Water Level Fluctuation Patterns in Restricted Intermediate Navigable Channels with Different Lock Emptying Processes

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Abstract: The fluctuation of water level caused by the unsteady flow of lock discharge, where the key problem is the relationships between the hydraulic factors in the restricted middle navigable channel and the transformation of unsteady flow and the corresponding scales are investigated. Based on the restricted middle navigable channel of the Baise navigation project, the relationship between the unsteady flow discharge process of lock and the water surface fluctuation process in the restricted middle channel is studied through systematic experiments, and the conclusion is drawn as follows. The main reason caused the flow fluctuation is attributed to the insufficient energy dissipation and rapid increase of discharge during the lock discharge process. And the sectional discharge method which reduces the peak value of the discharge process can reduce the fluctuation of upstream and downstream water level effectively. By reducing the peak value of the time-discharge curve, the energy dissipation along with restricted middle navigable channel increases, with the fluctuation amplitude of upstream and downstream flow reduces, and the attenuation rate of the energy dissipation increases. Furthermore, a fixed phase lag is formed between the reflection wave formed by the downstream ship lift gate and the discharge wave formed by the upstream ship lock discharge, which has little relationship with the discharge curve.

1. Introduction
The intermediate channel-ship lift combination type navigation complex scheme is one of the conventional layouts for high dams in western China, and it has been used in the design and construction of the Wujiang River (Gupitan and Shatuo)¹, ² and the Xijiang River (Baise) dam passing navigation complexes. The process of emptying the locks to the downstream produces unsteady flow, causing water surface fluctuations and changes in flow velocity and flow regime, which reduces the navigational safety of vessels and has a detrimental effect on the operation of hydraulic projects. In addition, the lock-intermediate channel-ship lift combination type navigation complex scheme is subject to the constraints of the mountainous terrain and the boundary of the restricted intermediate channel, disallowing emptying waves in the intermediate channel to achieve rapid diffusion and wave absorbing. Meanwhile, the downstream lift gates will reflect the emptying waves, and the emptying waves will propagate reciprocally in the intermediate channel, hence aggravating the adverse effects of the emptying on navigation³–⁷.
The study of the propagation and attenuation of emptying waves at locks and their impact on navigation is primarily carried out through theoretical analysis, model tests and numerical simulations. The emptying waves are usually formed by two reasons [8, 9]: (1) due to large emptying runoff and short time, the congested water level in the downstream lock cannot flow to the downstream in time; and (2) residual mechanical energy causes water level fluctuations after the discharged volume dissipates. When flow regime, water surface fluctuations and other changes in the intermediate channel fail to meet the navigation requirements, it is often necessary to optimize the flow structure by the following ways: extending the time and improving the emptying method, optimizing the intermediate channel layout, improving the lock energy dissipation method, and deploying wave absorbing measures [4, 5, 16-13].

As navigation in west China advances fast, the layout and application of the restrained intermediate channel has been involved in the design of high dam navigable complexes, but it is difficult to be carried out according to the existing specifications due to the topographic and geological conditions. However, the formation mechanism of emptying waves generated by the emptying unsteady flow in locks, emptying wave propagation and change laws, dissipation methods and mechanisms [14-16], especially the triadic relation among the hydraulic elements (fluctuation, specific drop, flow velocity, etc.), unsteady flow transformations, and intermediate channel scale in the restrained intermediate channel have not been systematically studied [17-20]. In this study, a systematic physical test was conducted on the unsteady flow emptying process and the water surface fluctuation in the Baise restricted intermediate channel. Then, the relationship between the water surface fluctuations in different zones of the intermediate channel and the emptying intensity was analyzed, as well as the mechanisms by which different emptying curves have influences on the fluctuation time, amplitude and phase difference.

2. Experimental design and working conditions
Given the specific topographic conditions, the Baise intermediate channel route was laid out in the Nalu Ditch on the left bank of the Baise Multipurpose Dam Project, composed of locks, an intermediate channel, a water retaining dam, a navigable flume and its flood control maintenance gates and a vertical ship lift as the facilities for ship passing. The route approximates 4245 m in length. Considering the total water balance in the intermediate channel, the stimulated model should be designed to cover the entire intermediate channel, the approach channel of the downstream lock, the approach channel of the upstream ship lift and the emptying branch, the section from the upstream model to the upper lock head of the lock, the section from the downstream model to the lower lock head of the downstream ship lift, and the low-lying section of the Nalu Ditch (Figure 1).

Figure 1. Layout for the Baise Intermediate Channel Model Test
To obtain accurate flow structure and wave characteristics, a normal model was opted, whose length was set as $\lambda_u = 30$, the corresponding velocity was $\lambda_v = \lambda_z^{0.5} = 5.48$, and the resistance scale was $\lambda_s = \lambda_z^{1.6} = 1.76$ in accordance with geometric similarity.

The Baise intermediate channel was excavated in the mountain and the slope was lined with concrete slates with roughness between 0.016 and 0.02. Accordingly, the model roughness ranged from 0.009 to 0.011 as per the gravity similarity. Therefore, cement mortar plastering was performed in the model, and the corresponding roughness was about 0.01. The model including the emptying branch was 120 m long and 10 m wide on average. In the experiment, the unsteady flow control system was used to accurately identify the unsteady process of different locks, and 11 wave altimeters were set up in different zones to measure the water surface fluctuations at different positions in the intermediate channel.

Based on the emptying data, Baise emptying working conditions were divided into water saving at normal storage levels and non-water saving at flood control levels. The water discharge - time change curve was attained via the preliminary lock hydraulics test as shown in Figure 2. In the original design where the single-peak emptying mode was adopted, water discharge was completed in 450s, the discharge volume was maximized to 50.85m$^3$/s within 54s after the lock turned on, and the water level in the restricted intermediate channel varied as much as 50cm. That seriously affected the navigation of ships and the operation of the downstream ship lift, so it was necessary to optimize the emptying curve by multiple water discharges. The double-peak emptying curve was adopted in Working Condition 1, which increased the discharge time to 550 s and effectively reduced the maximum discharge volumes, with the two peaks being 50.85 m$^3$/s at 54s and 50.77m$^3$/s at 408s respectively. In Working Condition 2, three-peak discharge was employed to further reduce the peak volume to 44.25 m$^3$/s at 47s, 49.63 m$^3$/s at 247s and 49.24 m$^3$/s at 407s respectively. Considering that the original water discharge mode cannot guarantee the operation stability and safety of the intermediate channel, this study only focused on the propagation and attenuation of the emptying waves in Working Condition 1 and Working Condition 2.

![Figure 2. Discharge volume-time curve for upstream locks under different working conditions](image)

3. **Results analysis and discussion**

During the emptying process of upstream lock, water was rapidly discharged into the restricted intermediate channel in a short period of time, resulting in the banked up water level in the upstream and an expansion to the downstream, hence a long propulsive emptying wave. During the propulsion process, the fluctuations decreased with energy decay, wave superposition and wave franking effects. As the wave passed to the end of the restricted intermediate channel, it was reflected by the
downstream lift gate and then passed upstream, forming an oscillating wave upon reciprocal reflection and superposition. Finally, a standing wave with the middle as the node in the channel was generated. The water level fluctuations in the upstream (observation point 1), downstream (observation point 10) and mooring area (observation point 6) of the intermediate channel under different working conditions were shown in Figure 3. Figure 3 (a) displayed the water level fluctuations in the upstream over time. Both Working Condition 1 and Working Condition 2 were susceptible to the lock emptying so that a huge water level fluctuation occurred as the emptying started. In Working Condition 1, the first peak was maximized to 35.7 cm between 50 s and 60 s and then minimized to -28.5 cm at 9-10min as the fluctuation decreased with the decay of the downstream volume. For Working Condition 2, on the other hand, the first peak of the emptying curve was reached between 40 s and 50 s after the start of emptying, as it was in front of that in Working Condition 1. However, the peak volume of Working Condition 2 was smaller than that of Working Condition 1, so its initial peak height was only 23.4 cm, less than that of Working Condition 1. And the first oscillation produced a minimum water surface value of -18 cm at 9-10 min after emptying, similar to that in Working Condition 1. The fluctuation period was 6-7 minutes under both working conditions, indicating that the discharge volume-time curve only moved the intensity of water level fluctuations, but not the fluctuation period. Due to the superposition of fluctuations in the channel and frictional energy loss, the highest oscillating water level approximated 20 cm and the lowest oscillating water level was around -10cm after 30 minutes of emptying in Working Condition 1. The figures were about 10 cm and -10 cm respectively, after 30 minutes of emptying in Working Condition 2. This indicated that reducing the peak discharge volume can effectively lower the intensity of fluctuations in emptying the upstream lock.

Since the phase difference lagged for 6-7 min after the upstream intermediate channel oscillated for one cycle, the water level began to fluctuate when the emptying wave flowed to the downstream ship lift gate. The time-dependent fluctuation was shown in Figure 3 (b). In Working Condition 1, the water level at the downstream ship lift gate peaked 8.6 minutes after emptying and came at 18.6 cm after frictional energy dissipation and peak flattening, 47.8% lower than the peak value of the intermediate channel. In Working Condition 2, the water level of the downstream ship lift gate peaked at 11.7 cm 8.5 minutes after emptying, which was attenuated by 50% compared with the upstream lock. The fluctuation of the downstream water level decayed over time after emptying for 30 minutes, varied between 0 cm and 10 cm in both Working Condition 1 and Working Condition 2. Figure 3 (c) illustrated the water level fluctuations in the mooring area of the intermediate channel under both working conditions. Under the influence of fluctuation reflection and superposition, the water level in the mooring area in Working Condition 1 and Working Condition 2 only fluctuated between -5 cm and 5 cm within 20 minute, but no obvious fluctuation process. And the water level was relatively stable.

Figure 4 showed the maximum and minimum water levels at different observation points along the intermediate channel. The maximum and minimum fluctuations were both large at the ends and small at the intermediate. Due to the reflection and superposition of fluctuations, a standing wave was formed in the middle of the channel, and the water level fluctuated more markedly in the upstream and downstream than in the middle. At the same time, the larger discharge volume peak would produce greater water level fluctuations in both the upstream and downstream of the intermediate channel, but the peak value had a greater impact on the emptying in the upstream. In the downstream, the water level fluctuation differed little under two working conditions.

Table 1 was the list of water level fluctuations in the upstream and downstream of the intermediate channel at different moments. In Working Condition 1, the maximum water level fluctuation in the upstream and downstream of the intermediate channel was attenuated by 34.4% and 32.2% respectively, while the that in Working Condition 2 decreased by 62.8% and 20.5% respectively, after being subject to emptying wave diffusion, reflection superposition and energy dissipation. This showed that the small discharge volume peak can effectively increase the energy attenuation along the emptying wave and reduce the water level fluctuation.
Figure 3. Water level fluctuations in the (a) upstream (observation point 1), (b) downstream (observation point 10) and (c) mooring area (observation point 4) of the intermediate channel under different working conditions.
Figure 4. Relationship between maximum & minimum water levels in the restricted intermediate channel and section distance

Table 1. Water level fluctuations in the upstream and downstream of the intermediate channel under different working conditions

| Working condition          | Maximum water level (cm) | Minimum water level (cm) | Maximum water level after 30 min (cm) | Minimum water level after 30 min (cm) |
|----------------------------|--------------------------|--------------------------|--------------------------------------|--------------------------------------|
| Upstream under Working Condition 1 | 35.7                     | -28.5                    | 23.4                                 | -11.7                                |
| Upstream under Working Condition 2 | 23.4                     | -18.0                    | 8.7                                  | -9.6                                 |
| Downstream under Working Condition 1 | 18.6                     | -5.4                     | 12.6                                 | 0.3                                  |
| Downstream under Working Condition 2 | 11.7                     | -3.3                     | 9.3                                  | -0.6                                 |

4. Conclusion

(1) During the rapid discharge of the emptying wave, inadequate energy dissipation and increased discharge volume lead to the banked-up water level in the upstream of the intermediate channel, which is the main reason for the formation of unsteady emptying waves.

(2) The segmented emptying for reducing discharge peak is an effective means of lowering upstream and downstream water level fluctuations. The fluctuations decay as the peak of the emptying curve decreases and they decay more quickly during propagation.

(3) There is a fixed phase difference between the reflected wave at the downstream ship lift gate and the emptying wave of the upstream ship lock, independent of the emptying curve. The water level fluctuation in the middle of the intermediate channel can be effectively reduced by fluctuation superposition; and

(4) A reduction in peak discharge volume can effectively increase energy transmission along the emptying wave propagation, so that water level fluctuations in the intermediate channel quickly attenuate to reduce the oscillation intensity on the water surface at the downstream ship lift gate and ensure the safe and effective operation of the navigation complex.

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