Engineering Geology 160 (2013) 103–109

Contents lists available at SciVerse ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Study on the ultimate depth of scour pit downstream of debris flow sabo dam based on the energy method

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ARTICLE INFO

Article history:
Received 23 February 2012
Received in revised form 2 March 2013
Accepted 30 March 2013
Available online 16 April 2013

Keywords:
Ultimate depth
Energy method
Scour pit behind debris flow sabo dam
Black box

ABSTRACT

The ultimate depth of a scour pit downstream of a debris flow sabo dam is an important design parameter in determining the foundation bearing depth of a debris flow for Sabo dam. This paper considers the scour pit system as a black box, neglecting the energy consumed by inter-particle collision of debris flow and the collision between debris flow and the valley bed. A formula was developed for the ultimate depth of a scour pit using the energy method to establish debris flow energy changes in and out of scour pit, combined with the energy needed by sediment incipient. When the results of the formula are compared with a series of indoor flume experiments, the error ranged from 3.1% to 17.6%. The calculated and experimental values agreed well, indicating that the method based on the energy method is reasonable and feasible.

1. Introduction

Debris flow sabo dam is one of the most widely used control engineering in the mountainous region as it can hinder sediment, store flood, dissipate energy. Its stability and safety operation is a key to controlling the effect of hazard prevention and avoiding secondary hazards. According to the investigation on the available sabo dam work condition, there are mainly two types of dam accidents caused by structure instability, one is the sabo dams collapsed by huge debris flow impact because of the lack of anti-overturning ability, and the other is because the foundation is rushed out by debris flow that then resulted to collapse (Pan et al., 2012). It was reported that about 65% of sabo dam failures were caused by the increase of scour depth downstream of dams (Chen, 1983). In order to protect the safety and stability of the dam, in addition to designing the dam at a reasonable bearing depth, auxiliary dams are typically constructed downstream of a sabo dam. The depth and length of a scour pit downstream of the sabo dam are the key to decide the location and height of the auxiliary dam.

Local scour is a very complex three-dimensional phenomenon. The basic mechanism of local scour is the formation of vortices (known as the horseshoe vortex) and downflow (Ettema, 1980; FHWA, 1995). There are two types of the researches on scour pit downstream of dams from the use of the dams, as one is for the scour pit downstream of hydraulic buildings and the other is for debris flow control engineering. At home and abroad, there are a lot of researches on scour pit downstream of hydraulic engineering including the causes and development laws (e.g. Laurent, 1962; Novak, 1984; Mason and Arumugam, 1985; Yasuyuki and Tadaoki, 1989; Freund and Nachtigal, 1994; Hayashi, 1995; Liriano and Day, 2001; Kothyari, 2001; Bouchut et al., 2008). Also, results on the controls on local scour were reported in recent decades (Richadson and Davis, 2001; Lai et al., 2009; Thomas and Jürgen, 2011). Many scholars proposed to calculate the formula of ultimate depth and length of scour pit according to field survey and flume experiments, e.g. D'Agostino and Ferro (2004) put forward an approach for predicting local scour downstream of grade control structures and summarized sour data downstream of both a free overfall jet and Italian check dams with broad crested weirs. Bormann and Julien (1991) also studied the scour downstream of grade control structures. Some other records based on field survey (Lenzi et al., 2002; Lenzi et al., 2003) and most of researches were based on experiments, theoretical analysis and simulations (O'Brien et al., 1993; Sheppard et al., 2004; Sheppard and Miller, 2006; Said et al., 2008; Huai et al., 2011; Termini, 2011). However, these researches were aiming at the scouring around the hydraulic engineering or bridges and focused on the scouring laws by water or normal sediment-laden water. However, debris flow is a special fluid with great differences on the sediment gradation, characteristics and movement from normal sediment-laden water; hence the scouring laws of debris flow must have great differences from water or normal sediment-laden water. The method from hydraulic engineering offers an idea, but it cannot be directly used in the calculation of scour pit depth and foundation design of debris flow control engineering.

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http://dx.doi.org/10.1016/j.enggeo.2013.03.026

The scour pit depth downstream of a debris flow sabo dam is an important parameter to determine the bearing depth of debris flow sabo dam and the auxiliary dam. Since the life span of a scour pit is short, the field observation of a scour pit downstream of a debris flow sabo dam is very difficult and the accuracy is very low. At present, most researches of scour pit depth downstream of a debris flow sabo dam refer to the hydraulic engineering formula. Based on field investigations and simulation experiments, modified with debris flow characteristics, some formulas were created (Zhang, 1992). Although there are lots of researches that focus on field observations, case studies as well as laboratory experiments aiming at characterizing its formation, movement, basic theory, burial disasters and risk assessment (e.g. Takahashi, 1977; Sassa, 1984; Fannin and Rollerson, 1993; Coussot and Meunier, 1996; Iverson, 1997), there is few special studies on the theoretical principles applicable to the scour pit eroded by debris flow up to now (Takahashi and Nakagawa, 1994; Wang, 1999). Ishikawa (1995) estimated the depth and length of scour behind a dam with a model test combining jet theory and hydraulic jump theory. Lien (1995) studied the scour pit maximum depth and its change over time. However, he just studied clear water and the gully bed was uniform sands. Due to the large number of variables involved in debris flow scour pit depth analysis, it is not practical to consider all the variables in the formula. In addition, it is not possible to apply a single formula to all the problems, since the condition varies from region to region.

Because of the particularity of a debris flow, it is difficult to observe the formation of a scour pit and its ultimate depth in the field. In this study, the calculation of scour pit ultimate depth for close-typed dams in full storage capacity condition is obtained by using theoretical analysis and flume simulation experiments in the laboratory. Nevertheless, as this is a tentative research about the process of scour pit downstream of debris flow sabo dams, the interaction between the gully and debris flow was ignored in this study.

2. Energy method

2.1. Overview of traditional energy method

In general river hydraulic engineering such as downstream of a dam, the use of the energy method is common for the calculation of scour pit depth. The energy method mentioned earlier is an engineering analogy and is a comprehensive estimation method which was first proposed by Spurr (1985). It is also a common way to calculate scour pit depth in general river hydraulic engineering such as downstream of a dam, at export of tunnels, and for local scour of bridges. It is a method to estimate scour by using the Estimating Scour Index, ESI, which represents the relationship of scour depth and mean remaining energy between the existing dam and the proposed dam. The principle of this method is that the scour pit depth $d_s(t)$ can be expressed as a function of jet energy by incident flow, E_a, absorbed energy by rock erosion, E_{th}, consumed energy by scour pit flow, E_x, that is $d_s(t) = f(E_a - E_{th} - E_x)$. The parameters in parentheses are surplus energy of incident flow and therefore the balance of scour pit depth is a function of surplus energy.

ESI is defined as the ratio of average energy lost in the process of jet scour at two dam locations, multiplied by the constraint coefficient of the scour pit. ESI reflects the difference in flow and rock condition, the scour time between two dams, and is used to correct the scour depth of the proposed dam.

The specific calculation steps of the energy method are as follows:

(1) Select a downstream scour pit of an existing dam as a reference. The existing dam and the proposed dam have similar discharging modes and geological conditions;
(2) After validating the balanced scour depth of the referenced dam site in a certain flow, select an empirical formula to estimate scour.
(3) By using the selected empirical formula for the research dam site, get the unmodified balanced scour depth in the maximum flow;
(4) According to the geological and hydraulic difference between the two dams, obtain the balanced scour depths $d_s = d'_s/ESI$ by modifying the results obtained in (3) with ESI.

The traditional energy method is more of an engineering analogy, which does not involve a specific energy calculation. It was widely used in the calculation of scour depth related to a hydraulic engineering. The method, called energy method, used in this paper mainly focused on the energy calculation of the flow and the energy exchange between flow and sediments. Therefore, it is distinctive from the traditional method used in hydraulic engineering.

2.2. Formation of scour pit system

In this study, from the perspective of energy, the scour pit is considered as a black box. The energy of debris flow consists of both kinetic energy and potential energy. After the debris flow reaches the downstream bed from over the top of the dam, it has to overcome the shearing force of mud and sand then to form a scour pit, so some energy is lost to form an erosion gully. At the same time, the collision between debris flow and particles inside the gully also partly contributes to energy dissipation. The magnitude of energy dissipation varies due to the difference in the bulk density, volume of the flow, channel slope, and the characteristics and grain composition of gully material.

We considered the scour pit system as a black box, and debris flow as a whole, namely neglecting the energy consumed by inter-collision of bed valley and debris flow particles. The scour pit system is generalized in Fig. 1.

When the flow reaches the downstream channel, the flow collides with the water in the downstream channel which serves as a cushion. The mainstream dives into the furrow bottom and two maelstroms form at the front and back which consume part of the energy. If a water jets' ability to scour is greater than the gully's anti-rush ability, the gully will be scoured, and a bed scour pit will be formed. Along with the increase of depth, the energy dissipation of the cushion increases while the scour ability of water jets reduces until equilibrium is reached, and the scour pit becomes stable.

Apparently, scour pit depth depends on the flow erosion ability and the gully's anti-rush ability. The flow jets' erosion ability is mainly a function of discharge per unit width, flow level upstream and downstream, the dispersion in the air and the degree of aeration of flow jets. The gully's anti-rush ability is governed by material composition and geological conditions.

2.3. Energy analysis of scour pit

The following assumptions are used in an energy analysis of a scour pit:

(1) The debris flow landslide dam is a close-typed and has reached the full capacity of the reservoir; therefore the upstream debris flow directly goes into the downstream channel.
(2) The gully bed's deposition and particle size composition of mud and sand are consistent with those of the upstream.
(3) The gully bed is dry before the debris flow. Therefore, the debris flow falls directly onto the gully bed's surface without a water cushion.
(4) The silt concentration of debris flow is constant and not changing during the whole process.

The schematic of a scour pit is shown as Fig. 2. Δh is the height difference between a landslide dam (mm) and a downstream gully bed; h_t is scour pit depth (m) and L_t is scour pit length (m). The downstream exit point O of scour pit is set as base point. Energy analysis

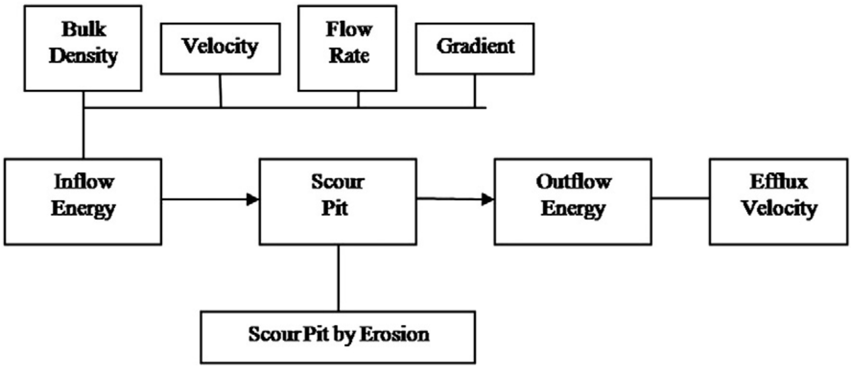

Fig. 1. The system of scour pit black box: the inflow energy can be expressed as the bulk density, velocity of flow, flow rate and gradient, while the out flow energy can be expressed as the efflux velocity, then the energy exchange was used to scour the gully and shape a pit.

is performed on section 1–1 and section 2–2, respectively. v_1 and h_1 are upstream debris flow velocity (m/s) and mud depth (m), respectively. v_2 is the scour pit exit flow velocity (m/s).

2.3.1. Micro-element division

As shown in Fig. 3, the flow through an upstream element is

$$dq = v_h dxdh \tag{1}$$

where

v_h = flow velocity;
dx = element length;
dh = element thickness.

2.3.2. Select cross section speed of flow formula

Debris flow is a dynamic process. The velocity distribution is not uniform over the entire vertical section (Figure 3). A number of velocity distribution formulas were proposed either based on theoretical analysis or field statistical methods (Takahashi and Nakagawa, 1993; Xiong, 1996). Gravel-rock flow can be approximated by a formula proposed by Takahashi (1978), in which the cohesion is ignored. The formula proposed by Chinntou et al. (1993) is more complicated which accounts for the distribution of cohesion and concentration.

Fei and Shu (2004) proposed the following empirical formula for viscous debris flow velocity, based on the Manning Formula and the monitoring of Jiangjia Ravine and Hunshui Gully, Yunnan, China:

$$v = 1.62\left[\frac{S_v(1-S_v)}{d_{10}}\right]^{\frac{2}{3}} h^{\frac{1}{3}} J^{\frac{1}{6}} \tag{2}$$

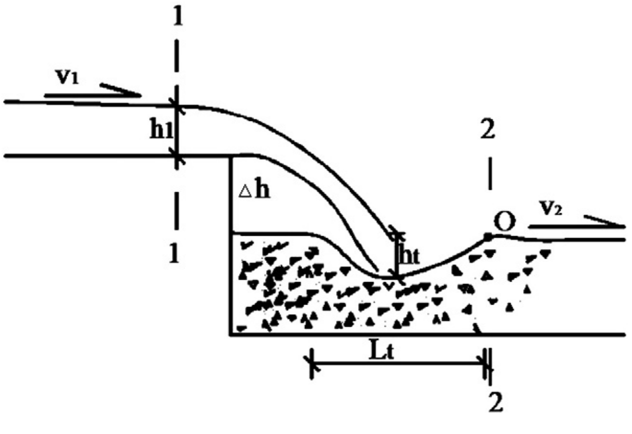

Fig. 2. Schematic of a scour pit: h1 is the depth of debris flow, Δh is the height difference, O is set as base point, h_t and L_t are the limiting depth and length of scour pit.

where

S_v = mud and sand volume concentration;
J = gully bed gradient;
d_{10} = particle diameter in millimeters at which 10% of the material passes the sieve, mm.

This paper focuses on the study of the scour pit behind a debris flow sabo dam, while the velocity distribution is ignored. Substitute Eq. (2) into Eq. (1), and integrate over the mud depth h_1, the discharge per unit width of debris flow is

$$q_1 = \int_{h_1} v_h dxdh = \int_0^{h_1} 1.62\left[\frac{S_v(1-S_v)}{d_{10}}\right]^{\frac{2}{3}} h^{\frac{1}{3}} J^{\frac{1}{6}} dh = 1.215\left[\frac{S_v(1-S_v)}{d_{10}}\right]^{\frac{2}{3}} J^{\frac{1}{6}} h_1^{\frac{4}{3}} \tag{3}$$

where

h_1 = mud depth of upstream debris flow, mm.

2.3.3. Expression of section energy

As shown in Fig. 2, the scour pit exit O is the base point. For a particular moment, flow energy E_1 before it enters the scour pit (section 1–1) consists of kinetic energy E_k and potential energy E_{a1}. Assuming that the elevation does not change before and after the formation of a scour pit, the debris flow energy can be expressed as

$$E_k = \frac{1}{2}\gamma_m q_1 v_1^2 \tag{4}$$

$$E_{a1} = \gamma_m q_1 \Delta h. \tag{5}$$

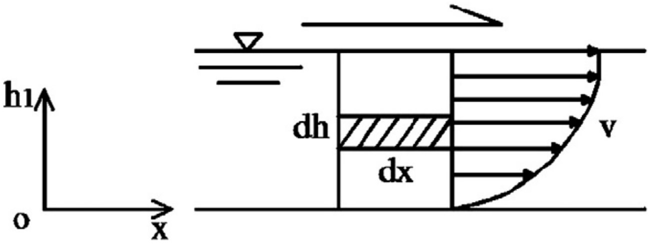

Fig. 3. Velocity profile of viscous debris flow and dh × dx is a micro-element division.

Substitute Eqs. (2) and (3) into Eqs. (4) and (5), the total energy at section 1–1 is

$$E_1 = E_k + E_{a1} = 1.59\gamma_m \left[\frac{S_{v1}(1-S_{v1})}{d_{10}}\right]^2 J^{\frac{1}{2}} h_1^2 + 1.215\gamma_m \Delta h \left[\frac{S_{v1}(1-S_{v1})}{d_{10}}\right]^{\frac{2}{3}} J^{\frac{1}{6}} h_1^{\frac{4}{3}} \tag{6}$$

where

$\gamma_m =$ density of debris flow, t/m^3;
$S_{v1} =$ mud and sand volume concentration in section 1–1, $S_{v1} = S_v$.

Let the bulk density of a scour pit exit flow be γ_2 (t/m^3), the corresponding mud and sand volume concentration be S_{v2} and flow mud depth behind pit be h_2 (m). Assuming that d_{10} of outflow does not change and ignore the variation of the gully bed slope behind the scour pit, the energy at section 2–2 is

$$E_2 = \frac{1}{2}\gamma_2 q_2 v_2^2 = 1.59\gamma_2 \left[\frac{S_{v2}(1-S_{v2})}{d_{10}}\right]^2 J^{\frac{1}{2}} h_2^2. \tag{7}$$

2.3.4. The expression of consumed energy in a scour pit

After passing the dam, debris flow reaches the downstream channel and impacts the gully bed with energy. When the debris flow energy is greater than the gully bed sediment's anti-erosion ability, mud and sand on the surface of the gully bed will be carried away, forming scour pits. This process consumes part of the energy of debris flow. Taking the mud and sand in the scour pit as a whole, the energy required to form the scour pit is equal to the energy required to overcome the buoyant weight of the scoured away sand and mud.

According to the analysis of experimental observation, the profile of a scour pit is deeper in the middle with the upstream slope steeper than the downstream slope. The profile can be approximated by a triangle as shown in Fig. 4, where tanα_1 and tanα_2 denote the upstream slope and the downstream stream slope, respectively. h_t is the maximum depth of the scour pit.

The buoyant weight of the sediment originally in the scour pit is

$$W_s' = (\gamma_s - \gamma)\left[\frac{1}{2}h_t\left(\frac{h_t}{\tan\alpha_1} + \frac{h_t}{\tan\alpha_2}\right)\right] = \frac{1}{2}h_t^2(\gamma_s - \gamma)\frac{\tan\alpha_1 + \tan\alpha_2}{\tan\alpha_1 \tan\alpha_2}. \tag{8}$$

Using a simple formula for the center of gravity, the energy required to lift the effective weight of that triangular shaped sediment out of the scour pit is

$$E_3 = W_s' \cdot \frac{1}{3}h_t = \frac{1}{6}h_t^3(\gamma_s - \gamma)\frac{\tan\alpha_1 + \tan\alpha_2}{\tan\alpha_1 \tan\alpha_2}. \tag{9}$$

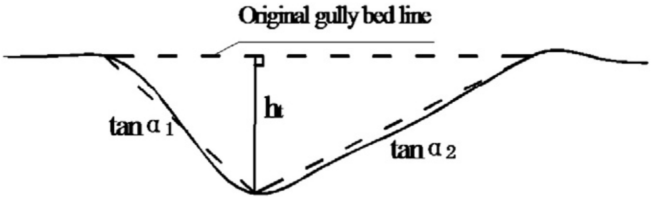

Fig. 4. Generalization graph of scour pit longitudinal profile: tanα_1 and tanα_2 are the upstream slope and the downstream slope respectively while h_t is the maximum depth of scour pit.

2.3.5. Energy balance

Ignoring the energy consumed in air entrainment and dispersion, with the law of conservation of energy, the energy consumed in the scour pit is the difference between the energy of the debris flow entering the scour pit and the energy of the debris flow exiting the scour pit. Considering the scour pit sediments washed away as a whole, neglecting the energy consumed by inter-collision of bed valley and debris flow particles, the energy consumed in the scour pit is the energy required to lift the effective weight of the sediment out of the scour pit. Thus, the energy balance relationship is as follows:

$$E_3 = \Delta E = E_1 - E_2. \tag{10}$$

Substituting Eqs. (6), (7), and (8) into Eq. (10), the limiting erosion depth can be derived,

$$h_t = \left\{\frac{9.54 J^{\frac{1}{2}}\left[\frac{\gamma_m S_{v1}^2(1-S_{v1})^2 h_1^2 - \gamma_2 S_{v2}^2(1-S_{v2})^2 h_2^2}{d_{10}^2}\right] + 7.29\gamma_m \Delta h \left[\frac{S_{v1}(1-S_{v1})}{d_{10}}\right]^{\frac{2}{3}} J^{\frac{1}{6}} h_1^{\frac{4}{3}}}{(\gamma_s - \gamma)\frac{\tan\alpha_1 + \tan\alpha_2}{\tan\alpha_1 \tan\alpha_2}}\right\}^{\frac{1}{3}}. \tag{11}$$

Let $\Theta = \frac{S_v(1-S_v)}{d_{10}} =$ mud and sand characteristic coefficient.
$\Psi = \frac{\tan\alpha_1 + \tan\alpha_2}{\tan\alpha_1 \tan\alpha_2} =$ scour pit formation coefficient.

Per Pan et al. (2009), $\tan\alpha_1 = 0.146\left(\frac{\tan\theta}{\tan\varphi'}\right)^{-0.626}$ and $\tan\alpha_2 = 0.023\left(\frac{\tan\theta}{\tan\varphi'}\right)^{-1.211}$, Eq. (11) can then be further expressed as

$$h_t = \left[\frac{9.54 J^{\frac{1}{2}}\left(\gamma_m \Theta_1^2 h_1^2 - \gamma_2 \Theta_2^2 h_2^2\right) + 7.29\gamma_m \Delta h \Theta_1^{\frac{2}{3}} J^{\frac{1}{6}} h_1^{\frac{4}{3}}}{(\gamma_s - \gamma)\Psi}\right]^{\frac{1}{3}} \tag{12}$$

where

$\phi' =$ underwater angle of repose of sediment, °.

Thus, from Eq. (12) the ultimate depth of the scour pit downstream of the debris flow sabo dam can be calculated as the function of the density of debris flow density γ_m, mud depth of upstream debris flow h_1, mud and sand volume concentration S_v and composition characteristic of mud and sand d_{10}, elevation of dam and downstream gully bed Δh, gully bed gradient J, and underwater angle of repose of sediment ϕ'. All of these parameters can be measured in practice or calculated based on the morphology of gully, the loose solid materials and the precipitation in the watershed, therefore, these two formulas can be used to calculate the scour depth and length of a pit under a debris flow sabo dam and provide basis to foundation engineering.

3. Verification and analysis of equations

3.1. Experimental equipment and materials

To verify the formulas deduced by the energy method above, a series of restricted flume experiments were carried out in a lab. The experiment was performed in the kinetic hall in Key Laboratory of Mountain Surface Progress and Hazards, Chinese Academy of Sciences. The equipment is mainly composed of a cycle device, a channel simulator and a tailings pool. The flume is 400 cm in length, 20 cm in width, and 60 cm in depth, with an adjustable slope between 0 and 30°with smooth toughened glass sides. At the beginning of section II, the channel simulator, is 18.5 cm lower than the end of section I and simulates a close typed sabo dams under a full reservoir capacity (Figure 5). The longitudinal slope of the gully varied in 10°–23°.

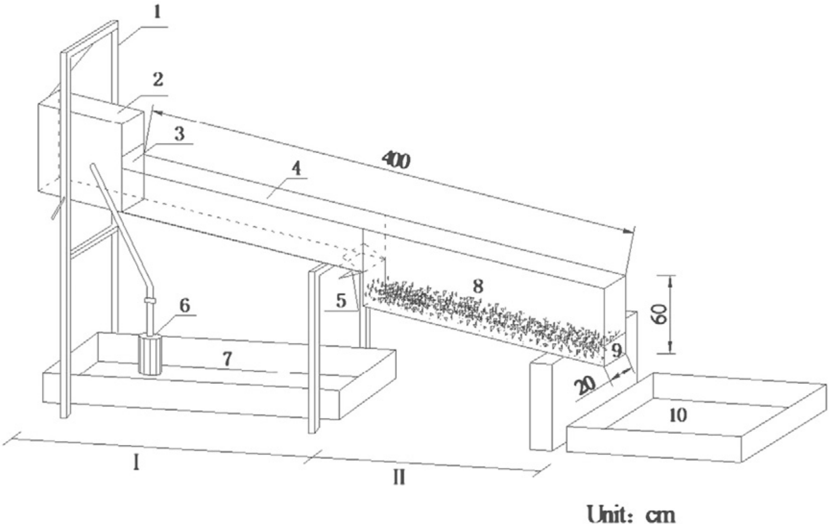

Fig. 5. Sketch of experimental flume: section I is the cycle device and section II is the channel simulator; 1: stent, 2: hopper, 3: gate, 4: glass flume, 5: flap, 6: power pump, 7: feed chute, 8: dynamic sediment body bed, 9: type-closed dam (erosion base), and 10: tailings pool.

Samples directly from Jiangjia Ravine, a famous debris flow gully in Yunnan province, China, with grain diameters less than 20 mm were used as solid materials (Figure 6). As we knew, the viscosity of debris flow was mainly from the slurry, therefore, in this study, the viscosity of slurry measured by JND-1006 was deemed as debris flows' viscosity. The main physical parameters of materials used in experiments were measured in the lab and were shown in Table 1.

Before starting, the slope of the flume was adjusted with a lifting device. Mud and sand are laid on the channel simulator (section II) which is saturated by watering. Debris flow, prepared already and whose density varied from 1.5 t/m^3 to 2.1 t/m^3, is released from upstream and flowed down to scour the downstream channel. The velocity of debris flow is scale and volume dependent, the energy of debris flow also depends on the scale and total volume. In experiments in this paper, the total volume of debris flow is 80 l. The change in elevation between the end of section I and the beginning of section II simulates the elevation difference between the top of the closed-type dam and the bottom of the downstream channel Δh. And in these experiments, $\Delta h = 0$. The change in sediment volume concentration of debris flow from scour pit exit to channel exit was ignored due to the short length of the channel. Hence, Sv_2 can be expressed as sediment volume concentration, with γ_2 as debris flow bulk density in Eq. (12). According to field observation and experimental results, the scour pit depth first increases and then decreases until the end of the debris flow process. Based on the flow process, debris flow head has the largest mud depth and erosion ability. The experiment indicates that the scour depth develops fastest when the head passes. Therefore, it is assumed that the ultimate depth is reached when the head passes.

To measure the surface velocity of debris flow and to observe the erosion process, transparent graph papers (1 cm × 1 cm) were pasted onto the side-wall glass. Digital cameras, 25 frames in 1 s, were layout to the side and to the end of flume separately to measure the surface velocity of debris flow by buoy method and to record the whole process. The longitudinal slope of flume should be measured by compass before starting the experiment. The depths of erosion in the gully were measured by marking pin as 5 cm × 10 cm when the experiments were finished. As there was a little slurry residual in gully, the slurry would be cleared out before measuring it. If there were a few large size sediments just at the measured point, it should measure a near point to avoid it. The results of experiments as well as the calculation were shown in Table 1.

3.2. Verify the results

A comparison of the calculated ultimate depth to the observed ultimate depth is shown in Fig. 7. And it shows that the values distribute

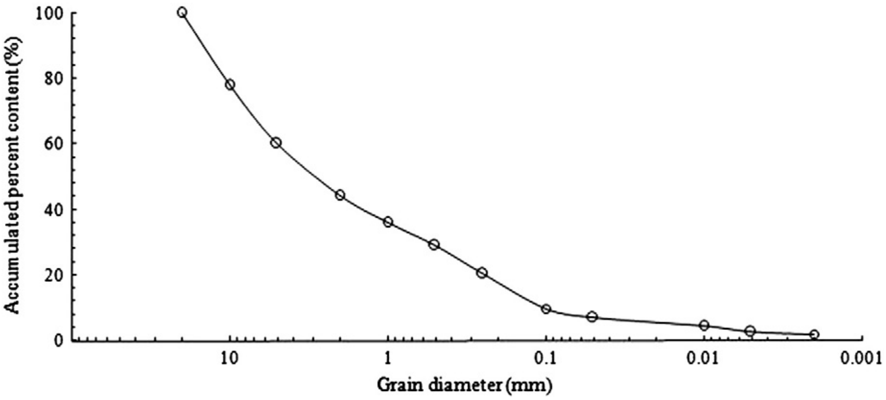

Fig. 6. Particle size distribution of experimental material.

Table 1
Calculated ultimate depth of scour pit h_{tc} and the experimented results of flume experiments h_{te}.

γ_m	θ	γ_s	S_{v1}	S_{v2}	d_{10}	Θ_1	Θ_2	$\tan\theta$	$\tan\varphi'$	$\tan\alpha_1$	$\tan\alpha_2$	Ψ	h_1	h_2	γ_2	h_{tc}	h_{te}
1.5	10	2.65	0.3	0.3	0.011	19.09	19.09	0.18	0.58	0.31	0.011	96.95	0.04	0.05	1.495	0.027	0.024
1.5	12	2.65	0.3	0.3	0.011	19.09	19.09	0.218	0.58	0.27	0.009	111.614	0.05	0.06	1.495	0.029	0.022
1.7	12	2.65	0.42	0.45	0.011	22.14	22.5	0.218	0.58	0.27	0.009	111.614	0.05	0.05	1.742	0.017	0.020
1.7	15	2.65	0.42	0.42	0.011	22.14	22.14	0.27	0.58	0.24	0.008	132.903	0.04	0.05	1.693	0.030	0.026
1.9	12	2.65	0.54	0.54	0.011	22.58	22.58	0.21	0.58	0.27	0.009	111.614	0.05	0.06	1.891	0.035	0.030
1.9	15	2.65	0.54	0.54	0.011	22.58	22.58	0.27	0.58	0.24	0.008	132.903	0.04	0.05	1.891	0.032	0.025
2.1	18	2.65	0.67	0.63	0.011	20.1	21.19	0.32	0.58	0.21	0.007	153.694	0.05	0.05	2.039	0.018	0.015
2.1	20	2.65	0.67	0.61	0.011	20.1	21.63	0.36	0.58	0.19	0.006	167.426	0.04	0.05	2.006	0.032	0.033
2.1	23	2.65	0.67	0.61	0.011	20.1	21.63	0.42	0.58	0.18	0.005	188.012	0.03	0.05	2.006	0.037	0.035

roughly near a 1:1 line. The error range is 3.1%–17.6%, reflecting that calculated and experimental data agree well.

3.3. Error analysis

As shown in Fig. 7, most of the data points lie above the 1:1 line, i.e., calculated value is generally slightly larger than experimental data. The error is mainly caused by the following aspects.

(1) Dispersion was ignored during the derivation of Eq. (12).
(2) Cohesion of the gully bed sediments was ignored during the derivation of Eq. (12).
(3) The impact of inter-particle collision between the debris flow and the gully bed was ignored during the derivation of Eq. (12).
(4) Flow, velocity, and sediment volume content of the debris flow decrease after the head passes. Thus, with the scour pit depth increasing, the follow-up mud and sand start depositing into the scour pit. Although at the final experimental measurement, mud in the scour pit was carefully cleaned out of the scour pit, there were still some coarse grained soil that remained in the bottom of pit, which led to a lower measured depth.

Furthermore, the result that the calculated value is generally slightly larger than the experimental data is a relatively safe error in practical engineering. The depth of foundation designed according to the formula is larger than its actual needs. Therefore, the engineering will be more safety.

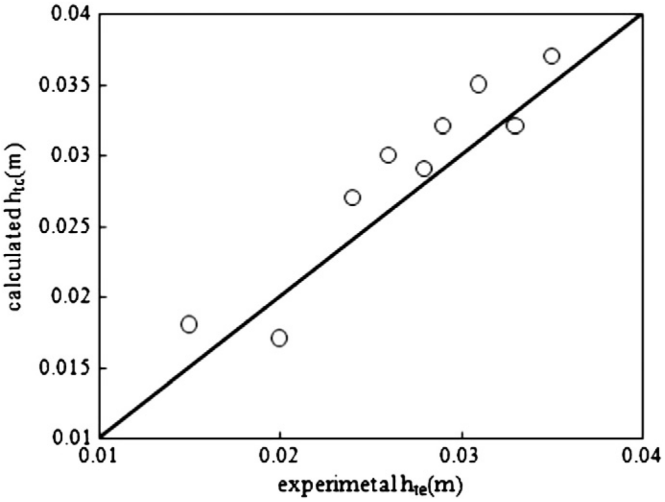

Fig. 7. Comparison of calculated values h_{tc} and experimental data h_{te} of the ultimate scour pit depth.

4. Elementary conclusions and discussions

4.1. Elementary conclusions

As the research on debris flow erosion is very complex and there were few pertinence researches on the ultimate depth of debris flow scour pit, this paper shows a tentative research by using energy methods as theory analysis. There are several conclusions based on the research:

(1) Based on the principles of energy calculation and some simplifications, this paper established a theoretical formula to calculate the ultimate depth of a scour pit downstream of a debris flow sabo dam, by analyzing the energy changes before and after pit erosion and the energy required for sediment transport. This method takes fully into account the density of debris flow, scale of debris flow, gully slope, characteristics of gully bed composition, particle size distribution and other particularities of debris flows.
(2) The calculated limiting scour depth compares well with the measured scour pit depth using an experimental method. At the same time, linking the formation development of a scour pit to the movement of a debris flow can be used to calculate the maximum depth in the formation of a scour pit and thus overcomes the difficulty in measuring the maximum depth of a scour pit after it is partially filled in field.

4.2. Discussions

This study is a tentative research on the maximum scour pit depth downstream of a debris flow sabo dams and there are lots of hypothesis and deficiencies that need further more study in future.

(1) There are mainly two kinds of sabo dam, close-typed and open-typed, but only close-typed was considered in this study. There are distinguished differences between these two kinds of sabo dam not only on the sediment-held but also on the flow pattern. Hence it needs to take special study on the open-typed sabo dam.
(2) It's easy to see that the sediment concentration is a dynamic process during a debris flow, however, to simplify the study it was supposed to a constant value. Actually, it should take account of the sediment exchange during the scour process between debris flow and gully bed.
(3) The velocity of debris flow is scale and volume dependent, so is the energy. In this study, the debris flow was total-volume controlled, that is to say it simulated a surge flows. If there are several surges in a debris flow, or it is a continuous flow, how does the scour pit develop and how about the ultimate depth of the scour pit? It is an interesting item and worthy to take further more study.
(4) The comparability of sediment is a worldwide problem that can't be solved yet. Although there is some development in the sediment comparability laws researches as the separation particle

size have achieved to an agreement, it still need further study in future. Especially for debris flow, whose grain size distribution is from clay to bowlder, the comparability is still an unfathomed problem. Although this study is a basic and theoretical research on the physical process of the scour pit and should not consider the comparability of the model at present, to study the comparability laws of debris flow must have great interesting and significance.

(5) Debris flow is a kind of particular flow with wide gradation, containing particle sizes varying from boulders to clay even colloid sands. Its movement characteristics and dynamic process differ from ordinary flow which contains a limited amount of sand particles. With the flux of debris flow decreased, the scour pit would be partially filled even disappeared by sediment carried by subsequent flow. Therefore, it's impossible to measure the real ultimate depth of a debris flow scour pit in field till now. Hence, the formulas didn't be verified by a field data. With there are more and more engineering are building and the development of the measured technology, it need to be revised in future.

Acknowledgments

The work was supported by the Chinese National Natural Science Foundation (No. 40901007, 50979103) and the research grant from Chinese Academy of Sciences (Grant No. SDS-135-1204-01). The authors are grateful to Shunli Chen and Juan Lv for the help during the experiment process.

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