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CHARACTERISTICS AND MECHANISM OF DEBRIS-FLOW SURGES AT JIANGJIA RAVINE

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ABSTRACT

Debris Flows in nature, for example at Jiangjia Ravine, were often observed moving in the form of intermittent surges which is considered as a kind of wave that is termed as roll wave in this paper. Spatial and temporal characteristics of the roll waves at Jiangjia, as well as their separation and superposition were described in details. First-arrived waves were observed to smooth rough bed at the gentle middle reach and produce a residual layer on which a sequent wave can move with steady profile and high velocity. The data measured by the Dongchuan Debris Flow Observation and Research Station shows the waves are not periodic and a kind of supercritical flow which only propagates downstream. Furthermore, it is observed that there are two kinds of wave profile, linear and non-linear, for the same debris-flow surge in Lagrange and Euler reference frames. A power relationship between the depth-averaged velocity and flow-depth of the surges is inferred from the different profile functions in the two frames. Finally, it was proposed that mass exchange between the residual layer and moving wave reduces frictional resistance and keeps the wave high-speed.

Key words: *Debris flows; Roll wave; Velocity profile; Flow depth; Residual layer*

INTRODUCTION

Debris flows in nature have been often observed as a succession of surges differing from a continuous hydrograph of flood. Descriptions on the surges have been given by many literatures, such as Pierson (1980) for Mt Thomas in New Zealand who called it standing wave, Okuda *et alii* (1980) for Mt Yakedake in Japan, and Marchi *et alii* (2002) for Moscardo torrent in Italy. Especially, the long-term observations on debris flows started from 1960s at Jiangjia Ravine in Southwest China have provided plentiful information on the characteristics of debris-flow surges (Li *et alii*, 1983; Zhang, 1991; Davies, 1997). Some of them concluded that debris-flow surge is the main flow pattern of viscous debris flow moving downstream in a channel, and suggested the surge may be due to intermittent debris supplies, discontinuous initiation of debris flows at the upstream or complex topography of debris-flow basin.

However, these factors can not convincingly explain why the surge flow only appears with respect to viscous debris flow. Pore-fluid pressure in debris flow was considered to play a key role on the motion of its surges (Iverson, 1997; Savage & Iverson, 2003). Noting similarities between the surge and roll wave that spontaneously develops on a shallow water layer in a long open channel such as zigzag profile, many researchers attempted to illuminate this phenomenon in term of intrinsic instability of shallow water equations that govern two-dimensional movement of some non-Newtonian fluids including hyper-concentration flow and debris flow (Engelund & Wan, 1984; Wang *et alii*, 1990; Ng & Mei, 1994; Liu & Mei, 1994; Davies, 1997; Zanuttigh & Lamberti, 2007).

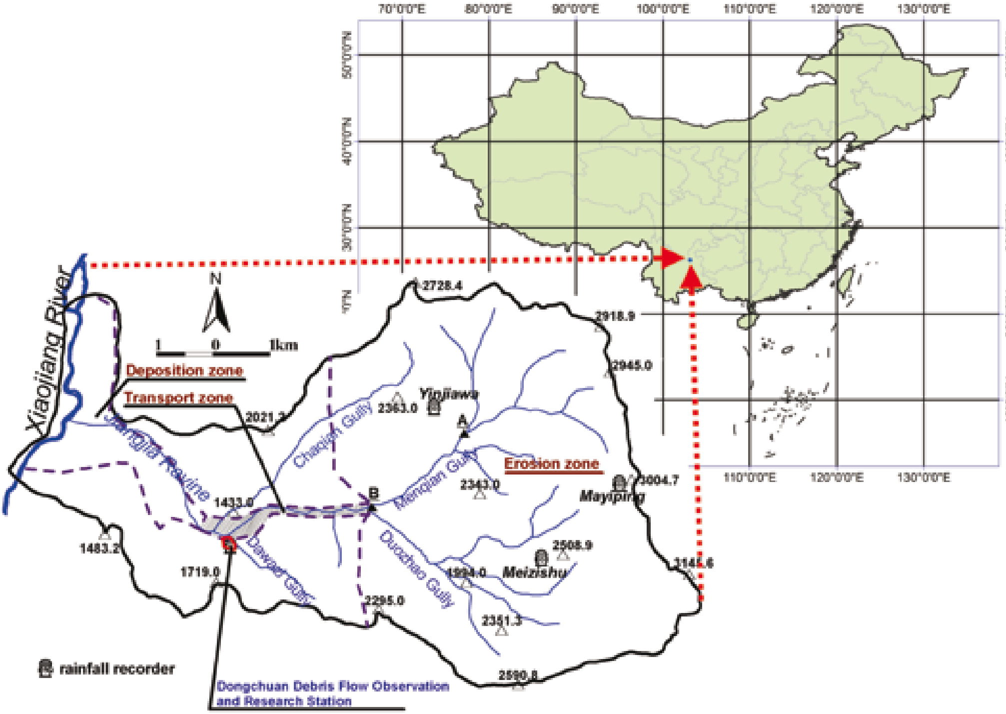


Fig. 1 - The location of Jiangjia Ravine (the elevation unit of the open triangle points is meter)

Roll waves are denoted as intermittent waves that are sandwiched between long stretches of gentle profiles increasing monotonically in depth from rear to front (Ng & Mei, 1994). With reference to them, we term the surges in debris flows as roll waves. This paper does not focus on theoretical analyses of the shallow water equations, but on the descriptions of debris-flow roll wave characteristics from the field investigations and measurements at Jiangjia Ravine. Based on the descriptions, the profiles of roll-wave flow depth and velocity are discussed.

STUDY AREA

Jiangjia Ravine with 48.6 km^2 watershed and 13.9 km main stream, a branch of Xiaojiang River in the upper reaches of Yangtze River, lies in Dongchuan, Kunming, Yunnan Province in southwest China (figure 1). It becomes a high frequent debris-flow Ravine because of 2227 m relative elevation, complex geological structure and fragile rocks, numerous landslides, and rich rainfall. Mean annual rainfall is 700 ~ 1200mm from the foot to top of the mountain and more than 80% rainfall concentrates in the rainy season between June and September when most of debris-flow events happen. The Ravine is an ideal site for observing debris flows as long-duration debris-flow event can appear every year and various debris flow regimes can be seen even in one event. There were 15 debris flow events per year on average, and the maximum was 28 events according to the record data of Dongchuan Debris Flow Observation and Research Station (DDFORS) which was set up in 1960s, a facility of the Institute of Mountain Hazards and Environment, Chinese Academy of Science. In order to study dynamic and static properties of debris flows DDFORS have installed some equipments such as debris-flow sampler, radar velometer, ultrasonic sensor for measuring debris-flow quantities such as velocity, flow depth. The debris-flow events lasted from several hours to some dozens of hours, each of which consisted of scores or hundreds of waves. The maximum discharge of debris flows is 2820 m^3/s, five times of the peak discharge of Xiaojiang River. The velocity of debris flows is up to 15 m/s, and the mass density is as high as 2370 kg/m^3 (Wu *et alii* 1990).

Fig. 2 - The residual layer (a. the residual layer smoothing the channel; b. the channel was re-emerged after the residual layer was scoured by hyper-concentration flow. The channel is about 80m wide. The first photo was taken on Jul 1st, 2001, the second on Jun 27th, 2004.)

CHARACTERISTICS OF ROLL WAVES

RESIDUAL LAYER

When first-arrived wave passes by rough bed at the gentle middle reach of Jiangjia, its debris material will deposit upon the channel bed and result in a temporary bottom which is called as residual layer (figure 2). The layer smoothes the bed, and allows subsequent waves to move farther towards downstream. Every roll wave makes the layer longer than its predecessor. Gradually, the layer will extend from the middle stream to downstream. This process is termed as 'pavement' and would not be interrupted until a roll wave reaches into Xiaojiang River if the debris-flow magnitude is adequate for the layer formation on the whole downstream reach.

One typical event occurred at 15:30 on July 24th, 1999 when there was no rainfall in the middle and down streams. So the residual layer's surface was not destroyed by the raining water washing, which helps us observe the paving process more clearly. As a roll wave moved into the observed section that not covered by the residual layer, the wave decelerated and debris-flow material was continuously left on the coarse and dry channel. The wave's head became thinner and thinner, and at last it stopped. Each of roll waves extended the layer 50-100m longer. The residual layer was 0.5~0.6 m and its edge 0.1~0.2m high. Compared with the height at the wave head, from 1m to 4m, the layer is rather shallow. After the successive waves travelled upon the layer, the layer's depth varied slightly. This implied that a kind of dynamic mass balance exists between the layer and the moving wave.

Fig. 3 - Three parts of one roll wave on Aug 5th, 2007 (The head was about 2m high and 40m wide. The mud surface ahead of the wave head is stationary)

The formation of residual layer is crucial for roll waves to keep moving. If no residual layer, it is impossible for viscous debris flows to move quickly and constantly in the gentle channel whose slope is less than 6%. First of all, the existence of the layer makes the bed smooth, and so reduces bed roughness for debris flows. Secondly, the residual layer increases flow depth of debris-flow surges. Thirdly, the fluid component in the layer has a lubricant effect.

SPATIAL AND TEMPORAL CHARACTERISTICS

Ng & Mei (1994) presented that there are distinctive parts within one wave profile. Actually, we observed that a roll wave exhibits several flow patterns at the different parts. In general, a roll wave is 10m to 200m long and can be divided into three distinctive parts: the head, turbulent flow; the body, laminar flow; the tail, laminar flow (Fig.3).

The head with semi-parabolic plan shape is the highest and widest one among the three parts. It was found that the surface of the residual layer before the head keeps stationary (Fig.3), which indicates roll wave propagation

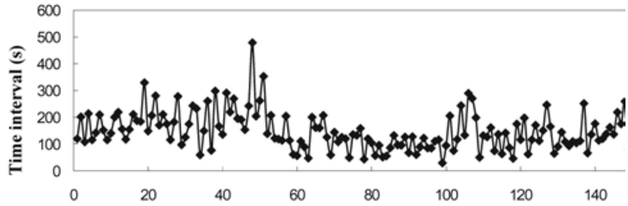


Fig. 4 - Time interval of roll wave's series on July 8th, 2001

speed is less than debris-flow particle speed. Based on the measured data (unpublished) on July 25th, 1999 from DDFORS, when the head's height is 2 m the velocity is 9.5m/s. The propagation speed is estimated roughly to be 4.43 m/s by virtue of $c = \sqrt{gh}$ for long wave of water, where *c* is wave speed, *g* gravity acceleration, *h* the head height. The particle velocity (9.5 m/s) is greater than the wave velocity (4.43 m/s). Then the roll waves are a kind of supercritical flow. Unlike at the head, the flow surface at the body is smooth and regular, and can be generally considered as a laminar flow. Nevertheless, it is still not clear whether there are some inner flow structures, e.g. vortices, in the body. The unimportant part is the tail which in fact is a wake left by the wave body.

The time interval between two successive waves that passed across the same section in the event on July 8th, 2001 is ranged from 29s to 478s (Fig.4). The averaged frequency is equal to 1/144.2 s^{-1}, approximately one wave per two minutes. Smaller interval is permitted if the wave head is higher. It is obvious that the roll waves are not quite periodic in one event. Although Davies (1997) mentioned debris-flow surges in one event often occur at quite regular intervals, Hu & Li (2001) analysed the time interval data, and didn't find any predominant frequency in the roll waves by using Fourier Transform. Based on the average frequency and the wave speed of 4.43 m/s, the average wavelength, namely average distance between two waves, is 638.81 m, 3-60 times of the surge's length itself.

SEPARATION AND SUPERPOSITION

Another interesting phenomenon is the separation and superposition of the roll waves. A roll wave would extend more widely and becomes thinner at the wider open channel, and when there are some topographic changes along the transverse direction the wave will be separated into two waves, each alone moving downstream (Fig.5a). On the other hand, along the longitudinal direction two or more waves can superpose together to a higher wave (Fig.5b). Generally speaking, the higher the wave head is, the faster it moves. So a higher wave catches up with its former at last if the stream channel is long enough (Fig.6). But unlike other kinds of wave such as ripple, the combined wave does not separate longitudinally again. The ripples can keep their shapes unchanged before and after superposition, but the roll waves of debris flows do not so. That is one of reasons why the discharge of intermittent flow is far more than that of continuous flow. Figure 6 taken on July 8th, 2001 shows five roll waves in the about 800 m channel. The distance between the first and the second was increasing while decreasing between the third and the fourth. At the wider section the first was extending more widely and separated into two waves. The third caught up with the second wave after a few moments.

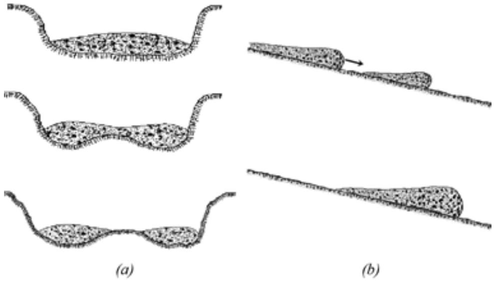
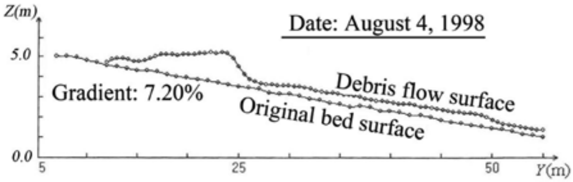
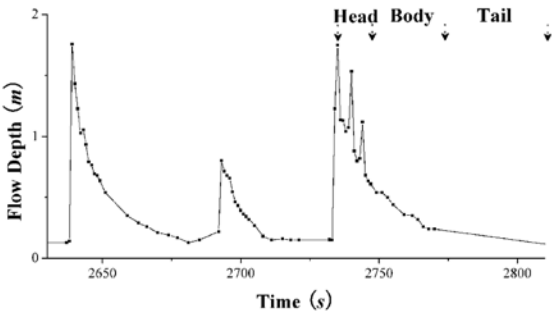


Fig. 5 - Schematic diagram of the separation and superposition (a. separation due to topographic change across transverse section; b. superposition due to different longitudinal velocities.)

Fig. 6 - Separation and superposition of surges (the first wave in the picture is dividing into two waves and the third will catch up with the second.)



(a)Flow depth profile of one roll wave on Aug 4th, 1998 interpreted by close-range photogrammetry with reference to Zhang & Chen (2003)



(b) Flow depth profiles of three roll waves on Aug 2nd, 1985 measured by ultrasonic sensors (the time origin point is 21:31:24)

Fig. 7 - Flow depth profiles of roll waves under Lagrange (a) and Euler observing systems (b)

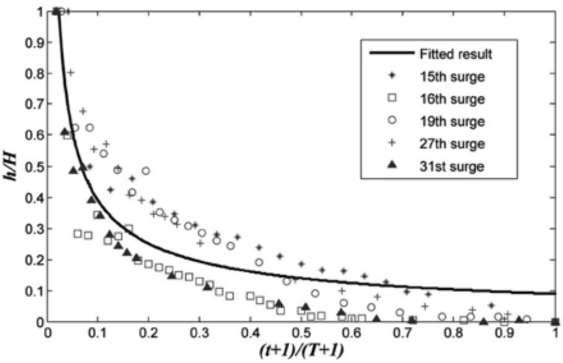


Fig. 8 - Fitted power curve between normalized flow depth and time for five surges on Aug 2nd, 1985 (H is the maximum flow depth of the surges.)

PROFILES OF FLOW DEPTH OF ROLL WAVES

Flow-depth profiles of roll waves show distinctive shapes in Euler and Langrange observing systems. Zhang & Chen (2003) measured longitudinal and transverse profiles of roll waves by image analysis based on the principle of close-range photogrammetry (Fig. 7a). The longitudinal profile is triangular and close to the shape by eyewitness. But, the roll waves recorded by ultrasonic sensor exhibits a distinctive longitudinal profile with abruptly decreasing front and gentle rear, resembling a power curve. The observing system in the image analysis measurement belongs to Lagrange reference frame in which the time point is fixed. On the contrary, the system in figure 7b is a kind of Euler reference frame because the observing point is fixed in space. Debris-flow longitudinal velocity within one wave must vary with flow depth. Otherwise, the shapes of the longitudinal profiles in the two observing systems would be same.

Based on different appearance of wave profile in the two frames, an empirical relationship between depth-averaged longitudinal velocity and flow depth can be derived from the transformation of linear function to power function. Given the wave profile in the Lagrange frame is represented by

$$h\,(x) \infty x,\ 0 \le x \le X \qquad (1)$$

and that in the Euler frame by

$$h\,(x) \infty t^n,\ 0 \le t \le T \qquad (2)$$

where t is time, x is longitudinal spatial coordinate, X is wave length, T is wave duration, h is flow depth, and n is power exponent. The origins in the two systems are the forefront of the wave. Furthermore, the depth-averaged longitudinal velocity can be represented as:

$$u = \frac{dx}{dt} = \frac{h_t}{h_x},\ 0 \le x \le X,\ 0 \le t \le T \qquad (3)$$

where u is the velocity, h_t and h_x denote respectively spatial and temporal derivatives of flow depth. Combined Eq.(1), (2) and (3), it can be obtained:

$$u(h) \propto h^{\frac{n-1}{n}} \qquad (4)$$

Many velocity profiles with similar form as Eq.(4) were proposed for one-dimensional non-Newtonian debris flows such as dilatant (Takahashi 1978), Bingham (Mainali & Rajaratnam 1994), and power-law (Ng & Mei 1994) models. However, the point of Eq.(4) is in that its velocity exponent is associated with the flow depth exponent n in Eq.(2), and therefore can be calculated from n. Non-linear regression analysis on the profile data of Aug 2nd, 1985 gave the power exponent an estimated value of -0.6417 with 95% confidence bound [-0.6996, -0.5839] (Fig. 8), which indicates that the longitudinal velocity is proportional to 2.56 power of flow depth. Fitted curve has a better agreement with measured data at the wave head and body than at the tail as Fig. 8 shows. This implies Eq.(4) is not applicable when the flow depth is lower than the tail height.

DISCUSSION AND CONCLUDING REMARKS

Based on the field observations in Jiangjia Ravine, characteristics of debris-flow roll waves are described in details. Some interesting phenomena such as the residual layer, the separation and superposition are introduced. The existence of residual layer is crucial for roll waves to keep moving at the gentle channel. The roll wave can be divided into three distinctive parts: head, body and tail, each of them corresponding to a kind of flow pattern. The time intervals between successive waves in one event indicate the roll waves are not periodic, at least not so regular, and their average wavelength is much longer than the length of themselves. According to these characteristics, a possible mechanism for the roll waves moving with high velocity at gentle channel is proposed. That is, mass exchange between the residual layer and moving wave makes less kinetic energy converse into thermal energy than direct frictional contact. The head with the highest velocity incorporate the depositional materials in the residual layer while the body and tail leave almost same amount of materials for the layer. Therefore, the frictional contact only limits in the head part. Of course, the existence of the layer also reduces bed roughness, increases flow depth of debris-flow surges, and has a kind of lubricant effect.

Debris-flow roll waves display two kinds of flow-depth profiles in Lagrange and Euler reference frames. Under the assumption that the flow-depth profile is linear in the Lagrange frame and power shape in the Euler, a power relationship between the depth-averaged longitudinal velocity and the flow depth is inferred for one-dimensional steady movement of debris-flow surge. The connection of the velocity profile with the flow-depth shape in the Euler frame provides a feasible method for estimating debris-flow velocity in protection engineering. The empirical value of 2.56 for the velocity exponent limits to the case of viscous debris flows with high density. The theoretical value is 1.5 for dilatant fluid, and 2.0 for Bingham fluid, which means this kind of debris flow at Jiangjia cannot be described by the two models.

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