NUMERICAL AND EXPERIMENTAL STUDY ON DEBRIS-FLOW DEPOSITION AND EROSION UPSTREAM OF A CHECK DAM

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Debris flow is a phenomenon that high-density water with mud and big gravel flows down along a stream at high speed. Because of its high density and speed, it has huge destruction power. Thus damages by debris flows are very severe and sometimes tragic. A check dam is commonly used for preventing the sediment disaster due to debris flow by storing the harmful sediment discharge and has various types. 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 erosion process by a normal scale flood flow. The simulations and experiments have been performed using closed type and grid type check dams. The simulated results agree well with the experimental results. 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.

Key Words **:** *Debris flow, check dams, deposition/ erosion, numerical simulation, laboratory experiment*

1. INTRODUCTION

Debris flows are among the most dangerous natural hazards that affect humans and properties, which are common in mountainous areas throughout the world[1)]. It is a phenomenon that high-density water with mud and big gravel flows down along a stream at high speed. Because of its high density and speed, it has huge destruction power. Thus damages by debris flows are very severe and sometimes tragic.

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. 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[2)].

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 erosion process by a normal flow discharge. The simulated and experimental results of closed type and grid type check dams are presented.

2. NUMERICAL MODEL

(1) Basic governing equations

The continuity equation of the flow mixture, continuity equation of the sediment particles, the momentum equation of the flow mixture, and the equation of bed variation, can be expressed as

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

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

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

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

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[3], 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 is bed surface elevation.

The erosion and deposition velocity that have been given by Takahashi et al.[3] 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 and C_∞ is the equilibrium sediment concentration described as follows.

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

where ϕ is internal friction angle of sediment.

(2) 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, before filling up upstream of the dam. This mechanism of deposition is incorporated in momentum equation of the flow mixture as considering yield stress in bottom shear stress. The bottom shear stress is evaluated as follows:

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

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

The constitutive equations of Takahashi et al.[4] and those of Egashira et al.[5] have been chosen for the study on deposition process upstream of a check dam. The constitutive equations of Takahashi et al.[4] for a fully stony debris flow are described as follows. The expression for the shear stress is as

$$\tau=p_s\tan\phi+a_i\sin\alpha_i\left\{\left(\frac{C_*}{C}\right)^{1/3}-1\right\}^{-2}\sigma d_m^2\left(\frac{\partial u}{\partial z}\right)^2 \tag{9}$$

where a_i is experiment constant, α_i is the collisions angle of the particle ($a_i\sin\alpha_i$=0.02)[1] and p_s is static pressure which can be expressed as follows [4].

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

in which $f(C)$ is described as

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

where $C_3=0.5$ is the limitative concentration.

By substituting the constitutive equations into the momentum conservation equation under a steady and uniform flow conditions, the bottom shear stress for a stony debris flow is derived as follows:

$$\tau_b=p_s\tan\phi+\frac{1}{8}\rho\frac{(\sigma/\rho)}{\{(C_*/C)^{1/3}-1\}^2}\left(\frac{d_m}{h}\right)^2|u|u \tag{12}$$

In the case of an immature debris flow ($0.02\leq C\leq 0.4C_*$) and a turbulent flow ($C<0.02$), the equations of bottom shear stress proposed by Takahashi et al.[3] are used.

Using the constitutive equations of Egashira et al.[5], the bottom shear stress is described as[6]

$$\tau_b=p_s\tan\phi+\rho\frac{25}{4}\{k_d(\sigma/\rho)(1-e^2)C^{1/3}+k_f(1-C)^{5/3}/C^{2/3}\}\left(\frac{d_m}{h}\right)^2|u|u \tag{13}$$

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

$$p_s=\left(\frac{C}{C_*}\right)^{1/5}(\sigma-\rho)Cgh\cos\theta \tag{14}$$

The deposition velocity models of Takahashi et al.[3] and others available 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. 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 (**Fig. 1**), the sediment discharge from the upstream will deposit in spatial mesh size Δx when yield stress exceeds the equilibrium shear stress. The sediment discharge per unit width from upstream is described as:

$$qs_{up} = C_{i-1}h_{i-1}u_{i-1} \tag{15}$$

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

$$i_{dep} \propto (\tau_{*e} - \tau_{*y}) \tag{16}$$

$$i_{dep} = K_{dep}(\tau_{*e} - \tau_{*y})\frac{C_{i-1}h_{i-1}u_{i-1}}{C_*\Delta x} \tag{17}$$

where i_{dep} is the deposition velocity upstream of a check dam (if $z_i < z_{dam}$ 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:

$$\tau_{*e} = \frac{\rho_T gh\sin\theta}{(\sigma-\rho)gd_m} \tag{18}$$

$$\tau_{*y} = \frac{(\sigma-\rho)Cgh\cos\theta\tan\phi}{(\sigma-\rho)gd_m} \tag{19}$$

(3) Grid dam blockage model

The opening of a grid dam is blockaded by large sediment particles in debris flow. This blockade phenomena is influenced by the width of dam opening, the maximum particle diameter of sediment, and the sediment concentration of debris flow[7), 8), 9), 10), 11), 12)]. Takahashi et al.[10)] 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[12)] is used as follows:

$$i_b' = i_b - a_2\frac{Chu}{C_*\Delta x} \tag{20}$$

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[12)].

(4) Erosion model upstream of a check dam

The large boulders deposited upstream of a dam can not be transported by a 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.[3)] is used as follows.

$$\frac{i_b}{\sqrt{gh}} = K\sin^{3/2}\theta\left\{1-\frac{\sigma-\rho_T}{\rho_T}C\left(\frac{\tan\phi}{\tan\theta}-1\right)\right\}^{1/2} \cdot\left(\frac{\tan\phi}{\tan\theta}-1\right)(C_\infty - C)\frac{h}{d_m} \tag{21}$$

where K is a numerical constant.

The condition setup for installation of closed dam proposed by Takahashi et al.[13)] is used.

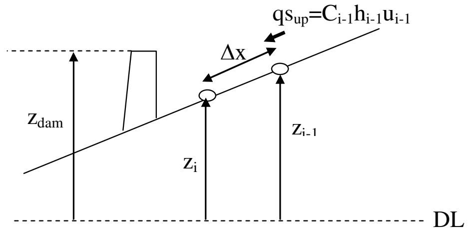

Fig.1 Definition sketch of deposition upstream of a check dam.

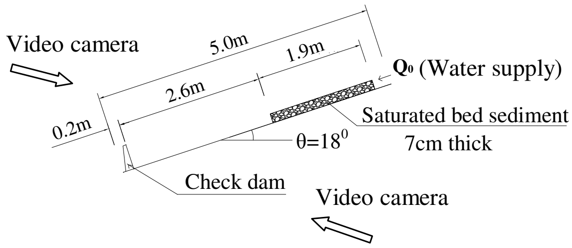

Fig.2 Experimental flume setup.

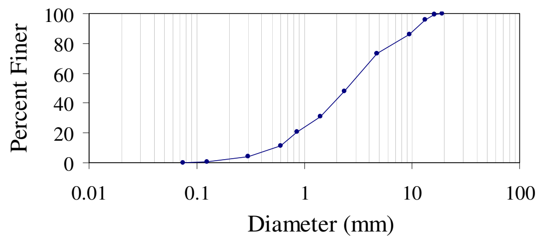

Fig.3 Particle size distribution of bed sediment.

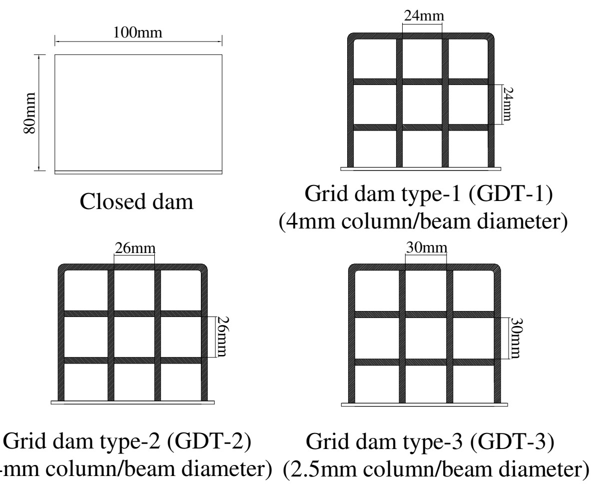

Fig.4 Check dam types.

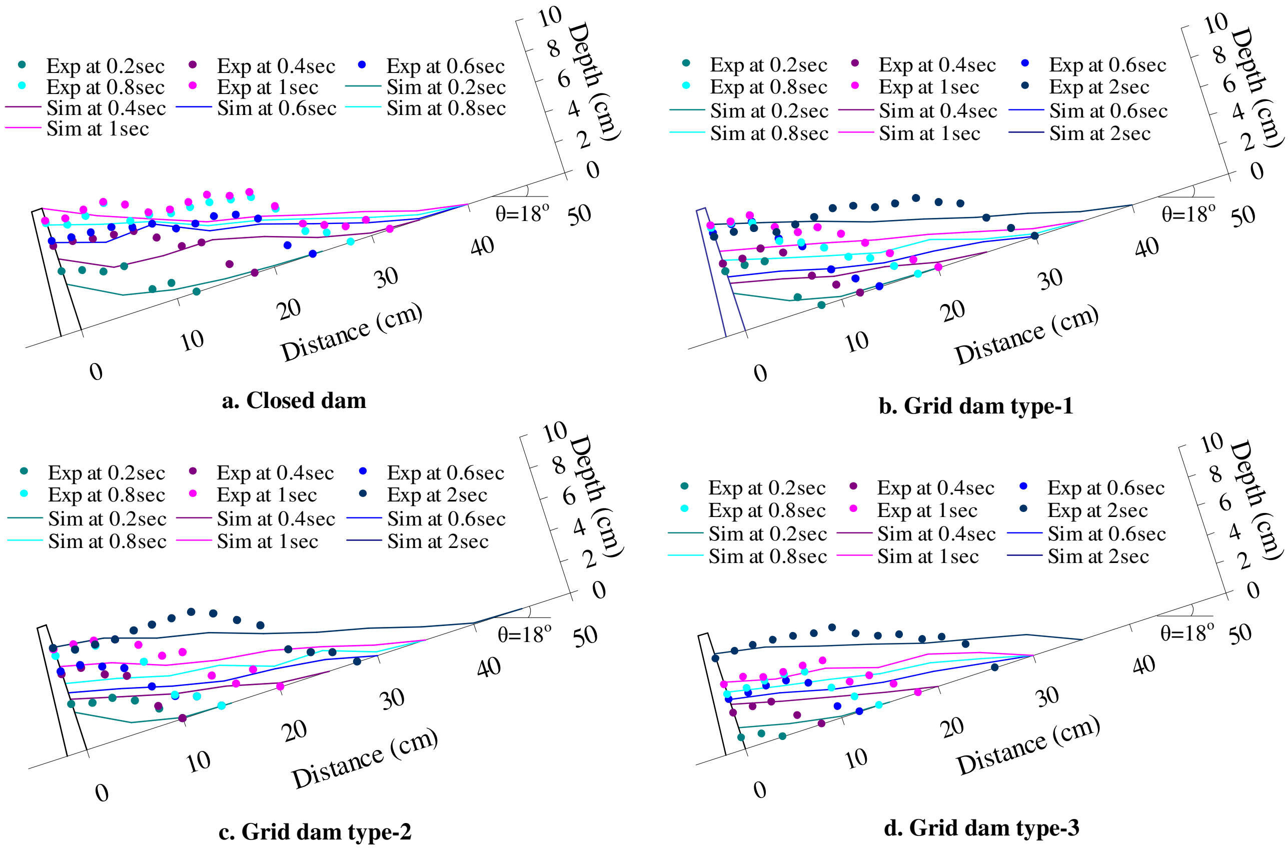

Fig. 5 Simulated and experimental results of debris flow deposition upstream of a check dam (using proposed deposition velocity model of upstream of a check dam and the constitutive equations of Takahashi et al.).

3. LABORATORY EXPERIMENTS

A rectangular flume of 5m long, 10cm wide and 13cm deep flume is used for the experiments. The slope of flume is set at 18 degrees. The details of experiment setup are shown in **Fig. 2**. Silica sand and gravel mixtures sediment 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, maximum sediment concentration at bed $C_* =$ 0.65, angle of repose $\tan\phi =$ 0.72 and sediment density $\sigma =$ 2.65g/cm^3 are used. The particle size distribution of sediment mixture is shown in **Fig. 3**. Check dams are set at the 20cm upstream from end of the flume. Four types check dam; one closed dam of 8cm in high and three open type grid dams with various spacing of grid are selected for the study. The details of the check dam types are shown in **Fig. 4**. Debris flow is produced by supplying a constant water supply 260cm^3/sec for 10sec from 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.

4. RESULTS AND DISCUSSIONS

To simulate the debris flow deposition upstream of a check dam, the blockage of grid by large sediment particles, and the erosion of deposited sediment upstream of check dam, numerical models described in **2 (2)**, **(3)** and **(4)** are used, respectively. The calculation conditions of the numerical simulation are as follows; the grid size Δx =5cm, the time interval $\Delta t =$ 0.001sec, $\rho =$ 1.0g/cm^3, e=0.85 (in eq.(13)), $K_{dep} =$ 1.0 (in eq.(17)) and $K =$ 0.1 (in eq. (21)).

(1) Debris flow deposition upstream of a check dam

Fig. 5 shows the simulated results using proposed deposition velocity model of upstream of a check dam and the constitutive equations of Takahashi et al.[4], and 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 a check dam using the constitutive equations of Egashira et al.[5] are shown in **Fig. 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

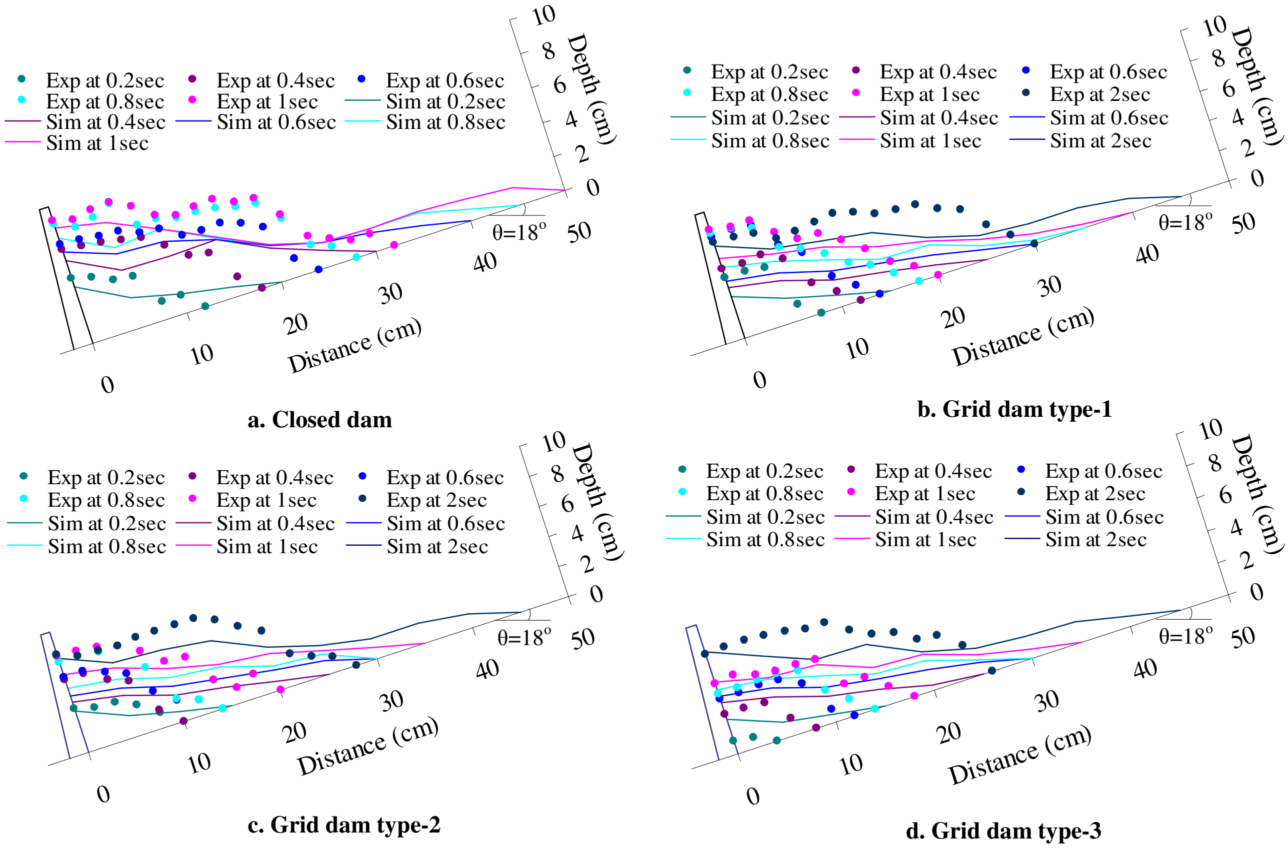

Fig. 6 Simulated and experimental results of debris flow deposition upstream of a check dam (using proposed deposition velocity model of upstream of a check dam and the constitutive equations of Egashira et al.).

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 proposed deposition velocity model upstream of a check dam and both the constitutive equations could calculate the debris flow deposition phenomenon upstream of a closed or a grid dam; however the results obtained from the model could not satisfactorily reproduce the debris flow deposition phenomenon upstream of a check dam in comparison with the experimental results. Some variations are also found in the simulated results with the comparison between **Fig. 5** and **Fig. 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.(14) they are predominant even for lower sediment concentrations.

(2) Erosion of deposited debris flow

The experiments on flushing out of deposited sediment upstream of a check dam due to erosion process are carried out in two cases. In CASE-I:

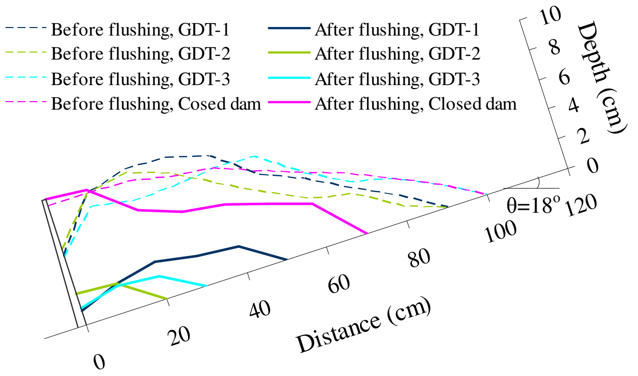

Fig.7 Experimental results of flushing out deposited sediment due to erosion and variations in depth, CASE-I.

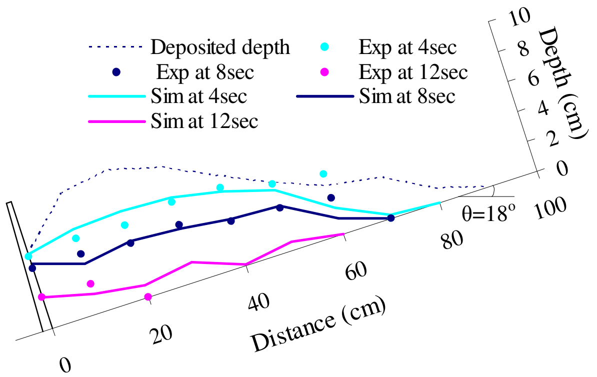

Fig. 8 Simulated and experimental bed variations of deposited sediment due to erosion process, CASE-I, GDT-2.

some large boulders deposited upstream of the check dam are removed and supplying clear water

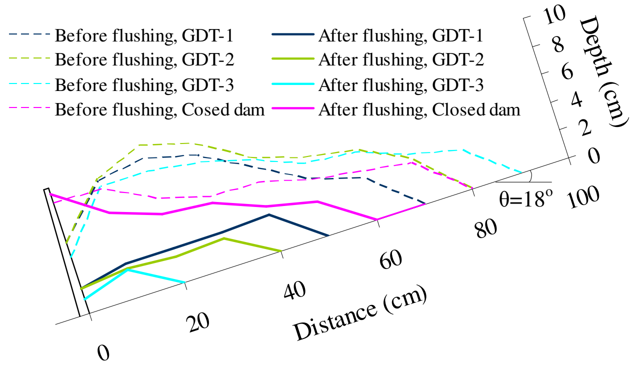

Fig.9 Experimental results of flushing out deposited sediment after removing large boulders, CASE-II.

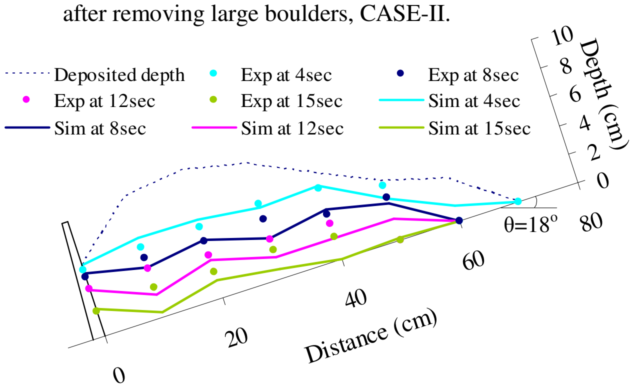

Fig.10 Simulated and experimental bed variations of deposited sediment due to erosion process, CASE-II, GDT-1.

discharge at a rate of 260cm^3/sec for 15sec. **Fig. 7** shows the experimental results of the time variation in shape of deposited sediment upstream of a closed or a grid dam. The sediment deposited upstream of a grid dam is flushed out more effectively than closed dam. The erosion process of deposited sediment upstream of a grid dam is investigated using erosion model and comparison between experimental and simulated results of one of the cases of Grid Dam Type (GDT)-2 are shown in **Fig. 8**. In the numerical simulation, measured mean diameter 3.21mm of deposited sediment is used.

In CASE-II: firstly clear water discharge at a rate of 260cm^3/sec is supplied for 15sec, 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. **Fig. 9** shows the experimental results, 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 by erosion of water supplying before removing large boulders. **Fig. 10** shows the comparison of the simulated and experimental results of deposition shape upstream of GDT-1 at different time steps.

5. CONCLUSIONS

The numerical model is developed to simulate debris flow deposition, and erosion upstream of a check dam. The simulated results 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 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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