Practice and Exploration of Integrated Operation of the Lower Jinsha River - Three Gorges Cascade Multifunctional Reservoirs

Pratique et exploration de l'exploitation conjointe de réservoirs multifonctionnels en cascade du cours inférieur de la rivière Jinsha aux Trois Gorges

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Abstract. The Lower Jinsha River - Three Gorges Cascade Multifunctional Reservoirs include 4 reservoirs: Xiluodu, Xiangjiaba, Three Gorges and Gezhouba, which have many functions such as flood control, power generation, navigation, ecology, water supply, and public safety. In order to give full play to the comprehensive benefits of the cascade reservoirs, the operation and management authority carries out integrated operation. In dry season, the power generation, navigation, ecology, and water supply needs are considered as a whole, and integrated drawdown operation are carried out. In flood season, take the needs of flood control, power generation, shipping and public safety into consideration, carrying out integrated flood prevention operation and connecting with water impoundment operation. This article summarized the practical experience of integrated operation of cascade multi-functional reservoirs, introduced the technical support system, and explored the development of a broader integrated operation of reservoirs. Key words: Cascade reservoir; multi-function; Integrated Operation; comprehensive benefits

Résumé. Les réservoirs en cascade du cours inférieur de la rivière Jinsha aux Trois Gorges comprennent les réservoirs de Xiluodu, Xiangjiaba, Trois Gorges et Gezhouba, avec des fonctions telles que le contrôle des inondations, la production d'électricité, la navigation, l'écologie, l'approvisionnement en eau et la sécurité publique. Afin de tirer pleinement parti des avantages globaux des réservoirs en cascade, l'unité d'exploitation

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et de gestion de la centrale a réalisé l'exploitation conjointe des réservoirs en cascade. En saison sèche, les besoins en matière de production d'électricité, de navigation, d'écologie et d'approvisionnement en eau sont considérés comme un tout, et des opérations intégrées de rabattement sont réalisées. En période de crue, les besoins en matière de contrôle des inondations, de production d'électricité, de navigation et de sécurité publique sont pris en considération, et des opérations intégrées de prévention des inondations sont menées, en liaison avec des opérations de retenue d'eau. Cet article résume l'expérience pratique de l'exploitation conjointe de réservoirs multifonctionnels en cascade, présente le système de soutien technique pour l'exploitation conjointe et explore le développement d'une gamme plus large d'opérations conjointes de réservoirs. Mots clés : Réservoirs en cascade ; Multifonction ; Opération conjointe ; Avantages intégrés.

1 Basic information of the cascade reservoirs

The cascade reservoirs from the lower reaches of Jinsha River to the Three Gorges include Xiluodu, Xiangjiaba, Three Gorges and Gezhouba, as shown in Figure 1. Xiluodu and Xiangjiaba hydropower stations are located in the lower reaches of Jinsha River, which is the mainstream of the upper Yangtze River. The Three Gorges and Gezhouba hydropower stations are located in the middle reaches of the Yangtze River. The length of the river from Xiluodu to Xiangjiaba reservoir is 148km, from Xiangjiaba to Sanxia reservoir is 622km, and from the Three Gorges to Gezhouba reservoir is 38km. The cascade reservoirs are under the management of China Three Gorges Corporation, with a total installed capacity of 45.5 GW and flood control capacity of 27.70 billion m3. The flood control capacity of Xiluodu and Xiangjiaba reservoirs is 5.55 billion m3, accounting for about 1 / 4 of the flood control capacity of the Three Gorges reservoir. Xiluodu, Xiangjiaba and Three Gorges reservoirs have seasonal regulation capacity. Gezhouba is a run-of-river hydropower station without regulation capacity. Its task is to reverse regulate the unsteady outflow of the Three Gorges, so as to give full play to the power generation benefits under the condition of ensuring the safety and smooth navigation.

Fig. 1. Location map of the cascade reservoirs.

Table. 1. Development scale of the cascade reservoirs.

Reservoir	XLD	XJB	TGP	GZB
Regulated storage capacity (billion m3)	6.46	0.9	22.15	0.084
Flood control capacity (billion m3)	4.65	0.9	22.15	\
Installed capacity (MW)	13860	6400	22500	2735
Count of Units	18	8	34	22

2 Comprehensive functions of the cascade reservoirs

2.1 Flood control function

Xiluodu and Xiangjiaba reservoirs are the backbone projects for flood control in the Chuanjiang River (the Yangtze River section from Yibin City, Sichuan Province to Chongqing city) and the middle and lower reaches of the Yangtze River. Their main flood control object is the Chuanjiang River. At the same time, the two reservoirs cooperate with the Three Gorges reservoir for flood control of the middle and lower reaches of the Yangtze River. During the flood season, the integrated operation of Xiluodu and Xiangjiaba hydropower stations will raise the flood control standard along the Chuanjiang river from once every 5-20 years to once every 50-100 years. Meanwhile, with large flood control capacity, they can reduce the inflow of the Three Gorges Reservoir continuously and stably.

The Three Gorges reservoir is the key project for harnessing and developing the Yangtze River and the core project for flood control in the middle and lower reaches of the Yangtze River. Its main flood control objects are Jingjiang area and Chenglingji area in the middle and lower reaches of the Yangtze River, so as to make the flood control standard of Jingjiang area reach once in a hundred years. In case of flood with a return period of 100 years to 1000 years, Three Gorges Reservoir needs to cooperate with the application of flood storage and detention area to ensure the safety of Jingjiang area. In addition, according to the flood control requirements of Chenglingji area, Three Gorges Reservoir needs to reduce the flood diversion and storage volume in Chenglingji area.

Fig. 2. River distribution map of the Yangtze River Basin.

2.2 Power generation function

The total installed capacity of the Three Gorges hydropower station is 22.5GW, and the designed annual power generation is 88.2 billion kwh. Three Gorges hydropower station is the backbone power supply point of China's "west to East power transmission" and "North South mutual supply" strategy. It is located in the middle of China, which is close to the power load center. It is designed to supply power to central China, East China and Guangdong province. On this basis, it will further connect with North China and South China to promote the formation of the national united power grid. Xiluodu and Xiangjiaba hydropower stations are the backbone power supply points of China's "power transmission from west to East" strategy. The total installed capacity is 13.86 GW and 6.4 GW

respectively. The cascade of Xiluodu and Xiangjiaba hydropower stations have an average annual power generation of about 88 billion kwh, and the power is transmitted to East China and South China through Ultra High-voltage Direct Current Transmission (UHVDC) technology.

2.3 Navigation function

After the Three Gorges project was put into operation, the navigation conditions in the upper reaches of the Yangtze River have been greatly improved. The main channel of the reservoir area has been upgraded from grade III to grade I; the tonnage of ships has been increased from 1000t to 3000t ~ 5000t. The whole line can be navigable day and night throughout the year, and the 10,000t fleet can reach Chongqing directly. The Xiluodu and Xiangjiaba reservoirs have greatly improved the 105 km channel conditions of above Yibin section of Jinsha River, and raised the channel above the dam site from V to IV. Before, the class of ships in the river course was no more than 100t, now a thousand-ton ship can be driven directly from Xiangjiaba to Xiluodu. In addition, through reservoir water replenishment in dry season, the navigation depth of the downstream channel is effectively increased, and the navigation capacity of the downstream is improved.

2.4 Ecological function

It is mainly reflected in ecological regulation and ecological water supply for downstream.

- Xiluodu hydropower station is equipped with stratified water intake stoplog gate, which can carry out ecological regulation of stratified water intake temperature. Through the stoplog gate, high temperature water is taken from the reservoir surface to improve the discharge water temperature and promote the reproduction of sticky egg fish.
- The integrated operation of cascade reservoirs can simulate the natural flood process to carry out ecological regulation, and promote the breeding of drifting egg fish.
- During the dry season, the runoff of Yichang station will be increased from 3000 m^3 to 6000 m^3 at least, and the runoff of Xiangjiaba downstream will be increased from 1370 m^3 to about 1700 m^3.

2.5 Sediment retention function

The middle reaches of the Jinsha River is one of the major sand-producing areas of the Yangtze River, with an average sediment content of 1.7 kg/m^3, which is about 1/2 of the sediment flow into the Three Gorges Reservoir. By taking advantage of the fact that sediment transportation highly concentrates in flood season, reasonable dispatch can make most of the sediment deposited in the dead storage capacity of Xiluodu and Xiangjiaba cascade hydropower stations, so that the inflow sediment of the Three Gorges Reservoir can be reduced by about 34.1%. In recent years, the actual annual sediment inflow and annual siltation in the Three Gorges reservoir is only 1/3 of the design value.

2.6 Public safety functions

This is mainly reflected in some emergency dispatching aspects, such as maritime rescue and evacuation vessel dispatching.

3 Integrated dispatch of the cascade reservoirs

3.1 Integrated falling dispatch

Every year from January to June is the falling period of Xiluodu, Xiangjiaba and Three Gorges reservoirs. The objectives of cascade reservoir dispatch during this period are:

- The water level of each reservoir should be draw down to the flood control limit water level before flood season to meet the flood control requirements.
- Meet the downstream shipping, ecological and domestic water supply requirements.
- Improve water utilization rate to generate more power.
- Carry out ecological dispatch to promote fish breeding.

Besides, during the falling period, it is necessary to take into account the complex constraints such as bank stability and safety, maintenance of the hydropower station, and maintenance of power transmission lines.

3.1.1 Integrated dispatch to ensure shipping and ecological water supply

There are mainly three points:

(1) When Xiluodu hydropower station is operating under low power load due to holidays or transmission line maintenance, its outflow which is the inflow of Xiangjiaba reservoir will be very small and not be able to meet the downstream shipping and ecological needs of Xiangjiaba hydropower station, so Xiangjiaba reservoir needs to replenish water to the downstream;

(2) When the inflow of Xiluodu hydropower station is very small and can't meet the downstream shipping and ecological demand of Xiangjiaba hydropower station, the integrated dispatch of Xiluodu and Xiangjiaba will be carried out to replenish water to the downstream;

(3) From March 1 to May 1, when the water level of the Three Gorges is very low, Xiluodu and Xiangjiaba reservoirs will increase their outflow which is part of the Three Gorges reservoir's inflow, so as to ensure the minimum water demand of the downstream of the Three Gorges.

3.1.2 Integrated dispatch to promote power generation

The principle is to consider the optimization of water head distribution of cascade reservoirs under the premise of avoiding or reducing water abandonment.

- Optimize the water level drawdown order of cascade reservoirs. Xiluodu project is arch dam with large regulating storage capacity and high water head, and it is the first one of the cascade. While the Three Gorges and Xiangjiaba dams are gravity dams with relatively lower water heads. When Xiluodu supply water first, the total power generation of the three hydropower stations is the largest. The regulating capacity of Xiangjiaba reservoir is the smallest, and its falling pressure is smaller. Therefore, from the point of view of power generation and the difficulty of accomplishing the task of water level drawdown, the overall order of drawdown is Xiluodu first, then Three Gorges, and finally Xiangjiaba.
- (2) The water level will fall slowly in the early stage of this period, then speed up later. Generally, the higher the water head, the better the power generation efficiency. In order to improve the utilization rate of water resources, it is necessary to complete the task of falling without abandoning water, at the same time, maintain the high water level as long as possible.

3.1.3 Integrated dispatch to protect ecology

In May, when the parent fishes of the Yangtze River is sexual mature, a continuous man-made flood process is carried out to promote the spawning and reproduction of drift spawning fishes by continuously increasing the outflow of Xiangjiaba and the Three Gorges reservoirs. During the centralized falling period of Three Gorges reservoir, on the basis of meeting the safety requirements of the reservoir bank, the daily variation of water level and the time limit of falling period, considering the power generation characteristics of the power grid within the week (the load demand at the weekend is usually smaller), the method of gradually increasing the outflow of the reservoir at the weekend is adopted. During the period of ecological regulation, considering the propagation time between cascade reservoirs, the discharge of Xiluodu, Xiangjiaba and Three Gorges is increased step by step to produce a continuous flood process.

3.2 Integrated Flood Control Dispatch

The main flood season in the Yangtze River Basin is from July to September, and the cascade reservoirs carry out flood control dispatch for downstream flood control objects on the premise of ensuring the safety of the projects, while taking into account the requirements of power generation and shipping.

3.2.1 Integrated Flood Control Dispatch of Xiluodu and Xiangjiaba Reservoirs

Xiluodu reservoir has a flood control capacity of 4.65 billion m^3 and Xiangjiaba reservoir has a flood control capacity of 0.903 billion m^3, their flood control capacity reserved from July 1 to September 10. The propagation time between the two reservoirs is only about 2h, so they undertake the flood control task for the Chuanjiang river and middle and lower reaches of the Yangtze rivers together. Xiluodu and Xiangjiaba reservoirs reserve 1.46 billion m^3 of flood control capacity for Yibin and Luzhou city which is along the Chuanjiang river, and the rest 4.093 billion m^3 of flood control capacity is reserved for Chongqing city and cooperating with Three Gorges Reservoir for the flood control of middle and lower reaches of the Yangtze rivers.

3.2.2 Integrated Flood Control Dispatch of Xiluodu, Xiangjiaba and Three Gorges Reservoirs

The flood control capacity of the Three Gorges reservoir is 22.15 billion m^3, which is mainly used for flood control of Jingjiang area. When the flood in the upper reaches of the Yangtze River is not very big and there is no need for flood control in Jingjiang area, but there is a flood occur in Chenglingji area, the Three Gorges Reservoir can use 5.65 billion m^3 of flood control capacity (water level below 155.0 m) to carry out flood control compensation dispatch for Chenglingji area. In real-time dispatch, combined with the water regime and flood control situation of upstream and downstream, through the joint operation of Xiluodu, Xiangjiaba and other upstream reservoirs with the Three Gorges reservoir, the capacity of the Three Gorges reservoir for flood control compensation in Chenglingji area can be further improved. Xiluodu and Xiangjiaba reservoirs can make use of the 4.093 billion m^3 of flood control capacity to carry out flood control dispatch together with the Three Gorges reservoir, so as to reduce the peak flood flow into the Three Gorges Reservoir. On the one hand, it can reduce the tail water level of the Three Gorges reservoir, so as to reduce or avoid the flood loss at the tail of the reservoir; on the other hand, it can reduce the flood volume entering the middle and lower reaches of the Yangtze River, so as to reduce its flood prevention pressure.

3.2.3 Efficient utilization of the water resources

There are mainly four points:

- when the downstream has no flood control requirements, combined with the hydrologic forecast, on the premise of fully guaranteeing the flood control safety, the reservoir can make use of the small and medium floods to increase the power generation, as well as extend the downstream navigation time.
- When carrying out flood control dispatch, the flood is detained in the reservoir, the water head for power generation is raised, and the flood is utilized as resources, which realizes the win-win situation of flood control and power generation. In the process of flood recession, combined with the hydrologic forecast, the water level can be reduced by power generation.
- In the process of flood control dispatch, if the conditions permit, the discharge flow should be less than the maximum navigable flow of the downstream as far as possible to extend the downstream navigation time. During the big flood period, the ships are overstocked and not navigable. So, during the flood recession process, it is necessary to choose the right time to reduce the discharge and carry out evacuation ship dispatch.
- The dispatch of sediment reduction at the tail of the reservoir should be carried out in time to discharge the sediment deposited in the reservoir.

3.3 Integrated water storage dispatch

In September, the cascade reservoirs begin to store water. The water storage capacity of Xiluodu and Xiangjiaba reservoirs is relatively small, and they usually full by early October. The storage capacity of the Three Gorges reservoir is very large, so its water storage process will last until the end of October or even early November. The objectives of reservoir dispatch during the water storage period are as follows:

- To ensure the full storage of cascade reservoirs, and avoid bank instability or reservoir tail land inundation caused by excessive water storage;
- To achieve the optimal balance between water head and amount benefit of power generation, raise the average water head in the water storage period, and reduce power generation surplus water;
- Water storage should be based on ensuring flood control safety, when flood is predicted, water storage dispatch should be suspended and turned to flood control dispatch.

3.3.1 Integrated dispatch to ensure full storage rate

- In general, there is no demand for flood control in Chenglingji area in mid and late August, combined with the flood resources at the end of flood season, the flood control compensation capacity of cascade reservoirs for Chenglingji area can be gradually released to raise the initial storage water level of the reservoirs.
- Optimize the water storage process, appropriately stagger the storage time of Xiluodu, Xiangjiaba and the Three Gorges reservoirs, to avoid they competing for water. The inflow of the cascade reservoirs is still very large in September, they can store as much water as possible so Xiluodu and Xiangjiaba reservoirs can complete most of the water storage tasks in September. By the end of September, the water level of the Three Gorges reservoir reaches 162 ~ 165m, the storage pressure in October can be greatly reduced, and the risk of flooding at the tail of the reservoir due to autumn flood can be avoided.

3.3.2 Integrated dispatch to promote power generation

- Make full use of the surplus water of power generation to store water. The power generation discharge of Xiluodu Reservoir and Xiangjiaba hydropower stations is relatively small, which are about 7300m^3/s and 6300m^3 s respectively. When their inflow is larger than 7300m^3/s, the two hydropower stations will be generating power at their full capacity and the surplus water will be stored; when the inflow is between 6300 ~ 7300m^3/s, the surplus water will be stored according to the installed capacity of Xiangjiaba Hydropower Station; when the inflow continues to decrease, the water storage by load reduction will be considered.
- In the early stage of impoundment, the water head of cascade reservoirs will raise rapidly. The water head of Xiluodu and Xiangjiaba reservoirs should be raised to the rated head of installed capacity as soon as possible. The water storage process of the Three Gorges reservoir is generally divided into two stages, the first one is mid-September and early October, the second one is late September and mid late October. Rapid water storage in the first stage is conducive to increasing the power generation head as soon as possible, and slow water storage in the second stage is conducive to reducing waste water and increasing power generation flow.

3.3.3 Integrated dispatch for flood control

During the impoundment period, when the water level of Shashi station and Chenglingji station is going to reach the warning water level in a short period of time, or the inflow of the Three Gorges reservoir will reach 35000m^3/s and it is predicted that the inflow will continue to increase, the reservoir will suspend the impoundment process and dispatch according to the flood control requirements. If Xiluodu and Xiangjiaba have not reached the normal water level at this time, they can store water to reduce the inflow of the Three Gorges reservoir.

4 Exploration of integrated dispatch

In order to better carry out the integrated operation of cascade reservoirs, China Three Gorges Corporation (CTG) has established a technical support system for joint operation. On the on hand, CTG built the biggest and most versatile in-basin water and rainfall regime telemetry system in domestic hydropower enterprises, which controls over 580,000 km^2 area on the upper reaches of the Yangtze River, and realized fast and reliable acquisition, storage and processing of in-basin water and rainfall regime as well as reservoir information. On the other hand, CTG established a complete set of meteorological and hydrological forecast system, with a forecast lead time of 7 days and forecast accuracy is at the leading level in the domestic industry. Furthermore, CTG has developed a decision support system for water resources management, a new generation of intelligent water dispatch automation system for cascade reservoirs, and a remote "integrated dispatch and control" automatic system for giant unit hydropower stations. The utilization rate of water energy of cascade hydropower stations has been increased by more than 4%.

In recent years, great changes have taken place in the dispatch environment, which poses higher challenges to the dispatch of cascade reservoirs. Firstly, with the commissioning of Wudongde and Baihetan Hydropower Stations, which are on the upper reached of Xiluodu hydropower station, the integrated dispatch of cascade reservoirs from the lower reaches of Jinsha River to the Three Gorges will be extended to 6 reservoirs. Secondly, the power market reform has made the original power generation dispatch mode of "determining power by water" no longer applicable, and the influence of power market demand on dispatch has been increased. Thirdly, flood control and ecology have raised the requirements for reservoir

dispatch, and multi-objective dispatch is even more complex. Next, it is necessary to comprehensively consider the comprehensive utilization requirements of water resources such as flood control, water supply, shipping and ecology, and the demand of electricity market. Through the combination of simulation and optimization, the decision-making suggestions for cascade reservoirs dispatch are generated dynamically, so as to realize the scientific allocation and intelligent management of water resources, and form the ability of integrated dispatch of cascade reservoirs on the upper reaches of the Yangtze River basin.