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Planar Velocity Distribution of Viscous Debris Flow at Jiangjia Ravine, Yunnan, China: A Field Measurement Using Two Radar Velocimeters

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Abstract: Characteristics of planar velocity distribution of viscous debris flow were analyzed using the measured data at Jiangjia Ravine, Yunnan, China. The velocity data were measured through using two radar velocimeters. The cross-sectional mean velocities were calculated and used to examine Kang *et al*'s (2004) relationship, which was established for converting the flow velocity at river centerline measured by a radar velocimeter into the mean velocity based on the stop-watch method. The velocity coefficient, K, defined by the ratio of the mean velocity to the maximum velocity, ranges from 0.2 to 0.6. Kang *et al*'s (2004) relationship was found being inapplicable to flows with K smaller than 0.43. This paper contributes to show the complexity of the planar velocity distribution of viscous debris flows and the applicability of Kang *et al*'s relationship.

Key words: viscous debris flow; planar velocity; velocity coefficient; Jiangjia ravine; radar velocimeter

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0 Introduction

Debris flow is one of the typical processes that usually result in significant morphological evolution and hazards in mountainous regions[1]. Forecasting, mitigation and prevention of debris flow hazards has been paid more and more attentions[2], among which formulation of debris flow velocity is of fundamental interest. To date, many empirical formulas of the mean velocity have been established based on field data, assuming a framework of Manning's equation in hydraulics[3-6]. Theoretical models that take into account more physics than the empirical formulas have also been proposed. The common feature of these models is the flow rheology or constitutive relations that are adopted[7-10]. However, these different formulas or models are usually for the mean velocity or the vertical velocity profile of debris flows. Few works have been devoted to characterizing the planar velocity distribution.

Extensive field observation and measurement have been carried out in the past decades to facilitate migration and prevention of debris flow hazards[1,11]. In the early stage, a stop watch is usually used to record the time that debris surge wave front passes a monitored river reach and, accordingly, to obtain the cross-sectional mean velocity of debris flows during the recorded period. In the late stage that has begun since 1980s, a radar velocimeter is usually installed by the river to measure the flow velocity along the river centerline. Obviously, the relationship between the cross-sectional mean velocity and the velocity at the centerline not only characterizes the planar velocity distribution of debris flows, but also is needed for characterization of debris flow behavior using the measured data at the two different stages. Kang *et al*[1] established an empirical relationship between the velocities based on radar data and stop-watch data. However, no work has been done to examine this empirical relationship.

Based on a field measurement using two radar velocimeters, this paper analyzes characteristics of the planar velocity distribution of viscous debris flows and also examines Kang *et al*'s relationship.

1 Measurements Using Two Radar Velocimeters

Dongchuan Debris Flow Observation and Research Station, Chinese Academy of Sciences, is located at Jiangjia Ravine, Yunnan, China. Debris flow frequently occurs in this ravine, and the maximum number of debris flow events is 28 in 1965. In one event of debris flow, the initial sediment-laden flow is followed by dilute debris flow that lasts 10 to 20 min. After a short time stop, tens of surges of viscous debris flow continue one by one, lasting two to three hours. The viscous debris flow, with a tongue-like surge wave front, has a density as high as 1.8×10^3 to 2.3×10^3 kg/m^3 and a mean velocity 7 to 15 m/s.

In 1985, two radar velocimeters were instrumented to measure planar velocity distribution of viscous debris flow (see Fig.1). Both the two radar velocimeters were installed on one side of the river since their effective monitoring distance is 50 m. The left radar monitored the river centerline, while the target of the right one was 10 m away. In this figure, $B = 53$ m is the river width, $b = 10$ m is the distance between the two monitored points, V_m is the velocity at the centerline, and V_s the velocity at the point 10 m away.

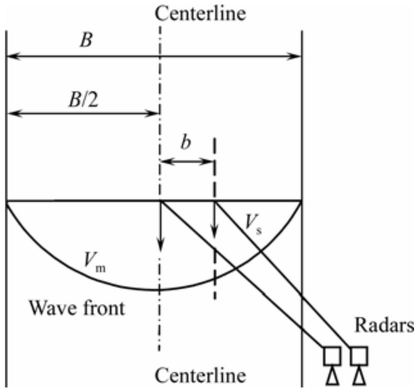

Fig.1 Configuration of the monitoring devices

Let the Cartesian coordinate x denote the flow direction and y the transverse direction, as shown in Fig.2, where 1 through 5 are point numbers, respectively.

The velocity of debris flow at a point y is

$$V = V(y) \tag{1}$$

The mean velocity averaged over the cross section of the observation station is

$$U = \frac{1}{B}\int_{-B/2}^{B/2} V(y)\,\mathrm{d}y \tag{2}$$

Assuming that the planar velocity distribution is symmetrical and the velocity at the bank is zero, as shown in Fig. 2, the mean velocity, U_{ra}, calculated using the measured data of the two radar velocimeters is

$$U_{ra} = \frac{1}{B}\left[V_s\left(\frac{B}{2} - b\right) + (V_s + V_m)b\right] = \frac{1}{2}V_s + V_m\frac{b}{B} \tag{3}$$

Eq.(3) also assumes that the velocity varies linearly between two adjacent points (1 and 2, 1 and 3, 3 and 5, 2 and 4) and gives a first order of approximation to Eq.(2).

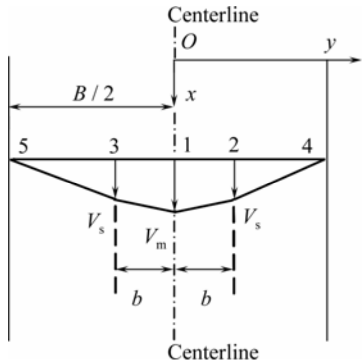

Fig.2 Assumed planar velocity distribution of viscous debris flow

2 Characteristics of Planar Velocity Distribution

The preceding measuring system measured four surges of viscous debris flows on June 25, 1985 before a radar velocimeter was damaged by a strong surge of debris flow three days later. Below presented are the results of the four surges.

2.1 Mean Velocity

The measured velocities, V_m and V_s, are listed in Table 1. The calculated mean velocity, U_{ra}, through using Eq. (3) are listed in Table 2.

Generally, the calculated mean velocity increases at first and then decreases for each surge. At the beginning, the mean velocity is around 5 m/s for Surge 1 and Surge

Table 1 Temporal variation of the measured velocities V_m and V_s (June 25, 1985)

Surge 1			Surge 2			Surge 3			Surge 4		
Time	V_m/m • s^{-1}	V_s/m • s^{-1}	Time	V_m/m • s^{-1}	V_s/m • s^{-1}	Time	V_m/m • s^{-1}	V_s/m • s^{-1}	Time	V_m/m • s^{-1}	V_s/m • s^{-1}
9∶12′30″	12.8	7.2	9∶20′25″	7.7	2.9	9∶22′40″	7.0	2.2	9∶23′43″	16.2	8.5
31″	15.9	8.9	26″	11.2	3.7	41″	10.4	3.4	44″	15.2	7.8
32″	17.2	8.8	27″	10.7	3.6	42″	12.2	5.4	45″	16.4	6.9
33″	19.5	10.1	28″	13.1	3.6	43″	14.4	4.1	46″	18.1	8.8
34″	20.8	9.2	29″	12.3	3.3	44″	12.3	4.4	47″	21.1	9.4
35″	24.5	10.4	30″	15.5	3.5	45″	14.0	5.1	48″	24.8	9.7
36″	20.7	9.3	31″	16.3	5.9	46″	15.8	5.0	49″	23.6	10.9
37″	19.5	8.0	32″	16.6	5.1	47″	17.8	5.9	50″	19.6	11.1
38″	21.1	7.5	33″	15.4	5.0	48″	18.7	6.1	51″	19.3	4.8
39″	19.7	4.0	34″	14.8	3.5	49″	22.2	7.1	52″	20.2	2.5
40″	19.0	3.9	35″	16.3	3.3	50″	16.3	6.9	53″	17.9	1.2
41″	16.8	1.2	36″	14.1	2.9	51″	15.4	4.2	54″	15.6	2.5
42″	14.8	0.7	37″	14.2	2.8	52″	16.2	4.7	55″	5.1	0.4
43″	4.3	0.8	38″	11.4	2.2	53″	12.7	4.3			
44″	0.5	0.4	39″	4.5	1.7	54″	11.0	2.2			
45″	0.2	0.1	40″	0.4	0.4	55″	3.2	2.0			

Note: t is time, the bed slope is J = 0.057, the flow width is B = 53 m, and the specific weight γ_m is 2.20, 2.15, 2.23, and 2.25 t/m^3 for Surge 1 through Surge 4, respectively

Table 2 Temporal variation of the calculated mean velocities U_{ra} (June 25, 1985)

Surge 1		Surge 2		Surge 3		Surge 4	
Time	U_{ra}/m • s^{-1}	Time	U_{ra}/m • s^{-1}	Time	U_{ra}/m • s^{-1}	Time	U_{ra}/m • s^{-1}
9∶12′30″	6.0	9∶20′25″	2.9	9∶22′40″	2.4	9∶23′43″	7.3
31″	7.5	26″	4.0	41″	3.7	44″	6.8
32″	7.6	27″	3.8	42″	5.0	45″	6.5
33″	8.7	28″	4.3	43″	4.8	46″	7.8
34″	8.5	29″	4.0	44″	4.5	47″	8.7
35″	9.8	30″	4.7	45″	5.2	48″	9.5
36″	8.6	31″	6.0	46″	5.5	49″	9.9
37″	7.7	32″	5.7	47″	6.3	50″	9.2
38″	7.7	33″	5.4	48″	6.6	51″	6.0
39″	5.7	34″	4.5	49″	7.7	52″	5.1
40″	5.5	35″	4.7	50″	6.5	53″	4.0
41″	3.8	36″	4.1	51″	5.0	54″	4.2
42″	3.1	37″	4.1	52″	5.4	55″	1.2
43″	1.2	38″	3.3	53″	4.5		
44″	0.3	39″	1.7	54″	3.2		
45″	0.1	40″	0.3	55″	1.6		

4 and 3 m/s for Surge 2 and Surge 3. Then, it increases and reaches its maximum value (around 10 m/s for Surge 1, 4, and 7 m/s for Surge 2 and 3) five to ten seconds later. After its maximum value, the mean velocity decreases for each surge. Since the radar measures the velocity at a spatial point, the variation of U_{ra} with time t suggests that of debris flow velocity from the surge front to the surge tail. Hence, the mean velocity at the surge front is usually smaller than that at the main body of the surge. Berti *et al*[12] and Lavigne and Suwa[13] also observed similar phenomena of debris flows.

2.2 Velocity Coefficient

For characterization of planar velocity distribution, define the velocity coefficient K as $K = U/V_m$. The value of K is larger, and the velocity distribution is flatter. Figure 3 shows the variation of K with time for the four surges, where U is approximated by U_{ra}. In this figure, K_{ra1} to K_{ra4} represent the K value for Surge 1 to Surge 4, respectively. It is shown that the K values range from 0.2 to 0.6 for most of the flow period. Generally, the K value decreases slowly during the first 10 s, and drops down and then increases rapidly during the last several seconds.

This suggests that the planar distribution of debris flow velocity usually changes with time for a given cross-section.

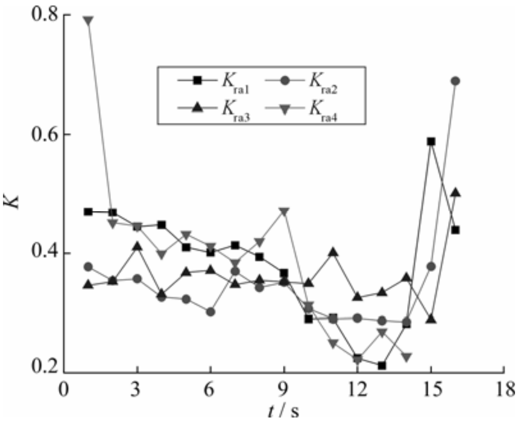

Fig.3 Variation of the velocity coefficient *K* with time *t*

3 Examination of Kang *et al*'s Relationship

Since one radar velocimeter was damaged in a strong debris flow event three days later, most velocity data measured by radar velocimeter was the flow velocity at river centerline. For converting the velocity at river centerline, produced by radar velocimeter, into the-cross-sectional mean velocity, Kang measured and analyzed tens of surges of debris flows using both the radar velocimeter and a stop watch simultaneously in 1986[1]. An empirical relationship between the velocities based on radar data and stop watch data was established. As the velocity at the river centerline is known through the radar velocimeter, the cross-sectional mean velocity (based on stop-watch method) will be obtained from the solid line. The error of this conversion will be ± 0.9 m/s.

The corresponding equations of the conversion line, the upper error line, and the lower error line are as follows:

$$U_a = \begin{cases} \frac{3}{20}(V_m - 6) + 6.2, & 6 \leqslant V_m \leqslant 18 \\ \frac{1}{2}(V_m - 18) + 8.0, & V_m > 18 \end{cases} \quad (4)$$

$$U_u = U_a + 0.9 \quad (5)$$

$$U_l = U_a - 0.9 \quad (6)$$

where U_a is the expected mean velocity obtained from the conversion line, and U_u and U_l are the upper and lower bounds of the expected mean velocity, respectively.

Figure 4 presents comparisons of the mean velocity calculated from Eq.(3) and that from Eq.(4) for each surge. For Surge 1 and Surge 4, the mean velocity U_{ra} based on Eq.(3) lies between U_l and U_u for the first half period, within which both V_m and V_s exceed 7-8

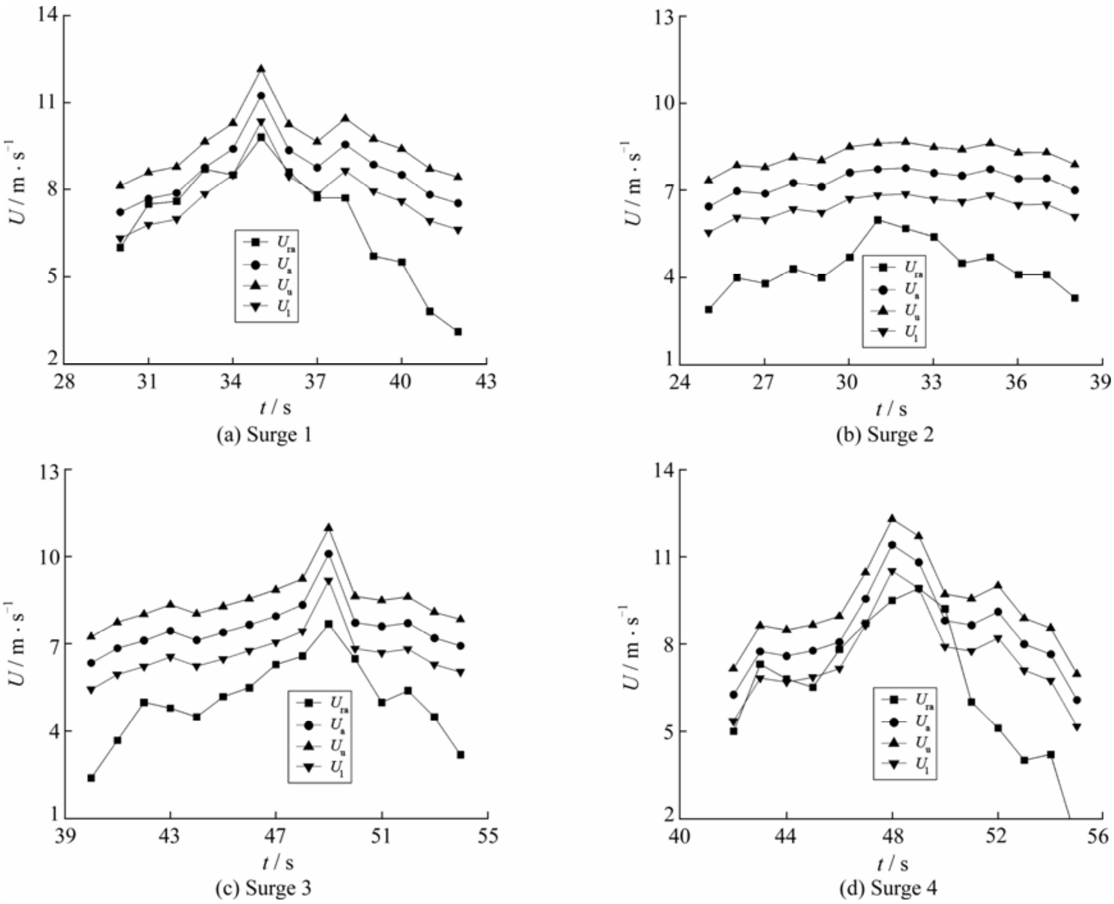

Fig.4 Comparisons of the mean velocity calculated from Surge 4 Eq.(3) and that from Eq.(4)

Note: *U* is the velocity

m/s. For the last half period, however, U_{ra} is distinctly smaller than U_1, which means that Eq.(4) may bring about significant errors. For Surge 2 and Surge 3, U_{ra} lies below U_1 during the whole period, which is similar to the other two surges in their last half time. One possible reason is that the K value predicted by Eq.(4) is always greater than 0.43 and, therefore, this equation can not be applied to the flows where K is smaller than 0.43. This also implies that it is difficult to accurately specify the average velocity through measuring the velocity at one point along the cross section since various pattern of planar velocity distribution exist.

4 Conclusion

Characteristics of planar velocity distribution of viscous debris flows were analyzed through using a field measurement of two radar velocimeters at Jiangjia Ravin, Yunnan, China. Kang *et al*'s relationship that was established for converting the flow velocity at river centerline into the cross-sectional mean velocity was examined.

① For the measured four surges of viscous debris flows, the cross-sectional mean velocity increases and then decreases during their lasting time. The maximum velocity at river centerline can reach 17 to 25 m/s, while the mean velocity can be as high as 12 m/s.

② The velocity coefficient characterizing planar velocity distribution ranges from 0.2 to 0.6. Generally, its value slowly decreases and then rapidly increases during the flow time.

③ Kang *et al*'s relationship assumes a velocity coefficient greater than 0.43 and, therefore, can not be applied to flows where the velocity coefficient is below 0.40 (e.g., Surge 2 and Surge 3).

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