PREDICTION OF 1999-SAN JULIAN DEBRIS FLOWS BASED ON DEPENDENT AND INDEPENDENT OCCURRENCES

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In this paper, a 1-D governing equations proposed by Egashira et al. is put forward first to describe the mechanics of debris-flow. Debris-flow simulations were conducted in order to understand what happens when rainfall occurs to cause numerous landslides on steep river basin, supposing several realistic occurrences in several tributaries. Multiple debris-flow surges were observed in 1999 San Julian debris-flow event, which was simulated in different contexts. The simulated results suggest that the different possible sequences can produce different amounts of sediment volume. Maximum sediment-volume difference between independent and dependent predictions was 0.12×10^6 m^3, which is very large and cannot be neglected. This shows that the order of debris flow occurrences should be taken into account for simulating debris-flow behavior at the fan-head.

Key Words : *Debris-flow simulation, Order of occurrences, Bed variation, Sediment hazards*

1. INTRODUCTION

In December 1999, Vargas state in the northern coastal region of Venezuela was attacked by numerous debris-flows, which were triggered by excess rainfall. Debris-flow and flash-floods on alluvial fans inundated coastal communities and caused severe property destructions. An accurate estimate of the number of deaths was difficult to determine but the death toll may have amounted more than 19,000 people. San Julian fan was one of the most heavily damaged areas due to that event.

Since debris-flow is episodic in nature and happens without prior notification, no one can precisely judge the real event and can make sure for possible safety measures. Predictions that based on statistic and numerical as well as experimental methods have been widely incorporated in practices. Some researchers proposed empirical equations for the prediction of sediment volume transported by debris flow, but these methods are now gradually replaced by more reliable mathematical methods. A 2-D numerical simulation was conducted to replicate the debris deposition on alluvial fan of Horadani basin in Japan[1]. However, calculated result was somewhat deviated from the recorded value. The result obtained by that research was mainly based on the specification of sediment supply conditions at upstream boundaries. In order to simulate debris flows in Mizunashi River in Mt. Unzendake, H. Hasimoto et al.[2] used 1-D governing equations. It has been concluded that the result depends not only on the model used but also often on characteristics and order of occurrences of debris flow. Debris-flow incidence of 1993 in Nigorisawa river basin was simulated by Honda et al.[3] by using the model proposed by Egashira. In that research, debris flow characteristics, which was activated by the erosion of natural dam formed in a steep reach was discussed and the performances of check-dams were evaluated with the help of calculated results. Recently, some methods of numerical simulation are proposed, which are based on the basic research of debris flow [4),5)]. Egashira et al. [6),7)] have explained how the bed material entrainment or erosion takes place and how the debris flow discharge varies along the reach. In addition, Egashira et al. [8)] investigated the influences of rainfall intensity and distribution of potential erosion depth on debris flow characteristics. Their results suggest that the rainfall intensity has little influence on debris flow discharge, if bed-sediment is beforehand saturated by water. Potential erosion depth and its distribution play an important role for the size of debris flow. Such numerical predictions have not treated the debris flows in complex river basin with several tributaries and different catchments properties. When we treat the debris-flow in a main stream composed of many tributaries, order of debris flow occurrences in each tributary will greatly influence the debris flow characteristics such as flow-discharge, flow-velocity, sediment-volume and overall size of the debris flow in downstream sections. In addition, even if the debris-flow is treated in a single reach, debris-flow characteristics will be different among first surge, second, third etc.

In this paper, we simulate the 1999-San Julian debris flow in Venezuela. The main objective is to develop a reliable prediction method and to analyze the characteristics of debris-flow i.e. sediment yield, taking account of independent and dependent as well as occasional debris-flow loading from different tributaries.

2. NUMERICAL METHOD

(1) Flow model

One-dimensional governing equations for the flow of sediment-water mixture developed by Egashira et al.[9),10)] are employed and their constitutive equations are used to solve the governing equations. The equations of mass conservation describing the water-sediment mixture and sediment only can be expressed;

$$\frac{\partial h}{\partial t}+\frac{1}{B}\frac{\partial \bar{u}hB}{\partial x}=\frac{E}{c_*} \tag{1}$$

$$\frac{\partial \bar{c}h}{\partial t}+\frac{1}{B}\frac{\partial \gamma\,\bar{c}\bar{u}hB}{\partial x}=E \tag{2}$$

Momentum conservation equation and equation for bed elevation are as follows.

$$\frac{\partial h\bar{u}}{\partial t}+\frac{\partial \beta h\bar{u}\bar{u}}{\partial x}=gh\sin\theta-gh\cos\theta\frac{\partial h}{\partial x}-\frac{\tau_b}{\bar{\rho}_m} \tag{3}$$

$$\frac{\partial z_b}{\partial t}=-\frac{E}{c_*\cos\theta} \tag{4}$$

In these equations, h is the flow depth, t is the time, x is the coordinate toward the flow direction, E is the erosion rate of bed sediment (its negative value denotes the deposition), $\bar{c}$ is the depth-averaged volumetric sediment concentration, c_* is the sediment concentration of underlying sediment bed, $\bar{u}$ is the depth-averaged velocity of mixture, g is the acceleration due to gravity, $\bar{\rho}_m$ is the depth-averaged mass density of sediment-water mixture defined as

$$\bar{\rho}_m=(\sigma-\rho)\bar{c}+\rho \tag{5}$$

in which σ is the mass density of sediment particle, ρ is the mass density of water including fine sediment, τ_b is the bed shear stress, z_b is the bed elevation from a reference level and θ is the bed slope, which is expressed as

$$\theta=\sin^{-1}\left[-\frac{\partial z_b}{\partial x}\right] \tag{6}$$

$\gamma=(1/A)\int_A\{(cu)/(\bar{c}\bar{u})\}dA$ in Eq. (2) is a shape-factor, whose value rages from 0 to 1, depending on the bed-slope and inter-particle friction angle. β in Eq. (3) is the momentum correction-factor and takes a value from 1.10 to 1.40 for debris-flow. Equations for bed shear stress and erosion rate that have been proposed by Egashira et al.[9),10)] are employed. They are

$$\tau_b=\tau_y+\rho f\bar{u}^2 \tag{7}$$

$$\frac{E}{\bar{u}}=c_*\tan(\theta-\theta_e) \tag{8}$$

in which τ_y is the yield stress caused by particle-to-particle contacts and f is the friction factor, θ is the bed slope, θ_e is the equilibrium bed-slope corresponding to sediment concentration $\bar{c}$ of debris flow. These are expressed as follows

$$\tau_y=\left(\frac{\bar{c}}{c_*}\right)^{1/5}(\sigma-\rho)\bar{c}\,gh\cos\theta\tan\phi_s \tag{9}$$

$$\tan\theta_e=\frac{(\sigma/\rho-1)\bar{c}}{(\sigma/\rho-1)\bar{c}+1}\tan\phi_s \tag{10}$$

$$f=\frac{25}{4}\left[k_f\frac{(1-\bar{c})^{5/3}}{\bar{c}^{2/3}}+k_d\left(\frac{\sigma}{\rho}\right)(1-e^2)\bar{c}^{1/3}\right]\left(\frac{h}{d}\right)^{-2} \tag{11}$$

in which $k_f=0.16$, $k_d=0.0828$, e and ϕ are the restitution coefficient (e =0.85) and the interparticle friction angle of sediment particles, respectively.

(2) Study area and conditions for computation

The topography of the region in the coastal mountains, Venezuela is extremely steep and rugged. The rivers and streams of this mountainous region drain to the north and merge onto Caribbean Sea after flowing through alluvial fans. A topographic map of the San Julian basin is shown in **Fig. 1**.

San Julian River drains the area of 23.6 km^2 and is composed of numerous tributaries. Three major torrents, abbreviated by T_1, T_2 and T_3, were chosen for debris-flow simulation. Longitudinal bed

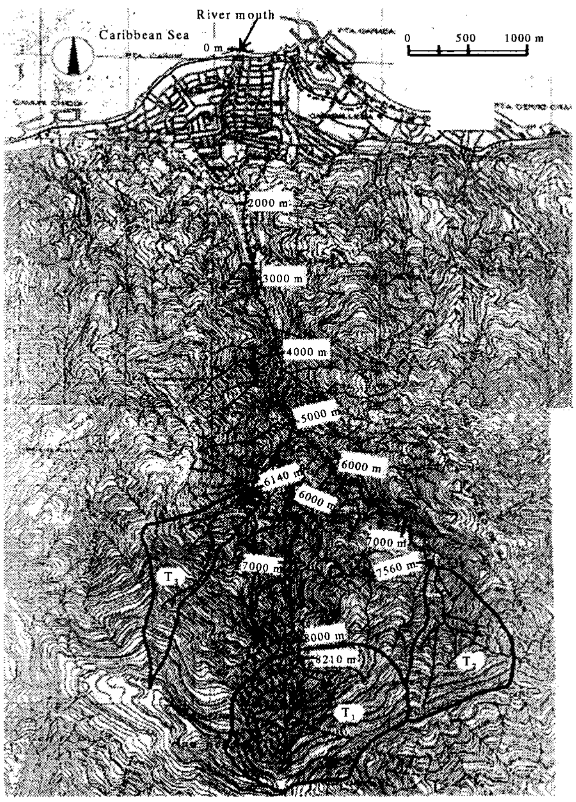


Fig.1 Topographical-map of the region

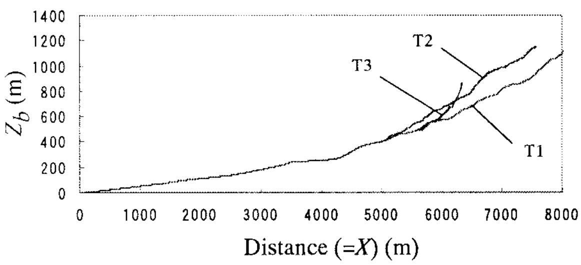


Fig. 2 Profiles of bed elevation for T_1, T_2 and T_3

profiles of three torrents are illustrated in **Fig. 2**, which has been plotted from the data obtained from the original map plotted in the scale of 1/25000. Some important parameters like flow-width, sediment size, potential erosion depth[3] etc. were determined from field survey. Upstream boundaries were located at 8210 m, 7560m and 6140 m from the river mouth for T_1, T_2 and T_3, respectively and corresponding drainage areas are 2.63 km^2, 1.42 km^2 and 1.43 km^2. The common downstream boundary was set at 3010m from the river mouth. Physical properties of the bed sediment were specified as e=0.85, d=20 cm, ϕ_s = 34 deg., ρ=1.33g/cm^3, c_*=0.52 and fine sediment was assumed 20% by volumetric concentration included in fluid phase, which was specified by the field investigation[11]. Potential erosion depth (D_p) was chosen 10 m, which was specified based on the field inspection[11]. Riverbed width (B) from all upper boundaries up to the lower confluence point at 5100m from river mouth was specified as 20 m and 40 m for common reach. Water discharge at the upper boundary for each torrent was estimated by using the rational equation,

$$Q = \frac{1}{3.6} f_p r A \tag{13}$$

in which f_p is the rainfall run-off coefficient, r is the rainfall intensity and A is the drainage area. Rainfall intensity of 50 mm/hr was assumed as uniform over these catchments. Equation 13 determined boundary discharges of 21.9 m^3/s for T_1, 11.8 m^3/s for T_2 and 11.9 m^3/s for T_3.

Different possible sequences such as T_1 gives first surge then T_2 and finally by T_3 i.e. T_1- T_2- T_3 as well as T_1- T_3- T_2, T_2- T_1- T_3, T_2- T_3- T_1, T_3- T_1- T_2 and T_3- T_2- T_1 were considered for numerical simulations. In addition to those tributarial sequences, multiple occurrences were also considered in tributary T_1. The finite leapfrog difference scheme was employed for computations with Δx = 5m and Δt = 0.003 sec..

3. NUMERICAL PREDICTION

The primary concern of this numerical simulation is to predict different debris flow circumstances. In independent case, every debris flow event in each tributary is dealt separately, supposing there is no influence of debris flow loading from different tributaries. **Figure 3** is the sediment discharge obtained from independent calculations at the fan head designated at 3,010 m from the river mouth. Peak discharges are observed at 86, 234 and 268 sec. due to tributaries T_3, T_2 and T_1, respectively. Total sediment independently supplied into the fan by T_3, T_2 and T_1 are 121,843 m^3, 129,239 m^3 and 109,340 m^3, respectively (**Table 1**), considering the original bed-profile as an input to each and every computational case.

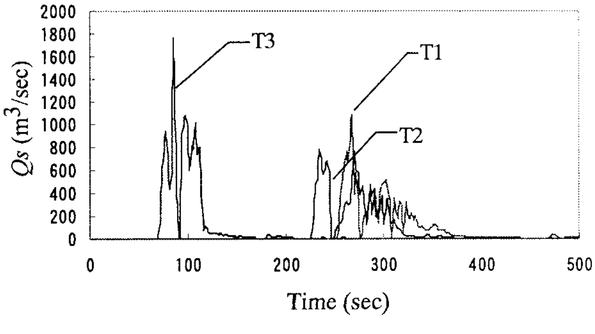


Fig. 3 Sediment discharge at the fan head (X=3010 m)

Simultaneous loading of debris flow from different tributaries is unusual because of the geometry of catchments as well as the occurrences of landslides in the region. Sediment volumes due to landslide are excluded in the calculation.

Egashira et al.[8] reported sediment volume that were deposited in the fan during San Julian debris desaster. Sediment yield that was caused by general bed and suspended loads, was estimated 0.26×10^6 m^3 and due to land slides in small tributaries was 0.35×10^6 m^3. Adding these two separate volumes to the present result, it gives total amount 0.97×10^6 m^3, which is quite close to to the observed value: i.e. 1.0-1.6 million cubic meters[11].

Table 1 Sediment volume transported into the debris-fan by tributaries T_1, T_2 and T_3 independently

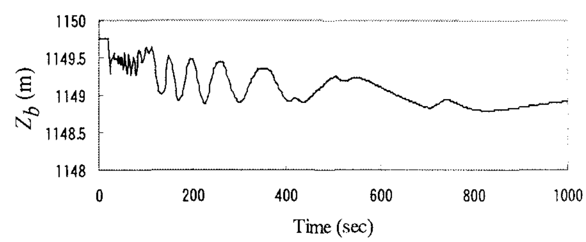
Sediment / Tributaries	Coarse (m^3)	Fine (m^3)	Sub-Total (m^3)
T1	33,600	75,740	109,340
T2	31,247	97,992	129,239
T3	34,818	87,025	121,843
TOTAL			**360,422**

4. INFLUENCES OF OCCURANCE ORDER ON SEDIMENT DISCHARGE

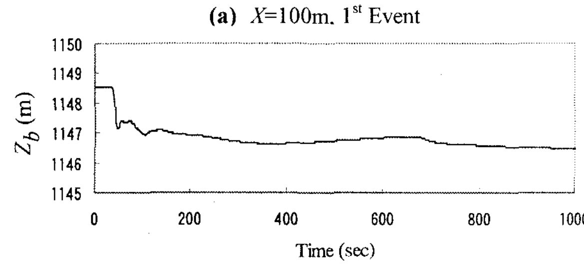
Tributary T_1 was considered to evaluate the debris flow characteristics for the second occurrence of debris-flow event, considering the bed-profile that left by the first event and same amount of rainfall over catchments. Typical temporal changes of bed elevation in different cross sections due to the first and second occurrences of debris-flow are illustrated in **Fig 4**, where x is measured from upper boundary. Total transportable sediment volume in second-event will be less because of restricted erodible bed in upper region and previously smoothened bed-slopes in lower region (**Fig. 5**). In **Fig. 4** we can visibly distinguish the effect of debris flow surges on temporal bed change. Highly unstable parts of the bed variation in **Fig. 4(a)** to **4(f)** are closely hanged with multiple sediment peaks of the same event that passes through the specified section, wheareas the unstable but gradually varying parts are caused by the tail of the surges. This phenomenon is also associated with temporal change of bed-slope at corresponding section. We have found another pattern of temporal bed-elevation change for second debris flow event, which deviates from the ending pattern of the first event, although all given conditions were made similar to the final stage of the former event. This case is elaboratly treated later.

In order to compare the independent and dependent effects, we have conducted numerical simulations for possible sequences (**Table 2**). Result shows, maximum debris volume supplied into the fan is about 0.35×10^6 m^3 due to T_1- T_3- T_2 sequence; whereas the lowest value i.e. 0.24×10^6 m^3 is given by T_2- T_3- T_1, just opposite to the former case. In all possible incidences, total sediment volume is less than the independently predicted volume where maximum difference observed is 0.12×10^6 m^3. **Figure 3** indicates the probable sequence i.e. T_3-T_2-T_1 in San Julian basin, which accounts only 0.33×10^6 m^3, which is all most 0.35×10^5 m^3 less than the independent case. It is well understood that the time, magnitudes and the shape of the hydrographs, thereby, sediment volumes are greatly affected by bed slope, length of the tributaries and little with supplied water discharge, which was also theoretically proven by Egashira et al.[8]. Moreover, the effect of sequential occurrences is significant. In independent cases, we gave original bed irregularities i.e. initial bed-slope in each and every computation. In dependent cases, previously deformed bed was given as an initial condition to each next calculation.

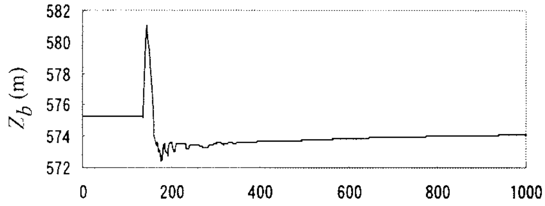
Difference between estimated sediment volume from field survey and the sediment volume predicted by numerical simulation is basically due to the following reasons: (a) the contribution from other small tributaries, which are not accounted for simulation and (b) the effect of run-time in calculation. Although almost all given physical-characteristics are of the same, calculated sediment volumes are different even from one



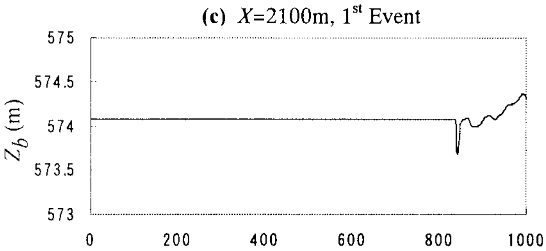
(a) X=100m. 1st Event



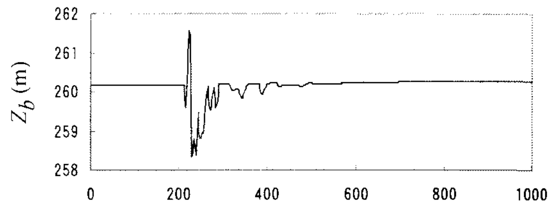
(b) X=100m. 2nd Event



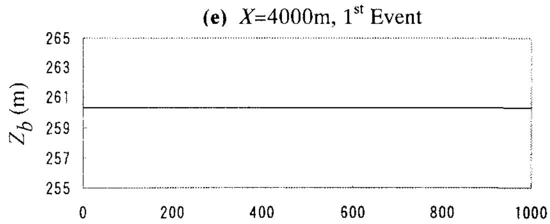
(c) X=2100m, 1st Event



(d) X=2100m, 2nd Event



(e) X=4000m, 1st Event



(f) X=4000m, 2nd Event

Fig. 4 Temporal change of bed elevation

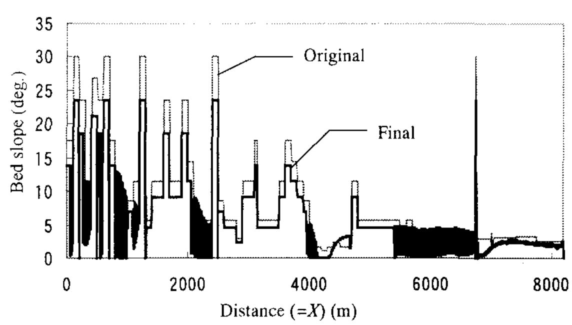


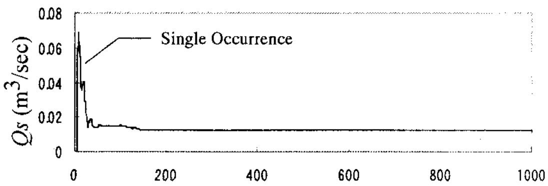
Fig. 5 Initial and final bed-slopes along tributary T_1

dependent case to another. Erosion equation can give better answer for this question where the temporal bed-slope and potential erosion depth have played a governing role.

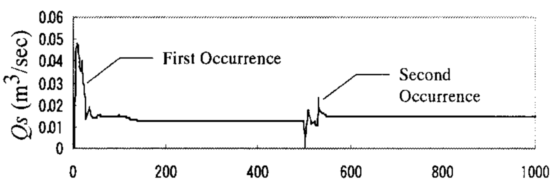
In order to explain our results, we have also simulated a case of 10 m long and 1 m wide model-flume with maximum erodable depth of 0.5 m and uniformly distributed slopes of 18-5-18-5

Table 2 Sediment-yield transported by trail sequences

Sediment / Sequence	Coarse (m^3)	Fine (m^3)	Total (m^3)
T1-T2-T3	84,080	204,853	288,933
T1-T3-T2	96,837	252,415	34,9252
T2-T1-T3	64,956	251,567	316,523
T2-T3-T1	56,006	187,629	243,635
T3-T1-T2	77,559	242,602	320,161
T3-T2-T1	87,883	242,022	329,905



(a) X=5m (Single occurrence)



(b) X=5m (1st and 2nd occurrences)

Figs. 6 (a) and 6 (b) Sediment hydrographs at X=5 m

degrees in every 2 m consecutive intervals, supplying 0.25 m^3/sec water for each event. **Figure 6** is the sediment hydrograph plotted at the middle section of the model-flume i.e. at 5 m.

In **Fig 6b**, two peaks can be observed within 1000sec in which two sequential computations were conducted and each was calculated for 500s, providing similar boundary conditions, whereas in the single-event case (**Fig. 6a**), it has single peak within 1000sec. This phenomenon can be explained by the following points: (a) In Eq. 3, second term of right hand part is the function of pressure gradient. This means, the frontal face of the debris flow has always steeper gradient. Therefore, erosion capacity is higher than in the case of tail. Following the frontal surge, the tail part of the flow makes unstable deposition, which can be flushed out by the next debris event and it helps to generate another peak (b) Unstable sediment associated with potential erosion depth is not transported by the first surge and is provided for the second surge in steep reach.

5. CONCLUSION

The main perception of this paper is to bring better understandings for the prediction of debris flow events in river basin, which is composed of many tributaries. San Julian debris flow event was numerically simulated considering debris flow events in each tributary on both independent and dependent circumstances. Multiple debris flow events were analyzed within a single tributary T_1 to explain the mechanics, and thereafter numerical simulations were conducted to evaluate the differences between the solutions given by dependent and independent events in sediment volume. Conclusions are summarized.

1. Temporal changes of bed elevation in different cross sections of tributary T_1 due to the first and second occurrences of debris-flow events are different. Total transported sediment volume in the second-event is less than in the first event because of restricted erodible bed in upstream reach and smoothened bed-slopes in downstream reach. The magnitude of the peak sediment discharge will be reduced gradually in each debris flow event.
2. Total sediment volume supplied into the debris fan, which is obtained from independent calculation is larger than the volume obtained from dependent calculation. Those results are affected by original bed irregularities, which are considered in each computation of independent events. This shows that the hysteresis of bed shape and slope changes plays an important role on transported sediment volume.

The results given by this research will help to optimize the structural countermeasures in San Julian River basin. In addition, predicted information will facilitate to prepare and implement several non-structural countermeasures.

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