Evaluation of Dissipated Energy in Granular Flows in Flume Tests

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ABSTRACT

Debris flow, which has often been treated in fluid mechanics, is studied from a viewpoint of granular materials. Flume tests are conducted in which influences of various parameters such as slope inclination, water content, fines content on dissipated energy during the flow are examined. Among the parameters, fines content has a significant effect on the energy dissipation mechanism in granular flow; equivalent friction coefficient $\mu$ tends to increase with increasing fines content up to a certain threshold, beyond which it suddenly decreases due to a shift from granular flow to mud flow.

INTRODUCTION

Debris flows are one of natural disasters recently increasing because of rapid urbanization in rural areas and also due to climate changes all over the world. Due to global warming, glaciers are retreating, expanding vast moraine lakes behind in high altitude regions of central Asia. Threats of gigantic debris flows triggered by breaching will be increasing as future extreme events (Kokusho 2005).

Despite its frequent occurrence and devastation, the mechanism of debris flow has not been
fully understood, yet. Though debris flow is a high speed mass movement of granular materials mixed with water with a specific density more than 2.0 t/m$^3$ in most cases, it has been studied in fluid mechanics more often than in solid or granular mechanics. Consequently, important granular properties such as water/soil ratio, soil particle gradation, fines content, etc. have not been sufficiently focused in studying the geotechnical impact of debris flow.

In this research, a series of flume tests are performed using granular soils with different particle gradations to investigate the effects of the above-mentioned parameters. The energy loss during the flow in the flume is evaluated and compared among different test parameters to understand the basic energy dissipation mechanism in granular flow. Some of the test results on the effect of various soil parameters have already been reported in Kokusho et al. (2008). In this paper, the effect of fines content on the granular flow is focused.

**TEST EQUIPMENT, METHOD AND SOIL MATERIAL**

A flume used in the test is made from acryl. The dimension is 200 mm deep and 120 mm wide in inner section and 3600 mm in length as illustrated in Fig. 1. The upper 800 mm of the length is separated from the main part of the flume by a pneumatically driven gate, where tested granular soils mixed with water are placed just before the test. The angle of the flume can be varied step by step from 20 to 30 degrees. Note that the friction coefficient of the acrylic face was measured as $\mu_s = 0.43$, evidently smaller than $\mu_s = 0.63$ measured for a sand paper.

Once the debris flow starts by opening the gate, its flow velocity at the outlet of the flume are continuously evaluated from the trajectory of flying granular particles monitored by a digital image sensor. At the same time, the discharge rate of the soil mass is measured at the end of the flume by an electronic balance. Based on the measured values, the energy loss $E_{DP}$ of the soil mass during the flow in the flume can be evaluated from Eq.(1).

$$
E_{DP} = MgL \tan \theta - \left\{ \frac{1}{2} \sum_i m_i (i\Delta t) \left[ v(i\Delta t) \right]^2 + \sum_j m_j g \left( L - l_j \right) \tan \theta \right\}
$$

(1)

and, the speed of debris flow $v$ at the outlet is expressed as Eq.(2)

$$
v(i\Delta t) = \sqrt{\frac{g}{z_0(1 + \cos \theta) - x(i\Delta t) \sin 2\theta}} \cdot x(i\Delta t)
$$

(2)

where, $Mg = \text{total weight of soil-water mixture.}$
\( L \) = horizontal distance from of soil-water mixture to the flume outlet at the start of the test.
\( \theta \) = angle of the flume from horizon.
\( m_1(i\Delta t) \) = mass discharge increment measured by the electronic balance at \( i \)-th time increment \( i\Delta t \).
\( v(i\Delta t) \) = velocity of debris flow at the outlet of the flume at \( i \)-th time increment \( i\Delta t \).
\( m_{2j} \) = mass fraction remained after completing the test in the \( j \)-th section (20 cm each) of the flume.
\( l_j \) = horizontal distance from the initial centroid of soil-water mixture to the center of the \( j \)-th section of the flume.
\( z_0 \) = constant height (100 mm)
\( x(i\Delta t) \) = horizontal flying distance for soil trajectory dropping by \( z_0 \) at \( i \)-th time increment \( i\Delta t \) as illustrated in Fig. 2.

The time increment was chosen as 0.02–0.017 s in the measurement of \( m_1(i\Delta t) \) and, \( v(i\Delta t) \) above. It is easy to understood that the energy loss \( E_{DP} \) can also be correlated to a unit loss energy \( e_{DP} \) corresponding to unit mass (1 kg) and unit horizontal flow distance(1m) as Eq.(3).

\[
e_{DP} = E_{DP} \left( \frac{L}{\Delta t} + \sum_j m_{2j} l_j \right)
\]

(3)

If \( e_{DP} \) is normalized by the potential energy change \( g\tan\theta \) which occurs for the unit mass during flowing in the same unit horizontal distance, it gives a dissipated energy ratio as

\[
R_d = e_{DP} / g\tan\theta
\]

(4)

In a series of tests carried out previously (Kokusho et al. 2008, Hiraga 2008), test conditions were changed parametrically; the water to soil ratio (W/S-ratio ) = 0.35–1.0, the
mean grain size = 1.84–14.4 mm, the fines content = 0–25% and the slope angle = 22.5–30º. Under the conditions, it was found that \( R_d \) varies from 0.60 to 0.85 indicating that 60% to 85% of the potential energy is dissipated in the debris flow and the rest remains for potential disaster. The decrease in \( R_d \) occurs with increasing W/S-ratio, increasing mean grain size, decreasing fines content and increasing slope angle. In the present test, the effect of fines content, which has previously been studied briefly will be investigated in more detail.

Soil materials used in the present tests are fluvial sands/gravels of semi-round shapes. Two basic granular materials were reconstituted by mixing sands and gravels called here as A (\( D_{50}=1.24 \), \( C_u = 12.2, C_c = 0.61 \)) and B (\( D_{50}=2.00 \), \( C_u = 20.18, C_c = 0.74 \)), the grain size curves of which are shown in Fig. 3. To the material A, non-plastic fines (rock flour) finer than 0.075 mm in diameter was added stepwise up to \( F_C=100\% \) to original sand-gravel mixture as illustrated in Fig. 3. Soil material of \( F_C=100\% \) is rock flour only. To the material B, non-plastic fines was added stepwise up to \( F_C=20\% \).

Dry soil mass of totally 10 kg was first slightly wetted for better subsequent mixture with water and placed in the upper part of the flume to which a given quantity of water is added. The weight ratio of water to dry soil (W/S-ratio or water content) was chosen 0.5 and 0.35.

**TEST RESULTS**

Fig. 5 shows percentage of the different energies of all test conditions; dissipated energy, residual potential energy and kinetic energy at the flume outlet, out of a total energy equal to the initial potential energy. For the material A, dissipated energy \( E_{DP} \) clearly increases with increasing \( F_C \) both for W/S=0.5 and 0.35. For W/S=0.5 in which \( F_C \) increases higher than 15%, \( E_{DP} \) takes a peak somewhere around \( F_C=15–20\% \). After that, \( E_{DP} \) shows drastic reduction with increasing fines content up to \( F_C=100\% \). The residual potential energy takes larger values with increasing fines content. The material B shows a similar trend for \( F_C=0–20\% \) with a peak somewhere around \( F_C=15\% \).
An equivalent friction coefficient $\mu$, which represents friction characteristics of the debris flow as a whole can be easily evaluated from the value $R_d$ as,

$$R_d = \frac{\mu}{\beta} = \frac{\tan\phi}{\tan\theta}$$

(5)

where, $\mu = \tan\phi$ and $\beta = \tan\theta$. Using Eq.(5), the equivalent friction coefficients are calculated from all the test results mentioned and plotted in Fig.6 against the fines content. The pairs of plots in the diagram represent the test repeated twice under the same conditions to check the reproducibility of the results, and the line connects the average of the two. Considering the strong effect of W/S-ratio, it seems reasonable to recognize that the $\mu$-value for W/S=0.35 is clearly higher than that for W/S=0.5.

The $\mu$-value for the two materials A and B clearly increases with increasing $F_C$, then after a peak around $F_C=15\%$ it shows drastic decrease. This value of $F_C$ is near a critical fines content $CF_C$ of sand-gravel mixture. The critical fines content is a threshold at which the fine soils saturate the voids of granular soils and start to overflow. According to previous studies (e.g. Kokusho 2007), the value of $CF_C$ for the material A is evaluated as 15.4–18.6%, and that for B is 10.9–14.4% as superposed on the diagram with shaded bands. The peak of the equivalent friction coefficient seems to occur within the bands, indicating a significant role of $CF_C$ in the manipulation of friction during granular flow. This implies that the granular flow changes to mud flow with lower equivalent friction coefficient or higher flow potential at a threshold $CF_C$. If fines start to overflow the voids of coarser grains, it completely changes the soil structure from grain-supporting to matrix-supporting, which inevitably will change the energy dissipation mechanism, too. Also noteworthy is that the absolute $\mu$-value is obviously smaller in the material B with larger $D_{50}$ than A even for $F_c=20\%$ after shifting to mudflow.
CONCLUSIONS
A series of flume tests were conducted for sand-gravel mixture to study energy dissipation mechanisms in debris flow from granular mechanics point of view, yielding the following major findings;

1) The equivalent friction coefficient $\mu$ increases with increasing $F_C$ up to a peak around $F_C = 15\%$ then it shows drastic decrease.
2) This value of $F_C$ is near a critical fines content $CF_C$ of sand-gravel mixture at which the fine soils saturate the voids of granular soils and start to overflow.
3) The peak of the equivalent friction coefficient occurs within the band of $CF_C$, indicating that the granular flow changes to mud flow with lower equivalent friction coefficient or higher flow potential at a threshold $CF_C$.
4) It may well be inferred that a similar mechanism may also be involved in prototype debris flow.

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REFERENCES