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Analysis on the Characteristics of Bed Materials in the Jinghong Reservoir on the Lancang River

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Abstract: Nine samples of bed materials along the Jinghong reservoir on the Lancang River were obtained using a gravity sampler. The grain size characteristics of the samples were analyzed by the laser diffraction particle size analyzer. The results show that the median grain size of bed materials is in the range of 6.7 to 18.9 μm. From the upstream to the front of the dam, the overall grain size of the bed materials tends to decrease significantly; the sorting is poor but becomes better along the way; the skewness gradually changes from negative to near symmetrical; the kurtosis is platykurtic and mesokurtic with little change along the way. Based on the measured data, an exponential model is constructed to describe the distribution of representative grain size of bed materials along the way. Furthermore, the concept of representative particle Reynolds number is proposed. The relationship between representative particle Reynolds number and flow parameters with boundary conditions is established, and the coefficient and exponents in the equation are determined based on the measured data of the Jinghong reservoir. This study provides valuable first-hand information for reservoir sediment research and new ideas for sediment sorting and deposition studies.

Keywords: bed material characteristics; grain sizes analysis; reservoir sedimentation; Jinghong reservoir; the Lancang River

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1. Introduction

The Lancang-Mekong River is one of the world's most significant rivers. The river rises in the Tibetan plateau and runs through six countries: China, Laos, Myanmar, Thailand, Cambodia and Vietnam. As the longest river in Southeast Asia, it has a total length of 4880 km, an average slope of 1.03‰, and a basin area of about 795,000 km^2 [1,2]. The section of the river from its source to the border between China and Myanmar in China is called the Lancang River, with a total length of 2085 km and constitutes 91% of the total drop of the mainstream in the basin, which is rich in hydropower resources [3]. The middle and lower reaches of the Lancang River in Yunnan Province are the key areas for the development and utilization of hydropower resources, and there are eight hydropower stations including Gongguoqiao, Xiaowan, Manwan, Dachaoshan, Nuozhadu, Jinghong, Ganlanba, and Mengsong hydropower stations, which have been built and are to be developed. While effectively utilizing the hydropower resources, the construction of the hydropower stations is bound to cause changes in water and sediment fluxes in the Lancang River, as well as reservoir siltation problems [4,5]. Previous studies have mostly focused on changes in river morphology, river ecology and biogenic materials caused by hydropower stations [6–11]. Other researchers have focused on the ecology of the reservoir area [12–15] as well as siltation [16–18]. Few systematic studies have been conducted on the sediment characteristics in the reservoir area of the hydropower stations [19,20].

The grain size and gradation of bed materials affect the sediment transport capacity and sediment concentration, as well as the dry density of siltation and scour material, which is one of the essential topics in the study of reservoir siltation [21]. Previously, due to the limitations of testing equipment and methods, natural reservoir bed material samples were difficult to obtain, and the gradation is not easy to measure accurately, so there was a lack of accurate, abundant and systematic measurement data. So far, there is still a lack of measurement data and related studies on bed materials of the Lancang River reservoirs. Therefore, the authors exploratively selected the Jinghong reservoir in the lower reaches of the Lancang River to carry out this study, obtained bed material samples along the reservoir, and analyzed the grain size and gradation characteristics. Moreover, the concept of representative particle Reynolds number is proposed for the first time, and the relationship between representative particle Reynolds number and flow parameters and boundary conditions was established to describe the law of sorting and deposition for bed materials in reservoirs. This work provides valuable first-hand information for the study of reservoir siltation, fills the gap in the study of grain size variation of bed materials in reservoirs, and provides new ideas to reveal the general process of sorting and deposition in reservoirs and rivers.

2. Study Area

The reservoir area of Jinghong hydropower station in Yunnan Province is selected as the study area. Jinghong hydropower station is the sixth of eight hydropower stations in the middle and lower reaches of the Lancang River, with Nuozhadu hydropower station upstream and Ganlanba hydropower station downstream. The dam site is located in Dai Autonomous Prefecture of Xishuangbanna, about 5 km away from Jinghong City. Construction of the Jinghong hydropower station started in December 2003; the first unit generated electricity in May 2008, and the project was completed at the end of December 2009. The dam of this reservoir is 108 m high with the dam crest at an elevation of 612 m and the normal storage level is 602 m. The installed capacity is 175×10^4 kW and the total storage capacity is 11.39×10^8 m^3, of which the adjusted storage capacity is 3.09×10^8 m^3. The reservoir is a narrow reservoir with weekly regulation capacity.

The reservoir area of Jinghong hydropower station belongs to the canyon landform. There are mostly "V"-shaped valleys with good vegetation. The tributaries and gullies are developed in the reservoir area, and the tributaries mostly merge into the Lancang River at a steep angle. There are normally alluvial deposits in the outlets of the tributaries. With the increasing frequency of human activities and the reduction of natural vegetation in the Lancang River Basin, soil erosion gradually intensifies, and the sediment concentration increases significantly [22]. The annual average sediment load entering the reservoir under natural conditions is 1.008×10^8 m^3, and the storage:sediment ratio of the reservoir is only about 10, which causes a serious situation of sedimentation [5]. It is one of the key problems that restrict the long-term utilization of Jinghong hydropower station.

3. Materials and Methods

3.1. Sample Collection

Nine samples of bed materials were collected from the Jinghong reservoir on the lower Lancang River in December 2018. According to the relevant specifications of a hydrological survey, samples were taken at regular intervals from the front of the dam to the end of the reservoir, depending on the water depth and topographic conditions.

The samples were collected by a gravity sampler, which consists of a sample tube, a penetrating head, a tail ring and counterweight. The sample tube is embedded with a rigid plastic sampling tube, which is convenient for storing a large number of samples. An orange peel closure device is installed inside the penetrating head to prevent sample loss from the bottom. The sampling process is as follows: a GPS positioning system was used to position the survey ship in the vertical line, and the survey ship is driven to the sample collection point; the assembled sampler is put into the water, and the sampler is pushed into the bottom by the counterweight; the sampler is lifted to the ship, the embedded sampling tube is removed and sealed for storage, and relevant data are recorded.

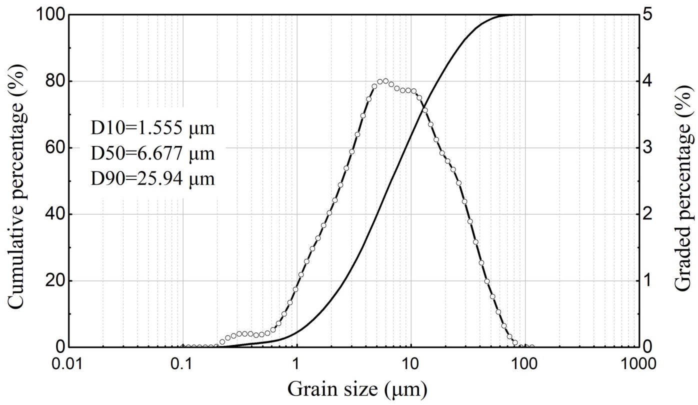
The topography of the reservoir area was also measured while bed material samples were collected. The equipment used was a HY1600 type depth sounder with a frequency of 208 kHz, a sounding range of 0.3 to 150 m and a resolution of 0.01 m.

3.2. Experimental Analysis

The grain size measurement of the samples was carried out by a laser diffraction particle size analyzer (LDPSA BT-9300Z, Dandong Company, Dandong, China). The measuring range of this instrument is 0.1 to 716 μm. The results give the percentage of the grain size in each interval as well as the median particle size, the average diameter of volume and the specific surface area. The repeatability error of measurement is less than 1% (the deviation of D_{50} when measuring the standard sample).

The samples were pre-treated to ensure that the sampled particles were measured as discrete particles rather than flocs. The pre-treatment steps are as follows: place 3 g of the sample into a beaker, add 10 mL of 10% hydrogen peroxide (H_2O_2), heat it on a hot plate to remove the organic matter; add 10 mL of 10% hydrochloric acid (HCl), continue heating to remove the carbonate; add distilled water and let it stand for 12 h; add 10 mL of 10% sodium hexametaphosphate ($[NaPO_3]_6$) as a dispersant, and then test on the laser diffraction particle size analyzer.

Figure 1 shows the analysis result of the sample collected in front of the dam of the Jinghong reservoir. The abscissa shows the grain size converted to a logarithmic scale. The ordinate on the left is the cumulative percentage of particle weight, which is less than a certain grain size. The ordinate on the right is the percentage of graded grain size, which represents the mass percentage of particle at each grade. The cumulative percentage of a certain particle size is the sum of the percentages of each grade with a particle size smaller than that size. The figure also provides many intuitive data, such as: the median grain size D_{50} of the sample is 6.677 μm, and 99.94% of the sediment with grain size < 75 μm.



Grain size(μm)	Percentage
0.200	0.02
0.500	1.40
1.000	4.52
2.000	14.35
5.000	39.82
10.00	63.69
20.00	84.00
45.00	97.90
75.00	99.94
100.0	100.0

Figure 1. Grading curve of bed material sample in a semi-log plot.

4. Analysis of Grain Size of Bed Materials

The commonly used grain size parameters are the main characteristic grain size, sorting coefficient, skewness and kurtosis. Each grain size parameter quantitatively expresses the grain size characteristics of the bed materials and reflects the hydrodynamic conditions of the bed materials transport [23].

The sorting coefficient σ represents the degree of uniformity of the grain size, i.e., the standard deviation, which is commonly used to analyze the material of the sediment source and to indicate the dynamical conditions of the depositional environment [24]. The sorting of bed materials can be expressed by the sorting coefficient; the smaller the sorting coefficient, the better the sorting. According to the Folk and Ward grain size analysis method, the sorting coefficient is calculated as:

$$\sigma = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_{5}}{6.6} \quad (1)$$

where ϕ is the negative logarithm of the particle diameter D(mm), $\phi = -\log_2 D$.

The skewness (SK) is a parameter indicating the symmetry of the distribution curve and can be used to identify the asymmetry of the grain size distribution. When the skewness value is positive, the sediment particle size is concentrated in the coarse part. On the contrary, when the skewness value is negative, the sediment particle size is concentrated in the fine part. The skewness can be calculated as:

$$SK = \frac{\phi_{84} + \phi_{16} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_{95} + \phi_5 - 2\phi_{50}}{2(\phi_{95} - \phi_5)} \tag{2}$$

The kurtosis (K_G) reflects the peak convexity of the distribution curve. If the kurtosis value is very high or very low, it indicates that the sediment has been well-sorted in the previous environment before being transported to the present one.

$$K_G = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})} \tag{3}$$

Based on the measurement results of the laser particle size analyzer, the main characteristic grain size, sorting coefficient, skewness and kurtosis values of the samples from the area of the Jinghong reservoir were calculated and listed in Table 1.

Table 1. Characteristics of grain size parameters of bed materials in the Jinghong reservoir.

Sampling Points	Distance from Dam/km	D_{16}/µm	D_{25}/µm	D_{50}/µm	D_{75}/µm	D_{84}/µm	D_m/µm	Sorting Coefficient σ	Skewness	Kurtosis
J01	0	1.2	3.3	6.7	14.2	20.0	9.3	1.80	−0.14	0.98
J02	6	2.1	3.1	6.7	14.8	21.1	10.0	1.61	−0.02	0.94
J03	12	2.5	3.6	7.7	16.5	22.9	11.0	1.58	−0.05	0.96
J04	18	2.5	3.7	8.3	17.6	23.9	11.5	1.59	−0.09	0.93
J05	24	2.9	4.3	10.1	22.2	29.8	14.3	1.65	−0.11	0.91
J06	30	3.0	4.6	11.5	25.5	34.3	16.3	1.71	−0.13	0.91
J07	36	2.9	4.5	12.5	30.9	42.9	19.4	1.85	−0.12	0.86
J08	42	3.4	5.3	14.7	34.2	46.9	21.7	1.84	−0.15	0.89
J09	48	4.1	6.6	18.9	41.9	57.3	26.8	1.86	−0.18	0.92

Similar to the method of river sediment grain size analysis, the representative grain size D_{50} can be used to represent the overall grain size change when analyzing the variation of the reservoir bed material grain size along the way [25]. The D_{50} of bed materials in the Jinghong reservoir ranges from 6.7 to 18.9 µm, and the overall grain size has an obvious trend of decreasing from upstream to the front of dam, but the magnitude of decrease varies from section to section, with a larger decrease in the upstream section and a smaller change in the near-dam section. This is the result of selective deposition. Selective deposition refers to the process of transporting sediment mixed with coarse and fine particles downstream, where coarse particles are deposited in preference to fine particles due to the greater incipient velocity required than fine particles. In practice, the process is more complex because sediment transport and deposition are significantly related to the flow dynamics and the grain size distribution of the sediment. The variation of grain size along the reservoir can be described by linear, power law and exponential models, among which the exponential model is most consistent with the measured data of the Jinghong reservoir (Figure 2).

$$D = D_0 e^{\alpha x} \tag{4}$$

where D_0 is the median grain size of bed materials at the source of observation; D is the median grain size of bed materials at a distance of x km downstream; the coefficient α reflects the rate of downstream refinement of grain size, and the larger the value, the faster the grain size change. For the Jinghong reservoir:

$$D = 18.9e^{-0.025x} \tag{5}$$

$R^2 = 0.94$ shows that the formula fits the measured data well and the median grain size of bed material at any distance upstream from the dam can be estimated according to Equation (5).

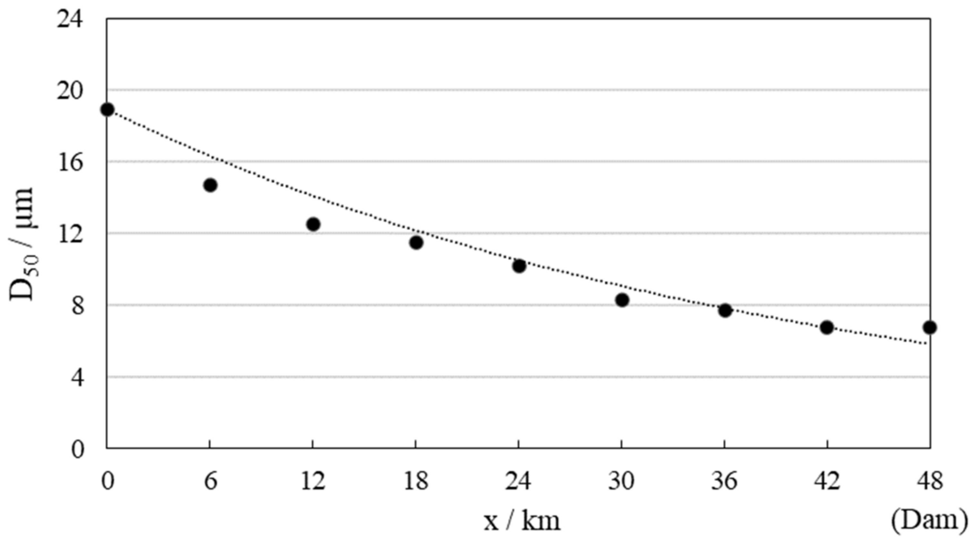


Figure 2. Variation of D_{50} of bed materials in the Jinghong reservoir.

The sorting coefficients of bed materials in the Jinghong reservoir range from 1.58 to 1.86. In general, the sorting coefficient of bed materials shows an obvious decreasing trend along the way from upstream to the dam. This indicates that the bed material gradually becomes better sorted as it is transported toward the dam. However, if the sorting is classified according to the sorting grade, the sorting of the entire reservoir area is poor. the sorting coefficient of the sampling point J01 in front of the dam is 1.80, which is significantly high and should be related to the frequent anthropogenic activities at the dock in front of the dam.

In the upstream section of the Jinghong reservoir (24 to 48 km from the dam), the skewness of grain size is negative and ranges from −0.18 to −0.11, indicating that the bed materials in this section are mainly composed of fine-grained components. In the downstream section (6 to 24 km from the dam), the skewness ranges from −0.09 to −0.02, which is nearly symmetric. It can be seen that from upstream to the dam, the skewness gradually changes from negative to nearly symmetric. The kurtosis of bed materials in the reservoir area ranges from 0.86 to 0.98, which is distributed in two ranges: platykurtic and mesokurtic. From upstream to the dam, the kurtosis value tends to increase but the overall change is not significant (Figure 3). This result indicates that the reservoir sediments entered the reservoir directly with little modification and were not significantly modified by the hydrodynamics in the reservoir area, from which it can be inferred that the reservoir received materials from the surrounding surface in a short period of time. This process may be an indication of soil erosion processes due to heavy precipitation, and also indicates weak hydrodynamics in the reservoir area [19].

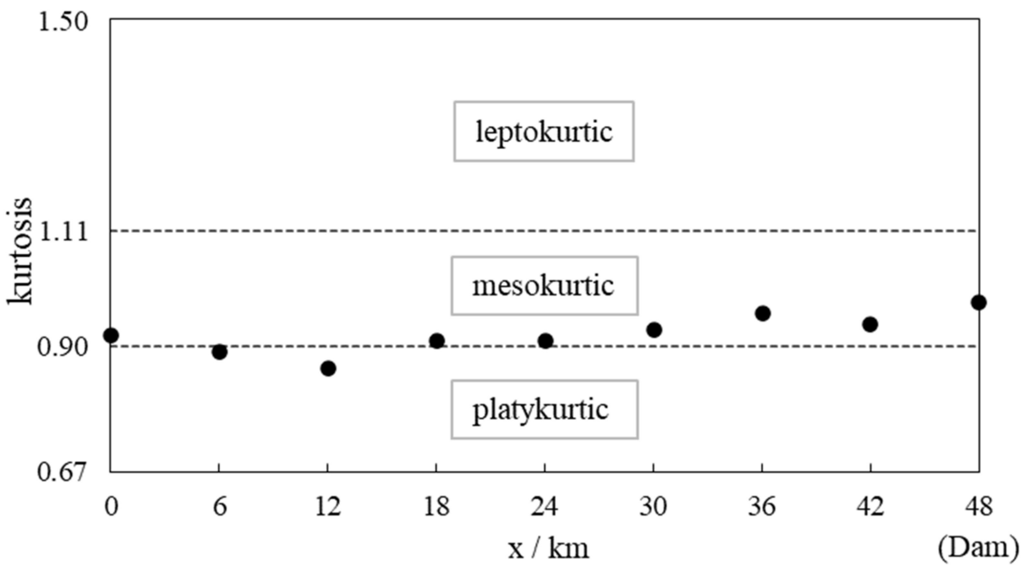


Figure 3. Variation of kurtosis of bed materials in the Jinghong reservoir.

5. Representative Particle Reynolds Number

Sediment in the reservoir is sorted and deposited by hydraulic forces to form the variation of the grain size characteristics for bed materials along the way, and its motility depends on the flow dynamics. In order to reveal the general law of separation and sedimentation in the reservoir, a concept of representative particle Reynolds number is proposed to reflect the flow and boundary conditions during the deposition of sediment with different grain sizes. The refinement of the grain size of bed materials along the way refers to the refinement of the overall grain size, which can be expressed by the representative grain size D_{50} in the analysis, and the corresponding particle Reynolds number is the representative particle Reynolds number:

$$\mathrm{Re}_{rep} = \frac{\omega_{rep} \cdot D_{rep}}{v} \quad (6)$$

where D_{rep} is the representative particle size of bed materials, ω_{rep} is the settling velocity of sediment with the corresponding particle size, and v is the kinematic viscosity coefficient.

The representative particle Reynolds number is related to the flow parameters and boundary conditions, which are exactly the main factors that determine sediment deposition. The size and bulk density of sediment particle are already included in the representative particle Reynolds number, so the main factors affecting the representative particle Reynolds number are the flow velocity U, water depth H, average size of bed materials D_m, and gravitational acceleration g. That is:

$$\mathrm{Re}_{rep} = f(U, g, H, D_m) \quad (7)$$

where $\rho_s - \rho$ is the difference of density between sediment and water, which can be used as the basic physical quantity of quality and has been considered in the settling velocity. Here, H and g are selected as the basic physical quantities of the length and time. Therefore, according to the principle of dimensional similitude:

$$\begin{cases} U = \pi_1 H^{\alpha_1} \mathrm{g}^{\beta_1} \\ D_\mathrm{m} = \pi_2 H^{\alpha_2} \mathrm{g}^{\beta_2} \end{cases} \quad (8)$$

The corresponding dimension is:

$$\begin{cases} LT^{-1} = L^{\alpha_1} \cdot (LT^{-2})^{\beta_1} \\ L = L^{\alpha_2} \cdot (LT^{-2})^{\beta_2} \end{cases} \quad (9)$$

From Equation (9), it can be obtained that $\alpha_1 = \beta_1 = 1/2$, $\alpha_2 = 1$ and $\beta_2 = 0$. The dimensionless quantities are:

$$\begin{cases} \pi_1 = \frac{U}{\sqrt{gH}} \\ \pi_2 = \frac{D_m}{H} \end{cases} \quad (10)$$

Then Re_{rep} can be expressed as:

$$\mathrm{Re}_{rep} = f\left(\frac{U}{\sqrt{gH}}, \frac{D_m}{H}\right) \quad (11)$$

According to the theorem of π:

$$\mathrm{Re}_{rep} = a_0\left(\frac{U}{\sqrt{gH}}\right)^{b_0}\left(\frac{D_m}{H}\right)^{c_0} \quad (12)$$

where $\frac{U}{\sqrt{gH}}$ is the Froude number, which reflects the flow conditions; $\frac{D_m}{H}$ is the relative roughness, which reflects the boundary conditions of the bed surface; a_0, b_0 and c_0 are the undetermined coefficients. Equation (12) indicates that the representative particle Reynolds number is a function of the Froude number and relative roughness, which reflects not only the characteristics of sediment but also the intensity of flow.

According to the data measured in the Jinghong reservoir, the representative particle Reynolds number Re_{rep}, Froude number $\frac{U}{\sqrt{gH}}$ and relative roughness $\frac{D_m}{H}$ are taken as logarithms and then subjected to multiple regression analysis. It was found that the three parameters had good correlation and the correlation coefficient $R = 0.98$, $\ln a_0 = 14.59$, $b_0 = 0.73$, $c_0 = 1.25$, that is:

$$\ln(\mathrm{Re}_{rep}) = 0.73\ln\left(\frac{U}{\sqrt{gH}}\right) + 1.25\ln\left(\frac{D_m}{H}\right) + 14.59 \quad (13)$$

Then:

$$\mathrm{Re}_{rep} = 2.18 \times 10^6\left(\frac{U}{\sqrt{gH}}\right)^{0.73}\left(\frac{D_m}{H}\right)^{1.25} \quad (14)$$

The above formula is the expression of representative particle Reynolds number for the bed materials in the Jinghong reservoir. The analysis of Formula (14) shows that the representative particle Reynolds number is related to the 0.73 power of Froude number and the 1.25 power of relative roughness.

The representative particle Reynolds number calculated according to Formula (14) is compared with the measured value in Figure 4. The abscissa and the ordinate are the measured and calculated values, respectively. The solid line represents the theoretical line, and the points are distributed on both sides of the theoretical line. Taking r as the ratio of the calculated value to the actual measured value, which indicates the degree of deviation from the actual measurement, the closer r is to 1, the smaller the error. The results of comparison show that the percentage of error within the range of 1.25 times ($0.8 \leq r \leq 1.25$) is 88.9%, within the range of 1.5 times ($0.67 \leq r \leq 1.5$) is 100%, and the average value of r is 1.02, indicating that Formula (14) has a high calculation accuracy.

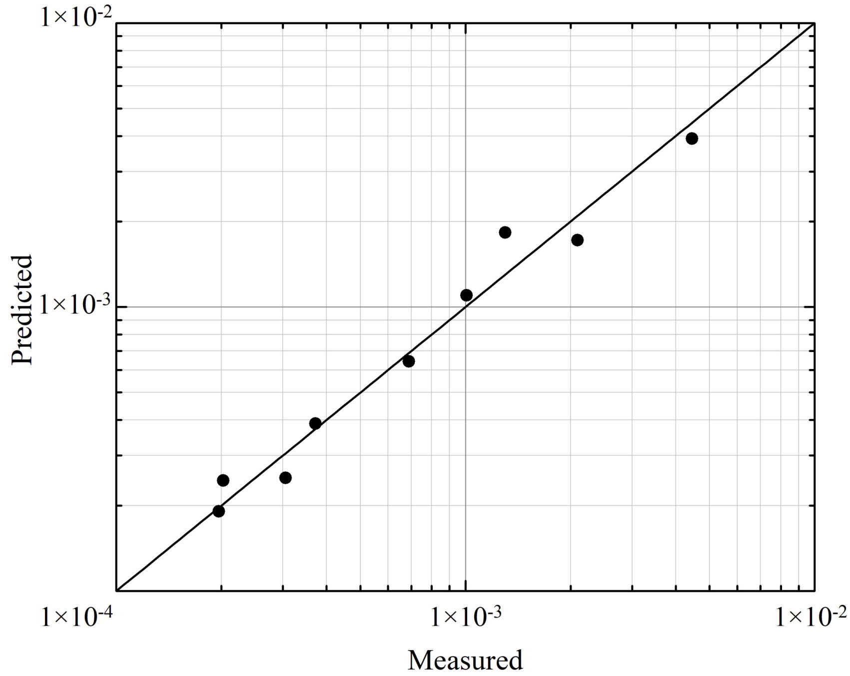


Figure 4. Comparison between the predicted and the measured values of representative particle Reynolds number.

6. Conclusions

The presented characteristics of bed materials are important for studying sediment transport, riverbed evolution, reservoir siltation and hydraulic engineering. Due to the limitation of testing equipment and methods, natural reservoir bed material samples are difficult to obtain, and the corresponding measurement data are scarce. This exploratory work has successfully obtained bed material samples along the reservoir area of Jinghong hydropower station on the Lancang River. The following results have been achieved by testing and analyzing the grain size characteristics of the samples.

1. The median grain size of bed material in the Jinghong reservoir ranges from 6.7 to 18.9 μm. From upstream to the front of the dam, the overall grain size of the bed material has a significant decreasing trend, but the magnitude of decrease varies from section to section, with the upstream section having a larger decrease and the near-dam section having a smaller change. The exponential model can accurately describe the variation of grain size along the way.
2. The sorting coefficients of bed material in the Jinghong reservoir range from 1.58 to 1.86, showing an obvious trend of decreasing along the way. The skewness of grain size ranges from −0.18 to −0.02, and gradually turns from negative to nearly symmetric from upstream to the dam. The range of grain size kurtosis is 0.86 to 0.98, distributed in two ranges of platykurtic and mesokurtic, with little variation along the way, indicating weak hydrodynamics in the reservoir area.
3. The concept of representative particle Reynolds number is proposed for the first time, which links the grain size along the reservoir with flow parameters and boundary conditions. Based on the measured data in the Jinghong reservoir, the coefficient and exponents in the formula are determined. The results show that the representative particle Reynolds number is related to the Froude number to the power of 0.73 and the relative roughness to the power of 1.25.

In conclusion, the results of this study provide quantitative first-hand information to fill the gap in the study of grain size variation of bed materials in reservoirs. It can be further used in the study of sediment transport, riverbed evolution, hydraulic engineering, and can even be utilized as baseline information in the numerical simulation of reservoirs for succeeding studies of reservoir sedimentation.

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