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

Huali Pan [a,*], Ren Wang [b], Jiangcheng Huang [c], Guoqiang Ou [a]

[a] Key Laboratory of Mountain Hazards and Earth Surface Process, IMHE, CAS, Chengdu 610041, China
[b] Institute of Rock and Soil Mechanics, CAS, Wuhan 430071, China
[c] Asian International Rivers Center, Yunnan University, Kunming 650091, China

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.

* Corresponding author at: Institute of Mountain Hazards & Environment, Chinese Academy of Sciences, #9, Block 4, Renminnanlu Road, Chengdu 610041, China. Tel./fax: +86 28 85224316.
E-mail address: hlpan@imde.ac.cn (H. Pan).

0013-7952/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
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