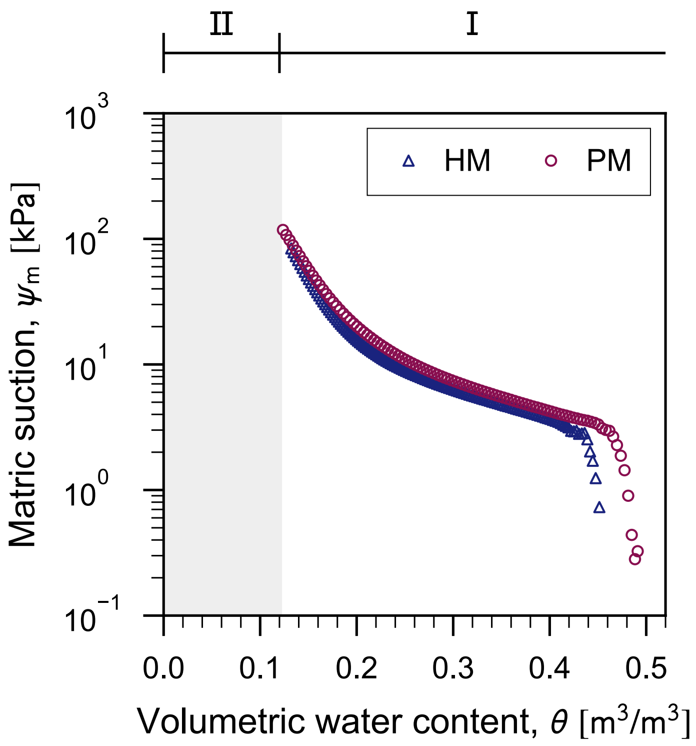
■ Measurement results of SWCC, HCF, and θ and β relation for Toyoura sand

Based on the trends in θ and β relation, SWCC and HCF are divided into I to II ranges.

Measurement results: SWCC (HM and PM)

Toyoura / Higashimata

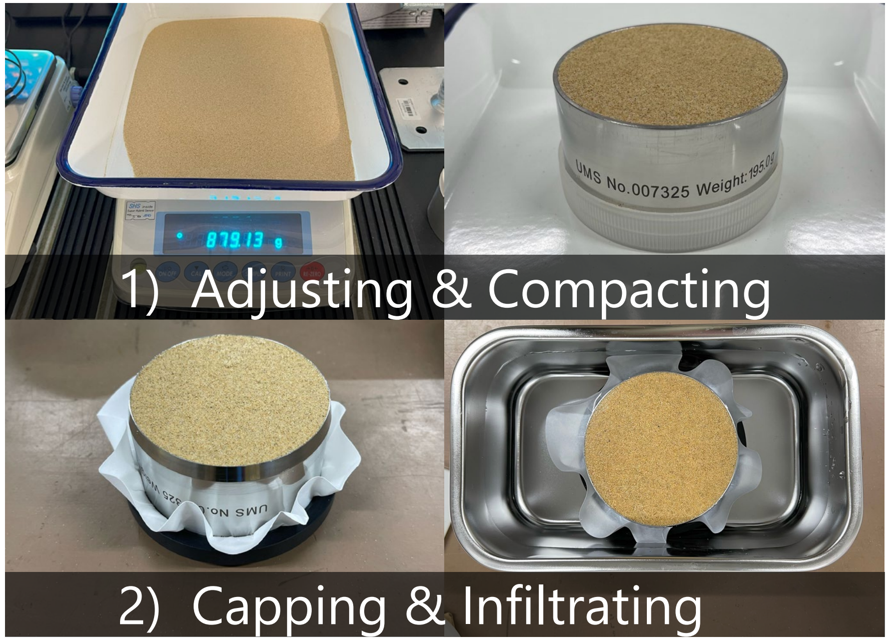




■ SWCCs (water retention properties) measured by HM and PM

Specimen preparation

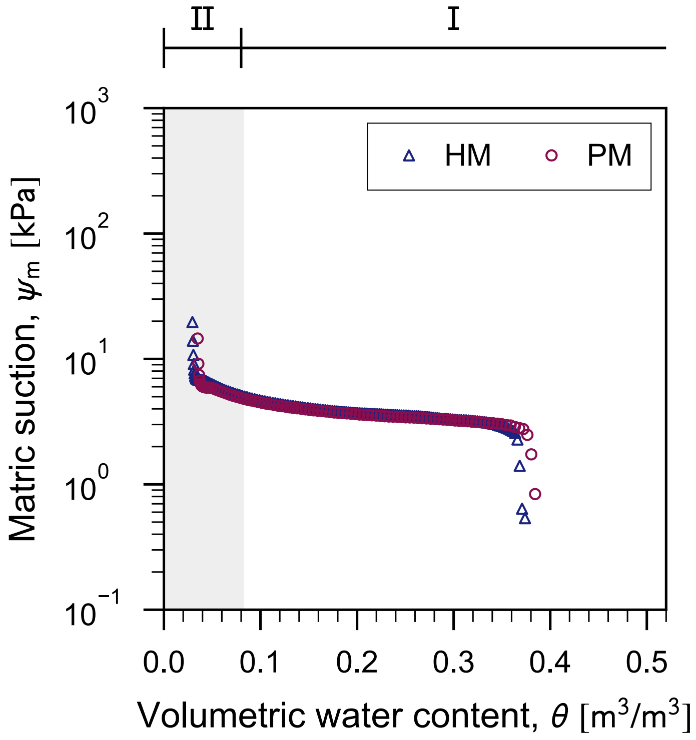
Infiltrate with degassed water for 24 hours

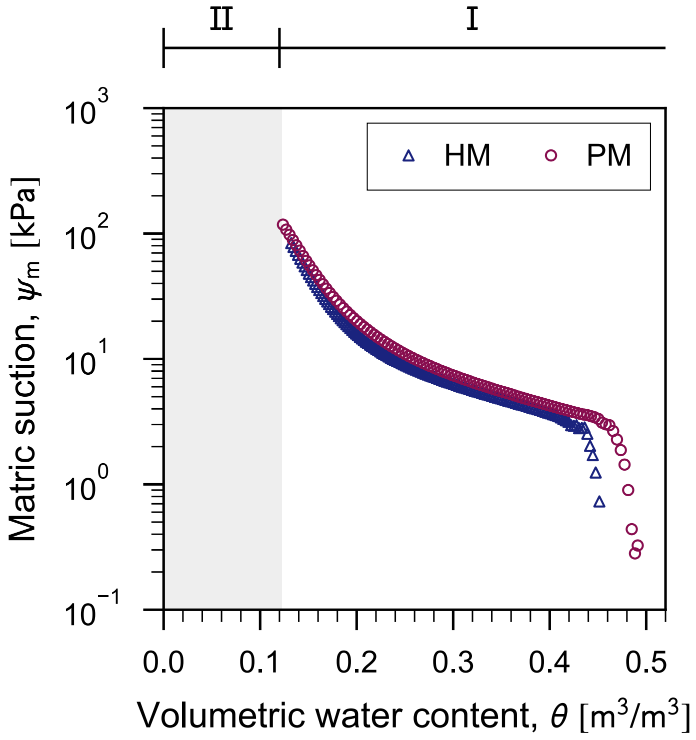


Until the ψ_{m} increases to the air-entry value, the results for HM and PM differ. These variations can be attributed to the differences in the initial conditions of the specimen.

Measurement results: SWCC (HM and PM)

Toyoura / Higashimata

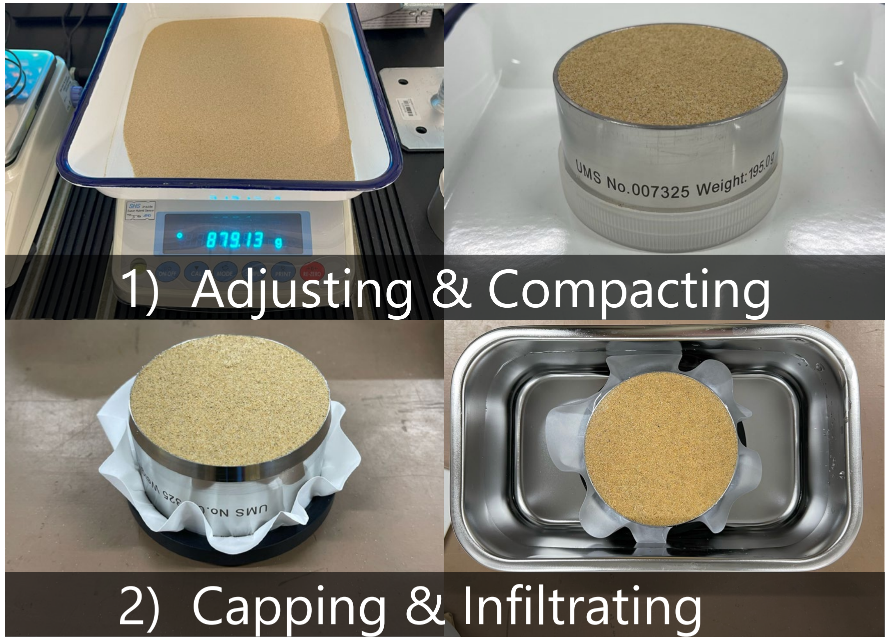




■ SWCCs (water retention properties) measured by HM and PM

Specimen preparation

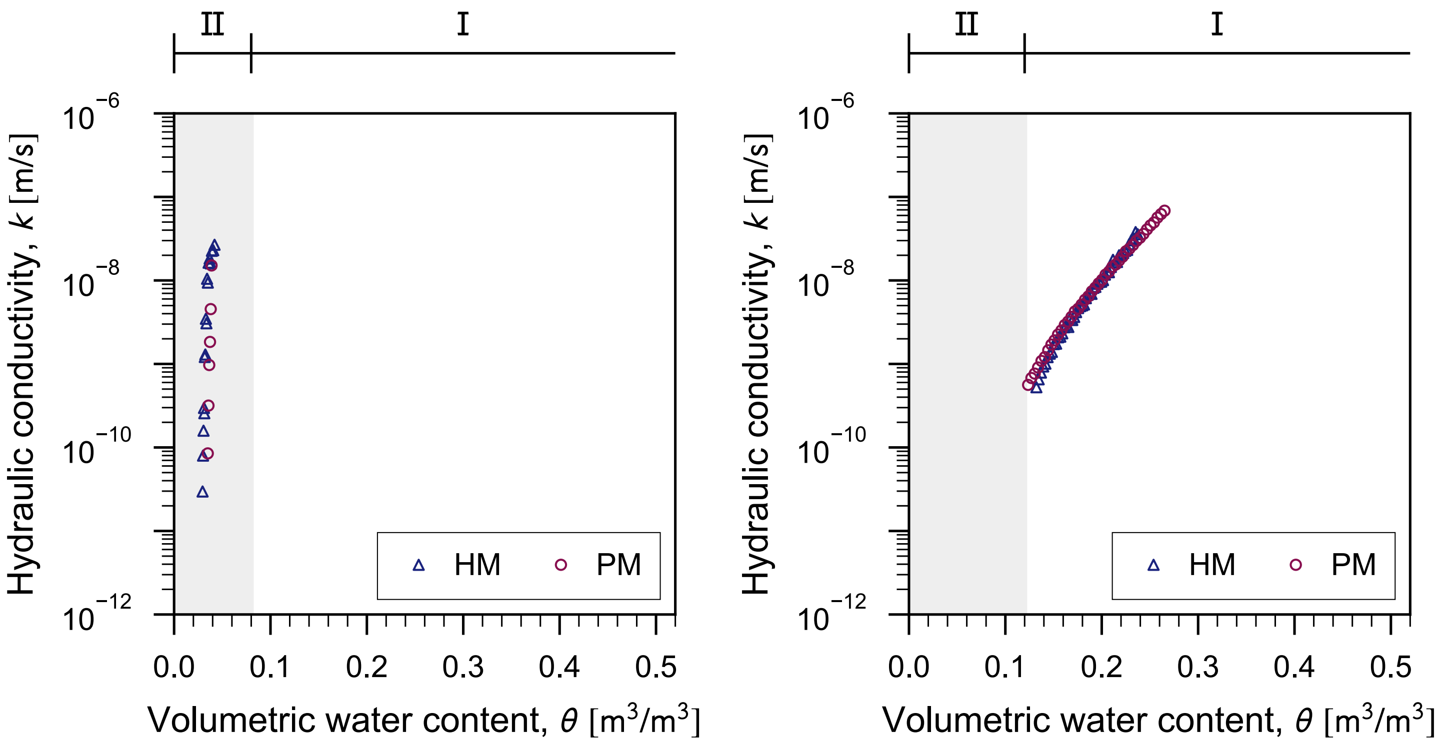
Infiltrate with degassed water for 24 hours



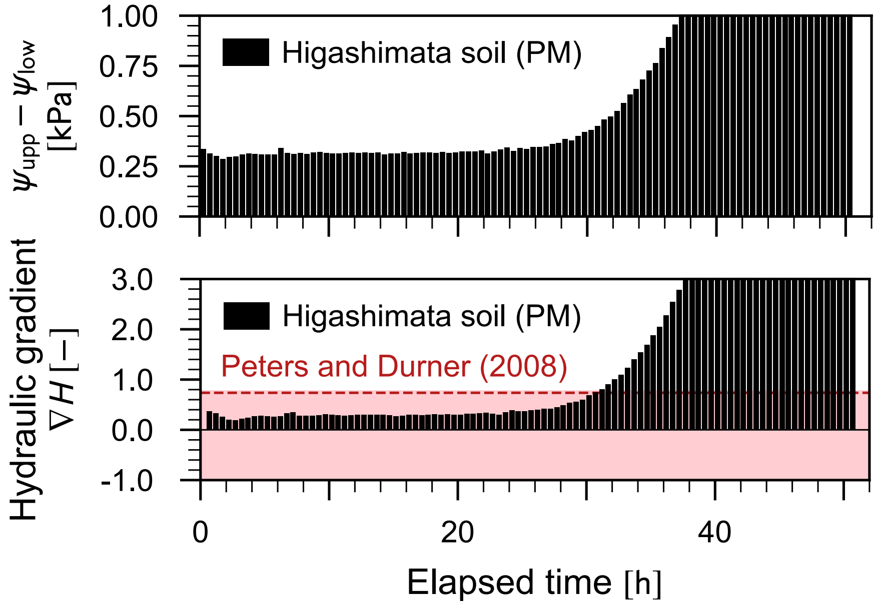
In the rest of the ranges, the results for HM and PM are roughly the same. Therefore, the heat supply to the HYPROP device has little effect on the measurement.

Measurement results: HCF (HM and PM)

Toyoura — Higashimata



■ HCFs (seepage properties) measured by HM and PM

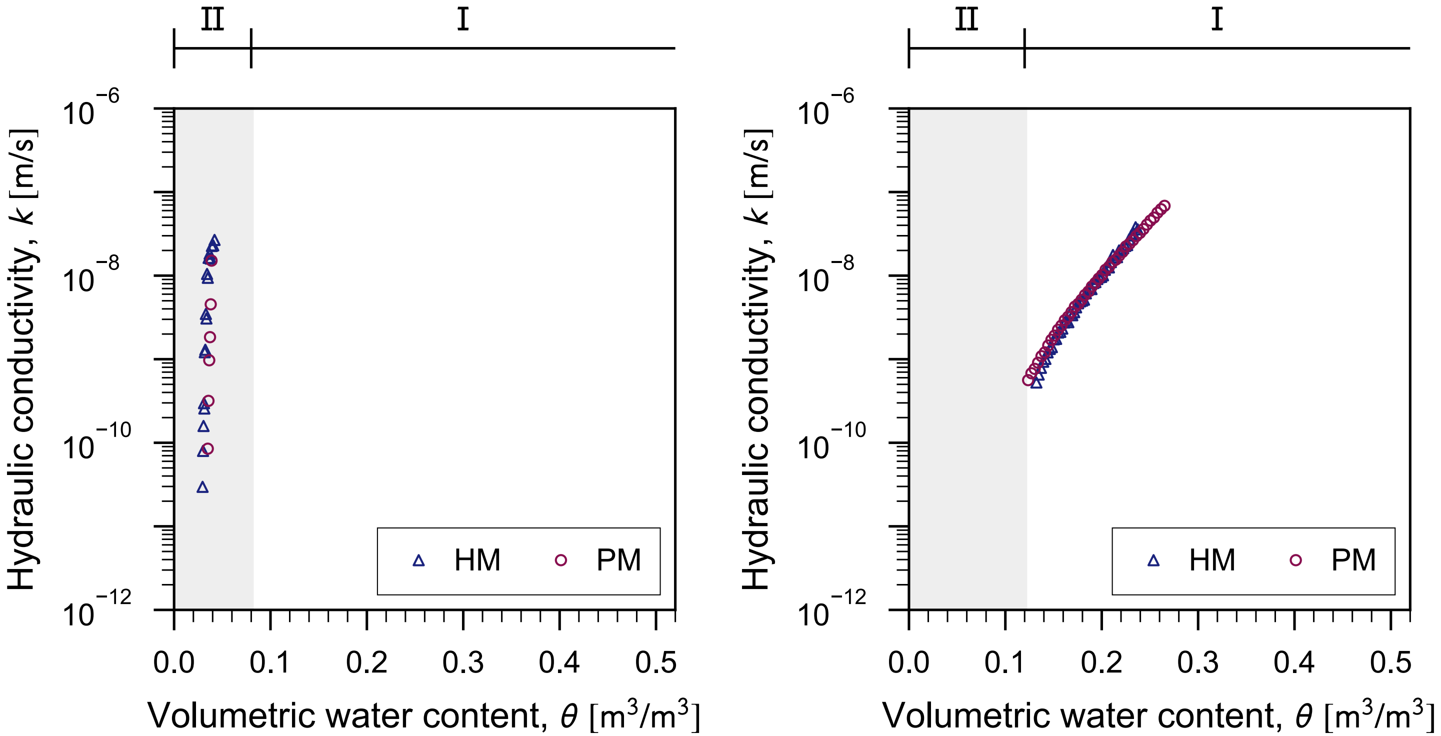


■ Time-series variation in difference between two tensiometers reading (Above) and hydraulic gradient (Below)

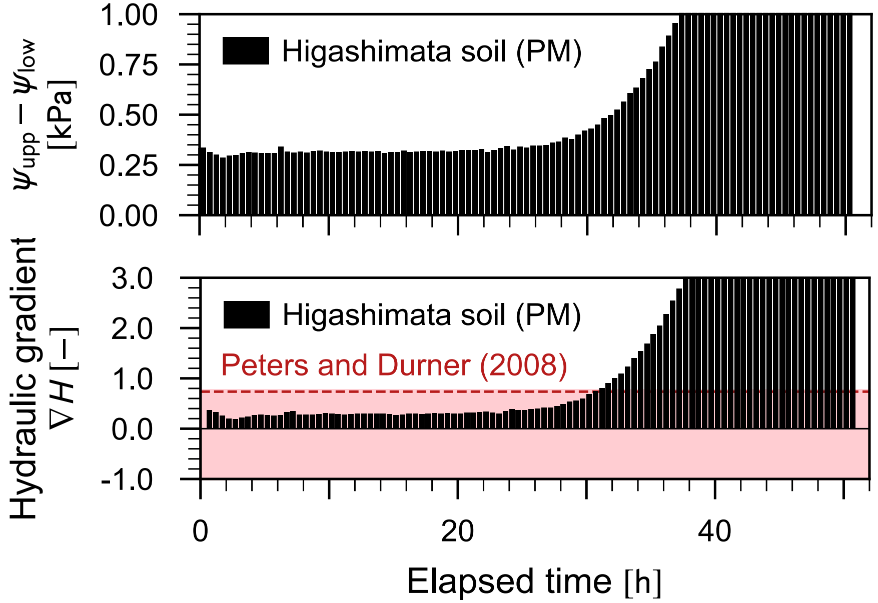
No measured values have been shown for relatively high VWCs. This is due to excluding the less reliable *k* calculated from the hydraulic gradients lower than the criterion value [4].

Measurement results: HCF (HM and PM)

Toyoura — Higashimata



■ HCFs (seepage properties) measured by HM and PM



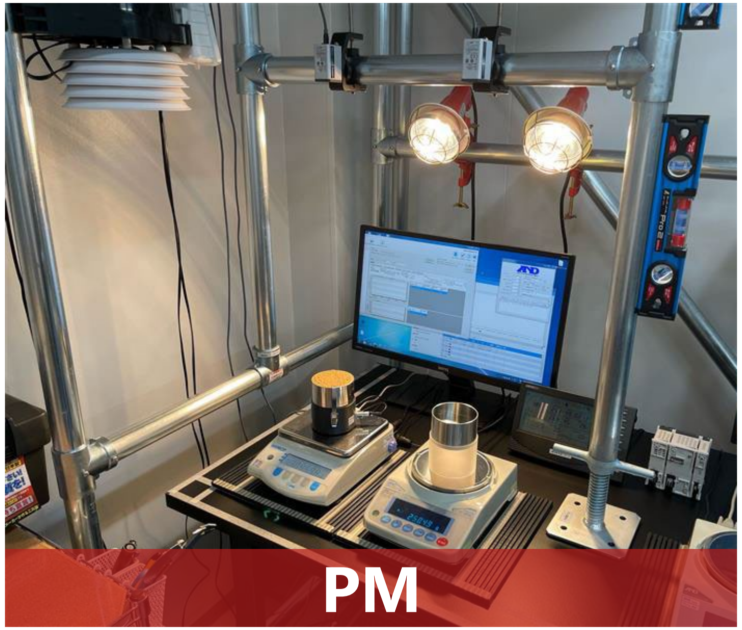
■ Time-series variation in difference between two tensiometers reading (Above) and hydraulic gradient (Below)

Although the VWCs at which k can be plotted varies with soil type, the results for HM and PM are roughly the same. As with the SWCC, the heat supply has little effect on the measurement.

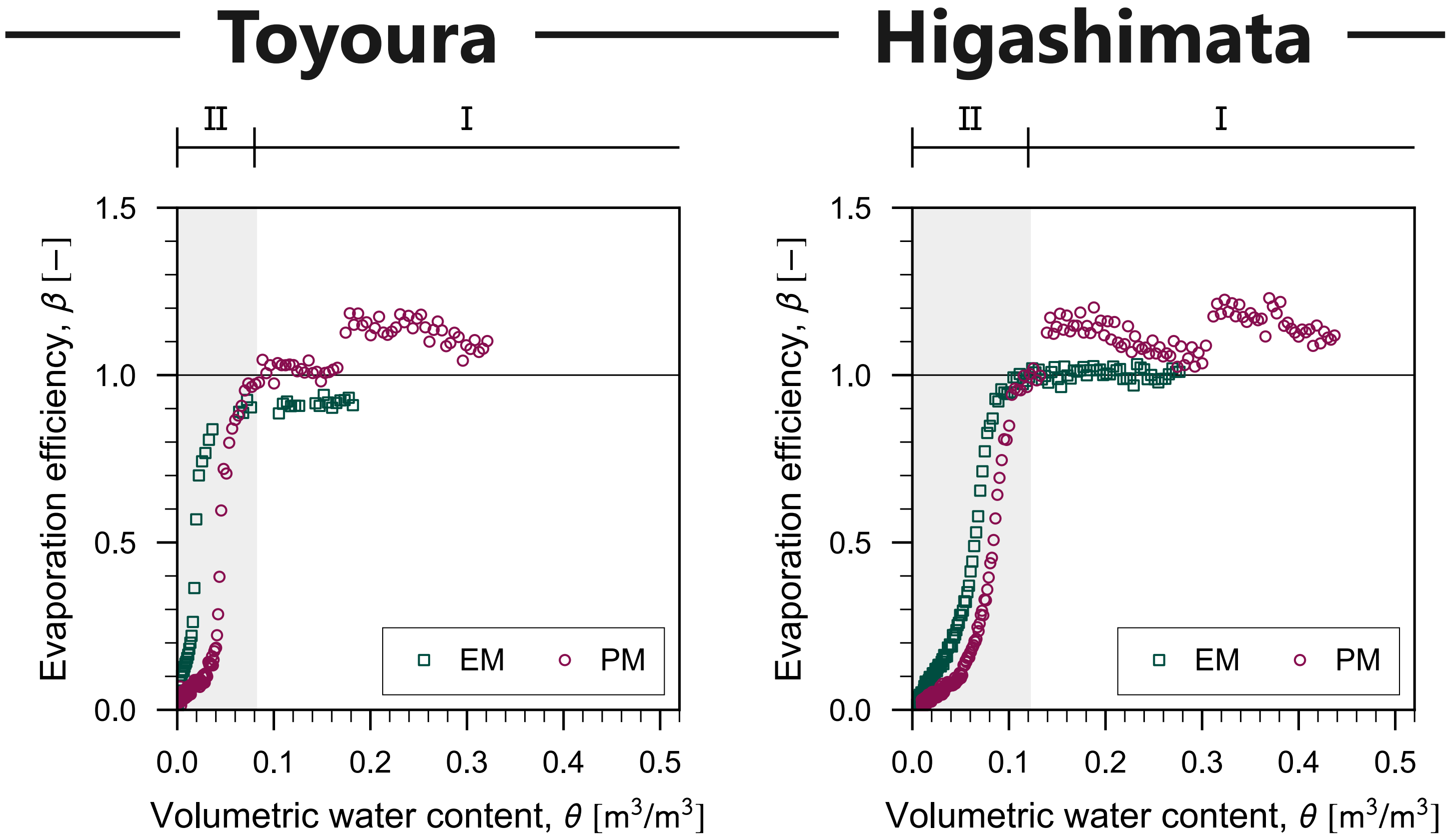
Measurement conditions

■ Measurement conditions and physical properties of the soil samples (the measurements were all taken on different days)

Measurement theory	HM		EM		PM	
Heat supply	×		○		○	
Specimen dimensions	$\varphi 8.0 \times 5.0$ cm		$\varphi 12.65 \times 2.0$ cm		$\varphi 8.0 \times 5.0$ cm	
Soil samples	**Toyoura** sand (sandy soil, with a soil particle density of 2.640 $\mathrm{Mg\ m^{-3}}$) **Higashimata** soil (volcanic sandy soil, with a soil particle density of 2.514 $\mathrm{Mg\ m^{-3}}$)					
	Toyoura	Higashimata	Toyoura	Higashimata	Toyoura	Higashimata
Void ratios e	0.750	1.147	0.750	1.197	0.759	1.220
Initial degree of saturation $S_{r,0}$ [%]	87.66	84.92	58.67	58.19	89.49	89.60



Measurement results: θ and β relation (EM and PM)



■ θ and β relations (evaporation properties) measured by EM and PM

Supplementary note

Exclusion of the unstable data (Jikuya et al., 2024)

For data affected by the unstable environment in the early stages of measurement.

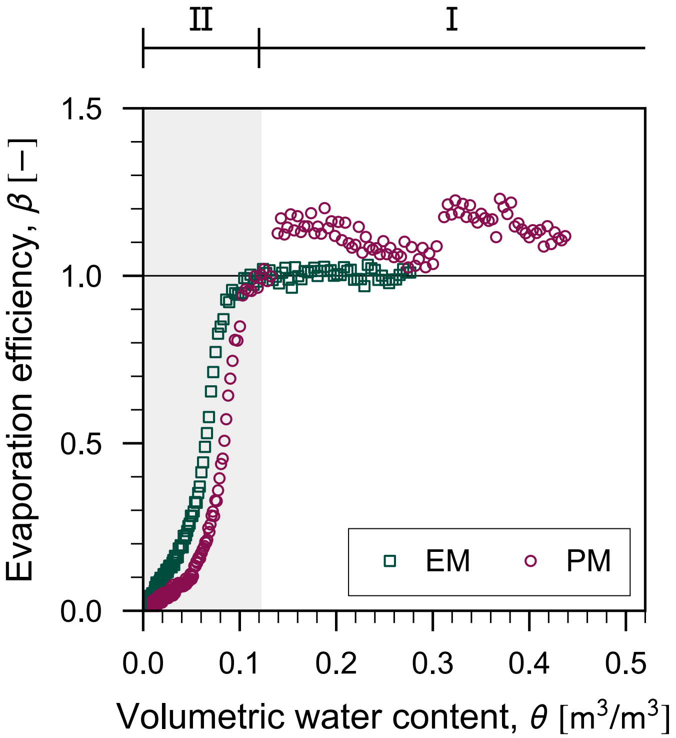
Step-like variation in β

Caused by the changes in water level as a result of refilling the water tank with distilled water.

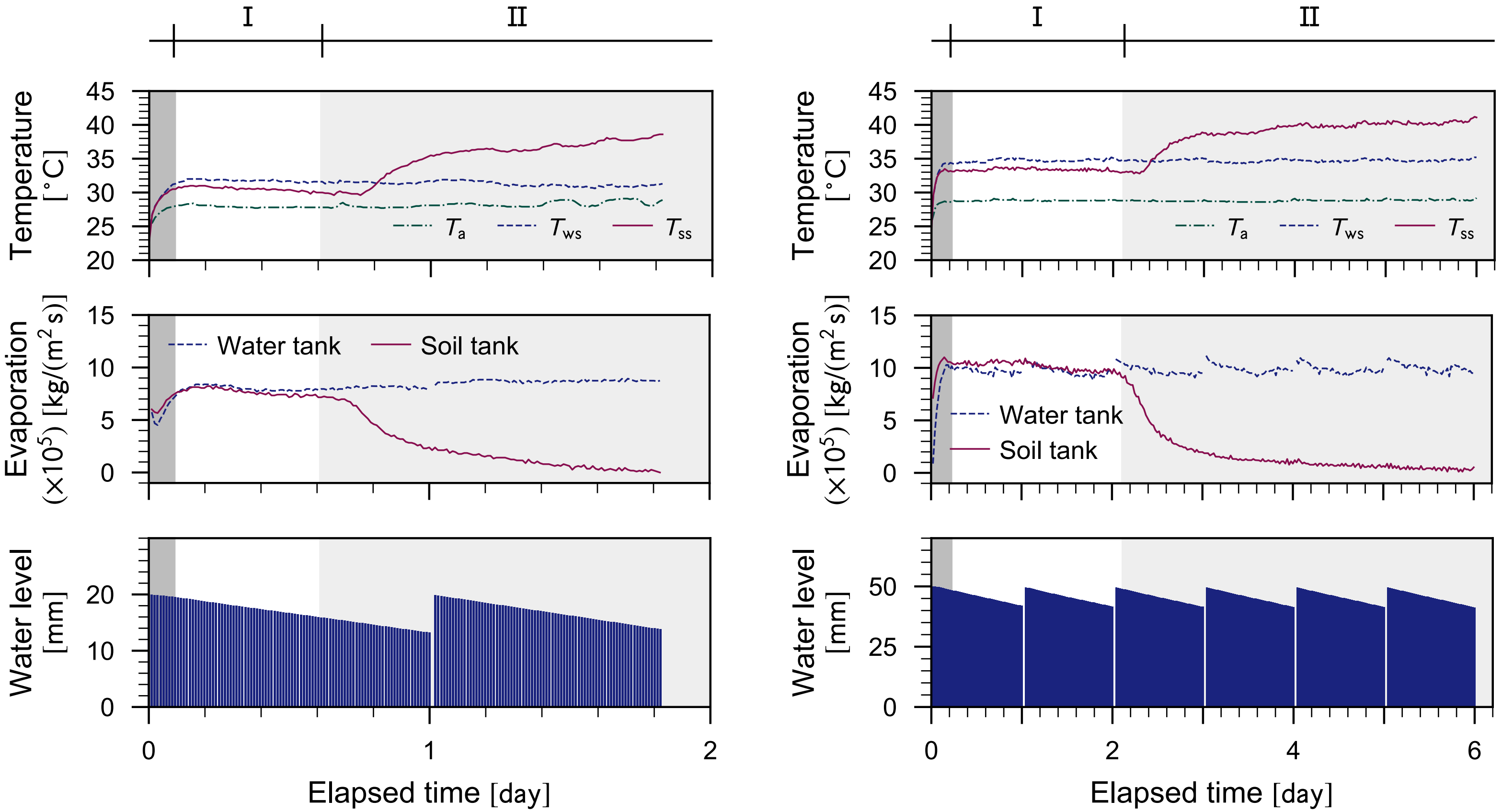
In the range of I, β obtained from the PM is above 1.0, higher than that obtained from the EM. Furthermore, in the PM, β begins to decrease at a slightly higher VWC than the EM.

Measurement results: θ and β relation (EM and PM)

— Higashimata —



■ θ and β relations



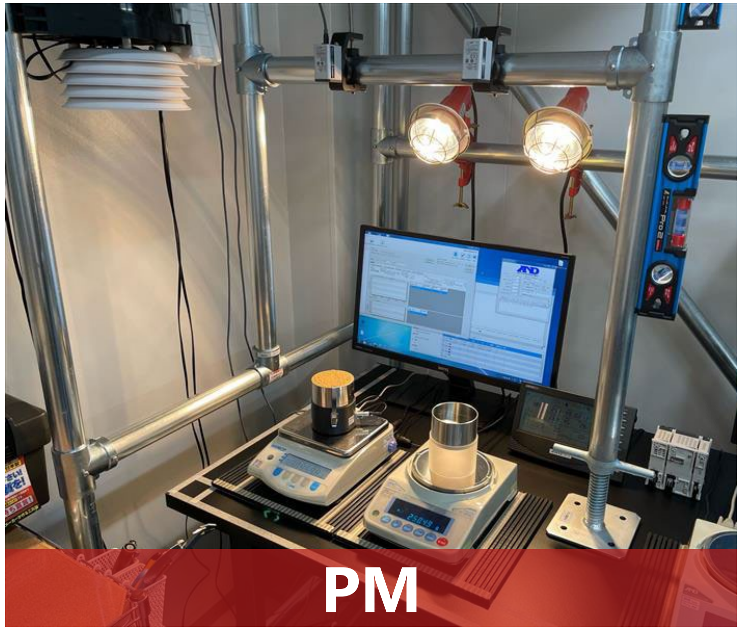
■ Time-series variation in measurement results for Higashimata soil: HM (Left) and PM (Right)

In PM, evaporation from the soil tank is relatively easy. So, β is estimated to be above 1.0. The timing when β begins to decrease is expected to be related to the moisture content distribution.

Measurement conditions

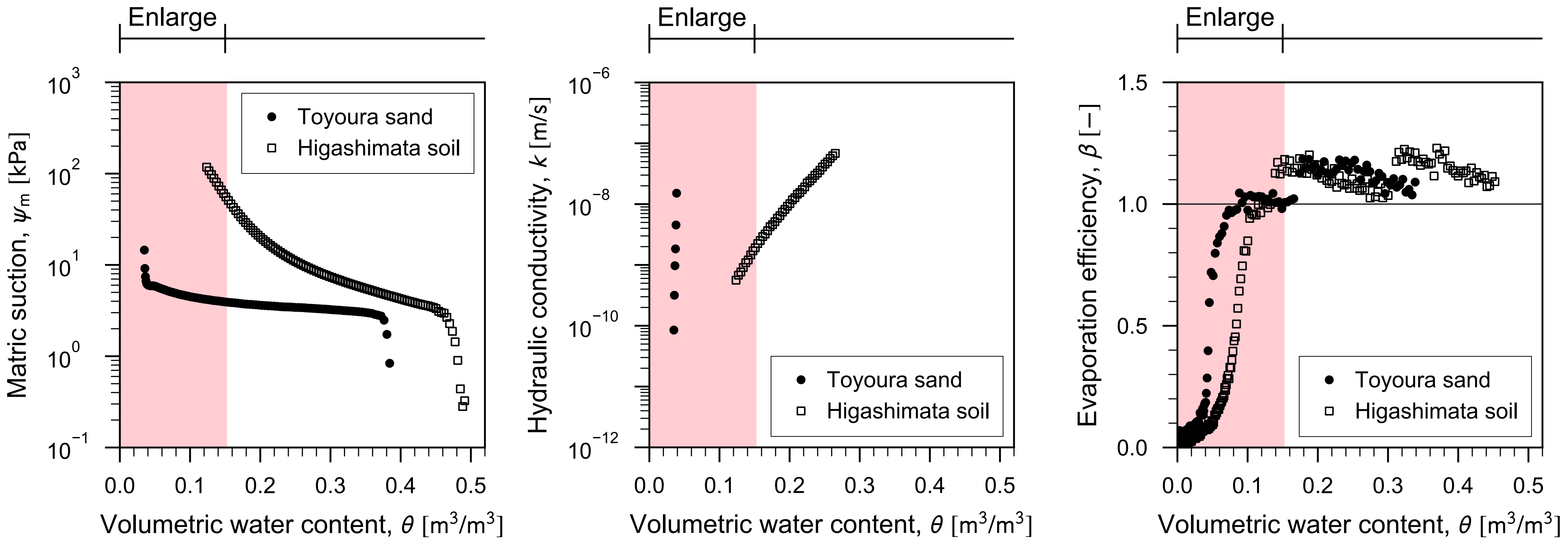
■ Measurement conditions and physical properties of the soil samples (the measurements were all taken on different days)

Measurement theory	HM		EM		PM	
Heat supply	×		○		○	
Specimen dimensions	$\varphi 8.0 \times 5.0$ cm		$\varphi 12.65 \times 2.0$ cm		$\varphi 8.0 \times 5.0$ cm	
Soil samples	**Toyoura** sand (sandy soil, with a soil particle density of 2.640 $\mathrm{Mg\ m^{-3}}$) **Higashimata** soil (volcanic sandy soil, with a soil particle density of 2.514 $\mathrm{Mg\ m^{-3}}$)					
	Toyoura	Higashimata	Toyoura	Higashimata	Toyoura	Higashimata
Void ratios e	0.750	1.147	0.750	1.197	0.759	1.220
Initial degree of saturation $S_{r,0}$ [%]	87.66	84.92	58.67	58.19	89.49	89.60



Simultaneous measurement results

SWCC — HCF — θ and β relation

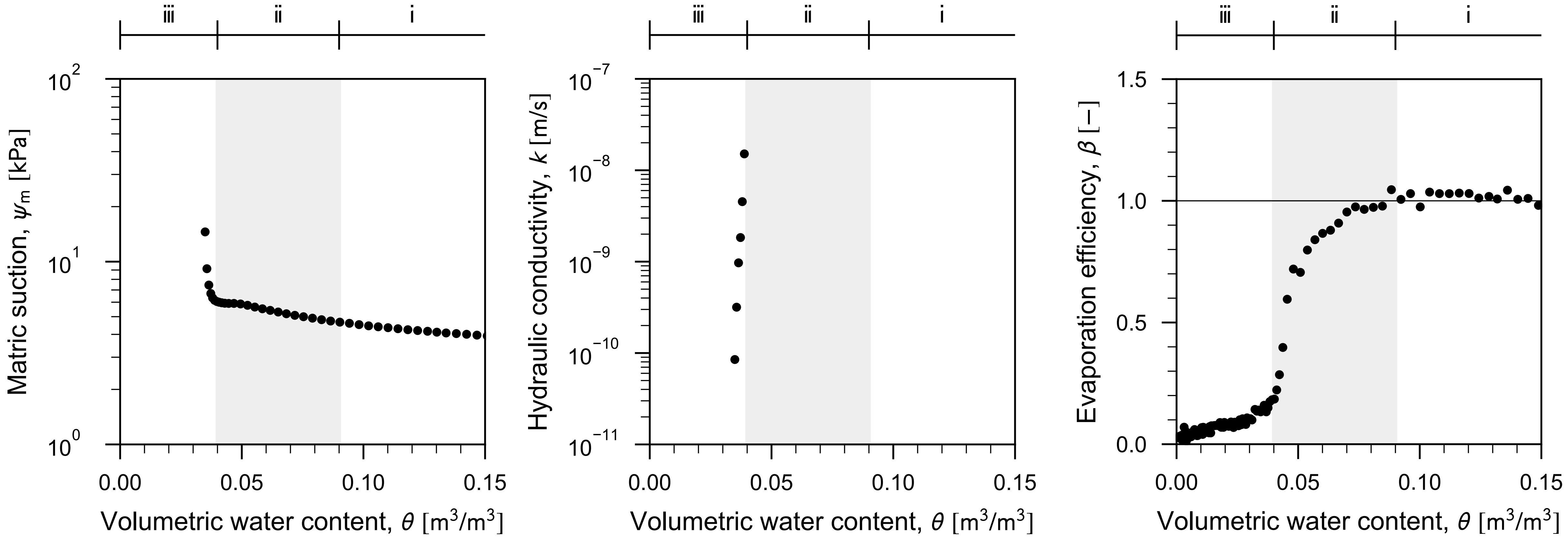


■ Simultaneous measurement results of SWCC, HCF, and θ and β relation for Toyoura sand and Higashimata soil

Focusing on the low-VWC region of Toyoura sand, the trend of β is discussed in relation to the SWCC and HCF.

Simultaneous measurement results: Toyoura sand

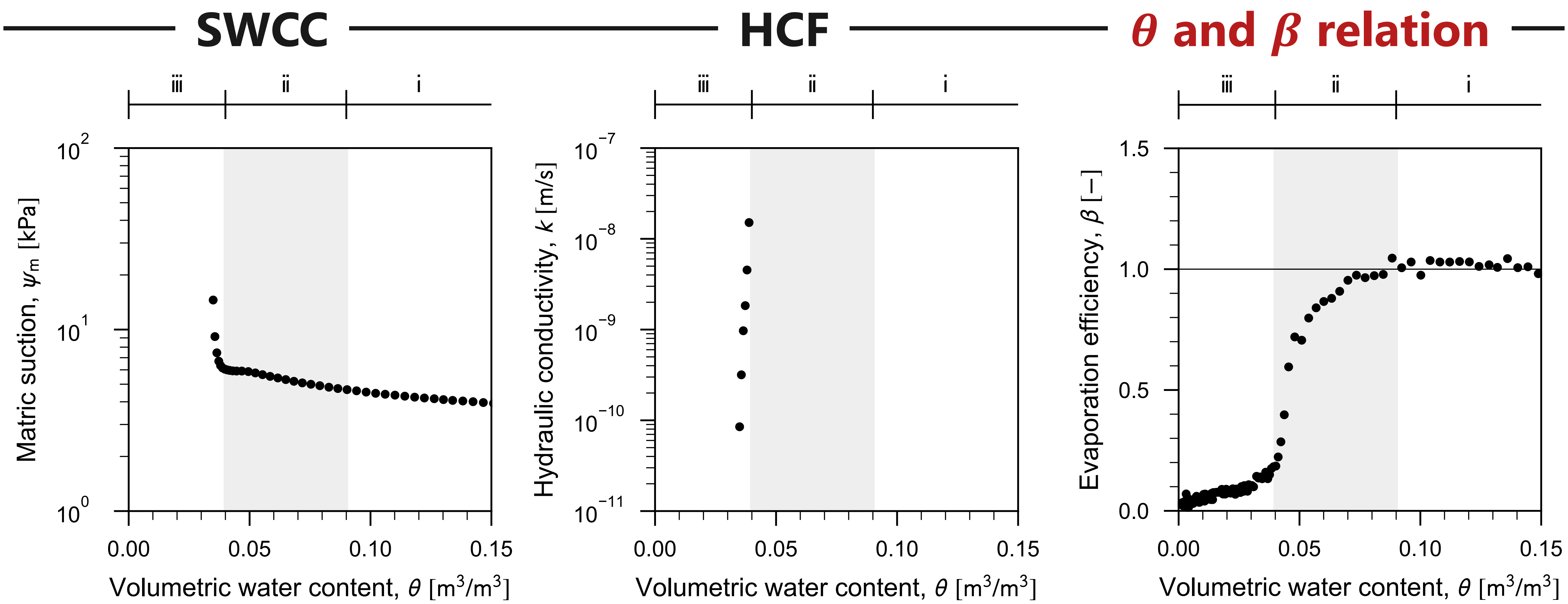
SWCC — **HCF** — **θ and β relation**



■ Simultaneous measurement results of SWCC, HCF, and θ and β relation for Toyoura sand (enlarged range in low-VWCs)

The θ and β relation can be divided into three trends:
i) β is stable, ii) β is rapidly decreasing, iii) β is slowly decreasing.

Simultaneous measurement results: Ranges of i - ii

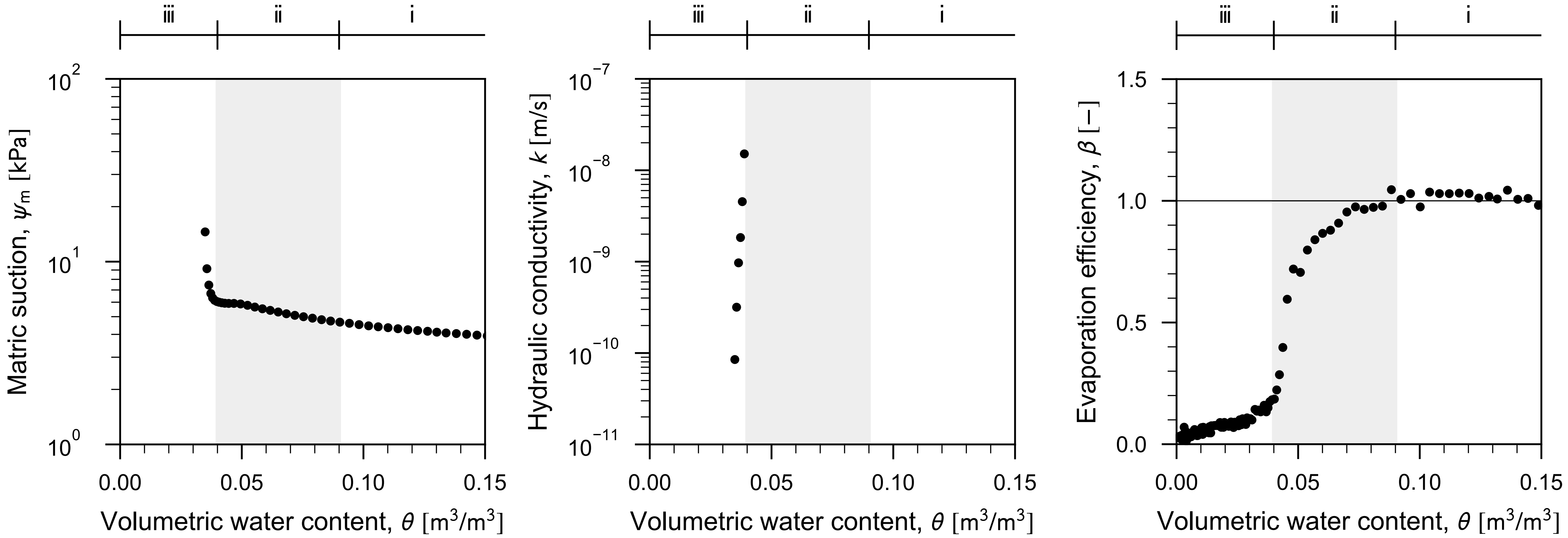


■ Simultaneous measurement results of SWCC, HCF, and θ and β relation for Toyoura sand (enlarged range in low-VWCs)

No clear relation could be confirmed to the SWCC and HCF for the timing at which β begins to decrease.

Simultaneous measurement results: Ranges of ii - iii

SWCC — HCF — θ and β relation



■ Simultaneous measurement results of SWCC, HCF, and θ and β relation for Toyoura sand (enlarged range in low-VWCs)

The boundary of the ranges of ii and iii, the SWCC rises sharply. So, this boundary is expected to correspond to the residual VWC.

Conclusions

Purpose: To discuss the evaporation efficiency functions based on the SWCC and HCF obtained from identical specimens.

1) **A method for the simultaneous measurement**
   - **Heat supply to the HYPROP device:** It was found to have little effect on the SWCC and HCF measurements.
   - **Difference in the specimen dimensions:** The β of the simultaneous measurement method began to decrease earlier than that of the previous method, and that it had been over-measured up to that point.
2) **The trends in the θ and β relation**
   - It can be divided into three major ranges, and it was suggested that these trends correspond to the residual VWC (the residual zone of the SWCC).

Remaining questions: What is the relationship between the moisture content and the SWCC and HCF when the β begins to decrease?

Thank you for your attention.

References

1) Japan Institute of Construction Engineering (2012):
Guideline for structural Investigation of River Levees (in Japanese).
2) Kondo, J., Saigusa, N., Sato, T. (1990):
A parameterization of evaporation from bare soil surfaces, *J. Appl. Meteor.*, Vol. 29, Issue 5, pp. 385-389.
3) Jikuya, Y., Sako K., Ito, S. (2024):
Study on the calculation method of evaporation efficiency in bulk method considering the difference in heat capacity between soil and water, *Japanese Journal of JSCE*, Vol. 80, Issue 15 (in Japanese).
4) Peters, A., Iden, S. C., Durner, W. (2015):
Revisiting the simplified evaporation method: Identification of hydraulic functions considering vapor, film and corner flow, *J. Hydrol.*, Vol. 527, pp. 531-542.