Shear strength of clay at different shear rates

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Abstract. A test procedure that involved shearing soil specimens at different shear rates was proposed to study the effect of shear rate on the strength recovery of three natural clays. The obtained results indicated that an increase in the shear strength occurred when the shear rate decreased. This strength regain was more pronounced for the higher plasticity clays which were sheared at a relatively lower confining pressure of 100 kPa.

Keywords: shear strength, ring-shear tests, strength recovery

Introduction

Strength recovery of soil from the shear zone of reactivated landslides during a stable period has been the topic of research in several studies. Gibo et al. (2002), Stark et al. (2005), Carruba and Del Fabbro (2008), Stark and Hussain (2010) carried out shear tests in which soil samples were subjected to alternating shearing and “healing” stages. The obtained results indicated that the strength recovery mostly occurred due to secondary compression as changes in the specimen height/volume were permitted during the healing stage. In contrast, this study proposes a test procedure in which soil specimens were sheared at different shear rates without the healing time to minimize the effect of secondary compression. Using this experimental setup, the capacity of three natural soils to recover shear strength was tested at

different confining pressures of 100 kPa and 200 kPa. This technical note presents and discusses the obtained results.

Soils used

Three soils from a reactivated landslide in Hyogo Prefecture of Japan were selected for this study. For convenience, the name of each soil was related to its colour: “amber” clay, “brown” clay, and “black” clay. The amber clay had a very high liquid limit (LL) of 96.3, plasticity index (PI) of 62.5, and clay content ($<2\mu\text{m}$) of 66%. The brown clay had LL=88.2, PI=54.5, and clay content of 19%. The black clay (LL=38.6, PI=19.0) had a clay content of 11%. X-ray diffraction analysis revealed that quartz, halloysite and mica were present in all three soils, while montmorillonite was found only in the brown clay.

Test procedure

A ring-shear apparatus, namely DPRI-ver.4 from Kyoto University, Japan, was used in this research (Gratchev and Sassa 2009). The ring-shear specimen was first prepared from slurry and then placed in the shear box. All specimens were fully saturated and normally consolidated to a confining stress (σ) of either 100 or 200 kPa.

The test procedure consisted of the “slow shearing” and “fast shearing” stages as schematically shown in Fig. 1. In the “slow shearing” stage, the specimen was subjected to shearing under drained conditions until the residual shear strength was obtained. A low shear rate of 0.1 mm/min was used to avoid the generation of excess pore water pressure. In the

“fast shearing” stage (Fig. 1), the specimen was sheared at a higher shear rate of 5 mm/sec for 15 minutes to achieve a new residual shear strength (τ_0). Without permitting any healing time, the shear speed was then lowered in a step-like fashion as shown in Fig. 1, and the following shear rates of 4.5, 4.0, 3.0, 2.0, 1.0, and 0.2 mm/s were used. Each step continued for 3 min, a period that was found to be sufficient for the shear resistance to reach a steady state. For each shear rate, a value of shear strength (τ_i) was recorded and used to obtain the shear strength recovery index (R_s), which is defined as

$$R_s = \frac{\tau_i - \tau_0}{\tau_0} \cdot 100\%$$

It is noted that although drainage was permitted during the “fast shearing” stage, some pore-water pressure was generated due to high shear rates.

Results and Discussion

1) Test results from the “slow shearing” stage ($\sigma=100$ kPa) are given in Fig. 2. Figure 3 presents the data from the “fast shearing” stage obtained for the brown clay ($\sigma=100$ kPa) to demonstrate the typical behavior which was observed for all three soils. A small increase in the shear strength was observed immediately after the shear rate increased from 0.1 mm/sec to 5 mm/sec at the beginning of the “fast” stage (Fig. 3). Such a “positive” effect of shear rate (higher strength at higher rates) also known as the “Isotach” behavior (Tatsuoka et al. 2008) was then followed by a decrease in the strength (“negative” effect of shear rate) as the shearing continued. Such a “P&N” type of soil behavior (Tatsuoka et al. 2008) has been

reported in the literature for fine-grained soils (Tika et al. 1996). However, the behavior of soil when the shear strength increased from 29.2 kPa to 36.7 kPa as the shear rate dropped from 5 mm/sec to 0.2 mm/sec doesn't seem to fit well in the already-established models for higher shear rates. In addition, there doesn't seem to be sufficient information in the literature related to this phenomena because in the previous studies, different test procedures were used, which allowed for the occurrence of secondary compression during the healing time, influencing the soil behavior.

2) Figure 3 shows that some excess pore water pressure was generated at higher shear rates - it reached a value of about 9 kPa in the first few seconds, and then remained in a narrow range of 6.5-8.8 kPa. No significant change in the pore water pressure throughout the test suggested that 1) somewhat undrained conditions were created by higher shear rates; and 2) changes in the shear strength at different shear rates may not be due to the excess pore water build-up. However, it is also noted that the measured pore water pressures might not reflect the actual values because sufficient time was not allowed for equalization. This may result in some uncertainties regarding the effect of pore water pressure build-up on the rate-dependent behavior of the clay.

3) The average values of shear strength obtained for each shear rate ($\tau_0, \tau_1 \dots \tau_6$, as shown in Figure 3) were considered in this analysis. In addition, a series of tests with the brown clay at 100 kPa were repeated to examine the reliability of the data. All the obtained results are

summarized in Fig. 4 in terms of shear rates against R_s . It is evident from this figure that regardless of the soil type, the shear strength increased as the shear rate decreased from 5 mm/s to 0.2 mm/s, which provides more evidence for the soil behavior discussed in Fig. 3. It is noted that the largest increase in the shear strength (in %) was obtained for the amber clay, which had the highest plasticity index. In addition, for all three clays, the largest increase was recorded for $\sigma=100$ kPa, compared to $\sigma=200$ kPa.

4) The small increase in the shear strength of all three soils, which was observed as the shear rate decreased from 5 mm/sec to 0.2 mm/sec, can be related to the ability of clay particles to restore broken bonds at different shear rates. Previous research (Osipov et al. 1984; Perret et al. 1996; Barnes 1997) indicates that at higher shear rates, the breakdown of the bonds between clay particles/flocs is greater than the bond restoration, resulting in decreased shear strength. However, at lower shear rates, the bonds are rebuilt rapidly and the recovery rate can be similar to the breakdown rate. In addition, particle rebound and reorientation during shearing may also play an important role in bond restoration. Stark and Hussain (2010) noted that at an effective normal stress of 100 kPa or less, the clay particles have a greater ability to rebound from being oriented parallel to the direction of shearing, resulting in a greater strength regain, compared to $\sigma=200$ kPa.

Conclusions

In this study, three clays were sheared at different shear rates. The main conclusions that can be drawn from this work are as follows:

1. For all three clays, in addition to the “positive” and “negative” changes in the shear strength at a higher shear rate of 5 mm/sec, a small increase in the shear strength was also observed as the shear rate decreased.

2. The increase in the shear strength for all three clays was more pronounced for a confining pressure of 100 kPa.

The data presented in this study indicate that the soil behavior at higher shear rates is still not well-understood. It appears that some increase in the shear strength occurs not only when the shear rate increases (from “slow” to “fast”), but also when higher shear rates decrease.

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126   **Figure captions**

127   Figure 1. Test procedure to obtain the shear strength of soil at different shear rates.

128   Figure 2. Results of drained shear rate-controlled tests on three clays confined to a normal
129   stress (σ) of 100 kPa.

130   Figure 3. Results of the “fast shearing” stage obtained for the brown clay at $\sigma=100$ kPa.

131   Figure 4. Summary of all test results plotted as shear strength recovery vs shear rates for
132      $\sigma=100$ kPa and $\sigma=200$ kPa.

133