Study on Classification Arrangement and Hydraulic Characteristics of Water-Saving Ship Lock Under Ultra-high Head

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Abstract. The ship lock with water saving basins can store part of water during the operation, which has the outstanding advantage of saving water resources. At the same time, the water-saving ship lock can divide the total water head into stages, significantly reduce the operating head of each stage, which can provide technical conditions for simplifying the ship lock's filling & emptying system and improving the operating conditions of lock's valves. For ship lock with high head and large water level variation, the layout of the saving basins and the division of water level are very important. They determine the overall layout, operation efficiency and safety performance of the ship lock. With the increase of water head and water level variation, the classification arrangement of water-saving ship lock will become very complex. Therefore, based on the Baishi water-saving ship lock project (60 m-class, ultra-high head), the analysis and calculation research are carried out in this paper. First of all, the influence laws of key factors such as water-saving rate, number of water saving basins, area of water saving basins and operating head on water level division are obtained. On this foundation, a reasonable water level classification scheme for 60m-class ship lock is proposed, and the hydraulic characteristics of ship lock under different operating conditions are analyzed, and the feasibility of ship lock layout scheme is demonstrated. The research results can provide direct technical support for Baishi ship lock project, and provide reference for the design and construction of similar water-saving ship lock projects.

Keywords: Water-saving ship lock · Ultra-high head · Classification arrangement · Hydraulic characteristics

1 Introduction

The water-saving ship lock is a special type of ship lock construction. Usually, water saving basins are arranged on one or both sides of the ship lock. Through the continuous water exchange between the lock chamber and the water saving basins, some water bodies are reused to achieve the effect of saving water resources. In addition, another important function of the water-saving ship lock is to divide the total head into stages, so as to significantly reduce the operating head of each stage, provide technical conditions for simplifying the filling & emptying system and improving the operating

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conditions of lock's valves, and have the advantages of improving the flow conditions of the upstream and downstream approach channels of the ship lock. It provides an idea for solving the problem of high head ship lock construction in alpine and gorge areas.

2 Layout and Engineering Background of Water-Saving Ship Lock

2.1 Construction, Application and Layout Type of Water-Saving Ship Lock

As a special type of ship lock construction, the water-saving ship lock is widely used in foreign canals, such as the three-stage water-saving ship lock of the Panama Canal, the series ship locks on the Rhine-Main-Danube in Germany, the cascade ship locks on the Seine Nordic canal (under planning and construction), etc. According to statistics, Germany is the country with the largest number of water-saving ship locks in the world, and has rich experience in design and construction. 《Innovations in navigation lock design》 published by the PIANC summarizes the characteristics and key technical problems of water-saving ship locks (PIANC 2009).

There are relatively few examples of water-saving ship locks in China. So far, almost no water-saving ship lock has been built and put into operation. However, in recent years, with the planning and construction of high head navigation buildings in southwest mountainous areas and the demonstration and implementation of major cross river canal projects, many water-saving ship lock design schemes have been put forward and experimental studies have been carried out (Zhu and Xuan 2019; Wu and Cao 2013; Wang and Liu 2013), such as the Yinpan ship lock on Wujiang River, the Baishi ship lock on Qingshui River, the Jinjiayan ship lock on Xiaoqing River, the Baima ship lock on Xiujiang River, the Bajiangkou ship lock on Guijiang River, etc.

According to the layout type of the water saving basins of the ship lock, the water-saving ship lock can be divided into two typical schemes (Wu and Xuan 2009): closed integral type and open decentralized type. Figure 1 shows the schematic diagram of two schemes. In the closed integrated scheme, the water saving basins are overlapped on one or both sides of the ship lock, which is relatively concentrated and covers a small area, but its structure is complex and the water level division of the water saving basins is difficult. In the open decentralized type, The water saving basins are arranged on one or both sides of the lock, which is scattered and covers a large area. However, this layout mode has simple structure and relatively flexible water level division.

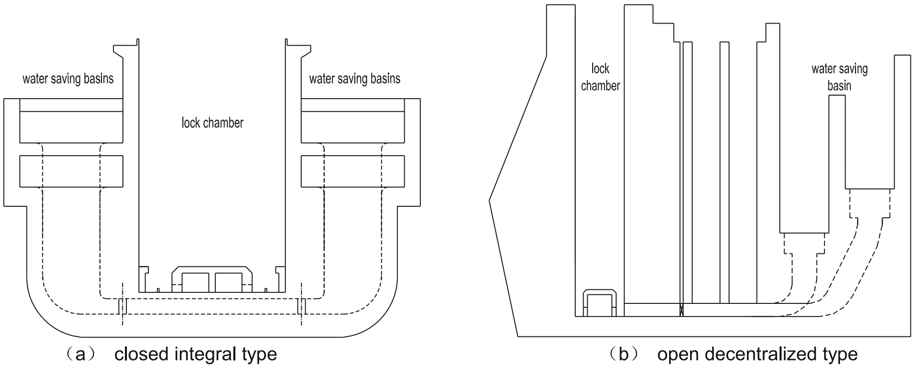

Fig. 1. Typical layout of water saving ship lock

2.2 The Engineering Background

The Baishi hydropower station on Qingshui River is the last cascade of Qingshui River in Guizhou Province. It is a project focusing on power generation and comprehensive utilization benefits such as flood control, shipping and aquaculture. From left to right, the existing buildings in the riverbed of the dam site are: connecting dam section, vertical ship lift, overflow dam, power plant and connecting dam section. The existing navigation structures do not meet the national standards for 500t ships. Therefore, it is proposed to build new navigation structures on the right bank of the hub and adopt the water-saving ship lock scheme. The effective dimension of the new ship lock is 140 m × 12 m × 4.0 m (long × wide × depth), and the maximum design water head is 59.6 m. The water saving basins are arranged on the right side of the ship lock, and the total water filling/emptying time is about 25 min.

The highest navigable water level in the upper reaches of Baishi ship lock is 300 m and the lowest navigable water level is 294 m; The highest navigable water level in the downstream is 251.44 m and the lowest navigable water level is 240.4 m. It is the single-stage water-saving ship lock with the highest water head in China (60 m class, which is a veritable ultra-high water head ship lock), and the water levels in the upstream and downstream vary greatly. It is very necessary to study its classification arrangement and relevant hydraulic characteristics.

3 Analysis on Key Influencing Factors of Classification Arrangement of Water-Saving Ship Lock

There are many factors affecting the classification arrangement of water-saving ship lock (Dong et al. 2020; Li et al. 2020; Liu et al. 2016). The following factors need to be paid attention to when arranging the water saving basins and dividing the water level of the ship lock: ① operating head; ② water saving rate; ③ number of stages; ④ area of water saving basins. The above influencing factors are not single variables, but multiobjective variables coupled with each other. In order to analyze each factor in detail, the schematic diagram of the filling and emptying process with three-stages water saving basins is drawn, as shown in Fig. 2.

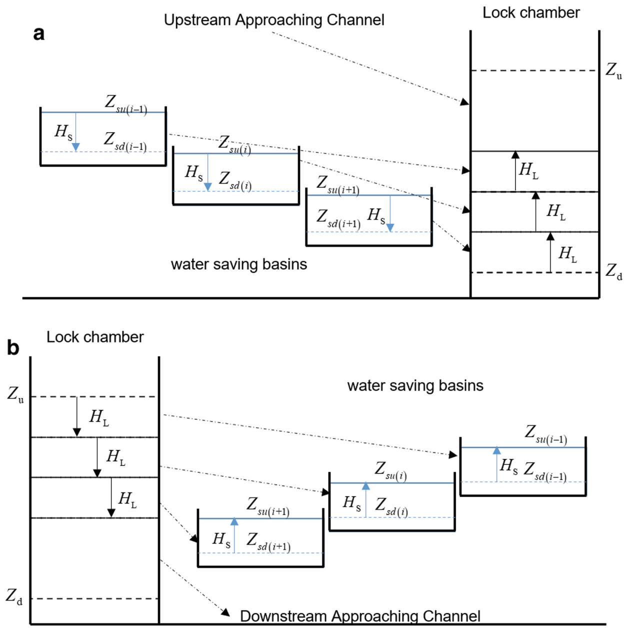

Fig. 2. The schematic diagram of the filling and emptying process

According to the Fig. 2, the following definitions are given in this paper. Z_u is the navigable water level upstream of the ship lock (m); Z_d is the navigable water level downstream of the ship lock (m); $Z_{u\max}$ is the highest navigable water level upstream (m); $Z_{u\min}$ is the lowest navigable water level upstream (m); $Z_{d\max}$ is the highest navigable water level downstream (m); $Z_{d\min}$ is the lowest navigable water level downstream (m); Z_{sui} is the high water level of 'stage i' water saving basin (m); Z_{sdi} is the low water level of 'stage i' water saving basin (m); ΔH_u is the variation of upstream water level(m); ΔH_d is the variation of downstream water level(m); H_L is the change of water level in the lock chamber during each stage of water-saving operation (m); H_S refers to the change of water level in the water saving basin during each stage of water-saving operation (m); H_n refers to the water head during each stage of water-saving operation (m); A_L is the water area of lock chamber (m^2); A_S is the water area of the water saving basin (m^2), we assume that all water saving basins have the same area; m is the water area ratio between the water saving basins and the lock chamber; E_S is the water saving rate of ship lock; n is the number of stages of the water saving basins.

According to the operation principle and mass conservation equation of the ship lock, the parameter variables in the process of water saving of the ship lock meet the following basic relations:

$$H_S \times A_S = H_L \times A_L \tag{1}$$

$$H_L = H_S \times m \tag{2}$$

3.1 Relationship Between Water Head H_n, Area Ratio m and Stage Number n

For a specific upstream and downstream water level combination, the operating head of each stage of the ship lock can be deduced, as shown in Eq. (3). When the ship lock is under the maximum design head condition, the operating head of each stage of water-saving operation is also the maximum value. The analysis shows that the water head (H_n) during the water-saving operation is related to the total head of the ship lock ($(Z_u - Z_d)$),the stage number n and the area ratio m of the water saving basin to the lock chamber. In order to master the response law of water head (H_n) and the key characteristic parameters, the dimensionless number $H_n/(Z_u - Z_d)$ is introduced, which means the ratio percentage of actual water head during water-saving operation to the total design water head of the ship lock. The relationship between $H_n/(Z_u - Z_d)$, m and n is shown in Fig. 3. It can be seen from the formula and figure that with the increase of the water-saving stage number and the area ratio of water saving basin to lock chamber, the ratio percentage of actual water head to the total head shows an obvious downward trend, but the downward range gradually slows down.

$$H_n = H_L + H_S = \frac{(m+1)(Z_u - Z_d)}{m(n+1)+1} \tag{3}$$

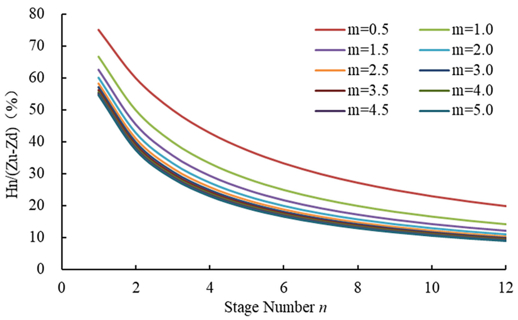

Fig. 3. The relationship between $H_n/(Z_u - Z_d)$, m and n

Further statistics on the relationship between the decline range (The decline range refers to the ratio of the change value of the dependent variable to the original value as the value of the independent variable increases. For example, if m = 1. When n is 1, the value of $H_n/(Z_u - Z_d)$ is 66.67%. When n changes from 1 to 2 and the value of $H_n/(Z_u - Z_d)$ changes to 50%, which means that the decline range is about 25%) of $H_n/(Z_u - Z_d)$, m and n are shown in Fig. 4. The research shows that: ① When the area ratio m between the water saving basin and the ship lock is fixed; If the number of water-saving stages is greater than or equal to 4 (n $\geq$ 4), all the decline range may be less than 20%; If n > 8, the decline range begins to be less than 10%. ② When the stage number n of the water saving basins is determined, with the change of the area ratio m between water saving basin and the ship lock, the decline range does not change significantly; Especially when m $\geq$ 2.0, it has little effect on the change of water head.

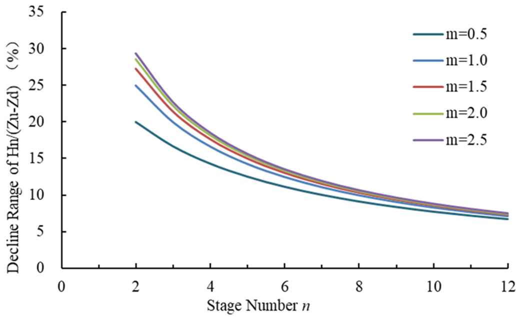

Fig. 4. Correlation between $H_n/(Z_u - Z_d)$, m and n

3.2 Relationship Between Water Saving Rate E_S, Area Ratio m and Stage Number n

The water saving rate of the ship lock measures the ability of the ship lock to save water in each operation, that is, the ratio between the water saved by the ship lock and the water body required for a single operation of the ship lock, which is recorded as E_S. According to the operation process of the ship lock, it can be deduced:

$$E_S = \frac{n \times V_S}{V_L} = \frac{mn}{mn + m + 1} \tag{4}$$

Based on this, the relationship between water saving rate E_S and area ratio m and stage number n is drawn as shown in Fig. 5. The research shows that the water saving rate of ship lock is closely related to the number of water saving stages and the area ratio of water saving basin to lock chamber. In order to quantitatively understand the influence degree of each parameters on the water saving efficiency, the variation law of the growth rate(Similar to the 'decline range', the growth rate of E_S refers to the ratio of the change value to the original value. For example, if m = 1. When n is 2, the value of E_S is 50%. When n changes from 2 to 3 and the value of E_S changes to 60%, which means that the growth rate is about 20%) with m and n is shown in Fig. 6. The comprehensive analysis shows that: ① On the premise that the area of the water saving basin remains unchanged, with the increase of the number of water saving stages, the water saving efficiency gradually increases, but the upward trend gradually slows down. When the number of water saving stages is greater than 4, the growth percentage of the water saving efficiency gradually decreases to less than 10%; ② On the premise that the number of water saving stages remains unchanged, with the increase of the area of water saving basin, which means that *m* increases, the water saving efficiency of the ship lock increases. Similarly, the upward trend gradually slows down with the increase of area. When *m* is greater than 2.0, the growth of water saving efficiency is very slow.

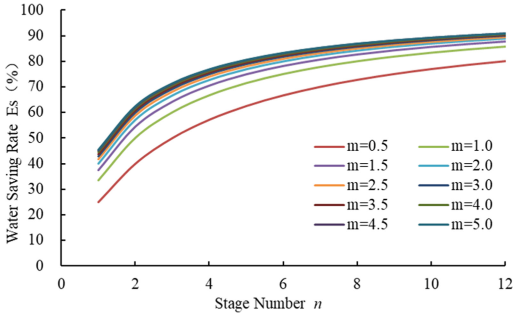

Fig. 5. Correlation between E_S, m and n

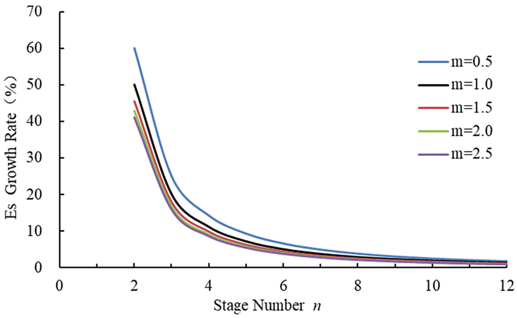

Fig. 6. Correlation between E_S growth rate, m and n

3.3 Relationship Between Water Level $Z_{su(i)}$, $Z_{sd(i)}$ and Area Ratio m, Stage Number n

It is defined that the uppermost water saving basin is the first stage, and the lowest water saving basin is the n-stage. According to the formula, the high water level of the i-stage water saving basin can be deduced as follows:

$$Z_{su(i)} = Z_d + [m(n - i + 1) + 1] \times \frac{Z_u - Z_d}{m(n+1) + 1} \tag{5}$$

The low water level of the i-stage water saving basin is:

$$Z_{sd(i)} = Z_d + m(n - i + 1) \times \frac{Z_u - Z_d}{m(n+1)+1} \tag{6}$$

According to the derivation of the above formula, after determining the water saving stage and the area of the water saving basins, the water level of the water saving basins at all stages can be analyzed and calculated. The results show that the water level of each water saving basin is closely related to the variation of upstream and downstream water level.

Generally, in practical engineering, we can approximate that when the water levels in the upstream and downstream are high water levels, the water levels in the water saving basins are also high water levels; When the water levels in the upstream and downstream are low water levels, the lowest water levels is in water saving basins.

4 Classification Arrangement of Water-Saving Ship Lock Under Ultra-high Head and Large Water Level Variation

In the design scheme, the maximum head of Baishi ship lock is 59.6 m (60 m-class). Table 1 shows the typical cases of high head large ship lock at home and abroad. The comparison shows that the current maximum head of the ship lock is only about 40 m (40 m-class). For the Baishi ship lock with the maximum water head of 60 m-class, if the conventional single-stage ship lock is directly adopted, the hydraulic index is expected to be very high, and there are still many technical problems to be solved. If the layout of water-saving ship lock is adopted, the working head can be significantly reduced and its working index can be within the application range of existing mature technology.

Table 1. Statistics of some high head and large-scale ship locks in the world (m)

Number	Name	Country	Dimensions (length × width)	Maximum head	Type
1	Walter Bouldin*	U.S.A	192.0 × 25.6	39.6	Single-step
2	Zaporojie	Russia	290.0 × 18.0	39.2	Single-stage
3	Lajeado	Brazil	210.0 × 25.0	37.3	Single-stage
4	Tucurui (upstream)	Brazil	210.0 × 33.0	36.5	Single-stage
5	Tucurui (downstream)	Brazil	210.0 × 33.0	35.0	Single-stage
6	John Day	U.S.A	205.7 × 26.2	34.5	Single-stage
7	Pak Beng	Laos	120.0 × 12.0	32.38	Single-stage
8	Lower Granite	U.S.A	205.7 × 26.2	32.0	Single-stage
9	Little Goose	U.S.A	205.7 × 26.2	30.8	Single-stage
10	Three Gorges	China	280.0 × 34.0	113.0(45.2)	Dual-way five-stage
11	Datengxia	China	340.0 × 34.0	40.25	Single-stage
12	Wan'an (second line)	China	180.0 × 23.0	32.5	Single-stage
13	Letan	China	120.0 × 12.0	29.1	Single-stage
14	Gezhouba	China	280.0 × 34.0	27.0	Single-stage
15	Baishi*	China	140.0 × 12.0	59.6	Water saving basin

Note:*For the research scheme.

According to the analysis results of H_n, m and n, the relationship between the operating head of Baishi ship lock, stage number and area ratio can be drawn in Fig. 7. It can be seen that the effect of increasing the area ratio m on reducing the operating head is relatively not obvious. Under the condition of the same stage number n, if you want to reduce the operating head by 5 m, the area ratio m needs to be 2.5 or more; Increasing the stage number n has an obvious effect on reducing the operating head of ship lock, but when the stage number is greater than 4, the effect slows down.

Combined with the specific conditions of Baishi ship lock, the relatively suitable regional scope is shown in the figure. This refers to reducing the operating head of each stage to 20 m–25 m. The technology of ship lock construction is mature at this level, and the hydraulic problems of the filling & emptying system are easy to solve. Therefore, it can be preliminarily determined that it is reasonable to adopt the layout scheme of three-stage water saving basins for Baishi ship lock.

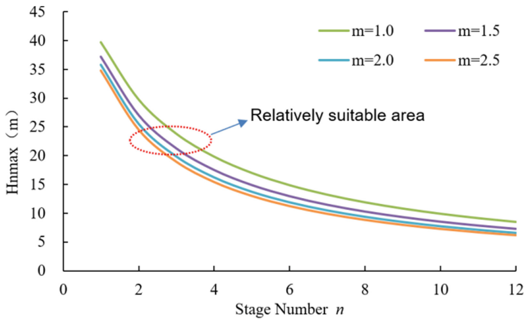

Fig. 7. Relationship between maximum operating head of Baishi ship lock, m and n

The green transportation development strategy is being implemented in China. The water-saving ship lock has achieved relatively good water-saving effect while significantly reducing the actual operating head of the ship lock. According to Eq. (4), the change trend of water saving rate of Baishi ship lock is shown in Fig. 8 under the arrangement condition of three-stage water saving basins. It can be seen from the figure that when the area ratio m changes from 0.5 to 1.0, the theoretical water saving rate E_S increases from 50.0% to 60.0%, and the effect is obvious; When the area ratio m changes from 1.0 to 1.5, the theoretical water saving rate increases from 60.0% to 64.3%; When it changes from 1.5 to 2.0, the theoretical water saving rate increases from 64.3% to 66.7%, and the growth rate is only 3.7%.

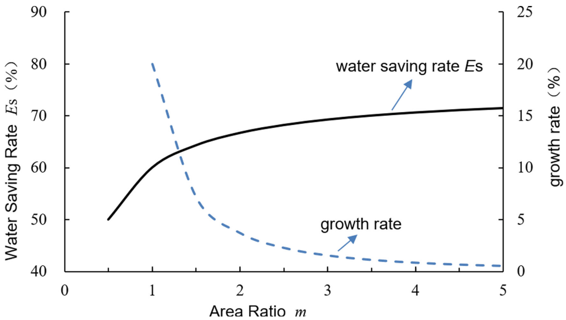

Fig. 8. Relationship between the change trend of water saving rate and m of Baishi ship lock

Based on the comprehensive consideration of spatial layout conditions, investment economy and other aspects, in Baishi ship lock project, it is preliminarily determined to adopt the open decentralized type of three-stage water saving basins, which are arranged on one side of the ship lock, and the area ratio of water saving basin to lock chamber is 1.0:1.0. Based on this, the water level is divided according to Eq. (5) and Eq. (6), and the results are shown in Table 2. The layout type is shown in Fig. 9.

Table 2. Water level classification scheme of Baishi ship lock

	300～251.44 (m)		300～240.4 (m)		294～240.4 (m)	
	High water level	Low water level	High water level	Low water level	High water level	Low water level
The first stage	290.29	280.58	288.08	276.16	283.28	272.56
The second stage	280.58	270.86	276.16	264.24	272.56	261.84
The third stage	270.86	261.15	264.24	252.32	261.84	251.12

Note: n = 3; m = 1; the theoretical water saving rate E_S = 60.0%

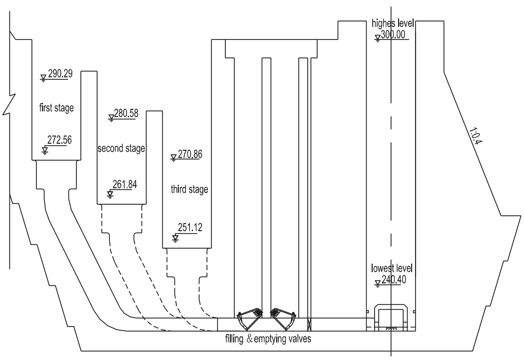

Fig. 9. The three-stage water saving scheme and water level classification of Baishi ship lock

5 Hydraulic Characteristics of Ship Lock Based on Water Saving Layout

According to the three-stage water saving scheme of Baishi ship lock determined in this paper, when all filling & emptying valves of the ship lock adopt the operation mode of opening time t_{v1} = 1.5 min and closing time t_{v2} = 1.0 min, the hydraulic characteristics of the whole process are estimated, and the typical hydraulic indexes such as filling & emptying time, discharge process and water flow velocity are obtained, as shown in Table 3. It can be seen that under the condition of this classification arrangement, the filling & emptying time at the maximum head of the ship lock is about 24 min, which can meet the design requirements; The maximum flow rate from the water saving basins of the ship lock is about 106.01 m^3/s–112.33 m^3/s, and the maximum flow rate from the lock head is about 216.82 m^3/s–244.70 m^3/s; Under this condition, the maximum velocity of the culvert section at each valve of the ship lock is about 10.59 m/s–11.95 m/s; The maximum lifting speed of water surface in the lock chamber is about 6.30 m/min–7.12 m/min.

The above indexes can meet the relevant requirements of the design code for filling and emptying system of ship locks. At the same time, compared with the ship lock projects at home and abroad, the hydraulic indexes are relatively good, which shows that the layout scheme of ship lock proposed in this study is reasonable and achieves the expected effect.

Table 3. Summary of hydraulic characteristic indexes of Baishi ship lock

Filling & emptying	Water level combination (m)	Filling & emptying time (min)	Maximum flow rate from WSBs (m^3/s)	Maximum flow rate from lock head (m^3/s)	Maximum lifting speed of water surface (m/min)	Maximum velocity of the culvert section at each valve (m/s)
Filling	300.00 ~ 251.44	21.48	106.01	216.82	6.30	10.59
	300.00 ~ 240.40	23.63	119.36	244.27	7.12	11.93
	294.00 ~ 240.40	22.52	112.26	229.65	6.68	11.21
Emptying	300.00 ~ 251.44	21.47	106.04	217.09	6.30	10.60
	300.00 ~ 240.40	23.60	119.39	244.70	7.12	11.95
	294.00 ~ 240.40	22.43	112.33	230.14	6.69	11.24

6 Conclusion and Prospect

(1) This paper makes a theoretical calculation and analysis of the key influencing factors, establishes the calculation models of water saving operating head, water saving rate and the water level of water saving basin. The mutual influence and variation laws of various parameters are put forward. According to the results, it is preferred to adopt: the number of stages of the water saving basins $n \leq 4$; the area ratio between the water saving basin and the lock chamber $m \leq 2.0$.

(2) Aiming at the 60 m class ultra-high head ship lock (Baishi ship lock), the overall layout of the water saving basins and a reasonable water level classification are carried out. The hydraulic characteristics of the filling & emptying process are analyzed and calculated. The research results can provide technical reference for the determination of the final scheme of the project.

(3) By setting multi-stage water saving basins, the utilization efficiency of water resources has been significantly improved. At the same time, the layout type of water-saving ship lock divides the filling & emptying process into stages, so as to reduce the actual operating head of the ship lock, which provides a solution to the hydraulic problems of filling & emptying system of ship lock under ultra-high head. Therefore, it has good applicability and application prospects in the navigation field of high dams.

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