 https://doi.org/10.1051/e3sconf/202341502023

Experiments on and numerical calculations of debris flows passing through narrowed and widened channel regions

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Abstract. We clarified the dynamics of debris flows in areas wherein the topography changes abruptly. First, the dynamics of debris flow through a constriction were investigated by experimentally generating non-uniform flow conditions. Then, numerical calculations were performed using an erosion/deposition rate equation that considers the pressure gradient in a constriction, and compared with the experimental data.

1 Introduction

When the topography changes abruptly, such as in narrow regions of canyons, debris flow would be expected to vary significantly. However, few detailed studies have appeared on this phenomenon. The erosional and depositional characteristics of debris flows are often evaluated based on the magnitude of the correlation between the gravity term in the equation of motion and the shear stress (yield stress) on the river bed surface; channel transitions have not been considered. Here, we describe experiments in which flow became non-uniform as debris passed through a narrowed channel region [1], and present a method for evaluating erosion and deposition based on effects of channel transitions. We also describe relevant applications [1].

2 Overview of channel experiments

We created narrowed and widened areas in the middle of a straight channel (length, 6 m; width, 10 cm). to obtain a saturated movable bed. We then supplied sediment and water on a constant basis. The channel slope was 15º, the water supply rate was 531 cm3/s, the sediment supply rate was 235 cm3/s; and the sediment proportion was 0.31.

3 Equilibrium slope with a pressure term and the erosion and deposition velocity equations

Motion equations for two layers [2] were combined to obtain the following motion equation for all layers:

$$\frac{\partial(\rho_w v_w h_w + \gamma_d \rho_s v_s h_s)}{\partial t} + \frac{1}{B}\frac{\partial\left(\rho_w \beta_w B {v_w}^2 h_w + \rho_s \beta_s B {v_s}^2 h_s\right)}{\partial x} = \rho_w g + h_w sin\theta + \rho_s g h_s sin\theta - \frac{\partial P_w}{\partial x} - \frac{\partial P_s}{\partial x} - \tau_b \quad (1)$$

where subscripts s and w denote the amount of solid/liquid motion and water flow, respectively. B is the channel width, h is the thickness of the fluidized bed of each layer, v is the mean flow rate of each layer, θ is the river bed gradient, ρ is the mean density of each layer, g is gravitational acceleration, P is the pressure acting on the side of each layer, and τ_b is the shear stress acting on the river bed surface[3]. In the equations, β_w and β_s are momentum correction coefficients for each layer, and γ_d is a shape factor reflecting the correlation between concentration and flow rate. All coefficients were assumed to be 1. Terms associated with the curvature of the river bed surface were omitted. The erosion rate s_T was obtained by extending [2] the erosion rate equation of Egashira et al. [4] to a two-layered flow, as follows:

$$s_T = v_t tan(\theta - \theta_e) \quad (2)$$

where v_t is the mean flow rate of the entire two-layered flow and θe is the equilibrium slope corresponding to the mean concentration of all layers (c_t). As the total fluidized bed thickness is h_t, we obtain:

$$v_t = v_s \frac{h_s}{h_t} + v_w \frac{h_w}{h_t} \quad (3)$$

$$tan\theta_e = \frac{(\sigma/\rho_w - 1)c_t}{(\sigma/\rho_w - 1)c_t + 1} tan\phi \quad (4)$$

$$c_t = c_s \frac{h_s}{h_t} \quad (5)$$

where cs is the mean volume concentration of gravel moving in the bed and ϕ is the internal friction angle. If

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we add a pressure term to the motion equation (1), and if the equilibrium slope at this point is θ_{ep}, we obtain the following equation:

$$\{(\sigma-\rho_w)c_t+\rho_w\}gh_t sin\theta_{ep} \\ -cos\theta_{ep}\frac{\partial(P_{w0}+P_{s0})}{\partial x} \\ -(\sigma-\rho_w)c_t gh_t cos\theta_{ep} tan\phi = 0 \quad (6)$$

where $h_t = h_s + h_w$, $P_{w0} = P_w/cos\theta_{ep}$, and $P_{s0} = P_s\, cos\theta_{ep}$. By introducing θ_{ep} into the erosion and deposition velocity equation, i.e., Equation (2), the effects of narrowed and widened channels can be considered when evaluating erosion and deposition. In such a case, the equilibrium slope θ_{ep} that considers the pressure gradient is expressed using θ_e, as follows

$$tan\theta_{ep} = tan\theta_e + \frac{\frac{1}{\rho_w g h_t}\frac{\partial(P_{w0}+P_{s0})}{\partial x}}{(\sigma/\rho_w-1)c_t+1} \quad (7)$$

Equation (7) shows that θep is smaller than θe in areas with sloping water surfaces (such as debris flow fronts), and that these areas are more susceptible to erosion. In contrast, erosion is suppressed and sedimentation occurs under certain conditions. Figure 1 shows the experimental data derived when debris flowed through narrowed regions, and the numerical calculations for erosion and deposition rates, when the equilibrium slope was that of Equation (7). The x-axis is parallel to the initial river bed. The top row shows the channel width in longitudinal section. The river bed is represented by black circles (●), indicating that the bed is degraded in narrowed regions. This is also evident in the calculation (thick solid line). However, the calculated free surface is linear; this does not mirror the experimental values. Regarding the effect of introducing a pressure term into a movable bed, debris entering a narrowed region is affected by the sidewalls, as narrowing gradually increases and flow height thus increases. Thus, flow depth becomes larger than that of flow just entering the narrowed regions (and is thus just upstream of that region). This causes a pressure difference between the debris flow upstream (where the flow depth is smaller) and that in the narrowed section (where the flow depth is greater); pressure is directed upstream. In other words, gravity (a shear stress on the river bed surface) acts in the downstream direction but the yield stress and pressure act in the upstream direction. Thus, the equilibrium slope becomes larger than that in a non-narrowed region, given that the slope reflects the balance between the different effects. After the debris flows through the narrowed regions, it is released from the effects of side walls as the new region gradually widens, and thus has more room to escape; this reduces the depth. In turn, this causes a pressure difference between the flow in the narrowed region (larger flow depth) and that in the widened region (smaller flow depth); this directs pressure downstream. In other words, gravity and pressure both act downstream but the yield stress acts upstream. The equilibrium slope is smaller than that in the non-narrowed region because this slope reflects the balance of the parameters. Therefore, the equilibrium slope in a narrowed region can be larger or smaller than in other regions, explaining the downward convex shape of the experimental curve.

4 Conclusions

We experimentally examined debris flows during channel transitions, and modeled abrupt channel transitions by introducing the flow pressure gradient to the equilibrium slope. We used the model to evaluate the results of experiments. We also conducted experiments on fixed beds; our intriguing results will be summarized during the presentation.

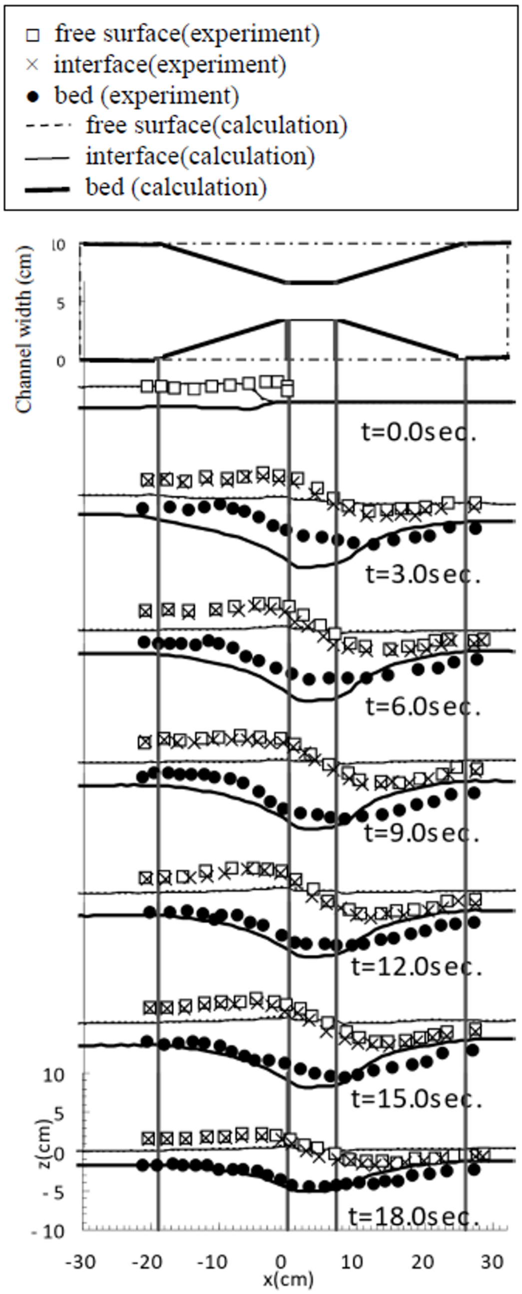

Fig.1 Comparison of experimental results of debris flow in a constriction with calculation results in which a pressure gradient is introduced into the erosion and deposition rate equation (on a movable bed)

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