Debris Flow Characteristics and Effectiveness of Check Dams for Trapping Debris Flows in the Garjuwa Watershed, Nepal

Badri Bhakta Shrestha

International Centre for Water Hazard and Risk Management, Public Works Research Institute, Tsukuba, Japan

Abstract

An understanding of the behavior of debris flows and the study of preventive measures are very important for managing sediment-related disasters in river basins and for preventing downstream hazards. Check dams are commonly used for preventing sediment-related disasters caused by debris flows by storing the excess, potentially hazardous sediment. In this study, debris flow behavior in the Garjuwa watershed of Nepal was investigated by using a one-dimensional numerical model. The effectiveness of check dams for trapping debris flows in the watershed was analyzed by considering both closed-check dam and slit-check dams. Methods for identifying the optimum location and height of check dams are also discussed. The closed-check dam traps all of the sediment until the dam is filled with sediment so that its sediment storage capacity decreases rapidly. In the case of the slit-check dam, harmless sediment is transported downstream before blockage of the slit opening, which keeps sediment storage capacities high for an extended period. In the Garjuwa watershed, installation of a check dam with height 15 m and located 1100 m downstream from the source of the stream (just upstream from a fan deposition area) is the most effective means of trapping debris flows in the watershed. The effectiveness of debris flow trapping was analysed by using closed-check dam and slit-check dam.

Keywords: Debris Flow, Check Dams, Preventive Measures, Numerical Simulation, Garjuwa Watershed

1. INTRODUCTION

Debris flows which contain varying amounts of mud, sand, gravel, boulders, and water, frequently occur in the mountainous areas of Nepal and other countries. These flows are capable of transporting huge boulders measuring several meters in diameter and their velocities can reach some tens of meters per second, so that the destructive force of these flows is very high (Shrestha, 2009). In addition to causing significant morphological changes along river beds and mountain slopes, these flows are frequently reported to have brought about extensive property damage and loss of life (Takahashi, 1991; Hunt, 1994; Huang and Garcia, 1997; Shrestha et al., 2008a, b). These flows stop at the mouth of a gully and fan area, and bury houses and farms and destroy roads. The occurrence of debris flows is usually so sudden that it is difficult to take refuge after realization of an outbreak (Takahashi, 2000; Nakagawa et al., 2002). Therefore, an understanding of the behavior and mechanism of debris flows and the study of preventive measures are very important for managing sediment-related disasters in river basins and for preventing downstream hazards and manage river basins in order to reduce the extensive damage and loss of life. For reduction of debris flow hazards, it is common to couple structural and non-structural preventive measures. Structural measures include check dams, levees and channel works, while non-structural measures include hazard mapping, warning and evacuation systems, emergency communication systems, proper land use, and improvement of buildings. Preventive measures require the consideration of various scenarios of hazards and involve the evaluation of hydrological, hydraulic, sediment-size distribution, topographical and other parameters (Brufau et al., 2000; Shrestha et al., 2008a, b; Shrestha, 2009).

Debris flows, the most devastating hazards in the mountainous region of Nepal, occur every year. It is thus
Debris Flow Characteristics and Effectiveness of Check Dams for Trapping Debris Flows in the Garjuwa Watershed, Nepal

Fig. 1 Photographs of Closed-check dam at Khahare Kholo stream in Muglin-Narayanghat Highway, Nepal (Source: DWIDP) and Slit-check dam at Rerukomabetsu River, Hokkaido Prefecture, Japan (Source: Nakagawa et al, 2002)

Fig. 2 Location of the study area

necessary to implement effective preventive measures in the mountainous region of Nepal. In order to reduce debris flow hazards, check dams are one of the effective structural countermeasures. A check dam is a small, temporary or permanent dam constructed across stream or channel to lower the speed of concentrated flows and trap the sediments. Check dam can be distinguished as closed-check dam and open-check dam. In closed-check dam, it is difficult to prevent from losing its trapping capacity unless sediments are continuously removed, whereas open-check dam may keep their trapping capacity without any need of artificially removing the sediment. The open-type check dam further can be subdivided into grid-check dam and slit-check dam. The check dam with slit opening is known as slit-check dam and the check dam with steel grid opening is known as grid-check dam. Figure 1 shows photographs of closed- and slit-check dams. Open-check dams such as a grid-check dam or a slit-check dam are commonly used for debris flow control because they are preferable to closed-check dams for preserving the natural environment and landscape of mountain streams as much as possible (Mizuyama and Mizuno, 1997; Miyazawa et al., 2003; Shrestha et al., 2012). Many experimental and numerical studies on debris flow control by check dams have been reported (Ashida and Takahashi, al., 1987; Mizuyama et al., 1995, 2003; Honda and Egashira, 1997; Takahashi et al., 2001; Shrestha, 2004; Satofuka and Mizuyama, 2005; Gotoh et al., 2006; Osti and Egashira, 2008; Liu, 2012). However, there has been a lack of consideration of deposition phenomena upstream of check dams.
In this study, the characteristics of debris flows in the Garjuwa watershed of Nepal were investigated by using a numerical model. The effectiveness of check dams for the control of debris flows was also investigated by using closed-check dam and slit-check dam.

2. STUDY AREA

The Garjuwa watershed is located in the Middle Mountain Physiographic Zone of eastern Nepal (Sharma and Shakya, 2008). Figure 2 shows the location of the study area. The Garjuwa Watershed is the main source of chronic problems for the Dharan-Dhankuta Road due to numerous landslides within the watershed and the transportation of huge amounts of debris onto the road during the monsoon season (Sharma and Shakya, 2008). The road is a part of the Koshi Highway connecting the industrial town of Biratnagar with Dhankuta, the Headquarters of the Eastern Development Region. The road has promising economic value and is the only gateway to the various districts of the Koshi Hills (Sharma and Shakya, 2008).

The catchment area of the watershed is about 0.859 km². The main stream draining the watershed is called the Garjuwa Stream, which flows northward for 1.394 km before joining the Leuti River. The stream carries the loose material produced by the landslide at various locations to the debris fan downstream and buries bridge, road and also some houses along the road every year. The debris flow from the Garjuwa Stream also occasionally blocks the flow in the Leuti River. It is therefore necessary to implement effective countermeasures in the Garjuwa Watershed in order to reduce the debris flow disasters.

Figure 3 shows the Digital Elevation Model (DEM) of the study area at 5 m resolution. The river bed profile and cross-sectional data were extracted by interpolation at 10 m intervals along the river using the DEM. The longitudinal river bed profile of the Garjuwa stream is shown in Fig. 4. The potential erosion depth of deposited sediment on the river was estimated to be about 3.0 m throughout the reach based on interpolation of river cross-sectional data and literature (Sharma, 2004). The average stream width is about 5 m. The total volume of deposited sediment in the stream is estimated to about 9,263 m³. Table 1 shows the values of some key characteristics of the watershed. The nearest available rainfall station is within 5 km of Garjuwa Stream at Ambote. Figure 5 shows the rainfall intensity duration curve of the storm event on August 9, 1997, as measured at Ambote station. The maximum rainfall recorded in 24 hours at this station was 358 mm on August 9, 1997 (Sharma, 2004). That same day included an extreme storm event of 225 mm lasting for 5 hours with maximum intensity of 106 mm/hr (See Fig.5). Since the rainfall of August 9, 1997, was a biggest event, the debris flow characteristics and effectiveness of potential check dams were analyzed for this rainfall event.
Debris Flow Characteristics and Effectiveness of Check Dams for Trapping Debris Flows in the Garjuwa Watershed, Nepal

Table 1 Some characteristics of the Garjuwa Watershed (Data source: Sharma (2004), Sharma and Shakya (2008))

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watershed area</td>
<td>0.859 km²</td>
</tr>
<tr>
<td>Length of principal water course</td>
<td>1.394 km</td>
</tr>
<tr>
<td>Average slope of watershed</td>
<td>0.395</td>
</tr>
<tr>
<td>Estimated time of concentration</td>
<td>7.35 min</td>
</tr>
<tr>
<td>Runoff coefficient</td>
<td>0.50</td>
</tr>
<tr>
<td>Elevation above sea level</td>
<td>300-1089 m</td>
</tr>
<tr>
<td>Average annual rainfall</td>
<td>1584.2 mm</td>
</tr>
<tr>
<td>Average monsoon rainfall (June-September)</td>
<td>1328.25 mm</td>
</tr>
<tr>
<td>Percentage of rain falling in monsoon</td>
<td>83.84%</td>
</tr>
<tr>
<td>Diameter of river bed sediment</td>
<td>0.4 m</td>
</tr>
</tbody>
</table>

Fig. 5 Rainfall intensity vs. duration plot of the storm event on 9th August 1997 as measured at Ambote station
3. NUMERICAL SIMULATION MODEL

Numerical models of debris flow based on the conservation of mass and momentum of the flow have been proposed by several researchers (Takahashi and Kuang, 1986; Takahashi et al. 1992; Egashira, 1993a, b; Nakagawa et al., 1996; Honda and Egashira, 1997; Brufau et al., 2000; Iverson, 2003, Shrestha et al., 2008a, b). Only some of them include erosion and deposition processes and the various behaviors of different classes of sediments within the flow. Erosion and deposition are directly related to both the temporal variation of debris flow density and the temporal evolution of the channel bed. A one-dimensional depth-averaged numerical model (Shrestha et al., 2008a, b), which considers erosion and deposition phenomena in the stream, was applied to analyze the debris flow characteristics and effectiveness of check dams for trapping debris flows in the Garjuwa Watershed. Since the Garjuwa Stream has a steep bed slope and narrow valleys in the upstream reach of the fan area, a one-dimensional depth-averaged model can approximately compute the debris flow characteristics along the stream in the upstream reach of the fan area. The stream bed variation model is also incorporated in the model and the vertical variation of the stream bed due to erosion/deposition processes and flow surface variation can also be computed approximately by the one dimensional depth-averaged model.

The applied model has been verified with experimental results (Shrestha et al., 2008a, b). The momentum equation of the flow, the continuity equation of the flow and the continuity equation of the sediment particles are given by (Shrestha et al., 2008a, b)

$$\frac{\partial Q}{\partial t} + \beta \frac{\partial (uQ)}{\partial x} = -gA \frac{\partial (z_b + h)}{\partial x} - gAS_f$$ (1)

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = B_i \{C_r + (1-C_r)s_b\}$$ (2)

$$\frac{\partial (CBh)}{\partial t} + \frac{\partial (CQ)}{\partial x} = B_i C_r$$ (3)

where Q is the flow discharge in the x direction, u is the mean velocity, A is the cross sectional area of the flow, h is the flow depth of mixture flow, B is the width of the channel, / is the erosion or deposition velocity, C is the sediment concentration in the flow, C$_r$ is the maximum sediment concentration in the bed, / is the momentum correction factor equal to 1.25 for stony debris flow and 1.0 for both a hyperconcentrated flow and a turbulent flow, g is the acceleration due to gravity, s f( = $\tau_b/\rho_f gh$) is the friction slope, $\rho_f$ is the bed surface elevation, $\tau_b$ is the bottom shear stress, $\rho_f$ is the mixture density, $\rho_f = \sigma C + (1 - C) \rho_s$, $\sigma$ is the density of the sediment particles, $\rho_s$ is the density of water, and s_b is the degree of saturation ($s_b = 0.9$ when erosion is occurring and $s_b = 1$ otherwise).

When the cross section of the channel is rectangular with fixed walls and erodible bottom, the movement of the bed due to erosion or deposition that takes place in the presence of given sediment concentration is represented by the following equation (Shrestha et al., 2008a, b):

$$\frac{\partial \tau_b}{\partial t} + i_b = 0$$ (4)

Many constitutive equations have been presented, e.g. Takahashi (1980, 1991), Ackermann and Shen (1982), Tsubaki et al. (1982), Miyamoto (1985), Chen (1988), O’Brien and Julien (1988), Egashira et al. (1989, 1997), Takahashi et al. (1992), Egashira and Ashida (1992), and Hunt (1994). The debris flow regimes can vary from fully developed stony type debris flow to turbulent type flow, which depends upon sediment concentrations in the flow. Such variation of debris flow regimes can be computed by constitutive equations given by Takahashi et al. (1992). The bottom shear stress based on constitutive relationships given by Takahashi et al. (1992) is described as follows. For a fully-developed stony debris flow ($C > 0.4C_r$)

$$\tau_b = \frac{\rho_f}{8} \left[ \frac{d_m}{h} \right]^2 - \frac{|u|u|}{|C + (1-C) \rho_s (C/C_r)^{0.9} - 1|}$$ (5)

For a hyperconcentrated flow (0.01 ≤ C ≤ 0.4C_r)

$$\tau_b = \frac{\rho_f}{0.49} \left[ \frac{d_m}{h} \right] \frac{|u|u|}{|C + (1-C) \rho_s (C/C_r)^{0.9} - 1|}$$ (6)

For a turbulent flow (C < 0.01)

$$\tau_b = \frac{\rho_f n^2 |u|u|}{h^{0.9}}$$ (7)

where $d_m$ is the mean diameter of the sediment particles and $n$ is the Manning roughness coefficient. A Manning roughness coefficient of $n = 0.04$ was used in this numerical simulation based on condition of river and waterway.

The erosion of sediment particles by debris flows has been investigated by several researchers (Takahashi et al. 1992; Egashira et al. 2001; Berger et al. 2010, 2011; Nakagawa et al., 2010, 2011; McCoy et al. 2013). The erosion and deposition velocity equations given by Takahashi et al. (1992) have been applied in actual field cases of de-
bris flows (Nakagawa et al. 2001a, b; Takahashi et al. 2001; Chau and Lo 2004). The erosion velocity equation given by Takahashi et al. (1992) can be used regardless of the type of sediment transport (e.g., fully developed debris flow, hyperconcentrated flow, or bed load transport). The erosion velocity equation is described as follows (Takahashi et al., 1992):

$\frac{i_e}{\sqrt{gh}} = K_s \sin^2 \theta \left\{ \left[ \frac{\sigma - \rho}{\rho} \right] \left( \frac{\tan \phi}{\tan \theta_b} - 1 \right) \right\}^{\frac{1}{2}} \left( \frac{\tan \phi}{\tan \theta_b} - 1 \right) C_a \left( \frac{h}{d_a} \right)$  \hspace{1cm} (8)

where $i_e$ is the erosion rate, $K_s (=0.06)$ is the erosion rate constant, $\phi$ is the angle of internal friction, $C_a$ is the equilibrium sediment concentration, and $\theta_b$ is the slope of the channel. The value of $\tan \theta_b$ in the above equations is taken to be the energy gradient as $\tan \theta_b = \tau_n / (\rho g d_b)$. The equilibrium sediment concentration in Eq. (8) is expressed as follows (Takahashi et al., 1992):

$C_a = \frac{\rho \tan \theta_b}{(\sigma - \rho)(\tan \phi - \tan \theta_b)}$  \hspace{1cm} (9)

When the sediment concentrations in the flow exceed the equilibrium value, deposition occurs in the river bed and the deposition velocity equation is expressed as follows (Takahashi et al., 1992):

$i_b = \delta_d \frac{C_a - C}{C_a} \frac{C_a}{C} \tan \theta_b$  \hspace{1cm} (10)

where $\delta_d (= 0.001)$ is the deposition coefficient.

4. CONDITIONS OF CHECK DAMS

4.1 Closed-check dam

Many researchers also investigated debris flow control by closed-check dams (Honda and Egashira, 1997; Takahashi et al., 2001; Nakagawa et al., 2002; Shrestha, 2004; Satofuka and Mizuyama, 2005; Osti and Egashira, 2008; Liu et al., 2012). Takahashi et al. (2001) proposed a method for taking into account the effect of a closed-check dam. This method uses the relationship between the dam height and the river bed height on the upstream side of the dam to determine whether materials will pass over the closed dam (Figure 6). The effective flow depth $h_{d, j}$ at the dam location for calculating the outflow flux and the flow surface gradient, $\theta_{d, j}$, are described as follows:

$h_{d, j} = \begin{cases} h_i + z_i - z_{d, h} & ; (h_i + z_i - z_{d, h}) > 0 \\ 0 & ; (h_i + z_i - z_{d, h}) \leq 0 \\ h_i & ; z_i > z_{d, h} \end{cases}$  \hspace{1cm} (11)

$\theta_{d, j} = \tan^{-1} \left\{ \frac{z_i + h_i - z_{d, h}}{(Ax/2)} \right\}$  \hspace{1cm} (12)

The gradient, $\theta_{d, e}$, to calculate the equilibrium sediment concentration at dam location, $C_a$, is described as follows:

$\theta_{d, e} = \tan^{-1} \left\{ \frac{z_i + h_i - z_{d, e}}{(Ax/2)} \right\}$  \hspace{1cm} (13)

4.2 Slit-check dam

Previous researchers (e.g., Mizuyama et al. (1990), Okubo et al. (1997), Armanini and Larcher (2001), Fujita et al. (2001), Campisano et al. (2013)) have investigated the sediment control function of slit-check dams only in terms of bed load transport. When a slit-check dam is used for debris flow control, the debris flow is deposited behind the slit-check dam by clogging of the open space of the slit-check dam due to the simultaneous arrival of two or more particles and the sudden reduction in flow width. The relationship between the sediment passing rate, $p_{sd}$, through a slit dam and the deposition velocity, $i_{dep}$, behind the slit-check dam caused by the clogging of open space due to the simultaneous arrival of two or more particles is expressed as follows (Shrestha et al., 2012):

$i_{dep} = -K_{sd} \frac{(1 - p_{sd}) Q_{sd}}{C_a \Delta x}$  \hspace{1cm} (14)
where \( P_{\text{sl}} = (b-d)/b \) (b the width of the slit opening and \( d \) is the diameter of sediment particles taken as \( d_{\text{max}} \) or \( d_{\text{min}} \)) \( (K_{\text{sl}} = 0.1) \) is a constant, and \( Q_{\text{sed}} \) is sediment discharge per unit width.

### 4.3 Deposition velocity equation upstream of check dams

The deposition velocity for the region upstream of a check dam given by Shrestha et al. (2008a, b) was employed to calculate deposition phenomena in the upstream area of the check dam. In the upstream area of a check dam, if bed elevation \( z_i \) is less than elevation of the dam crown \( z_{\text{dam}} \) at the calculation point \( i \), the sediment discharge from upstream will deposit in the distance increment of the calculating point \( \Delta x \) when the yield stress exceeds the equilibrium shear stress. The sediment deposition rate in the upstream region of a check dam is described as follows (Shrestha et al., 2008a, b):

\[
\begin{align*}
    i_{\text{dep}} &= K_{\text{dep}} \left( \tau_{\gamma} - \tau_{\gamma^*} \right) \frac{C_i h_i u_i}{C_s \Delta x} \\
    \text{where } i_{\text{dep}} &= \text{the deposition velocity upstream of a check dam if } z_i < z_{\text{dam}} \text{ or } z_i < z_{\text{rid}} \text{ (and } \tau_{\gamma^*} > \tau_{\gamma}) \text{, } K_{\text{dep}} (= 1.0) \text{ is a constant. } \tau_{\gamma^*} \text{ is the non-dimensional equilibrium shear stress and } \tau_{\gamma^*} \text{ is the non-dimensional yield stress. These non-dimensional stresses are described as follows:}
\end{align*}
\]

(15)

\[
\begin{align*}
    \tau_{\gamma^*} &= \frac{\rho gh \sin \theta}{(\sigma - \rho)gd_m} \\
    \tau_{\gamma} &= \frac{Cgh \cos \theta \tan \phi}{gd_m} \\
    \text{where } \rho \text{ is the density of the fluid, } g \text{ is the acceleration due to gravity, } h \text{ is the depth of flow, } \sigma \text{ is the static shear stress, } \phi \text{ is the angle of internal friction, and } g \text{ is the gravitational acceleration.}
\end{align*}
\]

(16)

(17)

Fig. 7 Flow and sediment discharges at Q1 and Q2 locations without check dams and the peak discharges and maximum flow depth along the stream.
5. RESULTS AND DISCUSSION

The partial differential equations of basic equations of flow and erosion model were obtained from the methods adopted by Nakagawa (1989) by using leapfrog scheme, in which upwind scheme was adopted in the advection term and implicit scheme was introduced in the friction term. The details of discretization of partial differential equations of flow and erosion model can be found in Shrestha (2009). In the model calculation, the parameter values of sediment properties and others such as sediment concentration in the bed \((C_s = 0.65)\), internal friction angle of the sediment \((\tan \phi = 0.7)\), sediment density \((\rho_s = 2650 \text{ kg/m}^3)\), water density \((\rho = 1000 \text{ kg/m}^3)\), mean diameter of the river bed \((d_m = 0.4 \text{ m})\) and the Manning roughness coefficient \((n = 0.04)\), were adopted based on reported values for the Garjuwa Watershed by Sharma (2004) and Sharma and Shakya (2008), which were determined based on field investigations. To define the inflow discharge boundary condition at the upstream end, the input discharge corresponding to the rainstorm was obtained using the Rational Formula by taking the contributing area from the upper reach of the stream as follows:

\[
Q = \frac{1}{3.6} C_f IA_c \tag{18}
\]

where \(Q\) is the flow discharge in \(\text{m}^3/\text{s}\), \(C_f\) is the runoff coefficient \((C_f = 0.5\), see Table 1\), \(I\) is the rainfall intensity in \(\text{mm/hr}\) and \(A_c\) is the catchment area in \(\text{km}^2\).

Various origins of debris flows include:

1. Surface water flow causes erosion of a river bed so that a steep accumulation of sediment becomes unstable.

2. Slope failure of a natural dam that was formed in a narrow valley due to deposition of sediment results in collapse of the dam.

3. The sediment mass of a landslide can be mobilized by slope failure.

Debris flows caused by erosion of the river bed commonly occur in the Garjuwa Watershed every year (Sharma, 2004). Thus, in this study, only debris flow occurrences due to erosion of the river bed were considered. Since the Garjuwa Stream has a steep slope and no lateral spreading occurs in the upstream reach of the fan area, a one-dimensional numerical model can approximately calculate debris flow characteristics even though there is a bend in the stream. The purpose of study is to analyze effectiveness of debris flow preventive measures for reduction of hazards in the debris flow fan areas. The flow characteristics were thus analyzed at just upstream of fan area, i.e., location Q2. The flow characteristics were also checked at approxi-
Fig. 9 Reduction of flow and sediment discharges by closed-check dam

Fig. 10 (a) Reduction of peak flow discharge, (b) reduction of peak sediment discharge, and (c) reduction of sediment volume transport at the Q2 analysis point in the case of closed-check dams

Debris Flow Characteristics and Effectiveness of Check Dams for Trapping Debris Flows in the Garjuwa Watershed, Nepal
Debris Flow Characteristics and Effectiveness of Check Dams for Trapping Debris Flows in the Garjuwa Watershed, Nepal

Fig. 11 Reduction of flow and sediment discharges by slit-check dam

Figure 9 shows the reduction of flow and sediment discharges by closed-check dams for the cases of closed-check dam installation at positions C1, C2 and C3 with check dam heights of 5 m, 10 m and 15 m. The results show that the installation of a closed-check dam at position C3 is more effective at reducing debris flows compared to the other two cases of check dam installation at positions C1 and C2. The figures also show that the check dam height of 15 m is a more effective height for trapping debris flows. Figure 10 compares the calculations in terms of (a) reduction of peak flow discharge, (b) reduction of peak sediment discharge, and (c) reduction of sediment volume transport. The results show that the reduction rate of peak flow discharge, peak sediment discharge and sediment volume transport are highest in the case of closed-check dam installation at position C3.

In the case of the slit-check dam, the check dam with slit opening of 1.5 m was used to analyze the effectiveness of a check dam for trapping debris flows (See Shrestha (2009) for determination slit opening based on particle size of river bed). Figure 11 shows the reduction of flow and sediment discharges by slit-check dams for the cases of slit-check dam installation at positions C1, C2 and C3 with check dam heights of 5 m, 10 m and 15 m. In this case also, the installation of a slit-check dam at position C3 is more effective at reducing flow and sediment discharges. The check dam
height of 15 m is more effective at trapping the debris flows. Figure 12 shows the results of calculations of reduction of peak flow discharge, peak sediment discharge and sediment volume transport for the cases of slit-check dam installation. The reduction rate of peak flow discharge, peak sediment discharge and sediment volume transport are higher also in the case of slit-check dam installation at position C3. The results reveal that the appropriate position for trapping sediment in the Garjuwa Watershed is position C3.

Figure 13 compares the calculations for the closed-check dam and slit-check dam at position C3 in terms of reduction of peak flow discharge, peak sediment discharge and sediment volume transport. The reduction of peak flow discharge, peak sediment discharge and sediment volume transport are higher slightly in the case of the closed-check dam as compared to the slit-check dam.

From the results, the reduction rate of debris flow and sediment discharge by using a closed-check dam is somewhat higher than a slit-check dam. The closed-check dam traps all the sediment until the dam is filled with sediment so that its sediment storage capacity decreases rapidly. In the case of the slit-check dam, harmless sediment is transported downstream before blockage of the slit opening, which keeps sediment storage capacity high for an extended period. Check dams can effectively store debris flow as long as there is an adequate storage capacity, but when a check dam loses such storage capacity, the check dam cannot trap enough sediment to effectively reduce the debris flow. It is difficult to prevent a closed-check from losing its trapping capacity unless sediments are continuously removed, whereas a slit-check dam may keep its trapping capacity without any need for artificial removal of sediment. In the Garjuwa Watershed, debris flows occur every year. Thus, for maintaining the trapping capacity of the check dam and for minimum impact on the natural environment and preservation of the landscape of mountain streams, the installation of a slit-check dam is more appropriate.
6. CONCLUSIONS

Numerical analyses were carried out to investigate the effectiveness of a closed- or slit-check dam for trapping debris flows in the Garjuwa Watershed. The numerical simulations reveal that the appropriate position of check dam installation is at position C3 in the Garjuwa watershed. The installation of a check dam at position C3 is more effective at reducing sediment discharge as compared to check dam installation at positions C1 and C2. A check dam height of 15 m is appropriate for trapping the sediment in the Garjuwa Watershed. With no check dam, the total calculated volume of sediment transported by the simulated rainfall event is about 9,158 m$^3$. The reduction of this value by a closed-check dam and a slit-check dam are about 48% and 38%, respectively, for the case of 15 m dam height and dam position at C3. The reduction of peak sediment discharge by a closed-check dam and a slit-check dam are about 65% and 61%, respectively, for the case of 15 m dam height and dam position at C3.

The optimum position for a check dam when a debris flow is arriving at its most developed stage is very important for planning efficient countermeasures for a watershed. Such analysis can be done using numerical simulation tools. From the results of this study, it is clear that by installing check dams in the river basin can significantly reduce sediment-related disasters in the basin. By the combination of these simulations for the selection of the optimum position and height of the check dam, we can design the most efficient check dam and the best place to install it. In case of a slit-check dam, the sediment deposited on the upstream side of the dam may be transported to the downstream side of the dam by a normal scale flood flow due to the erosion process after the debris flow event. Thus, the slit-check dams will have debris flow storage capacity for controlling the next debris flow event in the rainy season. However, in case of a closed-check dam, the sediment deposited on the upstream side of the dam must be removed manually in order to control the next debris flow event. The closed-check dam traps all the sediments until the dam is filled with sediment and so that sediment storage capacity decreases rapidly. In the case of slit-check dams, harmless sediment is transported downstream before the blockage of the opening, which keeps the sediment storage capacity for an extended period. When a check dam is installed in a river basin, it is not necessary to trap all debris flows and harmless flows can flow downstream.

Using a numerical model, the results obtained in this study such as debris flow characteristics, optimum location and height of check dams could be useful for planning and management of debris flow disasters in the Garjuwa Watershed. The model outputs also provide information on flow velocity, discharge and flow depth, which are important for planning infrastructures such as bridge, culverts, and roads, and also for evacuation purpose. The model output including peak discharge with and without dams also provides valuable information for local authorities to assist them in developing policies for ensuring adaptation strategies for coping with debris flow events in the area. An experimentally verified model was applied in this study and it was also validated in this study by comparing calculated sediment volume with reported values.

REFERENCES


Shrestha, B. B., Nakagawa, H., Kawaike, K., et al. (2008b). Numerical simulation on debris-flow deposition and erosion processes upstream of a check dam with experimental verification. *Annuals of the Disaster Prevention Research Institute, Kyoto University, 51B*, 613-624


