Review on Study for the Operation Mode of Xiaolangdi Reservoir in the Yellow River*

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ABSTRACT: Xiaolangdi Multipurpose Dam Project occupies a critical position in controlling both runoff and sediment of the Yellow River. There are many previous studies on the operation mode of Xiaolangdi Reservoir available in literature, especially for the purpose of sedimentation reduction in the reservoir. Since Xiaolangdi Reservoir was put in use, three times of experiment of flow and sediment regulation were carried out. After that, three times of practice for flow and sediment regulation was implemented with Xiaolangdi Reservoir, which not only made previous studies put into practice, but also recognized law of flow and sediment movement on the Yellow River further.

Keywords: Xiaolangdi Reservoir, operation mode, flow and sediment regulation, deposition reduction

1 Introduction

Xiaolangdi(XLD) Reservoir is one of major projects that were built on the sediment-laden rivers. Due to the extremely complex sediment problem and negative impact of sedimentation problem of Sanmenxia project, the planning of Xiaolangdi Reservoir lasted more than 40 years since 1954. From 1954 to 1960, XLD Project was mainly prepared for hydropower generation. From 1969 to 1974, the Class 1 and Class 2 development program between Sanmenxia and XLD were demonstrated. From 1975 to 1981, it was the first time to definitely propose to build high dam aiming to deposition reduction in the lower Yellow River, and the development mission was flood control, ice prevention, sedimentation reduction, irrigation, power generation, comprehensive utilization. It was compared with the operation of water stored and sediment conserved with water level highly rising for once and the operation of rough granules stored and fine flushed with water level highly rising gradually. From 1982 to 1984, feasibility study of the project was carried on. The development mission was definitely oriented to flood control (including ice prevention) and sedimentation reduction, and balanced water supply, irrigation and hydropower generation, and the indicators were demonstrated. From 1985 to 1988, the paper of

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the project design mission was compiled, and preliminary design was launched on. From 1989 to 1996, project planning was carried on, which was in the stage of inviting public bidding of design. In addition, during the phase of the National key project in 8th five-year plan and project construction, many researches was in the center of the reservoir deposition reduction, and it provided the base of the reservoir optimization operation. Since Xiaolangdi Reservoir was put in use, three times of experiment of flow and sediment regulation were carried out. After that, three times of practice for flow and sediment regulation was implemented with Xiaolangdi Reservoir, which not only made previous studies put into practice, but also recognized law of flow and sediment movement on the Yellow River further. More than half centuries of history, is tortuous and complicated process of research, but also the process of constantly deepen understanding, and lay the foundation for optimal scheduling of XLD Reservoir.

2 Phase of XLD Preliminary Design and Inviting Public Bidding Design

2.1 Design Condition of water and sediment

XLD Reservoir preliminary design chose the design level in 2000 and a combined 50 years representative series which is doubled 25 years series of 1950-1975. Moreover, the total annual average runoff and sediment at the four stations of Longmen, Huaxian, Hejin and Zhuangtou were 33.55 billion cubic meters and 1.475 billion tons respectively. After regulated by Sanmenxia Reservoir, the average annual inflow runoff and sediment to XLD Reservoir were 31.50 billion m^3 and 1.335 billion tons respectively.

On the phase of inviting public bidding of design, scientists adopted 56 years series of 1919-1975 and the design level in 2000. Moreover, in view of encountering rich, ordinary, or poor water discharge and sediment concentration conditions at the beginning of the reservoir operation, scientists combined 6 different 50 years series from 56 years series and carried on the sensitivity analysis of reservoir deposition and deposition reduction in lower Yellow River. The annual average volume of water and sediment of four stations of 56 years series were 30.2 billion cubic meters and 1.390 billion tons respectively. The annual average volume of water and sediment input of XLD of six different 50-years series were respectively 28.92 billion cubic meters and 1.274 billion tons.

2.2 Reservoir Operation Mode Research

The basic reasons of deposition in the lower Yellow River are more sediment and less water, which come from different sources. In addition, the nature combination of the inputs of water and sand does not have a good harmony with the sediment transport capacity in the lower Yellow River. In the main flood season of XLD (July 11th-September 30th), managers give prior to regulate water which is one of operation modes of flow and sediment regulation. During the period of reservoir sediment impounding, the benefit of sediment impounding and deposition reduction is enhanced through flow and sediment regulation. During the period of ordinary reservoir operation, flow and sediment regulation enhance the benefit of deposition reduction.

The aim of the flow and sediment regulation operation which give prior to regulate water is: the discharge with much water and much sediment play an important role on the module of beach deposition and scouring channel, and controlling beach fallen and upstream scouring and downstream deposition, and meeting the water supply and irrigation in the lower Yellow river, and enhancing the benefit of hydropower generation, improving the water quality and ecological environment of the downstream channel, and so on.

The operation mode of flow and sediment regulation can be summarized as follow: enlarging the dry discharge of less than 400 m^3/s to guarantee the power generation and improve the water quality and water environment, discharging the little flow between 400 m^3/s and 800 m^3/s to meet water supply in the lower, regulating the ordinary flow between 800 m^3/s and 2000 m^3/s to avoid upstream scouring and downstream deposition in the lower Yellow River, discharging the large flow between 2000 m^3/s and 8000 m^3/s to scouring channel or beach deposition, adjusting the high-concentrated flood of more than 400 kg/m^3, and conserving the flood of more than 8000 m^3/s. Obviously, the fundamental principles of the reservoir operation discharge polarize. The reservoir operation mode of the main flood season is stated in Table 1.

Table 1 XLD Reservoir Operation Mode of the Main Flood Season

Input discharge Q_{input} （m^3/s）	Output discharge Q_{output} （m^3/s）	Adjusting aim
< 400	400	① guaranteeing the least discharge for power generation；② keeping the baseflow in the lower Yellow River and improving water quality and ecological environment.
400～800	400～800	① meeting the water supply in lower Yellow River；② keeping the less deposition in the lower Yellow River.
800～2000	800	① avoiding the ordinary flow and upstream scouring and downstream deposition；② controlling the storage capacity less than 0.3 billion m^3.If more than 0.3 billion m^3，generate the flood with a discharge of 5000 m^3/s or 8000 m^3/s until the storage capacity of 0.1 billion m^3.
2000～8000	2000～8000	Making the lower channel scouring
> 8000	8000	Flood detention or storing floodwater

The phase of October to the first 10-days of July is regulation period of XLD Reservoir. Hereinto, during 1st to 15th of October the reservoir needs to obligate storage capacity of 2.5

billion m^3 for defending the upper flood. During January and February, the reservoir is in the period of ice prevention operation. In the remaining time the reservoir mainly adjusts the flow according to the irrigation demand and guarantees the basal flow along with the lower and mouth. At the end of June, the reservoir obligates water of no more than 1 billion m^3 for redeeming irrigation in the first 10-days of July.

2.3 Phase of the Reservoir Operation

For farthest enhancing the benefit of deposition reduction of the reservoir and meeting the need of power generation, managers adopt the operation mode of raising gradually the water level in the main flood season.

①Phase of water storage and sediment impounding: The beginning water level is 205m, and operation mode is water storage and sediment impounding.

②Phase of raising gradually water level: When the bottom height of the reservoir behind the dam comes to 205m, the reservoir operation changes to raise gradually water level in the main flood season and impounds the sediment during flow and sediment regulation. When the bottom height uplifts gradually from 205m to 245m, water level in the main flood season would increase with deposition surface elevation.

③Phase of beach deposition and scouring channel: When there is deposition without raising the gate completely and scouring with raising the gate high in the reservoir field, beach height elevates with deposition systematically, while channel stepwise shears downwards. At the end of the phase, the channel shape of high beach and deep trough, which is the beach elevation of 254m and channel elevation of 226.3m behind the dam, comes to true.

④Phase of normal operation: Managers adopt the operation mode of multi-year sediment regulation for flow and sediment regulation. In the main flood season, on the condition of discharge with ordinary water and sediment, managers make use of the volume of 1 billion m^3 below the beach for the operation of flow and sediment regulation; when there is large flood, flood control operation will be implemented. The deposition height behind the dam and deposition volume of different operation phase is stated in Table 2.

Table 2 Reservoir Deposition Volume of Different Operation Phase

Phase	Deposition elevation behind the dam（m）		Year order	Cumulating deposition（billion m^3）
	Channel	Beach		
Water storage and sediment detention	≤205		1～3	1.7
Raising gradually water level	205～245		4～15	7.6

Beach deposition and scouring channel	226.3～245	245～254	16～28	7.6～8.1
Normal operation	226.3～248	254	29～50	7.6～8.1

2.4 Benefit of Reservoir Deposition Reduction

Adopting six 50-years representative series in 2000, scientists had analyzed the benefit of the reservoir deposition reduction. The results show: after 50 years operation, the deposition volume of different series in the reservoir ranges from 10.43 billion tons to 9.99 billion tons. In the lower Yellow River, total deposition reduction volume ranges from 7.21 billion tons to 8.46 billion tons, corresponding to no deposition in the whole of the lower Yellow River in 18.3 to 22.3 years.

Averaged the deposition volume of six different series designed, the reservoir conservation is 10.17 billion tons, and deposition reduction of the lower Yellow River is 7.87 billion tons, which the ratio of sediment conservation and deposition reduction is 1.3. Number of correspondence years without deposition is 20 in the whole of lower Yellow River. Hereinto, the reservoir conservation of the first 20-years is 10 billion tons, and deposition reduction of the lower Yellow River up Lijin Station is about 6.9 billion tons, while deposition reduction of the mouth input is 3.1 billion tons. In the last 30-years there will be a dynamic balance in XLD Reservoir. The role of flow and sediment regulation would reduce 0.92 billion tons in the lower Yellow River.

3 Phase of the national key project in the 8th five-year plan

During the process of the national key project in the 8th five-year plan, scientists studied the operation of “controlling storage and scouring quickly”, “storing highly and scouring quickly”, “elevating with different phase”, and “elevating gradually”.

The dominant thought of the operation mode of “controlling storage and scouring quickly” is enlarging the regulating storage capacity and strengthening the regulating ability of water and sand. That means sediment needs to be transported when there is a large discharge. The function of flow regulation is emphasized. Artificial flood peak is decided by the volume of the regulating storage capacity below the limit water level of the reservoir in the flood season. The reservoir is operated by the scheme of water level rising gradually. Then, the storage capacity can be controlled by the limit water level of the reservoir in the flood season, the discharge ranging from 800 to 2500 m^3/s is avoided. When the deposition elevation of the reservoir field comes to some extent, sediment deposition can be scoured by lowering the water level according to the situation, the ability of the flow and sediment regulation of the reservoir increased. In order to study the effect of bulk of the regulating storage capacity to the deposition reduction of the lower Yellow River, two programs of minimum scouring water level of 180 m and 190 m are compared, and those two discharge ability are also analyzed.

The operation of “storing highly and scouring quickly” regulates water level according to the maximum water supply benefit. In the flood season, high concentrated flow would be generated by the reservoir focusing emptied and scoured. The reservoir is operated according to high water level with water conservation and sediment deposition. While the flood control level is less than 254 m, the reservoir would discharge according to power generation and water supply. At the time there is situation with sediment deposition of 6 billion m^3, input discharge more than 2300m^3/s and water level raising constantly, the reservoir would discharge empty and be scoured. Then, high concentrated flow forms and sours the deposition, and sediment is excreted.

The operation of “elevating with different phase” partitions the process of the reservoir deposition elevation rising to three phases. At every phase, the process is the same as phase from deposition elevation gradually rising to scouring the reservoir after lowering water level, and the deposition configuration designed becomes in the end. The reservoir operation mode differs little between deposition process and scouring process. The operation mode of elevating with different phase of XLD Reservoir in the main flood season is tabled in Table 3.

Table 3 Operation mode of Elevating with Different Phase of XLD Reservoir in the Main Flood Season

unit：m^3/s

Input condition	Output condition	
	Deposition process	Scouring process
Q_{input}=400	Q_{output}=400	Q_{output}=400
400≤Q_{input}＜800	Q_{output}=Qinput	Q_{output}=Qinput
800≤Q_{input}＜2500	Q_{output}=800	Q_{output}=800
2500≤Q_{input}＜5000	$Q_{output}=Q_{input}$	discharge，$Q_{output} \ngtr 5000$，After empty $Q_{output}=Q_{input}$
5000≤Q_{input}＜8000	When Q_{input}=120kg/m^3，$Q_{output} \ngtr 8000$，After empty $Q_{output}=Q_{input}$；When Q_{input}＜120kg/m^3，$Q_{output}=Q_{input}$	discharge，$Q_{output} \ngtr 8000$，After empty $Q_{output}=Q_{input}$
8000≤Q_{input}＜10000	Q_{output}=8000	Q_{output}=8000
Q_{input}＞10000	Q_{output}=10000	Q_{output}=10000

The operation of “elevating gradually” studies the joint regulating program between

Sanmenxia reservoir and XLD Reservoir and the joint regulating program among Qikou reservoir, Sanmenxia reservoir and XLD Reservoir at the same time.

The operation of "elevating gradually" has fundamentally similarity to the phase of preliminary design.

4 Phase of reservoir construction

Study on the reservoir operation during the phase of reservoir construction inclined to how to practical operate and work after built. A dynamic process is considered during the reservoir operation. At the same time, the operation should be constantly regulated in reason, with the problems coming from the reservoir deposition and scouring development in the lower Yellow River. Based on this thought, firstly, the operation mode during the preliminary phase of reservoir sediment conservation was studied. In addition, the operation program of deposition reduction during the preliminary phase of reservoir sediment conservation was studied out. The plan that has an operating water level 210 m and regulating storage capacity 0.8 billion m^3 avoids the discharge of Hua Yuan Kou station ranging from 800 m^3/s to 2600 m^3/s. The material discharge should be real-time regulated according to flow forecasting and deposition and scouring in the lower Yellow River. The operation programming considers not only enhancing sediment reduction effect of Ai Shan station downstream, but also avoiding the collapse of wide river scouring beaches, and other adverse conditions. While the demand of defending flood and deposition reduction has been met, benefit of synthetically utilization of irrigation and power generation has been enhanced.

According to the research above, the maximum regulating discharge is suggested adopting 2600 m^3/s and regulating storage capacity 0.8 billion m^3, at the beginning of water level of 205 m. The concrete regulating operation plan is:

(1) When the reservoir storage capacity is less than 0.4 billion m^3, the discharge of XLD Reservoir only meets the water supply, namely that reservoir discharge gathered meets Hua Yuan Kou station 800m^3/s. While the discharge of XLD Reservoir is more than 600 m^3/s, it can make two unit generating power.

(2) When the average discharge of Tong Guan station and Sanmenxia station are more than 2500 m^3/s and the reservoir regulating water volume is more than 0.4 billion m^3, reservoir discharge gathered together meets Hua Yuan Kou station more than or equal to 2600m^3/s until the reservoir regulating water volume is equal to 0.2 billion m^3 .

(3) From the second 10-days of June to the first 10-days of September, When the reservoir regulating water volume becomes 0.8 billion m^3, reservoir discharge gathered together meets Hua Yuan Kou station more than or equal to 2600m^3/s until the reservoir regulating water volume is

equal to 0.2 billion m^3 .

(4) In the second 10-days of September, the reservoir may store water ahead date.

(5)When the crossing discharge of Hua Yuan Kou station may surpass the bank-full discharge, which flows from beaches in the lower Yellow River, the reservoir has began to store water for regulating. Moreover, to the best of the operation controls the flood not to flow to beaches.

In the main flood season, XLD Reservoir operates as flow and sediment regulation and defends the flood. At the precondition of meeting defending upper flood in October, the regulating of water storage general considered the water supply in the lower Yellow River and meeting needs of power station. From November to the first 10-days of July next year, joint operation of XLD Reservoir and Sanmenxia reservoir regulates with the attempering flow demand of Sanmenxia station down stream in the non-flood season, which is unified arranged by the scheduling water allocation of the Yellow River.

Through the reservoir field physical model and lower Yellow River physical model and digital model, the reservoir operation mode studied out is verified. Especially, physical model test plays an important role in studying out the reservoir operation mode. The results of the reservoir field physical model tests show: the basic flush mode of the reservoir is density current in the initial stages of reservoir operation, and the entering point ordinary lies in the front of inclination downstream the peak point of the deposition delta The figuration of the reservoir field main flow deposition is delta and constantly advances downstream. When the branch lies in the entering point of main flow density current downstream, the main flow density current will move backward to the branch along the channel bottom. When the peak point of the deposition delta advances quickly and surpasses the mouth of the branch, the deposition elevation of the branch mouth rises highly during a short minute and a ridge that blocks the mouth forms. While the riverbed of the main flow is scoured and drops quickly, as is the deposition elevation and the ridge does not exist. The wandering river of lower Yellow River is obviously scoured from above to below. At the same time, the water level drops at large, and the bank-full discharge and ability of flood crossing increases, with the riverbed coarsening and slope from steep to gentle, the synthesis and stabilization index of the riverbed augments. The measure data after XLD Reservoir operation proves the validity of the tests conclusion above.

5 Phase of XLD Reservoir operation

The XLD Reservoir is formally operated in 2000.After the flood season in 2004, the total deposition is 1.528 billion m^3, and still less than the bound number between the initial stage and upper stage of sediment conservation, which is in the operation regulation of the initial stage of sediment conservation of the XLD project (total deposition of the reservoir field ranges from 2.1 to 2.2 billion m^3). Consequently, the operation stage of XLD Reservoir is also in the initial stage of sediment conservation from 2000 to now. The basic flush mode of the reservoir is density current. In the recent years, taking use of the analysis of measure data of density current of XLD Reservoir and combing the correspond test results, scientists has been studying the basic rules including happening, running and flushing of density current and other conditions, which contributed to the success of flow and sediment regulation.

There goes along three flow and sediment regulation tests from 2002 to 2004.Three basic modes of the flow and sediment regulation tests in Yellow River is concluded through the tests. After three tests, the XLD Reservoir is formally changed to practice. Flow and sediment regulation tests bring the research results in the long term into effect, which translate thoughts of harnessing Yellow River in use of flow and sediment regulation into productivity. This inherits, extends, and deepens the fruits anciently. Scientific study around three flow and sediment regulation tests, has not only successfully directed three tests, but also accumulated ample experience for optimizing the operation mode.

5.1 Research on Density Current in XLD Reservoir

At the stage of reservoir conservation, the reservoir often gets along with the state of water storage and keeps a large water body. While there is runoff and sediment in catchments under Rainfall in Yellow River middle reaches in the flood season, or Sanmenxia reservoir flushes sediment and discharges the flow, many sediments comes into XLD Reservoir, and only does density current shape , the sediment could be flushed out of XLD Reservoir. Barely, if the reservoir management has a better regulation, the rule that density current that transports many sediments without interblending the water above is taken into practice can be better used. This method flushes some portion of sediment with keeping an extent water head. It could achieve the aim to not only keep the benefit of water supply, but also reduce the reservoir deposition extending the life of reservoir.

The flushing of density current in XLD Reservoir obeys not ordinary rules but particularity. The particularity embodies the plane shape complexity, the numerous appearance of enlarging the width or shrinking or bending in the local break landform, where there generates the local energy losing. Especially, there are beyond 10 larger branches gathering into the reservoir. At the converging point of main and branch, density current of main usually pours inverse the branch. This makes the changes of density current particularity more complex. Through trimming, analyzing and secondly processing of the measured data of density current in XLD Reservoir, and the results of flume channel tests and physical model and other corresponding tests, combing the verification of the formula provided by formers, the formula that can quantify and describe the exact index of flushing, resistance, sediment concentration , Propagation time, pouring the branch inversely, velocity in different water and sediment combination, impact of flushing of density current is brought forward

（1）Integration resistance

The number of the average resistance of density current λ_m adopts the formula created by Fan Jia Hua:

$$\lambda_m = 8\frac{R'}{h_e}\frac{\eta_g g h_e}{V_e^2}\left(J_0 - \frac{dh_e}{ds}\left(1 - \frac{V_e^2}{\eta_g g h_e}\right)\right) \qquad (1.1)$$

Where, J_0 delegates the riverbed slope, dh_e/ds the change of density current depth along, h_e, V_e respectively depth and velocity of density current, η_g the gravity-amending coefficient. Integration resistance along the reservoir λ_m in different measured data of different density current had been computed with formula（1.1）.the average results ranges from 0.022 to 0.029.

（2）Sediment-Carrying Force of Density Current

Applied the energy dissipation principle, sediment-carrying force formula (1.2) of density current is achieved. The formula can reflect the sediment transport function of "more input, more output" of density current, and had been verified with data of measured in XLD Reservoir and physical model.

$$S_{*e} = 2.5\left[\frac{S_{ve}V_e^3}{\kappa\frac{\gamma_s-\gamma_m}{\gamma_m}g' h_e\omega_s}\ln\left(\frac{h_e}{eD_{50}}\right)\right]^{0.62} \qquad (1.2)$$

The formula above adopts the unit of kg, m, s. Hereinto, the settlement velocity could be computed by:

$$\omega_s = \omega_o\left[\left(1 - \frac{S_{ve}}{2.25\sqrt{d_{50}}}\right)^{3.5}(1 - 1.25S_{ve})\right] \qquad (1.3)$$

Where, κ is Kaman constant in sediment-laden flow, γ_m is Specific gravity in sediment-laden flow, ω_s is colony settlement velocity in sediment-laden flow, ω_0 is sediment settlement velocity in water, D_{50} is the middle average diameter of bed sediment, d_{50} is the middle average diameter of suspend sediment, S_{υ_e} is sediment concentration denoted with the volume ratio percent, others as former.

（3）Propagation Time of the Density Current

The bulk of propagation time of the density current T_2 mainly reflects by the input flood peak, sediment concentration, the backwater length in reservoir area, slope of reservoir bed and other factors. The movement of forward density current belongs to non-instable flow movement, but approximately can be considered to be computed by formula (1.4).

$$T_2 = C\frac{L}{(qS_iJ)^{\frac{1}{3}}} \quad (1.4)$$

Where, L is the length between the entering point and the dam, q is discharge per unit, S_i is sediment concentration of the entering section, J is slope of reservoir bed（‰）, C is coefficient calibrated with measured data in XLD Reservoir.

（4）the Flushing Compute of Density Current

The formula named Han Qi Wei that can describe the change of sediment concentration and grain gradation along the movement had been validated by the measured data of density current in Sanmenxia reservoir, Guan Ting reservoir and Hong Shan reservoir.

$$S_j = S_i\sum_{l=1}^{n} P_{l.i}e^{(-\frac{\alpha\omega L}{q})} \quad (1.5)$$

$$P_l = P_{l.i}(1-\lambda)^{\left[\left(\frac{\omega_l}{\omega_m}\right)^v - 1\right]} \quad (1.6)$$

Where, $P_{l,i}$ is grain gradation percent of the entering section, α is coefficient of saturation, validated by the measured data, l is number of grain gradation group, ω_l is settlement velocity of l^{th} group grain diameter, P_l is grain gradation percent of the discharge section, ω_m is virtual settlement velocity, λ is deposition percent, v is 0.5.

(5) Critical Water and Sediment Input Conditions on Density Current keeping Moving to the Dam

Density current in reservoir comes into being and creeps to the dam, with not only a period of flood, but also some extent discharge and sediment concentration. Meaning, density current needs the energy provided by the water and sediment process that generates density current enough to conquer the energy loss of density current movement.

Velocity and sediment-laden force of density current has a direct ratio to its sediment concentration. Moreover, the velocity and sediment concentration process that generates density current mends each other. Based on the measured data of output in Sanmenxia station when density current takes place, critical water and sediment input conditions on density current keeping moving to the dam is achieved:

On the base of conditions that the input process of XLD Reservoir lasts a period of time and weightiness percent of suspend sediment which d <0.025mm is about 50%,when 500 $m^3/s \le Q_i$ <2000m^3/s , $S_i \ge 280 - 0.12Q_i$ or Q_i >2000m^3/s and S_i >40 kg/m^3 is met. Furthermore, if the process is in the peak dropping period, resistance that density current needs to conquer during the movement is less than that the forward of density current needs. Or while the bed between the input of the reservoir and backwater area is scoured, and this makes sediment concentration of the entering point section increasing or weightiness percent of the input fine sand is all above 75%, too. Then, density current could creep to the dam.

The function relations of input discharge Q_i, sediment concentration S_i and weightiness percent of suspend sediment which d < 0.025mm d_i could be basically described by $S_i = 980e^{-0.025d_i} - 0.12Q_i$.

The reflection of density current transportation conditions correlates with not only the input water and sediment condition but also the boundary conditions in the reservoir. If the boundary conditions change much, critical water and sediment input conditions on density current changes along.

5.2 Flow and sediment regulation in Yellow River

It plays an important role to XLD Reservoir that lies in a connecting link between the preceding and the following location and has a key place of controlling the water and sediment in Yellow River. Therefore, the sticking point of flow and sediment regulation in Yellow River is the regulation of XLD Reservoir. During the preliminary phase of reservoir sediment conservation, the main flushing mode in XLD Reservoir is the density current flushing, and that means the regulation of sediment aims to generate and attemper the density current in practice during flow and sediment regulation.

To XLD Reservoir, the sediment that generates density current comes from not only the upstream but also itself supply. In principle, two ways come from the upstream and into the reservoir. The first is that there is a flood in the middle Yellow River. Through the optimization regulation of reservoirs, the flushing ratio of density current can be enlarged and the extended life of reservoir and other aims are achieved. The second is the sediment deposition in Sanmenxia reservoir during the non-flood season. If several reservoirs are joint regulated, the water and sediment process that met the demanding of density current flushing could have been made to reducing the deposition in reservoir. The sediment originated from it is the sediment deposition piles in the upper of reservoir. They suspend with the scouring of the larger input discharge. Some finer of them would be flushed as density current.

During the process of three flow and sediment regulation tests, aiming to different origins of water and sediment, the status of reservoir water storage and different boundary conditions, different modes had been brought forward. During the process of flow and sediment regulation test, not only are nature density currents regulated in reason, but also had density current been modeled and flushed out of the reservoir successfully, with taking use of the water storage above the flood limit water level before the flood season and reservoir sediment conservation in the non-flood season. Many anticipating aims are got including reservoir deposition reduction, increasing the bedclothes behind the dam, adjusting reservoir deposition figuration and optimizing the combination of the water and sediment output .

The water and sediment conditions, aims and steps adopted of three flow and sediment regulation tests finished are not the same, but those contain the basic modes of flow and sediment regulation in Yellow River during the preliminary phase of XLD Reservoir sediment conservation.

Guaranteeing non-deposition in the whole of the lower Yellow River or scored is one of the first flow and sediment regulation test's main aims. So keeping the discharge of Huayuankou station less than 2600m^3/s, a period more than 10 days, and average sediment concentration less than 20kg/ m^3 is demanded in the real-time regulation contingency plan. On the process of test, based on the following research on the density current transport, the regulation of sediment concentration output had been achieved and the regulation index had been met through the regulation of the holes in the discharge constructions. It has been defined a test mode based on the regulation with priority to single XLD Reservoir.

Second flow and sediment regulation test in Yellow river had been based on the understanding of the rules on the suspend sediment settlement in the turbid reservoir. When density current comes to the dam, sediment could centralize in front of dam without flushing out of the reservoir in time. Because of the suspend sediment in the turbid flow being finest, these settlement velocity is smallest and goes down as a whole of turbid surface form. In use of the phenomena of density current in XLD Reservoir, and raising the gates with different bottom elevation, and making an extent period process of different discharges and sediment concentrations, and loaded above the water the convergences between Yilou River and Qin River, and controlling the discharge meeting exactly in the Huayuankou section, a more harmonious combination of water and sediment had been come into being. At the same time, reservoir flushing and lower Yellow river scoured had been actualized. This test process has been defined a test mode based on the water and sediment meeting each other with a space scale.

On the situation that there is not a flood from the middle Yellow River before third flow and sediment regulation test in Yellow river, with the exact joint regulation of Wanjazhai reservoir, Sanmenxia reservoir and XLD Reservoir, managers had made best of the energy of the water storage discharge above the flood limit water level between Wanjiazhai reservoir and Sanmenxia reservoir. With the help nature force, sediment deposition piled on the upper beach in XLD Reservoir and deposed in the Sanmenxia reservoir in the non-flood season had been scoured. Density current had formed and flushed out of the reservoir. The aim of reservoir deposition reduction and the deposition figuration in the reservoir field adjusted had been achieved. This test has been defined a test mode based on the joint regulation of reservoir groups in main river.

The reservoir had been formally operated into production practice in 2005. According as the status of reservoir storage before the flood season, boundary conditions and water and sediment process forecasted, the third test mode had been chose. It had finished all right.

The three tests and the practice in 2005 successfully finished is a sign of the deepening and extending to the understanding on the density current transport rule. With the design of flow and sediment regulation and technology of water regulation sound and grown up gradually, this will establish a stable foundation for the production practice of flow and sediment regulation

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黄河小浪底水库运用方式研究综述*

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摘要　小浪底水利枢纽工程处在承上启下控制黄河水沙的关键部位。在工程规划设计过程中，围绕水库的开发目标，特别是水库减淤问题，针对水库运用方式进行了大量的研究。水库投入运用以来，进行了三次调水调沙试验，以及2005年调水调沙生产运行，不仅将长期的研究成果付诸实施，而且进一步深化了对黄河水沙运行规律的认识。

关键词　小浪底水库 运用方式 调水调沙 减淤

1　引言

小浪底水库是修建于多泥沙河流上的大型水流枢纽，由于工程所面临的问题极为复杂，加之受1960年投入运用的三门峡水利工程的负面影响，小浪底水库工程规划自1954年至工程开工，历时40余年。1954年～1960年拟定小浪底水利枢纽为以发电为主的径流电站；1969年～1974年进行了三门峡至小浪底之间的一级和二级开发方案的比较论证；1975年～1981年，首次明确提出从黄河下游减淤出发，小浪底工程修建高坝，开发任务为防洪、防凌、减淤、灌溉、发电，综合利用。进行了水库一次抬高水位蓄水拦沙运用和逐步抬高水位拦粗排细运用方案比较；1982年～1984年进行小浪底水利枢纽工程可行性研究，开发任务明确为以防洪（包括防凌）、减淤为主，兼顾供水、灌溉和发电，并进行了各项指标的论证；1985年～1988年进行了小浪底水利枢纽工程设计任务书的研究和初步设计；1989年～1996年进行了小浪底水利枢纽工程招标设计阶段的工程规划。此外，在国家“八五”科技攻关期间及水库施工阶段，围绕水库减淤问题进行了大量的研究，为水库优化调度奠定了基础。水库投入运用以来，黄河进行了三次调水调沙试验，2005年进行了调水调沙生产运行，不仅将长期的研究成果付诸实施，而且进一步深化了对黄河水沙运行规律的认识。半个多世纪的历程，既是曲折复杂的研究过程，又是不断深化的认识过程，为小浪底水库优化调度奠定了基础。

2　小浪底水库初步设计及招标设计阶段

2.1 设计水沙条件

小浪底水库初步设计选择2000年设计水平1950年～1975年25年系列翻番组合50年代表系列，龙、华、河、状四站年平均水沙量分别为335.5亿m^3及14.75亿t，经过四站至潼关及三门峡水库的调整，进入小浪底库区年平均水沙量分别为315.0亿m^3及13.35亿t。

招标设计阶段采用2000年水平1919年～1975年56年系列，并从水库运用初期遭遇丰或平或枯水沙条件的角度考虑，从56年系列中组合6个不同的50年系列进行水库淤积及黄河下游减淤效益的敏感性分析。56年系列龙、华、河、状四站年平均水沙量分别为302.2亿m^3及13.90亿t。6个50年系列平均，小浪底入库年水沙量分别为289.2亿m^3及12.74亿t。

2.2 水库运用方式

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黄河水少沙多，水沙异源，来水来沙的自然组合与黄河下游的河道输沙能力极不协调，是黄河下游河道淤积的根本原因。小浪底水库主汛期（7 月 11 日～9 月 30 日）采用以调水为主的调水调沙运用方式。水库拦沙期，通过调水调沙提高拦沙减淤效益，正常运用期，通过调水调沙持续发挥调节减淤效益。

小浪底水库以调水为主的调水调沙运用目标是：发挥大水大沙的淤滩刷槽作用、控制河道塌滩及上冲下淤、满足下游供水灌溉、提高发电效益、改善下游河道水质和生态环境等。

调水调沙调度方式可概括为：增大来流小于 400 m^3/s的枯水，保证发电，改善水质及水环境；泄放 400 m^3/s～800 m^3/s的小水，满足下游用水；调蓄 800 m^3/s～2000 m^3/s的平水，避免河道上冲下淤；泄放 2000 m^3/s～8000 m^3/s的大水，有利河槽冲刷或淤滩刷槽；调节 400 kg/m^3以上的高含沙水流；滞蓄 8000 m^3/s以上的洪水。显然，水库调度下泄流量的基本原则是两极分化，水库主汛期调节方式见表 1。

表 1　小浪底水库主汛前调度方式

入库流量$Q_{入}$（m^3/s）	出库流量$Q_{出}$（m^3/s）	调节目的
＜400	400	① 保证最小发电流量；② 维持下游河道基流，改善水质及水环境。
400～800	400～800	① 满足下游用水要求；② 下游淤积量较小。
800～2000	800	① 消除平水流量，避免下游河道上冲下淤； ② 控制蓄水量不大于 3 亿m^3，若大于 3 亿m^3，按 5000 m^3/s或 8000 m^3/s造峰至蓄水量 1 亿m^3。
2000～8000	2000～8000	较大流量敞泄，使全下游河道冲刷。
＞8000	8000	大洪水滞洪或蓄洪运用。

10 月～7 月上旬为水库调节期，其中 10 月 1 日～15 日预留 25 亿m^3库容防御后期洪水，1 月～2 月防凌运用，其他时间主要按灌溉要求调节径流，并保证沿程河道及河口有一定的基流，6 月底预留不大于 10 亿m^3的蓄水供 7 月上旬补水灌溉。

2.3 水库运用阶段

为最大限度地发挥水库拦沙减淤效益并满足水库发电的需要，水库采取逐步拦高主汛期水位运用方式。

① 蓄水拦沙阶段。起调水位为 205m，进行蓄水拦沙调水调沙运用。

② 逐步拦高阶段。当坝前淤积面高程达 205m 以后，水库转为逐步抬高主汛期水位拦沙调水调沙运用。坝前淤积面高程由 205m 逐步抬升至 245m，主汛期运用水位亦随淤积面的抬高而逐渐升高。

③ 淤滩刷槽阶段。随着库区壅水淤积及敞泄冲刷，滩地逐步淤高而河槽逐步下切，最终形成坝前滩面高程为 254m，河底高程为 226.3m 的高滩深槽形态。

④ 正常运用期。水库正常运用期采用调水调沙多年调沙运用。主汛期一般水沙条件下，利用滩面以下 10 亿m^3库容进行调水调沙运用，遇大洪水进行防洪调度运用。水库各运用阶段坝前淤积面高程及淤积量见表 2。

表 2　水库各阶段淤积量表（各设计系列年平均）

阶段	坝前淤积面高程（m）		年序	累积淤积量（亿m^3）
	槽	滩		

蓄水拦沙	≤205		1～3	17
逐步抬高水位拦沙	205～245		4～15	76
形成滩槽	226.3～245	245～254	16～28	76～81
正常运用	226.3～248	254	29～50	76～81

2.4 水库减淤效益

采用2000年设计水平6个50年代表系列进行水库淤积效益分析的结果表明，水库运用50年，各系列水库淤积104.3亿t～99.9亿t，黄河下游的总减淤量为72.1亿t～84.6亿t，全下游相当不淤年数18.3～22.3。

以设计的6个系列平均计，水库拦沙101.7亿t，下游减淤78.7亿t，拦沙减淤比1.3，全下游相当20年不淤积。其中，前20年水库拦沙100亿t，下游利津以上减淤约69亿t，进入河口段沙量减少31亿t；后30年小浪底库区为动平衡，调水调沙的作用，可使下游减淤9.2亿t。

3 “八五”攻关期间

在国家“八五”重点攻关项目的研究过程中，平行研究了小浪底水库“控蓄速冲”、“高蓄速冲”、 “分段抬高”、“逐步抬高”运用方式。

“控蓄速冲”运用方式主导思想是增大调节库容，增强对水沙的调节能力，把泥沙调到大流量洪水期输送，并强调调水作用，视水库汛期限制水位下调节库容大小决定造峰流量。水库逐步抬高水位运用，按汛限水位控制蓄水，避免下泄800～2500m^3/s流量。当库区淤积面抬高到一定高程后，相机降低水位冲刷库区淤沙，提高水库的调水调沙能力。为了研究调节库容大小对下游河道的减淤作用，还进行了最低冲刷水位180m和190m方案及两种泄流能力的比较。

“高蓄速冲”运用方式是水库按最大兴利效益调水，洪水期集中泄空冲刷产生高含沙水流。水库按高水位蓄水拦沙运用，汛期蓄水位不超过254m，按发电及供水要求泄水。当库区淤积量大于60亿m^3、来水流量大于2300m^3/s且继续上涨时泄空冲刷，形成高含沙水流冲刷排沙。

“分段抬高”运用方式是将水库淤积高程的抬升过程分三个阶段，在每一阶段均经历由逐渐淤积抬升至降水冲刷过程，最终达到设计的淤积形态。水库调节方式在其淤积及冲刷过程中略有不同，见表3。

表3　小浪底水库分段抬高主汛期水位运用方式　　单位：m^3/s

入库条件	出库条件	
	淤积过程	冲刷过程
$Q_{\text{入}}$=400	$Q_{\text{出}}$=400	$Q_{\text{出}}$=400
400≤$Q_{\text{入}}$＜800	$Q_{\text{出}}$=$Q_{\text{入}}$	$Q_{\text{出}}$=$Q_{\text{入}}$
800≤$Q_{\text{入}}$＜2500	$Q_{\text{出}}$=800	$Q_{\text{出}}$=800
2500≤$Q_{\text{入}}$＜5000	$Q_{\text{出}}$=$Q_{\text{入}}$	泄水，$Q_{\text{出}}$≯5000，泄空后$Q_{\text{出}}$=$Q_{\text{入}}$
5000≤$Q_{\text{入}}$＜8000	$Q_{\text{入}}$=120kg/m^3时泄水，$Q_{\text{出}}$≯8000，泄空后$Q_{\text{出}}$=$Q_{\text{入}}$； $Q_{\text{入}}$＜120kg/m^3时，$Q_{\text{出}}$=$Q_{\text{入}}$	泄水，$Q_{\text{出}}$≯8000，泄空后$Q_{\text{出}}$=$Q_{\text{入}}$
8000≤$Q_{\text{入}}$＜10000	$Q_{\text{出}}$=8000	$Q_{\text{出}}$=8000
$Q_{\text{入}}$＞10000	$Q_{\text{出}}$=10000	$Q_{\text{出}}$=10000

“分段抬高”运用方式同时研究了三门峡、小浪底水库联合调度方案及碛口、三门峡及小浪底水库联合调度方案。

“逐步抬高”运用方式与初步设计研究阶段基本相同。

4　工程施工期

在小浪底水库施工期所进行的水库运用方式的研究，更侧重于建成后如何进行实际操作和运用。认为小浪底水库运用是一个动态过程，应随水库淤积及下游河道冲刷发展过程中出现的问题不断作出合理调整。基于这种思路，首先开展水库拦沙初期运用方式的研究，拟定了拦沙初期水库减淤运用方案。推荐起始运行水位 210m调控库容 8 亿m^3，避免花园口断面800m^3/s～2600m^3/s的流量下泄。具体调控流量应根据水情预报及下游河道冲淤变化情况加强实时调度。运用方案的拟定，既考虑提高艾山以下河道的减淤效果，又注意避免宽河道冲刷塌滩等不利情况。在满足防洪减淤要求的同时，提高了灌溉、发电的综合利用效益。

根据研究结果，推荐调控上限流量采用 2600m^3/s，调控库容采用 8 亿m^3，自 205m水位起始运行。具体的调节操作方法是：

(1) 当水库蓄水量小于 4 亿m^3时，小浪底出库流量仅满足供水需要，即凑泄花园口流量800m^3/s，同时小浪底出库流量不小于 600m^3/s，满足 2 台机组发电。

(2) 当潼关、三门峡平均流量大于 2500m^3/s且水库可调节水量不小于 4 亿m^3时，水库凑泄花园口流量大于或等于 2600m^3/s，至水库可调水量余 2 亿m^3。

(3) 7 月中旬至 9 月上旬水库可调节水量达 8 亿m^3，水库凑泄花园口流量大于或等于2600m^3/s，至水库可调水量余 2 亿m^3。

(4) 9 月中下旬水库可提前蓄水。

(5) 当花园口断面过流量可能超过下游平滩流量时，小浪底水库开始蓄洪调节，尽量控制洪水不漫滩。

小浪底水库在主汛期进行防洪和调水调沙运用，10 月份在满足防御后期洪水的前提下，综合考虑下游用水和兼顾电站发电要求进行蓄水调节。11 月至翌年 7 月上旬，与三门峡水库联合运用，按照黄河干流水量分配调度预案统一安排的三门峡以下非汛期水量调度要求进行调度运用。

对拟定的水库调度方式，通过小浪底库区及黄河下游河道实体模型及数学模型的检验。特别是所进行的实体模型试验，对确定水库运用方式具有重要作用。模型试验结果表明：水库运用初期基本上为异重流排沙，潜入点一般位于三角洲顶点下游的前坡段；库区干流淤积形态为三角洲且不断向下游推进；若支流位于干流异重流潜入点下游，则干流异重流会沿河底倒灌支流，当干流三角洲顶点迅速推近并跃过支流沟口，沟口淤积面高程骤然大幅度抬升而形成拦门沙坎，当干流河床冲刷大幅度下降时，支流口淤积面随之下降，拦门沙坎不复存在；黄河下游游荡性河道将自上而下发生明显的沿程冲刷，水位普遍下降，平滩流量及过洪能力增加，河床粗化，比降变缓，河床综合稳定性指标增大。小浪底水库运用以来的实测资料证明了上述试验结论的正确性。

5 小浪底水库运用期

小浪底水库 2000 年正式投入运用，至 2004 年汛后，库区总淤积量为 15.28 亿m^3，仍小于《小浪底水利枢纽拦沙初期运用调度规程》中拦沙初期与拦沙后期的界定值(库区淤积量

达到 21 亿m^3～22 亿m^3）。因此，小浪底水库自投入运用至今，均处于拦沙初期运用阶段，水库排沙基本为异重流输沙流态。近年来，通过对小浪底水库异重流实测资料分析，并结合相关试验成果，研究了异重流发生、运行及排沙等基本规律，为黄河调水调沙的顺利实施奠定了基础。

2002 年～2004 年进行了三次调水调沙试验。通过试验总结出了小浪底水库拦沙初期黄河调水调沙的三种基本模式。继三次试验之后，2005 年调水调沙正式转入生产运行。黄河调水调沙试验，将长期研究成果付诸于治河实践，将调水调沙治黄思想由理论转化为生产力，是以往研究工作的继承、延伸与深化，围绕黄河三次调水调沙试验所进行的科学研究，不仅成功指导了三次试验，而且为优化水库运用方式积累了丰富的经验。

5.1　小浪底水库异重流研究

水库拦沙初期，水库经常处于蓄水状态，且保持较大的蓄水体。当汛期黄河中游降雨产沙或者三门峡水库泄水排沙时，大量泥沙涌入小浪底水库后，惟有形成异重流方能排泄出库。显而易见，若水库调度合理，可充分利用异重流能挟带大量泥沙而不与清水相混合的规律，可在保持一定水头的条件下排泄部分泥沙，达到既能保持兴利效益又能减少水库淤积，延长水库寿命的目的。

小浪底水库异重流排沙既遵循普遍性规律又有特殊性。其特殊性体现在库区平面形态复杂，频繁出现局部放大、收缩或弯曲等突变地形，在地形变化剧烈处会产生局部损失。尤其是库区十余条较大支流入汇，在干支流交汇处往往发生异重流向支流倒灌，使异重流沿程变化特性更为复杂。通过对小浪底水库异重流实测资料整理、二次加工及分析，以及水槽试验及实体模型相关试验成果，结合对前人提出的计算公式的验证等，提出了可定量描述小浪底水库天然来水来沙条件及现状边界条件下，异重流排沙的临界指标及其阻力、挟沙力、传播时间、干支流倒灌、不同水沙组合条件下异重流运行速度及排沙效果的表达式。

（1）　综合阻力

异重流平均阻力系数值λ_m采用范家骅的阻力公式：

$$\lambda_m = 8\frac{R'}{h_e}\frac{\eta_g g h_e}{V_e^{\,2}}\left(J_0 - \frac{dh_e}{ds}\left(1-\frac{V_e^{\,2}}{\eta_g g h_e}\right)\right)$$

（1）

式中J_0为河底比降，dh_e/ds为异重流厚度沿程变化，h_e、V_e分别为异重流厚度及流速，η_g为重力修正系数。用式（1）计算小浪底水库不同测次异重流沿程综合阻力系数λ_m，平均值约为 0.022～0.029。

（2）异重流挟沙力

运用能耗原理，建立异重流挟沙力公式（2）。该式可反映异重流多来多排的输沙规律，并利用三门峡、小浪底水库实测及模型试验资料进行了检验。

$$S_{*e} = 2.5\left[\frac{S_{ve}V_e^{\,3}}{\kappa\dfrac{\gamma_s-\gamma_m}{\gamma_m}g'h_e\omega_s}\ln\left(\frac{h_e}{eD_{50}}\right)\right]^{0.62}$$

(2)

上式单位采用 kg、m、s 制，其中沉速可由下式计算

$$\omega_s=\omega_o\left[\left(1-\frac{S_{ve}}{2.25\sqrt{d_{50}}}\right)^{3.5}\left(1-1.25S_{ve}\right)\right]$$

(3)

式中，κ 为浑水卡门常数，γ_m 为浑水容重；ω_s 为泥沙在浑水中的群体沉速，ω_0 为泥沙在清水中的沉速；D_{50} 为床沙中径；d_{50} 为悬沙中径；S_{υ_e} 为以体积百分比表示的异重流含沙量；其它符号意义同前。

（3）异重流传播时间

异重流传播时间T_2的大小主要受来水洪峰、含沙量、水库回水长度、库底比降等多种因素的影响，异重流前锋的运动是属于不稳定流运动，但作为近似考虑可按式（4）计算。

$$T_2=C\frac{L}{(qS_iJ)^{\frac{1}{3}}}$$

（4）

式中，L 为异重流潜入点距坝里程；q 为单宽流量；S_i 为潜入断面含沙量；J 为库底比降（$‰$）；C 为系数，采用小浪底水库异重流观测资料率定。

（4）异重流排沙计算

采用韩其为含沙量及级配沿程变化计算公式，并利用三门峡水库、官厅水库、红山水库等异重流资料进行了验证。

$$S_j=S_i\sum_{l=1}^{n}P_{l.i}e^{(-\frac{\alpha\omega L}{q})}$$

（5）

$$P_l=P_{l.i}(1-\lambda)^{\left[\left(\frac{\omega_l}{\omega_m}\right)^{\nu}-1\right]}$$

（6）

式中，$P_{l,i}$ 为潜入断面级配百分数；α 为饱和系数，由实测资料率定；l 为粒径组号；ω_l 为第 l 组粒径沉速；P_l 为出口断面级配百分数；ω_m 为有效沉速；λ 为淤积百分数；ν 取 0.5。

（5）异重流持续运动至坝前的临界水沙条件

水库产生异重流并能达到坝前，除需具备一定的洪水历时之外，还需满足一定的流量及含沙量，即形成异重流的水沙过程所提供给异重流的能量，足以克服异重流的能量损失。

异重流的流速及挟沙力与其含沙量成正比，形成异重流的流速与含沙量具有互补性。基于小浪底水库发生异重流时入库水沙资料，得到异重流持续运动至坝前的临界条件为：小浪底水库入库洪水过程在满足一定历时且悬移质泥沙中 d ＜0.025mm的沙重百分数约为 50％的前提下： 若 500 m^3/s ≤Q_i＜2000m^3/s，且满足$S_i\geq 280-0.12Q_i$或Q_i＞2000m^3/s，且满足S_i＞40 kg/m^3。此外，若是处于洪水落峰期，此时异重流行进过程中需要克服的阻力要小于其

前锋所克服的阻力，或在水库进口与水库回水末端之间的库段产生冲刷，使异重流潜入点断面含沙量增大或入库细泥沙的沙重百分数基本在 75%以上时，异重流亦有可能运行至坝前。

入库流量 Q_i、水流含沙量 S_i、悬移质泥沙中 d ≤0.025mm 的沙重百分数 d_i 三者之间的函数关系基本可用式 $S_i = 980e^{-0.025d_i} - 0.12Q_i$ 描述。

影响异重流输移条件不仅与水沙条件有关，而且与边界条件关系密切，若边界条件发生较大变化，上述临界水沙条件亦会发生相应变化。

5.2　黄河调水调沙

小浪底水库处在承上启下控制黄河水沙的关键部位，因此黄河调水调沙的关键是对小浪底水库的调度。在小浪底水库拦沙初期，水库基本上为异重流排沙，故调水调沙过程中对泥沙的调节实际上是针对异重流的塑造或输移的调度。

对小浪底水库而言，产生异重流的泥沙可来自其上游，亦可来于自身的补给。来自水库上游而进入小浪底库区的泥沙大体上有两种来源，其一是黄河中游发生洪水。通过水库的优化调度，可增加异重流排沙比，达到延长水库寿命等目标；其二是非汛期淤积在三门峡水库中的泥沙。若通过多座水库联合调度，可塑造出满足异重流排沙的水沙过程，以减少水库淤积。来于自身的泥沙为堆积在水库上段的淤积物，可随着入库较大流量的冲刷而悬浮，其中较细者会以异重流的形式排泄出库。

黄河三次调水调沙试验过程中，针对不同的水沙来源、水库蓄水状况及不同的边界条件，提出不同的调水调沙模式。黄河调水调沙过程除对天然异重流进行了合理调度外，还利用汛前水库汛限水位以上的蓄水及非汛期水库拦截的泥沙，通过水库联合调度，塑造出异重流且实现了排沙出库，达到了减少水库淤积、增加坝前铺盖、调整淤积形态、优化出库水沙组合等多项预期目标。

已开展的三次调水调沙试验，其水沙条件、试验目标及采用的措施不尽相同，涵盖了小浪底水库拦沙初期黄河调水调沙的基本模式。

黄河首次调水调沙试验以保证黄河下游河道全线不淤积或冲刷为主要目标之一，因此实时调度预案要求控制黄河花园口站流量不小于 2600㎥/s，历时不少于 10 天，平均含沙量不大于 20kg/㎥。试验过程中，在对异重流输移过程的跟踪研究基础之上，通过对泄水建筑物众多孔洞的调度，实现了对出库水流含沙量的调控，满足了调度指标。被定义为基于小浪底单库调节为主的试验模式；

黄河第二次调水调沙试验基于对浑水水库中悬浮泥沙沉降规律的认识，水库异重流运行至坝前后，若未能及时排出库外，则会集聚在坝前形成浑水水库。由于浑水中悬浮的泥沙颗粒非常细，泥沙往往以浑液面的形式整体下沉，且沉速极为缓慢。利用小浪底水库异重流及其坝区的浑水水库，通过启闭不同高程泄水孔洞，塑造一定历时的不同流量与含沙量过程，加载于小浪底水库下游伊洛河、沁河入汇的“清水”之上，并使其在花园口站准确对接，形成花园口站较为协调的水沙关系，同时实现水库排沙与下游冲刷。这次试验过程被定义为基于空间尺度水沙对接的试验模式；

黄河第三次调水调沙试验，是在黄河中游未发生洪水的情况下，通过万家寨、三门峡与小浪底水库精确联合调度，充分利用万家寨、三门峡水库汛限水位以上水量泄放的能量，借助自然的力量，冲刷三门峡水库非汛期淤积的泥沙与堆积在小浪底库区上段的泥沙，塑造异

重流并排沙出库，实现了水库减淤及调整库区淤积形态的目标。这次试验被定义为基于干流水库群水沙联合调度的模式。

2005 年调水调沙正式转入生产运行。依据汛前水库蓄水状况、边界条件及预测的来水来沙条件，选用了黄河第三次调水调沙试验模式，并得以顺利实施。

三次调水调沙试验及 2005 年调水调沙的顺利实施，标志着对水库异重流运行规律的认识得到了扩展和深化，以及调水调沙设计与调度技术日臻成熟与完善，为调水调沙生产运行奠定了坚实的基础。

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