Analysis of Sedimentation of Fenghuangshan Reservoir in Guangde City

Zeng Xin[1,2,3,*], Gong Ping[1,2], Yuan Yuan[1,2]

[1]River Research Department, Changjiang River Scientific Research Institute, Wuhan, 430010, China
[2]Key Laboratory of Ministry of Water Resources on River and Lake Regulation and Flood Control in the Middland Lower Reaches of Yangtze River, Changjiang River Scientific Research Institute, Wuhan, 430010, China
[3]Innovation Team for Flood and Drought Disaster Prevention of Changjiang Water Resources Commission, Wuhan, China

*e-mail: zengtsing@163.com

Abstract. After the operation of the reservoir, the sediment deposition in the reservoir will raise the bed elevation at the dam site and reduce the reservoir capacity, which will affect the comprehensive benefits of water supply, irrigation and power generation. Taking the Fenghuangshan reservoir in Guangde City, Anhui province as an example, the characteristics of sediment deposition of the Fenghuangshan reservoir was analyzed by using a one-dimensional mathematical model of sediment transport and bed evolution in the reservoir area. Because of the bottom hole, the sediment delivery ratio and out flow sediment concentration gradually increase with the operation time. During the 30 years of operation, the siltation elevation at the dam site increased rapidly, and then the rate of increase began to slow down. In general, the sediment volume into the Fenghuangshan reservoir is not much compared with the reservoir capacity, and the sedimentation is not serious. At the end of 100 years, the reservoir capacity under normal water level and beneficial reservoir capacity are reduced by only 8.79% and 8.24%.

Keywords: sediment deposition; mathematical model; Fenghuangshan reservoir; reservoir capacity

1 Introduction

Sedimentation occurs in the reservoir due to the decrease of sediment carrying capacity, which not only affects the comprehensive benefits of the reservoir such as water supply, irrigation, power generation and ect., but also shorten the service life of the reservoir[1-3]. In order to reduce the influence of sediment deposition on the operation of the reservoir and ensure the comprehensive benefits of the reservoir, it is necessary to conduct quantitative analysis about the sediment deposition in the reservoir area after the operation of the reservoir.

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At present, a lot of work has been done on the research of reservoir sedimentation at home and abroad, including the measured data analysis, flume experiments and numerical simulation[4-6]. Since the 1950s, a large number of reservoir siltation observations have been carried out in our country, and some scholars have analyzed and studied the siltation of specific reservoirs on the basis of the observed data of reservoir siltation[7-9]. With the development of the theory of water and sediment movement, flume experiments[10] and numerical simulation[11-13] have gradually become the important methods to study sediment deposition in the reservoir area. Previous research has explored various factors contributing to reservoir sedimentation, encompassing hydrodynamic conditions, sediment load and properties, reservoir operation modes, etc. In fact, reservoir sedimentation is influenced by several factors at the same time. However, it is unclear whether the characteristics of reservoir sedimentation with several controlling factors are the same with the case of one controlling factor. What's more, previous research is mostly focused on large reservoir mainly influenced by sediment load.

To address the knowledge gaps in sedimentation in the small reservoirs affected by several controlling factors and bed load, taking the Fenghuangshan reservoir in Guangde City, Anhui province as an example, this paper studies the characteristics of sediment deposition under complex situations with tributary inflow and sediment flushing bottom outlet by establishing a one-dimensional mathematical model of flow and sediment transport, including the analyses of the total amount and spatial distribution of sediment deposition in the reservoir area, the bed elevation at the dam site, the outflow sediment concentration and the loss of the reservoir capacity in different periods after the operation of the reservoir.

2 One-Dimensional Mathematical Model in the Reservoir Area

A one-dimensional mathematical model (HELIU-2 software) considered the non-equilibrium sediment transport was used to calculate hydraulic factors, sediment concentration, and riverbed deformation according to the selected typical year water and sediment data.

2.1 Equations of the Model

The continuity and momentum equations of flow

$$\frac{\partial Z}{\partial x} + J_f + \frac{1}{2g}\frac{\partial U^2}{\partial x} + \frac{1}{g}\frac{\partial U}{\partial t} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{2}$$

The continuity equation of suspended sediment

$$\frac{\partial(QS_i)}{\partial x}+\frac{\partial(AS_i)}{\partial t}+\alpha B(S_i-S_{*i})\omega_i=0 \qquad (i=1,2,\cdots 8) \tag{3}$$

The equation of sediment carrying capacity

$$S_*=S_*(U,H,\omega\cdots) \tag{4}$$

The equation of bed load transport rate

$$G_b=G_b(U,Z,d\cdots) \tag{5}$$

The equation of bed deformation caused by suspended load transport

$$\frac{\partial(QS)}{\partial x}+\frac{\partial(\gamma_s^{'}a_1)}{\partial t}+\frac{\partial(AS)}{\partial t}=0 \tag{6}$$

The equation of bed deformation caused by bed load transport

$$\frac{\partial(QS)}{\partial x}+\frac{\partial(\gamma_s^{'}a_2)}{\partial t}+\frac{\partial(AS)}{\partial t}=0 \tag{7}$$

In the formula: Z is the water level; Q is the flow rate; J_f is the energy slope; U is the flow velocity; A is the discharge area; H is the water depth; G is the acceleration due to gravity; S and S_* represent the average sediment concentration and carrying capacity of the cross-section, respectively; γ_s' is the dry bulk density of sediment; B is the width of the water surface; x is the distance along the longitudinal direction; t is the time; ω is the settling velocity of sediment particles in still water; The foot label "i" represents the i-th particle size group; D is the particle size; α is the recovery saturation coefficient.

2.2 Model Solution

Due to the fact that the study is over a long period of time and within a long river reach, the basic equations is simplified in practical calculations. We divide the entire calculation period into several small calculation periods, and divide the long river reach into several short river reaches. During the calculation period, except for the cross section area, other factors in the short river sections remain unchanged, that is, considering steady flow condition. However, in different periods and river reaches, each factor can be different. The bed load sediment transport rate is obtained using the empirical curve of bed load sediment transport rate proposed by Changjiang River Scientific Research Institute[14].

For the solution of sediment transport and riverbed deformation, diffusion theory is applicable in rivers with low sediment concentration. The diffusion theory has a premise that the movement of sediment particles in turbulent flow is not affected by the movement of adjacent particles. Therefore, each group of particle sizes in mixed sand can be analyzed separately, and the partial results of each particle size group can be superimposed to obtain the result of the total sediment. Based on the above theory, the riverbed deformation caused by erosion and deposition of each particle size group is solved separately, and then the results of each particle size group are superimposed to obtain the total riverbed deformation. The advantage of the method lies in its clear physical concepts and simplicity. Due to the calculation of erosion and deposition by particle size grouping, the exchange process between coarse particles in suspended sediment and fine particles in the riverbed can be automatically simulated. During the erosion process, the riverbed completes the coarsening process on its own, forming a coarsening layer.

When solving the equations, non-coupled solutions are used, and the calculation of each period is divided into three steps. Firstly, the water surface profile is deduced, and the hydraulic factors of each reach are calculated; The second step is to calculate the erosion and deposition (including bed load and suspended load) in each river reach; The third step is to modify the cross-sectional shape.

3 Model Validation

To verify the reliability of the mathematical model for flow and sediment transport, it is necessary to perform validation calculations. Because there are no relevant measured data to verify the simulation of Fenghuangshan Reservoir, we select the Danjiangkou Reservoir, which has been in operation for nearly 60 years, for verification. The Danjiangkou Reservoir was officially put into operation in November 1967. It has been in operation for nearly 60 years since then, and the field observation in the reservoir are complete, with reliable data of long term series. The Danjiangkou Reservoir has a normal water level of 157m and a total storage capacity of 17.45 billion m^3 (including 9.4 billion m^3 in the Hanjiang reservoir area).

The reach we select for the verification starts from Baihe River and ends at Danjiangkou Dam site, with a total length of 203km. The measured terrain in 1967 is used as the initial terrain. The period for the verification is from 1968 to 1985. The inflow water and sediment conditions is represented by Baihe Station on the main stream and Huanglongtan Station on the tributary, and the water level in front of the dam is based on the daily average water level measured at Longwangmiao Station from 1968 to 1985. The entire calculation for verification is divided into 1440 small calculation periods.

(1) Verification of bed erosion and deposition in the reservoir area of the Hanjiang River main stream

The calculation results of the total sediment deposition in the Hanjiang Reservoir area are shown in Table 1. From Table 1, it can be seen that the error between the calculated total deposited volume of sediment and the measured value is small, and the calculated results are reasonable.

Table 1. Verification of total sedimentation amount

Item	Measured value	Calculated value	Error(%)
Deposited volume(Billion m^3)	8.773	6.36	27.5

(2) Verification of spatial distribution of sedimentation in the reservoir area of the Hanjiang River main stream

Based on the range of backwater changes over the years and the characteristics of sediment erosion and deposition along the river, as well as the composition of bed sediment, the Hanjiang River main stream reservoir area is roughly divided into five small sections for verification. The verification calculation results are shown in Table 2. Comparing the calculated results with the measured data, although there is a slight deviation in the local sedimentation amount, the overall sedimentation distribution pattern is basically consistent.

Table 2. Calculated and Measured values of Segmented Sedimentation in Danjiangkou Reservoir

Billion m^3

Cross section number	Measured Segmented Sedimentation	Calculated Segmented Sedimentation
51-58	-0.016	0
47-51	0.051	0
35-47	0.537	0.361
28-35	1.063	0.850
1-28	7.138	5.152

From the results of verification, the model can simulate the total amount and spatial distribution of sedimentation in the reservoir. Therefore, the model can be used for this study.

4 Calculation Conditions

The normal water level of the Fenghuangshan Reservoir project is 48m and the dead water level is 39.5m. the total storage capacity of the reservoir is 145 million m ^{3} and the regulated storage capacity is 70 million m^3. The average water level in front of the dam is 47.2m, and the average annual water depth in front of the dam is about 17.2m. The water level variation during the operation period is 1.6m. The average annual inflow water volume is 359 million m^3, and the average annual total amount of sediment load is 116000 tons with the average annual inflow suspended sediment of 96400 tons.

4.1 Calculation Conditions

River Reach Selection and Terrain Data. The upstream of the reservoir is divided into two branches. The west branch is the Tongshui River and the eastern branch is the

Ruishui River. After the confluence of the two rivers, it becomes the Tongrui River, with a total length of 66.8km and an average gradient of 1.13 ‰. The calculation of riverbed terrain data adopts the data measured in February 2016, with a total of 37 cross sections and an average distance of 0.67km between each cross section. The schematic diagram of the layout of measured cross-sections is shown in Figure 1.

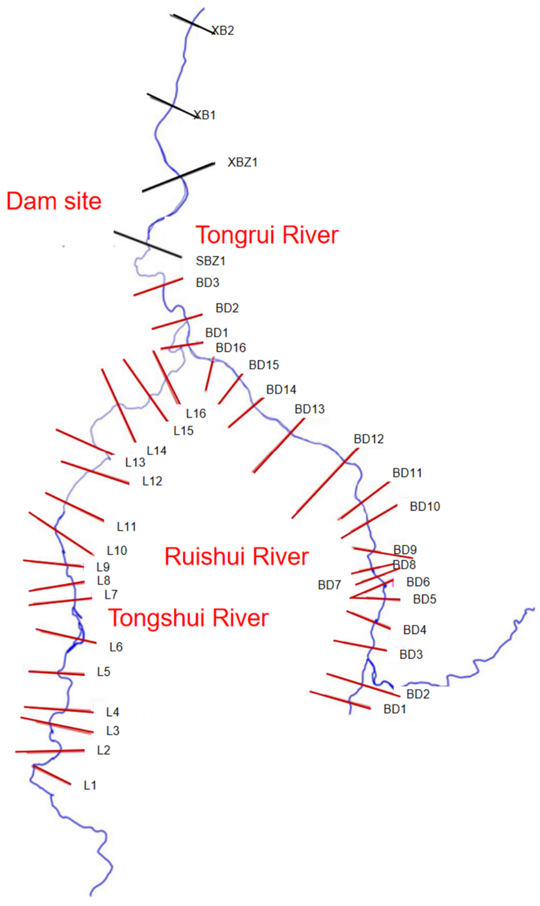

Fig. 1. The layout of measured cross-sections

Inflow Water and Sediment Conditions. Based on the principle of "the annual average sediment discharge and sediment concentration of the series should be close to the annual average value", the monthly average water and sediment data of Yangshanling and Shijiedu stations from 1972 to 1975 and 1977 to 2014 were analyzed, and the years 1984 to 1993 were selected as the typical data series for the calculation of reservoir sedimentation. The average annual runoff of this typical series is 363 million m^3, which is 1.1% lower than the average annual runoff of 359 million m^3 over the years. This typical series includes various combinations such as wet, normal, and dry years, which can basically represent the average situation over the years. The annual average sediment discharge of 116000 tons was used as the typical annual average sediment discharge for the inflow series. The suspended sediment discharge was 96400 tons, and the bed load content was calculated based on 20% suspended sediment, which was 19300 tons.

Boundary Conditions. Based on the water level-discharge relationship at the dam site, the water level at the dam site is determined as the downstream boundary condition. According to the principles of reservoir scheduling and the selected typical series of inflow water and sediment conditions, the ten-day average inflow runoff is used as the calculated flow rate, and the ten-day average water level in front of the dam obtained based on the reservoir scheduling principles is used as the downstream boundary water level.

Riverbed Roughness. According to the measured water surface profile, the roughness of the riverbed is determined, with a range of 0.029-0.046.

Sediment Grain Size Distribution. The grain size distribution of suspended sediment and riverbed sediment is shown in Tables 3-4. From the table, it can be seen that the majority of suspended sediment is fine sand less than 0.25 mm, with the median particle size of 0.012mm~0.116mm and the average particle size of 0.003mm~0.146mm. The average result of two tests is used in the calculation. The sand particles in the bed are finer and coarser, with a median particle size of 8.45mm~232mm and an average particle size of 13.1mm~34mm.

Table 3. The grain size distribution of suspended sediment at the dam site

Measured number	Percentage of sand weight smaller than a certain particle size (%)									
	Grain size(mm)									
	0.002	0.004	0.008	0.016	0.031	0.062	0.125	0.250	0.500	1.00
1	19.3	24.5	31.2	33.6	39.8	47.4	50.9	70.6	98.7	100
2	24.0	31.1	39.6	56.5	68.6	92.2	95.4	97.5	100	100

Table 4. The grain size distribution of riverbed sediment at the dam site

Measured location	Percentage of sand weight smaller than a certain particle size(%)											
	Grain size(mm)											
	0.062	0.125	0.25	0.5	1	2	4	8	16	32	64	128
Tongshui River	0.2	0.8	2.0	6.5	10.4	13.8	190	27.3	40.7	59.0	86.9	100
Ruishui River	0.4	1.2	2.5	6.9	15.0	26.0	33.9	48.5	69.0	89.2	99.0	100
Confluent area	0.6	1.7	3.0	4.8	5.9	7.0	8.5	12.8	28.1	58.7	75.7	100

4.2 Calculation Scheme

The duration of this calculation is 100 years, and the inflow flow and sediment rate adopts a typical water and sediment data series for 10 cycles. The normal water level of the reservoir is determined to be 48m based on the design data, and the dead water level is 39.5m.

5 Calculation Results and Analysis

5.1 Analysis of Sedimentation in the Reservoir Area

Table 5 shows the calculation results of sedimentation in the reservoir area under the normal water level of 48m, including the cumulative sedimentation amount, sediment discharge ratio, outflow sediment concentration, and bed elevation in front of the dam under different operating years. Accumulated sedimentation occurs in the reservoir, and with the increase of operating time, the accumulated sedimentation amount of the reservoir increases. At the end of the 20th year of reservoir operation, the sediment deposited in the reservoir area was 1.46 million m^3, accounting for 1.65% of the total storage capacity; At the end of the 50th and 100th year of reservoir operation, the sediment deposited in the reservoir area was 3.54 million m^3 and 6.5 million m^3, respectively, accounting for 4.0% and 7.3% of the total storage capacity, indicating that the sediment deposited in the reservoir is not significant under the average inflow and outflow conditions over the years.

The sediment accumulates in the reservoir. The sediment discharge ratio increases with the increase of reservoir operation years, from about 20% in the initial stage to 29% and 45% at the end of the 50th and 100th year of operation. The sediment concentration in the outflow increases with the increase of the operating years. The sediment concentration in the outflow increases from 0.004kg/m^3 at the end of the 10th year of operation to 0.054kg/m^3 at the end of the 100th year of operation. Analyzing the changes in bed elevation in front of the dam over time, it was found that the bed elevation in front of the dam increased rapidly within 30 years after the construction of the dam. However, due to the presence of sediment discharge bottom holes in the reservoir, sedimentation in front of the dam began to slow down to a certain extent. By the end of the 50 year after the construction of the dam, the bed elevation in front of the dam reached 34.46 meters, and then the sedimentation rate slowed down. By the end of 100 years after the construction of the dam, the bed elevation in front of the dam was 37.05 meters.

Table 5. Calculation results of sedimentation in the reservoir area

Time (year)	Sedimentation volume (10^4 m^3)	Sediment discharge ratio (%)	Outflow sediment concentration (kg/m^3)	Bed elevation in front of the dam (m)
10	72	19.2	0.004	30.55
20	143	20.4	0.007	31.60
30	212	21.7	0.009	32.57

40	280	23.9	0.013	33.52
50	344	28.6	0.023	34.46
60	405	31.5	0.028	35.19
70	463	34.7	0.035	35.71
80	517	39.4	0.044	36.22
90	568	42.3	0.050	36.63
100	617	44.6	0.054	37.05

5.2 Storage Capacity Analysis

Table 6 shows the remaining storage capacity and percentage reduction of storage capacity after different years of operation. From Table 6, it can be seen that after a period of reservoir operation, sediment deposited in the reservoir area will result in the loss of some reservoir capacity. However, overall, sedimentation has a relatively small impact on storage capacity. By the end of the 50th and the end of the 100th year, the storage capacity at the normal water level decreased by 4.73% and 8.79%, respectively, and the regulating storage capacity decreased by 4.61% and 8.24%, respectively.

Table 6. Calculation results of storage capacity change

Time (year)	Storage capacity at normal water level (10^4 m^3)	Regulating storage capacity (10^4 m^3)	Reduced storage capacity at normal water level (%)	Reduced regulating storage capacity (%)
0	8455	7004		
10	8372	6935	0.98	0.99
20	8287	6863	1.99	2.01
30	8204	6795	2.97	2.98
40	8128	6736	3.87	3.82
50	8056	6681	4.73	4.61
60	7984	6627	5.57	5.38
70	7915	6576	6.39	6.11
80	7846	6525	7.21	6.84
90	7777	6475	8.01	7.56
100	7712	6427	8.79	8.24

6 Conclusion

Selecting the typical years of the long series from 1984 to 1993 as the average inflow water and sediment conditions, the sedimentation in the reservoir area was calculated. The results show that the sedimentation of the Fenghuangshan reservoir are not significant.

Due to the installation of sediment discharge holes at the bottom, the sediment discharge ratio increases with the operation time of the reservoir, from around 20% in the initial stage to 29% and 45% at the end of the 50th and 100th years of operation. The sediment concentration in the outflow increases with the increase of the operation time. Within 30 years after the construction of the dam, the bed elevation in front of the dam increases rapidly, and then the sedimentation in front of the dam begins to slow down.

After a period of reservoir operation, sedimentation in the reservoir area will result in the loss of reservoir storage capacity. However, overall, sedimentation has a relatively small impact on reservoir capacity.

The bed load amount from upstream is assumed to be the ratio of 20% to suspended load. The bed load transport is a factor that affects the spatial distribution of reservoir sedimentation. We can improve the results with the measured data if we can obtain in the future.

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References

1. Phien, HN. (1981). Reservoir sedimentation with correlated inflows. J. Hydrolo, 53(3-4): 327-341. https://doi.org/10.1016/0022-1694(81)90009-3.
2. Zhao, Y.H., Zhang, G.J., Wu, Y.Y. (2010). Study on comprehensive benefits from assets of Sanmenxia water control project. Water Resources and Hydropower Engineering, 41(7): 68-71. https://doi.org/10.13928/j.cnki.wrahe.2010.07.011.
3. Guo, C., Jin, Z. W., Liang, D. F., et al. (2024). Spatiotemporal evolution and influencing factors of flood control storage sedimentation in the Three Gorges Reservoir, Changjiang River, China. Catena, 243: 108214. https://doi.org/10.1016/j.catena.2024.108214.
4. Zuo, Y. (2015). Analysis of Regulating Storage Capacity of Small Reservoirs Based on Synthetic Storage Capacity Method. Gansu Water Resources and Hydropower technology, 51(1): 31-33. https://doi.org/10.3969/j.issn.2095-0144.2015.01.009.
5. Tao, Y., Liu, T.C. (2011). Preliminary study on sediment prediction in the Three Gorges Reservoir area based on one-dimensional water- sediment model. Yangtze River, 42 (06): 65-68. https://doi.org/10.3969/j.issn.1001-4179.2011.06.018.
6. Jiang, L.L., Zhang, X.F., Jiang, T., etc. (2013). Analysis of Sedimentation and Backwater Impact of Yunnan Daqiao Hydropower Station. Yangtze River, 44 (S1): 13-16. https://doi.org/10.3969/j.issn.1001-4179.2013.z1.005.
7. Xu, Q.X. (2012). Research on Reservoir Sedimentation and Underdam Erosion since the Storage of Three Gorges Reservoir. Yangtze River, 43 (07): 1-6. https://doi.org/10.3969/j.issn.1001-4179.2012.07.001.

8. Han, Q.W., Shen, X.Q. (1984). A study on reservoir sedimentation with conical profile. Journal of Sediment Research, (02): 35-53. https://doi.org/10.16239/j.cnki.0468-155x.1984.02.004.
9. Deng, J.Y., Xu, F., Ma, C.Y., et al. (2024). Analysis of the sediment deposition characteristics in the Three Gorges Reservoir and its influence factors. Environmental Earth Sciences, 83: 476. https://doi.org/10.1007/s12665-024-11762-4.
10. Wang, P., Hu, T., Chu, W.B. (2018). Experimental study on sedimentation process model of Topa Reservoir. Journal of North China University of Water Resources and Electric Power (Natural Science Edition), 39 (05): 40-44. https://doi.org/CNKI:SUN:HBSL.0.2018-05-008.
11. Deng, C.Y., Wu, W.M., Xia, J.Q. (2013). Mathematical Model for Sedimentation Calculation of Yantan Reservoir. Journal of Wuhan University (Engineering Edition), 46 (01): 19-25. https://doi.org/CNKI:SUN:WSDD.0.2013-01-006.
12. Lu, J.Y., Huang, Y. (2013). Comparative analysis of sedimentation calculation prediction and prototype measurement results in the Three Gorges Reservoir. Journal of Changjiang Academy of Sciences, 30 (12): 1-6+27. https://doi.org/10.3969/j.issn.1001-5485.2013.12.001.
13. Liu, X.M., Wang, K.Z., Liu, T.X., et al. (2024). Operational Mode for Water–Sediment Regulation in Plain-Type Sand-Laden Reservoirs: A Case Study of the Haibowan Reservoir. Water, 16: 747. https://doi.org/10.3390/w16050747.
14. Jin, Z.W., Lu, J.Y., Yao, S.M. (2009). Verification on formulas of bed-load sedi ment transport rate at the upstream of Yangtze River. Shuili Xuebao, 40(11): 1299-1306. https://doi.org/CNKI:SUN:SLXB.0.2009-11-002.