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Study of viscous debris-flow surges moving on a residual layer in a flume

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Abstract Debris flows are observed as a series of surges in nature and are characterized as rolling waves. A residual layer plays a vital role during the movement of surges. This paper examines debris flow surges in a flume to study the mass exchange between the surge front and the residual layer. Initial findings show that the surge head incorporates materials from the residual layer in a rolling way. The ratio of mass exchange increases linearly with mean flow velocity and mass exchange has an impact on the resistance coefficient.

Key words debris-flow surge; head of surge; residual layer; mass exchange; flume

INTRODUCTION

Debris flows occur when masses of poorly-sorted sediment, agitated and saturated with water, surge down slopes in response to gravity (Iverson, 1997). This mass wasting process poses a tremendous threat to the residents in many parts of the world and it can cause loss of life and considerable economic losses (Munachen, 2006; Takahashi, 2007). Since the 1960s, scientists have begun to investigate mechanisms causing debris flows, especially in Japan and China (Cui *et al.*, 2005; Takahashi, 2007). Furthermore, some field observatories have been set-up to conduct long-term observations.

Field and experimental investigations show that under different climatic and geological conditions, debris flows usually emerge in a sequence of surges (Takahashi, 1981; Johnson, 1984; Davies, 1990; Zhang, 1991; Iverson, 1997), which has been referred to as a “roll wave” (Hu *et al*., 2011). Qualitative descriptions of moving surges have been reported (Kang *et al*., 1980; Okuda *et al*., 1980; Pierson, 1980; Li *et al*., 1983; Zhang, 1991; Wu *et al*., 1993; Davies, 1997; Zanuttigh *et al*., 2007). A theoretical understanding of surge formation has been provided by others (Pierson, 1986; Wang, 1990; Takahashi, 1991; Savage & Iverson, 2003; Hungr, 2000; Zanuttigh, 2004; Zanuttigh & Lamberti, 2004). Iverson (1997) was the first to conduct debris flow studies in a flume. Wang (2001) conducted a study on debris-flow surge head and related this data to energy theory. Munachen (2006) conducted experiments designed to study surge fronts. Other field studies have been conducted on debris flows in the Moscardo Torrent, Italian Alps (Marchi *et al*., 2002) and the Swiss Alps (Rickenmann *et al*., 2003).

The head of a typical debris-flow surge often fluctuates significantly and erodes the channel bed violently (Li *et al*., 1983; Davies, 1986; Wang *et al*., 2003). When advancing downstream on a dry bed, the surge produces a residual layer, which smoothes the bed and reduces resistance (Li *et al*., 1983; Wang *et al*., 2001; Wu, 2003; Zhang, 2003; Hu *et al*., 2011). However, the residual layer’s surface in front of the wave’s head generally stays static, which is different from shallow water waves (Fig. 1). The velocity gradient between the surface layer and the moving wave leads to mass and energy interchange (Hu *et al*., 2004, 2011). Two contrasting theories have been developed to explain the movement mode of the surge head. Wu (1990) proposed a longitudinal circulation flow system of debris flows (Fig. 2), while Hu (2004) suggested that the surge front resulted from a rolling motion (Fig. 3).

Few studies have been conducted on the mass exchange between the residual layer and the moving wave. The objective of this paper is to study the characteristics of mass exchange and resistance of rolling waves on the residual layer in a series of flume experiments.

Fig. 1 The residual layer surface in front of the head remained static.

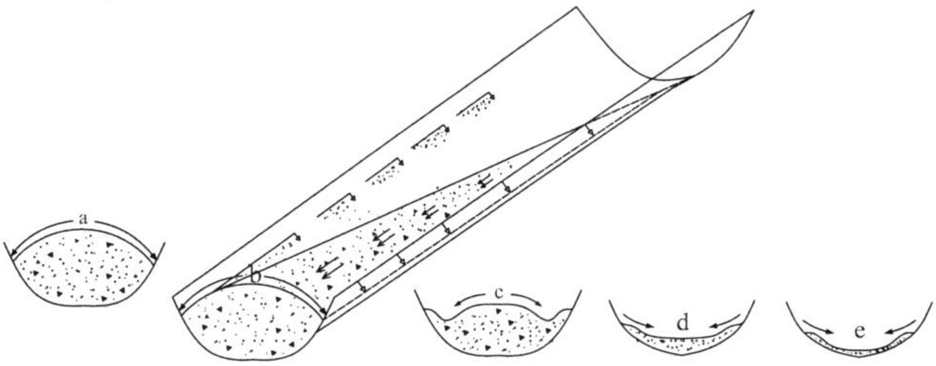

Fig. 2 Wu's circulation flow for the front of surge (Wu, 1990); a. cross circulation at the surge's head; b. longitudinal circulation along the whole surge; c. cross circulation at the surge's body; d and e. cross circulation at the surge's tail.

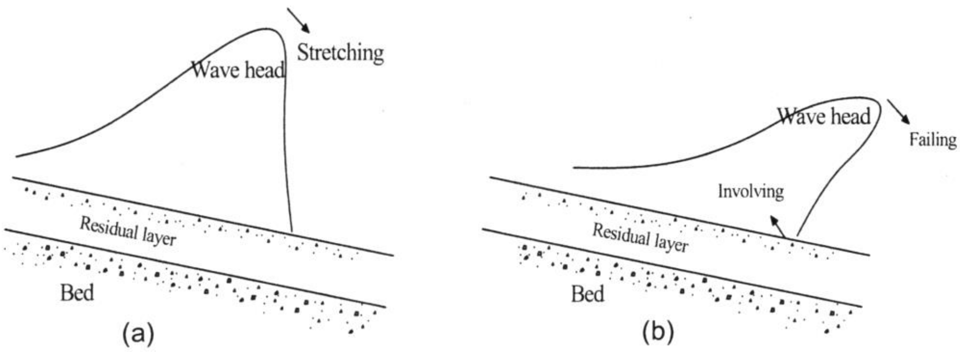

Fig. 3 The roll way of the front movement (Hu 2004): (a) the stretched front; (b) the front is falling and the remainder of the debris flows is involved.

METHODS

Experiment apparatus and procedures

A series of experiments were performed in the Debris Flow Simulation Laboratory at the Institute of Mountain Hazards and Environment, CAS (Chinese Academy of Sciences). A flume was designed to investigate the mechanism of mass exchange between the debris-flow surge head and

Fig. 4 Frontal and side views of the flume.

the residual layer in Jiangjia gully. Detailed descriptions of Jiangjia debris flows have been presented by Wu *et al.* (1993), Kang *et al* (2004), and Cui *et al*. (2005). The experimental flume shown in Fig. 4 has a 30-L top storage container. The flume is 8-m long and has a rectangular cross-section of 0.1 m (width) by 0.1 m (height). The slope of the flume is adjustable from 15° to 32°.

In order to distinguish the front of surges and residual layer, a mixture of glycerol, phenolic moulding powder and carborundum was used as the residual layer and a white mixture of glycerol and quartz sand for the debris flows. The flume was fitted with a 1-cm thick residual layer. A high-speed video camera was used to measure flow depth and analyse mass exchange processes between the front and the residual layer (Fig. 5).

The experiment was conducted in two parts. The first part focused on the comprehensive parameter affecting the mass exchange ratio, and the second part examined the relationship of mass exchange resistance characteristics of surges.

Fig. 5 Residual layer and high-speed video camera.

RESULTS

Relationship of mean velocity and the ratio of mass exchange

Large particles gathered together in the surge head before entering the residual layer. The surge head stayed white but when it advanced into the residual layer, black materials were observed only in the front. White materials from the debris flows were also left on the residual layer. Footage from the high-speed video camera showed mass and energy were exchanged at the surge front with the residual layer in a rolling way (Fig. 6).

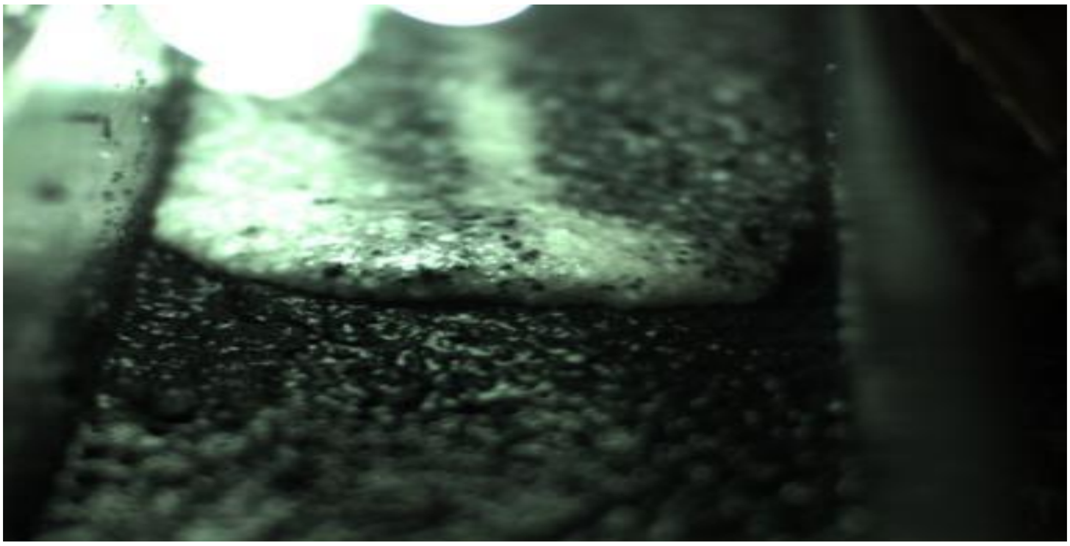

Fig. 6 The mass exchange between the front and residual layer.

The density of the debris flow materials, channel slope, and flow regime are factors that influence the flow velocity (Rickenmann 1999). High-speed surges move with great mass energy and momentum which will exert a direct impact on the residual layer and erode materials from it. Mean flow velocity is considered to be the most influential factor for mass exchange between surge fronts and the residual layer. The results of the flume study indicate that the ratio of mass exchange increases linearly with the mean flow velocity (Fig. 7).

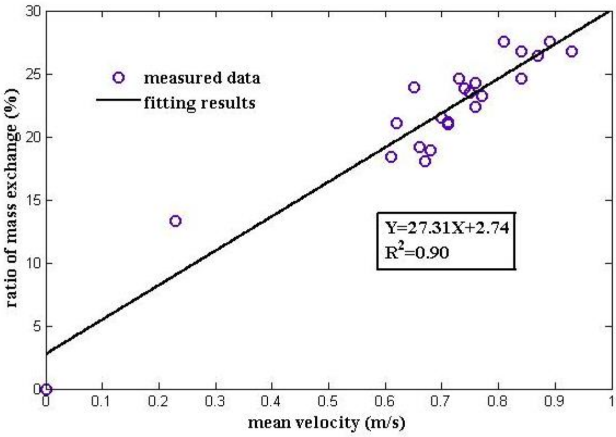

Fig. 7 Relationship between the mean velocity and ratio of mass exchange.

The corresponding equation has the following form:

$$Y = 27.31X + 2.74 \tag{1}$$

where Y is the ratio of mass exchange between the residual layer and moving surge, and X is the mean velocity. The data show that an increase in mean velocity increases the velocity gradient between the residual layer surface and the surge. Accordingly, the observed increased shear stress will accelerate mass exchange.

Relationship of mass exchange and resistance

The Manning resistance coefficient is considered as the index of energy loss for debris flows (Julien & Paris, 2010). Six separate experiments were conducted to study the influence of mass exchange on the Manning coefficient (Table 1). For all surge experiments, density and channel slope were held constant while the median particle diameter varied.

Strickler (1923) reported that the Manning coefficient increases with median particle diameter in the form of a power index. According to the data in this study (Table 1), it can be seen that although the particle diameters of groups 5 and 6 are larger than that of groups 3 and 4, the Manning coefficient of groups 5 and 6 are less than groups 3 and 4. The potential reason lies in the effect of mass exchange. The data show that the Manning coefficient increases with increasing mass exchange, which causes energy loss and increased resistance. Under the influence of these two aspects, mass exchange rate and particle diameter, the former plays a more important role than the latter, and finally makes the Manning coefficient of groups 3 and 4 increase.

Table 1 Experimental conditions and results.

Number	Slope (°)	Density (g/cm^3)	Median particle diameter (mm)	Mean velocity (m/s)	Flow depth (m)	Ratio of mass exchange (%)	Manning resistance coefficient
1	26	1.828	0.425	0.53	0.04	18.1	0.154
2	26	1.828	0.425	0.54	0.04	18.6	0.153
3	26	1.828	0.531	0.35	0.04	22.9	0.234
4	26	1.828	0.531	0.35	0.04	24.9	0.236
5	26	1.828	0.638	0.43	0.04	16.1	0.189
6	26	1.828	0.638	0.44	0.04	16.0	0.187

Note: Flow depth and mean velocity were obtained by analysis of video pictures. Ratio of mass exchange was the percentage of residual layer in the surge head. Manning resistance coefficient was calculated by the Manning formula.

However, because of experimental limitations, the surges in the experiments appeared in laminar flows and it is hard to see the head of turbulent surges. The average Froude number of the experiments is 0.7, which is less than that of Jiangjia gully (generally more than 1, Kang *et al*., 2007), and the effects of the flume wall increase the resistance coefficient. Although the experimental flow regime is not in agreement with the actual observations, the flume experiment showed that the surge head incorporates materials from the residual layer in a rolling way. These preliminary conclusions and results provide theory and reference for related research. Further theoretical analysis and studies are needed to obtain good understanding of the mass exchange.

CONCLUSION

A study of mass exchange between the front and residual layer of an experimental debris flow was conducted to improve our mechanistic understanding of this process. Initial experimental data demonstrated the surge front moved in a rolling way, which was in agreement with Hu *et al.* (2004, 2011). It was also discovered that:

1 Flow velocity has the most direct impact on the ratio of mass exchange. Mass exchange rate increases linearly with mean flow velocity.
2 The ratio of mass exchange plays an important role in affecting the resistance coefficient. More interchange of materials leads to greater energy loss and flow resistance.

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