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DEBRIS-FLOW DEPOSITION AND EROSION PROCESSES OF THE SEDIMENT DEPOSIT UPSTREAM OF A CHECK DAM

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ABSTRACT

Debris flow is a rapidly moving mass of a dense mixture of sediment and water that occurs in a wide variety of environments throughout the world. It is among the most dangerous natural hazards to humans and properties. Check dams are commonly constructed for preventing the sediment disaster due to debris flow by storing the harmful sediment discharge. In this study, the numerical simulations and experiments have been carried out to investigate the mechanism of debris flow deposition process upstream of a check dam, and flushing out of deposited sediment due to the erosion process by a normal scale flood flow. A new deposition velocity equation to reproduce the debris flow deposition upstream of a check dam is also developed. The simulations and experiments have been performed using closed type and grid type check dams. The simulated results agree well with the experimental results.

Keywords: debris flow, check dam, deposition/erosion, numerical model, experiments

1. INTRODUCTION

Debris flow is a rapidly moving mass of a dense mixture of sediment and water that occurs in a wide variety of environments throughout the world. It is among the most dangerous natural hazards to humans and properties (Takahashi, 1991). Thus, the understanding of behaviour and mechanism of debris flow and the study of preventive measures are very important in order to manage the sediment disaster in the river basin and prevent the downstream hazards.

Check dams are one of the effective structural counter measures for debris flow control. Check dams can effectively store the debris flow as long as there is an adequate storage capacity, when check dam loses such storage capacity, the check dam can not capture enough sediment to reduce the debris flow (Mizuyama et al., 1998). Check dams can be distinguished as closed and open types. In closed type check dam, it is difficult to prevent from losing its trapping capacity unless sediments are continuously removed; whereas open type dams may keep their trapping capacity without any need of artificially removing the sediment (Bovolin and Mizuno, 2000).

The main objective of this study is to develop a numerical model and to investigate the debris flow deposition process upstream of a check dam, and flushing out of deposited sediment due to the erosion process by a normal flow discharge. The simulations and experiments are performed for closed type and grid type check dams. Debris flow deposition model upstream of a check dam is developed based on the mechanism of static pressures. A deposition velocity equation to reproduce the debris flow deposition upstream of a check dam is also developed. To simulate the debris flow deposition upstream of a closed or a grid type check dam, a deposition model of upstream of a check dam, a model of grid dam blockage by large sediment particles in the case of a grid dam, are incorporated in the flow mixture model of debris flow. A riverbed erosion model under unsaturated bed condition is used to simulate the erosion process of deposited sediment upstream of a check dam.

2. NUMERICAL MODEL

2.1 Governing Equations

The flow of the solid-liquid mixture is described using one-dimensional depth averaged equations for the mass conservation of a sediment water mixture, the mass conservation of sediment particles, momentum conservation of the flow mixture, and equation of riverbed variation as

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}=i_b \tag{1}$$

$$\frac{\partial (Ch)}{\partial t}+\frac{\partial (CM)}{\partial x}=i_b C_* \tag{2}$$

$$\frac{\partial M}{\partial t}+\beta\frac{\partial (uM)}{\partial x}=gh\sin\theta\ -gh\cos\theta\frac{\partial h}{\partial x}-\frac{\tau_b}{\rho_T} \tag{3}$$

$$\frac{\partial z_b}{\partial t}+i_b=0 \tag{4}$$

where $M\ (=uh)$ is flow flux in x direction, u is the mean velocity, h is flow depth, i_b is erosion (>0) or deposition (≤ 0) velocity, C is the sediment concentration in the flow, C_* is maximum sediment concentration in the bed, β is momentum correction factor equal to 1.25 for stony debris flow, g is the acceleration due to gravity, θ is bed slope, τ_b is bottom shear stress, ρ_T is mixture density $(\rho_T=\sigma C+(1-C)\rho)$, σ is density of the sediment particle, ρ is density of the water and z_b is erosion or deposition thickness of the bed.

The erosion and deposition velocity that have been given by Takahashi et al. (1992) are used as follows. Erosion velocity, if $C<C_\infty$;

$$i_b=\delta_e\frac{C_\infty-C}{C_*-C_\infty}\frac{M}{d_m} \tag{5}$$

Deposition velocity, if $C\geq C_\infty$;

$$i_b=\delta_d\frac{C_\infty-C}{C_*}\frac{M}{d_m} \tag{6}$$

where δ_e is erosion coefficient, $\delta_e=0.0007$; δ_d is deposition coefficient, $\delta_d=0.01$; d_m is mean diameter of sediment, C_* is the maximum sediment concentration at the bed and C_∞ is the equilibrium sediment concentration described as

$$C_\infty=\frac{\tan\theta}{(\sigma/\rho-1)(\tan\phi-\tan\theta)} \tag{7}$$

where ϕ is internal friction angle of sediment.

2.2 Debris Flow Deposition Model Upstream of a Check Dam

In the upstream region of a check dam, sediment concentration is higher than that of equilibrium state and becomes maximum concentration due to existence of the check dam, and the yield stress exceeds the driving force, then debris flow stops and deposition occurs. This mechanism of deposition is incorporated in momentum equation of the flow mixture as considering yield stress in the bottom shear stress as

$$\tau_b = \tau_y + \rho f_b |u| u \tag{8}$$

where τ_y is the yield stress and f_b is the coefficient of resistance.

The constitutive equations of Takahashi et al. (1997) and those of Egashira et al. (1997) are chosen for the study on deposition process upstream of a check dam. By substituting the constitutive equations of Takahashi et al. (1997) into the momentum conservation equation under a steady and uniform flow conditions, the bottom shear stress for a stony debris flow is derived as

$$\tau_b = p_s \tan\phi + \frac{1}{8}\rho \frac{(\sigma/\rho)}{\left\{(C_*/C)^{1/3} - 1\right\}^2}\left(\frac{d_m}{h}\right)^2 |u| u \tag{9}$$

where p_s is static pressure which can be expressed as follows:

$$p_s = f(C)(\sigma - \rho)Cgh\cos\theta \tag{10}$$

in which $f(C)$ is described as

$$f(C) = \begin{cases} \dfrac{C - C_3}{C_* - C_3} & ; \quad C > C_3 \\ 0 & ; \quad C \le C_3 \end{cases} \tag{11}$$

where $C_3 = 0.5$ is the limitative concentration.

In the case of an immature debris flow ($0.02 \le C \le 0.4C_*$) and a turbulent flow ($C < 0.02$), the equations of bottom shear stress proposed by Takahashi et al. (1992) are used.

Using the constitutive equations of Egashira et al. (1997), the bottom shear stress is derived as

$$\tau_b = p_s \tan\phi + \rho\frac{25}{4}\left\{k_d(\sigma/\rho)\left(1 - e^2\right)C^{1/3} + k_f(1 - C)^{5/3}/C^{2/3}\right\}\left(\frac{d_m}{h}\right)^2 |u| u \tag{12}$$

where e is the restitution of sediment particles, k_d and k_f are empirical constants, k_d =0.0828 and k_f =0.16. The static pressure is as

$$p_s = \left(\frac{C}{C_*}\right)^{1/5}(\sigma - \rho)Cgh\cos\theta \tag{13}$$

The deposition velocity models given by previous researchers such as Takahashi et al. (1992), Egashira et al. (2001) and others are proportional to the flow velocity, and deposition upstream of a check dam can not be calculated, when the flow velocity becomes zero, also the calculated deposition upstream of check dam is too small. Debris flow deposition upstream of a check dam is very rapid phenomenon, which can not be calculated rapid deposition upstream of a check dam using such types of deposition equations. Therefore, new deposition velocity equation for upstream of a check dam is derived. Upstream of a check dam, deposition usually takes place when yield stress exceeds the equilibrium shear stress, before filling up the sediment storage capacity. In the upstream area of a check dam, if bed elevation z_i is less than elevation of the dam crown z_{dam} at calculation point i (Figure 1), the sediment discharge from the upstream will deposit in the distance increment of calculating

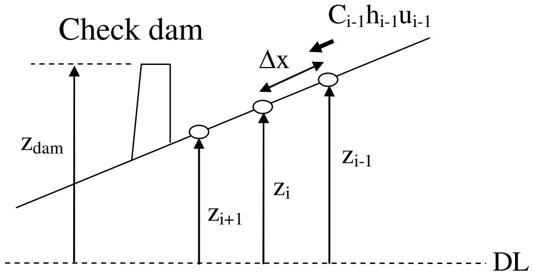


Figure 1 Definition sketch of deposition upstream of a check dam.

point Δx when yield stress exceeds the equilibrium shear stress. The sediment discharge per unit width from upstream is described as

$$qs_{up} = C_{i-1}h_{i-1}u_{i-1} \tag{14}$$

Effective non-dimensional shear stress on the bed responsible for the deposition should be $\tau_{*e}-\tau_{*y}$ and deposition velocity is written as

$$i_{dep} = K_{dep}(\tau_{*e}-\tau_{*y})\frac{C_{i-1}h_{i-1}u_{i-1}}{C_*\Delta x} \tag{15}$$

where i_{dep} is the deposition velocity upstream of a check dam (if $z_i < z_{dam}$ or $z_{i+1} > z_i$ and $\tau_{*y} > \tau_{*e}$), K_{dep} is constant, τ_{*e} is the non-dimensional equilibrium shear stress and τ_{*y} is the non-dimensional yield stress. These non-dimensional stresses are described as follows:

$$\tau_{*e} = \frac{\rho_T gh\sin\theta}{(\sigma-\rho)gd_m} \tag{16}$$

$$\tau_{*y} = \frac{(\sigma-\rho)Cgh\cos\theta\tan\phi}{(\sigma-\rho)gd_m} \tag{17}$$

2.3 Grid Dam Blockage Model

The opening of a grid dam is blockaded by large sediment particles in debris flow. This blockade phenomenon is influenced by the width of dam opening, the maximum particle diameter of sediment, and the sediment concentration of debris flow (Ashida and Takahashi, 1980; Ashida et al., 1987; Mizuyama et al., 1995; Mizuno et al; 2000; Takahashi et al., 2001b, 2002; Miyazawa et al., 2003, Satofuka and Mizuyama, 2006). Takahashi et al. (2001b) proposed stochastic model of blocking caused by formation of an arch composed of several boulders. They clarified the relationship between the probability of blockage of grid and parameters such as boulder's diameter, sediment concentration and clear spacing of dam. Based on this probability of blockage model, growing rate formula of grid dam developed by Satofuka and Mizuyama (2006) is used as follows:

$$i_b' = i_b - a_2\frac{Chu}{C_*\Delta x} \tag{18}$$

where a_2 coefficient parameter depends on the instantaneous blockade probability of grid and influence of horizontal beam, the details can be found in Satofuka and Mizuyama (2006).

2.4 Erosion Model Upstream of a Check Dam

The large boulders deposited upstream of a check dam can not be transported by a

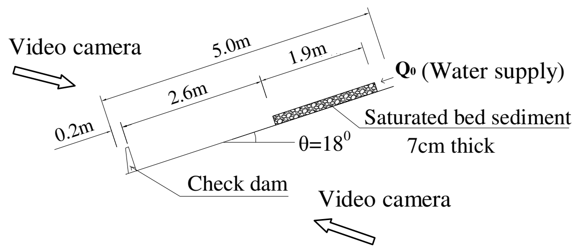


Figure 2 Experimental flume setup.

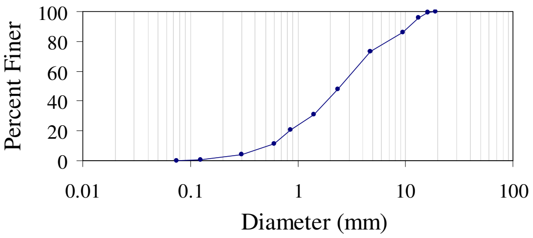
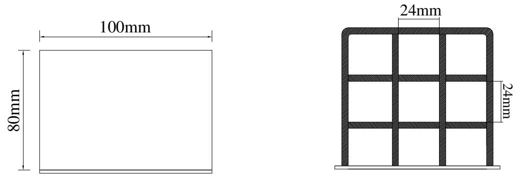
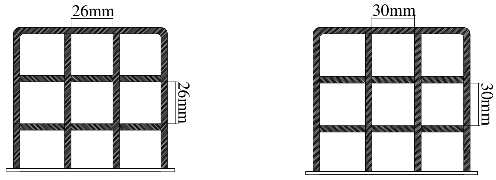


Figure 3 Particle size distribution of bed sediment.



Closed dam

Grid dam type-1 (GDT-1)
(4mm column/beam diameter)



Grid dam type-2 (GDT-2)
(4mm column/beam diameter)

Grid dam type-3 (GDT-3)
(2.5mm column/beam diameter)

Figure 4 Check dam types.

normal scale of flood flow. If we remove large boulders deposited upstream of a grid dam or blockaded large boulders at open spaces of grid, deposited sediment upstream of a grid dam may be transported by a normal scale of flood flow due to the erosion process. Hence, a one-dimensional mathematical riverbed erosion equation proposed by Takahashi et al. (1992) is used as follows.

$$\frac{i_b}{\sqrt{gh}} = K\sin^{3/2}\theta\left\{1-\frac{\sigma-\rho_T}{\rho_T}C\left(\frac{\tan\phi}{\tan\theta}-1\right)\right\}^{1/2}\left(\frac{\tan\phi}{\tan\theta}-1\right)(C_\infty - C)\frac{h}{d_m} \qquad (19)$$

where K is a numerical constant.

The condition setup for installation of closed dam proposed by Takahashi et al. (2001a) is used.

3. LABORATORY EXPERIMENTS

A rectangular flume of 5m long, 10cm wide and 13cm deep flume is set at 18 degrees for the experiments. The details of experiment setup are shown in Figure 2. A sediment bed with 1.9m long and 7cm deep is positioned 2.8m upstream from the outlet of the flume by installing a partition of 7cm in height to retain the sediment. This sediment bed is saturated by water. Sediment materials with mean diameter d_m = 2.53mm, maximum diameter $d_{\max}$ = 15mm, $C_* = 0.65$, $\tan\phi = 0.72$ and $\sigma = 2.65$g/cm^3 are used. The particle size distribution of sediment mixture is shown in Figure 3. Check dams are set at the 20cm upstream from the end of the flume. Four types of check dam; one closed dam and three grid dams with various spacing of grid are selected. The details of the check dam types are shown in Figure 4.

Debris flow is produced by supplying a constant water discharge 260cm^3/sec for 10sec from the upstream end of the flume. Debris flow produced in the experiments is the fully stony type debris flow and the largest particles are accumulated in the forefront. Debris flow deposition patterns upstream of check dams are captured by two standard video cameras located at side and above the flume end.

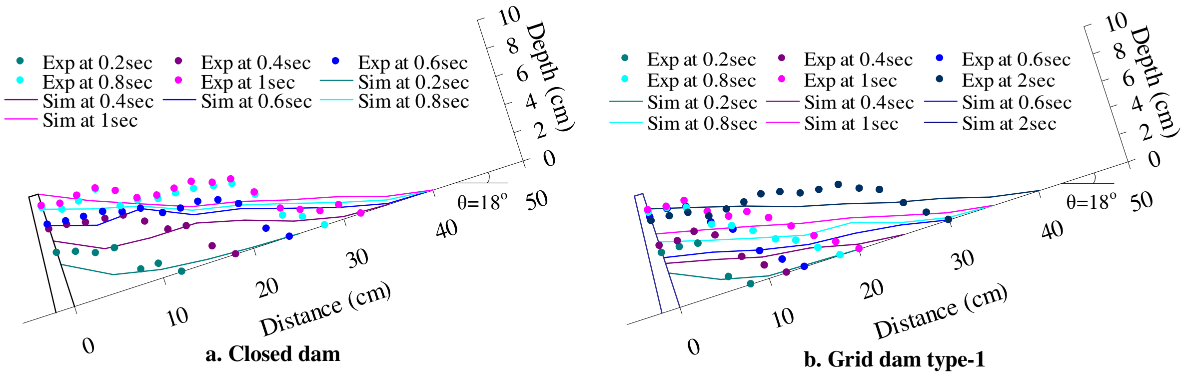
The experiments on flushing out of deposited sediment upstream of a check dam due to the erosion process are carried out in two cases, with removing and without removing large boulders from the upstream of the check dam. In CASE-I: some large boulders deposited upstream of a check dam are removed, and clear water discharge at a rate of 260cm^3/sec is supplied for 15sec. In CASE-II: firstly clear water discharge at a rate of 260cm^3/sec is supplied for 15sec without removing any large boulders deposited from the upstream of the check dam, the deposited sediment can not be effectively transported downstream, and after that some deposited large boulders are removed, then again clear water discharge at a rate of 260cm^3/sec is supplied for 15sec to check the flushing out of deposited sediment.

4. RESULTS AND DISCUSSIONS

The calculation conditions of the numerical simulation are as follows; the time interval $\Delta t = 0.001$sec, the grid size Δx=5cm, $\rho = 1.0$g/cm^3, e=0.85 (in Eq. 12), K_{dep}=1.0 (in Eq. 15) and $K = 0.1$ (in Eq. 19).

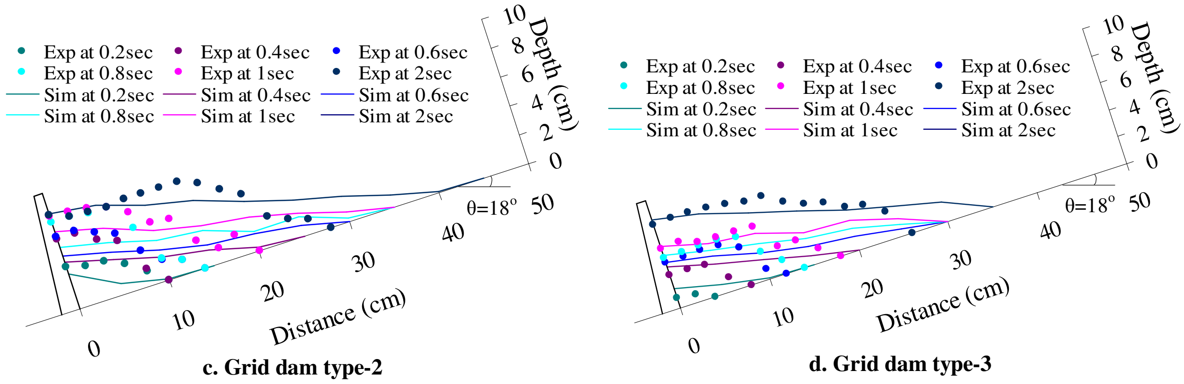
4.1 Debris Flow Deposition Upstream of a Check Dam

Figure 5 shows the simulated results using proposed deposition velocity model of



a. Closed dam

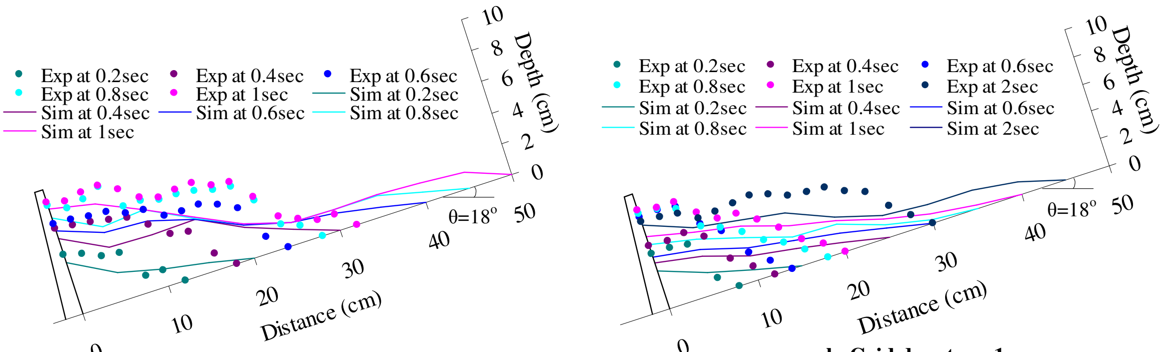
b. Grid dam type-1



c. Grid dam type-2

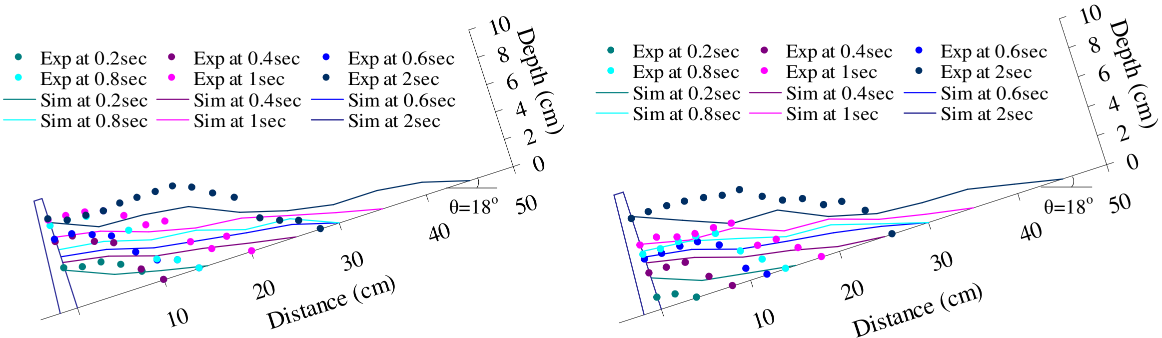
d. Grid dam type-3

Figure 5 Debris flow deposition upstream of a check dam (using proposed deposition velocity model and the constitutive equations of Takahashi et al.).



a. Closed dam

b. Grid dam type-1



c. Grid dam type-2

d. Grid dam type-3

Figure 6 Debris flow deposition upstream of a check dam (using proposed deposition velocity model and the constitutive equations of Egashira et al.).

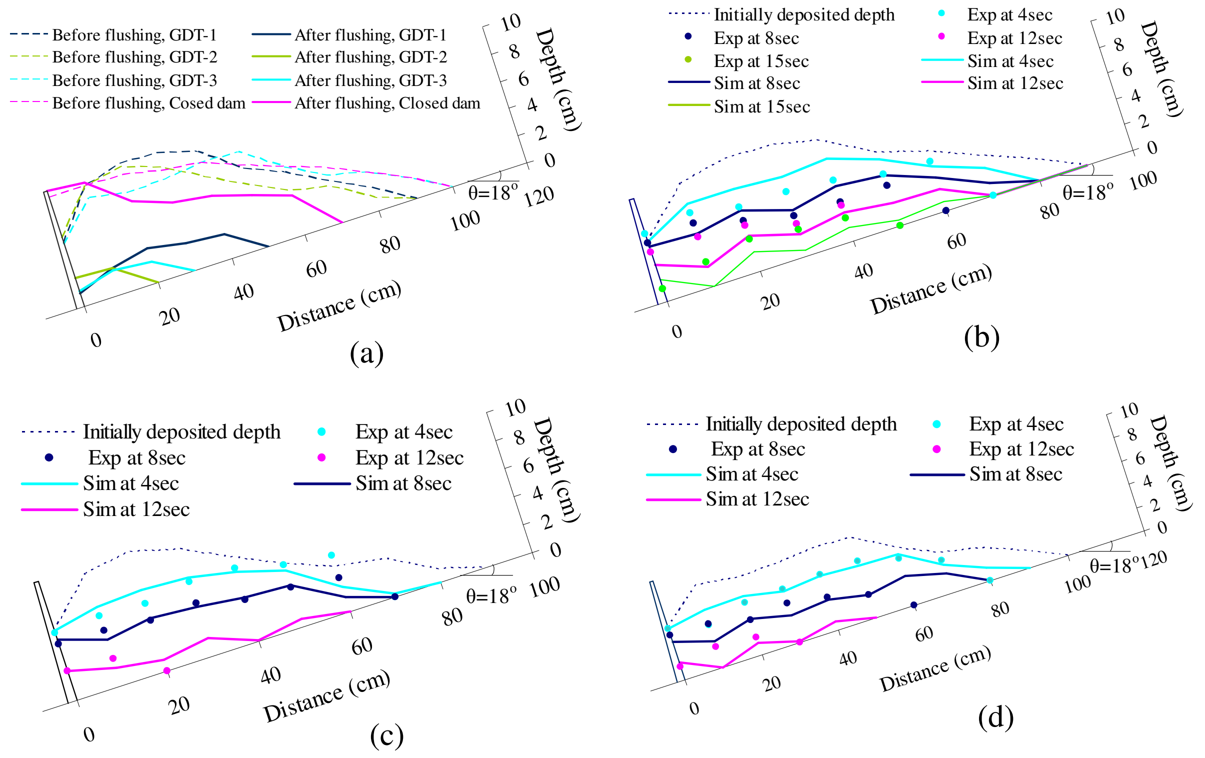
upstream of a check dam and the constitutive equations of Takahashi et al. (1997), and the experimental results of debris flow deposition upstream of a closed type or a grid type check dam. The calculated results of the debris flow deposition upstream of check dams using the constitutive equations of Egashira et al. (1997) are shown in Figure 6. From both figures, the simulated results of deposition depth upstream of a check dam are quite consistent with the experimental results at the front and near the check dam parts. However, some discrepancies can be found in the shape of deposition between simulated and experimental results at the most upstream part of deposition, which may be due to the effect of the air entrapped in the fluid, which results from churning up the flow, when a debris flow from the upstream collides with a check dam or deposited surface; and high turbulence is generated at upstream end of the deposition, in the experiments.

The debris flow deposition phenomenon upstream of a closed or a grid dam can be calculated by the proposed deposition velocity model and both the constitutive equations. Some variations are found in the simulated results with the comparison between Figure 5 and Figure 6, which may be due to the effect of the static pressures. The static pressures in Eq. 10 are influential when sediment concentration is higher than C_3, while in Eq. 13 they are predominant even for lower sediment concentrations. The experiments are carried out in fixed bed condition. The sediment deposit in the most upstream area of the deposition is eroded by the coming debris flow and the many sediments discharge downstream, which affects in the experimental results on depth of sediment deposition in the most upstream area.

4.2 Erosion of Deposited Sediment

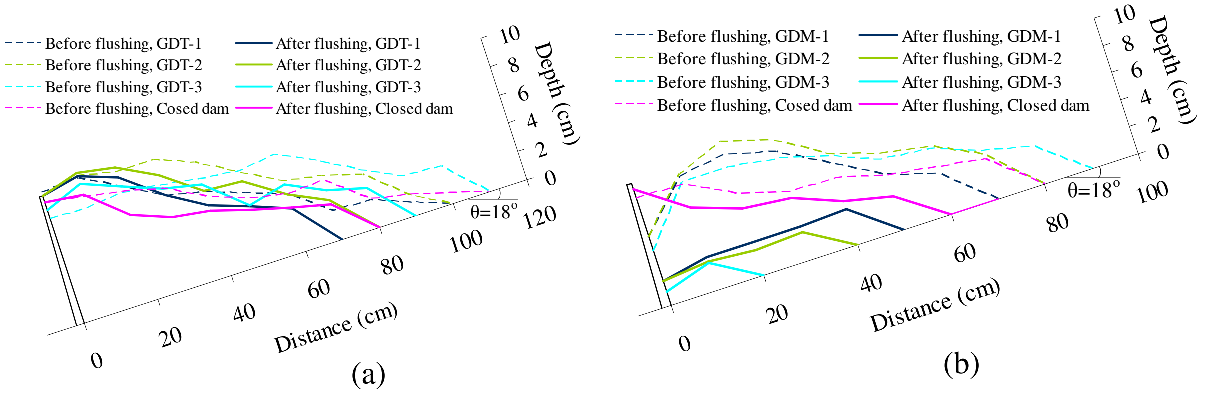
CASE-I

Figure 7 (a) shows the experimental results of the time variation in shape of deposited sediment upstream of different types of check dam due to erosion process after supplying the normal flow discharge. In which, dashed line indicates initially deposited depth of sediment and continuous line indicates depth of deposition after the erosion. The sediment deposited upstream of a grid dam is flushed out more effectively than the closed dam. The erosion process of deposited sediment upstream of grid dams is investigated using a riverbed erosion model and the comparison between the experimental and simulated results are shown in Figure 7 (b), (c) and (d) for Grid Dam Type (GDT)-1, GDT-2 and GDT-3, respectively. The deposited sediment upstream of grid dams is effectively transported to the downstream due to erosion process by a normal flow discharge. Thus, the grid type check dams will have debris flow storage capacity to control the next debris flow event in monsoon season.



(a) (b) (c) (d)

Figure 7 (a) Experimental results of erosion of deposited sediment; (b), (c) and (d) simulated and experimental bed variations of deposited sediment due to the erosion process for GDT-1, GDT-2 and GDT-3, respectively, CASE-I.



(a) (b)

Figure 8 Experimental results of erosion of deposited sediment, (a) before removing large boulders, (b) after removing large boulders, CASE-II.

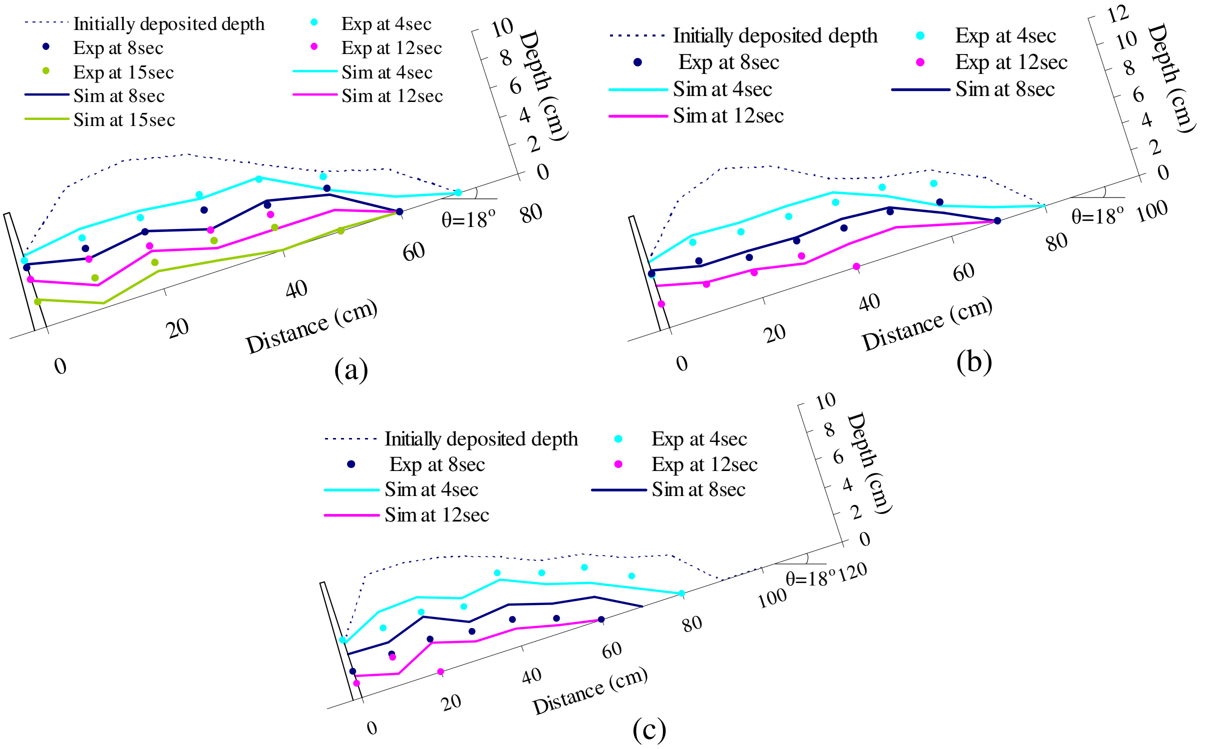


Figure 9 (a), (b) and (c) Simulated and experimental bed variations of deposited sediment due to the erosion process for GDT-1, GDT-2 and GDT-3, respectively, CASE-II.

CASE-II

In this case, firstly clear water discharge is supplied without removing any blockaded and deposited large boulders from upstream of a grid dam, and Figure 8 (a) shows the experimental results of erosion of deposited sediment, in which deposited sediment may not be effectively transported to the downstream. After that some blockaded and deposited large boulders from the upstream of a grid dam are removed, then again clear water discharge is supplied, and Figure 8 (b) shows the experimental results of erosion of deposited sediment by supplying a flushing discharge after removing some large boulders, where dashed line indicates the deposition shape after removing boulders at the end of first water supply. The deposited sediment could not be flushed out effectively due to erosion by water supplying before removing large boulders. Figure 9 shows the comparison of the simulated and experimental results of variations in deposition shape upstream of GDT-1, GDT-2 and GDT-3 at different time steps due to the erosion process after removing some large boulders from upstream of a grid dam. In all three types of grid dam, deposited sediment upstream of grid dam could be effectively transported to the downstream due to erosion process by normal flow discharge, when some large boulders blockaded in open spaces of grid and deposited upstream of a grid dam, are removed.

5. CONCLUSIONS

The numerical model is developed to simulate debris flow deposition, and erosion upstream of a check dam. A new deposition equation to calculate debris flow deposition upstream of a check dam is also developed based on the mechanism of effective non dimensional shear stress on the bed. The debris flow deposition phenomenon upstream of a closed or a grid dam can be calculated by the proposed velocity model and both the constitutive equations of Takahashi et al. (1997) and Egashira et al. (1997). The simulated results of debris flow deposition upstream of a check dam, and the erosion of deposited sediment using a riverbed erosion model agree well with the experimental results. The deposited sediment upstream of a grid dam can be flushed out more effectively than that of a closed dam due to the erosion process by a normal scale of flood flow when some deposited large boulders are removed. From the results, it is shown that the grid type check dam can keep their sediment trapping capacity more effectively than the closed type check dam.

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