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Research Paper

Characteristics of shear strength at the interface between two soil layers in ring shear apparatus

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The slopes containing discontinuous planes such as bedding planes, rupture, or boundary between two soil layers are often prone to sliding. Thus, the characteristics of shear strength mobilized along the discontinuous planes should be examined. In this study, the shear strength at the interface between two different soil layers will be investigated based on ring shear test. The combined sample comprising of one kaolin layer and one kaolin + bentonite mixture layer was used to simulate the discontinuous planes between two soil layers. A number of ring shear tests were conducted on these samples at a normal stress of 98 *kPa* and shear rates from 0.02 to 20 *mm*/*min* using a multi-stage of shearing rates procedure. The research results indicate that the shear strength at the interface sharply increases to reach the peak value after a small shear displacement, then drops to the residual value. The residual interface strength tends to increase with increasing shear rates above 2 *mm*/*min* and the level of increase in residual interface strength depends on the contact surface. Furthermore, the effect of the order sample layer in combined samples can be ignored when determining the peak, the residual interface strengths as well as the rate effect on residual interface strength in the laboratory.

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1 Introduction

The discontinuous planes such as bedding planes, rupture, or boundary between two soil layers in slopes often lead to instability of slopes [1-8]. On the coast of Southeast Britain, Bromhead and Ibsen [1] reported numerous landslides in

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sedimentary rocks which were referred to as the bedding-controlled landslides. Chigira and Yagi [2] and Wang et al. [8] also reported that most of the landslides occurred along the planar bedding during the 2004 Mid-Niigata Prefecture earthquake. These planar bedding surfaces were existed between sandstone and siltstone or between weathered and un-weathered rocks. Has and Nozaki [4] indicated that the bedding plane played an important role in landslides triggered by the 2007 Mid-Niigata Offshore earthquake. Therefore, the shear strength at the interface between two soil or rock layers should be investigated for evaluating and predicting the slope stability. However, the behavior of shear strength at the interface between two soil layers is rarely examined.

The residual interface strength between two layers was recently investigated by Suzuki et al. [9] and Scaringi et al. [10]. These investigations used the combined specimens which comprised of two soil layers and showed that the residual interface strength depended on the shear displacement rates, normal stress, and contact surface characteristics. These features are similar to the residual strength in the soil mass. However, these studies did not reflect the effect of sample order in combined specimens on the measured shear strength at the discontinuous plane. As reported by Tiwari et al. [7] and Tiwari [6], the shear surfaces of all landslides in Niigata Prefecture were the interfaces between highly weathered and less weathered Tertiary mudstones which contained a rather high content of smectite mineral, from 6.6 to 22.4%. Thus, the smectite mineral at the interface may play an important role triggering these landslides in this area. Therefore, the effects of smectite mineral at the contact surface and the sample order in combined specimens on the measured shear strength at the discontinuous planes should be investigated.

On the other hand, Duong et al. [11] reported the rate and acceleration effects on residual strength of kaolin and kaolin + bentonite mixtures based of the results of ring shear test. However, it was not shown how the combined specimen comprising kaolin and kaolin + bentonite mixture affected the rate dependency of residual strength. Furthermore, the structural influence of layers of combined specimen on shear strength has not been clarified yet since Suzuki et al. [9] reported.

In this study, the combined specimens comprise of one kaolin layer and one kaolin + bentonite mixture layer were used to simulate the discontinuous planes in slopes with the presence of smectite mineral at the contact surface. This study aims to investigate the behavior of peak and residual interface strengths, the effect of shear rate on residual interface strength, and the effect of order sample in combined specimens on the measured shear strength. Accordingly, a series of combined specimens were tested in the ring shear test at a normal stress of 98 *kPa* and shear rates from 0.02 to 20 *mm*/*min*. Two types of combined specimens were prepared, including kaolin (upper layer) – kaolin + bentonite mixture (lower layer); kaolin (lower layer) – kaolin + bentonite mixture (upper layer).

2 Materials and methods

2.1 Test apparatus

In this study, the Bishop's type ring shear apparatus was employed (Fig. 1). This apparatus uses the ring-shaped specimens with a height of 2 *cm*, an inner diameter of 6 *cm*, and an outer diameter of 10 *cm*.

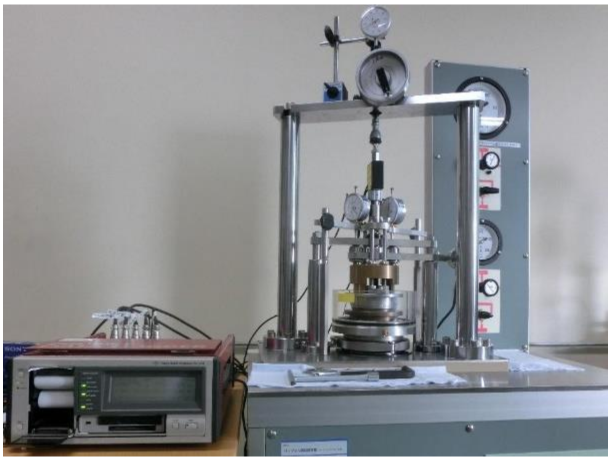

Fig. 1 –Ring shear apparatus (Bishop's type) [9, 11]

In this apparatus, the frictional force between the specimen and the inner circumference of the shear box is measured during shearing. The net normal stress acting on samples is calculated based on the measured frictional force. More information about this device can be found in Suzuki et al. [9] and Duong et al. [11].

2.2 Materials

Commercial kaolin and bentonite in the dry powder form are two constituents used for sample preparation in this study. Kaolin is mixed with bentonite in different proportions. Accordingly, the mixture of 90% kaolin + 10% bentonite (10B), 80% kaolin + 20% bentonite (20B), 70% kaolin + 30% bentonite (30B) were prepared for this investigation. Some physical properties of kaolin, bentonite, and their mixtures are listed in Table 1.

Table 1 – Physical properties of samples used [11]

Samples	Specific gravity, ρ_s	Clay fraction, *CF* (%)	Liquid limit, w_L (%)	Plasticity limit, w_P (%)	Plasticity index, *PI*
Kaolin (K)	2.645	46.0	77.5	35.4	42.1
Bentonite (B)	2.759	62.0	405.0	53.7	351.3
10B	2.656	47.6	116.0	36.3	79.7
20B	2.667	49.2	144.0	39.4	104.6
30B	2.678	50.8	172.0	42.9	129.1

2.3 Sample preparation

The pre-consolidated samples were prepared as testing samples in this study. Kaolin and its mixture with bentonite were mixed with distilled water in the form of slurry at the water content of their liquid limits. The slurry was then poured into a large consolidation tank and consolidated at a pressure of 98 *kPa* until finishing the primary consolidation. The consolidation tank for preparing testing samples is shown in Fig. 2. The primary consolidation was confirmed based on the 3t method [12]. This method has been widely used to confirm the end of primary (EOP) consolidation for sample preparation in laboratory tests in Japan [13].

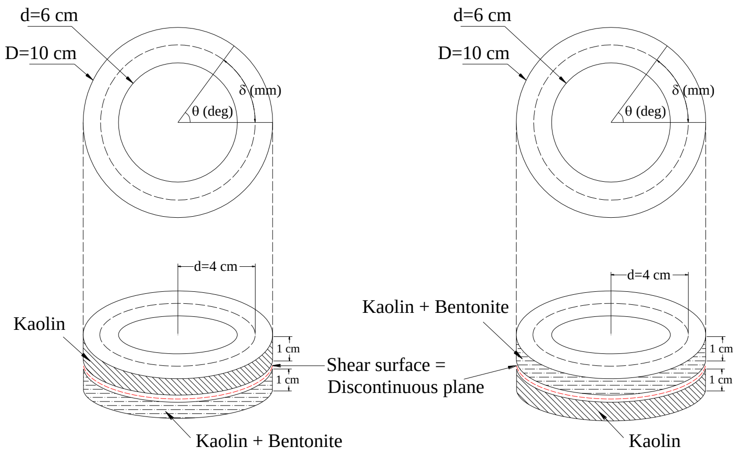

Fig. 2 – Model of combined samples used in this study

The specimens used in the ring shear test were cut from pre-consolidated samples. The combined specimens of two halves were used to simulate the discontinuous plane in slope. Each half has a height of 1 *cm*, an inner diameter of 6 cm, and an outer diameter of 10 cm. Two halves of combined specimens are kaolin and kaolin + bentonite mixtures (10B, 20B, 30B) with different orders that are kaolin for the upper layer and 10B, 20B, 30B for the lower layer, and vice versa. Two types of combined specimens were used to investigate the effect of the sample order on the measured shear strength (Fig. 2). The combined specimen of two kaolin halves was also used as a controlled specimen. Accordingly, six types of combined specimens were investigated, including K-K, K-10B, K-20B, K-30B, 10B-K, and 20B-K. The shear strength behavior of these samples was investigated at a normal stress of 98 *kPa* which corresponded to a shallow landslide of 5-7 *m* in depth.

2.4 Methods

Each half of the combined specimen was placed into the shear box according to the order as mentioned above. The combined specimens in the shear box were reconsolidated at a normal stress of 98 *kPa* to reach the EOP consolidation before shearing. The multi-stage of increasing shear rate procedure was applied. Firstly, the combined specimens were subjected to shear at a shear rate of 0.02 *mm*/*min* to a shear displacement of about 60 *mm*. Following that, the shear rates were then increased step by step from 0.02 to 20 *mm*/*min*. In this procedure, the peak strength value was measured at a shear rate of 0.02 *mm*/*min*. At each shear rate level from 0.05 to 20 *mm*/*min*, the specimens were sheared to a shear displacement of about 40 *mm* to obtain the residual strength. This amount of shear displacement is enough to reach the residual strength for soil samples which contain a pre-existing shear surface (pre-cut samples) [9, 14, 15]. The residual shear strength was calculated from the test result based on the hyperbolic approximation method as reported in Suzuki et al. [16].

3 Results and discussions

3.1 Peak interface strength behavior

Each combined specimen was sheared at a normal stress of 98 *kPa* and different shear rates from 0.02 to 20 *mm*/*min* following the multi-stage of increasing shear rate procedure. The test results of combined specimens in the ring shear test are shown in Fig. 3.

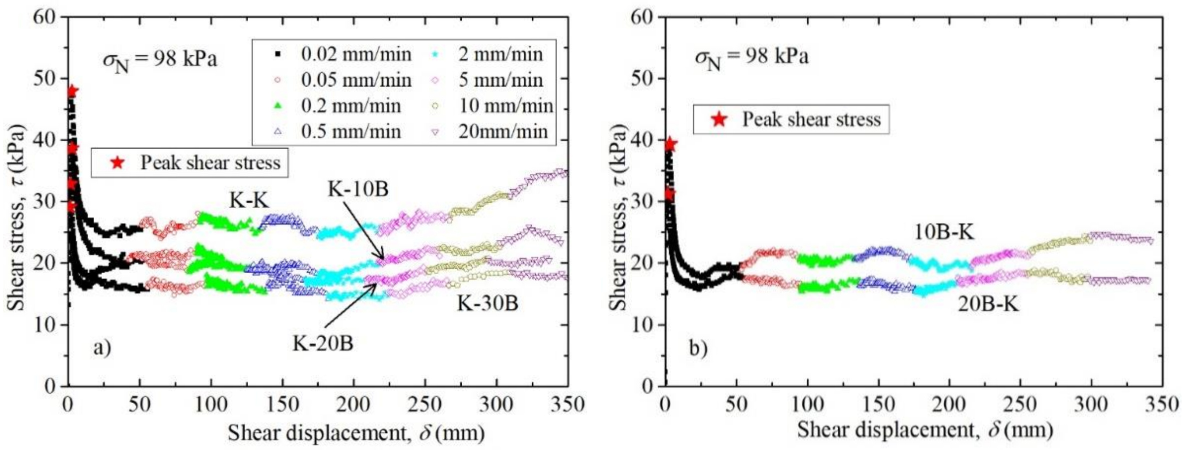

Fig. 3 – Test results of combined samples using a multi-stage shearing procedure

As presented in Fig. 3, the shear strength of combined specimens sharply increases and reaches the peak value after a very small shear displacement and then drops to the residual value. The results of peak strength and shear displacement to reach the peak strength at a shear rate of 0.02 mm/min are shown in Table 2. This table also shows the test result of intact samples (K, 10B, 20B, and 30B), which are collected from a previous study [11]. It can be seen that the peak strengths of combined specimens are obtained after a few millimetres of shear displacement (Table 2). After reaching the peak state, the shear strength of the combined specimen drops to the residual value. Thus, the peak strength at the interface should not be used for stability analysis of slopes that contain a discontinuous plane. In comparison with intact samples, the shear displacement to reach the peak strength of combined specimens is significantly lower than that of intact samples. In other words, the shear behavior of combined specimens is more brittle than that of intact specimens.

The variation of peak stress ratio which is the ratio of peak shear stress to the normal stress for combined specimens is shown in Fig. 4. As shown in Fig. 4a, the peak strength of combined specimens decreases as the content of bentonite at the contact surface increases (K-K > K-10B > K-20B > K-30B).

Table 2 – Results of peak strength and shear displacement at a shear rate of 0.02 *mm*/*min*

Sample types	Sample	Peak stress ratio, $(\tau/\sigma_N)_p$	Shear displacement to reach the peak strength, S_d (*mm*)
Combined samples	K-K	0.495	2.63
	K-10B	0.394	2.83
	K-20B	0.336	1.82
	K-30B	0.300	1.62
	10B-K	0.402	3.03
	20B-K	0.320	2.02
Intact samples [11]	K	0.536	6.27
	10B	0.435	7.49
	20B	0.335	6.47
	30B	0.239	4.25

This is attributed to the low shear strength of bentonite. As shown in table 2, the peak strength of intact samples (K, 10B, 20B, and 30B) decreases with increasing bentonite contents [11]. This indicates that the characteristics of the contact surface significantly affect the peak strength of combined samples

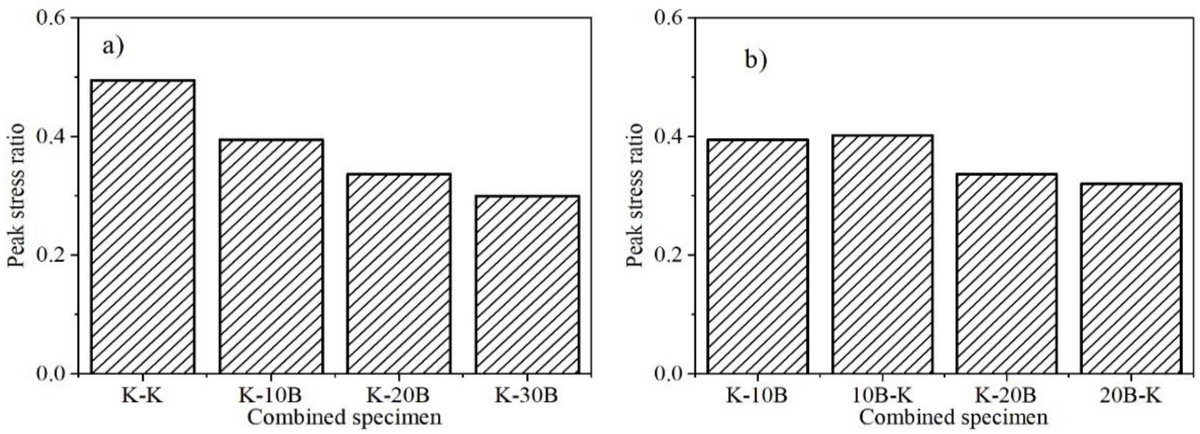

Fig. 4 – Variation of peak stress ratio of combined specimens

In this study, two pairs of combined specimens, including K-10B; 10B-K, and K-20B; 20B-K were used to investigate. The variation of peak stress ratio of combined specimens with different orders is shown in Fig. 4b. It is noted that the peak interface strength of 10B-K is almost same as that of K-10B. This tendency is similar with that in the case of 20B-K and K-20B. This indicates that the sample order in combined specimens has almost no effect on the measured peak interface strength. This finding proves that the order of sample in combined specimens does not need to consider when determining the peak strength value at the interface in the laboratory.

3.2 Residual interface shear strength behavior

In this study, the residual interface strength of combined specimens was determined at a normal stress of 98 *kPa* and shear rates from 0.02 to 20 *mm*/*min* using a multi-stage procedure. The rate dependency of residual interface strength of K-K, K-10B, K-20B, and K-30B combined specimens is shown in Fig. 5. As shown in this figure, the residual interface strength is almost independent of shear rates of less than 2 *mm*/*min*. At shear rates exceeding 2 *mm*/*min*, the residual interface strength tends to increase with increasing shear rates. The increase of residual interface strength here can be attributed to the change of shear mechanism from sliding to turbulent mode [17-19] or to the shear viscosity effect [17, 19]. However, the level of increase in residual interface strength may depend on the contact surface characteristics. The rate effect coefficient (α') as reported in Duong et al. [11] was used to evaluate the level of increase in residual interface strength. It was defined as the ratio of the change in residual stress ratio to the change in shear displacement rate. The results of the rate effect coefficient for residual interface strength are shown in Fig. 5. Accordingly, the rate effect coefficient values are 0.106, 0.044, 0.034, and 0.031 for K-K, K-10B, K-20B, and K-30B combined specimens respectively. It can be seen that the rate effect coefficient significantly decreases when the lower layer is 10B sample. In general, the rate effect coefficient decreases as the bentonite content at the contact surface increases. This indicates that the level of increase in residual interface strength depends on the characteristics of the contact surface.

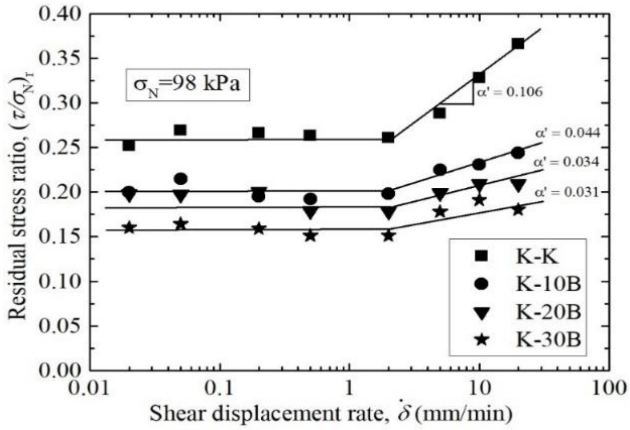

Fig. 5 – Variation of residual strength of combined specimens at different shear rates

The effect of sample order in combined specimens on the measured residual interface strength is presented in Fig. 6. In this study, the residual interface strength of two combined sample groups, including K-10B, 10B-K and K-20B, 20B-K was investigated. For both groups of combined specimens, the residual interface strength shows the rate dependency behavior. In addition, the effect of sample order in combined specimens on the measured residual interface strength is insignificant for all investigated shear rates. This indicates that the order sample in combined specimens can be ignored when determining the residual interface strength and its rate dependency in the laboratory.

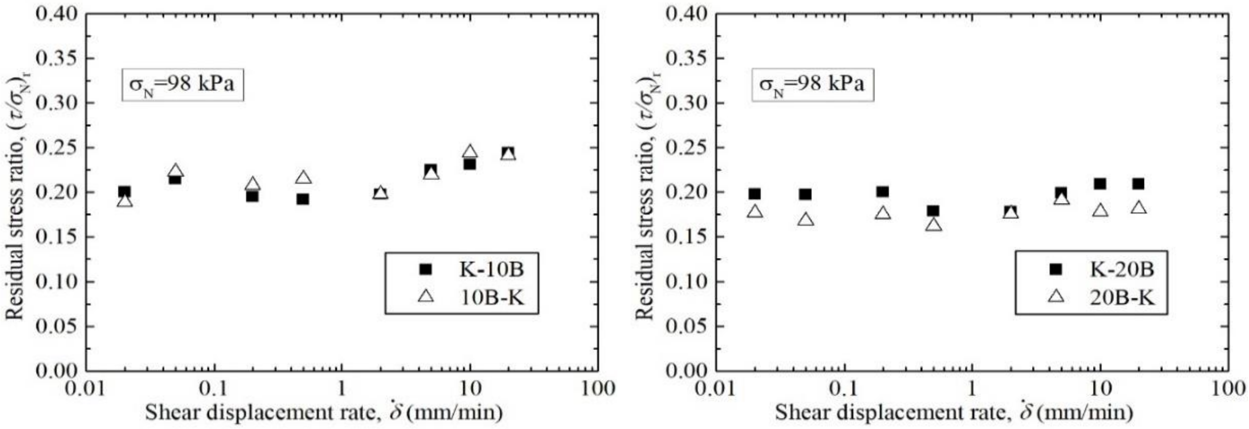

Fig. 6 – Effect of sample order in combined specimens on the residual interface strength

4 Conclusion

In this study, the characteristics of peak and residual strength at the interface between two different soil layers were extensively investigated in the ring shear test. Based on the analysis of test results, some conclusions are drawn as follows:

The peak interface strength is obtained at a very small shear displacement, then drops to the residual value. Thus, the value of peak interface strength should not be used for slope stability analysis.

For the residual interface strength, it is almost independent of slow shear rates of less than 2 *mm*/*min*. It tends to increase with increasing shear rates above 2 *mm*/*min* (positive rate effect). However, the magnitude of increase in residual interface strength depends on the characteristics of the contact surface. Accordingly, it tends to decrease as the bentonite content at the contact surface increases.

The order of sample in combined specimens has almost no effect on the measured peak, residual interface strength values as well as the rate dependency of residual interface strength. This indicates that the effect of the order sample in combined samples can be ignored when determining the peak, the residual interface strengths and the rate effect on residual interface strength as well in the laboratory.

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