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Classification of Grain Size Distribution Curves of Bed Material and the Porosity

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Synopsis

Among the qualitative features of bed material, the grain size distribution and the porosity are very important properties governing a habitat condition of aquatic living things. Two topics will be considered in this paper. The first is the identification and classification of grain size distribution curves and the second is measurement of the porosity of sediment mixtures and bed material. Grain size distribution of actual sediment mixture can be roughly classified into three types of distribution, namely, log-normal distribution, Talbot distribution and bimodal distribution, based on the mode of density distribution and indices β and γ. The porosity could be reasonably estimated by measuring the in-situ volume of sediment sample.

Keywords: classification, grain size distribution, porosity, sediment mixture, bed material

1. Introduction

Assessing the change in void structure of riverbed material is very important for an ecological issue in rivers. The effects of porosity changes from sedimentation on the riverbed environment have been widely investigated (Milhous, 1982; ASCE, 1992). Particularly, many ecologists are interested in the void structure of the bed material (Gayraud and Philippe, 2003). The previous bed variation models are available for the analysis of bed variation and the change in grain size distribution. However, they cannot provide information on the change in porosity. The porosity of bed material is usually assumed to be a constant. Fujita et al. (2005) have presented a framework of riverbed variation model to simulate the change of porosity as well as bed variation. A simple analytical model has been already presented under this framework, for a sediment mixture of particles with two much different grain sizes. However, it cannot be used for general grain size distribution. The porosity of sediment mixtures depends on the grain size distribution (Standish and Borger, 1979; Tsutsumi et al., 2006). If the porosity is related to the grain size distribution, the simple model could be improved in applying to general cases.

Actual sediment mixtures have various types of grain size distribution. Therefore, it is necessary to obtain the porosity for each grain size distribution one by one in calculation of bed variation. However, it is not practical. It is better to install some relationships between porosity and typical grain size distribution in the bed variation model in advance. For that modeling, classification and identification of the grain size distribution type are necessary.

This study aims to develop a method for classifying the type of grain size distribution curve and obtaining the porosity for the different type of grain size distribution. Two topics will be considered in this paper. The first is the identification and classification of grain size distribution curves and the second is measurement of the porosity of sediment mixtures and bed material. Firstly, three types of typical grain size distribution namely log-normal distribution, Talbot distribution and bimodal distribution were introduced. The grain size distributions of sediment mixture in natural rivers were classified into typical grain size distribution, and the parameters on those geometric properties were found out. Then, a method for identifying and classifying the type of grain size distribution was presented. Secondly, a method for measuring the porosity of sediment mixture and bed material was presented. A laboratory experiment and field observation was conducted to measure the porosity of the sediment-mixtures with different type of grain size distribution. The results of measured porosity were presented together with relationship between the porosity and the geometric parameter of grain size distribution was obtained by means of a packing model developed by Tsutsumi et al. (2006).

2. Classification of Grain Size Distribution Curves

2.1 Typical grain size distribution

Riverbed materials have a variety of different characteristic size of bed surface sediment, but the grain size distribution could be classified into some types. In this study, the grain size distributions are roughly classified into three types of grain size distribution, namely, log-normal distribution, Talbot distribution and bimodal distribution. Typical of the grain size distributions of sediment mixture are shown in Figure 1, where f is the percentage of the finer grain size and p(=df/d(log$d$)) is the density function of grain size.

The density function of log-normal grain size distribution is as follows:

$$p(\ln d) = \frac{1}{\sqrt{2\pi}\sigma_L}\exp\left[-\frac{(\ln d - \ln d_{mg})^2}{2(\sigma_L)^2}\right] \quad (1)$$

where d_{mg} is the geometric average of grain size and σ_L is the standard deviation of ln$d$. Normalizing d with d_{mg}, σ_L is only a parameter of the log-normal distribution. The porosity of the mixture is, therefore, dependent on σ_L. For Talbot distribution, we modified the original Talbot distribution function, Eq.(2), with considering the minimum diameter of the grain size as shown in Eq.(3). The porosity of the mixture is determined with a coefficient namely Talbot number, n_T, with $n_T > 1$, and ratio of maximum and minimum diameter, $d_{\max}/d_{\min}$.

$$f(d) = \left(\frac{d}{d_{max}}\right)^n \quad (2)$$

$$f(d) = \left(\frac{\log d - \log d_{\min}}{\log d_{\max} - \log d_{\min}}\right)^{n_T} \quad n_T > 1 \quad (3)$$

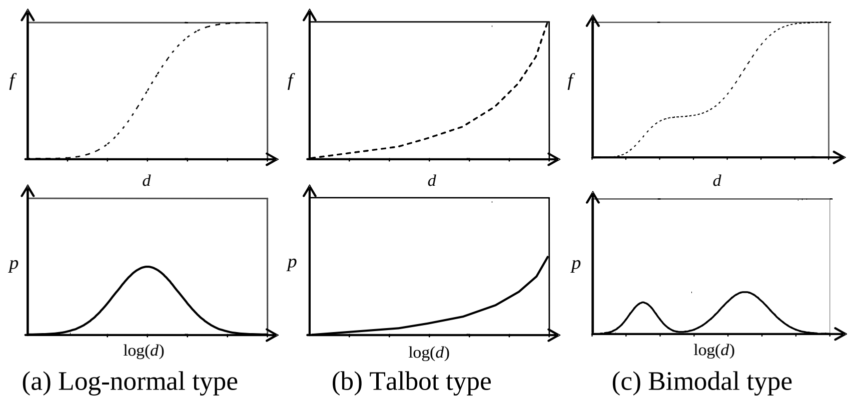
A grain size distribution is said to be bimodal if the density distribution $p(d)$, displays two distinct peaks. Each peak is a mode of a portion of the distribution. When the geometric averages of grain size are d_{mgA} and d_{mgB}, the standard deviation are σ_{LA} and σ_{LB}, the mixing ratio are p_A and p_B (=1-p_A), the parameters governing porosity are σ_{LA}, σ_{LB}, d_{mgA}/d_{mgB} and p_A.

2.2 Data

Riverbed materials have a variety of different characteristic size of bed surface sediment (Bunte and Abt, 2001), but the grain size distribution could be classified into some types. One of the most typical density functions of grain size is a log-normal distribution. The grain size distribution of bed material in most sand-bed streams is unimodal and that in many gravel-bed rivers is bimodal (Parker, 2004). Also in mountainous rivers, the surface bed material has usually Talbot distribution of grain size (Tatsuzawa et al., 1998).

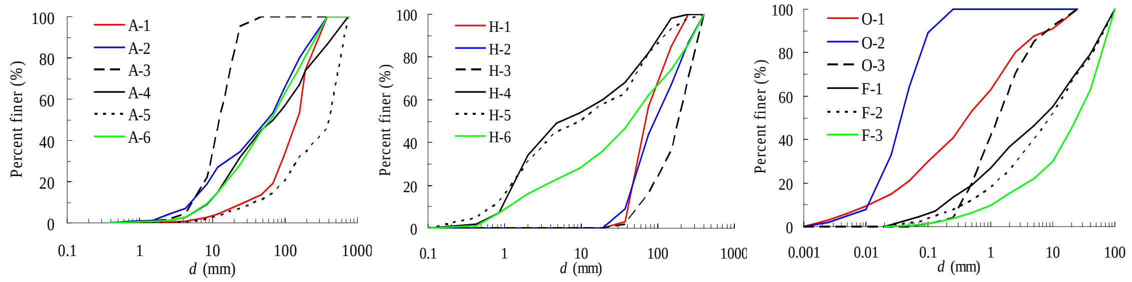
The grain size distribution of natural riverbed material and produced sediment were collected for analysis of identification and classification of grain size distribution. The samples were taken from Ai River (Fujita, 2004), Hino River (MLIT, 2004), Ohtaki River (Ashida and Fujita, 1987) and Fukadani bare slope. The grain size distributions and those density distribution are shown in Figures 2 and 3. Capital letter A, H, O and F denote the samples from Ai River, Hino River, Ohtaki River and a Fukadani bare slope, respectively. The sampling points are summarized in Table 1. The samples were classified by the characteristics of sampling points as follows:

a) Surface bed material (A-1, 5, H-1, 2, 3)
b) Sub-surface bed material (A-2, 6, H-4, 5, 6)
c) Sand bar (A-3)
d) Sediment deposition in a sabo dam (A-4)
e) Sediment deposition in a valley immediately after Ontake Lanslide 1984 (O-1)
f) Sediment deposition in a reservoir (O-2, 3)
g) Sediment produced at a bare slope (F-1, 2, 3)



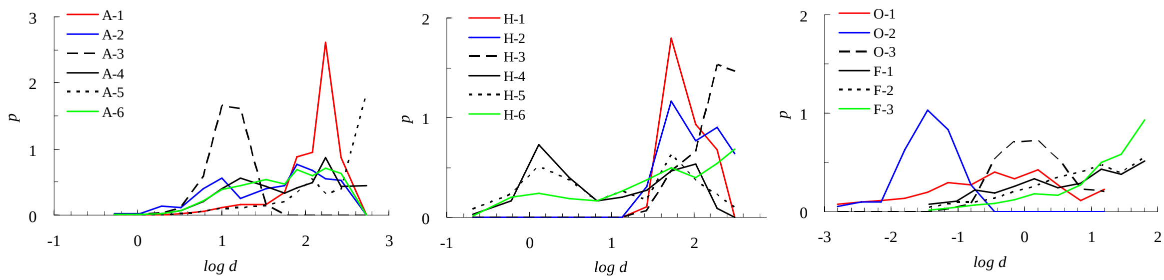
(a) Log-normal type (b) Talbot type (c) Bimodal type

Fig.1 Typical of grain size distribution of sediment mixture and the density function of grain size



a) Ai River　　b) Hino River　　c）Ohtaki River and Fukadani

Fig. 2 Grain size distributions of bed material and produced sediment



a) Ai River　　b) Hino River　　c）Ohtaki River and Fukadani

Fig. 3 Density distributions of grain size distribution shown in Fig.2

2.3 Identification and classification

The grain size distributions of natural sediment mixture can be identified and classified visually based on the shape of size distribution and density distribution. The grain size distribution classified into log-normal distribution if the trend of the size distribution curves similar to log-normal curve and the density distribution has a single peak. If the density distribution is skewed towards a high-end tail of distribution, the grain size distribution is classified into Talbot distribution. If the density distribution has two peaks, the grain size distribution classified into bimodal distribution.

As shown in Figure 3, the shapes of density distribution p are quite different from each other. Therefore, the type of grain size distribution can be identified if an index expressing the shape of density distribution p found out. Figure 3 shows the number of peak of density distribution for bimodal distribution is two. It is easy to understand that the number of peak, n_p, is an index for determine of unimodal or bimodal distribution. A-2, A-4, H-4 and H-5 are therefore, identified as bimodal distribution.

In addition, the following two indices are taken:

$$\beta = \frac{\log d_{max} - \log d_{peak}}{\log d_{max} - \log d_{min}}; \quad \gamma = \frac{\log d_{max} - \log d_{50}}{\log d_{max} - \log d_{min}} \quad (4)$$

where d_{min} is minimum size, d_{50} is 50% size, d_{max} is maximum size, and d_{peak} is a diameter which give maximum value of p. These indices designate the relative locations of d_{50} and d_{peak} between d_{min} and d_{max}. β and γ are 0.5 for ideal log-normal distribution and 0.0 for ideal Talbot distribution. Actually, the critical value of these indices should be determined for each type.

A type of the distribution can be determined by the shape of size distribution, the shape of density distribution, and values of β and γ. The values of β and γ for each grain size data are listed in Table 1. Figure 4 shows the relation between β and γ. A-1, A-5, A-6, H-6, F-1, F-2 and F-3 plotted with filled circles are visually identified as Talbot distribution. H-3 and O-1 plotted with triangles are visually identified the distribution between Talbot and log-normal. A-3, O-2, O-3 plotted with open circles are visually identified as log-normal distribution. H-1 and H-2 plotted with cross are the distribution between log-normal and anti-Talbot. Anti-Talbot distribution is defined by Eq. (3) with value of Talbot number, n_T, less than 1 ($n_T < 1$).

Based on the visual identification and the relation between β and γ, the critical value of these indices for each type distribution can be determined. The critical values of the indices were determined by adding and reducing the value of β and γ for log-normal distribution (0.5) with certain value α. According to the relation between β and γ as shown in Figure 4, the value of $\alpha=\pm0.2$ is reasonable. Grain size distributions are classified into Talbot type if $\beta \leq 0.3$ and $\gamma \leq 0.3$, log-normal type if $0.3<\beta<0.7$ and $0.3<\gamma<0.7$ and anti-Talbot type if $\beta>0.7$ and $\gamma>0.7$.

Table 1 Parameters of actual grain size distribution

No.	Sample sites	$d_{\min}$ (mm)	d_{50} (mm)	d_{peak} (mm)	$d_{\max}$ (mm)	β	γ	n_p	Type
A-1	Surface bed in upstream of Gokuraku Bridge in Ai River	0.740	149.23	159.00	381.00	0.14	0.15	1	**T**
A-2	Sub-surface bed in upstream of Gokuraku Bridge in Ai River	0.370	57.70	67.80	381.00	0.25	0.27	2	**B**
A-3	Sand bar in downsream of Gokuraku Bridge in Ai River	0.370	12.77	8.50	47.60	0.35	0.27	1	**L**
A-4	Deposit in Ai gawa sabo dam in Ai River	0.370	67.80	159.00	750.00	0.20	0.32	2	**B**
A-5	Surface bed near Kurumatukuri Bridge in Ai river	2.500	409.49	381.00	750.00	0.00	0.11	1	**T**
A-6	Sub-surface bed in Kurumatukuri Bridge in Ai river	0.370	62.75	159.00	381.00	0.13	0.26	1	**T**
H-1	Surface bed in the upstream of river mouth of Hino River	19.000	70.14	37.50	250.00	0.74	0.49	1	**AT**
H-2	Surface bed in Lower Hino River	19.000	94.57	37.50	400.00	0.78	0.47	1	**AT**
H-3	Surface bed in Middle Hino River	19.000	191.18	150.00	400.00	0.32	0.24	1	**T**
H-4	Sub-surface bed in the upstream of river mouth of Hino River	0.100	5.70	0.85	250.00	0.73	0.48	2	**B**
H-5	Sub-surface bed in Lower Hino River	0.100	9.50	37.50	400.00	0.29	0.45	2	**B**
H-6	Sub-surface bed in Middle Hino River	0.100	45.00	250.00	400.00	0.00	0.26	1	**T**
O-1	Deposit in Ohtaki River immediately after Ontake Landslide, 1984	0.001	0.44	1.00	25.00	0.32	0.40	1	**T**
O-2	Deposit of wash load in Makio Reservoir	0.001	0.03	0.03	0.25	0.42	0.38	1	**L**
O-3	Deposit of bed material load in Makio Reservoir	0.050	1.45	1.00	25.00	0.52	0.46	1	**L**
F-1	Sediment produced at Fukadani bare slope on May 28,2002	0.020	7.08	40.00	100.00	0.00	0.31	1	**T**
F-2	Sediment produced at Fukadani bare slope on July 1,2002	0.020	9.29	40.00	100.00	0.00	0.28	1	**T**
F-3	Sediment produced at Fukadani bare slope on November 12,2002	0.020	25.49	40.00	100.00	0.00	0.16	1	**T**

L: Log-normal distribution ; T: Talbot distribution; B: Bimodal distribution ; AT: Anti-Talbot distribution

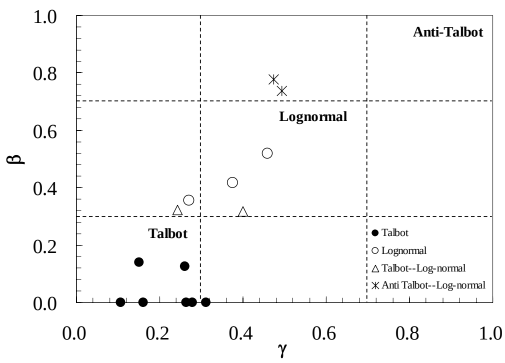


Fig.4 Relation between β and γ (after Sulaiman et al., 2007)

3. Measurement of Porosity

3.1 Measurement method

Porosity is the most widely used parameter for assess the interstitial space both in sediments and in soils. The porosity is normally defined as the ratio of the pore volume to the total volume of a given sample. The porosity could have been calculated from the measured sediment volume base on a water displacement process. A schematic diagram explaining the measurement method of the porosity is shown in Figure 5. The method use to determine the porosity is a simple method. The technique is to measure the in situ volume of sediment-mixtures sample by measuring the volume of a ring over the sediment-mixtures and then repeated the volume measurement after the sample is obtained from within the ring. The difference in the volumes is the total volume of the sample.

A PVC (Polyvinyl Chloride) ring with 30 cm of diameter and 5 cm height was used. The equipments needed to measure the porosity are: water level measure, point gauge, vinyl sheet, 2000 cc cylinder, and vinyl bag. All the equipment can be carried in. The process for determining the porosity is as follows:

1. Position and set the PVC ring stable and in horizontal position by using the water level measure, on the sediment sample or bed material where the porosity is to be measured.
2. Determine the volume of the ring below some datum (V_1); place the tripod with adjustable point gauge above the ring to control the water level. Place plastic sheet in the ring and fill the water, measuring the volume of the water placed in the ring. The filling of water was stopped when the water is up to the point gauge. Make careful note of the volume of the water placed in the ring (V_1). Remove the water from the ring being very careful not to disturb the ring.
3. Remove the surface sediment sample or surface bed material layer (armor layer) by tacking volumetric sample within the ring and continuing to be very careful not to disturb the ring. The required sample size is not well defined. In this study, reasonable results have been obtained when the sample size is between 3-5 kg. In the case of sampling riverbed material, the thickness of the armor layer is described as extending from the bed-surface plane down to the bottom side of the largest particle size ($d_{\max}$) or a frequently occurring large surface particle size (d_{dom}).
4. Retain the material removed for sieve analysis and measure the volume of the sediment. The hole should be as smooth sided as possible.
5. Determine the volume of the hole dug to remove the sediment or bed-material sample; place the plastic sheet on the surface and fill the water into the hole and ring to the same level as the first volume measurement (controlled by the point

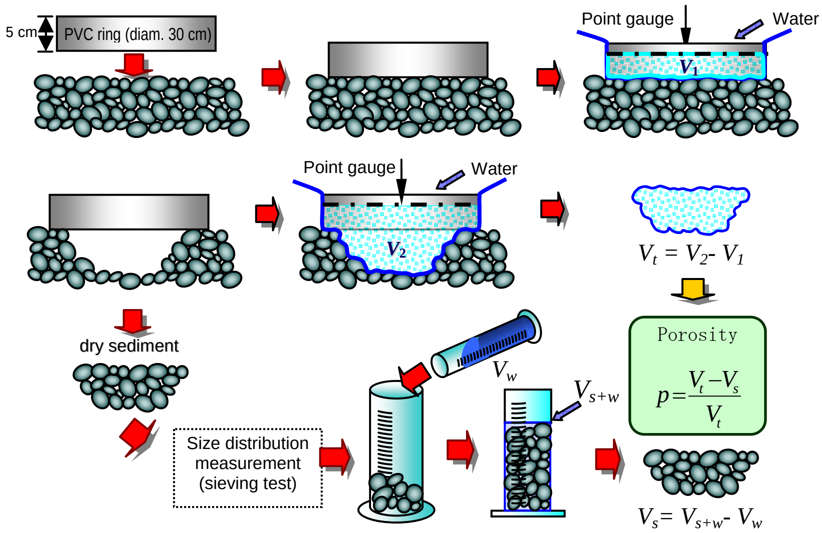


Fig.5 Measurement of porosity

gauge). The volume of the water must be determined during the process of filling (V_2).

6. Calculate the volume of the hole (V_t) by subtracting the ring volume (V_1) from the hole plus ring volume (V_2).
7. Dry and measure the weight of the sample. The specific weight is calculated from the weight and volume. Sieve the sample and determine the size distribution curve.
8. Measure the volume of the sediment (V_s); the sediment or bed-material sample and water were filled into a cylindrical vessel carefully up to a place marked on the inside of cylindrical vessel. Remove the air content in the bed material as much as possible during filling the sample by shaking the cylindrical vessel. Note the total volume of sediment and water (V_{s+w}). Make careful note of the volume of the water placed in the cylinder (V_w). The volume of the sediment (V_s) is calculated by subtracting the water volume (V_w) from the total volume of sediment and water (V_{s+w})
9. Calculate the porosity: $p = \frac{V_t - V_s}{V_t}$

3.2 Laboratory experiment and field observation

A laboratory experiment was conducted to measure the porosity of the sediment-mixtures with different type of grain size distribution. Ten different kinds of grain size distribution were prepared; consist of five lognormal distributions with different standard deviation (i.e., 0.02, 0.253, 0.29, 0.303, and 1.6), and five bimodal distributions. The characteristic of sediment for bimodal distribution is shown in Table 2. Five different fine proportions p_A (i.e., 0.1, 0.2, 0.3, 0.4, and 0.5) were prepared. The grain size distribution of the samples for lognormal distribution and bimodal distribution are shown in Figure 6 and Figure 7 respectively. The porosities were measured five times for each grain size distribution.

A field observation was conducted to measure the porosity of the armor layer and sub armor layer in a dry part of the streambed. The location of the field observation is in the bar of Uji River located in front of Ujigawa Open Laboratory. The grain size distribution of armor layer and sub armor layer is shown in Figure 8. Base on the shape of grain size distribution curve, the distributions were classified into Talbot distribution. By using fitting curve with Eq.(3), the Talbot number of the armor layer sample and the sub armor layer is 5.0 and 2.5 respectively.

3.3 Measurement results

The measured porosities as related to the grain size parameter for each type distribution are presented together with relationship between the porosity and the geometric parameter of grain size distribution was obtained by means of a packing model developed by Tsutsumi et al. (2006).

(1) Log-normal distribution

The mean porosity of five repetitions of the measured porosity for five different grain size distributions showed in Figure 6 are shown in Figure 9. The relationship between the standard deviation of the lognormal distribution, $ln\sigma$, and the simulated porosity presented by Tsutsumi et al. (2006) also shown in Figure 9 together with measurement results. The error bars indicate the ranges between maximum and minimum values of five repetitions. The porosity varied with the grain size distribution. For the relatively uniform distribution ($ln\sigma$=0.02), the measured porosity widely ranged from 0.282 to 0.376 with the mean porosity is 0.321. The mean value differed from the simulation result. The widely ranging measured porosity for this distribution arises from the difference in the particle packing and the shape of particle.

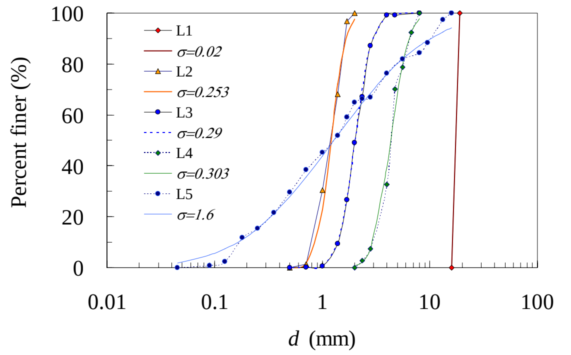


Fig. 6 Grain size distribution of lognormal distribution sample

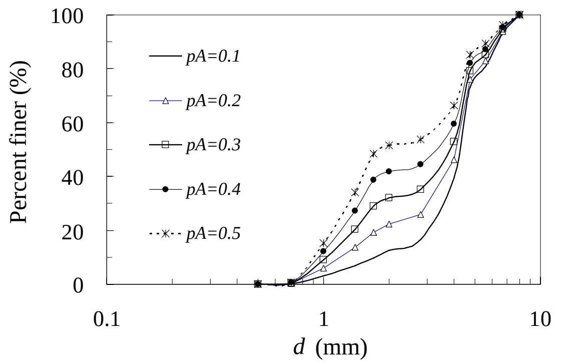


Fig. 7 Grain size distribution of bimodal distribution sample

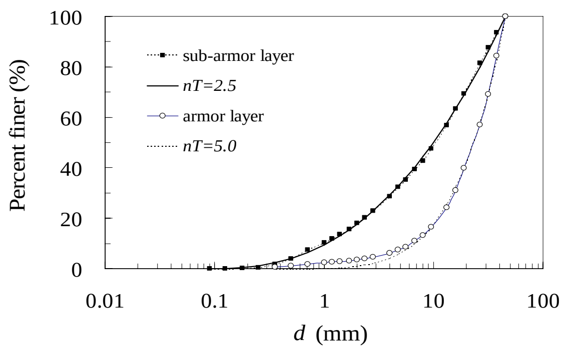


Fig. 8 Grain size distribution of the armor layer and sub armor layer of Uji River bar

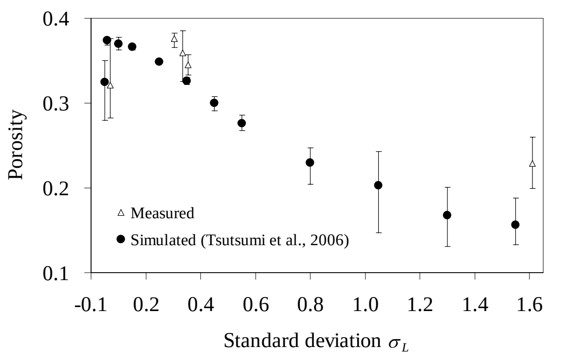


Fig. 9 Comparison of the porosity, between the measured and simulated results for lognormal distribution with different standard deviation

The mean value of the measured porosity decreased as the standard deviation $ln\sigma$ increased from 0.253 to 1.6. The mean measured porosity differed from the simulation result; the measured porosities are greater than simulations results. The discrepancy may be due to differences in the shape of particle. In the measurement, the particles were used is non-spherical particle, while in the simulation the particles were assumed as sphere.

(2) Bimodal distribution

Bimodal distribution generally ranges widely. In this study the artificial bimodal distributions with narrow distribution were used. The characteristic of materials are shown in Table 2. The characteristic is similar with the characteristic of materials were used for particle packing simulation by Sulaiman et al., (2007). Porosities for seven different fine proportions p_A (i.e., 0.0, 0.1, 0.2, 0.3, 0.4, 0.5 and 1.0) were measured. Relationship between fine proportion p_A (by volume) of mixture and the mean porosity of the five measured porosity for two fraction mixture are shown in Figure 10. The porosity of bimodal distribution depends on the percentage of each fraction in the mixture and a porosity minimum is observed.

Table 2 Characteristic of sediment for bimodal distribution

Fraction	σ	d_{min} (mm)	d_{50} (mm)	d_{max} (mm)
A	0.2	0.5	1.0	2.0
B	0.2	2.0	4.0	8.0

The results were compared with the mean porosity of the five repetitions of the simulated porosity for two fraction mixture by using particle packing model presented by Sulaiman et al. (2007). Interestingly, the change of porosity is similar and a porosity minimum is observed. The discrepancy between the measured and simulated porosity may be due to differences in the uniformity of the mixture of sediment sample and the packing of particle. In the measurement, the particles were used is non-spherical particle, while in the simulation the particles were assumed as sphere.

(3) Talbot distribution

The mean porosity of five repetitions of the measured porosity for two different grain size distributions showed in Figure 8 are shown in Figure 11. The relationship between the Talbot number, n_T, and the simulated porosity presented by Sulaiman et al., (2007) also shown in Figure 11 together with the measurement results. For the simulation results with d_{max}/d_{min}=10, the porosity increased from 0.241 to 0.314 when the Talbot number, n_T, increased from 2 to 8. The porosity increased from 0.173 to 0.273 for d_{max}/d_{min}=100 when the Talbot number, n_T, increased from 4 to 12. The porosity of Talbot distributions increased with an increasing of the Talbot number n_T. Smaller ratio of d_{max}/d_{min} gives the higher value of porosity.

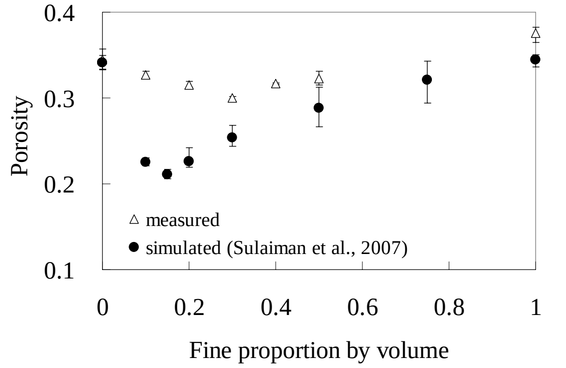


Fig. 10 Comparison of the porosity, between the measured and simulated results for bimodal distribution with different fine proportion.

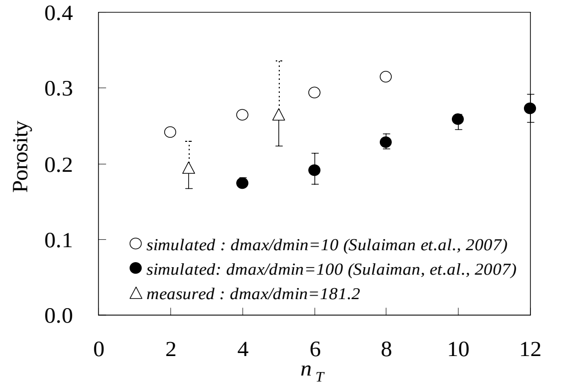


Fig. 11 Comparison of the porosity, between the measurement and simulated results for Talbot distribution with different Talbot number

The measured porosity of armor layer ranged from 0.224 to 0.336 with the mean value is 0.265. The measured porosity of sub-armor layer is smaller than surface bed material; ranged from 0.168 to 0.230 with mean value is 0.195. The porosity of sub-armor layer is smaller than armor layer because the sub-armor layer contains much more fine sediment than armor layer. The change of the porosity is similar with the simulation results, where the porosity increased with an increasing Talbot number.

4. Conclusions

A method for identifying the type of grain size distribution curve and obtaining the porosity for the different type of grain size distribution were developed. The results are as follows:

1) Grain size distribution of actual sediment mixture can be roughly classified into three types of distribution, namely, log-normal distribution, Talbot distribution and bimodal distribution, based on the mode of density distribution and indices β and γ. To determine the exact distribution type, it's necessary to find out another index.
2) The porosity of sediment mixtures and bed material could be reasonably estimated by measuring the in-situ volume of sediment sample.
3) Relationship between the grain size distribution and the porosity can be determined by using the geometric properties of grain size distribution. The porosity of log-normal distributions decreased with an increasing standard deviation. The porosity of Talbot distributions increased with an increasing of the Talbot number n_T and smaller ratio of d_{max}/d_{min} gives the higher value of porosity. The porosity of bimodal distribution depends on the percentage of each fraction in the mixture. The porosity of armor layer is higher than the porosity of sub-armor layer.
4) A method use to measure the porosity is a simple method and there is a need to improve the method for better accuracy.

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河床材料の粒度分布の分類と空隙率

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要　旨

河床材料の粒度分布と空隙率は，河川の水生生物の生息環境として非常に重要な要素である。本稿では，それらに関する事項のうち2点に関して検討した内容について発表する。ひとつは，河床材料の粒度分布曲線を特定し，分類する手法に関して，もうひとつは，自然河川の河床材料や人為的に調整した混合土砂材料の空隙率の測定方法に関するものである。河床材料の粒度分布は，その確率密度分布の関数指標βとγに基づき，対数正規分布，タルボット型分布，二山型分布の大まかに3種類の分布に分類することができる。一方，河床材料の空隙率は，砂礫体積の現位置測定によって評価することが可能である。

キーワード：分類，粒度分布，空隙率，混合砂礫，河床材料