Research on key technology for sediment management in large-scale reservoirs

DONGPO SUN[1]**, MINGQUAN GENG**[2] **& CHENG LIU**[3]

1 *North China University of Water Conservancy and Electric Power, Zhengzhou 450011, China*
sundongpo@ncwu.edu.cn

2 *Yellow River Henan Bureau, Zhengzhou 450003, China*

3 *International Research and Training Center on Erosion and Sedimentation, Beijing 100048, China*

Abstract The storage of the Xiaolangdi Reservoir on the Yellow River has been reducing rapidly due to sedimentation since the reservoir was commissioned. Experimental studies showed that discharging sediment with density currents at high water level was of low efficiency and the deposited sediment in the upstream part of the reservoir was difficult to discharge. Two methods of improving the de-silting capacity have been proposed, of which one is increasing the strength and transport capacity of density currents and the other is remobilising deposited sediment and pumping it out over the dam through special pipes. Both approaches require mechanical input to disturb and pump out the sediment. The authors propose a strategy to discharge fine sediment out of the reservoir by disturbing and pumping out the sediment using boats equipped with submersible pumps within an area 2–40 km in front of the dam during two periods of water-sediment regulation and power generation. This strategy can prolong the life of the reservoir and harmonise the relationship between the reservoir and the river.

Key words reservoir; density current; sediment remobilisation; sediment removal; sediment pumping; siphon pipe; Xiaolangdi Reservoir

INTRODUCTION

The Xiaolangdi reservoir is located on the trunk stream of the Yellow River, 40 km north of Luoyang, 130 km downstream of the Sanmenxia Multipurpose Project, and 128 km upstream of Zhengzhou (see Fig. 1). Its total storage capacity, sediment storage and long-term effective storage are 12.65, 7.55 and 5.1 billion m^3, respectively. It is the only large storage project on the Yellow River downstream of the Sanmenxia Dam. Its completion has greatly increased the potential for controlling the water discharge and sediment load of the Lower Yellow River by raising the flood control standard to cope with the 1000-year flood, relieving the ice flood threat and reducing deposition.

The reservoir began to store water in October 1999, and sediment deposition in the reservoir commenced immediately. About 0.7 billion m^3 of fine sediment had been deposited within the

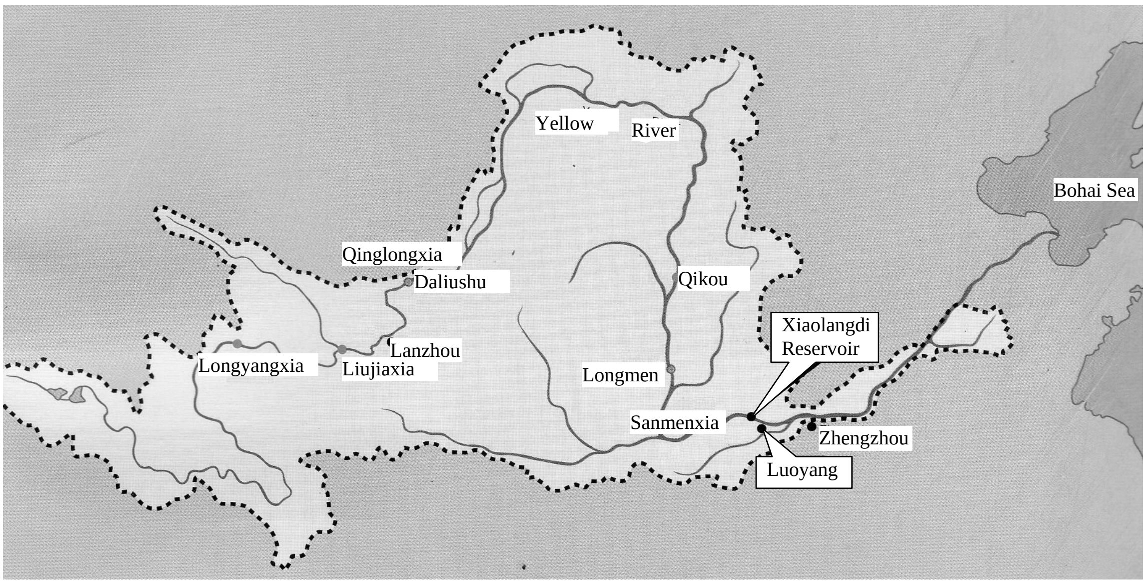

Fig. 1 Location of the Xiaolangdi Multipurpose Project on the Yellow River.

zone extending 40 km upstream of the dam by April 2006, and major loss of storage has therefore already occurred. Water and sediment regulation aimed at desilting the Xiaolangdi Reservoir have been carried out four times since June 2006, with some degree of success. The bank-full flow was increased from 800 $m^3 s^{-1}$ to 3500 $m^3 s^{-1}$, but no density flow was discharged at high water stage (about 248 m) during the early period of water and sediment regulation. Although a density flow exits from the dam when the reservoir stage is about 235 m, the density flow and amount of sediment discharged are insufficient. This reduces the potential for power flushing of sediment and limited the effect of the water-sediment regulation. Therefore, improving the capacity for desilting is imperative and must be seen as an important requirement for alleviating silting in the reservoir and harmonizing the relationship between the reservoir and the river.

Engineers and researchers have been carrying out investigations of reservoir silting and desilting for many years. In the early 1950s, Gottschalk, Koelzer, Lane, Miller and others investigated reservoir silting and methods of tackling the problem (e.g. Gottschalk, 1947; Lane & Koelzer, 1953; Miller, 1953; Koelzer & Lara, 1958). In China, Fan, Jiang, Fang and others undertook research on reservoir silting and sediment flushing with density currents in the late 1950s and early 1960s (e.g. Fan, 1957; Fang & Yin, 1958; Jiang, 1963). Later, Peng, Zhang, Tu, Han and Robert also explored issues of estimating reservoir siltation, scouring and sediment outflow and described a range of different methods (Peng, 1962; Han, 1978; Tu *et al.,* 1978; Robert & Pemberton, 1982; Zhang *et al*., 1982). In the 1960s, Dai undertook some experiments on a small reservoir in Shanxi Province aimed at flushing the deposited sediment using a siphon (see Peng, 1962). In the 1980s, Demmak also undertook research on methods for controlling silting in Algerian Reservoirs (see Zhang *et al*., 1982). In recent years, Jiao, Cao and Zhao (Jiao, 1980; Cao *et al*., 1997; Zhao, 2004) undertook theoretical and experimental studies of discharging sediment with density currents in some reservoirs of China. Several studies, especially work on desilting technology, undertaken in the Danjiangkou Reservoir (Sun & Geng, 2005), experiments on dredging the sediment deposited at the scouring sluice with submersible dredge pumps (Sediment Speciality Commission, 1992), and the six water and sediment regulation experiments undertaken in the Xiaolangdi Reservoir by the Yellow River Conservancy Commission (YRCC) since 2002 (Huang & Huang, 2007) have provided a sound basis for the research on desilting in the Xiaolangdi Reservoir during its early operational period.

RESEARCH ON DESILTING SCHEMES FOR THE XIAOLANGDI RESERVOIR

Characteristics of sediment distribution in the Xiaolangdi Reservoir

It is known from field measurements that the area within 40 km of the dam is an area where fine sediment is deposited with water depths of 60–75 m. The area of coarse sediment deposition is in a backwater region about 100 km from the dam, where the water depth is 8–15 m. The area between these two areas is the zone of transition from fine to coarse sediment, where the water depth is 15–60 m. The profile surveys, the sediment grain size distribution and the cross-section of the reservoir at different times are presented in Figs 2, 3 and 4.

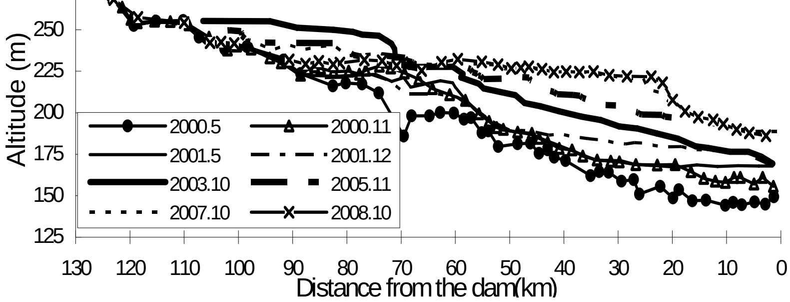

Fig. 2 The profile surveys of the thalweg of the Xiaolangdi Reservoir for different years.

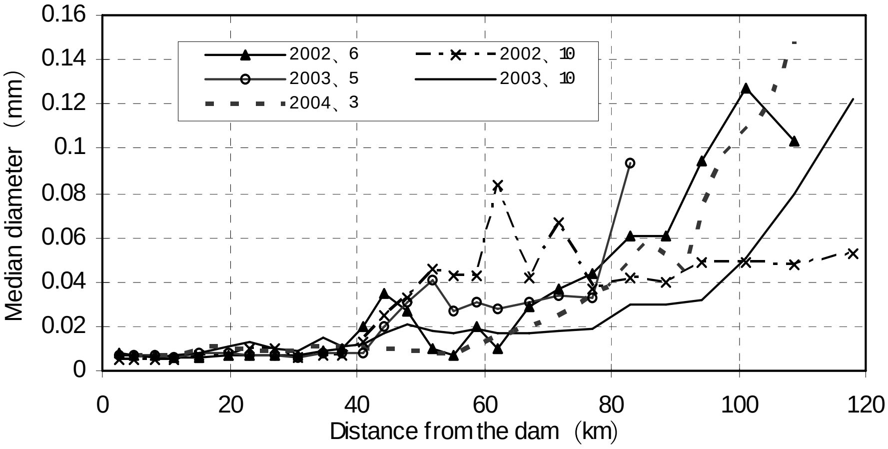

Fig. 3 The distribution of the median diameter of deposits in the Xiaolangdi Reservoir.

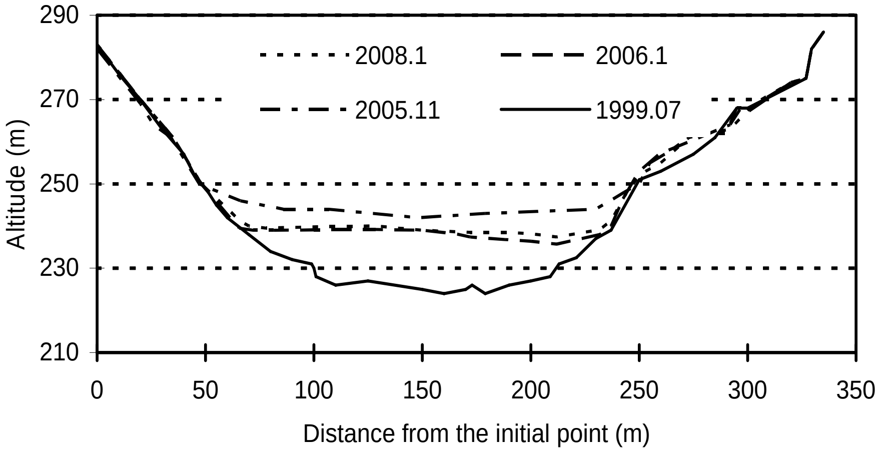

Fig. 4 Deposition in past years at cross-section 47 of the Xiaolangdi Reservoir (hh47).

The key issues to study

Taking account of the desilting technology adopted in other reservoirs and the characteristics of the Xiaolangdi Reservoir, it was decided that the approach required to increase the capacity to remove sediment from the reservoir should be based on improving the desilting efficiency of density currents, increasing the scope for backward scouring in the reservoir area, and undertaking desilting at high water levels. The key technical issues requiring further study therefore include:

(a) Strengthening the sediment transport capability of density currents (during the period of water-sediment regulation). In order to produce favourable conditions for driving the density flow forward, it is necessary to increase both the thickness of the turbidity layer and the sediment concentration at the bottom of the reservoir, by disturbing, and increasing the longitudinal slope of the silted bed in front of the dam.

(b) Desilting with mud pipes at high water level (during the period of water supply and power generation): Hyperconcentrated mud can be transported by pumping and discharging over the dam using the siphon principle. In the pipe, the clay can be transported over long distances with low energy loss by virtue of its Bingham fluid characteristics.

(c) Planning desilting operations. In order to discharge large volumes of sediment from the reservoir by prolonging the desilting time, there is a need to optimise the planning of disturbing, scouring and discharging the sediment.

To apply the desilting measures described above, mechanically assisted methods must be used to remobilise and pump the sediment. Special desilting equipment, which is suitable for working at water depths of up to 60 m, needs to be developed. During the periods of water-sediment regulation and the period of water supply and power generation, the fine sediment deposited within the area extending about 40 km in front of the dam (the permanent backwater zone), could be remobilised and removed from the reservoir by density currents and siphon pipes transporting hyperconcentrated mud.

Technical approaches for sediment remobilisation

At present, there are two well-established and reliable methods for remobilising underwater sediment mechanically. One is to loosen or scour the bed using high-pressure water jets or pulsed water jets. The other is to disturb the bed, pump the slurry and return it by spraying. This provides a double disturbance associated with both stirring and spraying the sediment. The first method has been applied for remobilising sediment in the Sanmenxia Reservoir and the Xiaolangdi Reservoir. The sediment is disturbed using high pressure water jets penetrating to the bottom of the reservoir, so that local sedimentation may be remobilised and carried away by the water (see Fig. 5). The second method has been successfully used in the Lower Yellow River during the sediment disturbance undertaken in 2004–2005 and the cutting of a flood plain diversion during 2005–2006 (see Fig. 6). The latter method is more efficient for fine sediment loosening than normal jet scouring, so it is more widely used and more reliable.

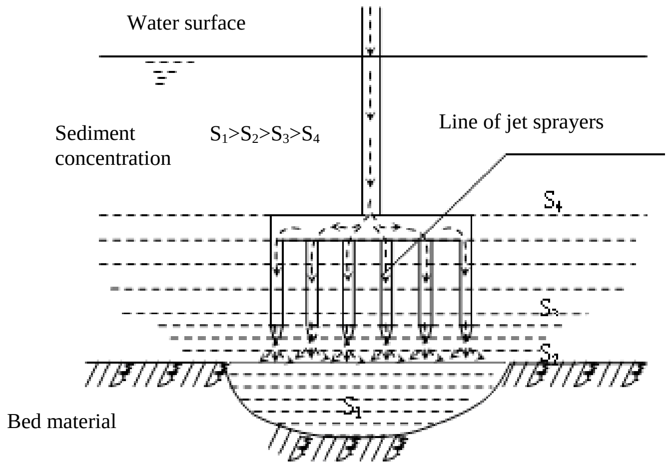

Fig. 5 Disturbing the bottom sediment with water jets.

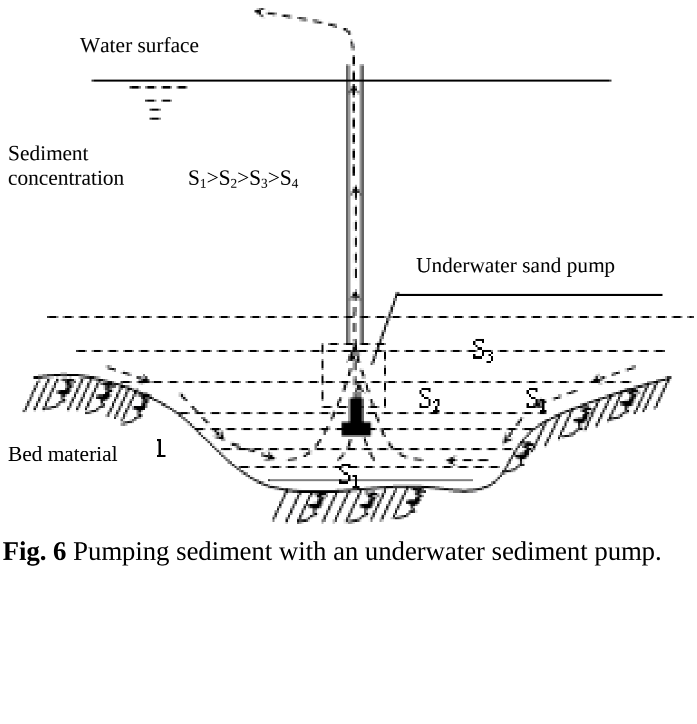

Fig. 6 Pumping sediment with an underwater sediment pump.

Technology and equipment for remobilizing reservoir sediment

Desilting in the Xiaolangdi Reservoir is a task made difficult by the deep water, the excessively long transport distances, and the large amounts of sediment involved. Special equipment suitable for the task is therefore required. At present, no equipment meets the requirements and it has been necessary to develop suitable large equipment to address the key problems. To meet the desilting requirements of the Xiaolangdi Reservoir, there is a need to develop a large desilting boat equipped with a submersible pump with a capacity of 4000 $m^3 h^{-1}$, a delivery lift of 60 m, and a capacity to deal with water depths of 70 m and maximum concentrations of 50%. The key equipment includes a large submersible motor of no less than 500 kW, a large deep-water, wear-resistant sediment pump, and corresponding piping and lifting devices, as well as the desilting platform (the boat) and high efficiency pressurized pumping systems to transport remobilised sediment over long distances.

Several universities and companies have collaborated with the authors to develop this special equipment. Based on frictional loss theory for the pump and velocity limiting theory (created by the authors) for two phase (solid-liquid) flow, a “sediment disturbing boat” equipped with a large submersible pump has been successfully developed. A series-parallel system with a variable frequency function has also been developed, which can remobilise, pump, and transport different kinds of sediment over long distances. In particular, successful research on the design of watertight underwater machinery made it possible to disturb and transport sediment in deep water. The equipment pumps slurry with a discharge of 1000 $m^3 s^{-1}$, a lift of 60 m, a pump depth of 4–20 m, an average concentration of 28%, and a maximum concentration of 33.51%, and these capabilities come close to the requirements for desilting in the Xiaolangdi Reservoir. The equipment has also been successfully used for remobilising sediment in the lower Yellow River in 2004 and 2005, cutting the central bar for diversion of the Yellow River in 2005 and 2006, and constructing the normalized dykes and sea reclamation works near Tianjin. This success has provided a solid foundation on which desilting equipment for the Xiaolangdi Reservoir can be further developed.

Sediment remobilisation and discharging using the large “Submersible Pump Boat”

During the period of water-sediment regulation of the reservoir, the submersible pump boats are deployed in a line extending from the edge of the zone that may be affected by back scouring to the dam at 300~500 m intervals. The motor-driven sediment pumps are lowered to the bottom of the reservoir, and when activated the deposited sediment will be stirred and mixed with water. Part of the disturbed sediment forms an artificial density current (with sediment concentrations of 600–800 kg m^{-3}) by virtue of the effect of the high-speed pulse spray. The sediment is carried by the flow to the hopper zone in front of the dam, causing headward erosion and streamwise erosion, and it is discharged out of the reservoir through the desilting bottom sluices. Part of the sediment will be pumped and conveyed to the dam through pipes in the form of hyperconcentrated slurry by the use of the submersible sediment pumps. This sediment can then be discharged over the dam through a siphon. It will then be transported downstream, where it will mix with the flow from the flood discharge tunnel (see Fig. 7).

Based on an analysis of the data collected during the two sediment remobilisation campaigns in 2004 and 2005, we found that: (a) the artificial density flow is greater than that obtained by submersible pumps; (b) within a zone extending 4 km upstream and downstream of the boat, and 200–300 m wide, an artificial density flow will be produced by the submersible pump boats, which will greatly increase the quantity of fine sediment remobilised and transported. During the non-flood period, the submersible pump boats will be located within the zone located 20–40 km in front of the dam. The boats can therefore increase the reservoir bottom slope and facilitate the forward movement of the density flow to the hopper zone in front of the dam during the water–sediment regulation period and, secondly, sediment can be discharged out of the reservoir through pipes by using the siphon principle (see Fig. 7).

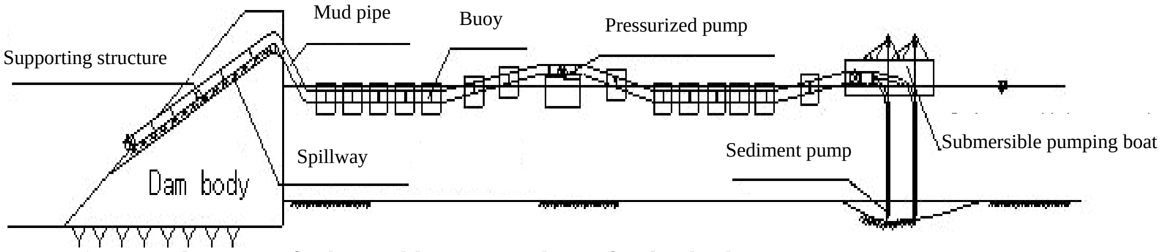

Fig. 7 Deployment of submersible pumping boats for the desilting operation.

According to the ideal requirement for water-sediment regulation of the Xiaolangdi Reservoir, when the reservoir discharge is 4000 $m^3 s^{-1}$, the corresponding sediment concentration is 20 kg m^{-3}, and the sediment discharge from the reservoir would be 103.68 Mt in 15 days. According to the principle of "coarse sediment depositing and fine sediment discharging" and the concept of time space substitution, if six submersible pumping boats operate at full load for 15 days during the water-sediment regulation period, and operate at full load for 210 days during the period of power generation or water supply for irrigation, the total quantity of sediment removed from the reservoir will be 102.297 Mt, which nearly matches the requirement for water–sediment regulation of the reservoir. The calculation result is given in Table 1.

Table 1 Calculation of the capacity of the desilting project.

Mode of operation	Discharge ($m^3 s^{-1}$)	Maximum sediment concentration of discharged water (kg m^{-3})	Quantity of sediment removed (Mt)	Remark
Water-sediment regulation	3000	3.289	12.787	Six submersible sediment remobilising boats with a capacity of 4 000 $m^3 hr^{-1}$ per boat (S_v=28%), operating for 15 days at full load during the water-sediment regulation period; pumping sediment for 10 months during the period of power generation or irrigation (effective rate:70%).
	4000	2.467		
Power generation or irrigation	600	8.222	89.510	
	800	6.167		
	1000	4.933		
	1500	3.289		

DESIGNING THE PROGRAMME FOR DESILTING FINE SEDMENT FROM THE RESERVOIR

The original water level in front of the dam during the period of water-sediment regulation ranges from 250 to 260 m, with the initial level around 225 m and the normal storage level 260 m. Because the top elevation of the spillway on the right bank of the Xiaolangdi Reservoir is 258.0 m, the reservoir desilting equipment and its mode of operation can be designed according to the arrangement of the spillway. In accordance with the siphon principle, the spillway, the existing discharge structure, can be used as the passageway for routing the sediment pipe over the dam, as seen as Fig. 7. The desilting system consists of a pumping boat, a pressurized pump, floating pontoons and a mud pipe in the reservoir, the mud pipe on the spillway, and a conveyor belt which is installed along the spillway, to permit operation and movement of the system. To reduce the damage to the desilting equipment by the wind, the mud pipe should be placed near the right bank of the reservoir and submerged 1.0 m beneath the surface.

Design of the operating modes for fine sediment removal

Because the consolidation of the deposited sediment varies for different periods, the resistance of the sediment accumulated in front of the dam to remobilisation and scouring will also vary. Two conditions should therefore be considered when planning desilting.

(a) During the period of water-sediment regulation in the Yellow River, the main operation mode involves using the submersible pump boats to disturb the sediment on the bed, to promote the development of artificial density currents. Emphasis is placed on remobilising the hyperconcentrated turbid layer that was deposited recently and is characterized by low consolidation strength, or is unconsolidated and still suspended close to the bed of the reservoir. The method of pumping and driving the sediment directly with a large submersible pump is adopted to promote the movement of the artificial density flow towards the hopper zone in front of the dam. At this time the submersible pumping boats are positioned in a grid formation at 300–500 m intervals in an appropriate area of the reservoir (see Fig. 8). Their lateral movement should be coordinated. A deep slot can be formed by the disturbing and pumping of the large submersible sediment pumps, and this serves to direct the density flow on the bottom forward towards the hopper zone in front of the dam. This increased the desilting of the reservoir during the period of water-sediment regulation.

(b) During the period of power generation and water supply, the submersible pump boats remobilise and pump the fine sediment that has been deposited for a longer time and is well consolidated and highly cohesive, in order to prevent and delay further sediment settlement and consolidation. In this period, the submersible pump boats are arranged in a dispersed pattern. The consolidated sediment deposits are disturbed, remobilised and pumped by the submersible pump boats. The sediment is then transported to the dam through pipes and discharged over the dam using a siphon. In addition, an increase in the longitudinal river slope and sediment suspension can be promoted by stirring with the sediment pumps, so as to provide conditions for discharging more sediment during the period of water-sediment regulation in the Yellow River, as shown in Fig. 6.

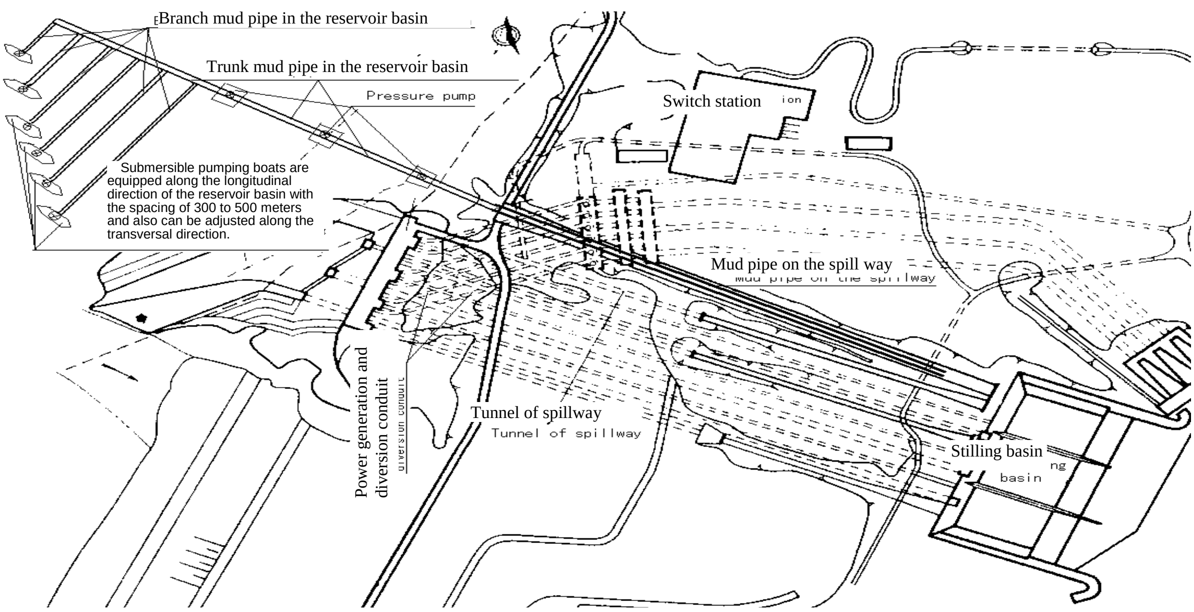

Fig. 8 The location of sediment pumping boats used for desilting the reservoir.

Design of the pipe network for transporting sediment in the reservoir

Calculation of the Bingham shear stress and stiffness coefficient According to the formula presented by Fei (Gottschalk, 1947), The Bingham shear stress τ_B and stiffness coefficient η for hyperconcentrated flow can be calculated as follows:

$$\tau_B = 0.098\exp\left(B\frac{S_v - S_{v0}}{S_{vm}} + 1.5\right) \tag{1}$$

$$S_{vm} = \frac{1}{1+6\sum p_i/D_i}, \quad S_{v0} = 12.6 S_{vm}^{3.2} \tag{2}$$

where, S_v is the sediment content (kg m^{-3}), S_{vm} is the extreme sediment content; D_i and p_i are typical grain size and percentage sediment content for a size grade i, respectively; and S_{v0} is the sediment content when the shear stress begins to develop.

$$\eta = \mu\left(1 - \frac{s_v}{s_{vm}}\right)^{-2} \tag{3}$$

where, μ is the coefficient of dynamic viscosity of clear water.

Table 2 presents the values of τ_B and η used when widening the dyke of the Lower Yellow River by using pipes to transport the mud.

Table 2 The values of Bingham shear stress τ_B and stiffness coefficient η in the pipe.

S (kg m^{-3})	S_V	γ_m (kg m^{-3})	S_{vm} (kg m^{-3})	S_{v0} (kg m^{-3})	τ_B (N m^{-2})	η	D (mm)	D_{90} (mm)
600	0.226	1374	0.42	0.078	8.65	0.047	0.101	0.026
			0.44	0.091	5.85	0.043	0.068	0.021
			0.46	0.105	4.04	0.039	0.047	0.032
700	0.264	1436	0.42	0.078	18.49	0.073	0.227	0.026
			0.44	0.091	12.15	0.063	0.149	0.031
			0.46	0.105	8.14	0.055	0.100	0.032
			0.59	0.233	0.67	0.033	0.008	0.33
800	0.302	1498	0.42	0.078	39.54	0.127	0.499	0.026
			0.44	0.091	25.46	0.101	0.321	0.031
			0.46	0.105	16.40	0.085	0.207	0.032
			0.59	0.233	1.84	0.042	0.023	0.33

It can be seen from Table 2 that S_{vm} and S_{v0} are related to the grain size composition of the sediment sample. The values of τ_B and η both increase with an increase of sediment concentration. For the same sediment concentration, an increase in the content of sediment <0.005 mm, causes the values of τ_B and η and the capacity to suspend coarse sediment to increase.

Because flows discharged from the Xiaolangdi Reservoir, with sediment concentrations of 600 kg m^{-3} or above, consisting of bed sediment, are hyperconcentrated flows, the rheological characteristic can normally be described as a Bingham body and the methods for calculating resistance can be selected as above.

Calculation of head loss in horizontal mud pipes A systematic investigation of resistance under hyperconcentrated conditions in a mud pipe was made by the authors during the operation of transporting sediment with a pipeline on the Yellow River flood plain. When the sediment concentration is about 600 kg m^{-3}, the linear resistance coefficient of the hyperconcentration mud pipes is 0.021–0.035 (Miller, 1953). According to the requirements for conveying flow and sediment, the mud velocity is inversely proportional to the pipe diameter, and must exceed the corresponding (non-silting) critical velocity, with the resistance remaining as small as possible. With pipe diameter d = 2 m, the Durand empirical equation is used to calculate the critical velocity U_T for non-silting:

$$U_T = \frac{1000\eta}{d\rho}\left(1+\sqrt{1+d^2\tau_B\rho/3000\eta^2}\right) \tag{4}$$

With a sediment concentration S = 600–800 kg m^{-3}, the calculation indicates that when the velocity U in the pipe is 1.0 m s^{-1}, the requirement for non-silting in the pipe can be met. Darcy's equation is used to calculate the linear head loss in the pipe:

$$J = \lambda \frac{U^2}{2gd} \tag{5}$$

where:

$$\lambda = \frac{0.136}{\mathrm{Re}_2^{0.25}} \text{ and } \mathrm{Re}_2 = \frac{Ud\rho}{\eta(1+\frac{\tau_B d}{8U\eta})} \tag{6}$$

Calculations have been made for three sediment samples with S = 600–800 kg m^{-3} and the head loss per km is shown in Table 3.

Calculation of head loss in vertical mud pipes When transporting the sediment during desilting, the sediment will be pumped 60 m vertically from the bottom by the pump and lifted 4–15 m from the water surface to the top of dam through vertical sediment pipes. The resistance loss can be calculated according to the expression for resistance presented in the "Sediment Handbook":

$$J_{\mathrm{m}} = J_{\mathrm{w}} + S_{\mathrm{v}}\left(\frac{\rho_{\mathrm{s}} - \rho_m}{\rho_m}\right) \tag{7}$$

in which, J_{m} and J_{w} are the energy gradient in turbid water and clear water, respectively; ρ_{s} and ρ_{m} are the densities of sediment and water respectively. For three sediment samples representing sediment in the size range 0.002–0.01 mm with S = 600–800 kg m^{-3} in the Yellow River, the head loss (per km) in the mud pipe has been calculated and is listed in Table 3.

Calculation of head loss in downslope pipes After passing over the dam, the sediment pipe used for desilting will pass down the slope of the emergency spillway (about 260 m long, with slope of about 60°). The resistance loss can be calculated with the expression for resistance loss caused by transporting hyperconcentrated flow through sloping sediment pipes provided in the "Sediment Handbook" (Sediment Speciality Commission, 1992):

$$J_{\mathrm{m}(\theta)} = J_{\mathrm{w}} + J_{\mathrm{s}(\theta)}\cos\theta - S_{\mathrm{v}}\left(\frac{\rho_{\mathrm{s}} - \rho_m}{\rho_m}\right)\sin\theta \tag{8}$$

where $J_{m(\theta)}$ and $J_{s(\theta)}$ are the resistance losses in sloping and horizontal turbid water pipes with a slope of θ, respectively.

Calculations have again been made for three sediment samples with S = 600–800 kg m^{-3}, and the resistance loss in the mud pipe (per km) is listed in Table 3.

Table 3 Head loss of pipes.

S (kg/m^3)	Loss through 2 km horizontal pipes (m)	Loss through 75 m vertical pipes (m)	Loss though 260 m sloping pipes (m)
600	28.0	15.75	0.40
700	33.0	16.76	0.53
800	36.4	17.44	0.65

Summarizing the calculations described above, as well as preliminary calculations made with the observational data obtained from sediment engineering works on the lower Yellow River, it can be seen that submersible pump boats can be used directly (with a delivery lift of 60 m) if desilting is done within 2 km of the dam. If the desilting extends to the zone within 15 km of the dam, two stage pressurization (with a delivery lift of 70 m) is required, because using the submersible pump boats is of low efficiency. If the desilting is undertaken outside 35 km of the dam, four stage pressurization is needed. According to the analysis, it is reliable and reasonable to use three stage pressurization to dredge the silt within 40 km in front of the dam of the Xiaolangdi Reservoir.

If the total quantity of fine sediment to be removed by desilting is 102.297 Mt, six 2000 kW submersible pump boats, plus two stage pressurization, are required, and the power consumption for sediment remobilizing or pumping would be 12 000 kW. Based on the experience provided by sediment engineering in the lower Yellow River, the power consumption of six 500 kW sediment pipes with three stage pressurization is 9000 kW (500 kW × 3 × 6), and thus the total power consumption for the reservoir desilting is 21 000 kW.

If the desilting operation lasts for 225 days, the total consumption of electric energy is 1.134×10^8 kilowatt-hours. If the cost of labour and machinery amounts to 6 million yuan (RMB), the annual operation cost for desilting is 51.36 million yuan, which is equal to a unit desilting cost of about 0.75 yuan m^{-3}. It is obvious that it is very cost effective to use submersible pump boats for desilting fine sediment in the reservoir. Considering the comprehensive benefits of the reservoir, prolonging the service life of the reservoir and transporting the sediment to the sea or creating land through silting will produce further benefits in terms of power generation, irrigation and ecology. The economic benefit of desilting is therefore clear.

CONCLUSIONS

(a) The efficiency of releasing sediment out of the reservoir by density currents at high water level is low in the Xiaolangdi Reservoir, and it is difficult to discharge sediment deposited far from the dam out of the reservoir. Based on analysis of the reservoir topography and deposited sediment distribution, two measures to increase the sediment releasing capacity are proposed. One is to increase the transport capacity of the density currents by using mechanical means to disturb and remobilise the sediment in order to promote density current generation. The other is to pump and transport fine sediment out of the reservoir by using the siphon principle.

(b) Based on engineering experience and recent study results, a boat with a special suction-type submersible pump has been developed for disturbing and pumping sediment. The fine sediment deposited on the bottom of the reservoir within a zone extending from 2 to 40 km in front of the dam can be resuspended by the boats and released during the periods of creating artificial floods for water–sediment regulation and water discharge for power generation. The sediment removed by density currents and siphons can be mixed with the discharged flow from the reservoir.

(c) Based on the characteristics of the sedimentation in the reservoir, it is possible to remobilise and transport the fine sediment deposited in front of the dam by using mechanical disturbance, sediment pumping and creating artificial density currents, and then to discharge the sediment out of the reservoir with the artificial floods during the period of water–sediment regulation. Analysis shows that this scheme is feasible and economically viable. It is possible to prolong the life of the reservoir on a heavily silt-laden river and to integrate the reservoir more closely with the river, by coordinating reservoir operation and desilting work.

Acknowledgements This study was funded by the National Natural Science Foundation of China (Grant no. 51079055). The writers would like to thank two students Yang Zhenzhen and Zhang Lida of the North China Institute of Water Conservancy and Hydroelectric Power for their assistance.

REFERENCES

Cao, W., Jiang, N., Fu, L. & Tan, D. (1997) Experimental research on Baishi Reservoir sediment. *Technology of Water Resources and Hydropower* **9**, 45–50 (in Chinese with English abstract).

Chen, J. & Zhao, K. (1987) Research on Nanqin Reservoir sediment discharge *J. Sediment Res.* **3**, 15–19 (in Chinese with English abstract).

Fang, Z. & Yin, X. (1958) Analysis of data on reservoir deposit dry density. *J. Sediment Res.* **3**, 21–26 (in Chinese with English abstract).

Fan. J. (1957) *Density Flow*. Water Conservancy Press, China (in Chinese).

Gottschalk, L. C. (1947) Analysis and use of reservoir sedimentation data. In: *Proc*. *Federal Inter-Agency Sedimentation Conf.* (Denver. Colorado), 139–140.

Han, Q. (1978) Research on the equilibrium form and cut-and-fill deformation of long-term reservoirs. *People's Yangtze River* **2**, 11–16 (in Chinese with English abstract).

Huang. Z. & Huang, L. (2007) Feasibility research on Xiaolangdi reservoir sediment discharge and transport at high water stage. Yellow River Website: http://rmhh.periodicals.net.cn

Jiang, N. (1963) Silting calculation method for silt-laden river deltas. In: *Research Paper Collection of China Institute of Water Resources and Hydropower Research*. China Industry Press, China (in Chinese).

Jiao, E. (1980) Discussion on reservoir silting form. In: *Selected Collection of Yellow River Sediment Research Papers, no.* 4 (in Chinese).

Koelzer,V.A. & Lara,E.M. (1958) Densities and compaction of deposited sediment. *J. Hydraul. Div. ASCE* **84**(HY2), 252–261.

Lane, E. W. & Koelzer, V. A. (1953) Density of sediments deposited in reservoirs. Report No.9: *A study of methods used in measurement and analysis of sediment loads in streams*, St Paul United States Engineering District, St Paul, Minnesota, USA.

Miller, R..(1953) Determination of the unit weight of sediment for use in sediment volume computation. US Bureau of Reclamation Memorandum.

Peng, R. (1962) *Calculation Method for Sanmenxia Reservoir Back Scour*. Institute of Water Resources and Hydropower Research, China (in Chinese).

Qian, N. (1989) *Hyper-Concentration Flow Motion*. Qinghua University Press, China(in Chinese).

Robert, I. S. & Pemberton, E. L. (1982) Reservoir Sedimentation, Technical Guidelines for the Bureau of Reclamation. Bureau of Reclamation, Denver, Colorado, USA.

Sun, D. & Geng, M. (2005) Research on pipe resistance and transport capacity of hyper-concentration slurry. *J. Hydraul. Engng* **36**(9), 29–34 (in Chinese with English abstract).

Sediment Speciality Commission (1992) *Sediment Handbook*. China Environmental Science Press, China (in Chinese).

Shanxi Province Department of Water Resources and Water and Soil Conservation (1989) *Reservoir Desilting Technology.* Water Resources and Hydropower Publishing House, China (in Chinese).

Tu, Q. (1978）*Design Handbook of Hydraulic Kinetic Energy*. Institute of Reconnaissance, Planning and Design, YRCC (in Chinese).

Zhang, Q & Zhang, Z. (1982) Reservoir scour-and-fill pattern and its process calculation. *J. Sediment Res*. **11**, 35–41 (in Chinese with English abstract).

Zhao, K., Chen, Y. & Ding, L (1995) Research on technology of Erlongshan reservoir deposit reduction by sediment discharge. *J. Sediment Res.* **7**, 12–17 (in Chinese with English abstract).

Zhao, W. (2004) *Yellow River Sediment*. Yellow River Conservancy Press, China (in Chinese).