Rheological properties of clayey soils at high water content measured by viscometer and laboratory vane shear test

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Introduction

Geotechnical engineering and soil mechanics are not quite easy to explain and understand. The behaviour of clayey soils and sandy soils or even clay-silt soils are different each other and more complex with water content. The transformation of soil from a plastic state to a viscous liquid state is primarily caused by a change in the water content of the soil mass. As the water content increases, the soil mass gradually starts to behave like a viscous liquid. The soils which have behaviour of viscous liquid can easily show its movement along a slope. Recently, clayey soil with high water content has been paid more attention mainly from two aspects: utilization of dredged soils for reclamation of sites (Fakher et al., 1999) and estimation of damaged areas or prediction of run-out distance caused by debris flow and even marine landslides (Gauer et al., 2006).

Based on the dredging operation, a numerical modeling produces a cost-effective tool to analysis operational parameters and forecast optimum dredging scenarios prior to actual dredging operations. Similarly a numerical model is used to explore the dependence of run-out behavior of debris flow or marine landslides on the controlling soil mechanics and fluid variables. In general, numerical models require input data as engineering properties which can be recognized as rheological parameters, i.e., yield stress, viscosity and shear stress relationships (Locat and Demers, 1988). These parameters are effectively used to predict the run-out distance of debris flow or marine slides and to achieve economical dredged soils transportation and management. This implies that to attribute better understanding of these two scenarios, rheology is paramount important to study under Engineering frame.

Background

The mechanical behaviour of soil with high water content can be expressed by several rheological models. Among them Bingham model is widely adopted in numerical calculation. In the Bingham model, the relationship between shear stress (\( \tau \)) and shear strain rate (\( \dot{\gamma} \)) is defined by two parameters (Eq. (1)): yield stress (\( \tau_y \)) and viscosity (\( \eta \)). Still the yield stress is not much distinct to understand because there are several different definitions of the yield stress by various researchers.

\[ \tau = \tau_y + \eta \dot{\gamma} \]  

(1)

However, the parameters including applicability of the Bingham model to high water content soil have been studied by several researchers and related to fundamental geotechnical parameters such as shear strength measured by vane shear test or fall cone apparatus. They mostly have reported that \( \tau \) measured from rotary viscometer is somewhat smaller than shear strength measured by laboratory vane shear test and fall cone (Locat and Demers, 1988; Boukpeti et al., 2012). Due to these uncertainties of yield stress and examined difference between yield stress and shear stresses measured by viscometer and conventional laboratory vane shear test, this study is concentrated to understand the characteristics of rheological parameters measured at high water content clayey soils by using the both test methods.

Objectives

In this study, the mechanism of the viscometer is studied by means of the vane shear apparatus with relatively slow rotational speed and focusing on several aspects:

- Influence of the shape of the spindle including material, i.e., cylinder and vane, confirmation of the uniformity of strain in the tested sample, effects of rotational speed (shear rate) from relatively slow to high.
- Additionally, effect of time and sand contents are investigated by viscometer.

Experimental materials and Techniques

Experimental materials

In this study, two types of commercial clays and one natural clay were used: Fujinormori, Kasaoka, and Tokyo Bay clays. Their indexes properties are summarized in Table 1. Commercial clays available in dry powder condition were mixed with required water content and kept about one day before testing for the soil particle well-adjusted and homogenous distribution of water. In contrast to commercial clays, natural clay sample, which was obtained under wet conditions, was first passed through a 425 micrometer sieve to remove coarser particles such as larger sea shells. Removal of coarse material was required to ensure that no particles between rotating spindle and specimen container could produce an error in measurement of the torque.

For understanding effect of sand content, only Kasaoka clay and Toyoura sand were used. After
The rotational speed was increased stepwise from 0.01 rpm to 200 rpm and each speed was allowed to maintain constant rotation (shearing) for 10 seconds, and the torque (T) was measured during this constant time while immediately after 10 seconds speed was changed to next. However, this constant time of rotation was changed from 10 seconds to 30, 60 seconds for understanding the effect of time on the rheological properties. As same as usual viscometer test, for the rotating spindle, a cylinder is used (Fig.1). In addition to the cylinder that is used in conventional viscometer test, the vane was used as a spindle to study the influence of the shape of the spindle. The material of vane and cylinder are aluminum and their diameter is 21.67 mm in height and 23.5 mm in diameter respectively. The density of this diameter to the diameter of the cylinder is 1.08 (= 23.5/21.67) and valid for specification of JIS. In contrast to that, the sample container having this ratio nearly 1.1 between rotating cylinder and sample container provides an easy access for sand particles of sample to jam between them which can produce an error in measurement of the torque.

Since the rotational viscometer is designed for condition under relatively high rotational speed, the laboratory vane shear test is used to study effect of low speed. Generally vane shear test is used a vane which consists of four thin blades in to right angle each other and it can be operated at very low constant speed of 0.06’/min to 600’/min (0.02 rpm to 2 rpm). In addition to the vane, the cylinder was also used to study the influence of the spindle shape. In this test, sizes of the vane and cylinder were 80mm in diameter and 40mm in height 1 mm in thickness.

$$\tau = \frac{T}{\pi \left( \frac{D^2}{2} H + \frac{R^2}{6} \right)}$$  \hspace{1cm} (2)

$$\gamma = \frac{2\alpha R_o}{1 [R_o^2 - R^2]}$$  \hspace{1cm} (3)

Under both test methods, to study the validity for deriving Eq. (3), the boundary effect was examined with narrow and wide gaps conditions between the spindle and the above container. Hereafter, the former and latter condition will be respectively called NG (Narrow Gap) and WG (Wide Gap). During the test fully submerged cylinder in soil sample is rotated under a controlled speed and the torque is measured. Considering the assumptions of no slip between spindle and sample and uniform shearing of sample, the measured torque and rotational speed (or angular velocity, $\omega$) are converted to shear stress and shear rate by using Eq. (2) and (3).

**Results and Discussion**

**Uncertainty of measured yield stress**

In this section a typical example measured by the Brookfield DV-II+Pro viscometer is shown in Fig.2. As can be seen in this figure, follows relationship between yield stress and shear stress (peak stress under 0.02 rpm) measured by using only cylinder from the conventional viscometer and vane from laboratory vane shear test respectively. Well-known fact is that shear stress increases with speed. Even though rotational speed of vane shear test is lower than the rotational speed at $\tau_i$ measurement in the viscometer, it can be clearly observed that $\tau_i$ is significantly smaller than shear stress measured by conventional laboratory vane shear test. This result implies that difference strength measured by the viscometer and vane shear tests may be caused by...
the difference in the shape of the rotating spindle between cylinder and vane and influence of mechanism between both test methods.

**Effects of low rotational by vane shear test**

Fig. 3 compares strength obtained by vane and cylinder for Kasaoka clay (w/w_L=1.21) under 0.02 rpm. As can be seen, vane needs a certain rotational angle (θ) to get the peak strength, but in cylinder very small θ is required to get the peak. Except for small θ, the vane provides much larger stress than the cylinder does, especially at residual state, the stress for the cylinder is less than a third of that for the vane. For further understanding of different stress measured by both spindles for three clays, Figs. 4 presents the strength ratios measured by the cylinder and vane (τc/τv) at peak state for different w/w_L. All tests were conducted under the same rotational speed i.e., 0.02 rpm. It can be seen that for all clays tested in this study τv is larger than the τc (same as Fig. 3), although ratio of (τc/τv) seems that depends on the type of clay and water content.

The reasons for different stresses by both spindles can be anticipated by slipping effect. For the rotation of cylinder, the occurrence of slip can be observed between the soil sample and the surface of the cylinder. Slip at the surface of the cylinder resulted in a lower shear stress value than that obtained from the vane, for an example of past experience, lower yield stress can be seen due to slip at the surface of cylinder (Liddell and Boger, 1996). This finding suggests that the vane and cylinder spindles behavior cannot be considered in the same manner and the strength for the cylinder is not fully mobilized as indicated in Eq. (2).

![Fig. 3. Relation between shear stress and rotational angle](image)

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![Fig. 4. Characteristics between peak stress ratio w/w_L](image)

**Fig. 4. Characteristics between peak stress ratio w/w_L**

**Impact of boundary conditions on low speeds**

The influence of boundary effect is reflected from Fig. 5, was not significant on the measured shear stress before as well as after the peak stress (compares NG and WG). NG condition of both vane and cylinder has given slightly lower stress than WG condition, probably due to additional slipping along the inside wall of the container. Therefore, it may be concluded from this result and the observed slip for the cylindrical spindle that the important assumption for calculation of γ cannot be applied to the rotational viscometer at least low rotational speed of 0.02 rpm.

![Fig. 5. Influence of boundary condition at 0.02 rpm](image)

**Stress level at different low speeds, $\dot{\gamma}$**

Several low rotational speeds, i.e., from 0.02 rpm to 2 rpm were studied by vane shear test. The test results only for residual stress ratio (τc/τv) at different water contents are shown in Fig. 6 except peak stress ratio because peak value of cylinder is difficult to obtain at high speed. For samples with low water content, the residual stress ratio measured by both spindles do not systemically increases with $\dot{\gamma}$, but sometimes the ratio decreases with increase in $\dot{\gamma}$. However, as many researchers reported, stress measured by both spindles increases with $\dot{\gamma}$ at high water content. The increase of the vane strength for the rotational speed has been recognized since old days by geotechnical engineers and Bjerrum’s correction factor is well known as a typical example. He indeed proposed the correction factor based on this rate effects in addition to the anisotropy in shear strength.

![Fig. 6. $\tau_c/\tau_v$ with speed for Kasaoka clay having w/w_L of 0.81, 0.94, 1.04 and 1.21.](image)

**Stress level at variable speeds by viscometer**

For Tokyo Bay clay (w/w_L=1.4), as can be seen in Fig. 7, much important fact is that the strength measured by the cylinder is larger than that by the vane at high $\dot{\gamma}$, which is completely opposite anticipation from vane
shear test (Figs. 3 and 4). For further understanding of impact of boundary condition, i.e., NG and WG, it is clear to notice that the effect of $R_o/R_i$ is very small even at high $\dot{\theta}$. Similar tendency can be obtained from other two clays. This test result implies that Eq. (3) is not suitable to apply to obtain the shear rate and the soil existing between the container and the spindle is not uniformly sheared even at high $\dot{\theta}$.

Impact of different shearing times on stress

From this section viscometer is concentrated on conventional condition, i.e., only cylinder is used as spindle. For Kasaoka clay, Fig. 8 shows the three different curves of relationship between shear stress and shear rate. As mentioned in experimental techniques, these three curves separately maintained three different constant shearing times for each shear rate of each curve, i.e., 10, 30 and 60s. It is reported that yield stress raises with shearing time that results in dominant of effect of thixotropy which increases strength with time (Seng and Tanaka, 2012). Obtained shear stresses at residual state show slightly change with time while it seems that there is no significant difference of viscosities with time. Still there is scattering of shear stresses at very low shear rate. This fact can be attributed by stick-slip phenomena at low shear rate.

Sand content on yield stress and viscosity

There are many different kind of dredged soils and debris flow which have various soils by region or country. Since such kind of soils can consist of not only pure clay but also some amount of sand content, influence of Kasaoka clay-Toyoura sand mixture on rheological properties is examined by viscometer. Although for an experiment it was used sample container having diameter ratio greater than 1.1($R_o/R_i$ > 1.1), this ratio is assumed as 1.1 for calculation of shear rate because there is no significant influence on different $R_o/R_i$ (See Fig. 7). When compare Fig. 9, influence of sand content on $\eta$ is significant than $\tau_y$ and $\eta$ increases rapidly and gives significant deference in value at high sand content (50 %). These factors are due to shearing resistance of sample at high sand content is much more dominant by reducing absolute water content than that of low sand content.

Conclusions

It is understood that for clayey soils, shear stress, yield stress and viscosity influence on several factors which are explained as follows:

- The measured shear stress or yield stress depends on the spindle types, i.e., vane and cylinder and shearing time. Equation of shear rate is not suitable to apply because between the container and the spindle is not uniformly sheared and existing of slip.
- Influence of sand content on $\eta$ is significant than $\tau_y$ while viscous resistance forces increases dramatically when sand content increases due to reduction of absolute water content of sample.

References


