Analysis on the dynamic characteristics of debris flow in Jiangjia Ravine, China

Dongri Song*
Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, 610041 Chengdu, China

Abstract. Dynamic characteristics determine the mobility of debris flow and are also key to hazard risk assessment. However, the dynamic process of natural debris flow is very complex. Based on the systematic analysis of the field observation data of 93 debris-flow events at Jiangjia Ravine (Yunnan, China), this study attempts to investigate the dynamic mechanisms and sources of flow resistance of debris flow. The Jiangjia Ravine debris flows are almost completely liquefied, indicating that grain contact friction plays a negligible role. Flow regime analysis shows that the flow regimes of the Jiangjia Ravine debris flows vary from viscous to inertial. The fluid viscous effect and particle collisions may be the main sources of flow resistance.

1 Field observation of debris flow at Jiangjia Ravine

1.1 The Jiangjia Ravine debris flows

Jiangjia Ravine is located in Yunnan Province, China. The main channel is 13.9 km long with a drainage area of 48.6 km² and extends from the drainage divide at 3269 m altitude west to the junction with the Xiaojiang River at 1042 m.

Jiangjia Ravine is known for its high frequency of debris flow. On average, dozens of debris-flow events occur every year (28 events in 1965), and each event contains tens to hundreds of surges (Kang et al., 2004). In the 1960s, the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences established the Dongchuan Debris Flow Observation and Research Station (DDFORS) at Jiangjia Ravine. Since the establishment of DDFORS, long-term observations and research on the initiation, transportation, and deposition of debris flow have been carried out, and a relatively complete debris-flow database has been established (Cui et al., 2005).

1.2 Debris flow observation at DDFORS

In DDFORS, the observation focuses on the kinetic parameters of debris flow. The measured physical quantities include the frontal velocity \( v \) (m/s), flow surface width \( W \) (m), flow depth \( h \) (m), and bulk density \( \rho \) (kg/m³).

According to field observations, the flow patterns (surge flow and continuous flow) of the debris flow are recorded. When there is an obvious interval between two debris flows, it is regarded as a surge flow. When the continuous discharge is large or the duration of one debris flow is long, it is regarded as a continuous flow.

Fig. 1. Observation of debris flow at Dongchuan Debris Flow Observation and Research Station (DDFORS)

A typical surge flow (Fig. 1) shows a steep front with the densest slurry and the highest concentration of particles, followed by a tail where the solid concentration gradually becomes dilute and the flow depth becomes shallower (Iverson, 1997; McArdell et al., 2007). In DDFORS, a debris-flow event consists of more than a dozen surge flows and several continuous flows. Based on the on-site ultrasonic measurements, the hydrographs of debris-flow events (29 August 2000 and 24 July 2001) are shown in Fig. 2, reflecting the periodicity of surge flows. The flow patterns of debris flow are controlled by upstream variations in channel slope. When the sediments stored in the low-slope section exceed its storage capacity, the channel blockage-breaking effect would occur, and then, the discharge of debris flow suddenly increased, forming surge flow downstream (Kean et al., 2013). The periodical blockage-breaking effect is an important reason for the formation of surge flow (Guo et al., 2020).

The wide gradation is also one of the obvious characteristics of Jiangjia Ravine debris flows. Particle size ranges from \( 10^{-6} \) m to 10 m, bulk density is between

* Corresponding author: drsong@imde.ac.cn
1600 to 2300 kg/m$^3$, and the total solid concentration is as high as 85% (Cui et al., 2005). The particle size distribution curves of surge flows and continuous flows are shown in Fig. 3. In particle size range of 0.5-100 mm, the particle size distribution curves of surge flows are steeper than that of continuous flows, and the sorting is poor.

The important reason why debris flow cannot be regarded as a simple Newtonian fluid is that the liquid phase of debris flow is not water, but slurry composed of fine particles (clay and silt) and water. Slurry plays an indispensable role in the movement of debris flows (Coussot, 1995; Kaitna et al., 2016). In DDFORS, it was found that the solid mass content of particles <2 mm generally does not vary with the total solid concentration (approximately 680 kg/m$^3$, Fei et al., 1991), indicating that particles <2 mm could be regarded as slurry. In this study, the critical particle size of the debris flow is 1.2 mm, as suggested by Cui et al. (2005). In the following analysis, the solid concentration $\phi_s$ excludes fine particles with a particle size of less than 1.2 mm.

The parameters of Jiangjia Ravine debris flows are summarized in Table 1. Since fine particles below 1.2 mm are considered as liquid phase, the median diameters of solid particles in surge and continuous flows are 12 mm and 6 mm, respectively, regarded as the characteristic diameters $\delta$. As for surge flows, the range of flow depth is 0.1-3.0 m and the range of flow velocity is 1.7-14.3 m/s. For continuous flows, the range of flow depth is 0.2-2.0 m and the range of flow velocity is 1.6-14.0 m/s. The viscosity of interstitial fluid (slurry) varies among several orders of magnitude. Rheological tests show that the ranges of viscosity $\eta$ of surge flows and continuous flows are 0.14-5.61 Pa·s and 0.05-4.66 Pa·s, respectively. The internal friction angle $\phi$ of the solid particles is 29.8° (Kang et al., 2004), and the density of solid particles $\rho_s$ is 2650 kg/m$^3$.

### Table 1. Parameters of Jiangjia Ravine surge flow and continuous flow

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Surge flow</th>
<th>Continuous flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of solid particle $\rho_s$ (kg/m$^3$)</td>
<td>2650</td>
<td>2650</td>
</tr>
<tr>
<td>Bulk density $\rho$ (kg/m$^3$)</td>
<td>1600-2390</td>
<td>1360-2350</td>
</tr>
<tr>
<td>Fluid density $\rho_f$ (kg/m$^3$)</td>
<td>1275-2076</td>
<td>1230-2193</td>
</tr>
<tr>
<td>Fluid viscosity $\eta$ (Pa·s)</td>
<td>0.14-5.61</td>
<td>0.05-4.66</td>
</tr>
<tr>
<td>Volumetric solid concentration of coarse grain $\phi_0$</td>
<td>0.24-0.55</td>
<td>0.10-0.34</td>
</tr>
<tr>
<td>Volumetric solid concentration of fines $\phi_f$</td>
<td>0.13-0.30</td>
<td>0.13-0.47</td>
</tr>
<tr>
<td>Characteristic diameter $\delta$ (mm)</td>
<td>0.012</td>
<td>0.006</td>
</tr>
<tr>
<td>Flow depth $h$ (m)</td>
<td>0.1-3.0</td>
<td>0.2-2.0</td>
</tr>
<tr>
<td>Velocity $v$ (m/s)</td>
<td>1.70-14.25</td>
<td>1.61-13.99</td>
</tr>
<tr>
<td>Slope angle $\theta$ (°)</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Stokes number $Sr$</td>
<td>0.46-91.14</td>
<td>0.23-32.28</td>
</tr>
<tr>
<td>Density ratio $\sigma$</td>
<td>1.13-1.44</td>
<td>1.01-1.47</td>
</tr>
</tbody>
</table>

### 2 State of liquefaction of debris flows at Jiangjia Ravine

The slope of the field observation section is approximately 3.7° in DDFORS. However, on such a gentle slope, there are debris flows with velocities higher than 10 m/s. An obvious reason is the state of liquefaction. The pore fluid pressure in a debris flow can remain elevated well above the hydrostatic pressure levels. In other words, excess pore fluid pressure is generated to maintain the debris flow in a nearly liquefied state and leads to lower flow resistance.

The liquefaction ratio is defined as the ratio of the pore fluid pressure $P$ to the normal stress $\sigma$, i.e., $LR=P/\sigma$. When $LR$ is close to unity, it indicates that the debris flow is in a completely liquefied state. Song et al. (2021) conducted a series of flume experiments adopting the sediments of Jiangjia Ravine debris flow as solid...
materials, and the normal stress, shear stress, and the pore fluid pressure of debris flow were measured using basal sensing modules. It is found that, for debris flow with a bulk density of 1990 kg/m³, the measured pore fluid pressure is close to normal stress (Fig. 4a), i.e., the liquefaction ratio \( LR \) is close to unity.

![Image](https://doi.org/10.1051/e3sconf/202341501023)

Fig. 4. The stress and liquefaction ratio of debris flow. (a) Measured stresses and pore fluid pressure of experimental debris flow (Song et al., 2021). (b) Deduced liquefaction ratio of Jiangjia Ravine debris flows.

Besides, equation (1), which considers the contributions of both solid phase frictional and liquid phase viscous effects, is a common formula for the flow resistance of debris flow (Ancey, 2007; Ancey & Evesque, 2000), and it can be used to estimate the liquefaction ratio \( LR \).

\[
\tau = \mu_p \sigma_e + \dot{\gamma} \eta
\]  

where \( \mu_p \) is the friction coefficient of particles, \( \mu_p = \tan \phi \), \( \phi \) is the internal friction angle of solid particles, and \( \sigma_e = \sigma - P \) represents the effective stress (Pa), for steady flow, \( \sigma = \rho g h \cos \theta \). In Equation (1), \( \mu_p \sigma_e \) is the resistance provided by particle contact friction, indicating that flow resistance is related to effective stress; \( \dot{\gamma} \eta \) is the contribution of the fluid viscous drag to the flow resistance, which depends on the shear rate. By substituting the above relations into Equation (1), the liquefaction ratio \( LR \) of debris flow can be deduced by a back-of-the-envelope approach.

\[
LR = 1 + \frac{\dot{\gamma} \eta}{\mu_p \rho g h \cos \theta} - \frac{\tan \theta}{\mu_p}
\]  

Note the contribution of collisional force is not considered. In other words, the contribution of frictional stress (effective stress) is exaggerated in Equation (1). Therefore, the liquefaction ratio calculated by Equation (2) should be the lower limit. According to Equation (2), for Jiangjia Ravine debris flows, the range of liquefaction ratio is 0.89-0.95, indicating that the debris flows are close to liquefaction (Fig. 4b). Thus, the contribution by particle contact friction is not the main source of flow resistance.

3 Flow regime of debris flow at Jiangjia Ravine

The solid-fluid interaction in debris flows, i.e., the coupling among the particle contact friction, instantaneous collision (inertia) and hydrodynamic effects by fluid viscosity, is the key to studying debris-flow dynamics (Boyer et al., 2011; Trulsson et al., 2012). There are three time scales for particle motion: free-fall, inertial, and viscous. These three time scales correspond to the three regimes of free fall, inertial, and viscous and are distinguished by the Stokes number \( St \), the density ratio \( r \), and the particle Reynolds number \( Re_p \) (Cassar et al., 2005; Courrech du Pont et al., 2003). The Stokes number \( St \) is defined as the ratio of particle inertia to the fluid viscous effect

\[
St = \frac{\rho_s \dot{\gamma} \sigma^2}{\eta}
\]  

The Stokes number \( St \) represents the ability of particles to follow fluid. The lower the \( St \) is, the stronger the following trend of particles. The density ratio is expressed as follows

\[
r = \frac{\rho_s}{\rho_f}
\]  

The range of Stokes number \( St \) for surge flows is 0.5-91.1, while the range for continuous flows is 0.2-32.3. According to the threshold of Stokes number \( St \), density ratio \( r \), and particle Reynolds number \( Re_p = 2.5 \), the flow regimes of surge flows and continuous flows are shown in Fig. 5. The flow regimes of the Jiangjia Ravine debris flows spread in the viscous and inertial regions, indicating that the flow regime of natural debris flows is not dominated by either viscous or particle inertial effect. Instead, as the solid concentration and viscosity vary, the flow regime gradually transitions from the viscous to particle inertial effects, and there is a continuous transition between these two flow regimes.

![Image](https://doi.org/10.1051/e3sconf/202341501023)

Fig. 5. Flow regimes of Jiangjia Ravine debris flows: flow regimes in \((St, r)\) space.

The above analysis indicates that either for surge flows or continuous flows, the particle contact friction
contributed by effective stress is negligible. Moreover, in the \((St, r)\) space, the flow regime of a debris flow varies from viscous to inertial. Therefore, it can be inferred that the flow resistance of the Jiangjia Ravine debris flow is weakly related to particle contact friction but comes from the fluid viscous effect and inertial collision (Chen et al., 2023).

References

1. B. W. McArdell, P. Bartelt, J. Kowalski, Geophysical research letters, 34, 7 (2007)
8. F. E. Boyer, Guazzelli, O. Pouliquen, Phys Rev Lett, 107, 18, 188301 (2011)