Drainage and shear velocity dependent shear characteristics of granular materials: rheological concept and debris flow mobility

Caractéristiques des cisaillements des matériaux granulaires selon la vitesse de cisaillement et drainage: Concept rhéologique et mobilization des coulée de débris

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ABSTRACT: This paper presents the shear characteristics of granular materials as a function of drainage and shear velocity using a ring shear apparatus, which was designed at Korea Institute of Geoscience and Mineral Resources (KIGAM). A series of ring shear tests were performed for the Jumunjin sands (SP) and gravels (GP) with mean grain diameter of 0.6 mm and 6 mm, respectively. The torque was measured for a given volume of sample (i.e., 2800 cm^3) placed in ring shear box. The upper ring is fixed while the lower ring is rotatable under the unlimited shear deformation. The test results were compared under the various normal stresses, drainage and shear velocity conditions for a given volumetric concentration of solid (i.e., density dependent soil behavior). According to the preliminary test results, it is clear that the strain softening behavior is observed for the shear velocity higher than 0.1 mm/sec; however, the distinctive nature of strain hardening is clearly observed when the velocity is lower than 0.1 mm/sec, irrespective of drainage condition. In the flow diagram (i.e., the shear stress-shear velocity plot), the slope can be viscous resistance; and the y-intercept value can be represented as the yield strength in soil rheology. Yield strengths (τ_y) are significantly influenced by sample density: as expected, the yield strength increases with increasing density. The yield strength obtained from the drained condition is larger than that from the undrained condition because of grain crushing effect.

RÉSUMÉ : Cet article présente les caractéristiques des cisaillement des materiaux granulaires en fonction du drainage et de la vitesse de cisaillement utilisant un appareil de cisaillement annulaire dévéloppe par l'Institut Coréen des Géosciences et des Ressources Minérales (KIGAM). Une série de tests de ciasaillement en anneaux a été effectuée pour les sables de Jumunjin (SP) et graviers avec un diamètre moyen des grains de 0.6 mm et 6 mm, respectivement. Le couple a été mesuré pour un volume d' échantillon donné (c'est-a-dire, 2800 cm^3) placé dans une caisse de cisaillement annulaire. La bague supérieure est fixe tandis que la bague inférieure peut tourner. Les résultats des essais ont été comparés sous les differentes contraintes normales, les conditions de drainage et de vitesse de cisaillement pour une concentration volumétrique donnée de solide. Selon les résultats préliminaires du test, il est clair que les comportment de l'anti-écrouissage est observé pour la vitesse de cisaillement supérieure à 0.1 mm/sec; cependant, le caractère distinctif d'écrouissage est clairement observé lorsque la vitesse est inférieure à 0.1 mm/sec, indépendamment de l' état de drainage. Dans le diagramme rhéologique, la pente peut être une résistance visqueuse; et la valeur d'intersection y peut être réprésentee comme la contrainte de cisaillement. Les valeurs sont fortement influencés par la densité de l' échantillon: comme prévu, les valeurs augmentes avec la densité. La contrainte de cisaillement obtenue à partir de l' état drainé est supérieure à celle de l' état non drainé à cause de l'effet de broyage du grain.

KEYWORDS: ring shear test, granular materials, sand-gravel mixture, rheology, debris flow.

1 INTRODUCTION

The shear strength of soil is one of important parameters to estimate the failure and post-failure features in mass movement (Lambe and Whitman 1979, Leroueil et al. 1996, Leroueil 2001, Locat and Lee 2002, Jeong et al. 2013). The shear strength can be influenced by many factors, such as drained condition, vertical loading, shear rate, and so on. In particular, grain size dependent shear characteristics still remain a question with respect to deformation and restoration. In this study, we examined the shear strength of sand-gravel mixtures dependent on drainage and shear velocity using a ring shear apparatus designed by Korea Institute of Geoscience and Mineral Resources (KIGAM). It is well known that the ring shear tests are good for examining the shear behavior with respect to the large deformation of slope failure (Sassa et al. 2003, Wang et al. 2002, 2010, Fukuoka et al. 2006, 2007, Li et al. 2013, Jeong et al. 2011, 2014). The ring shear box has 250 mm diameter and 75 mm height. The apparatus can measure the normal stress, shear stress, pore water pressure and vertical deformation during unlimited shearing. Drained and undrained conditions can be adjusted when the valves that locate in the ring shear box is open or closed. The degree of saturation is important in ring shear tests (Sassa et al. 2004). In general, vertical loading for a given time (i.e. 500 sec) is allowed for appropriate consolidation and saturation. Limited shear velocities were used for sand-gravel mixtures. In this study, the shear velocities are selected in order: for example, 0.01→0.1→1→10→100 mm/sec. However, it may be belong to the moderate shear velocity of landslides: i.e. 0.001-180 mm/sec (WP-WPI 1995).

The test results from the ring shear tests in a shear velocity-control mode can be presented as follows: (i) consolidation and saturation, (ii) shear stress-displacement or time plot, (iii) shear stress-shear velocity plot and (iv) grain crushing and grain size distribution in a shear plane. Therefore the shear characteristics of sand-gravel mixtures are examined with respect to the drainage, shear velocity and grain crushing. As a bonus, we discuss the effect of grain crushing on granular soil behavior and flow propagation in mass movements.

2 MATERIALS AND SAMPLE PREPARATION IN RING SHEAR TESTING

The materials were selected Jumunjin sands and aquarium gravels with mean grain diameter of 0.6 mm and 6 mm, respectively. The materials were mixed for 50% of sands and 50% of gravels in air-dry condition. The materials were put on the ring shear box; and the water slowly infiltrate into the soil samples. After full saturation, the shear velocity was selected; and the shear stress was measured during shearing. Figure 1 presents the consolidation and saturation process before shearing. Normal stress was slowly loaded for a given time of 500 sec in drained and undrained condition. Vertical displacement were sudden observed when the loading was imposed at the top of soil samples. After this procedure, air bubble was removed mannualy and rest for 1-24 hours for full saturation. The detailed test procedure can be found in Sassa et al. (2004).

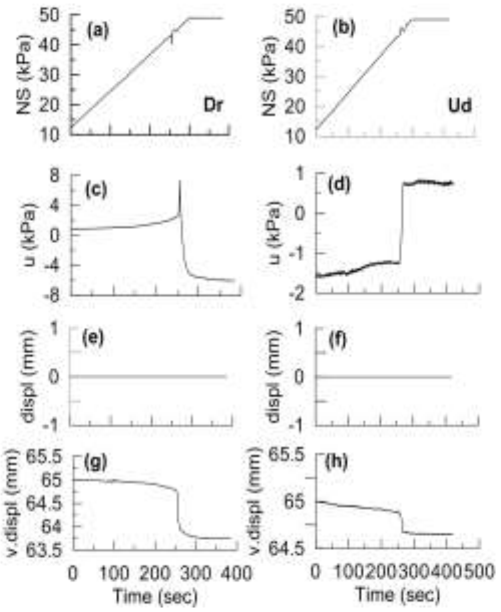

Figure 1. Test setup and saturation before shearing: (a, c, e, g) drained and (b, d, f, h) undrained condition. (a-b) normal stress (NS) is given for 400 sec, (c-d) water pressure (u) measured in the shear zone located between upper and lower ring shear box in apparatus, (e-f) horizontal displacement is negligible during consolidation and saturation and (g-h) vertical displacement is measured during time.

3 RESULTS AND DISCUSSION

Figure 2 presents the shear stress measurements obtained from the shear velocity of 0.01 mm/sec in different drained conditions at the same normal stress (50 kPa). At 300 sec, it seems that the materials would resist the shear deformation. The materials tested typically exhibited a strong strain-hardening behavior during shearing. It is clear that the shear stress is strongly influenced by the shear velocity (Fig. 3). For a relatively high shear velocity (V), such as V > 1 mm/sec in ring shear tests, the materials exhibited a strain-softening behavior; in this case, residual shear strengths of sand-gravel mixtures are easily visible. In particular, for a relatively low shear velocity, it seems that the vertical displacement is not very sensitive to the drainage condition. However, a sudden reduction in vertical displacement is observed at the initiation of grain-grain interlock and rolling in shearing. There is a little difference in pore water pressure at the first resistant stage. It remains a question for a relatively low shear velocity; the variation is very small and seems to be stable after the peak value.

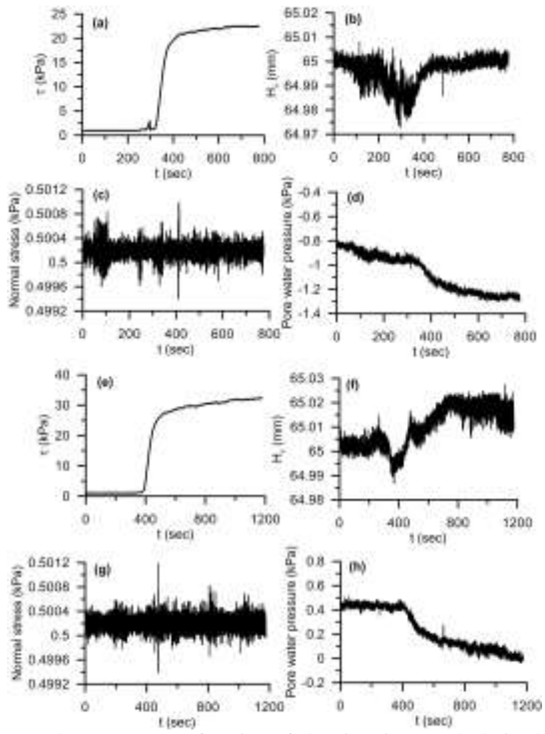

Figure 2. Shear stress as a function of shearing time. (a-d) drained and (e-h) undrained condition. (a and e) shear stress measured with shearing time, showing strain-hardening behavior, (b-f) vertical displacement with time, (c-g) normal stress (50 kPa is applied) measured during time and (d and h) pore water pressure measurement.

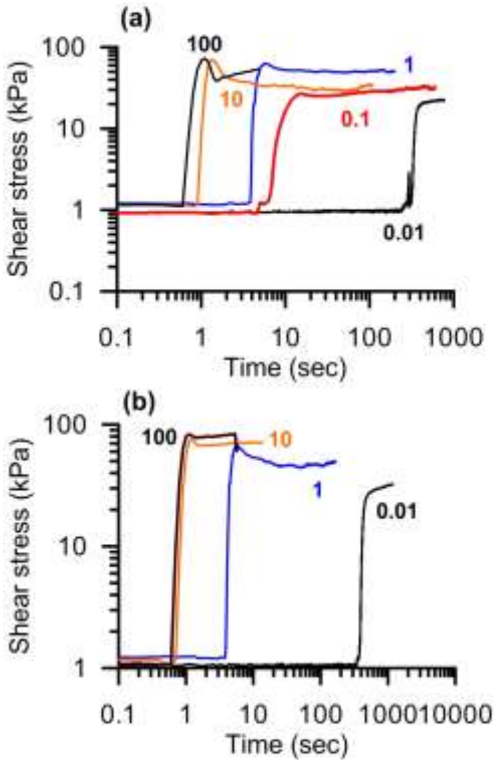

Figure 3. Shear stress as a function of shear velocity ranged from 0.01-100 mm/sec: (a) drained and (b) undrained condition.

Figure 3 shows the shear stresses-shearing time plots for given shear velocities, which are ranged from 0.01 to 100 mm/sec. Higher shear velocities result in higher shear stresses in ring shear tests; the greater the shear velocity the higher peak and residual shear strengths. The shear stress in the undrained condition is more easily observed than those in the drained condition. For V > 1 mm/sec, the strain-softening behavior may be distinct under both drained and undrained conditions.

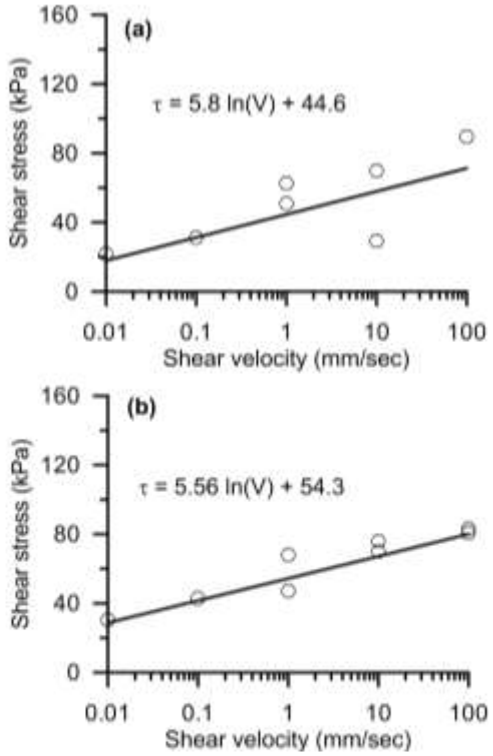

Figure 4. Shear stress and shear velocity in semi-logarithmic plot.

Figure 4 presents the shear stress-shear velocity plots obtained from different drainage conditions. Test results have linear relationships, even for some scatters. The relationships are obtained from both peak and residual shear strengths of sand-gravel mixtures. From a rheological point of view, the slopes in these plots are the viscous function, i.e. plastic viscosity; the y-intercepts are the yield strength. The viscous resistance under drained condition is much higher than those under undrained condition. The yielding surface under drained condition is smaller than those under undrained condition.

Equations obtained from the relationship between shear stress and shear velocity are given as below.

$$\tau = 5.8 \cdot \ln(V) + 44.6 \quad (1)$$

$$\tau = 5.6 \cdot \ln(V) + 54.3 \quad (2)$$

where, τ is shear stress (kPa) and V is shear velocity (mm/sec).

4 GRAIN CRUSHING AND DEBRIS FLOW MOBILIZATION FOR GRANAUAL MATERIALS

Figure 5 presents the slip surface examination of the sand-gravel mixtures after shear stress measurements. The previous research demonstrates that the effect of grain crushing on the granular soil behavior is significant (Feda 2002, Fukuoka and Sassa 1991). In debris flow dyanmics, sediment entainment with respect to grain crushing is important in mass movements (Wang and Sassa 2000, 2002, Okada et al. 2004, Hungr et al. 2005, Sassa et al. 2007, Wafid et al. 2014). According to Jeong et al. (2014), the slip surface can be clearly observed regardless of drainage and shear velocity conditions. For fines, it is very easy to find the slip surface in both drained and undrained conditions. However, it may be not so clear for large-particulared soil mixtures, such as sands and gravels, because of low cohesion and high disturbance in a ring shear box. In this case, the slip surface can be observed in the drained condition, but not for the undrained condtion. Higher grain cruching is dominant in both condition, but it can be concluded that the grain crushing is more significant under drained condition (Fig. 6). In general, grain crushing may be related to the sediment entrainment during flow propagation in mass movements. Under drained condition, compaction and fragmentation may contribute to generate more fines and increase the flow mobility. Under undrained condition, the degree of sediment compaction and fragmentation is slightly lower than drain condtion, but the increase in pore water pressure may result in high flow mobilization. Both can product high speed and long runout distance of failed masses in a post-failure stage. For a grain cruishing, the difference in the soil resistance between ring shear tests and rheometric tests remains a question. The future work will be examined the yield strength and viscosity determination with respect to the grain crushing.

(a) Drained (b) Undrained

Figure 5. Sand-gravel mixtures in a ring shear box.

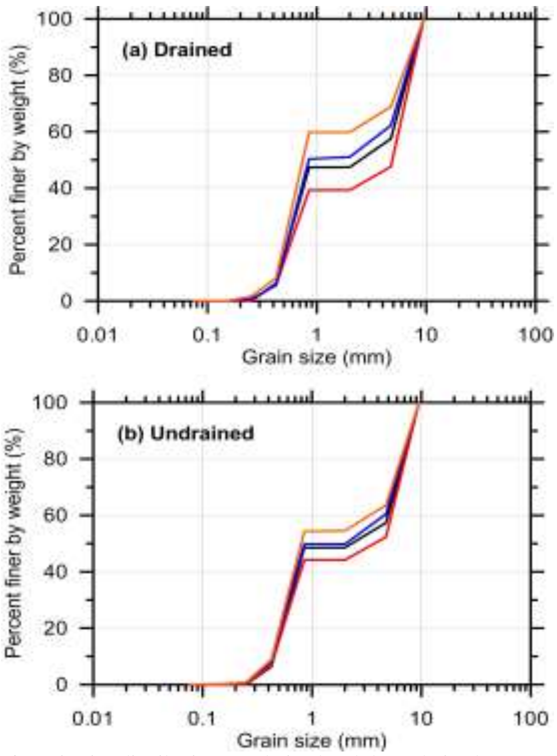

Figure 6. Grain size distribution: (a) drained and (b) undrained.

5 CONCLUSION

In this study, a series of ring shear tests were performed for sand-gravel mixtures. The shear stress characteristics were examined dependent on drainage (i.e. drained and undrained conditions) and shear velocity (i.e. 0.01-100 mm/sec). The test results are summarized as follows:

(1) It is clear that the shear stress is strongly influenced by the shear velocity. The materials tested typically exhibited a strong strain-hardening behavior when shear velocity (V) is lower than 0.1 mm/sec. For a relatively high shear velocity, such as V > 1 mm/sec in ring shear tests, the materials exhibited a strain-softening behavior.

(2) The slopes in τ-V plots are the viscous resistance; and the y-intercept values are the yielding points in the Bingham rheological concept. The viscous resistance under drained condition is much higher than those under undrained condition. The yielding surface under drained condition is smaller than those under undrained condition.

(3) High grain crushing is easily oberved in both drained and undrained conditions, but it can be concluded that the grain crushing is more significant in drained condition. In particular, the materials with larger particles, i.e. sands and gravels, can be easily crushed or miled during shearing.

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7 REFERENCES

Feda, J. 2002. Notes on the effect of grain crushing on the granular soil behaviour. *Engineering Geology* 63, 93-98.

Fukuoka H. and Sassa K. 1991. High-speed high-stress ring shear test son granular soils and clayey soils. General Technical Report, PSW-GTR-130, USDA Forest Service, 33-41.

Fukuoka H. Sassa K. Wang G. and Sasaki R. 2006. Observation of shear zone development in ring-shear apparatus with a transparent shear box. *Landslides* 3, 239-251.

Fukuoka H. Sassa K. and Wang G. 2007. Influence of shear speed and normal stress on the shear behavior and shear zone structure of granular materials in naturally drained ring shear tests. *Landslides* 4, 63-74.

Hungr O. McDougall S. and Bovis M. 2005. Entrainment of material by debris flows. In: Jakob, M. and Hungr, O. (eds.), Debris-Flow Hazards and Related Phenomena, Springer, New York, p. 135-158.

Jeong S.W. Fukuoka H. and Song Y.S. 2011. Ring-shear apparatus for estimating the mobility of debris flow and its application. Journal of the Korean Society of Civil Engineers, 33, 181-194. (in Korean)

Jeong S.W. Locat J. Leroueil S. and Robert J.-L. 2013. Fluidization process in submarine landslides: physical and numerical considerations, *Marine Georesources & Geotechnology* 31, 190-207.

Jeong S.W. Park S.S. and Fukuoka H. 2014. Shear behavior of waste rock materials in drained and undrained ring shear tests. *Geosciences Journal* 18(4), 459-468.

Lambe T.W. and Whitman R.V. 1979. *Soil Mechanics*. SI Version, John Wiley & Sons, 553p.

Leroueil S. Vaunat J. Picarelli L. Locat J. Faure R. and Lee H. 1996. Geotechnical characterization of slope movements. In: Senneset, K. (ed.), Proceedings of the 7th International Symposium on Landslides, Trondheim, Norway, 53-74.

Leroueil S. 2001. Natural slopes and cuts: movement and failure mechanisms, *Geotechnique* 51, 197-243.

Locat J. and H.J. Lee. 2002. Submarine landslides: advances and challenges. *Canadian Geotechnical Journal* 39, 193-212.

Li Y.R. Wen B.P. Aydin A. and Ju N.P. 2013. Ring shear tests on slip zone soils of three giant landslides in the Three Gorges Project area. *Engineering Geology* 154, 106-115.

Okada Y. Sassa K. Fukuoka H. 2004. Excess pore pressure and grain crushing of sands by means of undrained and naturally drained ring-shear tests. *Engineering Geology* 75, 325-343.

Sassa K. Wang G. and Fukuoka H. 2003. Performing undrained shear tests on saturated sands in a new intelligent type of ring shear apparatus. *Geotechnical Testing Journal* 26, 1-9.

Sassa K. Fukuoka H. Wang G. and Ishikawa N. 2004. Undrained dynamic-loading ring-shear apparatus and its application to landslide dynamics. *Landslides* 1, 7-19.

Sassa K. Fukuoka H. Wang F. and Wang G. 2007. *Progress in Landslide Science*. Springer, Berlin, 378p.

Wafid M.A. Sassa K. Fukuoka H. and Wang G.H. 2004. Evolution of shear-zone structure in undrained ring-shear tests. *Landslide* 1, 101-112.

Wang F.W. Sassa K. 2000. Relationship between grain crushing and excess pore pressure generation by sandy soils in ring shear tests. *Journal of Natural Disaster Science* 22, 87-96.

Wang F.W. Sassa K. and Wang G. 2002. Mechanism of a long-runout landslide triggered by the August 1998 heavy rainfall in Fukushima Prefecture, Japan. *Engineering Geology* 63, 169-185.

Wang G. and Sassa K. 2002. Post-failure mobility of saturated sands in undrained load-controlled ring shear tests. *Canadian Geotechnical Journal* 39, 821-837.

Wang G. Suemine A. and Schulz W.H. 2010. Shear-rate-dependent strength control on the dynamics of rainfall-triggered landslides, Tokushima Prefecture, Japan. *Earth Surface Processes and Landforms* 35, 407-416.

WP-WPI. 1995. A suggested method for describing the rate of movement of a landslide. International Union of Geological Sciences Working Group on Landslides. *Bulletin of the International Association of Engineering Geology* 52(1), 75-78.