A method for estimating the bed-sediment entrainment in debris flow

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ABSTRACT

The immense destructive impact induced by debris flow in mountainous region endangers human lives and infrastructure facilities. Previous studies have long indicated that the fatalities in a debris-flow event depend on the volume of debris flow, which may be conspicuously amplified by entraining bed-sediment along the trajectory as it descends the slope. Several lines of evidence by the previous studies have also highlighted this viewpoint that debris flow can grow dramatically in magnitude as accompanying by the entrainment. In this paper, we present an elementary model to estimate the dynamic entrainment rate of bed-sediment when overridden by debris flow. Following the preliminary studies done by Iverson (2012) and Medina et al. (2008), a temporal entrainment rate can be computed basing on the momentum conservation of the two-layer system. To take into account the influence of the pore water pressure on the entrainment rate, we employ two parameters, $\lambda_1$ and $\lambda_2$ into the model, which denote the saturate degree of debris flow and bed-sediment, respectively. Our approach demonstrates that if flow layer and bed layer shares the same friction angle, the condition $\lambda_2 > \lambda_1$ should be satisfied to provoke the entrainment. The performance of the approach is firstly tested on a simple scenario with the parameters of typical value, and then a debris-flow event that occurred in 2010 at the Yohutagawa torrent, Japan. The computed entrainment rate and accumulated depth show a good agreement with the in-situ surveys. Another advantage of our approach rests on the fact that entrainment rate is written in a differential form, thus it can be easily incorporated to the mass constitutive equation of the numerical model using a shallow water approximation.

Keywords: debris flow; dynamic approach; pore pressure; entrainment rate.

1. INTRODUCTION

A global analysis of debris flows from 1950 to 2011 demonstrated that fatalities in a debris flow are dependent on the total mass volume (Dowling and Santi, 2014; Han et al., 2014a; 2014b). However, several lines of evidences in previous researches (e.g., Hungr et al., 1984) suggest that the entrained material along the debris-flow trajectory may accumulate several times with respect to the initial volume. Many in-situ surveys and monitoring works have also highlighted this viewpoint (e.g., Berti et al., 1999; O’Connor et al., 2001; Breien et al., 2008).

Up to date studies have strongly improved the ability to estimate and predict the entrainment rate. These approaches can be divided into two principal groups: 1) empirical approaches and 2) physically-based approaches. The empirical approaches are usually derived from in-situ surveys and laboratory experiments. Worth mentioning studies have been done by McDougall and Hungr et al. (2005), Rickenmann et al. (2003), Guthrie et al. (2008), Christen et al. (2010), and Abancó and Hürlimann (2014). While the physically-based theoretical approaches include both static and hydrodynamic ones, Sassa (1998), Medina et al. (2008), Luna et al. (2012), and Iverson (2012) have done the significant progress in the quantification of the entrainment.

However limited work has been done to propose physical explanation for the mechanism of entrainment. In this paper, we present a new dynamic approach to explain the entrainment mechanism and consequently to estimate the entrainment rate.

2. THEORETICAL MODEL TO IMPLEMENT ENTRAINMENT

To simulate the entrainment rate, we apply a dynamic equilibrium approach. Previous studies (McDougall and Hungr, 2005; Medina et al., 2008; Luna et al., 2012; Iverson, 2012) revealed the main condition for bed-sediment entrainment is that, the basal shearing stress at the top surface of the bed is sufficiently high to overcome the resistance. Herein, we employ a three-layer model, which is similar to the one in Iverson’s work (Iverson, 2012).

In this system, the flow and bed layers can exchange momentum and mass, following the conservation
equation that expressed as:

\[
(\tau_{\text{hot}} - \tau_{\text{top}}) \frac{d}{dt} = \rho g (v_{\text{hot}} - v_{\text{top}}) \frac{d}{dt}
\]

(1)

where \(\tau_{\text{hot}}\) is the basal shearing stress; \(\tau_{\text{top}}\) is the boundary resistance exerted by the bed-sediment; \(v_{\text{hot}}\) and \(v_{\text{top}}\) are the boundary velocity for layer 1 and layer 2; \(\rho\) is the density of the layer; \(d_e\) is the entrainment depth; \(t\) is the elapsed time. Rearrangement of this equation shows that the entrainment rate depends on the following condition:

\[
\frac{\ddot{d}_e}{\ddot{t}} = \frac{(\tau_{\text{hot}} - \tau_{\text{top}})}{\rho g (v_{\text{hot}} - v_{\text{top}})}
\]

(2)

The term \((v_{\text{hot}}+v_{\text{top}})\) in Eq. (1) depends on the vertical distribution of the velocity, Johnson et al. (2012) has proposed a plausible velocity profile as represented mathematically by

\[
v_{\text{hot}} = (1 - s_t) \bar{v}_1
\]

(3)

where \(\bar{v}_1\) is the mean flow velocity; \(s_t\) is a fitting parameter ranging from 0 (no simple shear) to 1 (no basal slip), and \(s_t = 0.5\) may provide a better fit to the data measured in the large-scale experiments.

The top surface of the bed-sediment should be static prior to entrainment \((v_{\text{top}} = 0)\), and the shearing stress and resistance each obey the Mohr-Coulomb criterion, and they can be expressed as

\[
\tau_{\text{hot}} = \tan \phi_{\text{int}} (\rho gh \cos \theta - p_1) + c
\]

(4)

\[
\tau_{\text{top}} = \tan \phi_{\text{bed}} (\rho gh \cos \theta - p_2) + c
\]

(5)

Where \(p_1\) and \(p_2\) are the boundary pore water pressures for layer 1 and layer 2, respectively; \(\phi_{\text{int}}\) and \(\phi_{\text{bed}}\) are the dynamic friction angle of debris flow mass and bed, respectively. \(c\) is the cohesion strength of the bed-sediment. Similar to Blijenberg (2007), we assume that both the debris flow and the bed-sediment are partial liquefied. Two coefficient, \(\lambda_1\) and \(\lambda_2\) are the pore pressure ratios that indicate the liquefaction degree of layer 1 and layer 2, respectively.

\[
\lambda_1 = \frac{p_1}{\rho gh \cos \theta} ; \quad \lambda_2 = \frac{p_2}{\rho gh \cos \theta}
\]

(6)

Then Eq. (2) reduces to

\[
\frac{\ddot{d}_e}{\ddot{t}} = \frac{2gh \cos \theta [(1 - \lambda_1) \tan \phi_{\text{int}} - (1 - \lambda_2) \tan \phi_{\text{bed}}]}{\bar{v}_1}
\]

(7)

A contrast leading to the entrainment can result from the differences of liquefaction degree and internal friction, which causes \((1 - \lambda_1) \tan \phi_{\text{int}} > (1 - \lambda_2) \tan \phi_{\text{bed}}\) to arise. Eq. (7) indicates that rapid increase of pore pressure in the bed-sediment may generate a large entrainment rate. It also demonstrates that if no distinction exists between \(\phi_{\text{int}}\) and \(\phi_{\text{bed}}\), the condition \(\lambda_2 > \lambda_1\) should be satisfied to ensure the occurrence of entrainment. It can partly explain the phenomena that a severer entrainment is often observed on the wetter bed-sediment (Iverson et al., 2010). Moreover, if flow layer and bed layer shares the same degree of liquefaction, the condition \(\phi_{\text{int}} > \phi_{\text{bed}}\) should be satisfied to provoke the entrainment. It shows a good agreement with the trend revealed in Papa’s experiment (Papa et al., 2004), that entrainment rate decreases monotonically with the increasing of coarse degree of bed-sediment.

3 MODEL TEST

We test Eq. (7) with some applicable parameters, \(\lambda_1=0.45, \lambda_2=0.50\), \(h=0.2m\), \(\phi_{\text{int}}=28^\circ\), \(\phi_{\text{bed}}=30^\circ\), \(\theta=31^\circ\), and the mean flow velocity is 8m/s. Use of these values in Eq. (7) yields a certain entrainment rate 0.0217m/s. We also use these values to yield a graph of entrainment rate predicted as a function of \(\lambda_1\) and \(\lambda_2\). Figure 2 shows that the full range of plausible entrainment rate extends upward to 0.194m/s for the given conditions, if the bed-sediment is liquefied completely.

![Fig. 2. Entrainment rates predicted as a function of \(\lambda_1\) and \(\lambda_2\).](image-url)
(Iverson et al., 2010), and pore-pressure is more or less proportional to the change of flow depth (Sassa, 1988; Sovilla et al., 2006). Pore pressure immediately increases when depth of overriding debris flow increases, and dissipates when depth of debris flow decreases. To represent the complex change of pore pressure, we select a random value of $\lambda_2$ in each calculation step, that when bed-sediment is loading (expressed as: $\frac{\partial h}{\partial t} > 0$),

$$\lambda_2 = \text{random}(\lambda_2, \lambda_{2\text{max}})$$

while bed-sediment is unloading (expressed as: $\frac{\partial h}{\partial t} < 0$),

$$\lambda_2 = \text{random}(\lambda_{2\text{min}}, \overline{\lambda}_2)$$

where $\lambda_{2\text{max}}$ and $\lambda_{2\text{min}}$ are the manipulated maximum and minimum pore pressure ratios of bed-sediment, respectively; $\overline{\lambda}_2$ is the average pore pressure ratio. To illustrate the procedure above in detail, we still use the same parameters in Figure 2. Furthermore we assume that the variation of flow depth obeys an oscillation model and damps from 0.20m to 0.0m. Time interval is 0.2s. Pore pressure ratio $\lambda_2$ obeys a uniform distribution between (0.2, 0.7), with the mean value of 0.45. The given conditions yields a time-elapsed variation of entrainment rate as shown in the Figure 3, and the accumulated entrainment depth counts to 0.55m in total after undergoing 100s of debris-flow erosion.

4 APPLICATION

We select a test application of the Yohutagawa debris-flow event, 2010, to validate our approach. The Yohutagawa torrent ($28^\circ 24^\prime$ N, $12^\circ 31^\prime$ E) is located in AmamiOshima Island, southwest Japan. The torrent has a catchment area of 0.24km$^2$, and elevation varying from 20m to 250m. From a geological point of view, the massif consists of sandstone and mudstone, mainly composed of fragmented plates and flakes packed in clayey matrix. The bedrock on most slopes are covered by amount of colluvium deposits, which are typically a few meters thick. The incised channel has an average slope of about16°, ranging from 33° in the higher part to 10° on the alluvial fan. The total length of the channel is approximately 750m.

The selected event was triggered on October 20, 2010, by an intense rainfall accompanying by Typhoon Megi. Heavy rainfall provoked a failure of the colluvium deposits in the highest part of the massif, with a volume of 5843m$^3$. Field observations and subsequent interpretation of aerial photographs indicates that the initially failed mass rapidly transformed into a debris flow. Being overridden by the debris flow, the entire superficial deposits along the trajectory PA-PB (see Figure 4), was incorporated into the flow, entrainment depth was observed as 1.0-1.5m. A total volume of 8697m$^3$ was estimated in the elongated deposition region, which indicates that the volume of entrained bed-sediment was 2854m$^3$. The
heavy deposits at the alluvial fan damages two building, but luckily without any death. In this case, we follow our previous work (Wu et al., 2013), the parameters that best fitted the 2010 debris-flow event are adopted. The dynamic friction angle of debris flow is revealed as 28°. The density of the debris flow mass is estimated as 16.50kN/m³, which indicates that the degree of saturation λ₁ should be 0.56. The bed-sediment has an average internal friction angle of 29.5° as revealed by three sets of geotechnical tests at different places in the channel. The core parameter we manipulated is the liquefaction degree λ₂ of the bed-sediment. We assume the bed-sediment is partly saturated, and a value of λ₂=0.40 is selected (the sensitivity is discussed later). To obtain the variation of flow depth, we set two monitoring points marked as “M1” and “M2” at the entrainment region, and use a numerical simulation method (see Wu et al., 2013 for details) to record the temporal flow depth at the each point. As revealed by the simulated results, the mean velocity of debris flow at the entrainment region accounted to 7.0-8.0m/s.

5 DISCUSSIONS

The approach we presented in the paper allows to compute the dynamic entrainment rate. Comparing to other static methods, the additional advantage of our approach rests on the fact that entrainment rate is represented in a differential form, which make it to be easily incorporated to the mass constitutive equation of the numerical model using a shallow water approximation. In fact, we have already incorporated this approach to our previous numerical model, and test the performance using the Yohutagawa debris-flow event, 2010. We do not discuss this part in the paper, but exhibit the simulation results here. Figure 6 shows the final entrainment depth and deposit of this event, the maximum entrainment depth reaches about 1.47m at the higher part of the channel. The extension of the final deposition coincides with the area observed in the aerial photograph just after the event.

Figure 5 shows the time-elapsed variation of flow depth and consequent entrainment rate at the selected monitoring point of the channel. One can see that due to the variation of flow depth, bed-sediment is under an alternatively loading and unloading condition. Consequently, the rapidly changed pore pressure controls the entrainment rate. As shown in Figure 5, the peak entrainment rate may momentarily reach 0.65m/s when the surge of debris flow arrives, and the mean value of entrainment rate decreases from 0.15m/s to 0m/s when the debris flow passes by. The accumulated entrainment depth during the debris flow counts to 1.29m and 0.93m at M1 and M2 points, respectively. This theoretically computed entrainment depth also shows a good agreement with the result revealed by the in situ survey, in which entrainment was observed as 1.0-1.5m.

A limitation of the approach is the sensitivity of the
coefficient $\bar{\lambda}$. A sensitivity analysis of the parameter is carried out, to obtain a better understanding of its influence on the dynamic entrainment rate. We use seven different values of $\bar{\lambda}$, ranging from 0.30 to 0.60 to calibrate the simulation results of entrainment volume. Figure 7a compares the previously commented results using $\bar{\lambda}$ with six other values. Figure 7b summaries the results correlating the final entrainment volume with the different values of $\bar{\lambda}$, it indicates a conspicuous influence of $\bar{\lambda}$ on the entrainment rate and volume, especially when the values are larger than 0.5. For the Yohutagawa debris-flow event of 2010, we can state that a better fitted results of entrainment volume can be obtained applying a $\bar{\lambda}$ value of around 0.40–0.45. For practical work, $\bar{\lambda}$ is sometimes hard to estimate, therefore detailed in situ tests would be necessary to exactly validate this parameter.

6 CONCLUSION

Entrainment is a key feature mechanism that is able to amplify the magnitude of debris flow. To estimate the entrainment rate and consequent entrainment depth of the channel, in this paper we follow the studies done by Iverson (2012), and present a new dynamic approach based on the momentum conservation. The derived equation is written in a differential form, thus it can be easily incorporated to the common-used numerical model. The performance of the approach is prior tested on a simple scenario with the typical value of the parameters, and then a debris-flow event that occurred in 2010 at the Yohutagawa torrent, Japan. Results indicate that the presented approach can lead to a better estimation of the entrainment for the simulation of the debris-flow hazards.

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