Research on the dynamic control of the flood control level of Shimen Reservoir in the mode of pre-storage and pre-discharge regulation

HUANG Lingzhi, LI Shouyi and SI Zheng

Faculty of Water Resources and Hydraulic Power, Xi’an University of Technology, NO.5 South Jinhua Road, Xi’an, Shaanxi, China
hlzsz@126.com

Abstract. Given the static flood control level of Shimen Reservoir and its influence on the benefits for irrigation of the reservoir, the dynamic control of the flood control level is put forward in the paper to improve the utilization ratio of water resources. Based on the weather and hydrological forecasts of Shimen Reservoir, the pre-storage and pre-discharge regulation is adopted, the upper and lower limits of the flood control level in the dynamic control are analyzed and a specific implementation scheme is advanced. The results of the analysis demonstrate that the dynamic control of flood control level is feasible and can effectively increase the storage capacity of the reservoir, which will expand the benefit of the reservoir.

1. Engineering background

Shimen reservoir, built in 1960s, is located in the lower reaches of Bao River, a tributary of the left bank of the upper reaches of Hanjiang River, and boasts the comprehensive benefits of irrigation, power generation, flood control etc. The control station in the lower reach is Madao hydrological station and the average annual runoff remains $13.8 \times 10^8$ m$^3$ for many years. The standard of design flood is once-in-a-century and that of check flood is once-in-a-millennium. The static flood control level 615 m is adopted to measure different floods in the flood control and regulation of the reservoir in the flood season. At present, the sluices of Shimen reservoir mainly include the 6-hole middle outlet, 1-hole bottom outlet and a left-side discharge tunnel.

The size of the bottom outlet is 2 m×2 m (width × height); the height of the bottom still is 550.0 m; the discharge capacity of the design flood is 120 m$^3$/s. The middle outlet is symmetrical distributed on the two sides of the center line of the arch dam. The size of the middle outlet is 7 m×8 m; the height of the inlet is 596.0 m, the outlet is 596.7 m. The discharge capacity of the design flood is 495 0m$^3$/s and that of the check flood is 5150 m$^3$/s. The left-side discharge tunnel is only opened when the water level is over 618.0 m due to the negative pressure. As the water level is generally below the normal water level 618.0 m, the reservoir is of great discharge capacity.

Based on the calculation, only when a once-in-500-year flood strikes is it necessary to open the 6 holes simultaneously. As it has not occurred in recent years, the flood control level only need to be moderately elevated for an ordinary flood to obtain more benefits. Especially in recent years, the runoff of Bao River decreases markedly, so it is often the case that there is no rain for a long time after the flood season and there is a shortage of water for irrigation, which results in the fail to achieve the expected benefits. As a result, it is urgent to investigate the control of the flood control level and make best use of flood water.
2. Theory of the dynamic control of water control level

Dynamic control of flood water level refers to increasing the discharge intensity in the period before a flood occurs or in the rising period of a flood. The pre-discharge reduces the water below the flood control level; with the flood inflow increases, the reservoir water level rises to the flood control level, the reservoir begins to store water and the conventional method is used to regulate the flood; in the period of recession, flood tail is retained until the water is above the flood control level and it is ensured that power generating equipment or discharge equipment can be used to discharge the excess water storage before the next flood.

Figure 1 is a schematic diagram of retaining the flood in the recession period of the flood. In the diagram, \( Q(t) \) represents the inflow of the flood; \( q(t) \) is the discharge process of the flood discharging facilities; \( Q_{d} \) is the full discharge of the unit. To simplify the analysis and given the little influence of the water head on the generating discharge when the unit is in full discharge, the generating discharge is considered constant when the unit is in full discharge. In addition, \( t_{0} \) represents the decision-making time, assuming that the water storage of the reservoir at this time is \( V_{0} \); \( t_{1} \) is the closing gate time, and the corresponding water storage of the reservoir is \( V_{1} \).

The water reaches its highest level \( Z_{2} \) at the time \( t_{2} \) after the gate is closed, the corresponding water storage is \( V_{2} \); the water is discharged at the rate of the highest generating discharge \( Q_{q} \) after the gate is closed until the water level lowers to the flood control level \( Z_{L} \) at the time \( t_{3} \); \( \Delta W_{1} \) is the difference between the inflow amount and the discharge amount via the discharging outlets and by generating power discharge from the projected decision-making time to the closing gate time; \( \Delta W_{2} \) is the likely amount of water that is retained after the gate is closed; \( \Delta W_{3} \) is the actual excess water storage, that is, the storage between the excess storage level and the flood control level; \( Z_{m} \) is the highest regulation level; \( Z_{b} \) is the highest excess storage level of retaining flood tail.

![Figure 1](image)

**Figure 1. Regulation of retaining flood tail in the recession period of the flood**

As for the regulation model in Figure 1, \( q(t) \) can be determined by the regulation principle; \( Q(t) \) can be obtained by the recession law; the water storage \( V_{0} \) at the decision-making time \( t_{0} \) can be obtained from the storage curve by the observed value of the storage level; \( Z_{2} \) and the corresponding water storage \( V_{2} \) are determined by the excess water storage scheme; \( Q_{q} \) has been determined in the design of the generating station, so the retaining time and the time when water lowers to the flood control level can be obtained by mathematical calculation.
The calculation theory is as follows:

From Diagram 1, it can be easily seen that the discharge capacity is higher than the inflow capacity from \( t_0 \) to \( t_1 \), so storage \( \Delta W_1 \) can be emptied by pre-discharge.

\[
\Delta W_1 = \int_{t_0}^{t_1} (q(t) + Q - Q(t)) \, dt
\]

(1)

The amount of water that is retained from \( t_1 \) to \( t_2 \) is:

\[
\Delta W_2 = \int_{t_1}^{t_2} (Q(t) - Q(t)) \, dt
\]

(2)

By the water balance relation, it can be obtained:

\[
V_0 - \Delta W_1 + \Delta W_2 = V_2
\]

(3)

In addition, for the time \( t_3 \), the water balance equation of the process from the retaining water level \( Z_2 \) to the flood control level \( Z_L \) can be established, that is:

\[
V_2 - \int_{t_2}^{t_3} (Q_4 - Q(t)) \, dt = V_L
\]

(4)

The time \( t_3 \) can be obtained given the recession process \( Q(t) \).

3. Determination of the dynamic control range of the flood control level

3.1. Principle of the calculation of the dynamic control range

The basic idea of pre-storage and pre-discharge is that the foreseeable capacity of discharge in the forecast period determines the degree of the elevation of the flood control level. The factors influencing the elevation of the flood control level include: the conditions of water, weather and labor; the forecast period of the inflow flood, the amount of the foreseeable inflow in the forecast period and its error distribution; capacity of discharge in the forecast period; the allowable discharge of the lower reaches; the speed and stability of the decision-making and the transmission of feedback information, and the operation time of the gate.

\[
w_{yx} = (q_{out} - q_{in})T_y, \quad q_{out} \leq q_{an}
\]

(5)

\[
Z_d^+ = f[V(Z_d^0) + w_{yx}], \quad Z_d^+ \leq Z_{XL}
\]

(6)

The regulations stipulate that the rainfall forecast information is not considered in the pre-storage and pre-discharge, while this paper comprehensively considers flood forecast and rainfall forecast information, so the method in this paper is called the improved pre-storage and pre-discharge method. The so-called improvement mainly lies in the adoption of the values of \( T_y \), \( q_{out} \) and \( q_{in} \) in equation (5). The upper limit of dynamic control of the flood control level is determined by equation (6). The values in equation (5) and (6) that are the same as the standard values include: \( w_{yx} \), the dynamic pre-storage above the upper flood control level \( Z_d^0 \); \( V[Z_d^0] \), the capacity of the reservoir for the corresponding flood control level \( Z_d^0 \); \( Z_d^+ \), the upper limit of the dynamic control of the flood control level; \( Z_{XL} \), the storage of the reservoir for irrigation; \( f[-] \), the storage-water level relationship; \( q_{an} \), the allowable discharge of the reservoir for the safety of the embankment in the corresponding protection point. The values in equation (5) and (6) that are different from the standard values include: \( T_y \), the comprehensive forecast period of flood and rainfall minus the forecast period of decision-making, transmission of information and the operation time of the gate, it is an improvement that the forecast period of the rainfall forecast is taken into account; \( q_{in} \), the average inflow during the time of \( T_y \), mainly at the critical recession period in the dynamic control of the flood control level, which is also a difference; \( q_{out} \), the average discharge capacity or the amount of discharge during the time of \( T_y \), the maximum is taken, that is, \( q_{out} = q_{in} \).

3.2. Upper limit of the dynamic control of the flood control level of Shimen Reservoir
3.2.1. Effective pre-discharge time \( T_y \). The weather and hydrological forecasts of Shimen Reservoir are reported every 6 hours. According to the precision analysis of flood runoff forecast, the forecast of every 6 hours meets the requirements of dynamic control of flood control level. With the information transmission, decision-making, gate opening and other time taken into consideration, 5.5 hours is taken as effective pre-discharge time.

3.2.2. Allowable pre-storage amount \( w_{yx} \). By the analysis of several floods and taking the inflow when the level lowers as the standard, the average value 600 m\(^3\)/s of the beginning and recession flow values of several floods is taken.

\[
Q_{in}=1000 \text{ m}^3/\text{s}, \quad T_y=5.5 \text{ h}, \quad q_{in}=600 \text{ m}^3/\text{s}, \text{ it can be obtained:}
\]

\[
w_{yx} = (q_{out} - q_{in}) T_y = 7.92 \times 10^6 \text{ m}^3
\]

3.2.3. Calculation of the upper limit \( Z^* \) of the dynamic control of the flood control level. Given that the allowable pre-storage amount \( w_{yx} =7.92 \times 10^6 \text{ m}^3 \), the original flood control level equals 615.0 m and its corresponding storage \( I(V(615.00)=49.54 \times 10^6 \text{ m}^3 \), it can be obtained:

\[
Z^* = f(V(Z_d^o) + w_{yx}) = f(V(615.00) + w_{yx}) = 617.53 \text{ m}
\]

Finally, 617.5 m is taken as the upper limit of the dynamic control of the flood control level.

3.3. Lower limit of the dynamic control of the flood control level of Shimen Reservoir

According to the storage curve and the discharge capacity curve of Shimen Reservoir, when the water level of the reservoir lowers from the normal level 618.0 m to 610.0 m, the storage capacity is 9.71 million m\(^3\). When only the middle outlet is opened, it takes 1.2 hours; all the six outlets are opened, it takes only 15 minutes; when the upstream peak flow is less than 3000 m\(^3\)/s and the six outlets are opened one by one, the reservoir water level can rapidly drop to 610.0 m. Therefore, Shimen Reservoir has a great discharge capacity and it is only necessary to pre-discharge design floods and above, not ordinary floods.

Based on investigation, the six outlets were opened in advance in the regulation of the “19810820 historical flood” (flood peak flow of 6200 m\(^3\)/s), so the water level dropped to 607.8 m and the flood was successfully dealt with. Taking into account that Shihmen Reservoir has a long operation period, the lower limit of dynamic control of flood control level is taken as 610.0 m in order to avoid excessive discharge pressure.

4. Method of the dynamic control of the flood control level

The method of the dynamic control of the flood control level is that the beginning-discharge level of flood is flexibly determined by the feature of the rainfall. The beginning-discharge level of large floods is low, while of ordinary floods is high, that is, different levels are adopted for different grades of floods so as to ensure the safety of flood control and, in the meanwhile, store water for irrigation as much as possible. As a result, the method of the dynamic control of the flood control level should be determined in the actual operation and it should be simple, practical, accurate and easy to be carried out. In practical projects, the conditions of rainfall, water level and storage should be taken into account comprehensively. In this paper, the indicators of rainfall and flood flow of the river channel are taken as the key indicators of Shimen Reservoir.

From the analysis of the inflow of Bao River, it can be obviously seen that the annual runoff of Shihmen Reservoir shows a declining tendency in recent years. Therefore, the focus of flood control and safety control of the reservoir is on large floods and above. It is reasonable to use the specified flood control level of 615 m for the design standard floods and extraordinary floods. However, the vast majority of ordinary rainfalls are resources for irrigation. The control method of flood control level of
Shimen Reservoir put forward in the paper is as follows: the flood control level is determined by periods and grades of floods, that is, not rigidly adhere to the same flood control level, but to determine the flood control level according to different periods and different levels of grade of floods.

4.1. Classification of the flood season
According to the meteorological and hydrological laws, the flood season is divided into the main flood season (July, August and September) and the secondary flood season (May, June and October). The flood control level of the secondary flood season is 617 m, that of the main flood season is in accordance with the grades of the floods.

4.2. Classification of floods
The flood control level of Bao River is determined by the grades of rainfalls and floods. Floods are divided into four grades: ordinary flood, large flood, major flood and extraordinary flood. For extraordinary floods and above (flood recurrence $N$ is greater than or equal to one hundred years, that is, $N \geq 100$), the flood can be controlled by the flood control level of 615 m, or even discharge water to reduce the flood control level; for a large number ordinary floods, the flood control level can be 617.5 m.

In addition, the flood control levels should be strictly controlled in flood periods; in recession periods, especially the measured flow of storage has dropped to $Q < 300 \text{ m}^3/\text{s}$, it is not necessary to strictly control it.

What’s more, rainfalls and floods of different grades should have different corresponding flood control levels. The regulation indicator of flood control levels should be analyzed and determined in practical projects. The indicator should play a key role in flood control and regulation, and it should be simple, convenient, accurate, practical and easy to be carried out. In this paper, the flood flow of the river channel is taken as the indicator and the regulation method is shown in Table 1.

| Flood flows of Shimen damsite $Q (\text{m}^3/\text{s})$ | Flood control levels $H (\text{mm})$ |
|-----------------------------------------------------|-------------------------------------|
| $Q < 1850$                                           | 617.5–617                          |
| $1850 \leq Q < 2520$                                 | 616                                |
| $2520 \leq Q < 4850$                                 | 615                                |
| $Q \geq 4850$                                        | 615–610                            |

5. Conclusions
The static flood control level requires that, once water exceeds the level, the water above the level should be discharged as soon as possible, leaving enough space of the reservoir to store water of the possible design floods and check floods. In order to prevent floods, water cannot be stored in the flood season, after which, however, water level cannot reach the normal water level, especially for the reservoirs in the north, where the runoff is obviously different in different time periods, that is to say, after the flood season there is enough space of the reservoir but not enough water, which is not conducive to the benefits for irrigation.

With the rapid development of modern science and technology, the forecasts of meteorology and hydrology are becoming more and more mature and accurate and they have been widely used in the dispatching and management of reservoirs, which provides the method for the dynamic control of flood control level. In this paper, after taking the comprehensive consideration of hydrological and meteorological forecasts and other information, under the premise of ensuring the flood control safety of reservoirs, the storage capacity of the reservoir is reasonably adjusted to ensure the control of floods and its benefits for irrigation, and the safe and economical upper and lower limits of dynamic control of flood control level are determined, that is, flood control level is dynamically controlled to improve the utilization rate of water resources and better solve the contradiction between the flood season and the lack of water, which is a beneficial attempt to turn floods into resources.
Acknowledgments
This study was financially supported by Science and technology plan project of Shaanxi Provincial Water Resources Department (2014slkj-16); National Natural Science Foundation of China (51409207); National Natural Science Foundation of China (51609200).

References
[1] Guiyang Engineering Corporation Limited, “Preliminary design report on the reinforcement project of Shimen Reservoir in Hanzhong, Shaanxi Province”, 2015, 11.
[2] R. T. Qiu, et al., “Renewal theory and concept of the control of reservoir flood control level,” Advances in Water Science, Vol. 15, pp. 68-72, 2004.
[3] B. D. Wang and H. C. Zhou, Theory and Method of the Dynamic Control of Flood Control Level. Beijing: China Water & Power Press, 2006.
[4] Y. Y. Zhu, J. X. Yuan, G. L. Wang, et al., “Dynamic control of flood control level by real time pre-storage and pre-discharge method and its application,” Journal of Liaoning Technical University (Natural Science), Vol. 24, pp. 606-609, 2008.
[5] Y. M. Wang, C. G. Wu, C. Li, et al., “Research on the dynamic control of flood control level of Xihe Reservoir based on different pre-storage and pre-discharge methods,” Journal of Hydroelectric Engineering, Vol. 30, pp. 26-31, 2011.
[6] X. G. Li and B. D. Wang, “Research on the design of flood control level based on flood forecasts,” Journal of Hydroelectric Engineering, Vol. 28, pp. 52-56, 2009.
[7] J. Wan and H. Y. Chen, “Research on the water storage of Baipenzhu Reservoir in the flood season with forecasts and pre-discharge taken into consideration,” Engineering Journal of Wuhan University, Vol. 33, pp. 10-13, 2000.