Original Article

Investigation of volcanic deposits using a combined penetrometer-moisture probe : Application in Izu-Oshima Volcano, Japan

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A combined penetrometer-moisture probe (CPMP) was used to determine the structures of layers of volcanic deposits with differing permeability on the volcanic hillslopes of Izu-Oshima Island, Japan. Here, heavy rainfall in 2013 caused shallow landslides due to the hydrogeomorphological structure of the soil mantle. In these volcanic areas that are prone to landslides, accurate determination of the detailed structure of deposit layers with differing permeability is crucial as it would enable us to predict the depth at which pore water pressure could increase and where slip surfaces could be formed. Profiles of volumetric water content, θ , measured using the CPMP, successfully detected strata of deposits consisting of pure and alternating layers of loess, ash, and scoria regardless of the measurement date, point, and depth. Those different types of deposits clearly showed the different order of values of saturated hydraulic conductivity, K_s . We also demonstrated that K_s profiles of interlayered deposits could be determined using an identical relationship between θ , measured by the CPMP, and K_s for all types of deposit on the slope within a particular range of soil moisture, excluding extremely wet or dry conditions. This is because the variations in θ values for each deposit type according to the quantity of antecedent precipitation were small, except in saturated or near-saturated conditions. However, for determining strata deposit types, CPMP profiles of penetration resistance, N_c , may be considered a supplementary index.

Key words: CPMP, volcanic deposit, shallow landslide, hydraulic conductivity, slip surface

1. INTRODUCTION

On 15 – 16 October 2013, Typhoon No. 26 (Wipha) struck Izu-Oshima Island, bringing record-breaking levels of rainfall (24-h precipitation > 800 mm) and causing landslides that resulted in more than 40 casualties from debris downstream [Ishikawa *et al.*, 2014].

Shallow landslides in the large upstream area of the Okanazawa watershed were a major cause of the disaster. The Mount Miharayama volcano is located on Izu-Oshima Island and the collapsed slopes of the upper Okanazawa watershed consist of alternating layers of tephra (containing ash and scoria) and loess deposits, formed by a series of eruptions that occurred in historic times [Koyama and Hayakawa, 1996]. The

tephra was deposited by eruptions and the loess is eolian dust that accumulated during the intervening periods.

Some reports suggest that the landslides are attributable to the peculiar geology of volcanic regions as follows. The depth of slip surface is 0.5 – 2.0 m and generally less than 1.0 m, which corresponds to the upper surface of the loess layers. The loess layers act as a hydraulic aquiclude, leading to an increase in pore water pressure within the upper soil layers during heavy rainfall [Ministry of Land, Infrastructure, Transport and Tourism, Japan, 2015]. Hotta *et al.* [2016] studied the upper Okanazawa watershed and observed significant increases in pore water pressure at the outside edge of a landslide. These increases occurred during heavy rainfall and in the upper part of

the loess layer covered with tephra, approximately 90 cm below the ground surface layer. This is consistent with the observation that the slip surface occurs on the loess layer. The inherent characteristics of tephra strata are conducive to landslides in volcanic regions. Shimizu *et al.* [2016] reported that shallow landslides on hillslopes in Aso Volcano, Japan, in July 2012, could be caused by perched groundwater during heavy rainfall as well due to the layer composed of silty soil, which was covered with tephra deposits, acting as an aquiclude. These reports suggest that common mechanisms may govern subsurface water behavior and slope stability in volcanic regions where the soil consists of significantly different layers (e.g., tephra fall and loess deposits).

Therefore, in volcanic areas that are prone to landslides, determining the detailed structure of interlayered deposits with differing permeability is crucial. This would enable us to predict the depth at which pore water pressure could increase and where slip surfaces could be formed. However, detailed investigations of soil structure by excavating trenches, collecting soil samples, and performing laboratory tests is difficult. Characterizing the soil structure in a slope requires sampling at many locations because the structure of interlayered deposits differs due to spatial variations in tephra and loess accumulation [Koyama and Hayakawa, 1996] and secondary soil movement on a slope.

Yamakawa *et al.* [2010] reported that the combined penetrometer-moisture probe (CPMP), which was developed by Kosugi *et al.* [2009], can simultaneously measure soil water content and penetration resistance of the soil mantle on natural hillslopes. It can also accurately detect alternating sandy, loam, and gravel layers based on differences in soil water content among these layers in situ on a forested slope underlain by granitic bedrock. The CPMP can also determine the structures of interlayered deposits with differing permeability on volcanic hillslopes.

In this study, we validated the capabilities of a CPMP and examined its limitations in detecting strata consisting of soil layers with differing permeability on a volcanic hillslope. We performed penetration tests using a CPMP, measuring soil water content and penetration resistance, and we compared these data with the soil properties of undisturbed samples collected along soil profiles of CPMP tests on a slope in the Okanazawa watershed on Izu-Oshima Island. We also considered the moisture conditions in the soil mantle due to antecedent precipitation, which could affect soil water-content measurements.

2. STUDY SITE

Izu-Oshima Island is located approximately 120 km south of Tokyo (Fig. 1 a). Our test site was located in the upstream region of the Okanazawa watershed, corresponding to an upper section of the outer western slope of the caldera rim (Fig. 1 b and 2). Koyama and Hayakawa [1996] reported that 24 layers of tephra from previous eruptions overlie the slope outside the caldera, which was formed approximately 1450 years ago. We performed field observations, including the CPMP tests and soil-sample collections, on a slope located just outside the upper part of a landslide scarp created in 2013 (Fig. 2 and 3). The gradient of the slope ranges from approximately 33–35 degrees. The basin is covered by forest, which comprises mainly evergreen and deciduous broad-leaved trees. The mean annual precipitation is 2754 mm (1996–2015, Japan Meteorological Agency), most of which falls as rain.

3. METHODS

3.1 CPMP observations

The CPMP consisted of a moisture probe attached to a cone penetrometer (Hasegawa-type penetrometer) [Nishimura *et al.*, 1987] with a 60° bit and a cone diameter of 20 mm (Fig. 4). Operation of the penetrometer involves a 2-kg weight free-falling 50 cm along a guide-shaft to strike a knocking-head that drives the cone into the soil. The penetration resistance, N_c , is computed as the number of blows required for 10 cm of penetration. The moisture probe uses TDR (time-domain reflectometry) to determine the volumetric soil water content, θ . Kosugi *et al.* [2009] showed that θ profiles measured using the CPMP were approximately equal to those measured using a conventional gravimetric method, demonstrating that the CPMP can establish sufficient contact between the

Fig.1 Location of (a) Izu-Oshima Island and (b) the field observation site. A satellite image of the Landsat-8 (provided by GSI, TSIC, AIST, and USGS) and a map published online by the Geospatial Information Authority of Japan were used as the basic image and map for these figures.

Fig.2 Location and topographic maps of (a) landslides and the debris flow area on the outer western slope of the caldera rim in 2013 and (b) the observation points for the soil mantle consisting of volcanic deposits. A topographic map including the area affected by the 2013 disaster [red area in (a)] published online by the Geospatial Information Authority of Japan was used as the basic map for these figures.

Fig.3 Observation site : The landslide scarp produced by the slope failure in 2013 (A, B 1, and B 2 indicate the observation points located at the upper outer edge of the scarp).

waveguides and surrounding soil to provide reliable water-content measurements. TDR 100 and PCTDR software (ver.2.0; Campbell Scientific, Logan, UT, USA) was used for the CPMP θ measurements. Further details of the CPMP system are described by Kosugi *et al.* [2009] and Yamakawa *et al.* [2010].

Simultaneous θ and N_c -profile measurements were performed using the CPMP up to depths of approximately 220 cm at point A, 120 cm at point B 1, and 120 cm at point B 2 (**Fig. 2 b**). The CPMP was applied at point A on 4 September 2014, at point B 1 on 26 May 2015, and at point B 2 on 24 September 2015.

Daily rainfall data were derived from hourly rainfall measurements recorded at the Oshima Station of the

AMeDAS by the Japan Meteorological Agency, located approximately 1.5 km west of the study site (**Fig. 2 a**). As shown in **Table 1**, prior to the CPMP tests, the antecedent precipitation levels for 1 day, 3 days, and 1 week were 0.0, 16.5, and 56.5 mm at point A ; 0.0, 2.5, and 8.0 mm at point B 1 ; and 0.0, 0.0, and 46.5 mm at point B 2, respectively.

3.2 Tensiometer measurements

Between 5 September 2014 and 31 October 2015, we continuously monitored the soil pore water pressure (soil matric pressure head, ψ) at depths of 20, 50, 80, 90, 100, 110, 120, 150, and 200 cm at point A (**Fig. 2 b**) using tensiometers. We located the tensiometers in a small area (within 30 cm of the

Fig.4 Photograph of the combined penetrometer-moisture probe (CPMP), showing the penetrometer rod with a moisture probe near the tip, extension rods, and the weight guide-shaft (revised from Yamakawa *et al.*, [2012]).

Table 1 Antecedent precipitation at points A, B 1, and B 2 before the CPMP tests

Point / Date of the CPMP test	for 1 day (mm)	for 3 days (mm)	for 1 week (mm)
A / 4 September 2014	0.0	16.5	56.5
B1 / 26 May 2015	0.0	2.5	8.0
B2 / 24 September 2015	0.0	0.0	46.5

CPMP position) to compare results with the CPMP measurements at point A. Values (ψ) were recorded at 5-min intervals throughout the observation period using a data logger. Note that observations were suspended during the coldest part of winter (28 December 2014 until 18 February 2015) to avoid freezing temperatures, and ψ values at all depths were frequently lost when the batteries ran out or the data logger malfunctioned between July and October 2015.

3.3 Vertical profile of soil layers and soil property tests

Trenches were excavated to depths of 170 cm (point A) and 120 cm (points B 1 and B 2) to document the

vertical distribution of soil material and validate the CPMP data.

After studying the soil profiles and classifying them into tephra, loess, alternating sublayers of different soil types, etc., we collected soil samples to analyze their water content, saturated hydraulic conductivity, water retention, and grain size. The soil samples were obtained from typical layers of each type. 100-cm³ sample rings were inserted vertically into the soil to collect undisturbed samples. The sampling points were within 15 cm of the CPMP-measurement locations. The soil samples were collected on the dates the CPMP tests were performed, with the exception of point A samples (19 January 2016). We collected two samples at each of 10 depths at point A, two samples at each of 9 depths at point B 1, and three samples at each of 4 depths at point B 2.

Saturated hydraulic conductivity, K_s , was measured with a DIK-4011 permeameter (Daiki, Saitama, Japan) using the constant head test method for high-permeability soil samples and the falling head test method for low-permeability samples. Water content (measured by the gravimetric method), water retention, and grain size were analyzed on samples collected at points B 1 and B 2. For the water retention measurements, the relationship between ψ and θ was calculated using the sand column method for matric pressure head, ψ , values of 0.0, -4.1, -6.1, -10, -16, and -26 cm (corresponding to pF=0.0, 0.4, 0.6, 1.0, 1.6, and 2.5) and the pressure plate method for ψ values of -32, -80, -200, -500, and 1000 cm (pF=1.5, 1.9, 2.3, 2.7, and 3.0). For grain size analysis, coarse fractions were weighed and sieved at 0.075, 0.15, 0.25, 0.425, 0.85, and 2 mm, and fractions <0.075 mm were tested using the sediment method.

3.4 Assessment of the CPMP method used in this study

To validate the capabilities and limitations of the CPMP method for identifying strata consisting of soil layers with differing permeability on a volcanic hillslope, we considered the following, based on the observational data collected in this study :

- Actual soil mantle structures consisting of volcanic deposits.
- Moisture in the soil mantle during the CPMP-test observation periods and soil core sampling.
- Core sample soil properties for different types of deposits.
- Validation of the CPMP test data compared with the strata profiles and the soil properties.
- Reproducibility of the CPMP data for strata consisting of soil layers with differing permeability.
- Suitability of the CPMP method, depending on soil moisture conditions and antecedent precipitations.

Fig.5 Vertical distribution of tephra and loess deposits in cross-sections classified into four categories : (i) loess, (ii) alternating loess and ash, (iii) ash, and (iv) alternating ash and scoria ; and saturated hydraulic conductivity, K_s , (a) at point A, (b) at point B 1, and (c) at point B 2. Each yellow, red, and green bar-shaped symbol indicates the K_s value of a soil core sample and the thick black X marks indicate the geometric mean values of K_s for two or three samples at the same depths.

4. RESULTS

4.1 Soil mantle structures consisting of volcanic deposits

The soil profiles at all three points (A, B 1, and B 2) showed interlayered deposits with differing material characteristics that could be distinguished based on particle sizes. These deposits included loess, ash, and scoria. Throughout points A, B 1, and B 2, there was some visible accumulation of loess, ash, and scoria. Additionally, large sections of the soil profiles consisted of alternating sublayers of these deposits. As shown in **Fig. 5**, we classified the vertical soil mantle structures at each of the three points into four types of deposit : (i) loess, (ii) alternating loess and ash, (iii) ash, and (iv) alternating ash and scoria. The surface layers down to depths of 20–25 cm, which consisted of loess or tephra deposits, corresponded to a root mat layer at each of the three points (**Fig. 5**). We observed some differences in the vertical profiles among these three points. There were several differences even between points B 1 and B 2, although these points were very close together. Similar differences were described by *Koyama and Hayakawa* [1996] and could

reflect spatial variations in tephra and loess accumulation or soil movements on the slope. We observed purple-red colored ash-like materials mixed within some of the layers categorized as (iii) ash and (iv) alternating ash and scoria, and this was also described by *Koyama and Hayakawa* [1996].

At point A, the depth of the landslide slip surface was located 80 cm below the ground surface. This was determined by comparing the depth and soil material at the bottom of the landslide, on which no residual soil remained. The bottom surface was validated easily. The slip surface corresponded to the upper side of the loess layer at a depth of 80 to 107 cm (**Fig. 5 a**). At points B 1 and B 2, the depths of slip surface were estimated as 50–60 cm and 30–50 cm, respectively. However, these measurements were uncertain because points B 1 and B 2 were both located just above the scarp and too far from the base of the landslide. The inconsistencies among the slip-surface depth estimates might be linked to the differences in the vertical soil profiles at the three points.

Koyama and Suzuki [2014] reported that the Y 0.8 to Y 5.2 tephra layers (due to eruptions in the period between 1307 and 1821 [*Koyama and Hayakawa*,

Fig.6 Hyetograph (at Oshima Station of the AMeDAS) and temporal variations in the pressure head, ψ , observed at depths of 20, 50, 90, 110, 150, and 200 cm at point A (a) from 5 September 2014 to 31 October 2015; (b) at the period of the CPMP tests at point A, (c) at point B 1, (d) at point B 2.

1996]) had been disturbed on the outer western slope of the caldera rim during the disaster in 2013. They especially pointed out that the Y 1.0 tephra (due to the eruption in 1777) and layers overlying it, which are underlain by the Y 1.0/Y 2.0 loess (accumulated between the eruptions of 1684 and 1777), were removed as shallow landslides at many places in the upstream area of the Okanazawa watershed in 2013 and that this was the typical mechanism of the landslides in this disaster. The slip surface located at a depth of around 80 cm and underlain by the clear loess layer observed at point A seems to correspond well to the observation result of *Koyama and Suzuki* [2014]. However, we could not confirm a correspondence between the reported stratigraphy and the observed soil profiles at the three points (A, B 1, and B 2).

4.2 Moisture levels in the soil mantle during the observation periods

Throughout the observation period, pressure head (ψ) values at all point – A depths (from 20 – 200 cm below the ground surface) showed typical responses to increased/decreased rainfall (**Fig. 6 a**). Generally, we observed negative ψ values at all depths, indicating unsaturated soil layers throughout the entire tensiometer observation period, with the exception of a few large rainfall events that resulted in positive ψ values and saturated soil conditions at some depths (e. g., at the depth of 90 cm on 6 October 2014 and at the depth of 200 cm on 19 August 2015). The values of ψ were usually higher and the responses to rainfall more moderate at greater soil depths. This implies that subsurface water is characterized by relatively quick vertical infiltration of rainwater into the deeper part of the soil mantle and evapotranspiration from the ground

surface, but there is little lateral flow across the bedrock layer on this slope. This mechanism is frequently associated with volcanic regions where the shallow soil mantle consists of accumulated volcanic deposits with comparatively high permeability.

On each CPMP test date and soil sampling at points A, B 1, and B 2, the ψ values at all depths were estimated as within the range of -110 to -20 cm, based on the ψ observations recorded at point A. However, there were no ψ data corresponding to the date and time of the field tests at point A (4 September 2014) and B 2 (24 September 2015) (Fig. 6). Furthermore, the ψ values at depths shallower than 150 cm, which corresponded to the depth range for almost all soil core samples collected at the three points (except for the deepest samples at point A : 152 – 157 cm), were estimated as within the range of -110 to -40 cm.

4.3 Soil properties of core sample deposits

4.3.1 Saturated hydraulic conductivity

Saturated hydraulic conductivity values, K_s , varied significantly but were clearly linked to the different loess and tephra materials (Fig. 5). Core samples from the (i) loess layers at depths of 80 – 107 cm and 114 – 139 cm at point A, and 105 – 120 cm at point B 1 had low K_s values that ranged from 10^{-4} to 10^{-5} cm/s, although those at depths of 95 – 120 cm at point B 2 were 10^{-3} cm/s. In contrast, samples from layers categorized as (iv) alternating ash and scoria indicated relatively high K_s values of 10^{-2} cm/s. The K_s values of most other samples were intermediate between those from the categories of (i) loess and (iv) alternating ash and scoria. The K_s values of two or three samples collected at the same depth varied by approximately one order of magnitude at most in some sets of three points (e.g., the set of samples corresponding to layers of (i) loess at 131 – 139 cm and (iii) ash at 139 – 148 cm at point A) (Fig. 5 a). Nevertheless, we observed that the geometric mean K_s values of samples taken from the same depth (i.e., geometric mean K_s values of two or three samples with the same types of deposit) showed a consistent relationship : (i) loess < (ii) alternating loess and ash < (iii) ash < (iv) alternating ash and scoria.

4.3.2 Grain-size distribution characteristics

Fig. 7 shows grain-size accumulation curves for all core samples at points B 1 and B 2. The grain-size distribution characteristics varied significantly, but the curves of two or three samples collected at the same depth (i.e., the set of samples indicated by the lines of the same colors in each graph) were approximately the same in almost all of the sets of samples. The results of the grain size analysis demonstrated that the

Fig.7 Grain-size distributions of tephra and loess deposits (a) at point B 1 and (b) at point B 2. Figures in the legend indicate deposit type and depth of top and bottom end of the 5-cm-tall samplers of 100 cm³.

Fig.8 Observed water retention ($\psi - \theta$) data and functional $\psi - \theta$ curves fitted using a lognormal distribution model in the range $-1000 \leq \psi \leq 0$ cm (a) at point B 1, (b) at point B 2 and $-300 \leq \psi \leq 0$ cm (c) at point B 1 and (d) at point B 2. Figures in the legend indicate deposit type and depth of top and bottom end of the 5-cm-tall samplers of 100 cm³.

percentage of fine particles decreased in the following order: (i) loess, (ii) alternating loess and ash, (iii) ash, and (iv) alternating ash and scoria for the samples collected at points B 1 and B 2 (**Fig. 7**). The average D_{50} (50% pass particle size) values for samples from (i) loess, (ii) alternating loess and ash, (iii) ash, and (iv) alternating ash and scoria were 0.100, 0.121, 0.136, and 0.321 mm, respectively. However, soil samples from (iii) ash at point B 1 showed some variations in grain-size distribution, as shown in **Fig. 7 a**.

4.3.3 Water retention characteristics

Fig. 8 shows $\psi - \theta$ values observed within the ranges $-1000 \leq \psi \leq 0$ cm and $-300 \leq \psi \leq 0$ cm. The observed retention data (in the range $-1000 \leq \psi \leq 0$ cm) were fitted successfully using the lognormal distribution model [Kosugi, 1996]. The $\psi - \theta$ relationships also varied significantly, but the relationships of two or three samples collected at the same depth (i.e., the set of samples indicated by the lines of the same colors in each graph) were approximately the same in almost all of the sets of samples, with some exceptions (e.g., at the depths of

23–28 cm and 57–62 at point B 1). For the core samples collected at points B 1 and B 2, the $\psi - \theta$ relationships showed a tendency for θ values corresponding to any ψ value to decrease in the following order: (i) loess, (ii) alternating loess and ash, (iii) ash, and (iv) alternating ash and scoria (**Fig. 8**), although the magnitude of these relationships were not always maintained under saturated or near-saturated conditions. However, samples corresponding to layers classified as (iii) ash at point B 1 showed significant variations in $\psi - \theta$, as they did in grain-size distribution (**Fig. 7 a**).

4.3.4 Volumetric water content

The θ values for soil profiles at points B 1 and B 2, measured gravimetrically, also varied significantly (0.1–0.6; **Figs. 9 b and 9 c**). However, the θ values of two or three samples collected at the same depth varied by approximately 0.1 at most (e.g., the set of B 1 samples corresponding to layers of (iii) ash at 75–80 cm); the mean θ values of samples from the same depth showed a relatively consistent relationship: (i) loess > (ii) alternating loess and ash > (iii) ash > (iv)

Fig.9 Vertical profiles of volumetric water content, θ , (indicated by the blue lines) and penetration resistance, N_c , (indicated by the brown lines) measured using the CPMP method, and θ values measured gravimetrically (a) at point A on 4 September 2014, (b) at point B 1 on 26 May 2015, and (c) at point B 2 on 24 September 2015. Each yellow, red, and green bar-shaped symbol indicates θ values of a soil core sample and the thick black X marks indicate the arithmetic mean values of θ for two or three samples at the same depths. Background colors indicate the vertical distribution of tephra and loess deposits as in Fig.5.

alternating ash and scoria.

Although the sampling dates for points B 1 and B 2 were different, affecting the number of antecedent precipitations, the rank order of θ values by soil layer was identical. In fact, θ values for the same type of material were similar regardless of date, sampling point, and depth (Figs. 9 b and 9 c).

This result could be explained in terms of $\psi - \theta$ relationships (i.e., water retention characteristics, WRCs) of those different deposits as follows. On the dates of each of the soil sampling as well as CPMP tests at points B 1, and B 2, the ψ values at all depths (20–200 cm below the ground surface) were estimated as between -110 and -20 cm, and those at depths shallower than 150 cm were between -110 and -40 cm at point A. The moisture conditions at points B 1 and B 2 on each date were considered similar to those at point A. The $\psi - \theta$ relationships from the core samples at points B 1 and B 2 suggested that the θ values corresponding to this range of ψ values (i.e., $-110 \leq \psi \leq -20$ cm or $-110 \leq \psi \leq -40$ cm) would be between 0.1 and 0.6 (Figs. 8 c and 8 d). The

correspondence between these θ values and the observed θ values measured gravimetrically in situ was satisfactory. Furthermore, the $\psi - \theta$ relationships suggested that for this range of ψ values, the variations in θ values for each deposit type are so small that the relationship to the θ values of the core samples will vary little.

4.4 Validation of CPMP test data

4.4.1 Comparison of CPMP test data and strata profiles

Volumetric water content, θ , and penetration resistance, N_c , were measured simultaneously at points A, B 1, and B 2 using the CPMP (Fig. 2 b) to generate the soil mantle profiles shown in Fig. 9.

The θ values measured using the CPMP ranged from 0.1–0.6. A large percentage of each soil profile included layers with θ values of 0.2–0.3. High θ values (0.3–0.6) were occasionally observed and low θ values (0.1–0.2) were rarely observed in each of the three soil profiles.

We observed relationships among the θ values

measured using the CPMP tests and the four types of deposit, as shown in **Fig. 9**. Layers of (i) loess had extremely high θ values (up to 0.5 or 0.6); layers with (ii) alternating loess and ash had relatively high θ values (approximately 0.3); and layers with (iv) alternating ash and scoria had relatively low θ values (approximately 0.2).

Differences in the dates of CPMP tests, reflecting differences in the number of antecedent precipitations at A 1, B 1, and B 2, did not significantly affect the θ values measured using the CPMP. This would be also explained in terms of the WRCs of those deposits, as we already confirmed it about the core samples above. On the dates of each of the CPMP tests at points A, B 1, and B 2, the ψ values at all depths (20–200 cm below the ground surface) were estimated as between –110 and –20 cm, and those at depths shallower than 150 cm were between –110 and –40 cm.

The N_c values measured at all three points (A, B 1, and B 2) were generally less than 20 but local values of up to 60 were observed. We observed some relationships between the N_c profiles and the deposit strata (**Fig. 9**). At points A and B 1, layers of (i) loess and (ii) alternating loess and ash had relatively low N_c values compared with their neighboring (iii) ash and (iv) alternating ash and scoria layers. However, we found no consistent relationship between N_c values and deposit types across the three soil profiles. In fact, high local N_c values that did not correspond to deposit types were observed at points A and B 1. In contrast, N_c values at B 2 never exceeded 10, regardless of deposit type.

4.4.2 Comparison of CPMP test data and soil properties

We compared the gravimetrically measured θ values of core samples at points B 1 and B 2 with the θ values measured at the corresponding depths using the CPMP (**Fig. 10**) and observed a good 1 : 1 relationship ($R^2=0.80$) between averaged θ values at the same depths (i.e., arithmetic mean θ values of two or three samples from the same deposit type). This result indicates that the CPMP method provided reliable soil water content data for the different types of deposit on this volcanic hillslope.

Some of the inconsistencies between the θ values obtained using the core sample tests and the CPMP may be due not simply to slight differences in the measurement positions, but to differences in the methods themselves (i.e., θ measurements using the gravimetric method and the CPMP TDR moisture probe).

Then, the results of the core sample soil property tests (described in section 4.3) indicated, the $\psi - \theta$ relationships (i.e., water retention characteristics,

Fig. 10 Relationship between the θ values of core samples measured gravimetrically and the θ values measured at the corresponding depths using CPMP tests at points B 1 and B 2. Cross symbols indicate arithmetic mean values of θ for two or three core samples at the same depths.

WRCs) were attributable to grain-size distribution characteristics. Grain-size distribution characteristics at the same time would affect K_s values. Consequently, we found a consistent relationship between the different four deposit types (i.e., (i) loess, (ii) alternating loess and ash, (iii) ash, and (iv) alternating ash and scoria) in K_s values and magnitude relation of θ values of those deposits in situ. The reasonable correspondences between θ values by the CPMP tests and the four deposit types could be also attributed to accurate θ measurements by the CPMP in situ.

As a result, the CPMP method is highly suited to determining the structures of interlayered deposits with differing permeability on volcanic hillslopes. However, we must also consider how soil moisture conditions might be influenced by antecedent precipitations; this is discussed below.

4.5 Reproducibility of the CPMP data for strata consisting of soil layers with differing permeability

As shown in **Fig. 11**, there was a negative relationship between core sample θ and K_s values. This is probably due to the correlations among soil parameters discussed in section 4.4. Some of the inconsistencies may be attributable not simply to measurement errors, but also because there is no direct relationship among these parameters. However, these parameters depend on the grain-size distribution characteristics of each type of deposit.

Similarly, as shown in **Fig. 12**, we observed a

Fig.11 Relationship between θ and K_s values of core samples at points B 1 and B 2. Cross symbols indicate arithmetic mean values of θ and geometric means of K_s . The broken line indicates the fitted curve for the mean values. The solid line is Eq. (1) indicated in **Fig.12** for reference.

Fig.12 Relationship between the θ values determined by CPMP tests and K_s values of the core samples at points A, B 1 and B 2. Cross symbols indicate geometric means of K_s . The solid line is Eq. (1).

negative relationship between θ values measured using the CPMP and K_s values measured using the core sample tests at points A, B 1, and B 2. Some of the inconsistencies between these θ and K_s values may be attributable to slight differences in the measurement positions of the CPMP and soil core sample methods, as well as differences in the methods themselves. The slight difference in trend between the two correlations [θ (by core sample)– K_s (**Fig. 11**) and θ (by CPMP)– K_s (**Fig. 12**)] might be due not simply to differences in the data [θ (by core sample)– K_s plots were obtained only for points B 1 and B 2 (**Fig. 11**)], but also to differences between the core sample and CPMP tests, as mentioned above.

We determined the relationship between the θ values obtained using the CPMP, the depths of the core samples, and the geometric means of the K_s values from samples at the same depths (i.e., the geometric means of K_s values from two or three samples from the same type of deposit). The correlation coefficient was high ($R^2=0.85$) and is expressed in the following exponential equation, which is also shown in **Figs. 11 and 12**.

$$K_s = (5.0 \times 10^{-6}) \theta^{-4.974} (1)$$

To formulate the equation, we excluded the B 2 θ (by CPMP)– K_s dataset from the (i) loess layer at depths of 95–120 cm because these K_s values were much higher (10^{-3} cm/s) than those of the other (i) loess samples (**Fig. 5**) and may have been affected by measurement errors. The good correlation between the CPMP θ measurements and K_s values suggests that K_s profiles may be estimated accurately using the CPMP.

We generated K_s profiles for points A, B 1, and B 2 based on θ measurements by using Eq. (1) as shown in **Fig. 13**. By comparing the results with the K_s values measured using the hydraulic conductivity tests, we confirmed that the K_s values estimated using the CPMP θ measurements were accurate for almost all of the profiles.

5. DISCUSSIONS

5.1 Reliability and validity of the CPMP data and soil property tests

We compared the CPMP data with soil properties, including θ values measured gravimetrically, saturated hydraulic conductivity values, K_s , water retention characteristics, and grain-size distribution of interlayered deposits consisting of pure and alternating layers of loess, ash, and scoria. The property parameters, including θ values, which could be affected by the quantity of antecedent precipitation, were similar for the same types of deposit regardless of sampling point, measurement date, or depth. Furthermore, the rank orders of θ values according to

Fig.13 Vertical profiles of estimated K_s (indicated by the light blue line) based on θ measurements using the CPMP method and Eq. (1), and vertical distribution of K_s values measured by hydraulic conductivity tests (a) at point A, (b) at point B 1, and (c) at point B 2. Yellow, red, green, and the thick black symbols indicate K_s values already shown in Fig.5.

deposit type were identical.

These results indicate the availability of θ measurements as an index for detecting the structures of interlayered different deposit materials on volcanic hillslopes. We also validated the CPMP method as suitable for determining the soil water content of those deposits by comparing its results with θ values measured gravimetrically. Consequently, we demonstrated that CPMP θ measurements can effectively determine the structures of interlayered deposits with differing permeability on a volcanic hillslope.

On the other hand, N_c values for the same types of deposit differ according to observation point or depth. Actually, N_c values varied little, not indicating correspondences to the strata of deposits at point B 2. Nevertheless, we could find partially some correspondences between N_c profiles and strata of deposits as in the cases of point A and B 1, where N_c values change along soil profiles. Consequently, for determining strata deposit types, N_c values may be considered a supplementary index.

5.2 Suitability of the CPMP method depending on soil moisture conditions and antecedent precipitations

We could indicate the possibilities to detect the structures of interlayered deposits with differing permeability and furthermore to successfully reproduce the K_s profiles of those deposit layers based on the θ measurements by the CPMP tests on a volcanic hillslope. This might enable us to evaluate the

potential for landslides following heavy rainfall due to local increases in pore water pressure and the differing permeability of deposits. Nevertheless, these methods are based on CPMP θ measurements recorded on different dates and affected by differing quantities of antecedent precipitation. Then, the obtained clear correspondence between θ values and deposit types or $\theta - K_s$ relationship in this study might be attributed to the some appropriate moisture condition of these three days.

Therefore, there are two ways to apply the CPMP method and determine the K_s profile of deposit layers. Within an appropriate range of soil moisture that excludes extremely wet or dry conditions, the θ (by CPMP) - K_s relationship described by Eq. (1) can be used. In this study, for example, the appropriate soil moisture conditions for Eq. (1) included 4132 hours altogether. The conditions $\psi \leq -20$ cm at a depth of 200 cm, $\psi \leq -40$ cm at a depth of 150 cm, and $\psi \geq -110$ cm at all depths (20–200 cm) were satisfied. They accounted for 61.2% of 6750 hours (i.e., 281.2 days) altogether, for which ψ measurements were recorded (Fig. 6 a). The appropriate soil moisture conditions may be judged using antecedent precipitation indices (APIs) and should be investigated in a future study.

Conversely, ψ at all depths did not remain below -200 cm for the entire observation period (Fig. 6 a). The θ values vary less over a smaller range of ψ values (i.e., in drier conditions) as is clear from the $\theta - \psi$ relationships shown in Fig. 8. The corresponding θ values could still be used, even in extremely dry

conditions, to determine the structure of interlayered deposits with differing permeability. Another way to apply the CPMP method would be to use the K_s values previously measured in the core samples after evaluating the deposits based on the θ values. In this case, evaluating the quantity of antecedent precipitation before the CPMP tests would be unnecessary, except for extremely large rainfall events.

6. CONCLUSIONS

In this study, we evaluated the effectiveness of the CPMP method for determining the structures of interlayered deposits with differing permeability on a volcanic hillslope on Izu-Oshima Island, Japan. We conducted penetration tests using a CPMP, and measured volumetric water content, θ , profiles and penetration resistance, N_c , in the soil mantle on a slope in the Okanazawa watershed located just outside the upper edge of a landslide scarp that was created in 2013.

Profiles of θ measured using the CPMP successfully detected the strata of the deposits composed of loess, ash, scoria, and alternations of them regardless of the measurement date, point, and depth. Those different types of deposits clearly showed the different order of values of saturated hydraulic conductivity, K_s . We also showed that the K_s profiles of interlayered deposits with differing permeability could be estimated within a certain range of soil moisture, excluding extremely wet or dry conditions, using the relationship: θ (by CPMP)– K_s . Furthermore, we showed that determining the strata of different types of deposit based on their CPMP θ values was also feasible. In this case, evaluating the quantity of antecedent precipitation before the CPMP tests would be unnecessary, except for extremely large rainfall events. This is because the variations in θ values for each deposit type will vary little.

Conversely, although the N_c profiles showed some correspondence with the different types of strata at each observation point, no consistent relationship could be established. As a result, for determining strata deposit types, N_c values may be considered a supplementary index.

The soil mantle structure with alternating layers that differ in permeability investigated in this study included tephra fall and loess deposits. These structures, found on the outer slope of the caldera rim of the Izu-Oshima volcano, affected the stability of the slope and will also be present on other volcanic hillslopes. Consequently, the CPMP method may be widely applicable for these volcanic hillslopes.

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