Nat Hazards (2012) 60:689–701
DOI 10.1007/s11069-011-0033-0

ORIGINAL PAPER

Probability distribution of measured debris-flow velocity in Jiangjia Gully, Yunnan Province, China

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Received: 4 July 2011 / Accepted: 7 November 2011 / Published online: 1 December 2011

Abstract Debris flow moves in the form of surge waves and consists of dozens or even hundreds of surges that are separated in time and space and have a variety of appearances, as exemplified in Jiangjia Gully, China. Observations there indicate that the deposit is made up by superposition of successive surges and deposit of a single surge is in effect a "frozen" surge. Then the study of debris flow is reduced to the study of surge sequence, which leads to a probabilistic picture of debris flow. This study attempts to find the probability distribution of velocity of surge using a huge data set of Jiangjia Gully. Statistics of the data shows that the velocity satisfies the Weibull distribution, which is believed to be universally valid because the distribution parameters vary little between events, with the shape parameter being well related to the average of velocity. It follows that the same distribution applies also to other quantities of debris flow, such as the flow depth and the discharge. Therefore, the distribution can be used to assess the magnitude and overflow range of a potential debris flow, as well as to the parameter calculation for engineering design.

Keywords Debris flow · Surge · Velocity · Weibull distribution · Jiangjia Gully

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1 Introduction

Debris flow usually moves in the form of surge waves and consists of dozens or even hundreds of surges (e.g., Blackwelder 1928; Sharp and Nobles 1953; Pierson 1980, 1986; Takahashi 1991; Iverson 1997; Major 1997; Saucedo et al. 2005; Liu et al. 2008, 2009). Although it is rare to catch a living surge in field, the deposit retains many properties of the surge, such as the grain composition, the lobate front, lateral levee, and inverse grading (Naylor 1980; Costa and Jarrett 1981; Sohn 2000), lobate layer and blunt margins (e.g., Sharp and Nobles 1953; Johnson 1970; Whipple and Dunne 1992; DeGraff 1994). These are distinct from the alluvial fans in that they are conceived to be governed by the viscoplasticity of debris-flow fluid (Johnson 1970; Middleton and Hampton 1973, 1976; Lowe 1975, 1976, 1982; Takahashi 1980; Johnson and Rodine 1984; Coussot and Meunier 1996). Particularly, the deposit of a single surge can be even considered as the "frozen surge", as well exemplified by field observations in Jiangjia Gully (JJG), a famous debris-flow valley in the southwest China (Li et al. 1983; Liu et al. 2008, 2009). Although it is controversial to derive dynamic properties from the deposit configuration (Major and Iverson 1999), deposits or the flow depths are still of the most importance in evaluating debris flows, especially in assessing the potential overflow area.

In the previous studies, major quantities concerning the destructive potentiality, such as run-out distance and spread of the deposition, are estimated in empirical (Bathurst et al. 1997; Schilling and Iverson 1997), dynamical (Takahashi and Yoshida 1979; Hulme 1974), and statistical ways (Harvey 1984; Mizuyama and Uehara 1983; Liu and Tang 1995), which have been based either on dynamical simplification or on environmental variables specific to individual valleys, and have largely ignored the varieties during the process. But in reality, debris flow deposits are commonly piled up by deposition of successive surges (Major 1997; Vallance and Scott 1997; Sohn et al. 1999), while the surges fluctuate randomly and remarkably even within a single event (Liu et al. 2008, 2009). Therefore, it is necessary to seek for a probabilistic description which is believed of more practical significance for risk assessment (Li et al. 2008; Hu et al. 2008). The object of this paper is to present a method to derive the distribution of the flow depth using the observation data in JJG, which is expected to be applicable for evaluating the overflow area of debris flow in general conditions.

2 Field observation and measurement

2.1 Surge moving en masse

The JJG is well known for its debris flows of high frequency and variety of appearances, and it is also one of the rare sites allowing real-time observation of debris flows (Fig. 1). Observation there has been continuing since 1960s. A complete data set is now available (for more information of JJG, see, e.g., Li et al. 1983; Davies 1990; Li et al. 2003, 2004, 2008).

Each debris-flow event in JJG lasts for several or dozens of hours and contains tens or even hundreds of surges separated in time. Then an event is actually a sequence of surges in a variety of appearances. Observations in the upper tributaries show that a surge may stop like a "frozen" surge and then restart as a fresh surge (Fig. 2). The restart of a surge is like the reverse process of deposition. A flow continues or stops depending on whether the shear stress of the flow goes beyond or below the yield strength. Specifically, debris flow of high viscosity, as the case in JJG, is usually taken as a kind of Bingham fluid, which has a

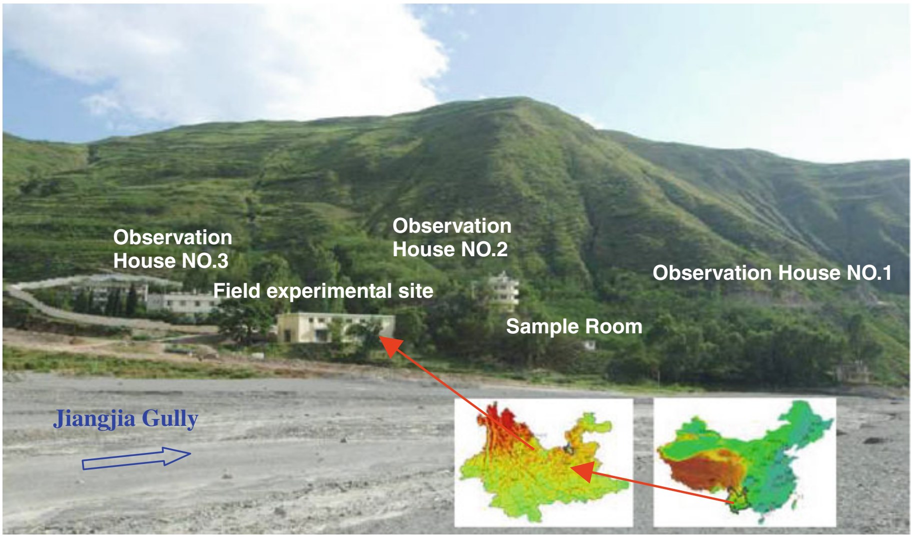


Fig. 1 The observation sites in Jiangjia Gully in Yunnan, China

Fig. 2 A surge body moving and terminating en masse in tributary channel

strength (yield stress) τ_0. And the material undergoes a shear stress, τ, determined by (Johnson 1970; Johnson and Rodine 1984; Sohn 2000; Wang et al. 2000):

$$\tau = \rho g j h \tag{1}$$

where ρ is the density of flow; *g,* the gravity acceleration; *j,* the slope gradient of the channel; and *h,* the flow depth. Once $\tau > \tau_0$, the debris deposit will start to move and flow; otherwise, a flow would stop and deposit. Figure 3 shows the similarity between configurations of surge in motion and in deposition, where the structure of lobate layer and front, lateral levee, and blunt margins are clearly present.

Fig. 3 Configuration of debris flow surges in motion and deposition. **a** Flowing surges in the channel. **b** Deposition of surges at the outlet of the channel

The photograph in Fig. 2 is a snapshot taken from the video of a surge in a tributary channel, showing an aggregation of unsaturated debris moves downslope, stops, and then restarts, keeping the original mass and form. From this viewpoint, a surge is considered as moving *en masse* while the deposit of a single surge appears like a "frozen surge."

2.2 Velocity measurement

As debris flow moves as a whole, from a macroscopic viewpoint, it is possible to describe the motion by a single velocity, despite the variations within the flow body. This single velocity can be considered as a characteristic quantity, which depends on the measurement. In JJG debris, flow velocity is measured in two ways: one measures the average velocity by timing the surge front passing through two fixed cross sections (Fig. 4); the other monitors the temporal fluctuation of velocity using ultrasonic sensors (Fig. 5).

Velocity fluctuation within a surge body can be derived from video analysis (e.g., Arattano and Marchi 2000). But in practice, the average velocity that characterizes the overall movement of the fluid body is sufficient to assess a potential debris flow. For example, the discharge, the energy, the run-out distance, the impact force, and the inundated area are all related to this velocity. Measurement shows that the velocity ranges between 2 and 12 m/s and fluctuates remarkably. Then there is not a single velocity that

Fig. 4 Measuring average velocity by timing the surge front passing through two cross sections (Liu et al. 2008)

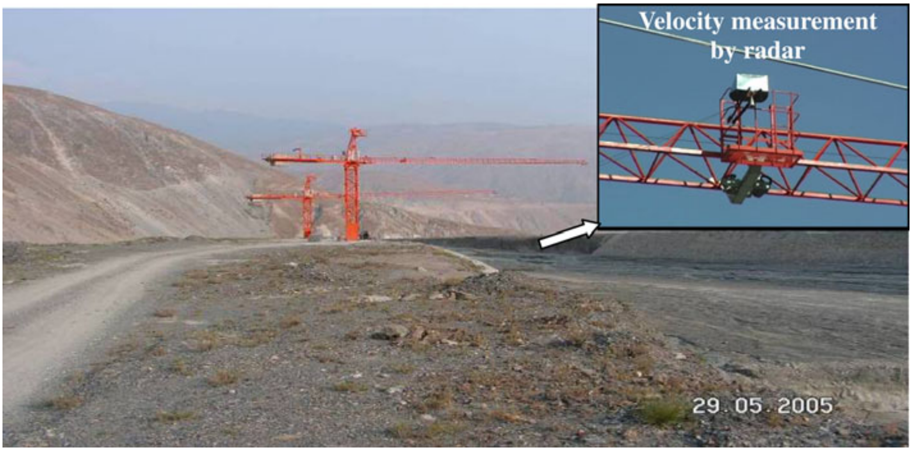


Fig. 5 The observation equipments for velocity measurement in JJG

can stand for an event; instead, it is necessary to consider the variations in surges and find the probability distribution of velocity.

3 Distribution of velocity and its implication

3.1 The probability distribution of velocity

The probability distribution would provide an overall description of velocities of surges that constitute a debris-flow event. Considering the fluctuations, the cumulative distribution is used in the following discussions. This is convenient to emphasize the overall characteristics of the data.

In order to make an easy comparison between events, the velocity is rescaled by the ratio of the first two moments: $\langle v^2 \rangle / \langle v \rangle$, where $\langle \rangle$ denotes the average. Then the distributions for different events almost collapse on the same curve (Fig. 6). In this figure, the numbers denote the date of the events, for example, 870823 means the debris flow on August 23, 1987. The coincidence of distributions indicates that the fundamental features remain the same despite the variations in different events and the systematic errors in the measurements, and this guarantees the statistical reliability of the data.

The curve in the rescaled unit can be well fit by the following function

$$P(<v^*) = 1 - 0.99\exp\left(-0.95v^{*5.26}\right) \quad \left(R^2 = 0.99\right) \tag{2}$$

where v^* denotes the rescaled value of velocity (for simplicity the asterisk is omitted thereafter). Noting that the coefficient of the exponential function is almost 1, it is reasonable to propose that the distribution is actually in the following form:

$$P(<v) = 1 - \exp\left(-(v/a)^b\right). \tag{3}$$

The corresponding probability density function (pdf) of Eq. (3) is

$$p(v) = ba^{-b}v^{b-1}\exp\left(-(v/a)^b\right) = f(a, b, v). \tag{4}$$

This is the well-known Weibull distribution, with a and b being the scale and shape parameter, respectively. The fitting parameters calculated by Matlab are listed in Table 1. Figure 7 shows the probability plot for the original data of some events, in which the data points for different events (i.e., surge sequences) present the curves in the same shape that fits the Weibull probability.

Alternatively, letting $a^{-b} = t$, Eq. (4) can be rewritten in a more convenient form:

$$p^{(v)} = f(t, b, v) = btv^{b-1}\exp\left(-tv^b\right). \tag{5}$$

For an intuitive version, Fig. 8 displays several examples of the distribution fitting the histograph. Most events are negatively skewed (i.e., with a left tail), suggesting that small velocity appears much more frequently.

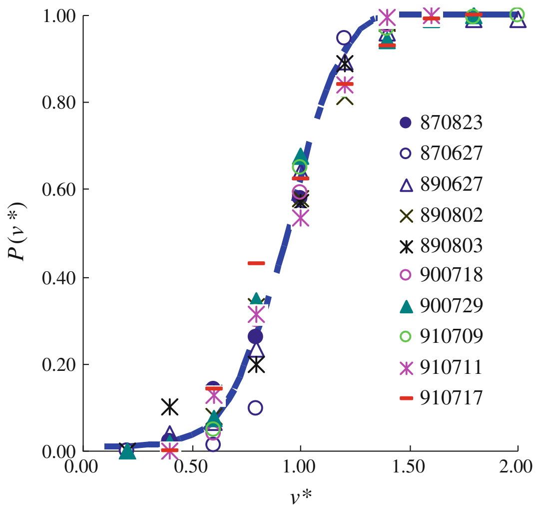


Fig. 6 Cumulative distribution for the rescaled surge velocity

Table 1 Parameters of the Weibull distribution for surge velocity

Events	Number of surges	*a*	*b*	Note
870627	51	5.3086	4.3165	The standard error of the parameters range between 0.06 and 0.30; the estimated covariance of the parameter estimates is 10^{-3} in order.
890627	120	7.2526	3.7949	
890802	129	6.4976	4.2065	
890803	166	5.4521	4.4070	
900718	125	6.4299	3.1536	
900729	130	6.2762	4.8055	
910708	201	4.9363	3.1329	
910709	427	6.1992	4.1525	
910711	253	6.6009	4.3055	
910715	114	5.9775	3.892	
910717	184	6.5187	3.4109	
910813	348	6.6348	4.9787	
920721	79	6.2320	3.8371	
930826	102	5.9468	3.5212	
940616	151	7.6137	3.8866	
940702	123	7.2350	3.7596	
950715	265	8.7384	4.1042	

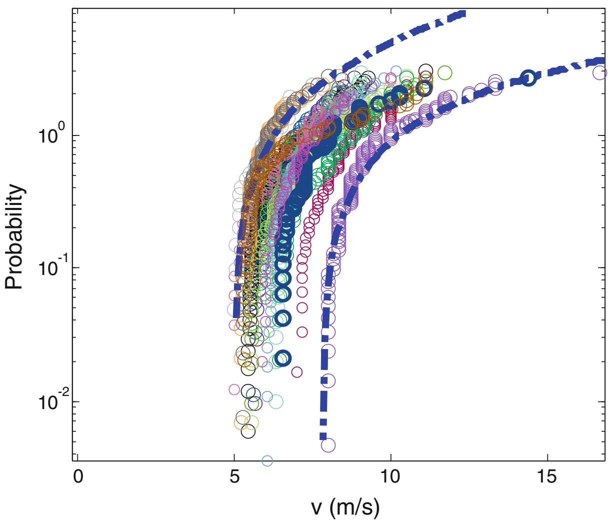
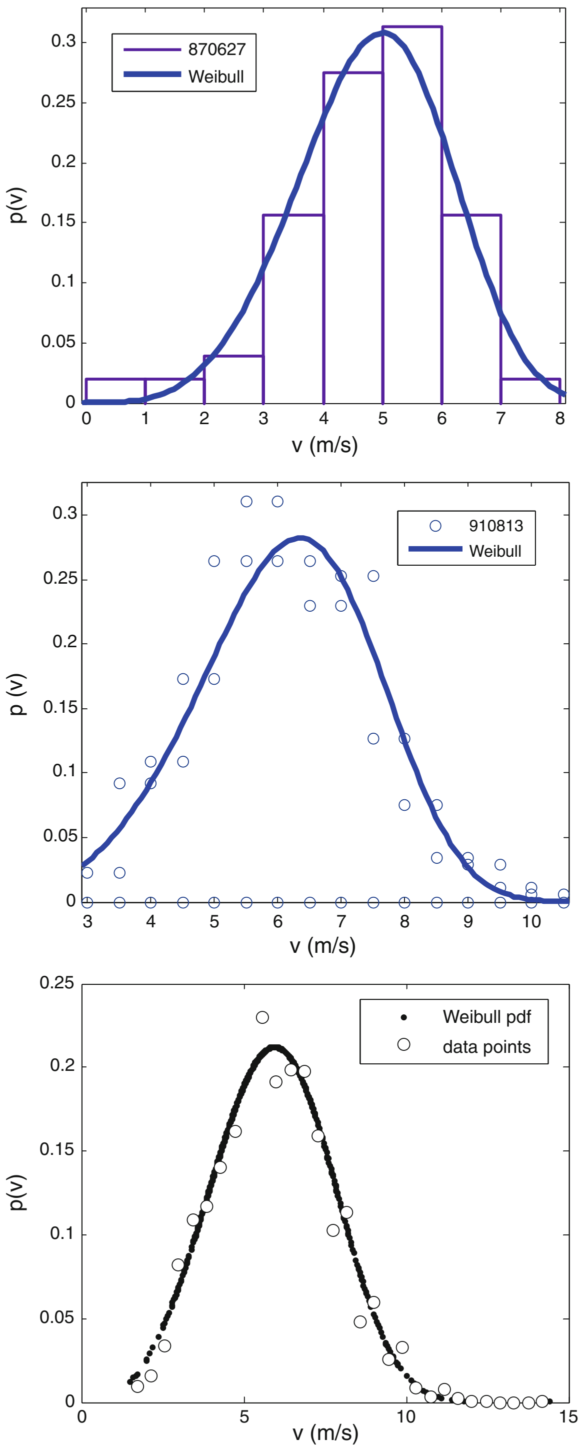


Fig. 7 Weibull probability distribution for surge velocity for different events of debris flow

3.2 Estimating the parameters

Weibull distribution of velocity is found to hold universally for all events of debris flows observed in JJG. Although the scale parameter varies much with events, as indicated by Table 1, the shape parameter keeps almost consistent. Moreover, the parameters are related to the average value of the velocity by

Fig. 8 Weibull distribution of surge velocity



$$\langle V \rangle = a\Gamma(1 + 1/b) \tag{6}$$

where $\Gamma(1 + x) = x\Gamma(x)(x > 0)$ is Gamma function. According to observation data of JJG, $1/b$ is less than 1/3 (Table 1), then $\langle V \rangle = a/b\ \Gamma(1/b) > 0.90a \sim a$. Then the scale parameter makes little difference while the scale parameter a can be estimated by the average velocity. Based on Table 1, $a = 6.4$, $b = 4.1$, and $t = a^{-b} = 0.0005$. Then the distribution function is

$$P(v) = \exp\left(-tv^b\right) = \exp\left(-0.0005v^{4.1}\right). \tag{7}$$

The medium velocity (i.e., with probability of 50%) is $v = 5.84$ (m/s), and the probability of $v > 9.26$ is less than 1%. The 1%-possible velocity may be properly taken as the maximal velocity for a potential debris flow. Indeed, observations in many sites indicate that 10 m/s is roughly the top velocity of debris flows in general conditions.

3.3 Distribution of velocity at given discharge

In engineering design and risk assessment of debris flow, a peak discharge is always presumed as the standard for structures or the disastrous potentiality of a possible occurrence. Such a presumed discharge is often derived from the possible rainstorm scale plus the material supplies, or from the empirical relations based on field surveys of the historical events (Wu et al. 1990, 1993, 1997; Li et al. 2008; Pareschi et al. 2002). In practice, the velocity is often derived from the discharge by setting a cross section for the flow, but in reality, the velocity fluctuates considerably even in the same discharge.

In order to see the velocity fluctuation, we plot the Q–v graph using observed data points in JJG. Apparently, the points are scattering under a definite envelop curve (Fig. 9), meaning that the discharge has an upper limit at a given velocity. The envelop curve can be drawn from the upmost points, which can be fitted by a power-law curve with exponent near 2:

$$Q{-}v^2 \quad \text{or} \quad v{-}Q^{1/2} \quad \left(\text{with}\, R^2 = 0.99\right). \tag{8}$$

This imposes a constraint on the discharge, and it also suggests that the velocity may fluctuate in the same way, despite the presumed value of the discharge. This relies mainly in the dynamics of the flow and may be universally valid for general cases. In fact, empirical relationships in power-law form have been established between the peak discharge and velocity (e.g., Rickenmann 1999).

Then we seek for the probability distribution of velocity at a given discharge. Considering the measurement error of 10%, we identify the surges with discharge between $(1 \pm 10\%)Q$ as having the given discharge of Q, Then we do statistics on the velocity of these surges and find that the velocity varies randomly and satisfies the lognormal distribution, with $R^2 \sim 0.90$ (Figs. 10, 11).

The Lognormal distribution, just as the Weibull distribution, is also a special case of the exponential family of probability distribution (Rohatgi 1976). The underlying difference is that the hazard function of Weibull is monotonously increasing or decreasing (for the present case it is increasing) and the hazard function for lognormal is unimodal, first increasing and then decreasing (Kleinbaum and Klein 2005). The emergence of peak in the lognormal hazard function is due to the cutoff of small velocities present in observation data. As shown in Fig. 12, the cumulative probability of Weibull is generally smaller than that of the Lognormal for high velocity (roughly above 10 m/s), that is,

Fig. 9 Velocity fluctuation under the discharge

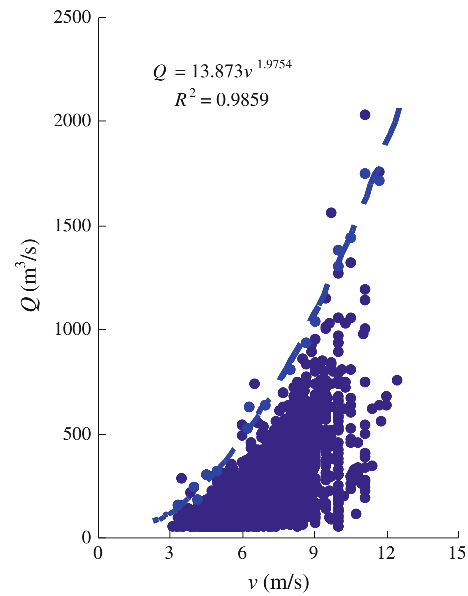
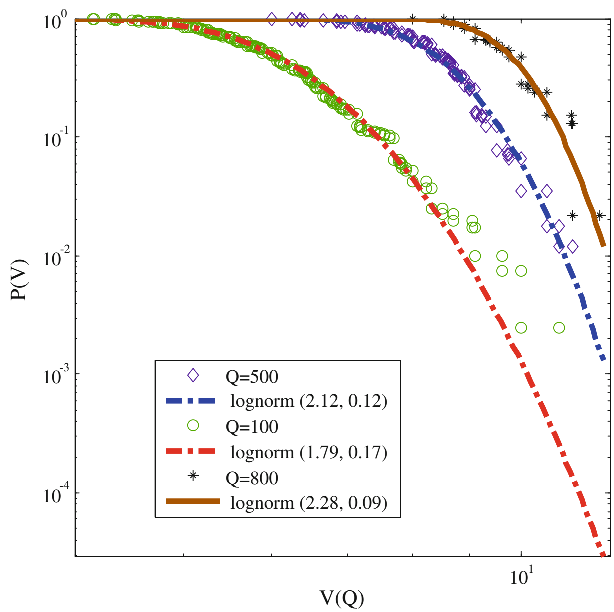


Fig. 10 Lognormal distribution of velocity at given discharges



$$P_{\mathrm{Weib}}(v) < P_{\mathrm{Log}}(v) \text{ for about } v > 10\,\mathrm{m/s}. \tag{9}$$

Noting that the difference is smaller than 5%, we can still, for practical purpose, take Eq. (3) or (7) as the marginal distribution of velocity at a given discharge, because this form is much simple and easily calculated than the cumulative function for the Lognormal distribution.

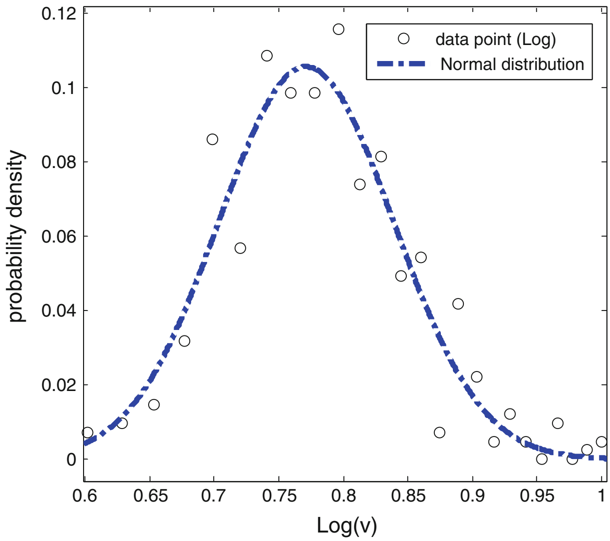


Fig. 11 Lognormal distribution of velocity at a given discharge ($Q = 100\ m^3/s$)

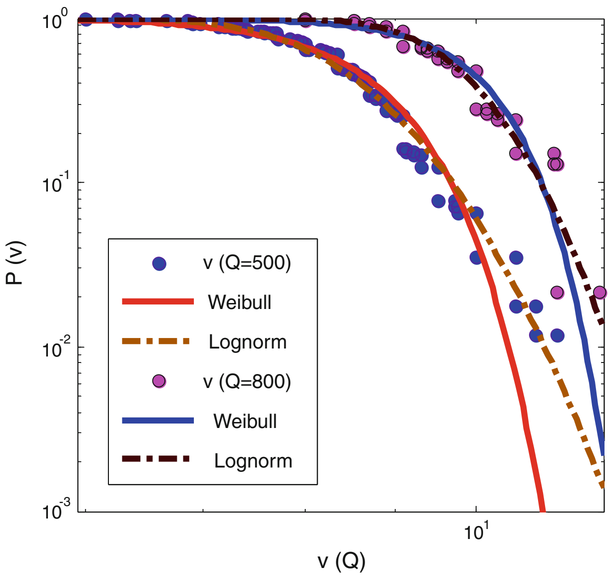


Fig. 12 Comparison between Lognormal and Weibull distribution for velocity at given discharges

4 Conclusions and discussions

A debris flow consists of a group of surges with a great variety of appearances, and the surge serves as the elementary unit from motion to deposition. Then a debris flow is reduced to a sequence of surges, and the probabilistic features of the surge sequence represent the probabilistic picture for debris flow.

Based on observation data in JJG, the surge velocity is found to satisfy the Weibull distribution, with distribution parameters varying little with events, and the shape parameter being related to the average velocity. This distribution is believed to be universally applicable for debris flows. For example, the medium velocity of 6 m/s and the 1%-probable velocity of 10 m/s are in good agreement with observations in different areas.

Weibull distribution has the virtue that it keeps the same form under power-law transformation. It follows that the same distribution applies to the discharge, the flow depth, and some other quantities concerning debris flow, which are power-law function of the velocity. These are important for both the engineering design and danger assessment of debris flow.

In particular, it provides a method to calculate the quantities at a given probability (or frequency), and this is what we are pursuing in practice of debris flow mitigation. For example, the distribution of deposit derived from the surge depth can be used to assess the potential overflow area at a given probability of velocity (or discharge).

Acknowledgments This research is supported by the National Program on Key Basic Research Project (973 Program) (2011CB409902), the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No. KZCX2-YW-Q03-5-2), and the Opening fund of State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (Grant No. SKLGP2010K003).

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