A SEDIMENT TRANSPORT MODEL CONSIDERING POROSITY VARIATION OF SEDIMENT MIXTURE COUPLED WITH A EULERIAN DEPOSITION MODEL

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ABSTRACT

Recently, sediment floods have frequently occurred in Japan due to heavy rains and have caused extensive damage. One reason for these floods is that the amount of sediment supplied from the sabo dams exceeds the amount of sediment that can be transported by water flow in the downstream river. Debris flow sediments captured by sabo dams have a wide particle size distribution. Therefore, it is necessary to evaluate the amount of sediment transported from the sabo dams as a function of grain size distribution. However, the conventional sediment transport model does not take into account the change in porosity induced by the change in particle size distribution. The objective of this study is to develop a sediment transport model to calculate the temporal variations in sediment height and size distribution simulating sediment porosity. In this study, the porosity of sediment was simulated by the Eulerian deposition model (Hayashi et al., 2019), which did not include any artificial thicknesses such as the active layer. This model was extended to an erosion model and coupled with computational fluid dynamic models and sediment transport models. This numerical analysis method was applied to an experiment using riverbed material, which was conducted to clarify the change in sediment volume and porosity. The present method captured the sorting process of the riverbed and reproduced variations in volume and sediment size distribution simulating the porosity of the sediment.

Keywords: Component, sediment transport, porosity, sediment mixture, packing model

1. Introduction

In a filled sabo dam, sediment flows out of the sabo dam due to the flow during the flood. A large amount of sediment discharged from the sabo dam flows into the downstream river, causing sediment flooding. Therefore, a method to evaluate the amount of sediment flowing out of the sabo dam is needed. It is known that the particle size distribution of the sediment trapped in a sabo dam is wide. An evaluation method that considers changes in porosity due to particle size distribution is necessary. A sediment transport model for mixed sediment has been extensively studied. A commonly used model uses the concept of an active layer (Hirano,1971). However, this conventional method based on the active layer concept has problems in evaluating the change in the sediment porosity and thickness of the layer. Many researchers have focused on the evaluation method of the porosity of sediment. The particle size distribution was classified into lognormal distribution, and talbot distribution and the porosity was expressed as a function of particle size distribution (Fujita et al., 2006). Hayashi et al. developed a calculation method for the riverbed height, proposed based on the Eulerian deposition model and validated it through comparisons with experimental results. In this study, the model (Hayashi et al., 2019) is coupled with sediment transport models and validated through comparison with the results of an experiment on sediment discharge from a sabo dam.

2. Numerical calculation method

In this study, the Eulerian deposition model, which is a continuity equation in static conditions, was coupled with a sediment transport model (Ashida & Michiue,1972). The grain shear stress was calculated by the following equation (1) by assuming uniform flow.

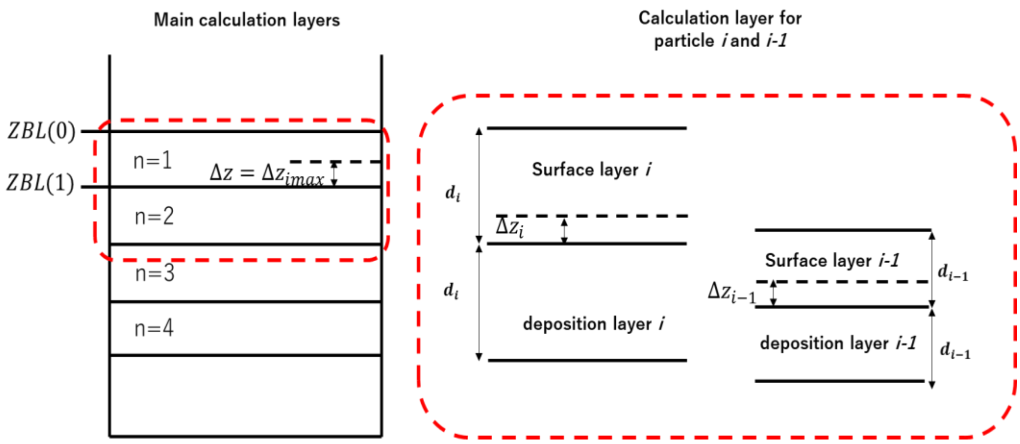

Fig.1 Calculation mesh

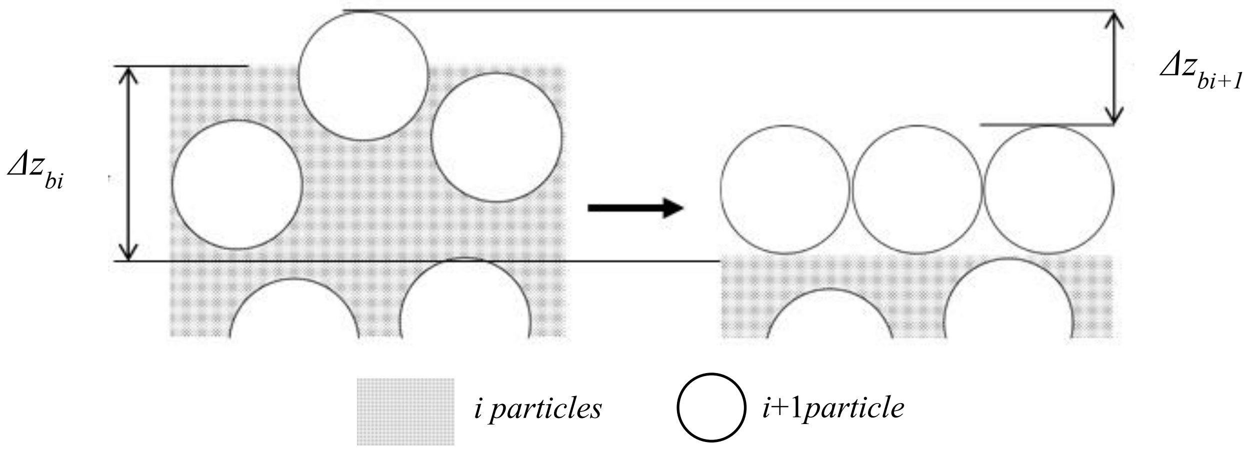

Fig.2 Erosion mode1
-changes in bed height of large particles following erosion of small particles-

$$\tau = \rho g h I \tag{1}$$

where τ is the grain shear stress, h is the water depth, I is the bed slope.

In the Euler-type sedimentation model used in this study, the height of each layer was defined by the maximum grain size, and calculations were performed separately for each analysis layer (Fig1.). The entire analysis layer is represented by a surface layer that represents voids that allow particles larger than a certain size to penetrate, and an arbitrary number of sedimentary layers from which the proportion of each particle is calculated. In order to calculate the entire analytical layer, the analytical layer is considered for each particle size, and the change rate of the particle abundance and the deposition height is calculated using the porosity that can penetrate.

In the erosion process, these changes can be divided into empty and unsaturated conditions. Calculation was done in the same way as in the deposition process. However, when the height of the particle i decreases, the height of the particles larger than i must also decrease. Assuming that the particle $i+1$ is the closest packed by the variation in deposition elevation of particle i , Δz_{bi}, the following formula is satisfied: (Fig.2).

$$\Delta z_{bi+1} = \Delta z_{bi} - \Delta z_{bi} \times (P_{i+1})_{\text{deposion layer}} / (\lambda_{i+1}(1 - \lambda_0)) \tag{2}$$

where, Δz_{bi}: i particle height change, Δz_{bi+1}: $i+1$ particle height change $(d_{i+1} \geq d_i)$, λ_0 : porosity for uniform spheres, and λ_i: available porosity of i+1 particle.

Table.1 Calculation condition

water discharge	m^2/s	0.046
bed slope	-	0.170
mesh	m	dx=0.05
dt	s	0.010

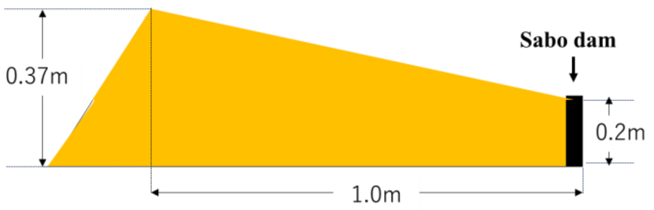

Fig.3 Experimental channel

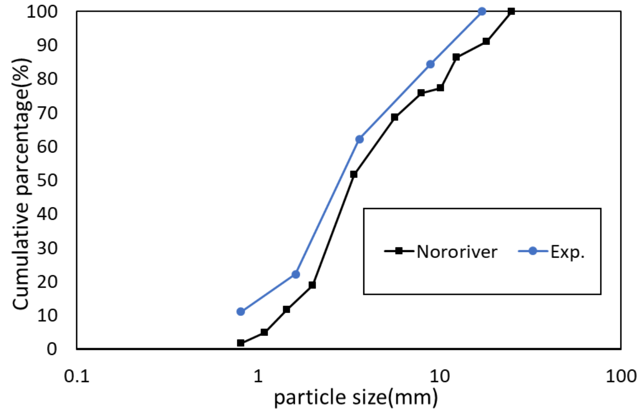

Fig.4 Particle size distribution

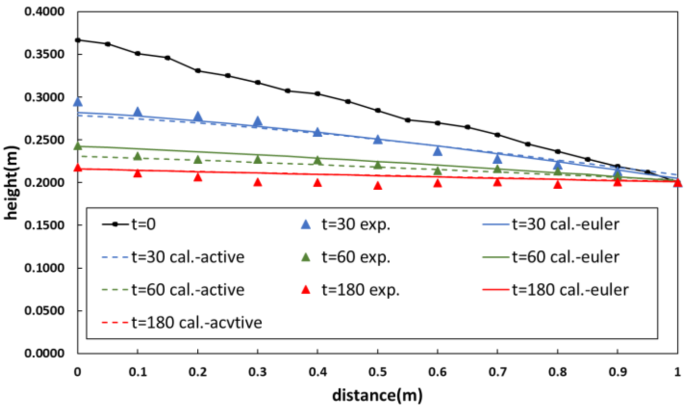

Fig.5 Bed height

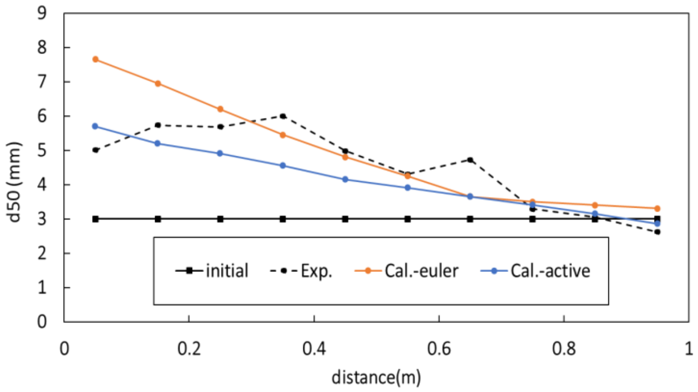

Fig.6 Distribution of d50 on the surface layer

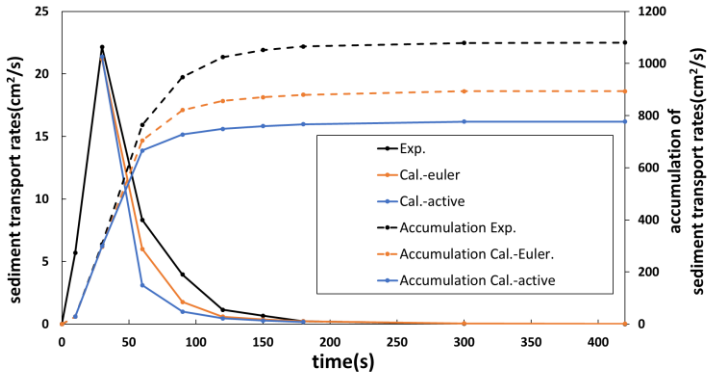

Fig.7 Sediment transport rate

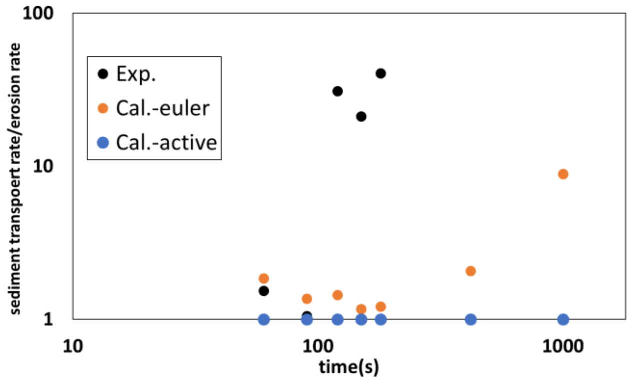

Fig.8 Sediment transport rate and erosion rate

3. Application to experiment

3.1 Experimental method

A 0.2 m sabo dam was installed downstream, and sediment of mixed grain size was deposited uniformly, as shown in Fig. 3. The experimental conditions were applied using the hydraulic conditions of the Oya-Okawa damaged by heavy rainfall in western Japan and the sediment gradient of the dam was planned using the Froude similarity rule. The particle size distribution of the mixed sediment used in the experiment was created with reference to the particle size distribution of the slope failure point upstream of the Noro River, which suffered the same damage as Oya Okawa. (Figure 4). Water flow was carried out for 30 min with sediment deposited upstream of the sabo dam installed in the experimental channel. Table 1 lists the analysis conditions. The initial abundance of each grain size in the Eulerian deposition model was determined from the experimental values using the initial porosity and grain size distribution. For comparison, it was calculated using the conventional model, where the thickness of the active layer was defined as the maximum grain size under the same conditions by the Eulerian deposition model.

3.2 Calculation results

Fig. 5 shows the temporal change in the bed height. The experimental and analytical values were almost identical. Fig. 6 shows the longitudinal distribution of the d50 particle size in the surface layer. Similar to the analytical and experimental values, there was a tendency to coarsen from downstream to upstream. Fig. 7 shows the amount of sediment transport per unit time. After 60 s, the amount of sediment in the analysis values was smaller than the experimental values. In the experiment, it is considered that the amount of sediment transport increased owing to the effect of kinetic sorting (Bacchi et al., 2014). Since the effect of kinetic sorting was not reflected in the sediment transport equation used in this study, the amount of sediment transport could not be reproduced.

Fig. 8 shows the ratio of sediment transport to the erosion rate. The calculation result is agreed with the experimental result at the beginning, but the experimental value after 120 s shows that the sediment discharge is more than 20 times the erosion amount. As time elapsed, the sediment discharge was more than 10 times larger than the erosion, even in the case of the Eulerian deposition model. In this analysis, the sediment transport and erosion rate could not be changed over time because the sediment discharge could not be evaluated properly. However, the apparent erosion and sediment discharge due to the porosity change over time could not be determined.

4. Conclusions

In this study, we proposed the Eulerian deposition model which can handle the spatiotemporal change of porosity of bed in graded sediment to better estimation of sediment runoff from the sabo dam. The model is then verified by comparing a laboratory experiment, showing that the riverbed fluctuation and temporal change in sedimentation were almost reproduced. However, the time required for the riverbed to reach a stable state was different between the analytical and experimental values, and it was not possible to reproduce the temporal relationship between the sediment discharge and the erosion rate.

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