

## Article

# Hydraulic Performance and Ship Safety Assessment of an Auxiliary Lock System Under Rapidly Varying Downstream Water Levels

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## Abstract

Rapidly varying downstream water levels induced by hydropower regulation and emergency shutdowns pose significant hydraulic challenges for safe vessel passage through ship-lift systems. This study investigates the hydraulic performance and navigational safety of an auxiliary lock chamber designed to buffer such fluctuations at the Baise ship lift on the Youjiang River, Guangxi, China. A centralized water filling/emptying system combining flat-gate bottom inflow with grid-based energy dissipation was evaluated through an integrated methodology comprising a one-dimensional unsteady flow mathematical model and a 1:30-scale physical hydraulic model. Under the design condition ( $H = 3.0$  m), through the recommended gate-opening speed, the filling time is 239 s with a peak discharge of  $162.41 \text{ m}^3/\text{s}$ ; the corresponding emptying time is 229 s with a peak discharge of  $163.22 \text{ m}^3/\text{s}$ . Under the normal condition ( $H = 1.5$  m), the filling time is 214 s with a peak discharge of  $85.57 \text{ m}^3/\text{s}$ . A staged gate-opening strategy at a controlled speed of 1 m/min, with vessel-type-specific stopping elevations and water-level equalization before full opening, ensures that mooring forces remain within regulatory limits under all conditions. Under the extreme condition ( $H = 5.64$  m), the maximum longitudinal mooring force is 31.80 kN for a 1000 t vessel (allowable: 32 kN) and 24.66 kN for a  $2 \times 500$  t fleet (allowable: 25 kN); without the staged protocol, forces reaching 88.71 kN were measured. Inlet conduit pressure measurements under the governing extreme-head scenario confirm no subatmospheric conditions. The findings provide validated operational guidance for auxiliary lock design in high-head navigation structures to rapidly varying downstream water levels.



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**Keywords:** auxiliary lock; ship lift; centralized filling/emptying system; grid-based energy dissipation; mooring force; gate opening strategy

## 1. Introduction

Efficient navigation through high-head navigation structures remains a critical challenge in inland waterway engineering, particularly in regions characterized by complex terrain and significant hydrological variability. With the rapid expansion of cascade hydropower development, high dams with water heads exceeding 70 m have become increasingly prevalent, creating new demands for reliable and efficient navigation structures [1–3].

Ensuring safe and continuous vessel passage across such navigation structures is essential for maintaining regional economic connectivity and sustainable waterborne transportation.

Two primary navigation structures are commonly employed in high dam projects: ship locks and ship lifts. Conventional ship locks are widely used due to their operational reliability and mature design principles; however, they are often associated with long transit times and substantial water consumption, especially under high-head conditions [3,4]. In contrast, ship lifts provide significant advantages, including reduced water usage, higher efficiency, and compact structural layouts, making them particularly suitable for large water head applications [5,6]. Consequently, ship lifts have been increasingly adopted in modern hydraulic engineering projects [7].

Despite these advantages, ship lift systems introduce additional hydraulic complexities, particularly at the interface between the lift chamber and downstream navigation channels [8]. A key challenge arises from rapid and frequent fluctuations in downstream water levels, which are typically induced by hydropower station operations, load regulation, or emergency shutdown events [9–12]. Such fluctuations can result in mismatched water levels during vessel transfer, thereby affecting operational safety and stability. Under extreme conditions, large water head differences may generate strong flow disturbances, leading to excessive hydrodynamic forces on vessels and compromising safe navigation and mooring conditions [11,12].

To mitigate these challenges, auxiliary structures such as auxiliary lock chambers have been proposed as transitional systems between ship lifts and downstream waterways [13]. These systems function as hydraulic buffers, allowing water levels within the chamber to be controlled independently of downstream fluctuations [14]. However, the hydraulic performance and operational reliability of such auxiliary systems under rapidly varying water level conditions have not been sufficiently investigated [15].

A considerable body of research has been devoted to the hydraulic characteristics of traditional ship lock systems, including studies on filling and emptying processes, flow distribution, and vessel safety under relatively stable operating conditions [16–18]. Both centralized and distributed filling/emptying systems have been extensively examined, with particular attention given to energy dissipation, flow uniformity, and the reduction in mooring forces acting on vessels [19–21]. In addition, numerical modeling techniques, ranging from one-dimensional analytical models to advanced computational fluid dynamics (CFD) simulations, have been widely applied to analyze hydraulic behavior and optimize lock design [22–24].

Existing studies predominantly focus on conventional lock systems operating under steady or gradually varying hydraulic conditions [25]. Several recent studies address related but distinct problems: Wan et al. [26] investigated hydraulic operational schemes for a multi-lane lock group subject to water-level fluctuations in a branched approach channel; Zhao et al. [27] examined the design of a filling/emptying system and gate operation mode for a ship-lift auxiliary lock; and Qi et al. [28] developed a new auxiliary diversion structure for a mountain ship lock at the Wuqiangxi project. To the authors' knowledge, however, none of these studies addresses a centralized filling/emptying system for an auxiliary lock chamber of this scale (120 m × 34 m effective), subject to a bidirectional working head reaching 5.64 m. The present study addresses this gap through three contributions. First, it extends the water-level-fluctuation problem addressed by [26] to the specific context of ship-lift auxiliary-lock operation. Second, it evaluates a centralized filling scheme combining flat-gate bottom inflow with grid-based energy dissipation, differing from the gate-operation approach of [27], the diversion-structure approach of [28], and the layered dissipation approach of Ma et al. [29] in its use of submerged bottom inflow with grid outflow specifically tailored to a bidirectional-head chamber. Third, it establishes

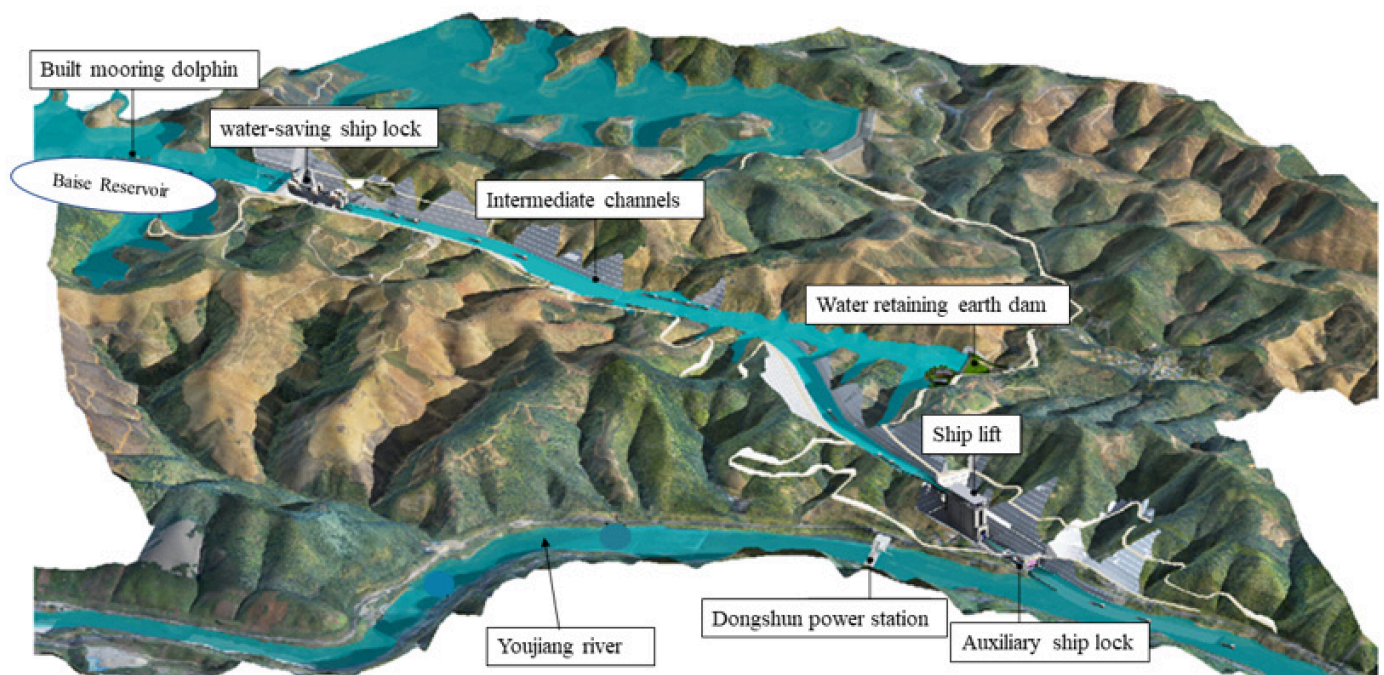
and validates a coupled one-dimensional numerical and 1:30-scale physical modeling framework incorporating vessel force assessment and ship-simulator maneuvering trials. The principal operational finding of this work, a vessel-type-dependent gate-stopping strategy, whereby the working gate is arrested at a lower elevation for a  $2 \times 500$  t fleet than for a 1000 t single vessel under the same extreme-head condition, is, to the authors' knowledge, not addressed in [26].

The validated results provide both a quantitative engineering solution and practical operational guidance, specifically the vessel-type-dependent gate-stopping strategy, that is directly applicable to similar high-head navigation projects under rapidly varying downstream conditions. To ground these contributions in a concrete engineering context, the Section 2 presents the Baise project as the prototype case, describing its multi-stage navigation system, the geometry of the auxiliary lock, and the range of hydraulic conditions that motivate the present investigation.

## 2. Engineering Background and System Description

### 2.1. Baise Navigation System

The Baise water control project is a large-scale hydraulic infrastructure project located in the upper reaches of the Youjiang River shown in Figure 1, serving multiple functions, including flood control, power generation, irrigation, water supply, and navigation. Due to the significant elevation difference across the dam, a multi-stage navigation system is required to ensure efficient vessel passage.



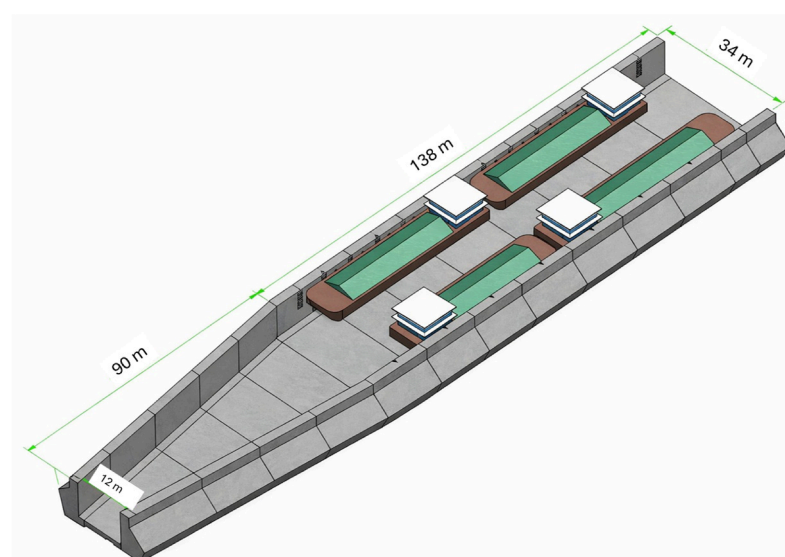
**Figure 1.** General layout of the Baise navigation structures. Components from upstream to downstream: first-stage water-saving ship lock, intermediate channel, second-stage vertical ship lift, and auxiliary lock chamber.

The navigation system adopts a two-stage arrangement comprising a conventional ship lock and a vertical ship lift. The first stage, a ship lock, is used to accommodate moderate water level differences, while the second stage employs a ship lift to overcome the remaining high head. These two systems are connected through an intermediate channel, forming a continuous navigation route.

The downstream water level at the ship lift fluctuates significantly due to hydropower regulation, resulting in unstable hydraulic conditions during vessel transfers. To address this issue, an auxiliary lock chamber is installed downstream of the ship lift. This auxiliary lock functions as a transitional buffer, maintaining a stable water level during vessel entry and exit from the ship lift, and subsequently adjusting its water level to match downstream conditions. This configuration ensures safe navigation and improves operational efficiency. With the overall navigation layout established, the Section 2.2 details the geometric configuration of the auxiliary lock, which is the central focus of this study.

## 2.2. Auxiliary Lock Geometry

The auxiliary lock is located immediately downstream of the ship lift lower head and serves as a key component of the navigation system. The total length of the auxiliary lock chamber is approximately 228 m, consisting of a transition section and a straight chamber section, shown in Figure 2.



**Figure 2.** Geometric layout of the auxiliary lock chamber (isometric view) showing the transition section (width increasing from 12.0 m to 34.0 m over 90 m) and the straight berthing section (width 34.0 m, length 138 m).

The transition section is approximately 90 m long, with the chamber width gradually increasing from 12.0 m to 34.0 m, allowing smooth adaptation of vessel movement and flow conditions. The straight section extends for approximately 138 m, providing sufficient space for vessel berthing and maneuvering.

The effective dimensions of the auxiliary lock chamber are 120 m in length, 12 m in width, and 4.7 m in sill depth, which are designed to accommodate both  $2 \times 500$  t fleets and 1000 t single vessels. The chamber bottom elevation is 109.7 m, and the wall crest elevation is 123.04 m, ensuring adequate operational safety under varying water levels.

The downstream approach channel has a bottom width of approximately 40 m, with an entrance width of 60 m, and includes flow-guiding structures to improve hydraulic conditions.

For clarity, the following elevation definitions are used consistently throughout this study: the chamber floor (sill) elevation is 107.7 m; the gate datum elevation of 109.7 m refers to the bottom edge of the gate leaf at its fully closed position, which is 2.0 m above the sill. All gate-stopping elevations reported in subsequent sections refer to the absolute elevation of the gate leaf bottom edge in meters above sea level. Having defined the physical dimensions of the auxiliary lock, it is necessary to specify the range of hydraulic

conditions under which this chamber must operate, as these directly govern the design requirements for the filling/emptying system and operational strategy.

### 2.3. Hydraulic Conditions

The hydraulic conditions of the auxiliary lock are governed by the downstream water level fluctuations and the resulting water head differences between the lock chamber and the downstream channel. Based on Dongsun power station operational records and hydrological analysis, three representative water-head scenarios are defined for design and evaluation purposes.

The normal operating condition corresponds to a water head difference of 1.50 m, representing typical daily operation. The design condition corresponds to a water head difference of 3.00 m, which is used as the primary basis for system design. An extreme condition with a water head difference of 5.64 m is also considered, representing sudden downstream water level rises caused by emergency hydropower shutdowns.

Under these conditions, the downstream water level varies approximately between 114.40 m and 120.04 m, while the auxiliary lock chamber initially maintains a constant water level before adjustment. These varying hydraulic conditions result in unsteady flow processes during filling and emptying, significantly affecting flow characteristics and vessel safety. All hydraulic conditions are summarized in Table 1. With the engineering context and hydraulic boundary conditions established, the next section presents the design of the filling/emptying system selected to manage these conditions and describes the physical model constructed to evaluate its performance experimentally.

**Table 1.** Representative hydraulic conditions considered in the study.

| Condition         | Water Head Difference, H (m) | Downstream Water Level (m) | Lock Chamber Initial Water Level (m) | Description                                  |
|-------------------|------------------------------|----------------------------|--------------------------------------|----------------------------------------------|
| Normal condition  | 1.50                         | 115.90                     | 114.40                               | Frequent operating condition                 |
| Design condition  | 3.00                         | 117.40                     | 114.40                               | Standard design condition                    |
| Extreme condition | 5.64                         | 120.04                     | 114.40                               | Emergency condition (sudden downstream rise) |

## 3. Hydraulic System Design and Experimental Setup

### 3.1. Water Filling/Emptying System Type Selection

For auxiliary navigation locks, it is necessary to choose a suitable water filling/emptying system to achieve efficient water transfer and ensure favorable hydraulic conditions for the safety of vessels and fleet. The selection of the filling/emptying system is based on the dimensionless parameter  $m$ , defined as the ratio between filling time and the square root of the water head.

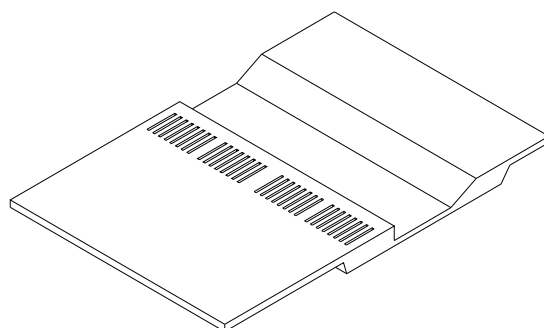
$$m = T/\sqrt{H} \quad (1)$$

According to standard design guidelines (JTJ 306-2001, China) [30], when  $m > 3.5$ , a centralized filling/emptying system is generally recommended, whereas for  $m < 2.5$ , a distributed filling/emptying system is preferred. For intermediate values ( $m = 2.5\text{--}3.5$ ), the selection should be based on technical and economic considerations. Although the calculated value of  $m$  for the present system falls within this intermediate range, a centralized water filling/emptying system is adopted.

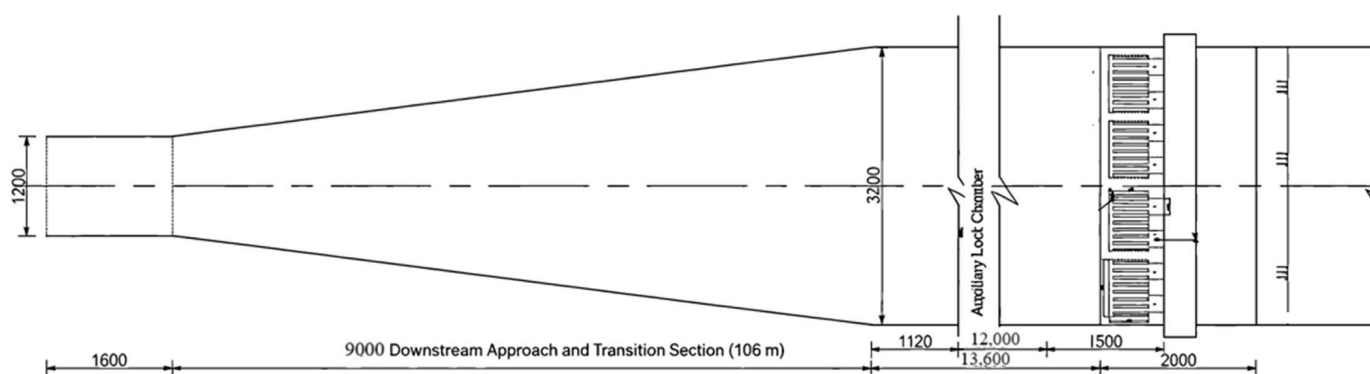
The water filling/emptying system consists of eight bottom inlet openings, each with dimensions of 2.0 m × 1.4 m, resulting in a total inlet area of 22.4 m<sup>2</sup>. The inflow is directed into four grid-type energy dissipation chambers, each measuring 7.0 m × 5.0 m × 1.4 m.

At the outlet, 32 grid openings are arranged to distribute the flow uniformly into the lock chamber. This configuration differs from conventional short-culvert or door-slit centralized systems in that the energy dissipation occurs in a dedicated chamber volume before the flow is redistributed into the lock chamber through the outlet grids. The total volume of the four dissipation chambers is  $196 \text{ m}^3$  ( $4 \times 7.0 \text{ m} \times 5.0 \text{ m} \times 1.4 \text{ m}$ ), which provides a residence time sufficient for the kinetic energy of the inflow jets to be absorbed by turbulent mixing before the flow reaches the vessel zone. The outlet grid total area of  $42.24 \text{ m}^2$  (32 openings of  $4.4 \text{ m} \times 0.3 \text{ m}$  each) is approximately 1.88 times the inlet area of  $22.4 \text{ m}^2$ , deliberately engineered to reduce outlet velocity and thereby minimize hydrodynamic forces on vessels. This design follows the same underlying principle demonstrated by Ma, Hu, and Li [29], who showed that optimized layered energy dissipation reduces flow instability and improves mooring safety in high-head lock chambers. In the present system, the ratio of total outlet-grid area to total inlet area is  $42.24 \text{ m}^2 / 22.4 \text{ m}^2 \approx 1.88$ , deliberately sized to reduce outlet velocity relative to the inlet jet and to allow sufficient residence time (chamber volume  $196 \text{ m}^3$  across four dissipation chambers) for the incoming jet to dissipate before discharge into the chamber proper. Unlike the layered dissipation elements employed by Ma et al. [29], energy dissipation here is achieved through a submerged bottom-inflow arrangement combined with grid-controlled outflow, reflecting the differing constraints of a bidirectional-head auxiliary chamber as opposed to a unidirectional high-head lock.

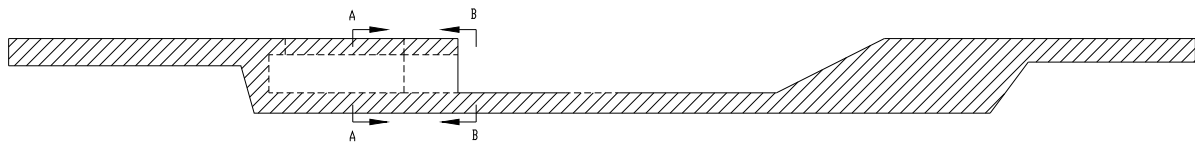
The hydraulic configuration and flow path are illustrated in Figures 3–6. The three-dimensional arrangement of the system is shown in Figure 3, while the plan layout of the inlet openings and outlet grids is presented in Figure 4. The internal structure of the dissipation chamber is further illustrated by the cross-sectional view in Figure 5, and the front view of the outlet grid arrangement is shown in Figure 6. These figures collectively demonstrate the flow transition from concentrated inflow to distributed outflow.



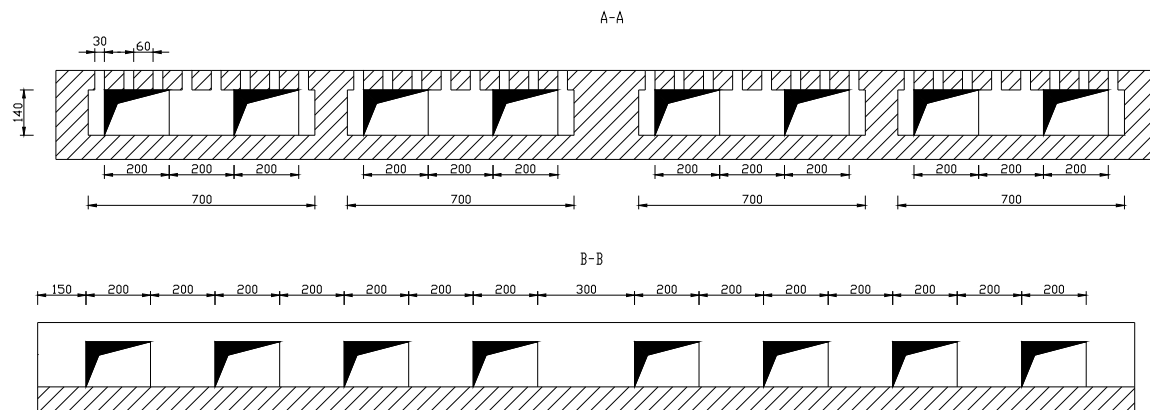
**Figure 3.** D Three-dimensional configuration of the bottom inflow and grid-based energy dissipation system.



**Figure 4.** Layout of inlet openings and outlet grids in the auxiliary lock system.



**Figure 5.** Cross-sectional view of the energy dissipation chamber.

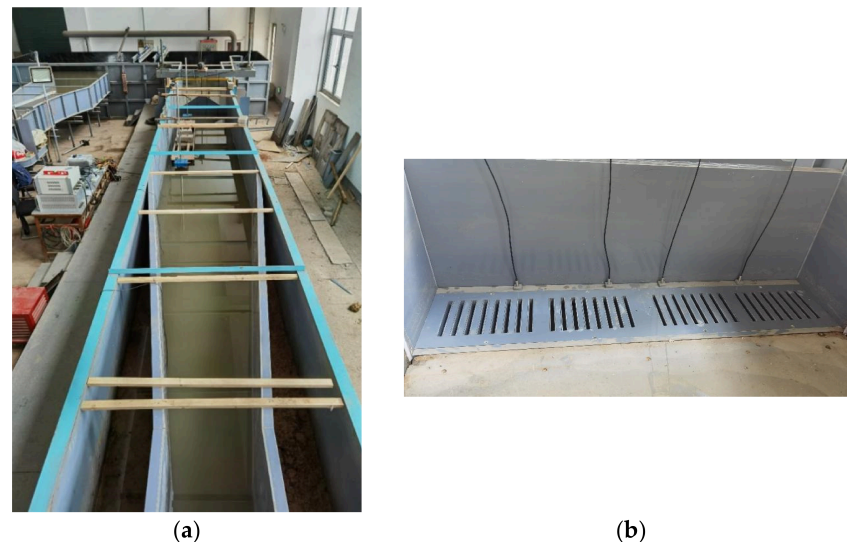


**Figure 6.** Front view of the energy dissipation structure.

The bottom inflow configuration ensures the submerged entry of water, which reduces free-surface disturbances. Meanwhile, the grid-based dissipation system decreases flow velocity and redistributes kinetic energy, thereby suppressing high-velocity jets and improving flow uniformity within the chamber. Based on this filling/emptying system configuration, a scaled physical model was constructed to experimentally validate the hydraulic performance and to capture the complex transient flow phenomena that cannot be fully resolved by one-dimensional analysis alone.

### 3.2. Physical Model Setup

The physical model was constructed using gravitational similarity (Froude scaling) with a geometric scale ratio of 1:30, faithfully reproducing the auxiliary lock chamber, inlet system, grid-type energy-dissipation chambers, and downstream approach channel as shown in Figure 7. The corresponding scale conversion relationships are force and weight scale  $L^3 = 27,000$ ; velocity and time scale  $L^{(1/2)} = 5.48$ ; and discharge scale  $L^{(5/2)} = 4929.5$ . Chamber sidewalls were fabricated from steel plate and polyethylene board, while the base slab and gate-slot dissipation structures were constructed entirely from polyethylene. An overflow-type motorized flat-water tank maintained downstream water levels, and a variable-speed stepper motor actuator controlled the gate drive, enabling precise control of the tested gate-opening rates (1.0 and 2.0 m/min) and stop elevations. Water-level histories and the non-steady pressure downstream of the working gate were both measured using resistive point pressure transducers; four pressure taps (1#–4#) were installed at the roof of the four inlet-conduit branches immediately downstream of the gate, one per branch, to capture the minimum pressure condition at the conduit crown. Vessel mooring-line tension was measured using full-bridge resistive load cells developed in-house, with three force channels recorded per vessel: one longitudinal line and two transverse lines (bow and stern). All acquired data were recorded and processed using a computer-based data acquisition system. Instrument calibration followed *SL 233-2016*, “Calibration Methods for Instruments Commonly Used in Hydraulic and River Models”.



**Figure 7.** Physical scale model (1:30) of the Baise auxiliary lock: (a) overall layout of the model showing the chamber, transition section, and downstream approach channel; (b) close-up of the grid-type energy dissipation structure at the downstream gate head.

The validity of the Froude-scaled model is assessed by examining potential viscous and surface-tension scale effects. At the design condition ( $H = 3.0$  m, gate stop elevation 110.7 m), the mean flow velocity in the inlet conduit cross-section is  $u_i = 7.25$  m/s in the prototype, corresponding to a model velocity of  $u_i/\sqrt{Lr} = 7.25/5.48 = 1.32$  m/s. The hydraulic diameter of each inlet opening ( $2.0 \text{ m} \times 1.4 \text{ m}$ ) scales to 68 mm in the model. The resulting model Reynolds number is  $Re = D_h/\nu = 1.32 \times 0.068/(1.0 \times 10^{-6}) \approx 9.0 \times 10^4$ , which lies well within the fully turbulent regime ( $Re > 4 \times 10^4$ ) where Darcy–Weisbach friction factors are effectively Reynolds-number-independent. For the lock chamber flow, the depth-averaged velocity is on the order of 0.05–0.10 m/s in the model; the corresponding Weber number  $We = \rho u^2 L/\sigma \approx 350\text{--}1400$ , confirming that surface-tension effects are negligible. Wall roughness similarity is ensured by the use of smooth polyethylene (*Manning*  $n \approx 0.010$ ) for both the chamber walls and the gate-slot dissipation structures; the equivalent prototype concrete surface has a *Manning*  $n$  of 0.013–0.016. Given the turbulent flow regime and the relatively minor role of wall friction compared with form losses at the gate and inlet openings, this small roughness discrepancy is not expected to introduce significant scale error in the measured resistance coefficients or mooring forces. On this basis, the physical model results are considered free from significant viscous or surface-tension scale effects under all tested operating conditions.

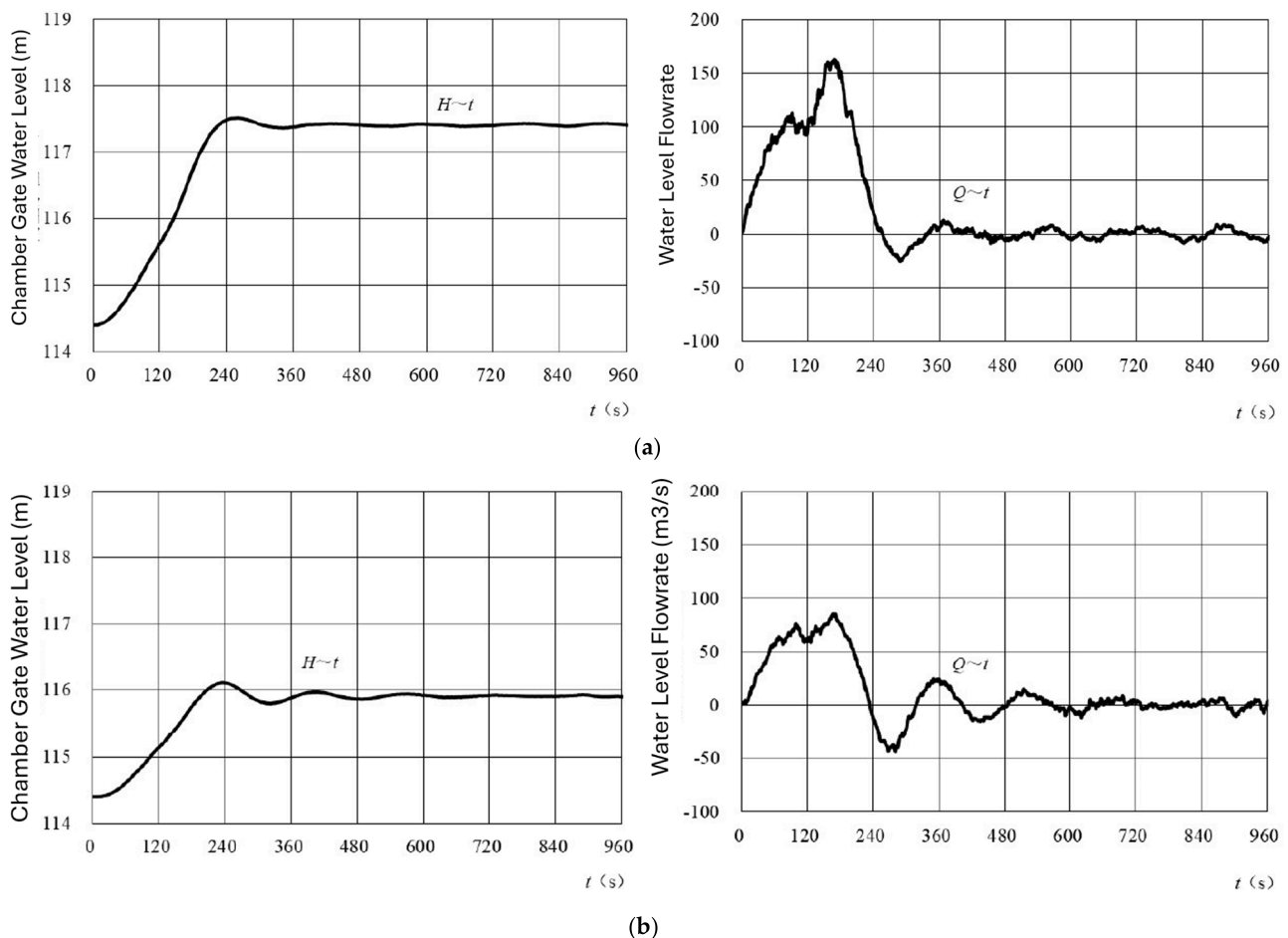
A recognized source of laboratory-to-prototype discrepancy in Froude-scaled physical models of hydraulic structures is the mis-scaling of sub-atmospheric pressure phenomena, since air-cavity and cavitation-related pressure effects do not follow simple geometric similitude (e.g., in spillway aerator flows) [31]. This is a relevant consideration for the present study, given the regulatory requirement that inlet-conduit pressure remain above  $-3.0$  m of water column.

The experimental model includes the auxiliary lock chamber, bottom inlet system, dissipation chambers, and downstream approach channel, corresponding to the prototype layout shown in Figure 1 above and the hydraulic system configuration illustrated in Figures 3–6. This ensures consistency between the prototype design and the experimental model. The tests were carried out under three representative hydraulic conditions with water head differences of 1.50 m, 3.00 m, and 5.64 m, respectively, as summarized in Table 1 above. These conditions represent normal, design, and extreme operating scenarios. In addition, various gate-opening strategies were implemented to simulate practical opera-

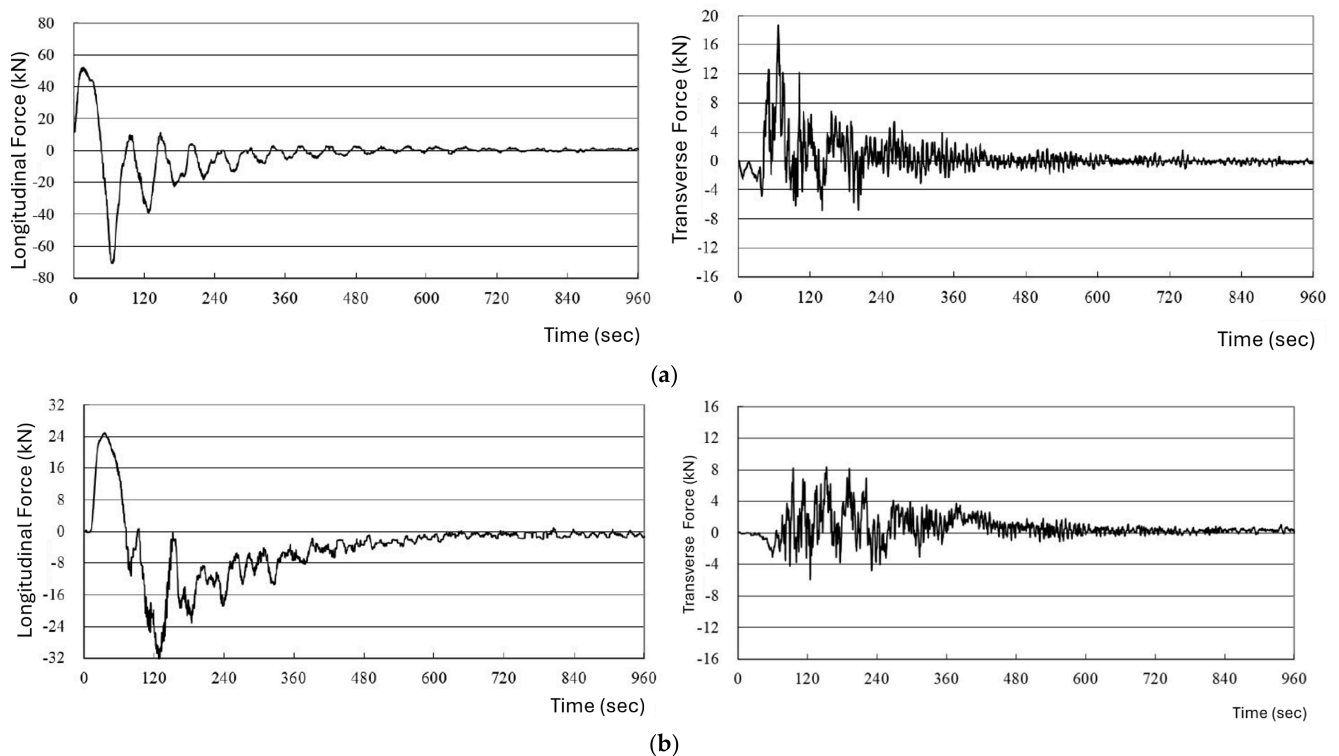
tion. The gate was initially lifted at a controlled speed to a specified height, followed by full opening after water level equalization. This staged opening process allows for the assessment of the influence of operational parameters on hydraulic performance. With the physical model established and scale effects confirmed to be negligible, the Section 3.3 defines the hydraulic and vessel-related parameters measured during testing and specifies the evaluation criteria used to assess system performance.

### 3.3. Measurement Parameters and Evaluation Criteria

During the experiments, key hydraulic and vessel-related parameters were measured to evaluate system performance, including flow rate, water level variation, and longitudinal mooring force acting on vessels. Flow rate and water level were continuously recorded to characterize the transient filling process. The resulting time-history curves were used for comparison with numerical simulations, as presented in Figures 8 and 9. These comparisons form the basis for validating the mathematical model. The longitudinal mooring force was measured to assess vessel stability under varying hydraulic conditions. This parameter is used as the primary criterion for evaluating navigation safety and ensuring that the system meets design requirements. To complement the physical model experiments and to enable parametric analysis across a broader range of operating conditions, a one-dimensional unsteady flow mathematical model was developed in parallel, as described in the following Section 4.



**Figure 8.** Physical model test results: time variation in lock chamber water level  $H \sim t$  and discharge  $Q$  for the filling process under the recommended gate-opening scheme. (a) Design condition  $H = 3.0$  m (case PF21, gate stop at 110.7 m); (b) Normal condition  $H = 1.5$  m (case PF32, continuous opening). The inertia-driven water-level overshoot above the equilibrium level is visible in panel (a).



**Figure 9.** Longitudinal and transverse mooring force time histories for a 1000 t single vessel under the extreme condition ( $H = 5.64$  m): (a) gate speed  $V = 2$  m/min, stop at elevation 109.7 m (non-compliant); (b) gate speed  $V = 1$  m/min, stop at elevation 109.7 m (recommended, compliant). Note the difference in vertical scale.

## 4. Mathematical Modeling

### 4.1. Governing Equations

The filling and emptying processes of the auxiliary lock are described using a one-dimensional unsteady flow model derived from the Bernoulli equation and continuity relationships. The system is simplified into interconnected control volumes representing the upstream reservoir, lock chamber, and downstream water body. The governing equations account for inertia effects, head losses, and transient variations in discharge and water levels.

The unsteady flow momentum equations can be expressed as follows:

$$h_1 - h_2 = (\zeta_1 + \zeta_{v1}) \frac{Q_1^2}{2gA_1^2} + (\zeta_2 + \zeta_{v2}) \frac{Q_2^2}{2gA_2^2} + \frac{L_1}{gA_1} \frac{dQ_1}{dt} + \frac{L_2}{gA_2} \frac{dQ_2}{dt} \quad (2)$$

$$h_0 - h_2 = \zeta_0 \frac{Q_0|Q_0|}{2gA_0^2} + (\zeta_2 + \zeta_{v2}) \frac{Q_2^2}{2gA_2^2} + \frac{L_0}{gA_0} \frac{dQ_0}{dt} + \frac{L_2}{gA_2} \frac{dQ_2}{dt} \quad (3)$$

The continuity equations governing the water level variation in each control volume are given by

$$Q_1(t) = -S_1 \frac{dh_1}{dt} \quad (4)$$

$$Q_0(t) = -S_0 \frac{dh_0}{dt} \quad (5)$$

$$Q_2(t) = S_2 \frac{dh_2}{dt} \quad (6)$$

The flow balance condition linking all three discharges is expressed as

$$Q_2(t) = Q_0(t) + Q_1(t) \quad (7)$$

where  $h_1$ ,  $h_0$ , and  $h_2$  are the water levels in the upstream reservoir, lock chamber, and downstream channel, respectively (m);  $Q_1$ ,  $Q_0$ , and  $Q_2$  are the corresponding discharges ( $\text{m}^3/\text{s}$ );  $A_1$ ,  $A_0$ , and  $A_2$  are the cross-sectional areas of the respective conduit segments ( $\text{m}^2$ );  $S_1$ ,  $S_0$ , and  $S_2$  are the water surface areas of the respective control volumes ( $\text{m}^2$ );  $L_1$ ,  $L_0$ , and  $L_2$  are the equivalent inertial lengths of the conduit segments (m);  $\zeta_1$ ,  $\zeta_0$ , and  $\zeta_2$  are the distributed resistance coefficients for each a conduit segment;  $\zeta_{v1}$  and  $\zeta_{v2}$  are the local resistance coefficients at the gate valves; and  $g$  is the gravitational acceleration ( $\text{m}/\text{s}^2$ ). For a single-chamber filling operation, the upstream supplement is suppressed by setting  $\zeta_{v1} \rightarrow \infty$  and  $S_0 \rightarrow \infty$ , which eliminates Equations (2) and (5) and reduces the system to a standard single-chamber unsteady filling model. The subscript notation follows the generalized lock-system schematic in which subscript 1 refers to the supplementary (upstream) water body, subscript 0 refers to the supply conduit, and subscript 2 refers to the receiving (lock) chamber. With the governing equations fully formulated, a finite difference scheme was employed to solve this nonlinear system iteratively at each time step.

The system is solved iteratively using a Newton-type inner loop until the residuals satisfy a convergence tolerance of  $10^{-6}$  m for water levels and  $10^{-4}$   $\text{m}^3/\text{s}$  for discharges. The gate valve resistance coefficient  $\zeta_v$  is updated at each time step according to  $A_k = t/t_v$ , where  $A_k$  is the fractional gate opening,  $t$  is elapsed time, and  $t_v$  is the total gate opening duration. The time step  $\Delta t$  was set to 1 s, which was verified to produce time-step-independent results by comparison with  $\Delta t = 0.5$  s runs (differences in peak discharge less than 0.1%).

The key geometric and numerical parameters used in the one-dimensional model are summarized in Table 2.

**Table 2.** Key parameters of the one-dimensional unsteady-flow model.

| Parameter                           | Value                               |
|-------------------------------------|-------------------------------------|
| Number of inlet openings            | 8                                   |
| Inlet opening size                  | 2.0 m $\times$ 1.4 m                |
| Total inlet cross-sectional area    | 22.4 $\text{m}^2$                   |
| Number of dissipation chambers      | 4                                   |
| Dissipation chamber size            | 7.0 m $\times$ 5.0 m $\times$ 1.4 m |
| Total dissipation chamber volume    | 196 $\text{m}^3$                    |
| Number of outlet grids              | 32 (8 per dissipation chamber)      |
| Outlet grid size                    | 4.4 m $\times$ 0.3 m                |
| Total outlet grid area              | 42.24 $\text{m}^2$                  |
| Chamber dimensions (effective)      | 120 m $\times$ 34 m $\times$ 4.7 m  |
| Chamber sill/floor elevation        | 109.7 m                             |
| Gate-opening law                    | $A_k = t/t_v$                       |
| Time step, $\Delta t$               | 1 s                                 |
| Convergence tolerance (water level) | $10^{-6}$ m                         |
| Convergence tolerance (discharge)   | $10^{-4}$ $\text{m}^3/\text{s}$     |

Distributed and local resistance coefficients ( $\zeta$ ) for each conduit segment and the working gate were estimated from standard local-loss relations appropriate to the gate, bend, and expansion geometry, and were calibrated indirectly through the cross-structure validation, rather than measured directly at the Baise chamber.

The hydraulic solution for discharge and water-level histories obtained from the above scheme provides the input required for evaluating hydrodynamic forces on vessels, which is addressed in the Section 4.2.

#### 4.2. Model Validation and Verification

The accuracy of the mathematical model is verified through comparison with another physical model's test results. The validation focuses on key hydraulic parameters, including filling time and maximum discharge.

The comparison results indicate that the numerical model predictions are in good agreement with experimental data. The maximum error in filling time is less than 3%, while the error in peak discharge is approximately 1.42%, as reported in Table 3.

**Table 3.** Comparison between numerical simulation results and physical model measurements for filling and emptying processes.

| Operation | Gate Opening Time (tv) (min) | Filling/Emptying Time (s)—Measured | Filling/Emptying Time (s)—Calculated | Error (%) | Maximum Discharge (m <sup>3</sup> /s)—Measured | Maximum Discharge (m <sup>3</sup> /s)—Calculated | Error (%) |
|-----------|------------------------------|------------------------------------|--------------------------------------|-----------|------------------------------------------------|--------------------------------------------------|-----------|
| Filling   | 6                            | 558                                | 544                                  | 2.51      | 115.63                                         | 115.72                                           | −0.08     |
| Filling   | 7                            | 590                                | 580                                  | 1.69      | 107.83                                         | 108.26                                           | −0.40     |
| Emptying  | 6                            | 639                                | 620                                  | 2.97      | 102.25                                         | 101.94                                           | 0.30      |
| Emptying  | 7                            | 660                                | 658                                  | 0.30      | 97.38                                          | 96.00                                            | 1.42      |

The cross-structure validation presented above establishes the general reliability of the mathematical framework for single-chamber centralized filling/emptying systems. Rather than a separate mathematical-model comparison for the Baise geometry itself, the design- and normal-condition hydraulic characteristics reported in Section 5 (filling time, peak discharge, and gate-opening behavior) are taken directly from the instrumented 1:30 physical model. Additional confidence in the model's representation of local hydraulic behavior at the Baise geometry is provided by the inlet-conduit pressure measurements (Section 5.5), which are consistent with the head-loss behavior expected at the working gate under the tested conditions.

## 5. Results and Discussion

### 5.1. Hydraulic Characteristics

The hydraulic performance of the auxiliary lock system is evaluated based on the filling process under different water head conditions. The temporal variations in water level and discharge obtained from the numerical model are consistent with the physical model measurements, as demonstrated in Figure 8. The close agreement confirms the reliability of the modeling approach.

Under the design condition ( $H = 3.0$  m), the filling time is approximately 239 s, with a maximum discharge of 162.41 m<sup>3</sup>/s. For the normal condition ( $H = 1.5$  m), the filling time decreases to approximately 214 s, with a peak discharge of 85.57 m<sup>3</sup>/s. The hydraulic characteristics are obtained from the numerical model under different water head conditions, which present the variation in filling time, maximum discharge, and flow velocity with increasing water head.

Two complementary datasets are presented. Table 4a summarizes the hydraulic characteristics predicted by the one-dimensional mathematical model under an initial gate opening speed of 2.0 m/min, serving as the baseline for evaluating the effect of gate-operation strategy. Table 4b presents the physical model test results under the optimized gate-opening scheme (1.0 m/min, *staged*), covering both filling and emptying processes under all three hydraulic conditions.

**Table 4.** Hydraulic characteristics (a) Results from mathematical model (preliminary, gate speed 2.0 m/min, stop at sill elevation 109.7 m after equalization). (b) Physical model test results under recommended gate-opening scheme (gate speed 1.0 m/min, staged stopping). Hydraulic characteristic values of gate chamber filling and discharging water.

| (a)      |       |                              |       |                                |                    |                  |
|----------|-------|------------------------------|-------|--------------------------------|--------------------|------------------|
| Case     | H (m) | Gate speed (m/min)           | T (s) | $Q_{\max}$ (m <sup>3</sup> /s) | $u_{\max}$ (m/min) | $u_{imax}$ (m/s) |
| F11      | 5.64  | 2.0                          | 476   | 168.79                         | 1.32               | 7.53             |
| F21      | 3.00  | 2.0                          | 352   | 120.83                         | 0.92               | 5.39             |
| F31      | 1.50  | 2.0                          | 255   | 83.05                          | 0.72               | 3.71             |
| (b)      |       |                              |       |                                |                    |                  |
| Filling  |       |                              |       |                                |                    |                  |
| Case     | H (m) | Gate stop elevation (m)      | T (s) | $Q_{\max}$ (m <sup>3</sup> /s) | $u_{\max}$ (m/min) | $u_{imax}$ (m/s) |
| PF11     | 5.64  | 110.7                        | 293   | 223.00                         | 1.55               | 9.96             |
| PF12     | 5.64  | 109.7                        | 513   | 161.28                         | 1.22               | 7.20             |
| PF13     | 5.64  | 108.3 (2 × 500 t fleet only) | 1292  | 73.60                          | 0.49               | 3.29             |
| PF21     | 3.00  |                              | 239   | 162.41                         | 1.20               | 7.25             |
| PF22     | 3.00  |                              | 371   | 117.66                         | 0.85               | 5.25             |
| PF31     | 1.50  | 110.7                        | 235   | 84.63                          | 0.62               | 3.78             |
| PF32     | 1.50  | Continuous                   | 214   | 85.57                          | 0.63               | 3.82             |
| Emptying |       |                              |       |                                |                    |                  |
| Case     | H (m) | Gate stop elevation (m)      | T (s) | $Q_{\max}$ (m <sup>3</sup> /s) | $u_{\max}$ (m/min) | $u_{imax}$ (m/s) |
| PE11     | 5.64  | 110.7                        | 272   | 251.51                         | 1.95               | 11.23            |
| PE12     | 5.64  | 109.7                        | 438   | 167.71                         | 1.33               | 7.49             |
| PE21     | 3.00  | 110.7                        | 229   | 163.22                         | 1.22               | 7.29             |
| PE22     | 3.00  | 109.7                        | 322   | 121.08                         | 0.91               | 5.41             |
| PE31     | 1.50  | 110.7                        | 195   | 86.23                          | 0.63               | 3.85             |
| PE32     | 1.50  | Continuous                   | 194   | 86.70                          | 0.64               | 3.87             |

**Note:** T = filling time;  $Q_{\max}$  = peak discharge;  $u_{\max}$  = maximum chamber water-level rise rate;  $u_{imax}$  = maximum mean velocity at inlet cross-section. Values in Table 4a are preliminary estimates used for initial system sizing only. The recommended operational parameters are those derived from physical model testing and presented in Table 4b.

The results indicate that the proposed system achieves rapid filling while maintaining controlled flow conditions. As shown in Table 4b, the increase in maximum discharge with water head is moderated, which is consistent with a significant portion of kinetic energy being dissipated within the chamber system. This behavior is inferred from the global discharge and water-level histories predicted by the one-dimensional model and is consistent with the design intent of the bottom-inflow and grid-based dissipation arrangement; the one-dimensional formulation does not resolve local jet penetration or flow redistribution directly, and this inference should be understood accordingly (see Section 6). Consequently, the system is expected to achieve a balance between filling efficiency and hydraulic stability, consistent with the requirements for safe lock operation.

In addition to filling, the emptying process, required when the auxiliary lock chamber must drain from an elevated level to match a lower downstream level, was also characterized under the recommended gate-opening scheme. The results are presented in Table 4b (PE-series cases). Under the extreme condition ( $H = 5.64$  m), with the gate raised to elevation 110.7 m, the peak emptying discharge reaches  $251.51 \text{ m}^3/\text{s}$ , exceeding the corresponding filling value of  $223.00 \text{ m}^3/\text{s}$  for the same gate height. The maximum chamber water-level drop rate is  $1.95 \text{ m}/\text{min}$ . Under the design condition ( $H = 3.0$  m), the emptying time is 229 s with a peak discharge of  $163.22 \text{ m}^3/\text{s}$ . For the normal condition ( $H = 1.5$  m), the emptying time and peak discharge are 195 s and  $86.23 \text{ m}^3/\text{s}$ , respectively. In all cases, the emptying hydraulic parameters satisfy the applicable design criteria. The asymmetry between filling and emptying peak discharges, particularly at high water heads, reflects the different hydraulic boundary conditions: during emptying, the chamber water level is initially elevated, creating a higher effective head at the instant the gate begins to open. To better understand how these hydraulic outcomes evolve with changing boundary conditions, the following Section 5.2 systematically examines the influence of water head difference on filling performance across all three representative scenarios.

### 5.2. Effect of Water Head

The influence of water head on hydraulic behavior is analyzed by comparing the three representative conditions (1.5 m, 3.0 m, and 5.64 m). As the water head increases, both the maximum discharge and flow velocity within the system increase significantly.

Under the preliminary gate-opening speed of  $2.0 \text{ m}/\text{min}$  (Table 4a), the mathematical model predicts a filling time of 476 s and a peak discharge of  $168.79 \text{ m}^3/\text{s}$  for the extreme condition. Under the recommended scheme (gate speed  $1.0 \text{ m}/\text{min}$ , staged stopping at elevation 108.3 m for the  $2 \times 500$  t fleet), the physical model results (Table 4b, case PF13) show a filling time of 1292 s and a peak discharge of  $73.60 \text{ m}^3/\text{s}$ . The significantly longer filling time under the recommended scheme reflects the additional equalization stage introduced to control mooring forces.

In conventional lock systems, high water head differences often lead to rapid acceleration of flow and significant fluctuations in discharge. In contrast, the present system exhibits a smoother variation in hydraulic parameters, consistent with the dissipation chambers effectively absorbing excess energy. This is consistent with the proposed configuration handling extreme hydraulic loads without inducing significant flow instability, as inferred from the discharge and water-level histories reported in Section 5.1; because the governing model is one-dimensional, this conclusion reflects chamber-averaged behavior rather than a directly resolved three-dimensional flow field (see Section 6).

### 5.3. Ship Mooring Safety

The safety of vessels during the filling process is evaluated based on the longitudinal and transverse mooring forces acting on the ship. The results obtained from the combined physical model experiments and numerical analysis indicate that the mooring forces remain within the allowable limits specified by relevant design standards under all tested conditions.

The safety of vessels during the filling process is evaluated against the allowable mooring force limits prescribed in the applicable navigation design standard (JTJ 306-2001, China) [30]. For a 1000 t single vessel, the permissible longitudinal force is 32 kN and the permissible transverse force is 16 kN. For the  $2 \times 500$  t fleet (individual vessel rating 500 t), the respective allowable values are 25 kN longitudinal and 13 kN transverse.

Results from the combined physical model experiments and numerical analysis indicate that, under the recommended gate-opening scheme ( $1 \text{ m}/\text{min}$  opening speed, staged

stopping), mooring forces remain within these limits under all three operating conditions. For the 1000 t single vessel, the maximum longitudinal mooring force is 24.54 kN under the design condition ( $H = 3.0$  m), rising to 31.80 kN under the extreme condition ( $H = 5.64$  m), a value that satisfies the 32 kN standard but leaves a margin of only 0.20 kN. The transverse force under extreme conditions reaches 8.59 kN, well within the 16 kN limit. For the  $2 \times 500$  t fleet, the maximum longitudinal force is 22.45 kN under design conditions and 24.66 kN under extreme conditions, both comfortably below the 25 kN allowable. The transverse force under extreme conditions is 6.86 kN, within the 13 kN limit.

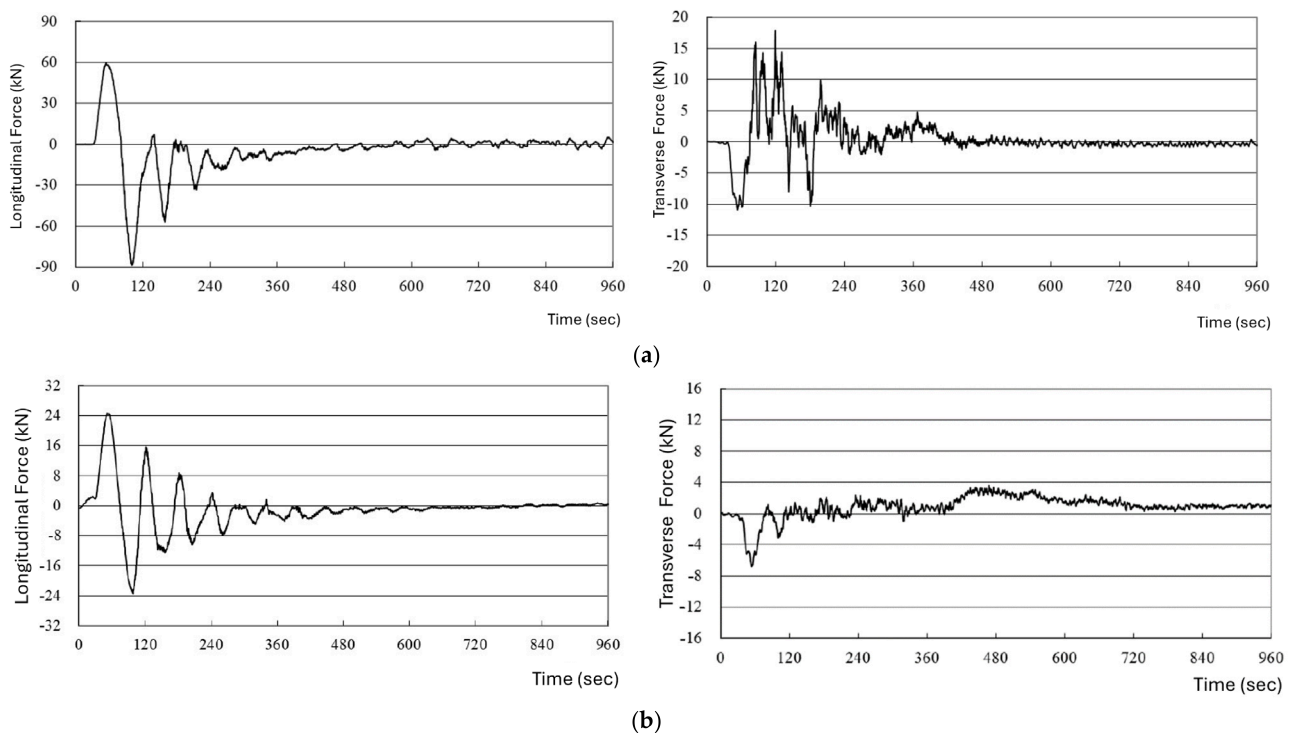
It is important to note that these compliant results are achieved only under the recommended gate-opening scheme. Physical model tests conducted at the initially proposed gate opening speed of 2.0 m/min (without staged stopping) produced longitudinal mooring forces of 70.93 kN (1000 t vessel, extreme condition) and 88.71 kN ( $2 \times 500$  t fleet, extreme condition), both far exceeding the allowable limits. This finding underscores the critical importance of the staged gate-opening strategy derived from this study. The quantitative comparison between unrestricted and optimized gate operation is summarized in Table 5. Also, the mooring force histories for two contrast cases are shown in Figures 9 and 10.

**Table 5.** Maximum vessel mooring forces under all tested operating conditions using the recommended gate-opening scheme (gate speed  $V = 1$  m/min). Allowable limits are based on applicable navigation design standards: longitudinal 32 kN and transverse 16 kN for 1000 t vessels; longitudinal 25 kN and transverse 13 kN for 500 t vessels.

| Vessel Type          | Condition | H (m) | Gate Stop Elevation (m) | Max Longitudinal Force (kN) | Allowable (kN) | Max Transverse Force (kN) | Allowable (kN) | Compliant?            |
|----------------------|-----------|-------|-------------------------|-----------------------------|----------------|---------------------------|----------------|-----------------------|
| 1000 t single vessel | Normal    | 1.50  | 110.7                   | 15.53                       | 32             | 3.57                      | 16             | Yes                   |
|                      | Normal    | 1.50  | Continuous              | 14.39                       | 32             | 3.38                      | 16             | Yes                   |
|                      | Design    | 3.00  | 110.7                   | 24.54                       | 32             | 8.73                      | 16             | Yes                   |
|                      | Design    | 3.00  | 109.7                   | 21.71                       | 32             | 6.21                      | 16             | Yes                   |
|                      | Extreme   | 5.64  | 109.7                   | 31.80                       | 32             | 8.59                      | 16             | Yes (margin: 0.2 kN)  |
| $2 \times 500$ t     | Normal    | 1.50  | 110.7                   | 19.26                       | 25             | 3.41                      | 13             | Yes                   |
|                      | Normal    | 1.50  | Continuous              | 20.31                       | 25             | 3.81                      | 13             | Yes                   |
|                      | Design    | 3.00  | 110.7                   | 22.45                       | 25             | 5.59                      | 13             | Yes                   |
|                      | Design    | 3.00  | 109.7                   | 22.13                       | 25             | 5.54                      | 13             | Yes                   |
|                      | Extreme   | 5.64  | 108.3                   | 24.66                       | 25             | 6.86                      | 13             | Yes (margin: 0.34 kN) |

**Note:** Allowable mooring force limits are prescribed by JTJ 306-2001 [30]: longitudinal 32 kN and transverse 16 kN for 1000 t single vessels; longitudinal 25 kN and transverse 13 kN for  $2 \times 500$  t fleet vessels. Values in the 'Allowable' columns correspond to the vessel type listed in the same row.

The measured maximum longitudinal mooring forces under the extreme-head condition ( $H = 5.64$  m) are close to the allowable limits specified by design code: 31.80 kN against a 32 kN allowable for the 1000 t single vessel at a gate-stop elevation of 109.7 m, and 24.66 kN against a 25 kN allowable for the  $2 \times 500$  t fleet at a gate-stop elevation of 108.3 m. These correspond to margins of only 0.20 kN and 0.34 kN, respectively. Given the narrowness of these margins, we recommend that operators apply a conservative operational buffer beyond the tested gate-stop elevations pending confirmation through prototype observation during initial operation, consistent with the general recommendation given in Section 6. The mooring force analysis demonstrates that compliance with safety limits is critically dependent on the gate-opening procedure applied; the following Section 5.4 therefore consolidates the physical model findings into a set of practical, condition-specific operational recommendations for implementation.



**Figure 10.** Longitudinal and transverse mooring force time histories for a  $2 \times 500$  t vessel fleet under the extreme condition ( $H = 5.64$  m): (a) gate speed  $V = 2$  m/min, stop at 109.7 m (non-compliant); (b) gate speed  $V = 1$  m/min, stop at 108.3 m (recommended for fleet, compliant).

#### 5.4. Recommended Gate-Opening Strategy

A critical practical output of this study is the optimized gate-opening strategy, which directly determines whether vessel mooring forces remain within allowable limits. Based on the physical model test results, the following staged gate-opening procedures are recommended for operational implementation, differentiated by water-head condition and vessel type.

**Normal condition ( $H = 1.5$  m):** The downstream gate is raised at  $V = 1$  m/min to an elevation of 110.7 m (3 m above the sill elevation of 107.7 m), then continues to full open at the standard design speed. Under this procedure, the maximum longitudinal mooring forces are 15.53 kN for a 1000 t single vessel and 19.26 kN for a  $2 \times 500$  t fleet, both with substantial margins below the respective allowable limits of 32 kN and 25 kN.

**Design condition ( $H = 3.0$  m):** The gate is raised at  $V = 1$  m/min to an elevation of 110.7 m, then held stationary until water levels inside and outside the lock are equalized, after which full opening proceeds at normal speed. The measured filling time under this scheme is 239 s with a peak discharge of  $162.41 \text{ m}^3/\text{s}$ , and maximum mooring forces are 25.54 kN (1000 t) and 22.45 kN ( $2 \times 500$  t fleet).

**Extreme condition ( $H = 5.64$  m):** The procedure is vessel-type dependent. For a 1000 t single vessel, the gate is raised at  $V = 1$  m/min to an elevation of 109.7 m (2 m above the sill), held for equalization, then opened at normal speed; the resulting longitudinal mooring force is 31.80 kN, within the 32 kN limit but with a narrow margin of 0.20 kN. For a  $2 \times 500$  t fleet, the gate opening height is further restricted to only 0.6 m above the sill (elevation 108.3 m) before equalization, limiting the mooring force to 24.66 kN against the 25 kN allowable (margin 0.34 kN). This vessel-type differentiation is essential: if the 1000 t procedure (elevation 109.7 m) is applied to the  $2 \times 500$  t fleet, the longitudinal force reaches 31.52 kN, exceeding the 25 kN limit. Given the narrow margins at both tested elevations,

a conservative operational buffer beyond these tested values is recommended pending confirmation through prototype observation during initial operation.

The recommended operating parameters are summarized in Table 6. To provide operational flexibility and accommodate conditions not explicitly tested, it is further recommended that the gate drive system be designed for continuously variable speed in the range 0.5–2.0 m/min. Beyond the operational strategy for gate control, a deeper understanding of the internal flow mechanisms responsible for energy dissipation and pressure safety is equally important for evaluating the robustness of the filling/emptying system design, as discussed in the following Section 5.5.

**Table 6.** Recommended gate-opening procedures for the downstream gate of the auxiliary lock under three hydraulic conditions. Sill elevation = 107.7 m; gate datum elevation = 109.7 m.

| Condition | H (m) | Vessel Type     | V (m/min) | Gate Stop Elevation (m) | Subsequent Action                            |
|-----------|-------|-----------------|-----------|-------------------------|----------------------------------------------|
| Normal    | 1.50  | Both            | 1.0       | 110.7                   | Continue to full open at design speed        |
| Design    | 3.00  | Both            | 1.0       | 110.7                   | Wait for level equalization, then fully open |
| Extreme   | 5.64  | 1000 t single   | 1.0       | 109.7                   | Wait for level equalization, then fully open |
| Extreme   | 5.64  | 2 × 500 t fleet | 1.0       | 108.3                   | Wait for level equalization, then fully open |

**Note:** The gate-stopping elevations of 109.7 m (1000 t vessel) and 108.3 m (2 × 500 t fleet) under the extreme condition are the tested values reported in Table 3 (cases PF12 and PF13, respectively), corresponding to measured longitudinal mooring forces of 31.80 kN and 24.66 kN against allowable limits of 32 kN and 25 kN.

### 5.5. Inlet Conduit Pressure Safety

To confirm compliance with the regulatory requirement that inlet-conduit pressure remain above −3.0 m of the water column, pressure was measured at four locations (1#–4#) at the roof of the inlet conduits under the extreme-head condition (H = 5.64 m), which governs the highest inlet velocities (up to 11.23 m/s during emptying, compared with 7.29 m/s at design head and 3.87 m/s at normal head) and therefore the greatest risk of subatmospheric pressure. Results are summarized in Table 7.

**Table 7.** Minimum inlet-conduit pressure heads under the extreme-head condition (H = 5.64 m).

| Flow Direction | Gate Stop Elevation | Minimum Pressure Head | Pulsation Amplitude |
|----------------|---------------------|-----------------------|---------------------|
| Filling        | 110.7 m             | 3.86 m                | ±1.64 m             |
| Filling        | 109.7 m             | 3.85 m                | ±1.64 m             |
| Emptying       | 110.7 m             | 3.64 m                | ±1.32 m             |
| Emptying       | 109.7 m             | 3.11 m                | ±1.44 m             |

All measured minimum pressures remained comfortably above the −3.0 m regulatory threshold. Pressure was not separately instrumented for the design- and normal-head conditions, since the extreme-head condition produces the governing (highest-velocity) hydraulic loading.

## 6. Limitations and Future Works

The present study provides validated hydraulic and navigational safety results for the Baise auxiliary lock, but several limitations should be acknowledged.

First, the hydraulic analysis relies on a one-dimensional unsteady flow model, which accurately reproduces global filling and emptying characteristics but does not resolve three-dimensional flow structures across the full chamber. Specifically, the statements in Section 5

regarding effective energy dissipation, jet attenuation, and the absence of significant flow instability are inferred from chamber-averaged discharge and water-level histories and from the physical design rationale of the bottom-inflow-plus-grid arrangement; they are not derived from directly resolved local velocity fields, jet trajectories, or turbulence measurements, and should be interpreted with this in mind. A comprehensive 3D CFD study covering all three hydraulic head conditions, multiple gate-opening heights, and all vessel berthing positions would provide a detailed characterization of jet penetration depth, lateral flow non-uniformity, and spatially varying vessel forces that the one-dimensional model cannot resolve, and is identified as a priority for future work. Notwithstanding these limitations, the results of this study offer substantive and validated guidance for the design and operation of auxiliary lock systems under rapidly varying downstream water levels, and the key findings are summarized in the following concluding Section 7.

Second, the study is based on a single prototype configuration; the generalizability of the recommended gate-opening strategy to auxiliary locks of different chamber dimensions, inlet geometries, or  $m$ -values has not been explicitly demonstrated. Future work should develop a dimensionless parameterization that allows the gate-stopping elevation to be determined as a function of water head, vessel type, and chamber geometry without requiring a dedicated physical model for each case.

Finally, a comparative evaluation of an equivalent distributed filling/emptying system under the same hydraulic boundary conditions was not performed in the present study. Without this comparison, the present work demonstrates that the centralized system is a viable option at intermediate  $m$ -values (2.5–3.5) applied to a large chamber, but cannot establish whether it is preferable to a distributed alternative in terms of mooring force performance, operational flexibility, or overall cost-effectiveness. Future work should conduct side-by-side hydraulic model tests of centralized and distributed configurations under identical chamber dimensions and head conditions to provide definitive guidance for design selection.

## 7. Conclusions

This study investigated the hydraulic performance and vessel safety of an auxiliary lock system designed to accommodate rapidly varying downstream water levels at the Baise ship lift. A centralized filling/emptying system with bottom inflow and grid-based energy dissipation was proposed and evaluated through combined numerical modeling and physical model experiments.

- (1) The results demonstrate that the proposed system provides stable and efficient hydraulic performance under a wide range of operating conditions. Under the design condition ( $H = 3.0$  m), the filling time is approximately 239 s, with a maximum discharge of  $162.41 \text{ m}^3/\text{s}$ , while under the normal condition ( $H = 1.5$  m), the filling time is reduced to 214 s, with a peak discharge of  $85.57 \text{ m}^3/\text{s}$ . These results indicate that rapid filling can be achieved while maintaining controlled flow behavior.
- (2) Under the extreme condition ( $H = 5.64$  m), the system maintains safe operation only when the vessel-type-dependent staged gate-opening scheme is applied. For the  $2 \times 500$  t fleet, the gate is arrested at elevation 108.3 m before equalization, resulting in a filling time of 1292 s and a peak discharge of  $73.60 \text{ m}^3/\text{s}$  (case PF13). For the 1000 t single vessel, the gate is arrested at elevation 109.7 m, corresponding to the tested case PF12 (filling time 513 s, peak discharge  $161.28 \text{ m}^3/\text{s}$ ). The controlled hydraulic parameters confirm the effectiveness of the staged scheme in moderating flow intensity under extreme loading.
- (3) Vessel mooring safety is achieved under all tested conditions only through the recommended staged gate-opening scheme ( $V = 1$  m/min, vessel-type-dependent stopping

elevation). For a 1000 t vessel under the extreme condition, the optimized procedure yields a longitudinal force of 31.80 kN against a 32 kN allowable limit, a margin of only 0.6%. For the  $2 \times 500$  t fleet under the same conditions, the gate must be raised no more than 0.6 m above the sill (to elevation 108.3 m), limiting the longitudinal force to 24.66 kN against an allowable of 25 kN. Without this control, forces up to 88.71 kN were measured, underscoring that the gate-operation strategy is the decisive safety parameter in this system. Inlet conduit pressure was measured under the extreme condition, the governing case for minimum pressure, at four locations downstream of the working gate (Table 6); minimum recorded pressure heads ranged from 3.11 m to 3.86 m, comfortably satisfying the  $\geq -3.0$  m requirement with no subatmospheric conditions observed.

- (4) In addition, ship simulator results indicate that vessels can safely enter and exit the ship lift chamber and interact with vessels within the auxiliary lock, confirming the rationality of the transition section and berthing area layout.

Overall, the proposed auxiliary lock system provides a reliable and effective solution for navigation under rapidly fluctuating downstream water levels. The combined design of bottom inflow, grid-based energy dissipation, and staged gate operation ensures both hydraulic efficiency and navigation safety. From an engineering perspective, it is recommended that the gate opening speed be adjustable within 0.5–2.0 m/min, and that prototype monitoring be conducted during initial operation to support further optimization.

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## Nomenclature

| Symbol         | Definition                       | Units          |
|----------------|----------------------------------|----------------|
| A              | Conduit cross-sectional area     | m <sup>2</sup> |
| A <sub>k</sub> | Gate opening degree ( $=t/t_v$ ) | —              |
| b <sub>k</sub> | Lock chamber width               | m              |
| b <sub>s</sub> | Vessel breadth                   | m              |

|                      |                                                                 |                   |
|----------------------|-----------------------------------------------------------------|-------------------|
| $C_b$                | Vessel block coefficient                                        | —                 |
| $C_e$                | Wave amplitude attenuation coefficient                          | —                 |
| $c_k$                | Long-wave celerity in the lock chamber                          | m/s               |
| $c_s$                | Long-wave celerity in the vessel-occupied section               | m/s               |
| $F_p$                | Initial wave-induced force amplitude                            | kN                |
| $F_{si}$             | Flow-velocity-induced longitudinal mooring force                | kN                |
| $F_t$                | Steady-state wave-induced force                                 | kN                |
| $F_{tw}$             | Transient wave-induced longitudinal mooring force               | kN                |
| $g$                  | Gravitational acceleration (9.81)                               | m/s <sup>2</sup>  |
| $H$                  | Water head difference (downstream minus chamber, or vice versa) | m                 |
| $h_{bow}, h_{stern}$ | Water levels at vessel bow and stern                            | m                 |
| $h_k$                | Initial lock chamber water level                                | m                 |
| $h_w$                | Effective flow depth at vessel position                         | m                 |
| $h_{woel}$           | Inlet conduit roof elevation                                    | m                 |
| $L$                  | Equivalent conduit inertia length                               | m                 |
| $l_k$                | Lock chamber length                                             | m                 |
| $l_s$                | Vessel length                                                   | m                 |
| $m$                  | Dimensionless filling time parameter ( $= T/\sqrt{H}$ )         | —                 |
| $Q$                  | Discharge                                                       | m <sup>3</sup> /s |
| $Q_{max}$            | Peak discharge during filling or emptying                       | m <sup>3</sup> /s |
| $S$                  | Water surface area of a control volume                          | m <sup>2</sup>    |
| $T$                  | Filling or emptying time                                        | s                 |
| $T_k$                | Natural period of long waves in the lock                        | s                 |
| $t$                  | Time                                                            | s                 |
| $t_s$                | Vessel draught                                                  | m                 |
| $t_v$                | Gate full-opening time                                          | min               |
| $u_{imax}$           | Maximum mean velocity at inlet cross-section                    | m/s               |
| $u_{max}$            | Maximum chamber water-level rise/drop rate                      | m/min             |
| $V$                  | Gate lifting speed                                              | m/min             |
| $x_b$                | Gate-to-vessel-bow distance                                     | m                 |
| $x_s$                | Vessel-bow-to-gate distance                                     | m                 |
| $z_k$                | Lock chamber floor elevation                                    | m                 |
| $\zeta$              | Conduit resistance coefficient                                  | —                 |
| $\zeta_v$            | Gate valve resistance coefficient (function of $A_k$ )          | —                 |
| $\rho$               | Water density                                                   | kg/m <sup>3</sup> |

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