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Original Research Paper

A New Estimation Method of Sediment Deposition in the Harbour Basin

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ABSTRACT

By taking into account, the effect of upstream hydro-junction, a new estimated method of sedimentation amount in the Harbour basin was discussed. In the paper, the annual average sediment concentration and the median grain size were the key points to be considered. By the measured data, the ranges of the two key influencing factors were determined. The ranges of annual average sediment concentration and median grain size were 0.16 kg/m^3 to 0.21 kg/m^3 and 0.018 mm to 0.025 mm respectively. In the ranges of the two, combining with the results could be found that the theoretical value by the new method agreed with the value by the physical model test. This method was a sensible and valid method for calculation of the siltation in Harbour basin by taking into account the effect of the upstream hydro-junction. According to the theoretical value, the total sedimentation amount of Fueryan Wharf Phase II Project was not large. After the completion, the sedimentation intensity and the sedimentation amount of suspended sediment and bed load in Harbour basin were low. The same to Harbour basin, the sedimentation amount of the upstream and downstream of the Harbour basin were low. If only reserves certain depth for deposition, it can completely meet the requirements of navigation and Wharf working.

INTRODUCTION

Excavated Harbour basin has many advantages, it has been widely used all over the world. In recent years, more and more scholars paid attention to the excavated Harbour basins. Combining with the current status of Harbour basins in coastal region can be found that many excavated Harbour basins have been built and proposed. However, due to the reflux, turbid density flow and tides, sediment deposition appears in the excavated Harbour basin. The sediment deposition is the main problem affecting the operation of excavated Harbour basin.

Liu (1995) presented that the movement of water and sediment is a typical three-dimensional spiral flow in recirculation regions. Sediment deposition in Harbour basin includes suspended sediment deposition and bed load deposition after excavation. Xu (1999) proposed for several tributaries of the Yellow River that the grain-size characteristics of suspended sediment are closely influenced by precipitation, seasonal alternations of wind and water action, and the nature of surface materials. Zhao et al. (2005) established a formula of grain size of deposition material which is in the river bed erosion and deposition by introducing the concept of equilibrium grain size of deposition material.

Some scholars paid attention to the other influencing factors on suspended sediment (Hoque et al. 2010, Gu et al. 2011). Wang & Lu (2010) suggested that Terra MODIS could be used to estimate suspended sediment concentration (SSC) in large turbid rivers. Pang et al. (2011) obtained that the long-term transport of suspended sediment is controlled mainly by the circulation pattern, especially the current in winter. Fan et al. (2013) analysed the variability in suspended sediment concentration at different temporal scales (within event, monthly, seasonal, annual and inter-annual variability).

Presently, there were many results on bed load transport obtained by domestic and overseas scholars (Camenen & Larson 2005, Yu et al. 2009, Papanicolaou et al. 2009, Franklin 2013). By analysing the bed load rate of western American mountain river, Barry et al. (2004) thought that bed load rate can be fitted into a simple power function on flow, and the coefficient is a parameter of river area which reflected the account of sediment, and the index is a parameter which can reflect the change of riverbed. Azamathulla et al. (2009) used bed load data of Kulim River to verify the feasibility of adaptive neuro-fuzzy inference system (ANFIS) and found that this technique can more accurately evaluate the measured bed load data when compared to a regression equation. Gao (2011) introduced a new formula of bed load transport capacity of non-uniform sediment and compared with Mayer Peter and Muller's and Bagnold's bed load equations. Zhong et al. (2012) presented a new bed load formula based on the kinetic theory. Haddadchi et al. (2012) found that the equations presented by Van Rijn, Meyer-Peter and Mueller, and Ackers and White can adequately predict bed load transport in the range of field data by analysing 19 sets of data and 14 series of data in Node River. Yu et al. (2012) found that the bed load movement was highly associated with streambed condition by observing and measuring the movement of bed load particles on three typical streambeds.

Based on the above reviews it can be found that the current study is limited to uniform sediment particles, and less important aspects associated with bed-load are not included. Although there were so many results of bed load transport rate, many of them were established from specific rivers. All existing equations over-predicted the measured values, and none of the existing bed load equations gave satisfactory performance when tested on local river data because most of methods have not considered riverbed sediment conditions and structural affect on bed load transportation. In summary, the determination of river bed load transport rate will remain to be an ongoing concern question.

This article will explore an effective estimated method for analysing the condition of sediment deposition by taking into account influence of upstream hydro-junction in Harbour basin, and then calculating the amount of sediment deposition of Fueryan Wharf Phase II Project. After that the value by the new method with the value by physical model test was compared. The result showed that this method is feasible.

MATERIALS AND METHODS

Calculation Method

After the excavation of Harbour basin, sediment deposition mainly includes suspended sediment deposition and bed load deposition.

Suspended sediment deposition: Harbour basin represents U-turn area and berthing positions. Generally, it can be divided into two categories: unsheltered basin and shield basin (including excavated Harbour basin).

(1) *Unsheltered basin*: The formula of Liu can be used to calculate the sedimentation intensity of Harbour basin in special cases:

$$P = \frac{\omega ST}{\gamma_0}\{k_1[1-(\frac{H_1}{H_2})^3]\sin\theta + k_2[1-\frac{H_1}{2H_2}(1+\frac{H_1}{H_2})]\cos\theta\} \quad ...(1)$$

Where, P is the sedimentation intensity of suspended sediment in T period (cm/a); ω is the settling velocity of fine particle sediment (m/s); S is the average sediment concentration of shallow areas (kg/m^3); T is the duration of deposition (s); γ_0 is the average dry density of deposits (kg/m^3); k_1, k_2 are the sedimentation coefficients of cross-flow and downstream respectively, if lacking field data, they can be taken as 0.35 and 0.13; H_1 is the average water depth in shallow region and H_2 is the average water depth after excavation (m); θ is the angle of channel direction and flow direction (°).

When the aspect ratio of basin is greater than 10, and the ratio of circumferential shallow water depth and the basin water depth is greater than 0.6, the Harbour basin can be considered as a downstream channel. Substituting $\theta = 0°$ into eq.(1), we can obtain a formula for calculating the sedimentation intensity in this case.

When the aspect ratio of basin is less than 10, and the ratio of circumferential shallow depth and the basin depth is less than 0.6, the Harbour basin can be considered as a cross flow channel. Substituting $\theta = 90°$ into eq.(1), we can obtain a formula for calculating the sedimentation intensity in this case.

(2) *Shield basin*: Considering various factors of siltation of Harbour basin, the formula of sedimentation intensity can be written as:

$$P = \frac{k_0\omega ST}{\gamma_0}[1-(\frac{H_1}{H_2})^3]\exp\left[\frac{1}{2}\left(\frac{A}{A_0}\right)^{1/3}\right] \quad ...(2)$$

Where A is the area of shallow region in the Harbour basin; A_0 is the total area of Harbour basin; k_0 is an empirical coefficient, having generally a value of 0.14 to 0.17.

Excavated Harbour basin belongs to shield basins, the calculation formula is:

$$P = \frac{mk_1\omega ST}{\gamma_0}[1-(\frac{H_1}{H_2})^3] \quad ...(3)$$

Where, m is the revised coefficient of Harbour basin, generally can be taken as 1.3 to 1.6. If reflux occurs in the Harbour basin, the sedimentation amount will increase 2.0 to 3.5 times.

Bed load deposition: The determination of non-uniform sediment transport rate formula should connect with bed load composition, fracture morphology, effective sediment hydraulic factor, bed sediment movement state transition and other factors.

(1) Sharmov formula: If it is the uniform sediment, the bed load transport rate formula is:

$$g_b = 0.95 D^{\frac{1}{2}} (U - U_c^{'}) (\frac{U}{U_c^{'}})^3 (\frac{D}{h})^{\frac{1}{4}} A \quad ...(4)$$

If it is the non-uniform sediment, the bed load transport rate formula is:

$$g_b = m D^{\frac{2}{3}} (U - U_c^{'}) (\frac{U}{U_c^{'}})^3 (\frac{D}{h})^{\frac{1}{4}} \quad ...(5)$$

Where U is the average discharge velocity; U_c is the incipient velocity, and $U'_c = 3.383\, D^{1/3}\, h^{1/6}$; D is the average grain size of the coarsest non-uniform sediment (mm). If this group accounted for 40% to 70% of all the sands, then m=3; if this group accounted for 20% to 40% or 70% to 80% of all the sands, then m=2.5; if this group accounted for 10% to 20% or 80% to 90% of all the sands, then m=1.5.

(2) Dou formula:

$$g_b = \frac{K_0}{C_0^2} \frac{\gamma_s}{\frac{\gamma_s - \gamma}{\gamma}} (U - U_c) \frac{U^3}{g\omega} \quad ...(6)$$

Where,

C_0 is the dimensionless Chezy coefficient, it can be obtained by $C_0 = 2.5 \ln(11h/K_s)$ or $C_0 = h^{1/6} / \sqrt{gn}$.

K_0 is the comprehensive coefficient, for all bed load, $K_0 = 0.1$; according to measured data from hydrometric station of Yangtze River, for sandy bed load, $K_0 = 0.01$; for bed material load in suspended sediment, $K_0 = 0.09$

U_c is the incipient velocity of sediment, it can be obtained by the formula:

$$U_c = (\frac{H}{d})^{0.14} (17.6 \frac{\gamma_s - \gamma}{\gamma} + 0.65 \times 10^{-7} \frac{10 + H}{d^{0.72}})^{1/2} \text{ (m/s)},$$

Where d is the grain size of sediment (mm).

In this new estimated method, eq.(3), eq.(7) and eq.(8) were used to calculate the sedimentation intensity of suspend sediment. eq.(4) was used to calculate the bed load transport rate. Then we can get the alluvium thickness, and the sedimentation amount of suspend sediment and bed load.

Determination of Parameters

The main factors influencing Harbour basin siltation include sediment settling velocity, annual average sediment concentration, water depth before and after excavation of Harbour basin, discharge velocity before and after excavation of Harbour basin, and dry density and the area of Harbour basin. 90+ series means the measured data in different sediment conditions of wet year, normal year and low-flow year from 1992 to 2003.

Settling velocity (ω): The settling velocity is an important parameter which mark the characteristics of sediment movement. Sediment settling velocity can be obtained by the formula of Zhang:

$$\omega = \left[\left(13.95 \frac{\nu}{d} \right)^2 + 1.09 \frac{\gamma_s - \gamma}{\gamma} g d \right]^{1/2} - 13.95 \frac{\nu}{d} \quad ...(7)$$

Where, d is the median grain size of suspended sediment (mm), it can be obtained from the measured data according to 90+ series of water and sediment conditions; γ_s, γ are the bulk density of sediment and bulk density of water respectively (kg/m^3); ν is the kinematic viscosity coefficient.

Annual average sediment concentration (S): The annual average sediment concentration mainly depends on the effect of lifting sand by the wind and waves. In the paper, it was determined according to the measured data in 90+ series of water and sediment conditions.

Water depth (H_1, H_2) before and after excavation: The water depth before and after excavation (H_1,H_2) were obtained from topographic mapping and engineering programs. With the Harbour basin excavated deeper, the sedimentation intensity will become greater. If reaching a certain depth of the excavation, the sedimentation intensity tends to be at a certain limit.

Dry density of sediment (γ_0): The main parameter influencing the dry density is the median grain size. Also the median grain size is an important parameter in siltation. The dry density of sediment is determined by the formula of Liu:

$$\gamma_0 = 1750 \times d_{50}^{0.183} \quad ...(8)$$

Where, d_{50} is the median grain size (mm).

Harbour basin area (A): According to Cord for Master Design of River Port Engineering (JTJ212-2006), berthing area should not be built in the main channel and the width of berthing area should be 2 times to the design breadth. Turning area should be 2.5 times to the design length, and the width is 1.5 times to the design length.

APPLICATION OF MODEL

Engineering Situation

Fueryan Wharf Phase II Project is located at the exit of the right branch section of Zhongdui. The location of the reach from Xiaonanhai Hydro-junction to Yudong Bridge and the location of Fueryan Wharf Phase II Project is shown in Fig. 1.

Fig.1: The location of the Fueryan Wharf Phase II Project.

Table1: The value of influencing parameters.

Influencing parameters		Value
Median grain size		0.018 mm
Settling velocity		0.00018 m/s
Dry density		839 kg/m^3
Annual average sediment concentration		0.16 kg/m^3
Harbour basin area	Berthing area	8100 m^2
	Turning area	33818 m^2

This project used the total length of shoreline of approximately 250m. It would build two 3000 tons berths and corresponding supporting facilities. The design of throughput and through capacity were 1.5 million tons per year and 1.7 million tons per year respectively. The design of ship scale was 95m × 16.2m × 3.5m. The plane dimensions of pontoon were 80m × 23m and 75m × 18m, and the molded depth and the draft were 2.9m and 1.4m respectively.

The width of berthing area in front of wharf should be 2 times to the design breadth. In this paper, taking the largest breadth of 16.2m, then the width of berthing area is 32.4m. Turning area should be 2.5 times to the design length, and the width is 1.5 times to the design length. Taking the largest length of 95m, the length of turning area is 237.5m and width is 142.5m.

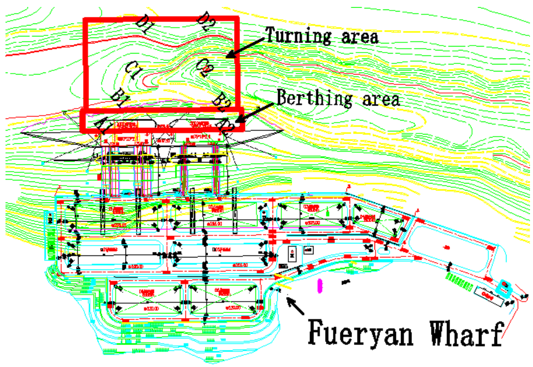

Fig.2: Location of calculated cross sections, measured points and calculated area.

Xiaonanhai hydro-junction located about 5 km to the upstream of Fueryan Wharf Phase II Project. After the completion of Xiaonanhai hydro-junction, discharged flow of the hydro-junction influenced to the working area of Fueryan Wharf.

Applications of Engineering

The location of turning area and berthing area in Fueryan Wharf Phase II Project can be seen in Fig. 2.

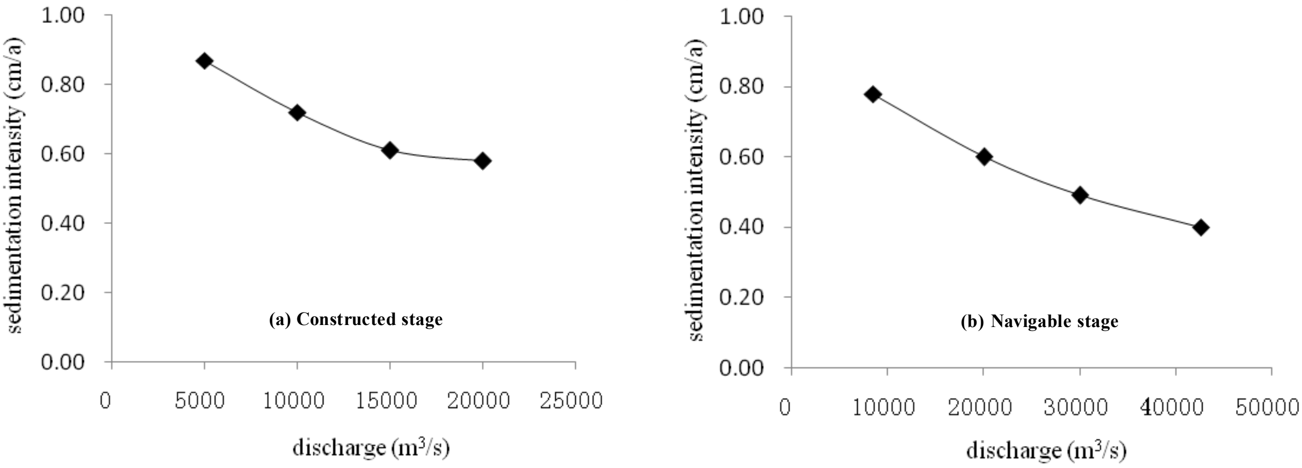

Fig. 3: Relationship of sedimentation intensity and discharge in different stages.

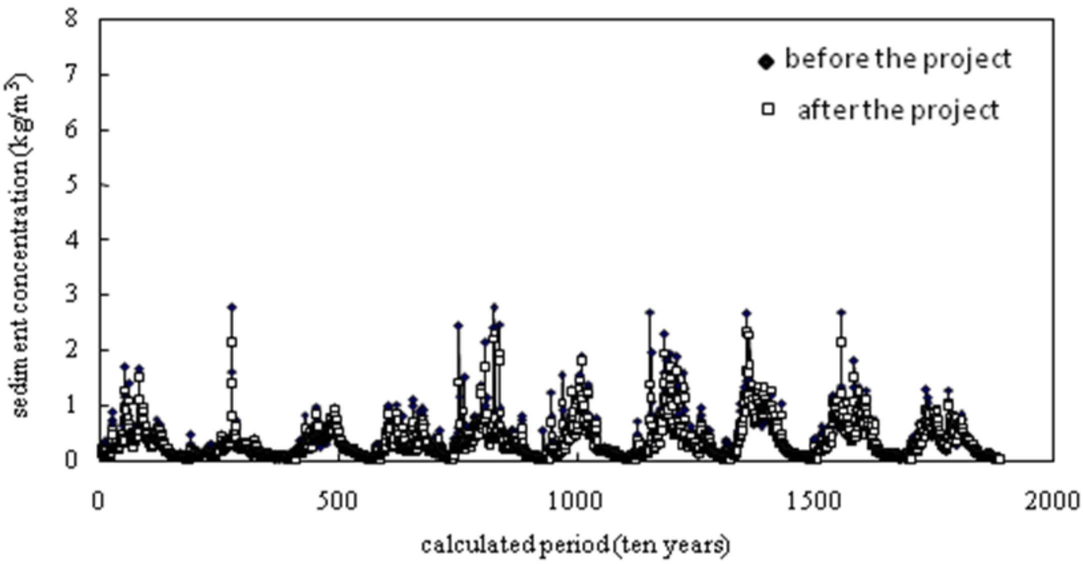

Fig. 4: The change of sediment concentration from Xiaonanhai hydro-junction to Chaotianmen in 90+ series.

Table 2: Suspended sediment and bed load sedimentation intensity.

Location		Measured points	SS sedimentation intensity (cm/a)	Average value (cm/a)	BL sedimentation intensity (cm/a)	Average value (cm/a)
Harbour basin	Berthing area	A1	18.5	11.6	2.5	2.0
		B1	14.8		0	
		A2	13.2		5.4	
		B2	0		0	
	Turning area	C1	17.8	13.0	5.8	2.1
		D1	14.6		0	
		C2	12.9		0	
		D2	6.7		2.5	

SS represents suspended sediment; BL represents bed load.

Table 3: Alluvium thickness and sedimentation amount.

Location	SA (10^4m^3)	TSA (10^4m^3)	AT (m)	AAT (m)
Berthingarea	1.10	6.2	1.36	1.43
Turningarea	5.10		1.51	

SA and TSA represent sedimentation amount and total sedimentation amount; AT and AAT represent alluvium thickness and average alluvium thickness.

Table 4: Comparison of the results by the new estimated method and Xiaonanhai hydro-junction physical model test.

	TSA (10^4m^3)	AT (m)
MTR	3.75	0.86
EMR	6.20	1.43
Error	2.45	0.57

MTR and ETR represent physical model test result and estimated method result.

Navigable stage (ten years) of Xiaonanhai hydro-junction: The value of influencing parameters in navigable stage can be seen in Table 1.

1. *Sedimentation intensity*: The results of suspended sediment and bed load sedimentation intensity in navigable stage are given in Table 2.

2. *Alluvium thickness and sedimentation amount*: The results of alluvium thickness and sedimentation amount in navigable stage are given in Table 3.

From Table 3, it can be seen that the alluvium thickness in Harbour basin is in the range of 1.36m to 1.51m in navigable stage (ten years) of Xiaonanhai hydro-junction.

According to 90+ series of water and sediment conditions, Table 5 indicates that the sedimentation amount of Harbour basin in navigable stage (ten years) of Xiaonanhai hydro-junction is 62,000m^3.

According to the above analysis, it can be seen that the sediment deposition of Fueryan Wharf is greatly reduced by the influence of blocking sand of Xiaonanhai hydro-junction. However, discharged water causes erosion in local river, but scouring depth is not big, so it is a better way to ensure the normal operation of wharf after the completion of Fueryan Wharf Phase II Project.

Table 6: The trend of the change of settling velocity and dry density.

D_{50} (mm)	Settling velocity (m^3/s)	Dry density (kg/m^3)	Sedimentation amount (10^4m^3)
0.025	0.00031	891	10.1
0.023	0.00027	877	8.9
0.020	0.00022	855	7.4
0.018	0.00018	839	6.2

COMPARISON OF MODEL

Comparison of the results calculated by the new estimated method and the results by the Xiaonanhai hydro-junction physical model test (2012) can be seen in Table 4.

According to Table 4 it can be found that the total sedimentation amount calculated by the new estimated method is 62000 m^3, and 37500 m^3 by the physical model test. The alluvium thickness calculated by the new estimated method is 1.43m, and 0.86m by the physical model test. The error of total sedimentation amount and alluvium thickness is 24500 m^3 and 0.57m respectively. The results calculated by the new estimated method are close to it by physical model test. It can be a feasible method in sedimentation calculation.

DISCUSSION

Water Depth (H)

Comparing with the data of Xiaonanhai physical model test, it can be found that when discharge increases, water depth will increase accordingly, but the sedimentation intensity will decrease, the trend can be seen in Fig. 3 (a).

According to trend of the curve in Fig. 3(b), it can be found that with the discharge increases further, the decreasing trend of sedimentation intensity will become slower. If reaching a certain depth of the excavation, the sedimentation intensity tends to be at a certain limit.

Table 5: The sedimentation amount by two working conditions.

Working condition	Location	Sediment concentration (kg/m^3)	Sedimentation amount (10^4m^3)	Total Sedimentation amount(10^4m^3)	Sedimentation amount per year (($10^4m^3/y$)
Constructed stage (7.5 years)	Berthing area	0.21	1.13	5.88	0.784
	Turning area		4.75		
Navigable stage (10 years)	Berthing area	0.16	1.10	6.20	0.62
	Turning area		5.10		

Sediment Concentration (S)

According to eq. (3), and the sedimentation amount in constructed stage (7.5 years) and navigable stage (10 years) in Table 5, it can be seen that as the sediment concentration increases, the sedimentation amount will increase. Fig. 4 shows the change of sediment concentration from Xiaonanhai hydro-junction to Chaotianmen. From Fig. 4, it can be seen that the change of sediment concentration is not particularly obvious except a few special years. The sediment concentration in Fueryan Wharf decreased from $0.21 kg/m^3$ to $0.16 kg/m^3$ before and after the completion of Xiaonanhai hydro-junction.

Median Grain Size (D_{50})

D_{50} is an important parameter influencing the sediment deposition. In the paper, the change of D_{50} directly affected the settling velocity and the dry density. In other words, the change of median grain size directly impacted on the sedimentation intensity and sedimentation amount.

According to the range of the grain size before and after the completion of the project, and substituting D_{50} into eq. (7) and eq. (8) by taking D_{50} = 0.025, 0.023, 0.02, 0.018 respectively. The trend of the change of settling velocity and dry density can be seen in Table 6.

From Table 6, it can be seen that in the range of 0.018-0.025 of D_{50}, as the median grain size decreases, the settling velocity and the dry density will decrease, and accordingly, the sedimentation amount will decrease.

CONCLUSIONS

According to the theoretical study, some conclusions can be drawn as follows:

1. According to the previous study, it can be seen that there are many factors affecting the siltation in Harbour basin. In the paper, by analysing the main influencing parameters of sediment deposition, the ranges of annual average sediment concentration and median grain size can be determined. In the range of 0.018mm-0.025mm of D_{50} and $0.16 kg/m^3$-$0.21 kg/m^3$ of S, comparing with the physical model test, data can be found that the theoretical value by the new method agreed with the value by the physical model test. The result shows that this method is simple in principle, practical in implementation, and reasonable in results.
2. By analysing the parameters of water depth, annual average sediment concentration and median grain size, we can obtain that as the water depth increases, the sedimentation intensity increases, but after reaching a certain depth, the sedimentation intensity tends to at a certain limit. And in the ranges of 0.018mm-0.025mm of D_{50} and $0.16 kg/m^3$-$0.21 kg/m^3$ of S, the sedimentation amount will increase as the D_{50} and S increased.
3. Through this new method, the estimation of the sedimentation amount of the Harbour basin can be made, but the range of the parameters must be considered. May be small changes of median grain size or sediment concentration will have a huge effect on the siltation. Nowadays, siltation remains to be an ongoing concern question. If we want to study deeper, we need to pay more attention to the unknown influencing factors.

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