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DETERMINATION OF SLIP SURFACES IN FRACTURE ZONE LANDSLIDES USING ORIENTED BOREHOLE CORE SAMPLES

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ABSTRACT: In situ and laboratory observation, geophysical measurement and digital imaging analysis of oriented borehole core samples are performed to determine slip surfaces in two large fracture zone landslides in Shikoku, Japan. The following data are obtained from each oriented borehole: (1) a depth distribution of rock quality designation, magnetic susceptibilities, the Equotip hardness values and wet unit weight of core samples, (2) geometric orientation of geologic discontinuities (cracks, joints, faults, etc.), and (3) a depth distribution of numerical color values from digital imaging of borehole core samples. As a result, the rock quality designation, the Equotip hardness value and unit weight, and the orientation of cracks and joints showed a clear change near the slip surfaces respectively, but the digital color values clearly varied only in one of the landslides and no change of magnetic susceptibility of core samples was found at both sites. The results demonstrate that it is capable of locating the slip surface in a fracture zone landslide by using the above-mentioned data in combination.

Keywords: Oriented Core Sample, Slip Surface, Digital Imaging, Equotip, Magnetic susceptibility, CIELAB

1. INTRODUCTION

The huge numbers of active and potential landslides in Japan are usually divided into three categories, namely Tertiary type, facture zone type and hot spring type of landslides [1]-[2]. Shikoku Island in the southeast part of Japan has been designated as a highly landslide-prone region with a large number of facture zone landslides induced primarily due to tectonic activities. Many of these landslides are in relatively slow movement, some of which were restarted to move rather slowly due to heavy rainfall after a long term stop [3]-[4]. There also are natural slopes in Shikoku region that shows clearly landslide topography but so far there have been no movements to be observed or/and recorded [4]-[5].

An essential part of the investigation of a landslide is the determination of the depth and geometry of the slip surfaces that characterize it. For moving landslides the slip surfaces are easily inferred from data which can be obtained using surface movement observations, direct measurements of sub-surface displacements and geo-acoustic sensing. However, it is difficult to locate the slip surfaces in stationary and/or very slow-moving landslides, to which the above mentioned methods are usually not applicable. The available techniques for slow-moving landslides include direct observation of slip surfaces in exploratory and other excavations and in large diameter boreholes, observations on recovered samples, inference from the contrast in properties between materials above and below a slip surface and sub-surface geophysical techniques [6]-[8]. However, using such methods to find slip surfaces usually requires careful logging of borehole data and certain experiences and skills [7]-[9].

Most of fracture zone landslides in Shikoku are distributed in the two geological strips sandwiched between the three tectonic lines (Fig. 1) [10]-[11]. The fractured state of bedrocks particularly near the tectonic faults and hytrothermal alteration of rock minerals into weaker clay minerals produced highly favorable conditions for landslides in the region. Such geological structures together with weathering of the bedrock minerals result in formation of multi-layers of clayey soil in different depth [10]-[11], and this causes the difficulties in locating slip surfaces for stationary and slow-moving landslides. Usually, it is required to use a number of different techniques in combination for site characterization of landslides in fractured geologic zones [8]-[9], [12].

This paper employed oriented borehole core samples for determining slip surfaces in two large fracture zone landslides (i.e. “A landslide” and “B landslide” in Fig. 1) in Shikoku, Japan. In situ and laboratory observation, geophysical measurement and digital imaging of oriented borehole core samples were performed. It was shown that the slip surfaces in fracture zone landslides could be located using the data obtained from the above techniques in combination.

2. GEOLOGICAL CHARACTERISTICS

Shikoku Island is divided into four strips of geological formations by the three major faults in east-west direction, namely the Median Tectonic Line (also known as *Chuokozosen* which is the longest tectonic fault system in Japan and passes cross Shikoku Island), the Mikabu Tectonic Line and the Butsuzo Tectonic Line (Fig. 1) [13]. Most of the fractured zone landslides in Shikoku region are distributed in the Sanbagawa and Chichibu belts between the three tectonic lines [10]-[11]. The Sanbagawa belt is a deposit of metamorphic rocks consisting mainly of green and black schist, and the Chichibu belt consisting of the three sub-belts forms a narrow strip of the Mikabu green stone as a metamorphic deposit along the tectonic line itself. The rock type in the Chichibu belt is sedimentary composed mostly of green schist, mudstone and conglomerate [10]-[11].

The *A* landslide is located in the Chichibu belt (Fig. 1). This slide occurred just after slope failure and debris flow triggered by the heavy rainfall of typhoon Namtheun in 2004. Fig. 2 shows the slope failure and debris flow site in the *A* area [14], plan view and cross section of the landslide. This huge sliding block was found just above the main scarp, and numerous cracks were observed on the slope above the main scarp just after the event. Surface and borehole investigations of the unstable block suggest that sliding surface reaches depths of up to 50m [14]-[16]. Stabilization works carried out to reduce the movement of the landslide mass are the construction of several water collection wells in the landslide mass for deep drainage. The slip surface observed from the well walls is illustrated in Fig.3. It is seen that the slip surface has developed at or close to the interface between the strong weathering green rock and the underlying bedrock. It is smooth and also exhibits striations or scratches in the down-slope direction. A thin layer of the slip-surface clay was formed along the failure plane where small size round gravel could be occasionally found.

The *K* landslide is located in the south side of the Sanbagawa geological belt (Fig. 1). This huge slide took place in fractured rocks consisting of muddy and basic schist. Due to large scale tectonic activity, the rocks around the landslide area are highly fractured and weathered. Fig. 4 illustrates plan view and cross section of the *K* landslide. The average inclination of the slope surface is 24 degrees. The head of the landslide is located at 950 m above sea level, and the toe is located at 650 m near the Kashio river bed. This slide is divided into a main block and two small blocks in the lower part. The main block slide is structurally controlled and occurred within the weathered muddy schist. The failure planes are located at depths of 10 to 30 m deep for the main block.

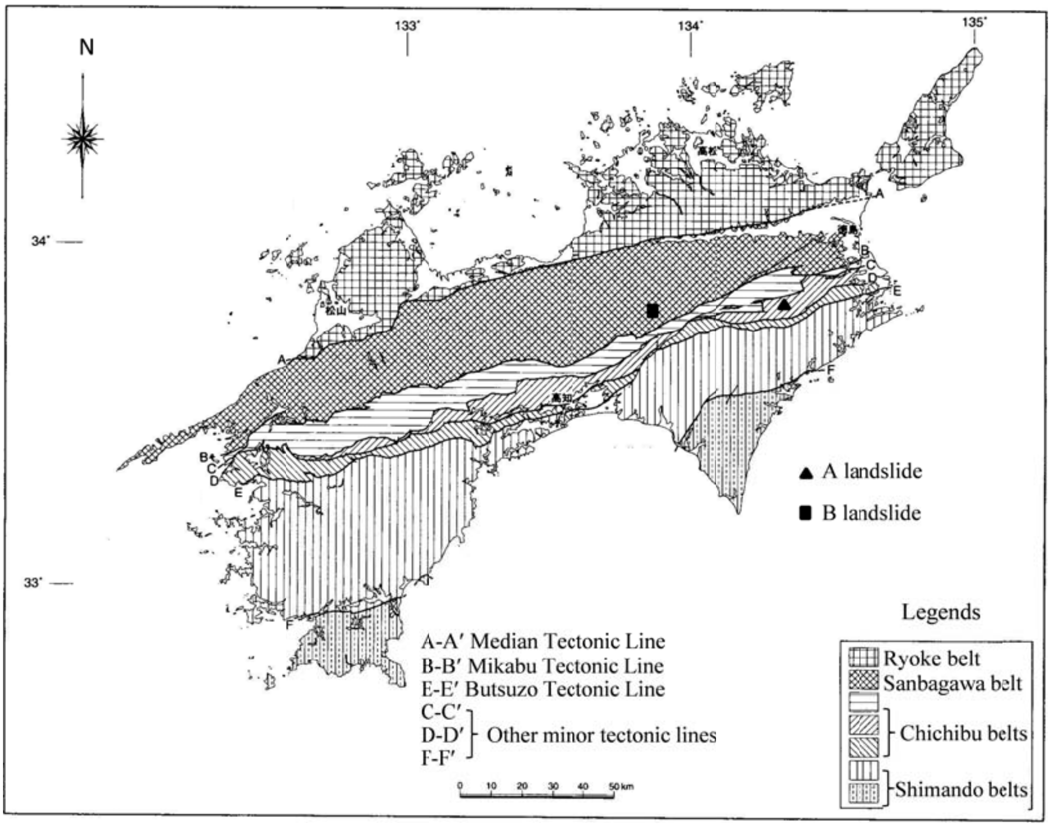
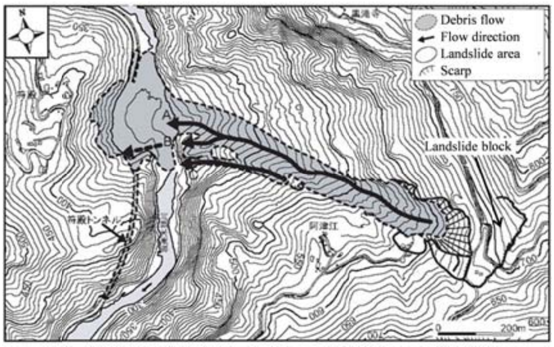
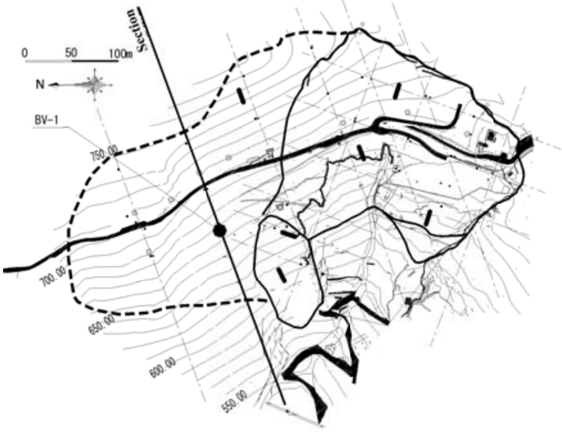


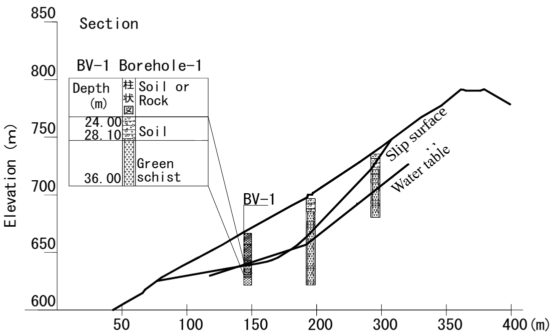
Fig. 1 Map of Shikoku showing major tectonic lines, geological belts and locations of two landslide sites in fracture zones (after [13])



(a) Plan view of the site of slope failure and debris flow in the landslide area [14]



(b) Plan view of the landslide block



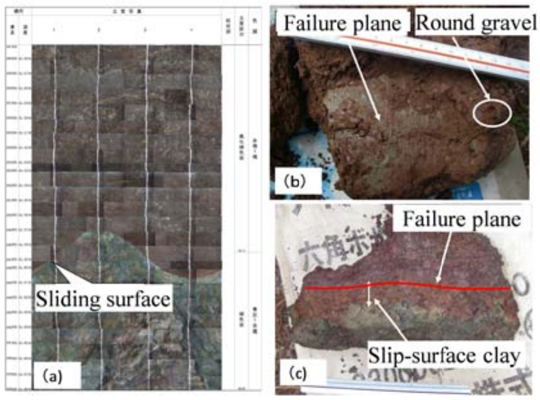
(c) Cross section of the landslide block

Fig. 2 *A* landslide

3. METHODS

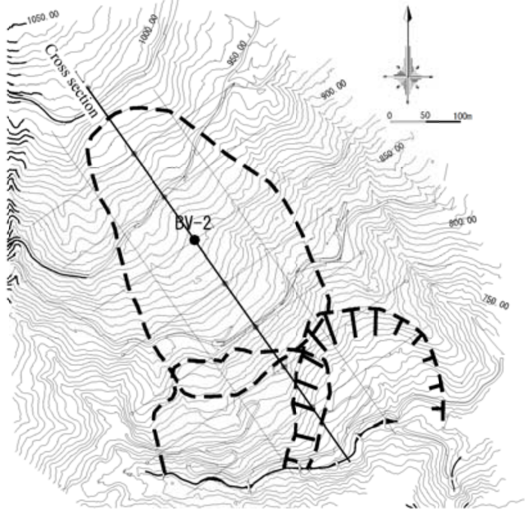
3.1 Obtaining Oriented Core

Oriented borehole core provides data whereby the geometric orientation of geologic discontinueties (joints, cracks, faults etc.) may be determined. An oriented drilling technique and double tube sampling system were employed to obtain oriented core samples [17]-[18]. The system is composed of three parts: dual tube drilling rods, dual tube sampler and a direction fix rod, as shown in Fig. 5. Dual tube sampling uses two sets of probe rods to

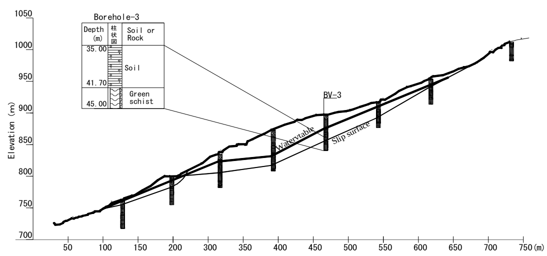


(a) Photograph of the wall of an excavated hole for water collection; (b) Slip surface with striations in downslope direction; and (c) Slip-surface clay along the failure plane

Fig. 3 Slip surfaces observed from the water collection wells in *A* landslide



(a) Plan view of the landslide area



(b) Cross section of the landslide block

Fig. 4 *K* landslide

collect continuous soil rock cores. One set of rods is driven into the ground as an outer casing (tube). These rods receive the driving force from the drilling machine. The other set of rods are placed inside the outer tube. Outer tube rotates and allows for the removal of the cuttings while inner tube is fixed with the inside rod and does not rotate as it is supported by the bearings inside of the joint. The

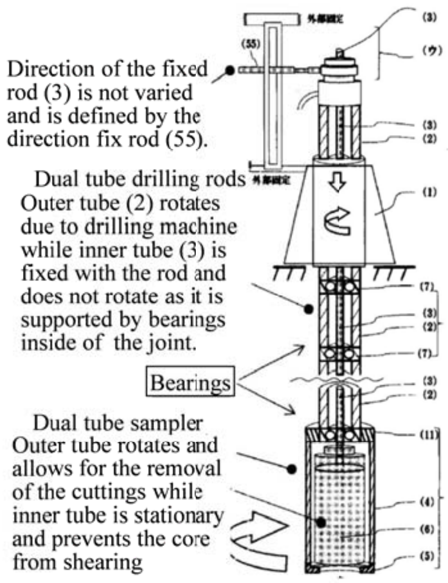


Fig. 5 Drilling/sampling systems used for oriented core samples

direction fix rod is fixed on outer fixing arms and defines direction of the fixed rod together with the inner tube, allowing us to obtain oriented core samples.

3.2 Oriented Core Treatment and Logging

The following steps are carried out for oriented core samples in laboratory:

1) Confirm and re-mark the base line on the core samples showing a known direction.
2) Clean the core of drilling fluids or mud in order to obtain clear photo image of the core outside.
3) Perform observation and sketching of the core through the full length for visual description logs.
4) Determine a new defined parameter called rock quality designation, which will be described in next section later.
5) Measure physical/geophysical properties of the core along the base line, including wet unit weight, magnetic susceptibility and Equotip values.
6) Photograph the core samples by rotating them to obtain oriented, 360° photo image of the outer surface. The digital images such obtained are used later to calculate the orientation of discontinuities and to obtain digital color values.

3.3 Rock Quality & Weathering Grade

3.3.1 Rock Quality Designation (*RQD*)

This parameter (*RQD*) is defined by summing the length of all core pieces more than 5cm long as a percentage of the total core length.

$$RQD(\%) = \frac{Length\ (m)\ of\ \ core\ \ pieces \geq 5cm}{Total\ \ length(m) core run} \times 100\%$$

Double tube sampling system used in this study ensured high quality of the core [17]-[18] and a carful measurement of core pieces more than 5cm long was carried out along the base line marked on the core, as shown in Fig. 6.

3.3.2 Weathering/fracture grade

The weathering/fracture grade is a measure of how the core properties (i.e. strength, mineralogy, etc.) have been changed from their original form. Table 1 shows the suggested weathering/fracture grades and their associated description.

3.4 Geophysical Measurement of Core Samples

3.4.1 Magnetic susceptibility

Magnetic susceptibility measures the 'magnetisability' of a material. In the natural environment around a landslide, the magnetisability tells us about the minerals that are found in rocks, particularly Fe- bearing minerals. It is used to classify different types of materials and to find the subsurface of a landslide [19]-[20]. In this study, magnetic susceptibility of the core was continuously measured along the base line using a KT-10 magnetic susceptibility meter by Terraplus [21]. Its sensitivity is $1{\times}10^{-6}$ SI units with a measurement range of $0.001{\times}10^{-3}$ to $1999.9{\times}10^{-3}$ SI units and an operating frequency of 10 kHz.

3.4.2 Equotip values for rock hardness assessment

The Equotip is an electronic hardness testing device. It was originally designed for testing metals, but it has now been used extensively for testing rock hardness[22]-[24]. An Equotip hardness tester produced by Proceq with a maximum hardness of 940 HV and an accuracy of +4L (+ 0.5%) was used to measure the hardness of the core samples.

Fig. 6 Base line marked on the borehole core

Table 1 Weathering grades and descriptions

Grade	Field (Rocks)	identification (Discontinuities)	Description
W1	Original rock fabric is almost destroyed.	Structural discontinuities are perceived only between interface of W1 & W2.	Fracture structure
W2	Rock fabric is partially destroyed and rock is friable or changed almost to a soil.		
W3	The original fabric of the rock is visible. No clay soil is observed in rocks.	Discontinuities are open and gravel is disposed in cracks along joints etc.	
W4	Rock may be slightly discolored adjacent to discontinuities that partially exist in rock.	Discontinuities are slightly open along bedding joints, etc.	Crack structure

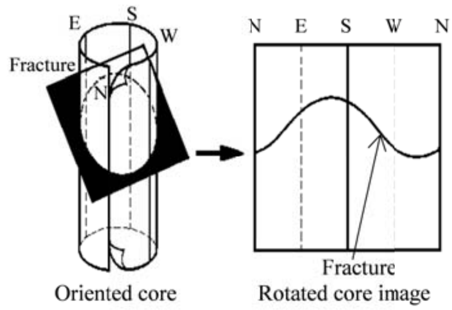
3.5 Digital Imaging Analysis

3.5.1 Geometric orientation of discontinuities

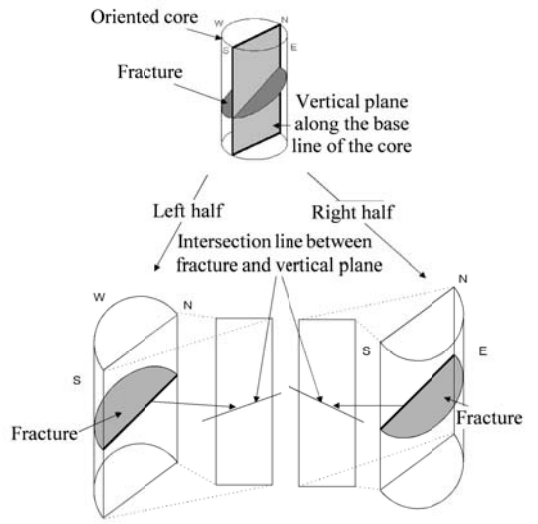
The oriented, 360° photographs of the outside of the core are first treated and displayed as a 2-D image showing the core's entire outer surface. The images are then used to locate and measure the dip and orientation of structural features in the core sample, as shown in Fig. 7. This operation was carried out using the WELL CAD software [25].

3.5.2 Color values based on CIELAB model

CIELAB is an opponent color system based on the system of Richard Hunter [26]. This system indicates distinctions between light and dark, red and green, and blue and yellow by using numerical values with three axes: L^*, a^*, and b^*. The L^* axis represents lightness whose values run from 0 (black) to 100 (white). As a color can't be both red and green, or both blue and yellow (because these colors oppose each other), the values run from positive to negative on the a^* or b^* axes. On the a^* axis, positive values indicate amounts of red while negative values indicate amounts of green. On the b^* axis, yellow is positive and blue is negative. For both axes, zero is neutral gray. Therefore, values are only needed for two color axes and for the lightness or grayscale axis (L^*). CIELAB color system is device independent and become a very popular color model in practice. We used a SPAD-503 device for color measurement to obtain values of L^*, a^*, and b^* for the core samples.



(a) Oriented 360° core and rotated core image



(b) Calculation of strike and dip of planar fracture

Fig. 7 Analyses of orientation of fractures

4. RESULTS AND DISCUSSION

Results of observation and measurement of the cores of the *A* landslide are shown in Figs. 8 and 10(a). There are highly and slightly weathered green rocks above and below the slip surface at depth of 28.2m (Fig. 8), respectively.

Average unit weight measured between 24-28m and 28-36m was 2.36 kg/m^3 and 2.76 kg/m^3, respectively. The *RQD* defined for this study increased from 42% above the slip surface to 92% below the slip surface. A clear change in the Equotip value is also found near the slip surface. Fracture and crack structures in the rocks above and below the slip surface are analyzed. It was found that discontinuities are oriented in a very narrow range in the vicinity of the slip surface but in a wide range in other depths. Their inclination is less than 50° above the slip surface and more than 50° for most discontinuities below the slip surface. Such a change in the structural fractures might be produced by large shear deformations along the slip surface and weathering. From Fig.10 (a) it is seen that the magnetic susceptibility and the color values do not indicate a meaningful change near the slip surface in the *A* landslide.

Results of observation and measurement of the core samples of the *K* landslide are illustrated in Figs. 9 and 10(b). The rock type is politic schist. Weathering grade of the rocks at depth of 35~45m is from W1 to W4, gradually decreased, while there is highly(W1) weathered muddy schist above the slip surfaces around a 41-42m depth.

The unit weight is increased with decrease in the weathering grade, ranging from 1.6~2.5 kg/m^3 for the W1-W3 rocks to 2.6~2.7 kg/m^3 for the W4 rocks. The decrease in the unit weight may be caused by increase of void ratio and water content due to grain refining of fractured rocks. The RQD values and Equotip harness index and measured are almost consistent with the distribution of unit weight, as shown in Fig. 10(b). A change of the color values of a^* and b^* and a positive peak value of L^* are also found near the slip surfaces. Note that such a peak of the color values of L^* also appeared at other depths. Rocks above and below the slip surface can be categorized to fracture and crack structures, respectively. Discontinuities are oriented in a wide range in rocks of above and below the slip surface but in a very narrow range in the vicinity of the slip surfaces. No meaningful change in the magnetic susceptibility was found in the *K* landslide.

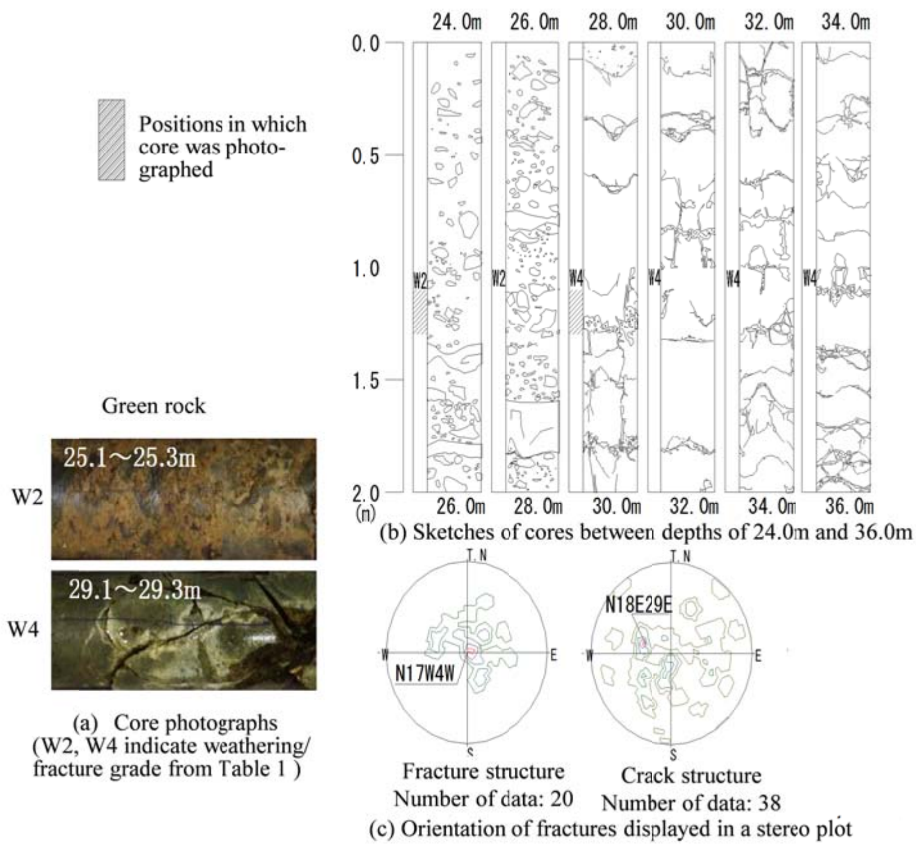


Fig. 8 Observation of core samples from the *A* landslide

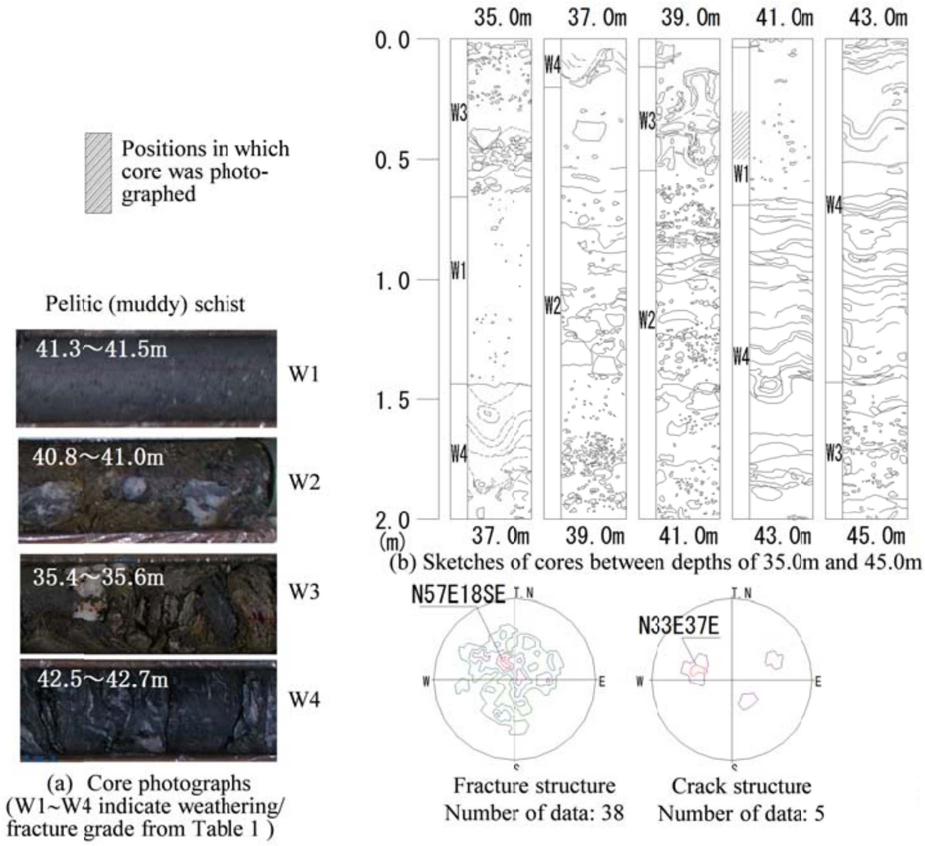


Fig. 9 Observation of core samples from the *K* landslide

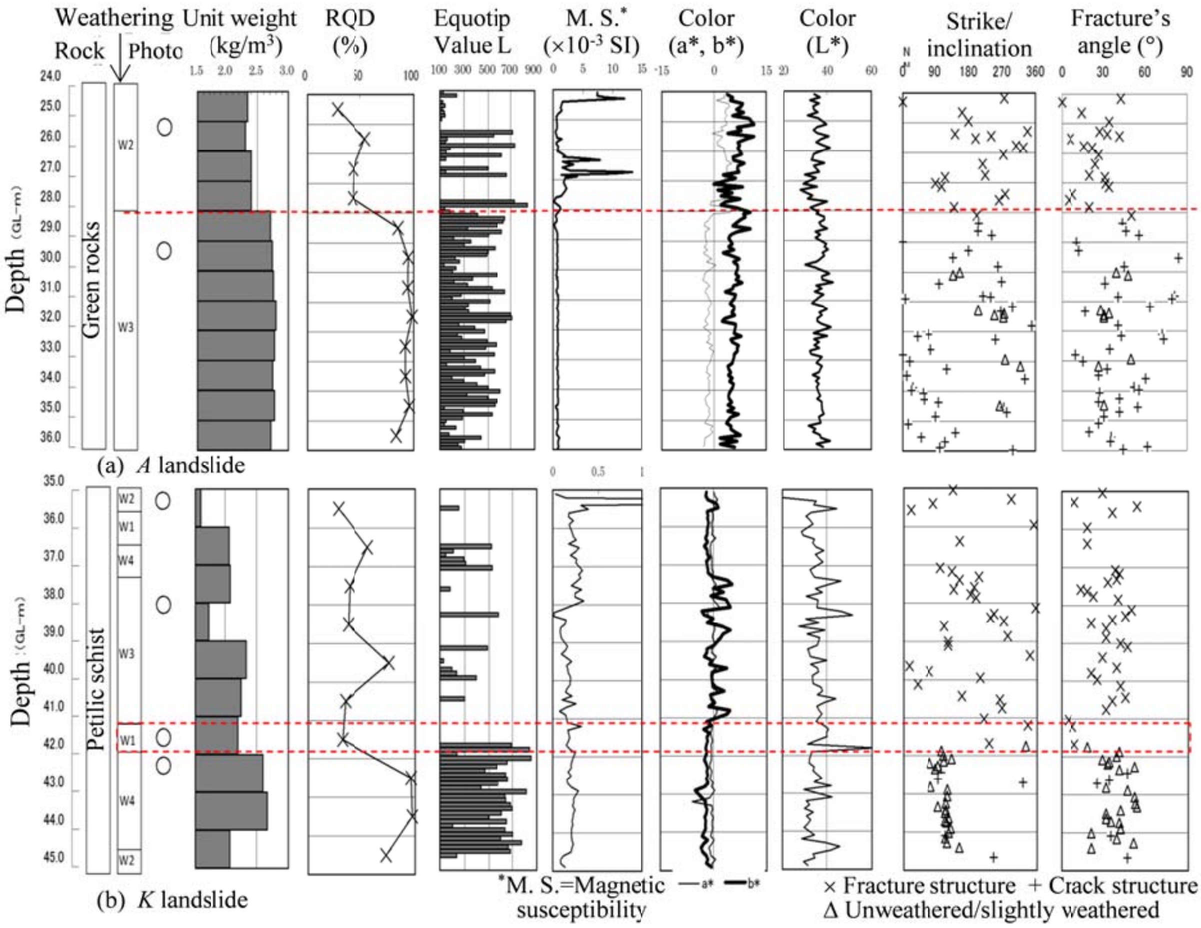


Fig. 10 Results of measurement and image analysis of core samples from the *A* and *K* landslides

Fractured bed rocks near the tectonic faults and hydrothermal alteration of rock minerals are the main reasons of fracture zone landslides in the Shikoku. The geological conditions together with weathering may result in different distributions of geologic discontinuities, rock quality designation, Equotip hardness, and numerical color values in rocks/soils above and below a slip surface. The data gained from observation, measurement and digital imaging analysis of oriented core samples, such as those shown in Figs. 8-10, allowed the successful determination of slip surface depths in fracture zone landslides.

5. CONCLUSION

This study presented examples of laboratory observations, geophysical measurement and digital imaging analysis of oriented borehole core from two study sites in Shikoku, Japan where many fracture zone landslides are distributed. The data obtained from each site include (1) a depth distribution of *RQD* (rock quality designation) defined in this study, the magnetic susceptibilities, the Equotip hardness values and wet unit weight of the core samples; (2) Orientation and inclination of geologic discontinuities (cracks, joints, faults, etc.) involved in the core samples, and (3) a depth distribution of numerical color values from digital imaging of borehole core. It was indicated that a clearer change in RQD, the Equotip hardness value and unit weight, and the orientation and inclination of discontinuities are observed respectively near the slip surfaces for both sites, while the color values clearly varied only near the slip surface in the *K* landslide. In addition, no change of magnetic susceptibility of core samples was found at both sites. The results demonstrate that the data gained from observation, geophysical measurement and digital imaging analysis of oriented core samples can be successfully used to determine the slip surfaces in fracture zone landslides.

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