J. Mt. Sci. (2011) 8: 109–116
DOI: 10.1007/s11629-011-2083-x

Measuring the Internal Velocity of Debris Flows Using Impact Pressure Detecting in the Flume Experiment

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Abstract: Measuring the internal velocity of debris flows is very important for debris flow dynamics research and designing debris flow control works. However, there is no appropriate method for measuring the internal velocity because of the destructive power of debris flow process. In this paper, we address this problem by using the relationship between velocity and kinetic pressure, as described by surface velocity and surface kinetic pressure data. Kinetic pressure is the difference of impact pressure and static pressure. The former is detected by force sensors installed in the flow direction at the sampling section. Observations show that static pressure can be computed using the formula for static water pressure by simply substituting water density for debris flow density. We describe the relationship between surface velocity and surface kinetic pressure using data from seven laboratory flume experiments. It is consistent with the relationship for single phase flow, which is the measurement principle of the Pitot tube.

Keywords: Internal velocity; Measurement; Debris flow; Impact pressure

Introduction

Debris flow velocity is not only a key part of debris flow kinematics but also one of the key parameters in designing debris flow control works. However, it is difficult to measure debris flow movement because this kind of fluid is nontransparent and heterogeneous. Furthermore, it is difficult to measure its internal velocity because conventional current meters would be destroyed by the impact force of this heterogeneous fluid which contains gravels and boulders. Some methods have been developed for measuring the surface velocity and surge velocity of debris flows. Using a stopwatch and floaters is the simplest way (Kang and Hu 1990). Ultrasonic sensors and ground vibration sensors (geophones) have been used to detect the times a debris flow passes two observing sections and the velocity can be calculated using the arrival time difference and the distance between the two sections (Pierson 1986; Arattano et al. 1997; Itakura et al. 1997; Berti et al. 2000; Arattano and Marchi 2005). Surface and mean velocities have been estimated through measurements of debris flow discharge in flume experiments (Boyarskiy et al. 1970). A theory of movement for the core and gradient layer of debris flows, and equations of velocity curve have been developed (Natishvili et al. 1963). The pressure of a debris flow at different depths has been studied (Gagoshidze 1970; Kherkheulidze 1984). Doppler

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Received: 21 December 2010
Accepted: 30 January 2011

radar has been employed to measure the surface velocity of debris flow with Doppler effect (Stepanov 1982; Itakura et al. 1985; Suwa et al. 1993; Zhang 1993). Images analysis also has been used to measure the surface velocity of debris flows (Inaba et al. 1997, 2000; Uddin et al. 1998, 1999, 2001; Arattano and Grattoni 2000). As yet there is no effective method for measuring the internal velocity of debris flows. Itakura et al. (2000) and Hanisch et al. (2003) tried to use instruments immersed in a debris flow to measure internal velocity but these were easily destroyed. In this paper, the measurement of debris flow internal velocity based on impact pressure detecting is described and discussed.

1 The Principle of Measuring Internal Velocity Using Impact Pressure Detecting

Pitot tubes have been used to measure fluid internal velocity on the basis of a pressure difference between two openings. One opening faces towards the flow direction and detects impact pressure. The other opening is orthogonal to the flow direction and detects static pressure. The pressure difference between them is induced by kinetic head and is noted as p_k in this paper. According to Bernoulli's equation, it follows that:

$$p_k = \frac{1}{2}\rho_f v^2 \tag{1}$$

in which ρ_f is fluid density, and v is velocity.

A debris flow is a mixture composed of solid particles of various sizes and water. It remains uncertain whether equation (1) is applicable for this kind of two-phase flow. However, some researchers have studied kinetic pressure on a debris dam surface. Debris flow movement is stopped by the dam in this case, so the pressure is noted as p_d. Its general expression follows as:

$$p_d = k\rho_c v^2 \tag{2}$$

in which ρ_c is the debris flow density and k is a coefficient that has been given different values in the literature. For example, it was set at 1.33 in Fleishman's formula, 0.65 in Izbash-Haldra's formula, 1.0 in Kherkheulidze's formula (Fleishman 1986), and 3.0 in Zhang-Yuan's formula (Zhang and Yuan 1985). Although equation (2) was used for a debris dam, it has the same form as equation (1). As a result, if the kinetic pressure of debris flow is obtained in a similar way as the Pitot tube, we can imagine that it also has the same form as equation (1). In this case the internal velocity of a debris flow can be derived from kinetic pressure with the following equation:

$$v = A\sqrt{p_k/\rho_c} \tag{3}$$

in which coefficient A can be regressed from surface velocity and surface kinetic pressure data.

2 The Method for Measuring Internal Velocity of a Debris Flow

2.1 System for detecting impact pressure.

Kinetic pressure is the difference between impact pressure and static pressure. The system for detecting impact pressure consists of sensors, an upright post, a data acquisition instrument and a computer for data storage as shown in Figure 1.

A group of impact force sensors is needed in this system to detect impact pressures at different depths. The sensor used is a strain transducer with a circular front. Its main technical features are listed in Table 1. An upright post is needed in this system to fix the sensors. It has several circular openings to install them (Figure 2). A data acquisition instrument with multiple independent channels of signal input is needed in this system.

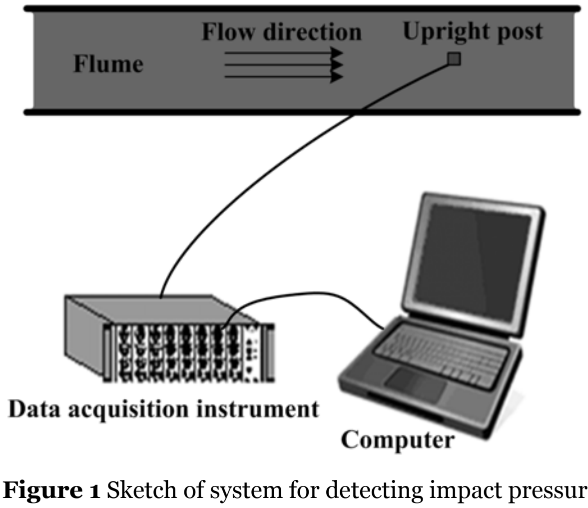

Figure 1 Sketch of system for detecting impact pressure

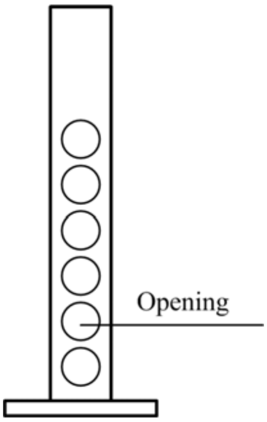

Figure 2 Sketch of the upright post

Table 1 Main technical features of the impact force sensor

Parameter	Value	Parameter	Value
Measuring range	60N	Response frequency	4KHz
Sensitivity	2.2±0.2mV/V	Voltage	5V DC
Error	±0.05%F.S	Overload capacity	150%F.S

All channels can acquire data in synchronism with a maximum sampling frequency of 100 KHz.

2.2 Equipment installation and impact pressure detection

The sensors are fixed in the openings of the upright post. The circular front and the post surface with the openings must be kept in the same plane as in Figure 2. The upright post is installed in middle of the detecting section (Figure 1). The sensor signal cables are attached to the data acquisition instrument which, in turn, is connected to a computer by a USB cable. In order to obtain surface velocity, a camera is installed above the flume to monitor and record the movement of floaters. A laser distance measuring instrument is also installed to record debris flow depth. With the equipment installed, in order to obtain complete impact pressure data for all the debris flow movements, the system is started prior to the debris flow arrival.

2.3 Data analysis and velocity calculation

The measurement data for impact pressure, debris flow depth and floater movement are used for velocity calculation. Firstly, surface velocity is calculated by images analysis of floaters and graphs of debris flow depth, surface velocity and impact pressure are drawn. There is noise in the impact pressure graph induced by the sensors or equipment shock and particle impact. Therefore, these data are filtered before analysis. The method of filtering includes low-pass filtering and high-pass filtering. Which filtering method is selected is decided by analysis of the power spectral density. Low-pass filtering should be adopted to eliminate the noise if the energy of the signal is in a low frequency range, otherwise, a high-pass filtering should be adopted. Secondly, kinetic pressure is computed as the difference between impact pressure and static pressure. Static pressure can be detected with impact force sensors installed in the sidewall of flume. It can also be detected by putting the upright post in a vessel containing the debris flow material. Thirdly, coefficient A in equation (3) is regressed with surface velocity and surface kinetic pressure data. Finally, equation (3) is used to obtain a velocity hydrograph for any position of interest.

3 Testing the Methodology by Flume Experiments

In order to test the methodology, flume experiments were carried out at the Dongchuan Debris Flow Observation and Research Station, Chinese Academy of Sciences.

3.1 Flume and system for detecting impact pressure

The flume is 600cm long, 30cm wide and 30cm deep. Its bottom is made from steel plate and sidewall is made from glass (Figure 3). A tank is installed at the head of the flume to supply fluid for the debris flow while a pool is installed at the end of the flume to collect the material for reutilization. A detecting section is selected in the latter half of the flume, where the debris flow motion is relatively uniform.

Eight impact force sensors are fixed in the upright post, which is installed in middle of the detecting section. The sensors are located at 14, 29, 44, 59, 74, 89, 104 and 119mm above the flume bed.

Figure 3 Flume and system for detecting impact pressure

The diameter of each sensor is 10mm. The data acquisition instrument, the computer with data accepting software and the sensors comprise the system for detecting impact pressure (Figure 3). In addition, the laser distance measuring instrument with a sampling frequency of 30Hz is installed upstream of the detecting section. A high definition camera is installed high above the flume.

3.2 Preparing the debris flow sample

In order to make the experimental debris flow resemble a natural debris flow, a sample of debris flow deposit material is collected from Jiangjia Gully near which the Dongchuan Research and Observation Station is located and which is noted for typical viscous debris flows. Particles of more than 10mm grain size are removed by screen separation with the remaining material comprising the experimental sample with a particle size distribution as shown in Figure 4.

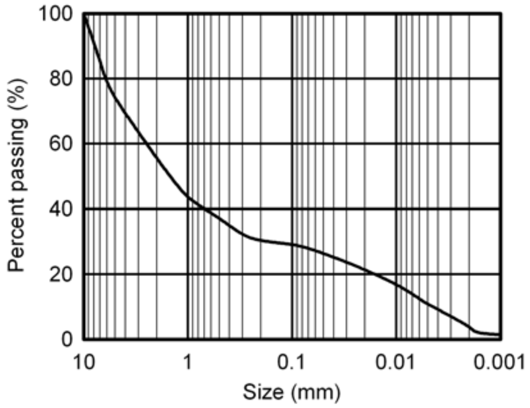

Figure 4 Particle size distribution of the experimental debris flow sample

3.3 Debris flow experiments and data processing

3.3.1 Debris flow experiments and impact pressure detecting

In order to ensure that the experiment is replicable, seven flume debris flows were carried out under similar conditions. The flume bed slope was set at 0.14 (14%) and debris flow density was set at 2095kg/m^3. Maximum debris flow depth ranged from 99mm to 105mm for the seven debris flow events. Mean surge velocity ranged from 2.33m/s to 2.59m/s.

Mean surface velocity in the 100cm upstream from the detecting section was calculated from image analysis. Using one debris flow event as an example, Figure 5 illustrates graphs of debris flow depth, surface velocity and impact pressures detected by the sixth sensor, which is located at 89mm above the bed. We can see that debris flow depth reaches its maximum in 2s while surface velocity decreases with time. Devices for obtaining these data are not operated at one time. In order to make them comparative, we have moved these data points along the time axis according to the occurrence time of debris flow. Errors in this operation for depth and surface velocity approximate time intervals of the corresponding data and image record, which are 0.03s (i.e.1/30) and 0.04s (i.e.1/25) separately. For impact pressures, occurrence time of debris flow is determined with data detected by the lowest sensor. So error in this operation is time duration for debris flow depth to increase from 0 to 9mm (lower edge of the lowest sensor). It is smaller than 0.03s.

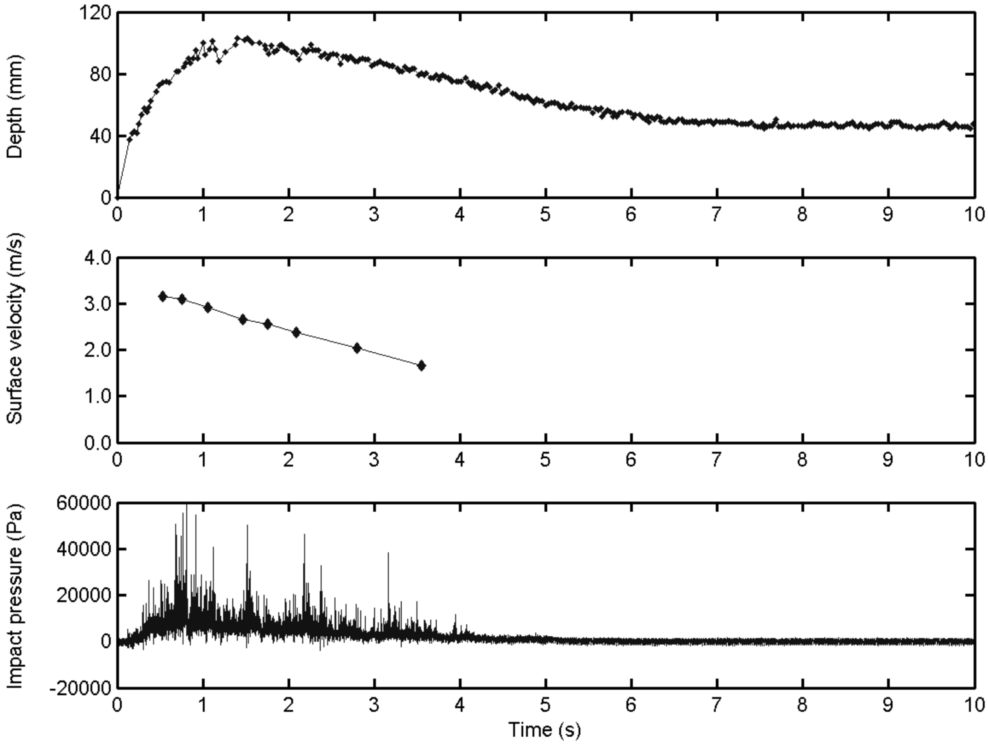

Figure 5 Graphs of debris flow depth, surface velocity and impact pressure

3.3.2 Data filtering

A debris flow is composed of solid particles and water. Since the particles impact sensors discontinuously and induce many spikes, or noise, in the graph of impact pressure, as illustrated in the early part of the curve in Figure 5. Noise in the later part comes from the sensor and the environment. The power spectral density of impact pressure signals is shown in Figure 6. Energy of the signal focuses in the low frequency range. Consequently, low-pass filtering is adopted to eliminate the noise as shown in Figure 7.

A cut-off frequency is needed in the low-pass filtering. The criteria for selecting a cut-off frequency are that the graph after filtering looks relatively smooth and it retains the shape of the original graph. The mean impact pressure values after filtering with different cut-off frequencies are calculated as listed in Table 2. They show that when the cut-off frequency is greater than 3Hz, there is little change in the mean values and they are close to the mean value in the original data. Thus 3Hz was selected as the cut-off frequency and the impact pressure graph after filtering is shown in Figure 7.

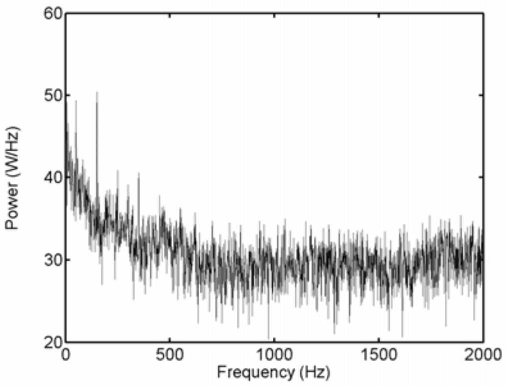

Figure 6 Power spectral density

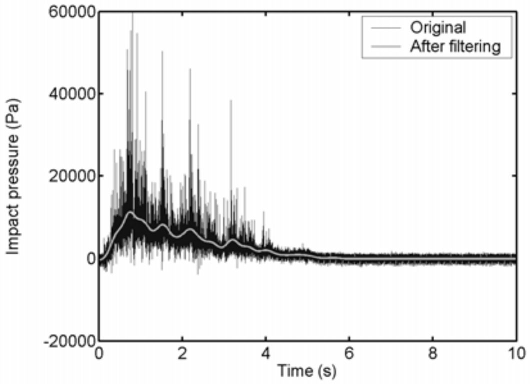

Figure 7 Impact pressure after low-pass filtering

Table 2 Mean impact pressure values after filtering with different cut-off frequencies

Frequency (Hz)	Original	1	2	3	4	5
Mean value (Pa)	2297.4	1237.1	2227.2	2297.7	2297.6	2296.8
Frequency (Hz)		6	7	8	9	10
Mean value (Pa)		2297.1	2297.1	2297.1	2297.1	2297.0

3.3.3 Static pressure and kinetic pressure determination

Kinetic pressure is the difference between impact pressure and static pressure. In order to detect static pressure of debris flow, the upright post attached with sensors is put into a vessel containing the debris flow sample. Table 3 lists the results. They agree well with pressures calculated with the equation for static water pressure. The mean absolute difference between them is 100Pa. So we can use the following equation to compute static pressure:

$$p_s = \rho_c g (h - z) \cos\theta \qquad (4)$$

in which g is acceleration of gravity, h is debris flow depth, z is vertical distance between the sensor and flume bed, and θ is the flume obliquity. Sampling frequency for debris flow depth is much less than that for impact pressure, so depth data are linearly interpolated when equation (4) is applied. Figure 8 shows graphs of static pressure and kinetic pressure for the example in figure 7. Sensors for impact pressure detection are force sensors and pressure data are quotients of force data and the area of the sensor. So figure 8 only shows the period when the sixth sensor is entirely submerged by debris flow.

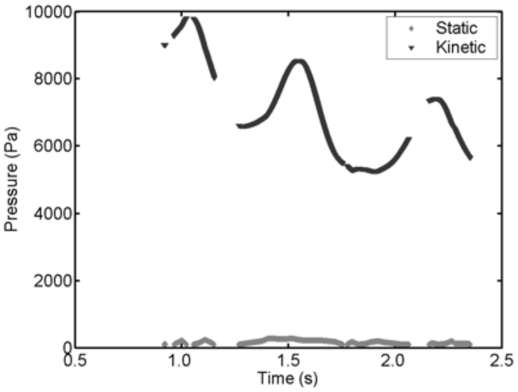

Figure 8 Graphs of static pressure and kinetic pressure

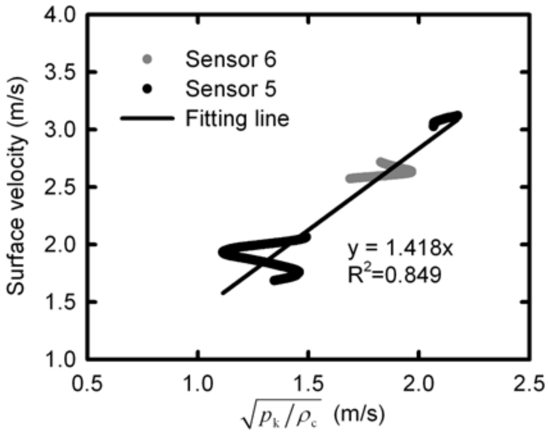

Figure 9 Relationship between surface velocity and surface kinetic pressure

3.3.4 Relationship between surface velocity and surface kinetic pressure

When the debris flow depth h is greater than 95mm, the sixth sensor is just submerged and can be considered as surface sensor. When h is greater than 80mm and less than 90mm, the fifth sensor is considered as the surface sensor. Thus, we can obtain the relationship between surface velocity and surface kinetic pressure with equation (3). Just as in the case for debris flow depth, surface velocity data also require linear interpolation. Figure 9 shows the results. The coefficient of determination (R^2) is 0.849, indicating a remarkable relationship. Table 4 lists the regressed coefficient A in equation (3) and the R^2 for each experiment. Coefficient A ranges from 1.315 to 1.481 with a mean of 1.410. It

Table 3 Detected and calculated static pressure

Sensor	1	2	3	4	5	6	7	8
Buried depth (mm)	123	108	93	78	63	48	33	18
Detected pressure (Pa)	2710	2414	1912	1702	1255	908	587	256
Calculated pressure (Pa)	2528	2220	1911	1603	1295	986	678	370

Table 4 Regression coefficients for flume experiments

Experiment	1	2	3	4	5	6	7
A	1.408	1.432	1.418	1.401	1.413	1.481	1.315
R^2	0.451	0.840	0.849	0.853	0.920	0.967	0.791

is in agreement with the value for single phase flow—1.414, which is derived from equation (1). Therefore, we can conclude that equation (1) is also applicable for debris flows.

3.3.5 Computing internal velocity with the relationship between velocity and kinetic pressure

Taking one debris flow experiment as an example, we can use the process described in sections 4.3.2-4.3.3 to obtain kinetic pressures at z=14, 29, 44, 59, 74 and 89mm. Then, equation (3) and coefficient A for that experiment are used to compute internal velocity. The result is shown in figure 10. Velocity paragraphs are fluctuant. One source is disturbance of the post to flow field. The diameter of sensor is equal to the maximum size of particles in our experiment, so larger particles randomly impact on the sensor. This is another source of fluctuating. However, velocities for different positions show the same trend with time and velocities for higher positions are larger than those for lower positions. It indicates that mean values for certain duration are more reliable than instantaneous values.

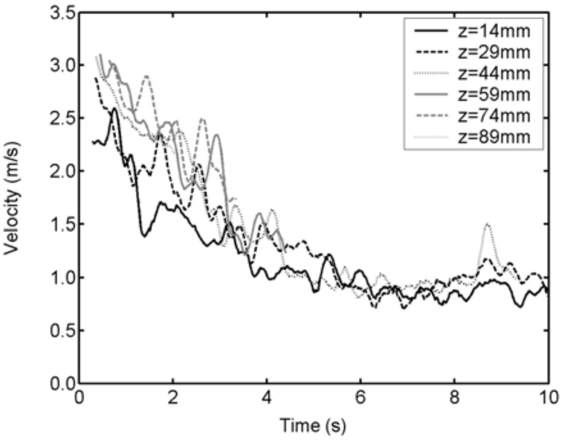

Figure 10 Velocity graph for each detecting position in one experiment

4 Conclusions and Discussion

The internal velocity of a debris flow is difficult to measure. In this paper, we have described an attempt to address this problem by using the relationship between velocity and kinetic pressure, which is estimated by surface velocity and surface kinetic pressure data, kinetic pressure being the difference between impact pressure and static pressure. The former was detected by impact force sensors installed towards flow direction at the detecting section. Low-pass filtering was used to eliminate noise in the original detected data. Observations show that static pressure can be computed with the formula for static water pressure by simply substituting water density for debris flow density. The relationship between surface velocity and surface kinetic pressure was established through a flume experiment. It is consistent with the relationship for single phase flow.

The main problem with this method is that the flow field is disturbed by the force sensor. Therefore, the sensor should be as small as possible compared with the detecting section to reduce the relative magnitude of disturbance. At the same time, it should be larger than particles in the debris flow to make detected data representative. Particles are relatively homogeneously distributed in a viscous debris flow, so we can compute internal velocity with equation (3) using the mean density. For a dilute debris flow or water-stone flow, particle concentration usually increases from the surface to bottom. Debris flow density for the detecting position therefore should be measured in that case. In addition, when this method is applied to natural debris flows, the upright post should be partly buried in the channel to withstand impact pressure.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 40771026) and the NSFC-RFBR project (Grant No. 40911120089, 08-05-92206 NSFCa). The authors appreciate the editorial suggestions of Dr. J. S. Gardner, the Visiting Professor for Senior International Scientist of CAS.

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