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Fine Sediment Transport in Open Channel Flow with a Simulated Grass Strip

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Résumé

Le déversement de sédiments fins provenant des champs cultivés pose des problèmes pour l'environnement dans des zones côtières à Okinawa, Japon. Les bandes de gazon réduisent efficacement le flux des sédiments des champs vers les cours d'eau, mais leur conception nécessite un outil pour évaluer leur performance. Nous avons entrepris des expériences en laboratoire utilisant un modèle physique muni d'une bande de gazon pour modéliser le processus de transport des sédiments fins dans le flux en chenal ouvert, puis des simulations numériques sur la base des résultats. Des comparaisons entre résultats observés et calculés ont montré que le modèle numérique simulait de façon assez satisfaisante le processus de transport dans le modèle physique. Ce modèle numérique peut s'avérer utile pour calculer la performance à court terme d'une bande de gazon en ce qui concerne des sédiments fins.

1. Introduction

Fine sediment discharge from agricultural fields causes environmental problems in coastal areas in Okinawa, Japan. Grass strips located at the down-slope edges of agricultural fields reduce runoff of eroded materials from fields into streams (Dillaha *et al*., 1989). A plot-based field study indicated the effectiveness of grass strips at reducing fine sediment runoff from a field with a fine-textured soil in Okinawa (Shiono *et al*., 2005). The efficiency of grass strips at removing sediment depends on field conditions, so their design requires a tool to evaluate their performance under a variety of conditions. Numerical simulation can help to predict efficiency. Although a few simulation models have been proposed for calculating the efficiency of sediment reduction (Hayes *et al*., 1984; Rose *et al*., 2003), the models have not yet been fully tested under a range of conditions. Limited technical information exists on evaluating performance of grass strips to trap fine sediments.

The objective of this study was to propose a numerical model to simulate the process of fine sediment transport in open channel flow with a simulated grass strip. Our results will be essential to developing a method for estimating the efficiency of grass strips at reducing fine sediment flow under a variety of field conditions.

2. Materials and Methods

Laboratory Experiments: We simulated the transport of fine sediment in open channel flow

Table 1. Summary of parameters from Runs 1 and 2 of physical model.

	Run 1	Run 2
Flow rate Q (m^3 s^{-1})	$7.13 \quad 10^{-5}$	$1.31 \quad 10^{-4}$
Flow depth of inflow stream h_0 (m)	$4.4 \quad 10^{-3}$	$5.6 \quad 10^{-3}$
Flow velocity of inflow stream u_0 (m s^{-1})	$1.12 \quad 10^{-1}$	$1.61 \quad 10^{-1}$
Froude number of inflow stream Fr_0	0.53	0.72
Sediment concentration of inflow stream C_0 (m^3 m^{-3})	$7.73 \quad 10^{-4}$	$1.38 \quad 10^{-3}$
Sediment concentration of outflow stream C_1 (m^3 m^{-3})	$3.91 \quad 10^{-4} – 5.13 \quad 10^{-4}$	$9.36 \quad 10^{-4} – 1.15 \quad 10^{-3}$
Sediment removal efficiency ($1 – C_1/C_0 \quad 100$) (%)	34–49	17–32
Average sediment removal efficiency (%)	38	23

in a physical model with a simulated grass strip. The channel was 12.0 m long by 0.145 m wide and had a 2.0% slope. A simulated grass strip 1.5 m long by 0.145 m wide was installed at the downstream end of the channel. Sand and gravel particles 1 to 5 mm in diameter were glued onto the bed of the channel upstream from the strip to simulate the roughness of a field. The simulated strip was composed of uniformly spaced cylindrical bamboo rods 2.5 mm in diameter and 15 cm high, and rod density was 40,000 rods m^{-2}. A constant flow of water was supplied to the upstream end of the channel, and a sediment–water mixture was added at a constant rate at a point 3.6 m above the channel exit. The median diameter of the sediment was $1.28 \quad 10^{-2}$ mm, and its specific gravity was 2.71. Flow rate in the channel was measured with an HS flume at the channel exit. We performed two experiments, Runs 1 and 2. The experiment duration per run was 4 hours. Initial and final water surface and bed surface profiles along the length of the channel were obtained. Sediment concentrations in inflow and outflow streams were measured at 20-min intervals. Adapted flow rates and sediment concentrations of the inflow stream in Runs 1 and 2 are shown in Table 1.

Numerical Simulation: We derived a numerical model to simulate the transport of fine sediment in the physical model and carried out numerical simulations. The model was based on the energy equation for steady non-uniform flow given in Equation (1), the continuity equation for sediment given in Equation (2), and the continuity equation for bed level given in Equation (3). The last term on the left-hand side of Equation (1) represents resistance on the simulated grass strip.

$$\frac{dz}{dx}+\frac{dh}{dx}+\frac{d}{dx}\left(\frac{u^2}{2g}\right)+\frac{n^2u^2}{h^{4/3}}+\frac{1}{2g}NdC_du^2=0 \qquad (1)$$

$$\frac{Q}{B}\frac{dC}{dx}=q_{su} \quad w_0C \qquad (2)$$

$$\frac{dz}{dt}= \quad \frac{1}{1}(q_{su} \quad w_0C) \qquad (3)$$

where z is bed level, x is distance from the channel exit, h is flow depth, u is flow velocity, g is gravity acceleration, n is Manning's roughness coefficient, N is rod density of the simulated

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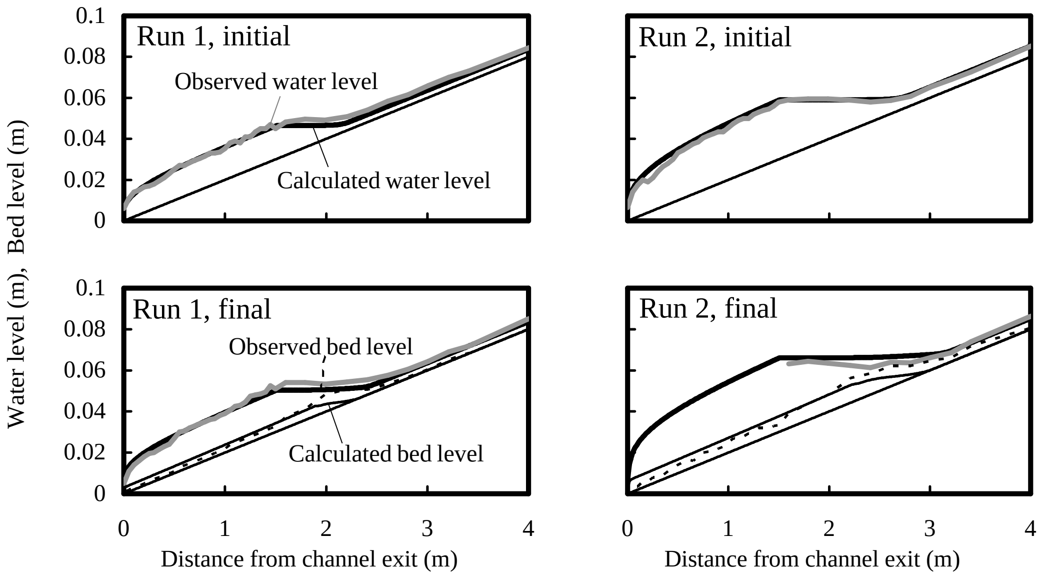

Figure 1. Comparisons of observed and calculated profiles of water level and bed level in Runs 1 and 2.

grass strip, d is rod diameter, C_d is drag coefficient of the rod, Q is flow rate, B is channel width, is volumetric water content of the water flow, C is sediment concentration, q_{su} is detachment rate on the channel bed formed with deposited sediment, w_0 is settling velocity of a sediment particle, and is porosity of the deposited sediment. The detachment rate was calculated by using an empirical formula obtained from flume experiments with the sediment used in this study. The settling velocity was calculated by means of Rubey's formula.

3. Results

Laboratory Experiments: Table 1 summarizes parameters from the physical model. The upstream flow in both runs was sub-critical because the Froude number of the flow was less than 1.0. In Run 1, the sediment concentration of the inflow stream was 7.73 10^{-4} m^3 m^{-3}, and that of the outflow ranged between 3.91 10^{-4} and 5.13 10^{-4} m^3 m^{-3}. Average sediment removal efficiency was 38%. In Run 2, the inflow stream concentration was 1.38 10^{-3} m^3 m^{-3}, and that of the outflow ranged between 9.36 10^{-4} and 1.15 10^{-3} m^3 m^{-3}. Average removal efficiency was 23%. Sediment was deposited within the strip and in the backwater region in each run. The length of the backwater region increased with time owing to deposition during each run. The location of maximum sediment depth remained in the upper part of the backwater region, and the sediment depth decreased toward the channel exit (Figure 1). These results are similar to earlier findings (e.g. Dabney *et al.*, 1995).

Numerical Simulation: We compared calculated and measured sediment concentrations, water surface profiles, and bed profiles. The calculated sediment concentrations of the outflow stream ranged between 4.43 10^{-4} and 4.61 10^{-4} m^3 m^{-3} in Run 1 and between 9.30 10^{-4} and 9.67 10^{-4} m^3 m^{-3} in Run 2. The average sediment removal efficiencies based on the simulations were 42% in Run 1 and 30% in Run 2. These calculated results are similar to the

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observed results. The calculated profiles of the initial and final water surfaces in each run agreed well with the measurements, as shown in Figure 1. The calculated pattern of the final bed level in each run differed somewhat from the corresponding measurement. Differences between calculated and observed sediment depths in the upper part of the backwater region in each run were larger than those in other parts of the physical model.

4. Discussion and Conclusions

The calculated sediment concentrations and water level profile during each run agreed well with the corresponding measurements, but the calculated final bed level profiles differed somewhat from the measurements. These results indicate that our numerical model simulated the process of fine sediment transport in the physical model reasonably well. Simulations based on the numerical model will accordingly be useful for calculating the ability of grass strips to trap fine sediment.

Calculated sediment depths in the upper part of the backwater region differed somewhat from observed values in both runs. This may be explained by the fact that actual sediment diameter varied, but was modeled as being uniform. Were the run duration to be increased, the differences between simulated and observed sediment depths in the channel would also increase. The increase in difference would lead to increased errors in simulation of the water level profile and sediment concentration. Therefore, the accuracy of prediction of sediment depth would need to be improved in order to evaluate the performance of the strips over the long term.

In order to better simulate the process of fine sediment transport in water flow across an actual grass strip in a field, further investigation will be required to determine a substitute term representing the resistance of the strip in Equation (1).

In conclusion, the numerical model simulated with reasonable accuracy the process of fine sediment transport seen in the physical model. The numerical model will be useful for calculating the short-term performance of a grass strip at trapping fine sediment. To simulate the process of fine sediment transport in water flow across an actual grass strip in a field, the model requires improvement.

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