

A Study of the Debris Flow Activity on the One-Stepped Channel Slope

SUNGDUK KIM¹ and HOJIN LEE²

¹*Department of Civil Engineering, Chung-Ang University in Seoul, Republic of Korea;* ²*School of Civil Engineering, Chungbuk National University in Cheongju, Chungbuk, Republic of Korea*

Abstract

Kim S., Lee H. (2015): A study of the debris flow activity on the one-stepped channel slope. *Soil & Water Res.*, 10: 32–39.

The purpose of this study is to evaluate the behaviour and mechanism of debris flow on various slopes through numerical simulation. The numerical simulation was performed using the Finite Difference Element Method based on the equation of mass conservation and momentum conservation. In order to measure the behaviour of the debris flow, the debris flow of the straight rectangular channel slope and that of the one-stepped channel slope were compared. Firstly the water flow discharge, the water flow depth, and the sediment volume concentration at the slope downstream of the channel, depending on the different inflow water flow discharges at the upstream of the channel, were analyzed. The smaller the supply from the upstream of the channel, the water flow discharge and the water flow depth surged only at the point after the debris flow reached the downstream of the channel, and showed a tendency to decrease thereon after. On the other hand, when the supply at the upstream of the channel increased, the curve of the water flow discharge and the water flow depth was unsteadily high. Through the Root Mean Square ratio (RMS) comparison, the water flow discharge and water flow depth of the one-stepped channel slope was lower than that of the straight rectangular channel slope. Secondly, the water flow discharge, water flow depth, and sediment volume concentration depending on the change in the slope of the one-stepped channel slope were analyzed. The larger the slope, the larger the fluctuation in amplitude of the curve and this resulted in a higher water flow discharge distribution as well as in a wider fluctuation bandwidth. In the results of the study at each point, in the case of the straight rectangular channel, the water flow discharge and depth increased as it went downstream. This is because more erosion than deposition occurs when debris flow occurs at the upstream of the channel.

Keywords: disaster; finite difference element method; momentum conservation

Heavy rainfall causes debris flow in mountainous terrains with many slopes bringing casualties and property damages. This sort of debris flow contains various amounts of mud, sand, gravel, boulders, and water. Disasters due to debris flow have continuously increased due to urbanization and reckless development in mountainous terrains. On a global scale, debris flow is not only caused by heavy rainfall but it can also be induced by earthquakes, volcanic eruptions, and rapid collapse of ice bergs (ARMANINI & GREGORETTI 2000; CHEN & LING 2000; TAKAHASHI 2000; NAKAGAWA *et al.* 2002). In order to reduce such debris flow disasters, it is important to understand the behaviour and mechanism of the debris flow.

Debris flow is a phenomenon during which a mixture of sediment and water gains gravity and flows like a continuous fluid and because the void of the particle is saturated with water or slurry it allows for great mobility (TAKAHASHI 2007). If we look at the studies published on debris flow, there is a study that uses the Depth Average Model (DAM) based on the mechanism of deposition and erosion (SAVAGE & HUTTER 1997; O'BRIEN *et al.* 1993; DENLINGER & IVERSON 2001), however, the model does not apply to the combination of deposition and erosion.

On the other hand, TAKAHASHI *et al.* (1992) and GHILARDI *et al.* (2001) have supplemented the existing research by combining the potential of the

doi: 10.17221/17/2013-SWR

deposition and erosion of debris flow. In the present study the model of EGASHIRA *et al.* (1997) combining the erosion and deposition caused by debris flow was applied. The behaviour of debris flow according to time elapse and different supply water flow discharge at the straight rectangular channel slope and at the one-stepped channel was estimated. Also the behaviour of the debris flow according to the variation of the one-stepped channel slope at the downstream of the channel was investigated. In order to figure out the level of erosion of the debris flow at the upstream of the channel, the water flow discharge q of the debris flow at each point of the entire channel was analyzed.

The study provides useful information on predicting disaster caused by debris flow at the downstream of a steep mountain slope depending on time-space rainfall distribution, and also information useful when planning various counter measures to prevent debris flow disasters at mountainous areas with various slopes.

MATERIAL AND METHODS

Governing equation. The governing equation to analyze the point from where the debris flow forms to where the deposition boundary is composed of the momentum conservation of the flow mixture, the mass conservation of the sediment-water mixture, and the mass conservation of the sediment:

$$\frac{\partial h}{\partial t} + \nabla \times (\nabla \phi h) = B_v \quad (1)$$

$$\frac{\partial(ch)}{\partial t} + \nabla \times (c \times \nabla \phi h) = C_s B_v \quad (2)$$

$$\frac{\partial(\nabla \phi h)}{\partial t} + \nabla \times (\nabla \times \nabla \phi h) = gh (\sin \theta - \cos \theta \times \frac{\partial h}{\partial x}) - \frac{\tau_b}{\rho_m} \quad (3)$$

$$\frac{\partial \zeta_b}{\partial t} + B_v = 0 \quad (4)$$

where:

h – water depth

ϕ – velocity potential

B_v – erosion velocity or deposition velocity

c – sediment concentration in debris flow

C_s – maximum sediment concentration in the bed

g – gravity acceleration

θ – angle formed by the bed slope and water surface elevation

ρ – water density

ρ_m – mixture density of water and sediment

$$(\rho_m = (\sigma - \rho)c + \rho)$$

σ – density of sediment particles

τ_b – bottom shear stress

ζ_b – deposition thickness of the bed measured from the original bed surface elevation

Regarding erosion velocity B_v , the equation suggested by EGASHIRA *et al.* (1997) was used.

The bottom shear stress in the mass conservation of the sediment-water mixture equation can be shown with yield stress τ_y (EGASHIRA *et al.* 1997):

$$B_v = -\nabla \phi \tan(\theta_e - \tan \theta) \quad (5)$$

$$\theta_e = \arctan\left(\frac{(\sigma/\rho - 1)c}{(\sigma/\rho - 1)c + 1}\right) \tan \phi \quad (6)$$

$$\tau_b = \tau_y + \rho f_y \nabla \phi |\nabla \phi| \quad (7)$$

where:

θ_e – equilibrium slope of c

ϕ – internal friction angle of sediment

τ_y – yield stress

f_y – coefficient of resistance

When the constitutive equation of EGASHIRA *et al.* (1997) is used, the yield stress and coefficient of resistance can be shown as below:

$$\tau_y = \left\{ \rho g \left(\frac{\sigma}{\rho} - 1 \right) c \left(\frac{c}{C_s} \right)^{1/n} h \cos \theta \tan \phi \right\} \frac{\nabla \phi}{|\nabla \phi|} \quad (8)$$

$$f = \frac{25}{4} \left\{ k_d \frac{\sigma}{\rho} (1 - e^2) c^{1/3} + \frac{k_f (1 - c)^{5/3}}{c^{2/3}} \right\} \left(\frac{d}{h} \right)^2 \quad (9)$$

where:

n – 5

e – restitution of sediment particles

k_d – empirical constant (= 0.0828)

k_f – empirical constant (= 0.16)

d – mean diameter of sediment

RESULTS AND DISCUSSION

Condition of numerical simulation. Figure 1 shows the numerical simulation of the present analysis of the debris flow behaviour. Figure 1a shows the case of the straight rectangular channel slope and Figure 1b of the one-stepped channel slope. For the purpose of the numerical simulation, the one-stepped channel slope is divided into 3 slopes – a 5 m upstream channel slope θ_1 , a 2 m one-stepped channel slope θ_2 , and a 2 m downstream channel slope θ_3 .

In the case of the straight 9 m rectangular channel, the slope θ_1 is considered. Also, in both cases the

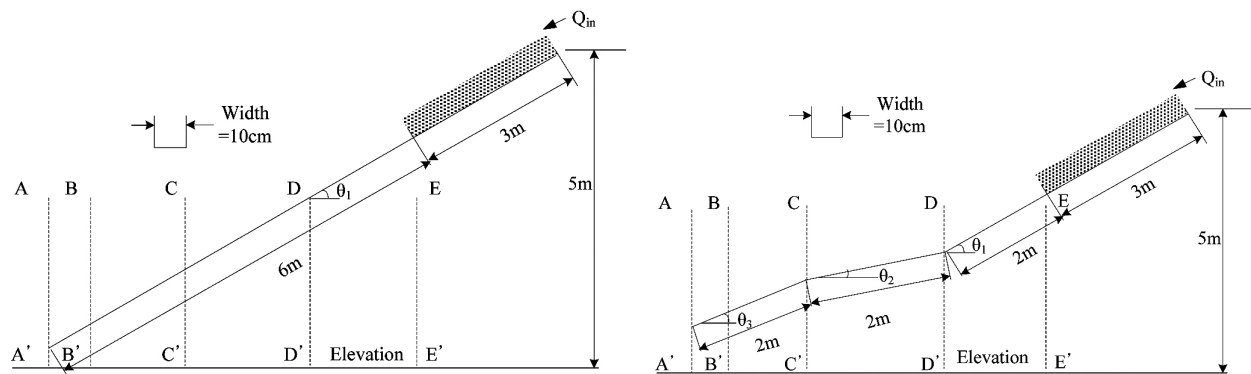


Figure 1. Definition sketch for numerical simulation of debris flow: straight rectangular channel slope (a), one-stepped channel slope (b)

width is 10 cm, and the height from the bed surface elevation to the upstream channel is 5 m. At the 3 m part of the upstream channel, the saturated sand sediment was characterized by the mean particle size of 3.1 mm, density of the sediment particle of 2.65 g/cm^3 , maximum sediment concentration in bed $C_s = 0.65$, and internal friction angle $\tan \phi = 0.7$. The sediment layer had 10 cm in thickness. Line A–A' and line B–B' indicates the investigation point at the downstream of the channel.

The numerical analysis. The numerical model applies the Finite Difference Element Method using the change in time. Figure 2 presents the numerical calculation used in this study. It shows that the input condition is advantageous at the boundary surface so the water flow discharge (q) and water velocity (u) were placed on the grid line, and the sediment volume

concentration (c) and water depth (h) were placed in the centre of a cell.

$I, I + 1, \dots$, in Figure 2 shows the position level on the channel line and can be expressed as follows:

(a) For the case of the straight rectangular channel slope

$\sum_{I=1}^{\text{total}} I = 90$ – number of total points on the channel slope for numerical calculation

(b) For the case of the one-stepped channel slope

$\sum_{I=1}^{\text{upstream}} I = 50$ – number of points on the upstream channel for numerical calculation

$\sum_{I=1}^{\text{downstream}} I = 20$ – number of points on the one-stepped channel for numerical calculation

$\sum_{I=1}^{\text{downstream}} I = 20$ – number of points on the downstream of the channel for numerical calculation

$\sum_{I=1}^{\text{total}} I = 90$ – number of total points on the one-stepped channel slope for numerical calculation

$J, J + 1, \dots$, shows the elapse of time Δt when performing the numerical model. If the input condition of the numerical model is categorized by time, there is time of water supply discharge (t_1), the time it takes to perform the numerical model calculations (t_2), the time it takes the debris flow to reach the downstream of the channel or a specific location of the channel (t_3), and the time interval of the numerical model calculation (t_4), where t_4 is the linear set time interval. In the numerical model the behaviour of the debris flow according to the input values of the time terms can be displayed.

Numerical results for variation of the inflow water flow discharge. Recently, due to changes in climate, heavy rainfall occurs in the mountainous regions and debris flow damage occurs frequently in the downstream channel area. Therefore, in order to investigate the level of debris flow disaster due to the changes in rainfall intensity, the water flow discharge, water flow depth, and sediment volume

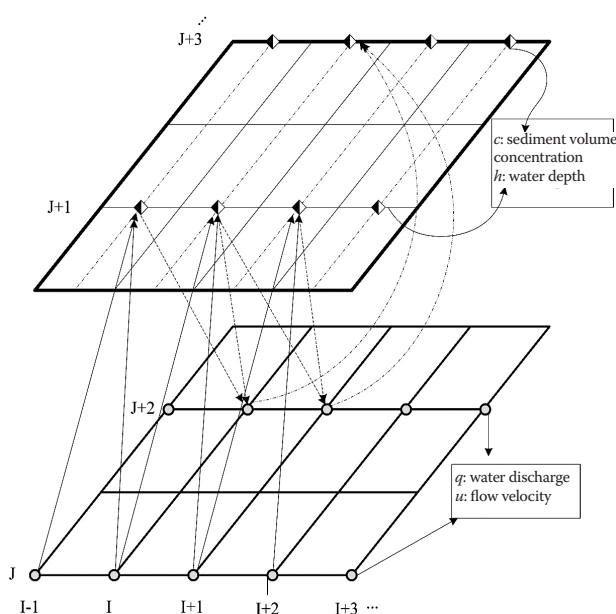


Figure 2. Performance of the numerical calculation

doi: 10.17221/17/2013-SWR

concentration of the debris flow according to the variation of the supply water flow discharge at the downstream channel (line A–A' and line B–B' in Figure 1) was analyzed. Here the calculation conditions were set into two cases, $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$ and $800 \text{ cm}^3/\text{s}$ in order to consider the change in heavy rainfall. Also taking in the fact that the lowest slope in a debris flow occurrence was about 15 degrees (TAKAHASHI 2007), the channel slope of the straight rectangular channel slope was set to $\theta_1 = 20^\circ$. On the other hand, in the case of the one-stepped channel slope, the slope of the upstream of the channel was set to $\theta_1 = 20^\circ$, one-stepped channel slope $\theta_2 = 14^\circ$, and the slope of the downstream channel $\theta_3 = 20^\circ$. The levels regarding time were set to one-stepped $t_1 = 20 \text{ s}$, $t_2 = 60 \text{ s}$, $t_3 = 30 \text{ s}$, and $t_4 = 0.2 \text{ s}$.

In order to compare the change in water flow discharge at the straight rectangular channel slope and the one-stepped channel slope, the Root Mean Square Ration (RMS ratio) was used. The RMS ratio equation is as follows:

$$R(q) = \sqrt{\sum_{j=1}^{t_3} [(q_{\text{straight}})_j - (q_{\text{berm}})_j]^2 / t_3} \quad (10)$$

where:

- q_{straight} – water flow discharge per unit width that goes through the straight rectangular channel slope
- q_{berm} – water flow discharge per unit width that goes through the one-stepped channel slope
- t_3 – time after the debris flow has reached the downstream of the channel

As indicated in Figure 1, Figures 3–5 show the water flow discharge, water flow depth, and sediment volume concentration in the straight rectangular channel slope and the one-stepped channel slope when the debris flow reaches the downstream of the channel at 30 s ($t_3 = 30 \text{ s}$). In Figures 3 and 4, when

the supply water flow discharge is low at the straight rectangular channel slope ($Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$), the water flow discharge and water flow depth only surge right after the debris flow reaches the downstream of the channel and after a few seconds it looks as though it is receding, however after 13 s there are approximately 6 s of fluctuation.

Meanwhile, as the supply water flow discharge increases, the curve of the water flow discharge and water flow depth becomes unstable, and after approximately 10 s, fluctuation with high water flow discharge and high water flow depth continues for 15 s. Even after some time the debris flow reaches the downstream channel in heavy rainfall areas, the water flow discharge and water flow depth does not decrease. And the debris flow continues to flow even further at unstable high amplitude. Thus, Figures 3 and 4 show that as the water flow discharge increases, the unstable fluctuation appears more quickly.

In the case of the one-stepped channel slope, 10 s before the debris flow first reaches the downstream of the channel, low water flow discharge and low water flow depth distribution begin and build up gradually. After these 10 s, the fluctuation appears in a high amplitude as seen in the straight rectangular channel slope, but the time this fluctuation continues for is shorter than the time in the case of the straight rectangular channel slope. This shows that the one-stepped channel slope can reduce the damages occurred by a debris flow in mountainous terrains. If the change in the water flow discharge in the channels of the straight rectangular channel slope and the one-stepped channel slope during a 30 s time interval is compared using the RMS ratio, in the case of $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$ in the A–A' line, the one-stepped channel slope shows by 30.9% lower water flow discharge than the straight rectangular

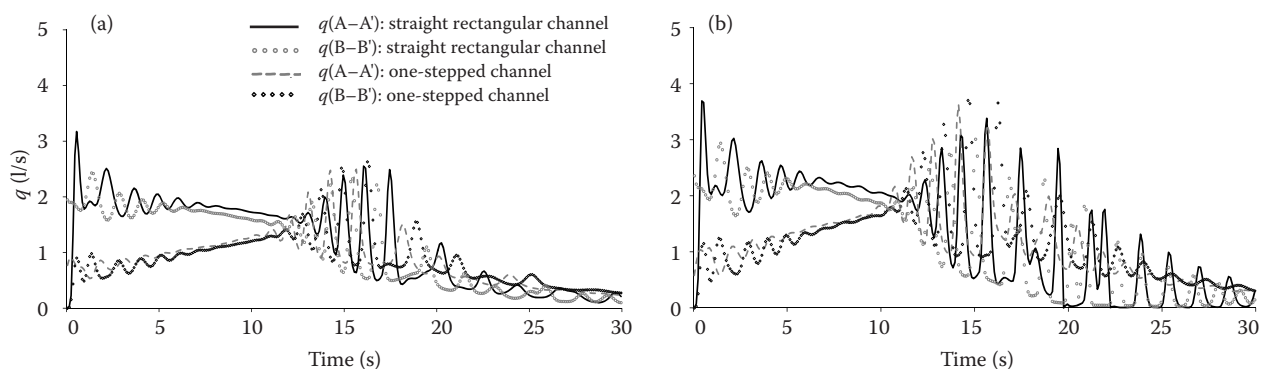


Figure 3. Water flow discharge (q) at the downstream boundary of the channel according to time for $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$ (a) and $Q_{\text{inflow}} = 800 \text{ cm}^3/\text{s}$ (b)

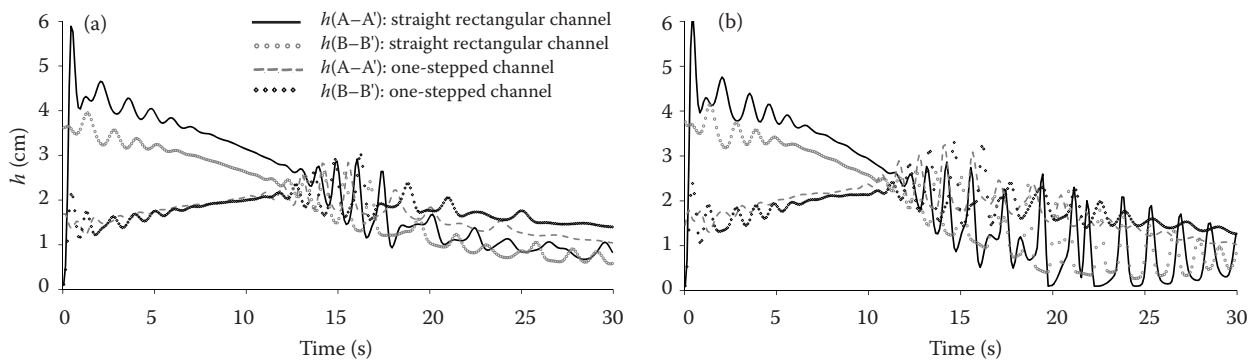


Figure 4. Flow depth (h) at the downstream boundary of the channel according to time for $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$ (a) and $Q_{\text{inflow}} = 800 \text{ cm}^3/\text{s}$ (b)

channel slope, and by 21.9% smaller water flow discharge in the B-B' line.

In the case of $Q_{\text{inflow}} = 800 \text{ cm}^3/\text{s}$, the one-stepped channel slope showed by 15.5% lower water flow discharge than the straight rectangular channel slope in line A-A', and by 7% lower water flow discharge in line B-B'. The sediment volume concentration graph in Figure 5 shows that in the case of the straight rectangular channel slope the sediment concentration gets very high and then decreases at the point right after the debris flow reaches the downstream of the channel. Because a very large amount of sediment and mixture reaches the downstream, the moment a debris flow occurs in a mountainous terrain and reaches the downstream where the damages occurred through a debris flow will be quite extensive.

On the other hand, in the case of the one-stepped channel slope, the sediment volume concentration shows a relatively gentle curve from the moment the debris flow reaches the downstream of the channel. It is perceived that in the case of the actual debris flow in mountainous terrains, because the one-stepped channel slope allows for the amount of sediment

with mixture water not to increase suddenly, it is effective in delaying the debris flow.

Numerical results for variation at the one-stepped channel slopes. Mountainous terrains are made up of various slopes. In order to figure out the debris flow at various slopes, in the case of the one-stepped channel slope, the water flow discharge, water flow depth, and sediment volume concentration of the debris flow according to the variation of the one-stepped channel slope at the downstream of the channel (line A-A' at downstream in Figure 1) were analyzed.

Here the calculation conditions were set at $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$, the slope at the upstream of the channel slope with a berm at $\theta_1 = 20^\circ$, and the slope of the downstream of the channel at $\theta_3 = 20^\circ$. Three cases were studied for the one-stepped channel slope and these were: $\theta_2 = 12^\circ, 14^\circ$, and 16° . The time levels were set at $t_1 = 20 \text{ s}$, $t_2 = 60 \text{ s}$, $t_3 = 30 \text{ s}$, and $t_4 = 0.2 \text{ s}$. As indicated in Figure 1, Figures 6–8 show the water flow discharge, water flow depth, and sediment volume concentration according to variation in the one-stepped channel slope when the

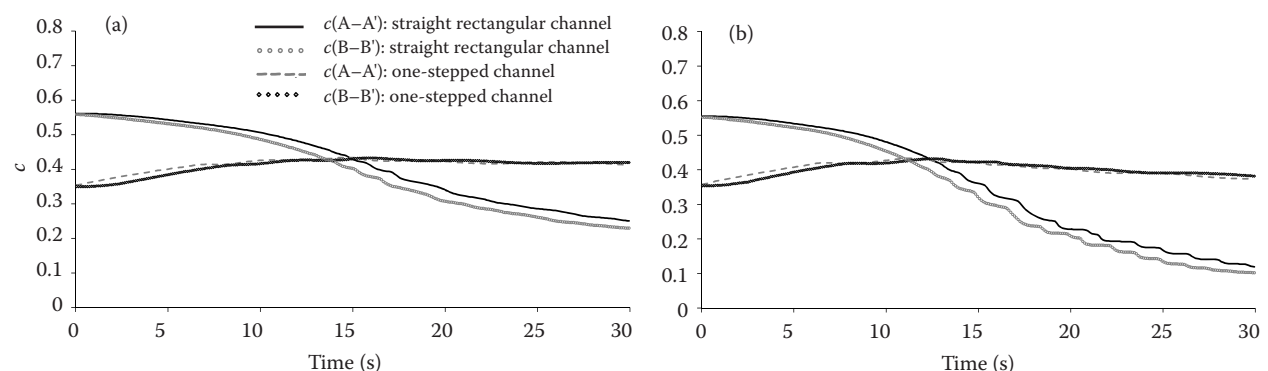


Figure 5. Sediment concentration (c) at the downstream boundary of the channel according to time for $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$ (a) and $Q_{\text{inflow}} = 800 \text{ cm}^3/\text{s}$ (b)

doi: 10.17221/17/2013-SWR

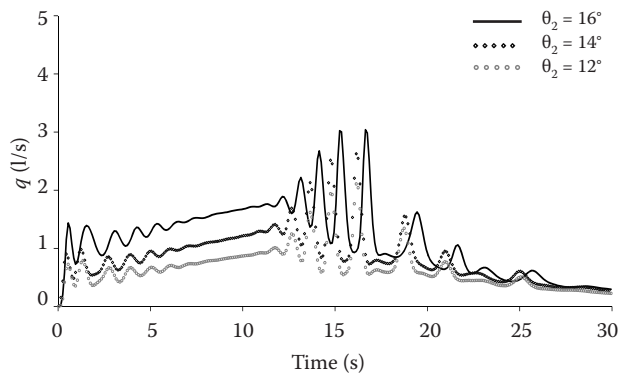


Figure 6. Water flow discharge (q) at the downstream boundary of the channel by variance of the one-stepped channel slope with $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$ according to time for A–A' line

debris flow reaches the downstream of the channel at 30 s ($t_3 = 30 \text{ s}$). In Figure 6, as the angle of the one-stepped channel slope increases, the fluctuation of the amplitude increases, and a high water flow discharge distribution is shown. Also as the angle of the one-stepped channel slope increases, the bandwidth of a high amplitude fluctuation becomes wider. Therefore this sort of analysis results will provide useful information when in the case of the one-stepped channel slope.

Figure 7 shows the change of the water flow depth. The high water flow depth distribution is shown at the one-stepped channel slope with $\theta_2 = 16^\circ$, and this slope shows great differences compared to the other slopes. Because the possibility of debris flow occurrence begins at the slope of $\theta_2 = 15^\circ$, it results in big differences of the amplitude.

Figure 8 shows the change of the sediment volume concentration. In the case of the one-stepped

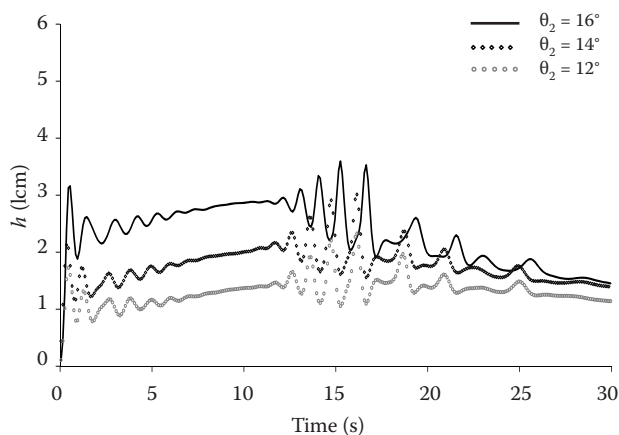


Figure 7. Flow depth (h) at the downstream boundary of the channel by variance of the one-stepped channel slope with $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$ according to time for A–A' line

channel slope, the sediment volume concentration is uniform without fluctuation occurrence, and as the slope lowers, the sediment volume concentration distribution decreases. The average concentration is 3.5 at this time.

Numerical results for each point of the channel. Debris flow developed at the upstream of the mountainous terrain goes through a repetition of erosion and deposition as it either passes through the downstream of a mountainous terrain or deposits into the downstream area. Therefore, water flow discharge, water flow depth, and sediment volume concentration of debris flow at each point in the cases of the straight rectangular channel slope and the one-stepped channel slope were analyzed. The investigation point is as shown in Figure 1 and the calculation condition was set at $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$.

Figure 9 shows the water flow discharge and water flow depth. In the case of the straight rectangular channel slope (Figure 9b), as the debris flow reaches downstream, the water flow discharge and water flow depth increase. This is because when debris flow develops at the upstream of the channel, erosion caused by debris flow occurs more than deposition and thus it flows to the downstream of the channel.

On the other hand, in the case of the one-stepped channel slope (Figure 9a) the debris flow occurs at the upstream of the channel, and water flow discharge fluctuation occurs after 12 s. The amount of water flow discharge and water flow depth at the one-stepped channel slope is significantly lower than the amount at the straight rectangular channel slope. This means that erosion can be reduced at the one-stepped channel.

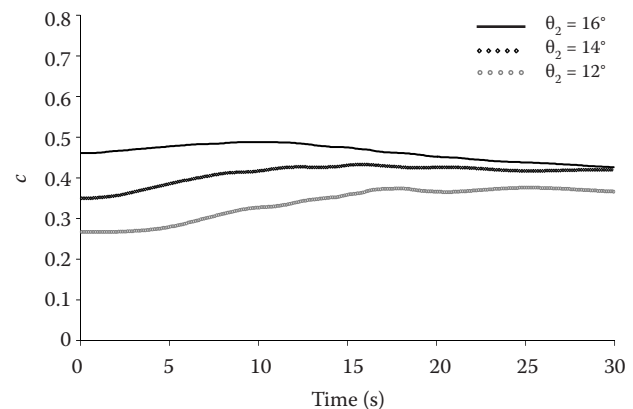


Figure 8. Sediment concentration (c) at the downstream boundary of the channel by variance of the one-stepped channel slope with $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$ according to time for A–A' line

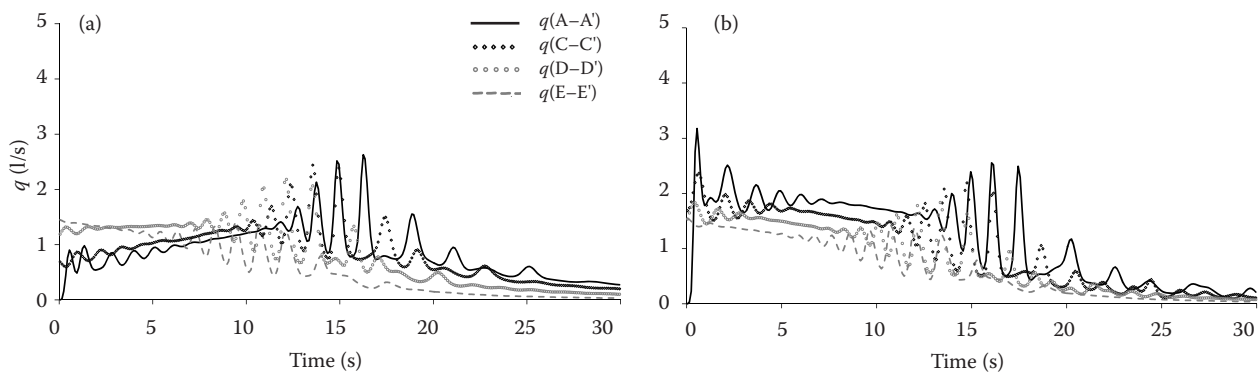


Figure 9. Water flow discharge (q) at the line of the channel slope with $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$ according to time for one-stepped channel slope (a) and straight rectangular channel slope (b)

CONCLUSION

Frequent rain and heavy rainfall cause debris flow in mountainous terrains with many slopes, bringing about casualties and property damages. Such disasters due to debris flow have continuously increased due to urbanization and reckless development in mountainous terrains. Therefore the purpose of this study was to verify the behaviour and mechanism of debris flow on various slopes. The water flow discharge, the water flow depth, and the sediment volume concentration of debris flow in the cases of the straight rectangular channel slope and the one-stepped channel slope were analyzed and compared. Numerical simulation was performed using the Finite Difference Element Method based on the equation of mass conservation and momentum conservation.

When the supply water flow discharge is low at the straight rectangular channel slope, the water flow discharge and water flow depth only surge right after the debris flow reaches the downstream of the channel and after a few seconds it appears to recede and low fluctuation is produced.

Whereas when the supply water flow discharge increases, the curve of the water flow discharge and water flow depth becomes unstable, and water flow discharge and water flow depth occur at an unstable and high fluctuation. This implies that in the downstream channel of mountainous terrains that are in heavy rainfall areas, high and unstable fluctuation is the reason behind the increase of damages occurring by such disasters. In the case of the one-stepped channel slope, low water flow discharge and low water flow depth distribution begin and build up gradually. Using the RMS ratio, in the case of $Q_{\text{inflow}} = 600 \text{ cm}^3/\text{s}$, at line A–A' of the channel, the one-stepped slope shows by 30.9% lower water flow discharge than the straight

rectangular channel slope, and by 21.9% smaller water flow discharge in line B–B'. In the case of $Q_{\text{inflow}} = 800 \text{ cm}^3/\text{s}$, the one-stepped channel slope showed by 15.5% lower water flow discharge than the straight rectangular channel slope in line A–A' and by 7% lower water flow discharge in line B–B'.

The sediment volume concentration graph in Figure 5 shows that in the case of the straight rectangular channel slope the sediment volume concentration gets very high and then decreases at the point right after the debris flow reaches the downstream of the channel. Because a very large amount of sediment and mixture reaches the downstream, the interval between the debris flow is formed in a mountainous terrain and reaches the downstream causing damages through a debris flow is quite long.

In the case of the one-stepped channel slope, the sediment volume concentration shows a relatively gentle curve. It is perceived that in the case of the actual debris flow in mountainous terrains, because the one-stepped channel slope allows for the amount of sediment with mixture water not to increase suddenly, it is effective in delaying the debris flow. As the angle of the one-stepped channel slope increases, the fluctuation of the amplitude increases and a high water flow discharge distribution is shown. Also as the angle of the one-stepped channel slope increases, the bandwidth of a high amplitude fluctuation becomes wider. High water flow depth distribution is shown at the one-stepped channel slope of $\theta_2 = 16^\circ$, and this slope shows great differences in comparison to other slopes. Because the possibility of debris flow occurrence begins at the slope of $\theta_2 = 15^\circ$, it results in notable differences in the amplitude.

In the investigation of each point, in the case of the straight rectangular channel, the water flow discharge and water flow depth increased as the debris

doi: 10.17221/17/2013-SWR

flow reached the downstream of the channel. This is because when the debris flow was developed at the upstream of the channel, erosion caused by debris flow was greater than the deposition and thus it flowed to the downstream. On the other hand, in the case of the one-stepped channel slope, the amount of water flow discharge and water flow depth was higher than the amount at the straight rectangular channel slope. This means that erosion can be reduced at the one-stepped channel.

The results from this study will provide useful information in predicting disaster caused by debris flow at the downstream of a steep mountain slope depending on changing rainfall. It will also provide useful information when planning various counter measures to prevent debris flow disasters at mountainous areas with various slopes.

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Received for publication March 11, 2013

Accepted after corrections May 26, 2014

Corresponding author:

Prof HOJIN LEE, Ph.D., Chungbuk National University in Cheongju, School of Civil Engineering, Chungbuk, Republic of Korea; e-mail: hojinlee@chungbuk.ac.kr
