EXPERIMENTAL INVESTIGATION OF POROSITY AND VOLUME OF SEDIMENT MIXTURE IN STRAIGHT OPEN CHANNEL FLOWS

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ABSTRACT

It is necessary to develop a calculation method for the topographical riverbed changes due to the variations in grain size distributions, to evaluate the deposition, sediment-flushing mechanism in the reservoir, and the effect of sediment supply downstream of the river. However, the conventional method, which is based on the concept of active layers, has limitations in evaluating the change in sediment porosity and thickness of the layer. In this study, an experiment was conducted in a straight horizontal channel to clarify the change in sediment volume and porosity using sediment sorting. The sediment, which was well mixed with a wide grain size distribution, was installed in the channel. For a constant flow rate, the depth of the downstream end was reduced in stages. It was discovered that the porosity increased in the flow direction. Although the change in volume associated with the variation in grain size distribution was large at the initial stage, it decreased rapidly, approaching asymptotically to about 1.1 times of the erosion volume in this experiment. The experimental porosity in a finite thickness was reproduced by the Eulerian deposition model. A calculation method for evaluating riverbed height is proposed based on the model and was validated through the comparisons with the experimental results.

Keywords: *volume variation, sediment sorting, packing model, porosity, sediment mixture*

1. INTRODUCTION

Sediments in a riverbed are composed of particles with varying sizes. During the sediment transport process, the grain size distribution changes due to the water flow accompanying with porosity change. When calculating the change in the riverbed height with the variation in the grain size distribution, it is necessary to appropriately consider the change in porosity for the grain size distribution. However, previous calculations using the conventional method for riverbed change have limitations in evaluating porosity. A majority of the methods have considered porosity as a constant parameter. As a result, a method to evaluate the change in porosity and the sediment volume due to the variations in grain size distribution has not been established thus far.

Several formulas for sediment discharge have been proposed. For example, to express the sediment discharge in mixed gravel, Ashida and Michiue (1972) modified the critical tractive force for sediment mixture proposed by Egiazaroff (1965), using the ratio of each particle size in the riverbed. For the continuity equations of riverbed materials, Hirano (1971) introduced the active layer which was defined as a well-mixed layer with various sediment particles between the mobile and immobile subsurface sediment layers. This method is currently widely applied; however, it is difficult to determine the temporal change in the thickness and porosity of the exchange layer using this method. The riverbed variation for the mixed particle size cannot be appropriately evaluated under the condition of constant porosity in the continuity equation.

In an experiment on sediment sorting, Seal et al. (1997) examined the longitudinal change in sediment deposition under a constant flow rate in a narrow-long channel; they reported a change in the amount of sediment supply, similar to the grain size distribution observed in rivers. However, it is considered that the changes in porosity and sediment volume are not discussed enough.

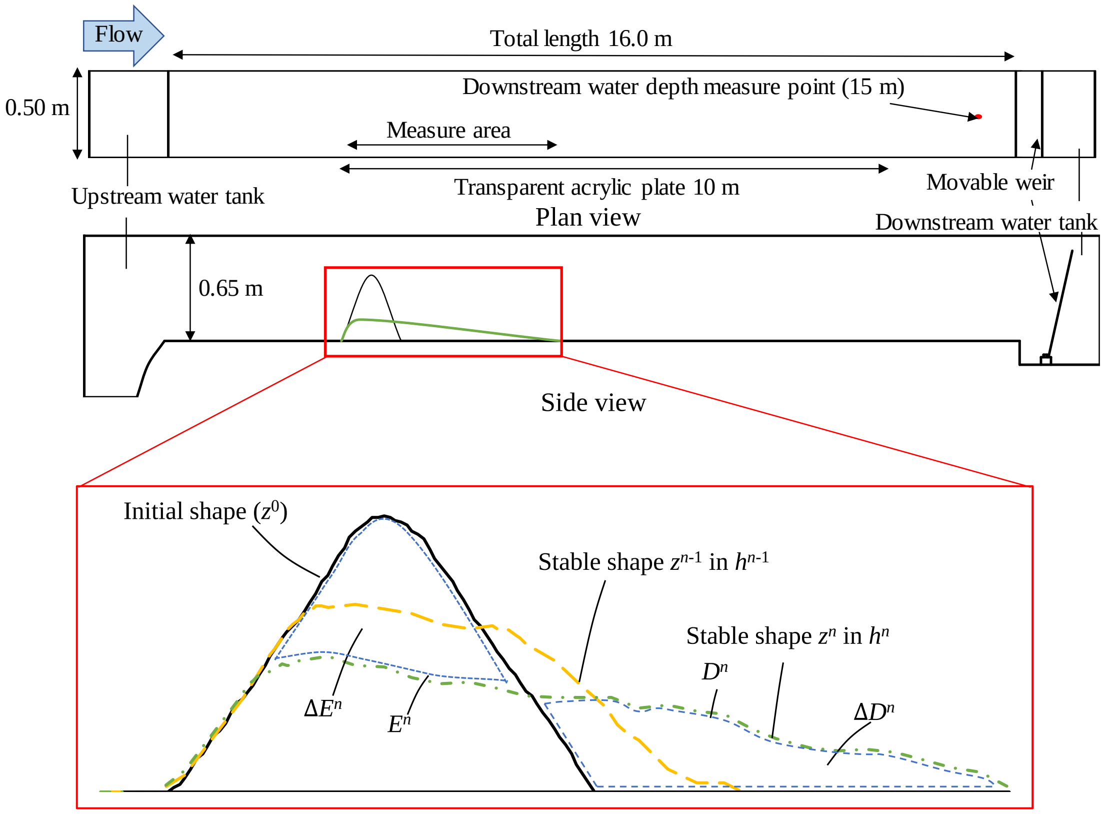


Figure 1. Plan view and side view of experimental channel and definition of erosion E^n and deposition D^n volume at each downstream end water depth h^n

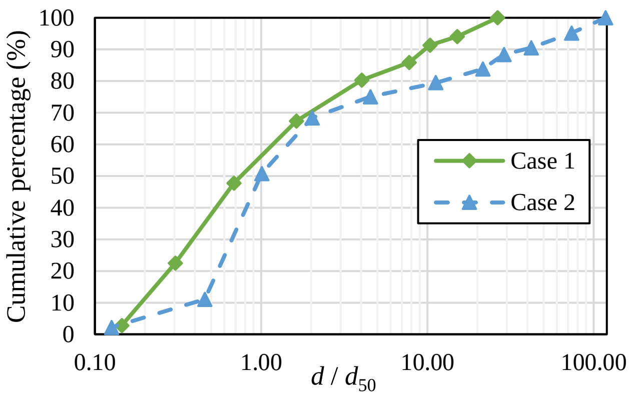


Figure 2. Grain size distribution of dimensionless at d_{50} for experiment

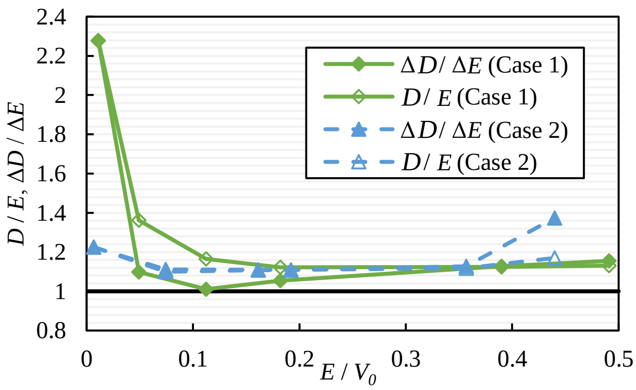
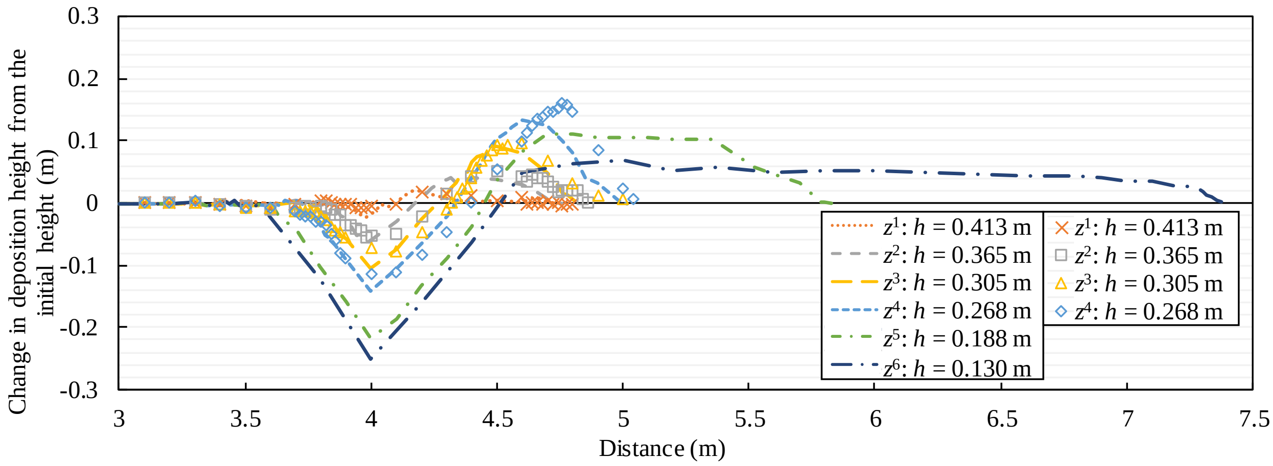


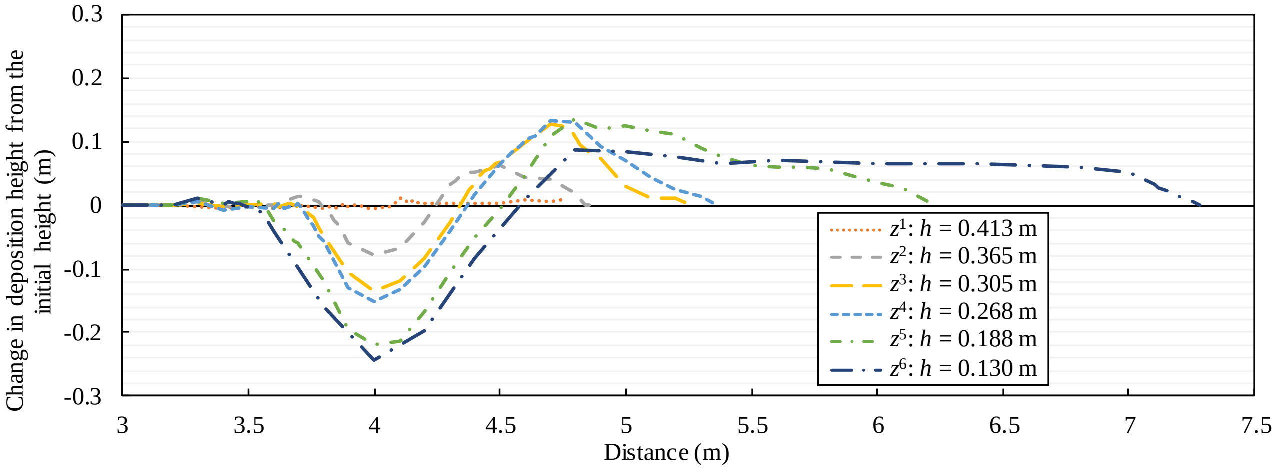
Figure 3. Change in erosion and deposition ratio

In recent years, there has been a growing interest in the porosity of riverbeds; hence, several methods for estimating porosity have been proposed. Tsutsumi et al. (2006) proposed a packing simulation model wherein particles were filled in a rectangular container with the closest packing in spherical particles. It was revealed that small particles filled the voids between large particles and that the porosity reduced; the decrease in porosity was directly proportional to the width of the grain size distribution. However, this method is insufficient for un-spherical riverbed material. Wu et al. (2006) modeled the relationship between the representative particle sizes and the porosity of sediments. Fujita et al. (2008) developed a sediment mixture model to calculate variations in bed height and grain size distribution employing considering the porosity variation determined as a function of the grain size distribution. However, it is difficult for different grain size distribution type. Recently, the Eulerian deposition model that could calculate the height and porosity for a wide grain size distribution in the closest packing condition was proposed (Tateishi et al., 2018). To calculate the riverbed variation, it is necessary to verify the sediment deposition mechanism as well as its classification and examination at finite height.

This study aims to investigate the change in porosity and volume of sediment induced by sediment sorting with water flow in the reservoir, and to develop an analysis method for the deposition height.



(a) Case 1



(b) Case 2

Figure 4. Changes in shape of erosion and deposition at each downstream end of water are shown in (a) Case 1 and (b) Case 2

2. VOLUME CHANGE DUE TO SEDIMENT SORTING OF GRAIN SIZE DISTRIBUTION

2.1 Experiment method

A flat rectangular channel (Figure 1) with a width, length, and depth of 0.50, 16, and 0.65 m, respectively, was used in the experiment. The right-side wall of the channel is composed of a transparent acrylic plate from 3 m to 13 m at the upstream end (x = 0 m). The amount of erosion and deposition are defined as follows: when comparing the initial shape z^0 to the stable shape z^n at the nth downstream water depth, the amount of erosion E^n and deposition D^n are defined as shown in Figure 1. The change at each downstream water depth at the nth depth is given by ΔE^n, ΔD^n(Figure 1). As shown in Figure 2, two grain size distributions were used: the grain size distribution for Case 1 was made referent to that observed in the Noro-River Dam, while Case 2 was based on the grain size distribution of the alluvial river.. The sediment of the initial volume V_0(= 0.123 m^3) with a smooth convex shape was placed in static water in the channel from x = 3.32 m to 4.42 m and compacted. We measured the initial shape at 0.02 m in the downstream direction and at 5 points from the right bank—0.05, 0.15, 0.25, 0.35, and 0.45 m—in the transverse direction. The water discharge Q (= 0.020 m^3/s) remained constant. The downstream water depth (x = 16 m) in each case was gradually lowered from the initial water surface of 0.56 m, keeping a constant water level until the equilibrium state which means no sediment motion at each downstream water level. The shape of the bed profile for each downstream water level was measured at the 5 points in the transverse direction and 0.10 m intervals in the downstream direction. Moreover, the change near the boundary between the erosion and the deposition sections was measured at intervals of 0.02 m in the longitudinal direction. The riverbed height of the gravel bed is defined as the cross-averaged height measured downward from above (Dey et al., 2012). We conducted experiments in Case 1 and Case 2 to clarify the effect of differences to grain size distribution. To compare the classification, the porosity and grain size distribution were measured after the shape measurement in two cases of a downstream end water depth of 0.268 m (pattern 1) and a downstream end depth of 0.13 m (pattern 2), for Case 1. In pattern 1, the sediment was removed at each 0.06 m in the vertical direction and 0.10 m in the longitudinal direction. In pattern 2, the sediment was removed at each 0.20 m in the longitudinal direction for the deposited sediments. Additionally, the surface particle-size distribution at each downstream end depth was measured using a photograph.

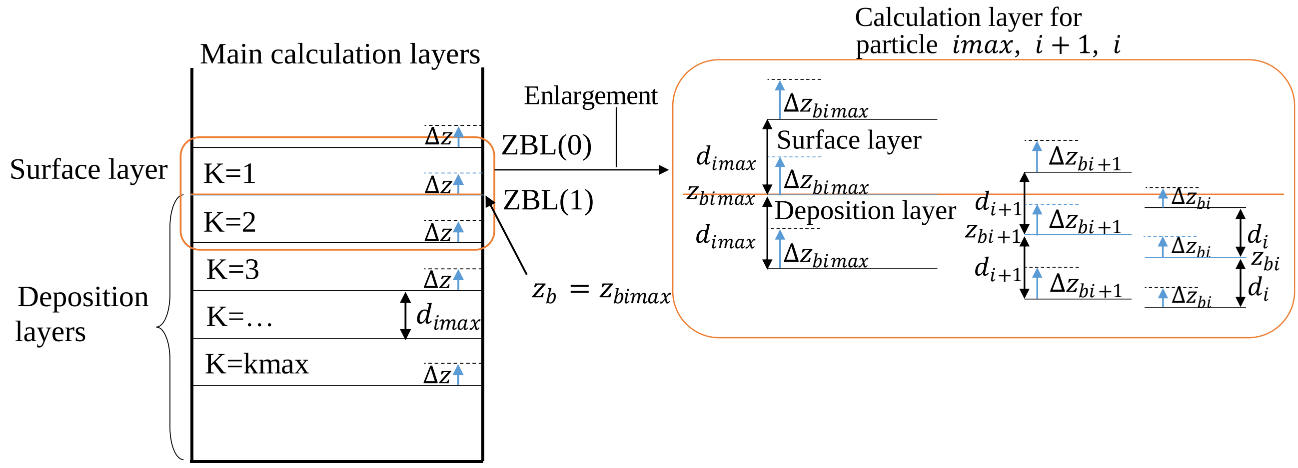


Figure 5. Calculation procedure for mixture sediment deposition with calculation layers

2.2 Experimental results

In Figure 3, the horizontal axis is the ratio of erosion volume E to the initial volume V_0, and the vertical axis is the ratio of the deposition volume to the erosion volume. For Case 1, during the initial change, the amount of deposition was more than twice the amount of erosion. It decreased rapidly in the next step. Finally, the amount of deposition reduced to approximately 1.1 times the amount of erosion. In the early change, the deposited sediment volume D was larger than the erosion sediment volume E, because particles smaller than the average particle size flowed out and were deposited on the downstream slope; however, particles exceeding the average particle size remained under stable conditions. Therefore, the porosity percentage increases, whereas the apparent erosion sediment volume decreases.

When sediment sorting was carried out in a lower water depth, the large sediment particles flowed out with small sediments and redeposited themselves on the downstream slope. This downstream slope was composed mainly of sand. Because the volume of the erosion was deposited on the downstream slope and the sediment smaller than the average particle size was carried downstream, the amount of change was almost equal, and it was believed that only the influence of the flowing sand was affected. The surface layer was sorted by the outflowing of the sand and the supply of gravel from the upstream was deposited. The ratio of the amount of deposition ΔD to the amount of erosion ΔE gradually became constant. Therefore, it can be seen that the sand flows out, and the exposure of the gravel increases, and armoring proceeds.

Alternatively, in Case 2, the ratio of volume increase did not change significantly from the initial shape, but the ratio of volume change increased at the last downstream end depth. Although sediments smaller than the average particle size flowed during the initial change, the proportion of sand in the initial sediment was large. Therefore, the area of its surface exposed to the surface was reduced, compared to that in Case 1, and the ratio of the erosion volume to deposition volume was almost equal. The change in $\Delta D/\Delta E$ increased because particles smaller than the average particle size flowed out and the gravel was exposed, and the amount of the apparent erosion sediment volume decreased. These results suggested that the sediment volume increases due to the classification of flow even in waterway experiments with a narrow grain size distribution.

3. EVALUATION METHOD OF RIVERBED HEIGHT BY EULERIAN DEPOSITION MODEL

3.1 Calculation method

The Eulerian deposition model is used to calculate the deposition height and volume fraction of each grain size of the main calculation layers. The calculation method is summarized as follows. Please find the detail in our forthcoming paper (Uchida et al., Forthcoming). Main calculation layer thicknesses for each layer is defined by the maximum particle size separated from the surface layer top height (Figure 5). The grain size distribution of bed sediment is used as input data. In the calculation, the deposition process of sediment mixture is divided into calculation steps composed of a small amount of sediment volume. To calculate the volume fraction of particles P_i in the main calculation layers (left in Figure. 5), calculation layers were established for each particle size to calculate the deposition height z_{bi} and volume fraction of particles P_i of the surface layer and the deposition layers of particles i (right in Figure 5). The subscript "i" is the ith size class in the grain size distribution. The volume fraction of other particle sizes P_j in the calculation layer of the particle i in each particle size is determined via spatial interpolation from the main calculation layer. The main calculation layer height z_b is defined by the deposition height z_{bimax} of the maximum particle-size $imax$.

Here, we assume that a particle j larger than the particle i cannot penetrate into the porosity where the particle i cannot penetrate. The deposition high z_{bi} is always lower or equal than the deposition high z_{bi+1} as:

$$z_{bi+1} \geq z_{bi} \tag{1}$$

The change in the deposition height z_{bi} and volume fraction P_i of each particle in the deposition process can be divided into saturated conditions, in which there are no available porosity for particles i, and unsaturated conditions, represented by the following equations:

$$\delta z_{bi} = \frac{\delta D_i}{\lambda_i(1-\lambda_0)},\ \delta P_i = 0 \ \text{(Saturated condition: } P_i = \lambda_i(1-\lambda_0)\text{)} \tag{2}$$

$$\delta z_{bi} = 0,\ \delta P_i = \frac{\delta D_i}{d_i} \ \text{(Unsaturated condition: } P_i < \lambda_i(1-\lambda_0)\text{)} \tag{3}$$

where δD_i is the deposition volume of particle i in a calculation step, z_{bi} is the top of the deposition layer, and λ_0 is the porosity for uniform spheres. For evaluating the value of λ_0, the average value obtained by the packing experiment at each grain size was used (λ_0=0.363). The λ_i is the available porosity for a particle i, represented by the volume fraction of particle j that is larger than particle i, calculated by the following equation (4):

$$\lambda_i = 1 - \sum_{j=i+1}^{k} \alpha_{ij} P_i \tag{4}$$

where α_{ij} is a function of the particle size ratio that is represented by the following equations (5) to (7), extended by the binary packing formula.

$$\alpha_{ij} = 1 + \frac{\lambda_0}{1-\lambda_0} \gamma_{ij}^n (1-\beta_{ij})^m \tag{5}$$

$$\beta_{ij} = (1-\gamma_{ij})\left(1 - \frac{P_j}{1-\lambda_0}\right) \tag{6}$$

$$\gamma_{ij} = \min\left(a\frac{d_i}{d_j}, 1\right) \tag{7}$$

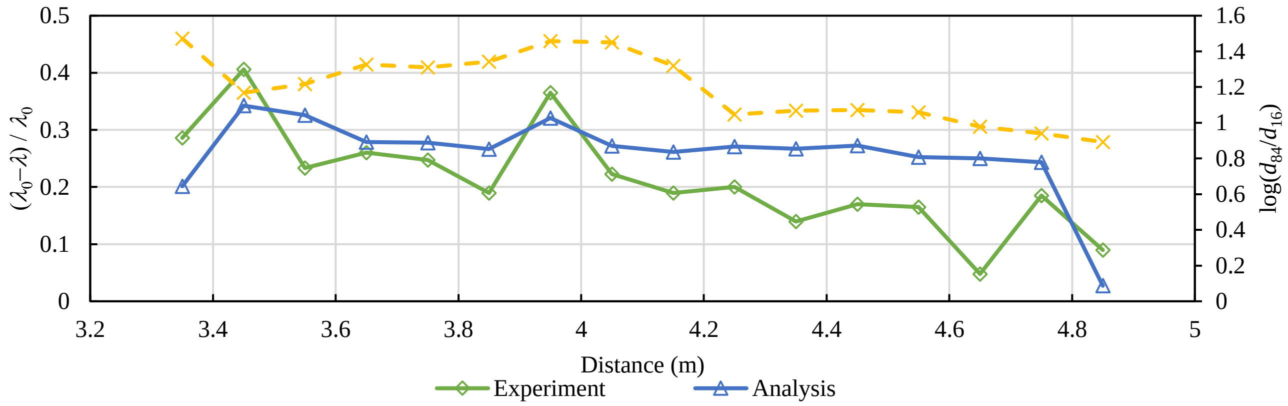
where the, d_i is particle size of i, d_j is particle size of j, a = 2, m = 1, and n = 0.5. The coefficients are determined using previous packing experiments (Tateishi et al., 2018; McGeary, 1961; Suzuki et al., 1984). The main calculation layers porosity is given by equation (8).

$$\lambda = 1 - \sum_{i=1}^{imax} P_i \tag{8}$$

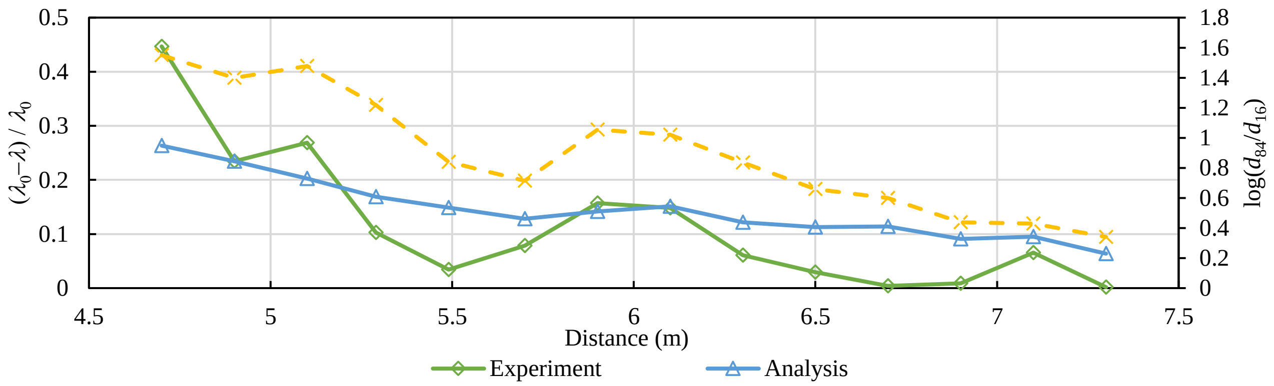
In this calculation, the volume fraction and deposition height for each particle sediment class i is obtaind.

In a previous study (Tateishi et al., 2018; Uchida et al., forthcoming), porosity and height were calculated for a certain particle-grain size distribution with an infinite deposition height. In this experiment, these values are applied to shallow sediment depositions on a fixed floor. The each particle deposition volume D_i for input data of the calculation is measured being taken out from the bed load shape at 0.10 m intervals in the downstream direction. In this calculation, a small deposition volume δD_i of each particle size on the riverbed is filled in the initial riverbed. In this study, δD_i was set as 0.0001 mm, which was sufficiently less than the minimum particle size d_{imin} (=0.1 mm).

To calculate the riverbed height, equation (9) is used. The left side in Figure 5, ZBL(0) is defined as the height of the top of the surface layer for the main calculation layers (ZBL(0) =z_b+d_{imax}). ZBL(1) is the height of the deposited top layer in the main calculation layers (ZBL(1)= z_b). Because the thickness of the layer is defined by the maximum particle size at that point, ZBL(0) is much higher than the experimental riverbed height. The average riverbed height measured from the top is considered to be between ZBL(0) and ZBL(1). Therefore, the averaged riverbed height elevation by equation (9) was assumed using the porosity of the surface layer in the main calculation layers λ_s (k = 1) and the porosity of the deposition layers (k =2) under the surface layer λ_d.

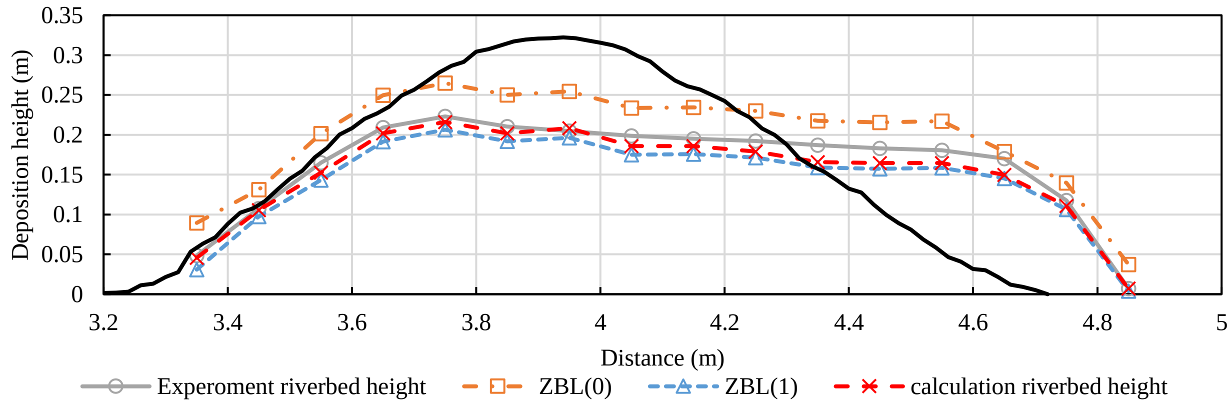


(a) pattern1

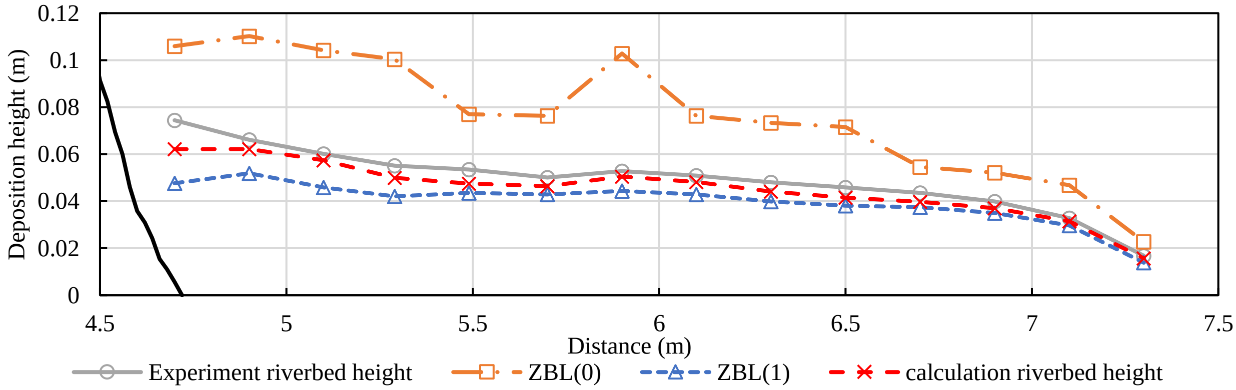


(b) pattern2

Figure 6. Comparison between experimental and analysis of porosity in the downstream direction and relationship between d_{84}/d_{16} (a) is shown in pattern1, downstream end water depth of 0.268 m, (b) is shown in pattern2, downstream end depth of 0.13 m for Case 1. The green and blue lines correspond to the left axis, and the yellow line corresponds to the right axis.



(a) pattern1



(b) pattern2

Figure 7. Comparison of the riverbed height between experiment and calculation (a) is shown in pattern1, (b) is shown in pattern2

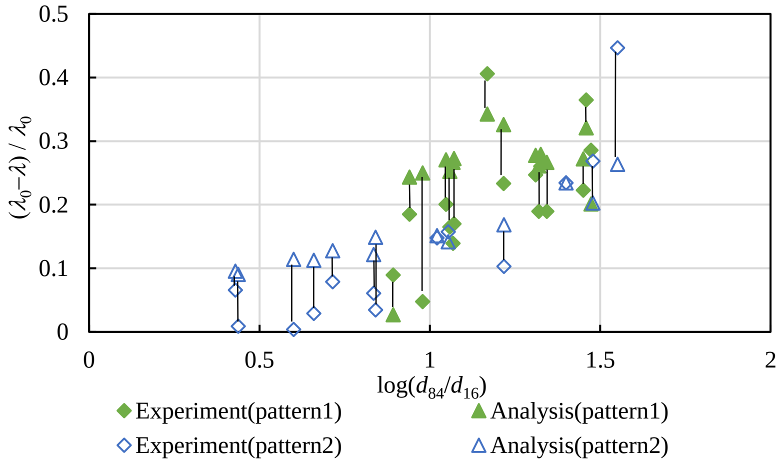


Figure 8. Relationship between the porosity of experiment, analysis, and d_{84}/d_{16}

In Equation (9), the calculated riverbed z_{cal} height is defined as the sediment volume of the surface layer. $d_{imax}(1-\lambda_s)$

$$z_{cal} = d_{imax}\frac{1-\lambda_s}{1-\lambda_d} + z_b \tag{9}$$

3.2 Calculation results and discussion

Figure 6 shows the comparison between the experiment and the porosity analysis. The horizontal axis is the distance from the upstream end, left side vertical axis is the porosity, and right side vertical axis is d_{84}/d_{16}. The porosity of the experiment was calculated using the amount of deposition volume from the dry volume. The grain size distribution was measured by sieving the section where the sediment was deposited from the initial deposition. The analysis value of the porosity indicates the average deposition layer above the bottom of the channel, excluding the surface layer (K =1).

The porosity obtained via analysis is greater than the experimental value for the points where the deposited sediment volume is small and the deposition layer is less than one layer. The porosity of both values generally increases due to the effects of sediment sorting. As sediment sorting goes downstream, d_{84}/d_{16} decreases and approaches a uniform particle size, and the porosity increases in the downward direction. Thus, it can be said that the analytical value of porosity captures the change in the overall porosity of the experimental results.

Figure 7 shows the riverbed height of each cross section by experiment and calculation. The grain size distribution becomes narrower as it moves downstream owing to the effect of sediment sorting. The calculation results of the deposition height using the grain size distribution at that point roughly agree with the riverbed height, therefore, it can be said that the riverbed height defined by equation (9) can be calculated accurately, and it is possible to evaluate the surface layer with a large porosity.

Figure 8 shows the relationship between the porosity of the experiment, analysis, and d_{84}/d_{16} in Case 1. The porosity of the same d_{84}/d_{16} is connected by a line between the experiment and the analysis. Overall, when d_{84}/d_{16} increases, the porosity tends to decrease, but the relationship is not that simple, and it can be observed that it is difficult to estimate porosity using d_{84}/d_{16}. Although the analysis value shows that the deviation is wider than that of the experimental value, it is smaller than the variation in the relationship between the porosity and d_{84}/d_{16}, and the change in porosity can be seen in the particle-filling model.

4. CONCLUSIONS

In this study, a one-dimensional experiment with a wide grain size distribution was conducted; it was observed that the volume of the deposition sediments with various grain size particles increased due to sediment sorting in the longitudinal direction of the water flow. In this experiment, the volume of the accumulated deposited sediment was approximately 1.1 times the volume of the erosion sediment. Sediment armoring was caused by the flow of sand and the exposure of the gravel bed, which was deposited downstream by the simultaneous supply of gravel from the upstream. It was shown that porosity is strongly related to the grain size distribution and increases in the downward flow direction. Additionally, it was revealed that the porosity observed in the experiment on the finite sediment thickness can be reproduced using the sediment deposition model. Moreover, the precise method of calculating the riverbed height using this model was shown, and its validity was demonstrated.

ACKNOWLEDGMENTS

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REFERENCES

Ashida, K. and Michiue, M. (1972). Study on hydraulic resistance and bed-load transport rate in alluvial streams. *Proceedings of JSCE*, 206:59-69.

Dey, S. and Das, R. (2012). Gravel-bed hydrodynamics: Double averaging approach. *Journal of Hydraulic Engineering*, 138(8):707-725.

Egiazaroff, I.V. (1965). Calculation of nonuniform sediment concentrations. *Journal of the Hydraulics Division Proceedings of the American Society of Civil Engineers*, 91(4):225-247.

Fujita, M., Muhammad, S., Jazaul, I., and Tsutsumi, D. (2008). A bed-porosity variation model and its application. *Advances in River Engineering*, 14:13-18.

Hirano, M. (1971). On riverbed variation with armoring. *Proceedings of JSCE*, 195:55-65.

McGeary, R.K. (1961). Mechanical packing of spherical particles. *Journal of the American Ceramic Society*, 44(10):513-522.

Seal, R., Paola, C., Parker, G., Southard, J.B., and Wilcock, P.R. (1997). Experiments on downstream fining of gravel, Ⅰ. Narrow-channel runs. *Journal of Hydraulic Engineering*, 123(10):874-884.

Suzuki, M., Yagi, A., Watanabe, T., and Oshima, T. (1984). Estimation of void fraction in a three component random mixture of spheres. *Kagaku Kogaku Ronbunshu,* 10(6):721-727.

Tateishi, A., Uchida, T., and Kawahara, Y. (2018). A calculation method of porosity and sediment height of riverbed material with broad particle-size distribution in gravel bed river. *Advances in River Engineering,* 24:95-100.

Tsutsumi, D., Fujita, M., and Muhammad, S. (2006). A simulation model for the void properties in gravel riverbed. *Hydraulic Engineering,* 50:1021-1026.

Uchida, T., Kawahara, Y., Hayashi, Y., and Tateishi, A. (Forthcoming). Eulerian deposition model for sediment mixture in gravel-bed rivers with broad particle size distributions, Journal of Hydraulic Engineering. 10.1061/(ASCE)HY.1943-7900.0001783

Wu, W. and Wang, S.S.Y. (2006). Formulas for sediment porosity and settling velocity. *Journal of Hydraulic Engineering*, 132(8):858-862.