Chapter 5
Preliminary Investigations of Rheological Properties of Busan Clays and Possible Implications for Debris Flow Modelling

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Abstract To investigate the post-failure dynamics of subaerial and subaqueous landslides in various environments, we need a detailed analysis of the geotechnical and rheological behaviour of fine-grained sediments. For fine-grained sediments found in the subaerial and subaqueous environments, rheological research should be conducted as a prelude to understanding flow behaviour and hazard assessment. In this paper, the rheological characteristics of Busan clays from the Nakdong deltaic plain are examined in a shear rate-controlled system. A comparison is made between the Busan clays and low-activity clays in terms of rheometer geometry. Flow curves obtained from the controlled shear rate and the shear stress mode are examined. The viscosity and yield stresses obtained from different geometries, which may produce wall-slip among cylinder, ball-measuring and vane-measuring systems, are highlighted. Based on the relationship between the liquidity index and rheological values (viscosity and yield stress), flow motions are compared. Results

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show that the differences in mobility are significant when assuming that the flowing materials behave as a Bingham fluid. The runout distance is controlled by the yield stress of fine-grained sediments. Differences in yield stress may be caused by wall roughness and the distance between the ball (vane) and the wall in the rheometer. Under the same geomorphological conditions, the runout distance calculated from vane-measuring systems is much lower than that from ball-measuring and cylinderic systems. These difficulties must be minimized to predict debris flow mobility and to correctly perform hazard risk assessment.

Keywords Rheological properties • Busan clays • Ball-measuring and vane-measuring rheometer • Debris flow mobility

5.1 Introduction

The high mobility of subaqueous debris flows is strongly influenced by the geotechnical and rheological properties of the fine-grained sediments. To estimate the runout distance and velocity of debris flows, we need yield stress and plastic viscosity values. Yield stress is one of the most important parameters in debris flow modelling. There are two ways to determine yield stress: (i) geomorphological analysis and (ii) laboratory experiments using rheometers. For specific research sites, rheometrical analysis is required. For sediment-water mixtures, we can use different types of measuring rheometers, such as coaxial cylinder, cone-plate, plate-plate, vane-penetrated and ball-rotated measuring rheometers. Rheological parameters are generally influenced by physical and chemical factors such as grain sizes, clay minerals, soil types, volumetric concentrations of solids, salinity, liquidity index, and so on (Locat 1997; Jeong et al. 2010). In particular, the influence of grain size distribution in a debris flow is essential. The effect of rheometer geometry also cannot be neglected. Rheological parameters are very sensitive to the effects of the geometry of the rheometer, such as wall-slip, roughness at the wall and end effect (Coussot 1994). In this study we determine the general flow behaviour of Busan clays using ball-measuring and vane measuring rheometry and compare the differences between the Busan clays and low-activity clays as found in the literature. The aim of this study is to examine the rheological properties of Busan clays and implications for debris flow modelling from different rheometric systems.

5.2 Materials and Methods

The material examined was obtained in the city of Busan, in the deltaic plain of the Nakdong River, which is located on the southeastern coast of Korea. The normally consolidated Busan clay is known as an unusually thick deposit, varying from 20 to 70 m thickness (Chung et al. 2010). Ongoing research projects related to reclamation

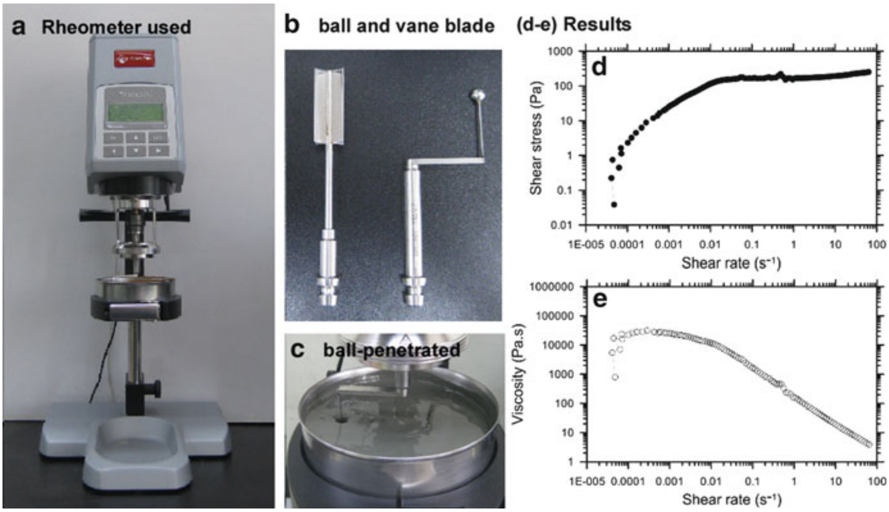

Fig. 5.1 Rheometric system and testing results: (**a**) Rheometer (RheolabQC, Anton Paar series), (**b**) ball and vane blade, (**c**) set up for rheological measurements, (**d**) plot of shear stress against shear rate and (**e**) plot of viscosity against shear rate

works in the Nakdong deltaic plain are focused on consolidation and hydraulic characteristics, which are still poorly understood (Chung et al. 2009). The Busan clays used in this study consists of soft silty clay to soft clay. These clays consist of illite-rich materials with small proportions of kaolinite, quartz and hornblende, with a very low percentage of montmorillonite. The natural water content of the Busan clays ranges from 35 to 60 %. The salinity and organic matter of the Busan clays range from 5 ~ 15 % and 2 ~ 8 %, respectively. The liquid limit and plasticity indices are approximately 43 ~ 72 % and 18 ~ 35 %, respectively. In general, the liquidity index is very close to unity with depth. In short, Busan clays have low to medium activities (i.e., $A_c = 0.5 \sim 1.2$). The geotechnical and rheological properties of these clays can thus be compared with that of low-activity clays (e.g., rheological compilation from Locat 1997). Furthermore, the geotechnical properties of the Busan clays are similar to the low-activity clays examined by Jeong et al. (2010).

The rheological analyses were carried out using either ball-measuring or vane-measuring rheometry on the <0.075 mm fraction. Ball and vane types (RheolabQC, Anton Paar series, Fig. 5.1) were developed to determine the yield stress and viscosity for large-particulated fluids. The ball and vane-measuring systems consist of a sphere (8 mm diameter) and a vane blade (20 mm wide × 40 mm high), which penetrate the soil samples. The maximum volume of the soil samples is 500 cm^3. The rotational speeds are recorded when the torques exerted on the sphere and vane blade is recorded within a wide measuring range. The distance between the sphere and the container wall is 20 mm. For the vane-measuring system, it is 48 mm. The ball-measuring and vane-measuring systems and the testing program are described in detail by numerous researchers (e.g., Schatzmann et al. 2009; Sosio

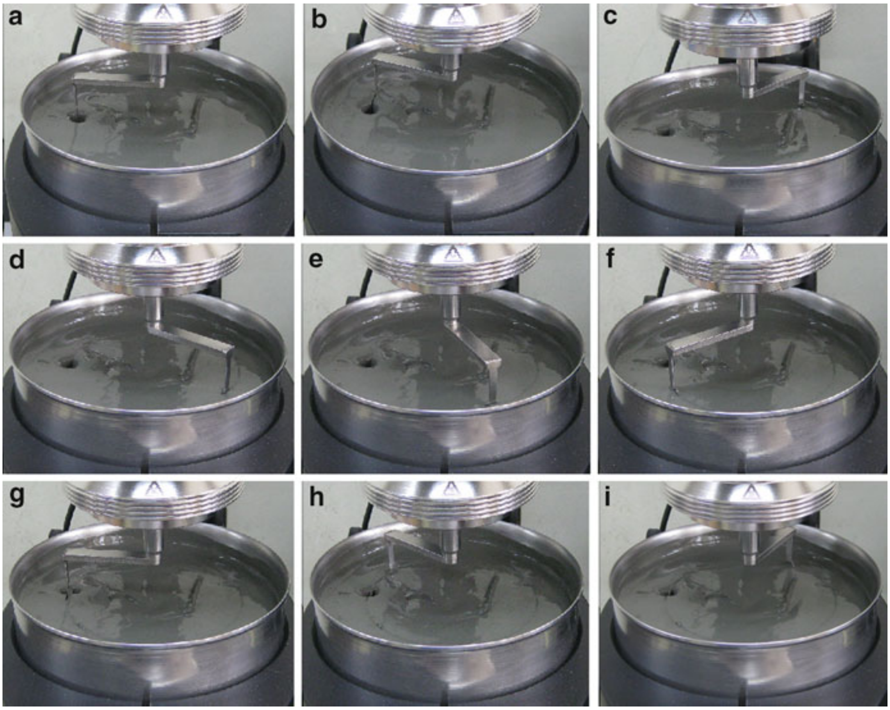

Fig. 5.2 Ball-measuring system for examining the rheology of the Busan clays (**a–g** is the first rotation; **g–i** is the post-failure stage)

and Crosta 2009; Scotto Di Santolo et al. 2012). Two types of shear mode can be applied: (a) shear stress controlled and (b) shear rate controlled. The measurements of torques are fully automated within the range of shear rates of $0.001 \sim 100\ s^{-1}$. Shear stress (T) and shear rates (D) can be measured within $0.5 < T < 10{,}000$ Pa and $0.001 < D < 4000\ s^{-1}$. Figure 5.1 shows the rheometrical system with the ball and the vane blade, set up for rheological measurement, and test results in the shear stress-shear rate and viscosity-shear rate plots. Figure 5.2 depicts the ball-inserted rheometric system and shows how rheological measurements were performed.

For each rheological test, the soil-water mixtures were prepared by adding a given amount of water to the solid fraction and thoroughly mixing by hand to ensure complete homogenization. The mixtures were left at rest for $30 \sim 60$ min for hydration. Before performing the rheological tests, the mixtures were re-mixed. The mixtures were then poured into the container and were left at rest for 5 min. For the next desired level, the liquidity index (water content) was slowly increased at a constant salinity of the pore water by adding water with the same salinity. Following each step the remoulded undrained shear strengths was measured using the Swedish fall cone (i.e., 60°–30 g and 60°–60 g cones) according to ASTM and BNQ standards. The flow curves were obtained for the given shear rates. An example is shown in Fig. 5.1d (see the log-log plot of shear stress against shear rate).

5.3 Results

5.3.1 Rheological Behaviour of the Busan Clays

Figure 5.3 presents the flow curves of the Busan clays when the shear rates were given in the range of 10^{-4} to 10^{2} s^{-1} for various liquidity indices. The liquidity index varied between 2.2 and 5.4; this value was determined using the empirical relationship proposed by Leroueil et al. (1983). Figure 5.3a, b show the test results from the controlled shear rate in the ball-measuring system, while Fig. 5.3c, d present the test results from the controlled shear rate in the vane-measuring system. The Busan clays generally exhibited a shear thinning flow behaviour; i.e., viscosity decreases with an increasing shear rate (Fig. 5.3b, d). In the shear rate controlled system, the rotational speed gradually increased with time (i.e., the variation in shear rate = 0.0001 ~ 62 s^{-1}). The shear stress increases with increasing shearing mode at the beginning of rotation and at the shear rate between 10^{-5} and 10^{-3} s^{-1}. The

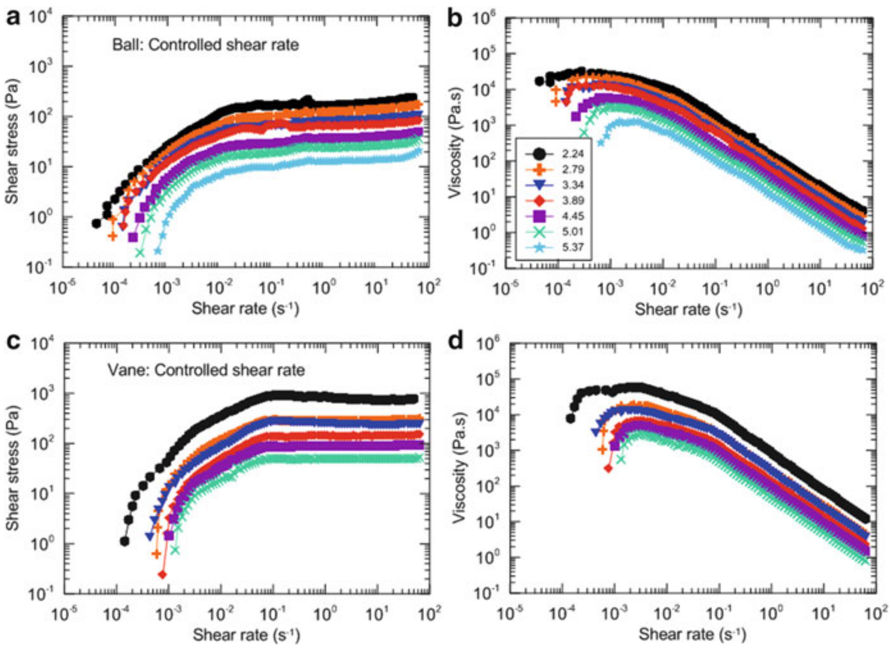

Fig. 5.3 Flow curves of the Busan clays: (**a**–**b**) ball measuring system and (**c**–**d**) vane measuring system. *Symbols* indicate the liquidity index

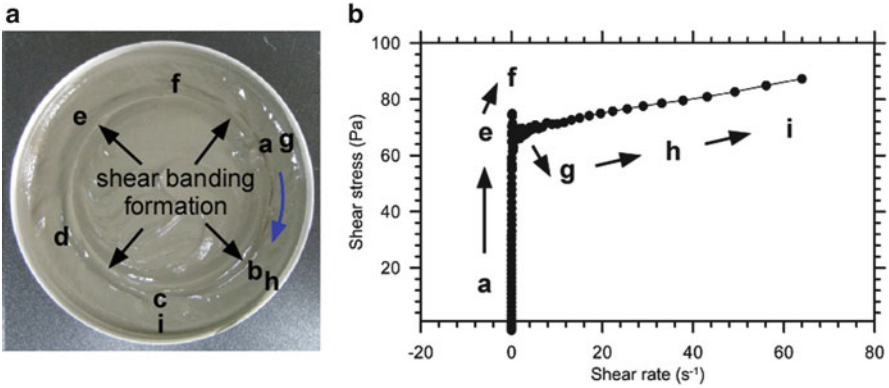

Fig. 5.4 Shear banding in ball-measuring rheometry and flow curve for $I_L = 3.9$

transition from a Newtonian plateau to a power-law regime is observed when the shear rate is larger than 10^{-3} s^{-1} (see Fig. 5.3b, d). A sudden abrupt change in shear stress was often observed in ball-measuring systems for relatively sticky materials (i.e., high plasticity), because of the small uplift just before the ball returns to the original position (see Fig. 5.2f, g for $I_L = 2.2$, 2.8 and 3.3). However, this change is almost undetectable in the vane-measuring system. The power-law regimes are distinct in the range of 10^{-1} and 10 s^{-1}, both for the ball and the vane-measuring systems. Similar results were found by Barnes (1999). When the shear rate reaches the highest value (i.e., shear rate → 100 s^{-1}), the Busan clays examined behave as an ideal Bingham fluid (see Fig. 5.4b). This occurs in the stage where the sphere rotates from point (g) to point (i) in Fig. 5.2 (see Fig. 5.3a, c).

Assuming that the flow behaves like a Bingham fluid, we can determine the plastic viscosity (η_h) and the Bingham yield stress (τ_c) for various volumetric concentrations of solids. It should be noted that, for fine-grained sediments, the Bingham yield stress is very close to the apparent yield stress (i.e., Imran et al. 2001) when the bi-viscosity model was applied (Jeong 2013). Hereafter, we can use the term Bingham yield stress rather than apparent yield stress. The shear banding formation after one rotation of the sphere in the soil samples is shown in Fig. 5.4a for an $I_L = 3.9$. The flow curve for this specific test is shown in Fig. 5.4b. Here the letters (a) to (i) represent the different location of the ball during the test (also see Fig. 5.2). The first rotation is completed when the ball reaches point (g). An apparent yield stress appears just before reaching point (g). After the appearance of yield stress, the results show that plastic viscosity governs the flow (from point **g** to point **i**). The same results were observed for coaxial cylinder and vane rheometry.

For fine-grained sediments encountered in various environments, rheological properties can be correlated with a liquidity index in a semi-logarithm or log-log diagram (Locat 1997): (*i*) liquidity index and plastic viscosity and (*ii*) liquidity index and yield stress. It is generally accepted that these findings can be utilized as input parameters to model subaerial and subaqueous debris flows. Based on these relationships, a comparison between Busan clays and low-activity clays is

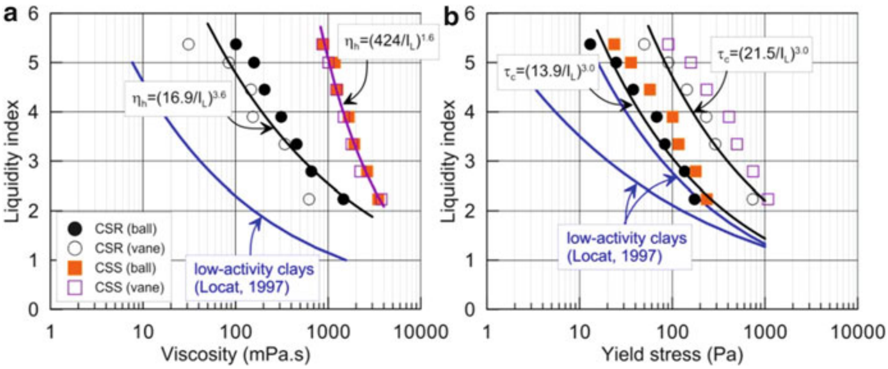

Fig. 5.5 Relationship between liquidity index and rheological values: (**a**) viscosity and (**b**) yield stress

shown in Fig. 5.5. There is a positive relationship between the liquidity index and the rheological values, but the differences in correlations are significant in the controlled shear rate mode. The viscosities determined from the ball and the vane are very close, but the differences in yield stress are distinct. Similar findings are also observed in the controlled shear stress mode.

5.4 Discussion

The rheological characteristics of Busan clays typically exhibit a shear thinning and thixotropic behaviour. Similar results were observed for low-activity clays (e.g., Coussot and Piau 1994; Møller et al. 2006; Locat 1997). The flow motion of clay-rich materials can be modelled using the bi-viscosity rheological law (Locat et al. 2004). These findings will help in understanding the motion of a debris flow with a long travelling distance. Practically, Fig. 5.5 may be useful for a preliminary numerical analysis for subaerial and subaqueous landslides (Locat and Lee 2002). Similar research using these relationships for fine-grained sediments was completed by Locat et al. (2009). In general, rheological characteristics depend on shear rate and geometry. In this research, it was assumed that the observed rheological differences for the Busan clays between cylinder, ball and vane geometries will be the same as those of marine clays found in the Ulleung basin, East Sea, Korea. For the same geomorphological and geotechnical conditions, therefore this study can compare the flow mobility using the rheological properties obtained from different geometries of viscometers.

Based on the geomorphological features in the Ulleung Basin, East Sea, various types of submarine landslides are identified (Fig. 5.6a), including slumps, slides, rockfalls, debris flows and turbidites that occurred along the entire margin of the basin overlain by Holocene hemipelagic muds (Chough et al. 1985). Flow

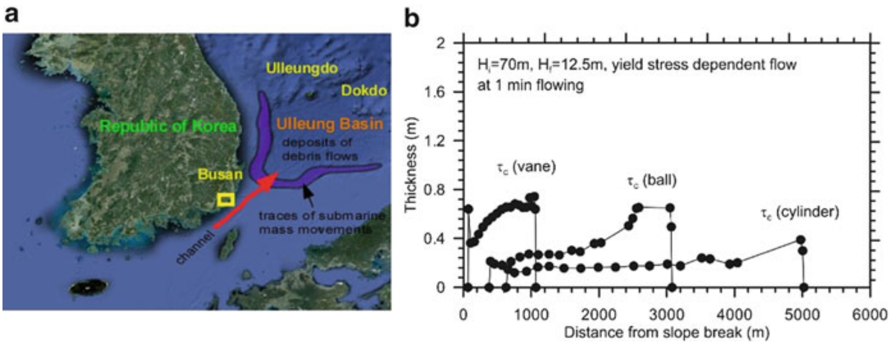

Fig. 5.6 Shearing in the post-failure stage and possible implications of debris flow modelling: (**a**) submarine mass movements in the Ulleung Basin, East Sea and (**b**) runout distance prediction for the Bingham fluid case

transformation (i.e., the transition from slide to flow) may be one of the possible mechanisms for explaining high mobility mass movements encountered in the Ulleung Basin. To investigate the post-failure dynamics of submarine landslides in the Ulleung Basin, we need a detailed investigation of geotechnical and rheological characteristics of fine-grained sediments and to develop a robust rheological model.

In debris flow mobility, yield stress is an important parameter for estimating the final deposition. For the determination of rheological properties for fine-grained sediments, a detailed analysis of the rheological properties and the complete methodology are described by Locat and Demers (1988). We compared debris flow mobility as a function of yield stress determined from Fig. 5.5. At the liquidity index equal to 3, the yield stresses can be given as 20, 100 and 400 Pa (these values are most likely too low to compare in situ conditions, but in this research the authors tried to compare flow motion; in other words, this paper doesn't deal with the exact determination of rheological characteristics of fine-grained sediments encountered in the Ulleung Basin) for cylinder, ball and vane-measuring rheometry, respectively. The yield stress calculated from vane geometry is the largest value, and the yield stress calculated from cylinder geometry is the lowest value, which may be because the wall-slip cannot be avoided. Based on geotechnical and rheological compilations, debris flow mobility was analyzed using a BING (Imran et al. 2001). Based on the Bingham rheological law (for numerical simulation, mud density = 1,500 kg/m^3, Herschel-Bulkley exponent $n = 1$, and reference shear rate = 1), the yield stresses can be determined: τ_c vane > τ_c ball > τ_c cylinder. As a consequence, assuming that the materials behave as a Bingham fluid, runout distances can be predicted at 1 min flowing conditions when the height and deposits of the debris flows are 70 and 12.5 m (data from Locat et al. 2004 for comparison), respectively (Fig. 5.6b). It should be noted that rheological measurements are related to wall roughness and the distance between soil samples and the wall. In a coaxial cylinderic system, there are no rough surfaces in a viscometer with a very small container (the samples can be placed in a container of 6 ~ 70 cm^3).

The ball-measuring and vane-measuring systems are relatively larger (0.5 L) than the cylinderic type. The distance between the ball and the container wall is much smaller than the distance between the vane and the container wall. Wall-slip has a minor effect for highly diluted suspensions; however, for sticky materials (highly structured soil samples), the wall-slip effect cannot be neglected. Therefore, geotechnical and rheological tests should be carried out in the future for muddy sediments, which are sampled from the landslide deposits in the Eastern part of the Ulleung Basin. A comparison should be made for the materials from the Busan clays in the Nakdong deltaic plain and from muddy sediments from the Ulleung Basin.

5.5 Conclusions

Rheological properties of the Busan clays were examined using ball-measuring and vane-measuring rheometry. In particular, the effect of wall-slip was emphasized. The Busan clays have characteristics of a shear thinning fluid similar to other low-activity clays. Rheological properties are positively correlated with index properties. For this reason, the relationships between liquidity index and rheological properties can be used to provide a first estimate of debris flow mobility. However, to provide guidance in the selection of strength parameters where numerical models are used to simulate debris flows, technical errors should be minimized. There are significant differences in rheological properties between coaxial cylinder and ball (vane)-measuring systems. The yield stresses can be determined: τ_c vane > τ_c ball > τ_c cylinder. Different yield stresses directly affect the runout distance of flowing materials, and wall-slip is the main cause of inconsistency in the results. More laboratory data and field observations are needed to confirm the relationships proposed in this study.

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