7th International Conference on Debris-Flow Hazards Mitigation

Effect of rheological properties on debris-flow intensity and deposition in large scale flume experiment

Ba-Quang-Vinh Nguyen[a], Ji-Sung Lee [a], Yun-Tae Kim [a*],
Seung-Rae Lee [b], Tae-Hyuk Kwon [b]

[a] *Dept. of Ocean Engineering, Pukyong National Univ., Busan, Republic of Korea*
[b] *Dept. of Civil and Environmental Engineering, KAIST, Daejeon, Republic of Korea*

Abstract

Debris flows are one of the most serious hazards in the mountainous areas. To assess and mitigate the debris-flow hazard, debris-flow intensities and deposition on fans must be estimated. Rheological properties including yield stress and viscosity are major parameters to describe and predict behaviors of debris flow. In the present study, the effect of rheological properties on debris-flow intensities and deposition on fans of natural clay was investigated using large scale flume experiments. The experimental device employed in the tests consists of a tilting flume with an inclination 17°, on which a steel tank with a removable gate was installed. A final horizontal plane works as the deposition area. Natural soil samples of different water contents were tested. Rheological properties of soil mixtures were obtained from vane-rheometer tests. Non-linear regression analysis was used to assess the effect of yield stress and viscosity on debris-flow velocity, runout distance, deposited area and deposited volume. We found that the relationship between surface velocity profile and horizontal distance was complicated and could be expressed by sixth order polynomial function. Mean velocity, runout distance, deposited area decreased following a power law with an increase in yield stress and viscosity. Empirical equations were proposed to estimate these properties. The results of laboratory tests compared reasonably well with the results from numerical analysis. The results indicated that yield stress and viscosity play a significant role in the behavior of debris flow.

Keywords: Debris-flow intensities; debris-flow deposition; flume test; rheological properties.

1. Introduction

A debris flow is a moving mass of loose mud, sand, soil, rock, water and air that travels down a slope under the influence of gravity. High velocities and deposition on debris-flow fan are a hazard to residential areas. On July 27, 2011, a large catastrophic debris flow occurred in Seoul in Korea, this debris flow event caused the deaths of 49 people and affected 125,000 people. Therefore, the evaluation of debris-flow intensities and their deposition on fans are a key requirement to reduce the risk from debris flow. The debris-flow intensities can be expressed through velocity and runout distance. The deposition on fan can be represented by deposited area and deposited volume. Until now, many researchers have focused on the estimation and assessment of velocity, runout distance and volume of debris flow. The velocity and runout distance of a debris flow can be assessed via two methods including: theoretical methods (Hungr et al. 1984, Cannon and Savage 1988, Van Gassen and Cruden 1989, Takahashi 1991, Hungr 1995, VanDine 1996, Iverson 1997, Rickenmann 2005, Armanini et al. 2009) established mass and momentum conservation equations using the depth-integrated method based on the continuum theory; empirical methods estimated debris-flow properties using regression analysis based on data from field observatory or flume experiment (Hungr et al. 1984, Johnson 1984, Ikeya 1989, Corominas 1996, Rickenmann 1999, Chen and Jan 2000, Marchi and D'Agostino 2004). The key steps in theoritical methods are the selection of parameters that can be difficult to accurately estimate, such as rheological properties, flow depth, flow velocity along the channel, etc…; while the formulas obtained from

* Corresponding author e-mail address*: yuntkim@pknu.ac.kr*

empirical methods are limited to specific regions or flow conditions. In addition, the above studies have not considered clearly the effect of soil properties: grain size, clay fraction, water content, solid volumetric concentration, yield stress and viscosity on debris-flow behavior. From this point, this paper assess the effect of rheological properties on velocity, runout distance and deposition on fan of debris flow using the series of large scale flume experiment with natural clay at different water contents. Rheological properties of natural clay including yield stress and viscosity were obtained by large scale vane rheometer test. We compared results of flume tests with analysis using the BING numerical model. The results indicate that rheological properties like yield stress and viscosity play an important role in debris-flow behavior.

2. Materials and Methods

The laboratory tests were carried out using natural clay were collected from Miryang and Hwangnyeong mountains in Korea. Both soils in Miryang and Hwangnyeong mountains were classified as well graded sand-clay (SW-SC) with particle size distribution curve is shown in Fig. 1. In the laboratory tests, water content of material sample ranges from 48.9% to 83.2% in flume experiments and from 36% to 59% in vane rheometer tests as presented in Table 1. A series of large scale vane rheometer test and flume experiments were carried out to assess the effect of debris-flow rheological properties on velocity, runout distance and deposition on fan. A woody flume with a cross section is a isosceles trapezoid, with 4 m long and was adjusted to a slope angle of 17° for this set of experiments (Fig. 2). Then, the results of laboratory tests were compared with the results from simulations using Bing model. BING is a one-dimensional model for simulating the flow of debris flows. The governing equations are integral forms obtained from the slender flow approximations typical in the application of Boundary Layer Theory. Slope angle is assumed to be sufficiently small to allow the approximations $\sin\theta \approx \tan\theta \approx S$ and $\cos\theta \approx 1$; here S is bed slope. The general formulation used in BING is described in Imran et al. (2001). It is based on the formulation for a Bingham slurry. The numerical formulation is the Lagrangian scheme.

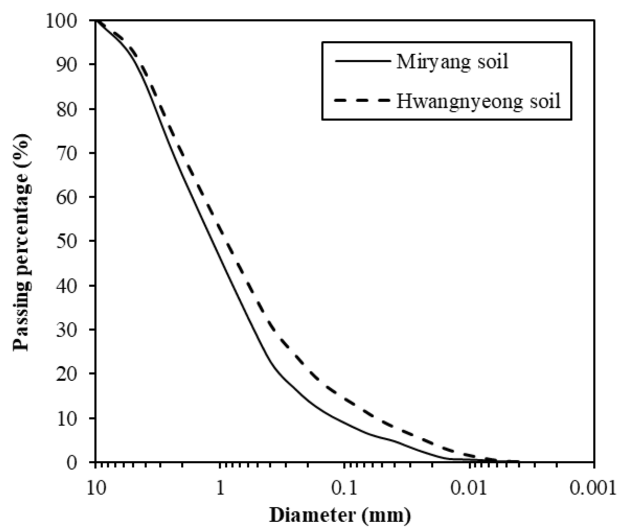

Fig. 1. Particle size distribution curve of soil sample

Table 1. List of the experiments of flume test and vane rheometer test

Soil	Flume experiment		Vane rheometer test	
	No.	Water content (w, %)	No.	Water content (w, %)
Miryang	1	48.9	1	36.4
	2	49.1	2	37.2
	3	56.8	3	40.9
	4	68.5	4	44.6
			5	49.0
Hwang-nyeong	1	51.5	1	44.7
	2	63.8	2	46.8
	3	67.3	3	49.8
	4	75.4	4	54.6
	5	79.1	5	59.3
	6	83.2		

3. Results and Discussion

3.1. Rheological properties

Fig. 3 presents a series of flow curves of the experimental results for Miryang soil (Fig. 3a) and Hwangnyeong soil (Fig. 3b) at different water content. All soil mixtures have a non-Newtonian fluid behavior. Experimental results showed that shear stress increased as shear rate increased at given water content. The test results are consistent with the results reported by Scotto Di Santolo et al. (2010), Jeong (2010), Kang (2016) and Nguyen et al (2018). Fig. 4a expresses the influence of water content on the yield stress (τ_y, Pa) for Miryang soil and Hwangnyeong soil. As water content increases an exponential decrease in the yield stress is observed. This relationship is in line with the experimental results of Kang (2016) and Nguyen et al. (2018). Fig. 4b shows the relationship between plastic viscosity and water content of soil materials in Miryang and Hwangnyeong mountains. An increase in water content is accompanied by an exponential decrease in the plastic viscosity (η, Pa.s) of all the tested soil mixtures, which is in line with the results obtained in a study of Ghezzehei and Dani (2001), Parsons et al. (2001), Kang (2016) and Nguyen et al. (2018). From these results, the yield stress and viscosity of soil mixtures used in the flume experiments were calculated from Fig. 4.

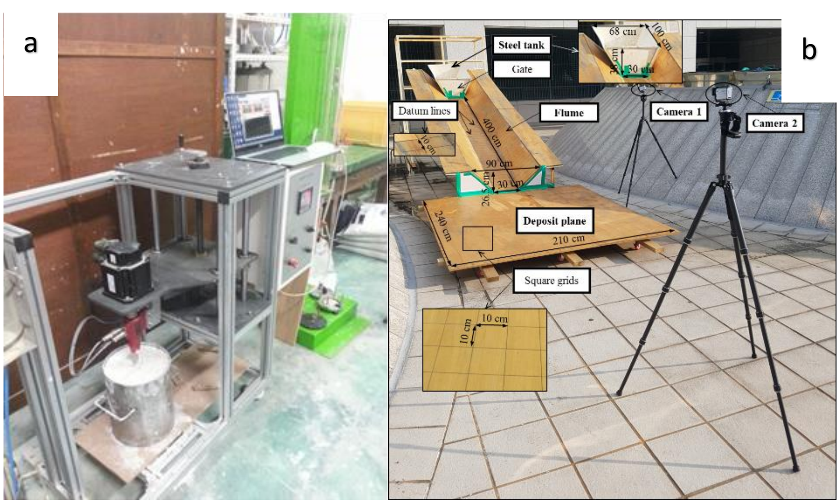

Fig. 2. (a) The large scale vane rheometer (Kang and Kim, 2016); (b) The large scale flume experimental device

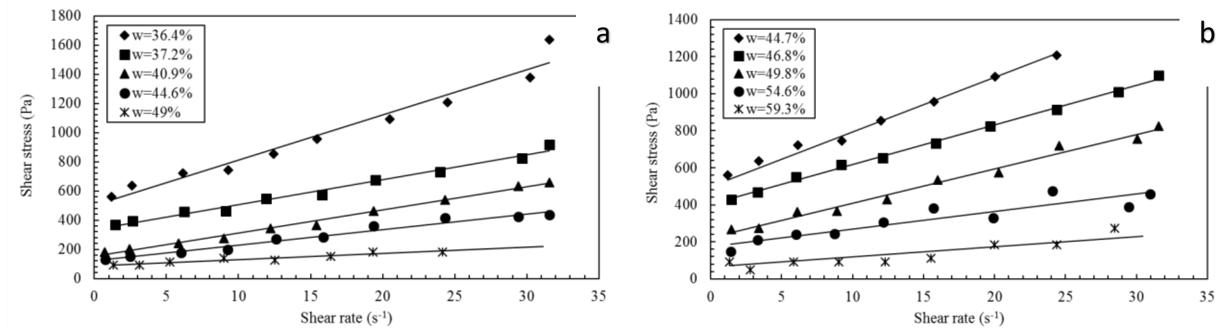

Fig. 3. Fitting rheological models obtained from experimental results at the different values of water content (a) Miryang natural clay; (b) Hwangnyeong natural clay

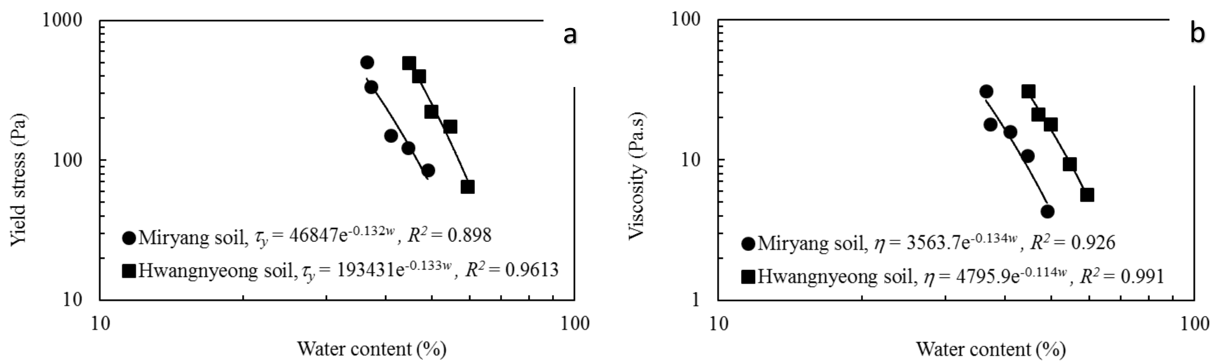

Fig. 4. Relationship between rheological properties and water content (a) Yield stress; (b) Viscosity

3.2. The effect of rheological properties on debris-flow properties

Fig. 5 shows front velocity profile of debris flow verus distance from the gate with different water content for Miryang soil (Fig. 5a) and Hwangnyeong soil (Fig. 5b). The sixth order polynomial function is a regression line of the front velocity profile with R^2>0.7. The front velocity can be described through three phases including: Phase 1, front velocity increases linearly with time and the rate of increase slightly depends on the rheological properties; Phase 2, the velocity increases to reach peak value. This value increase when water content increases. Location to reach peak front velocity also depends on water content. This result indicates that the peak velocity was very sensitive to the change of rheological properties of debris-flow material; Phase 3, front velocity decreases from peak then it increases again to reach another high value. Finally, it decreases to zero at the end of deposition area. The results of flume experiment were also compared with velocity profile obtained from BING simulation (Fig. 6). There were differences in the shape of experimental front velocity profiles from those of the BING model. In the Bing model, the velocity profile can be divided to two phase: firstly, velocity increases linearly to archive a peak value; secondly, the velocity decreases from peak value to zero at the end of deposition area. However, the effect of rheological properties on front velocity was clearly observed with the rate of increase of front velocity and the peak velocity increases with a decrease in values of the rheological properties-namely, viscosity and yield stress. These results indicate that front velocity of debris flow behaved in a complex manner with time and was very sensitive to the change of rheological properties.

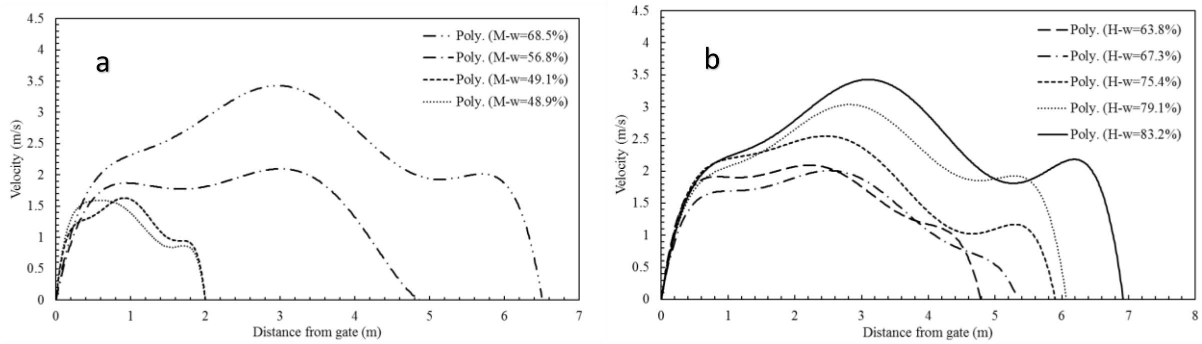

Fig. 5. Regression curve of front velocity profile of debris flow verus distance from gate at different water content (a) Miryang natural clay; (b) Hwangnyeong natural clay

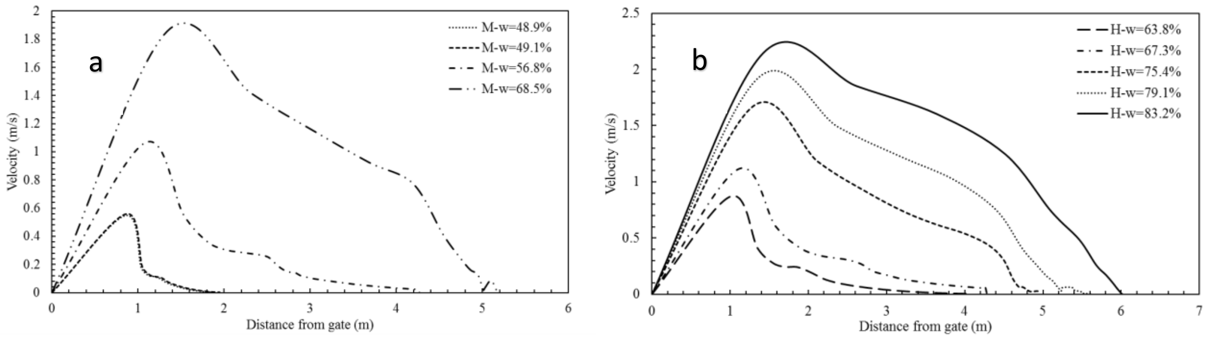

Fig. 6. Front velocity profile of debris flow verus distance from gate at different water content obtained from BING simulation (a) Miryang natural clay; (b) Hwangnyeong natural clay

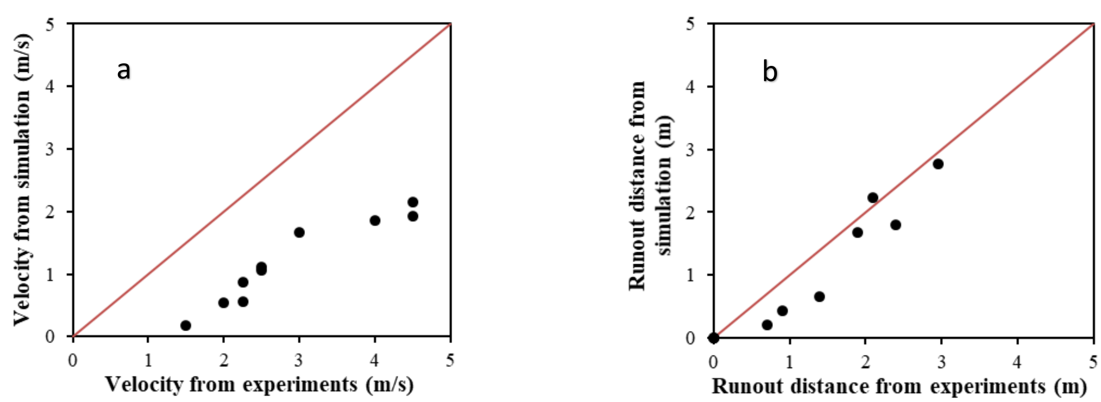

Fig. 7. Correlation between experiments and numerical simulation (a) Maximum velocity; (b) Runout distance

Fig. 7 presents the correlation of results between flume experiments and numerical simulation. Fig. 7a shows maximum velocity correlation between experiments and simulation with correlation coefficient is 0.827. Fig. 7b shows runout distance correlation between experiments and simulation with correlation coefficient is 0.937. There are underestimations in simulation results compared with experiment results. It could be explain as follows: in flume experiment, there is the change in viscosity of debris-flow material due to deposition on the flume during flow process, while in numerical simulation, Bing model could not consider this phenomenon.

Fig. 8 expresses the relationship between yield stress, viscosity and maximum front velocity (v_{max}, m/s) on the flume in a 3D-coordinate system. An increase in yield stress and viscosity is accompanied by an exponential decrease in the maximum front velocity, which is in line with the results obtained in a study of Ilstad et al. (2004) and Breien et al. (2007). These studies had not presented directly the relationship between average front velocity of debris flow and rheological properties but, they assessed the effect of clay fraction in debris-flow material on front velocity of debris flow using laboratory flume experiments. In general, the velocities of debris flow are decreasing with increasing in clay content of soil sample. Fig. 8 also shows the comparison between the results from laboratory experiments and the results from BING simulation. The results from numerical simulation also expresses the effect of yield stress and viscosity on front velocity following an exponential fit.

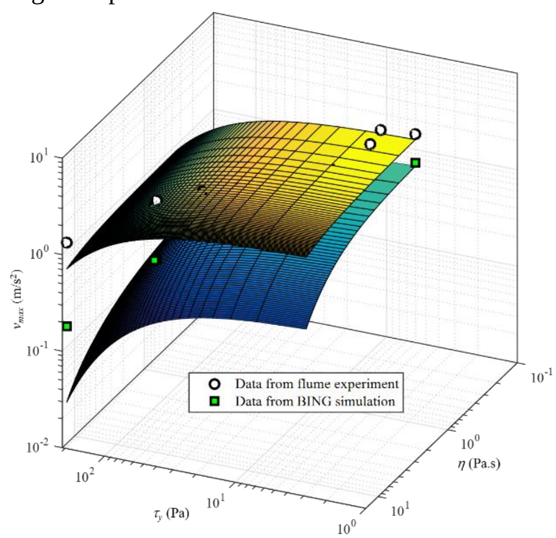

Fig. 8. Relationship between front velocity and yield stress, viscosity based on laboratory experiments and BING simulations

The relationship between runout distance (*R*, cm) and yield stress and viscosity is reported in Fig. 9. It can be observed that runout distance exponentially decreases with an increase in yield stress and viscosity. This result is consistent with the conclusion obtained in a study of D'Agostino et al. (2010) that reported the effect of solid volume concentration of debris-flow material on travel angle of debris flow. Hurlimann et al. (2015) also presented the relationship between runout distance and water content of soil mixture based on flume experiments. In general, runout distance increases when water content increases. Fig. 9 also shows the comparison between the results from laboratory experiments and the results from BING simulation. The results from numerical simulation also express the effect of yield stress and viscosity on runout distance following an exponential relationship.

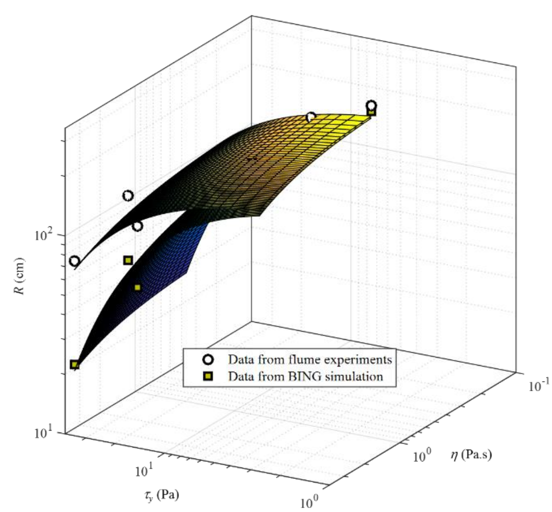

Fig. 9. Relationship between runout distance and yield stress, viscosity based on laboratory experiments and BING simulations

Fig. 10 expresses the relationship between yield stress, viscosity and deposited area (A, m^2) in a 3D-coordinate system. An increase in yield stress and viscosity is accompanied by an exponential decrease in deposited area and deposited volume, which is in line with the results obtained in the studies of Ilstad et al. (2004) and Hurlimann et al. (2015). Ilstad et al. (2004) reported the influence of clay content of the material on deposition thickness of debris flows, such that the deposit thickness increases as clay fraction decreases. Hurlimann et al. (2015) also presented the relationship between deposited area and water content of the soil mixture. In general, deposited area increases when water content increases.

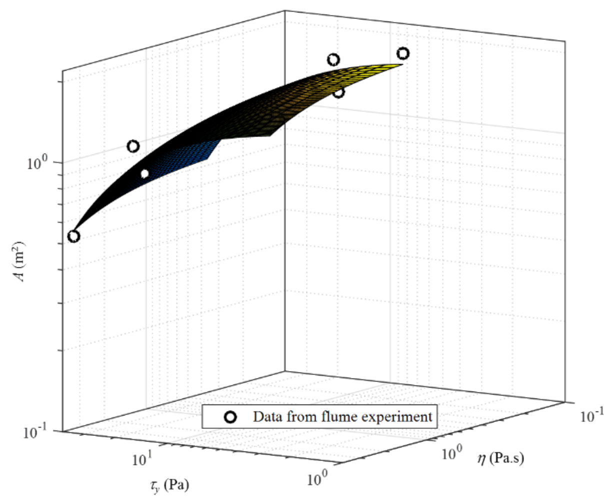

Fig. 10. Relationship between deposited area and yield stress, viscosity obtained from laboratory experiments

Average front velocity, runout distance and deposited area of debris flow can be calculated from best fit equation from Fig. 8, 9 and 10; as follows:

$$v_{max} = 3.840e^{-0.007\tau_y - 0.023\eta}, R^2 = 0.808 \quad (1)$$

$$R = 296.9e^{-0.030\tau_y - 0.104\eta}, R^2 = 0.903 \quad (2)$$

$$A = 2.260e^{-0.027\tau_y - 0.103\eta}, R^2 = 0.861 \quad (3)$$

It is noted that front velocity, runout distance and deposited area are more sensitive to the change of viscosity than the change of yield stress.

4. Conclusions

Several series of large size vane rheometer tests and large scale flume experiments were carried out in order to evaluate the effect of both yield stress and viscosity on the debris-flow intensities and deposition on fan. The following conclusions were drawn from the experimental test results: The front velocity profile could be described through three phases: Phase 1, front velocity increased linearly with time and the rate of increase was slightly dependent on rheological properties; Phase 2, the velocity increased to reach peak value at the middle of debris flow. This value increased when yield stress and viscosity decreased. The location of the peak front velocity also depend on the yield stress and viscosity; Phase 3, front velocity decreases from peak then it increases again to reach another high value. Finally, it decreases to zero at the end of deposition area. An increase in yield stress and viscosity was accompanied by an exponential decrease in the maximum and maximum front velocity. The maximum front velocity on the flume were more sensitive to the change of viscosity than the change of yield stress. Runout distance exponentially decreased with an increase in yield stress and viscosity and was more sensitive to the change of viscosity than the change of yield stress. Deposited area exponentially decreased with an increase in yield stress and viscosity, and was more sensitive to the change of viscosity than the change of yield stress.

Acknowledgements

This research was supported by a basic research grant from the National Research Foundation of Korea (NRF), funded by the Ministry of Education, Science and Technology (grant no. 2018R1D1A1B07049360), from the National Research Foundation of Korea (NRF), funded by the Korea government (grant no. 2018R1A4A1025765) and by funding from the Brain Korea 21 Plus (BK 21 Plus) initiative.

References

Armanini, A., Fraccarollo, L., and Rosatti, G., 2009, Two-dimensional simulation of debris flows in erodible channels: Computers & Geosciences, v. 35(5), p. 993-1006.

Breien, H., Pagliardi, M., De Blasio, F. V., Issler, D., and Elverhøi, A., 2007, Experimental studies of subaqueous vs. subaerial debris flows– velocity characteristics as a function of the ambient fluid: Submarine Mass Movements and Their Consequences, p. 101-110.

Cannon, S. H., and Savage, W. Z., 1988, A mass-change model for the estimation of debris-flow runout: The Journal of Geology, v. 96(2), p. 221-227.

Chen, J. C., and Jan, C. D., 2000, Debris flow occurrence probability on hillslopes, Proceedings of Debris Flow Mitigation: Mechanics, Prediction and Assessment.

Corominas, J., 1996, The angle of reach as a mobility index for small and large landslides: Canadian Geotechnical Journal, v. 33(2), p. 260-271.

D'Agostino, V., Cesca, M., and Marchi, L., 2010, Field and laboratory investigations of runout distances of debris flows in the Dolomites (Eastern Italian Alps): Geomorphology, v. 115(3), p. 294-304.

Gassen, W. V., and Cruden, D. M., 1989, Momentum transfer and friction in the debris of rock avalanches: Canadian Geotechnical Journal, v. 26(4), p. 623-628.

Ghezzehei, T. A., and Or, D., 2001, Rheological properties of wet soils and clays under steady and oscillatory stresses: Soil Science Society of America Journal, v. 65(3), p. 624-637.

Hungr, O., Morgan, G. C., and Kellerhals, R., 1984, Quantitative analysis of debris torrent hazards for design of remedial measures: Canadian Geotechnical Journal, v. 21(4), p. 663-677.

Hungr, O., 1995, A model for the runout analysis of rapid flow slides, debris flows, and avalanches: Canadian Geotechnical Journal, v. 32(4), p. 610-623.

Hürlimann, M., McArdell, B. W., and Rickli, C., 2015, Field and laboratory analysis of the runout characteristics of hillslope debris flows in Switzerland: Geomorphology, v. 232, p. 20-32.

Ikeya, H., 1989, Debris flow and its countermeasures in Japan: Bulletin of the International Association of Engineering Geology, v. 40(1), p. 15-33.

Ilstad, T., Elverhøi, A., Issler, D., and Marr, J. G., 2004, Subaqueous debris flow behaviour and its dependence on the sand/clay ratio: a laboratory study using particle tracking: Marine Geology, v. 213(1), p. 415-438.

Imran, J., Harff, P., and Parker, G., 2001, A numerical model of submarine debris flow with graphical user interface: Computers & geosciences, v. 27(6), p. 717-729.

Iverson, R. M., 1997, The physics of debris flows: Reviews of geophysics, v. 35(3), p. 245-296.

Jeong, S. W., 2010, Grain size dependent rheology on the mobility of debris flows: Geosciences Journal, v. 14(4), p. 359-369.

Johnson, A. M., 1984, Debris flow: Slope instability.

Kang, H. S., 2016, Physical vulnerability assessment of buildings considering rheological properties of debris flow and rainfall return period, Doctor thesis, Department of Ocean Engineering, Pukyong National University, Korea.

Marchi, L., and D'Agostino, V., 2004, Estimation of debris-flow magnitude in the Eastern Italian Alps: Earth Surface Processes and Landforms, v. 29(2), p. 207-220.

Nguyen, V. B. Q., Kang, H. S., and Kim, Y. T., 2018, Effect of clay fraction and water content on rheological properties of sand–clay mixtures: Environmental Earth Sciences, v. 77(16), p. 576.

Parsons, J. D., Whipple, K. X., and Simoni, A., 2001, Experimental study of the grain-flow, fluid-mud transition in debris flows: The Journal of Geology, v. 109(4), p. 427-447.

Rickenmann, D., 1999, Empirical relationships for debris flows: Natural hazards, v. 19(1), p. 47-77.

Rickenmann, D., 2005, Runout prediction methods: In Debris-flow hazards and related phenomena, p. 305-324.

Scotto di Santolo, A., Pellegrino, A. M., and Evangelista, A., 2010, Experimental study on the rheological behaviour of debris flow: Natural Hazards and Earth System Sciences, v. 10(12), p. 2507-2514.

Takahashi, T., 1991, Debris Flow: IAHR Monograph Series, AA Balkema: Rotterdam. Doi. org/10.1201/9780203946282.

VanDine, D. F., 1996, Debris flow control structures for forest engineering. Res. Br., BC Min. For., Victoria, BC, Work. Pap, 8, 1996.