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Operating Force Characteristics of Sector Gates Based on Prototype Testing

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Abstract: With the widespread use of sector gates in tidal river locks, there is a growing interest in the operating force during the gate operation. This study investigates the characteristics of operating forces in a sector gate hydraulic cylinder system using prototype testing and focuses on the effects of different heads and flow velocities under the operating forces. The results reveal significant differences in the opening processes between normal and reverse heads, with head differentials and direction playing crucial roles in determining the operating force under flowing conditions. In still water, both gate opening and closing processes are divided into four and three stages, respectively, with the operating force remaining stable during the low-force operation stage. In particular, during gate closure under flowing conditions, flow velocity emerges as a key factor influencing the operating force, with the force during the small gate opening stage exhibiting a parabolic relationship with flow velocity. These findings provide valuable insights for the design and selection of hydraulic gate control systems, contributing to the safe operation of gates and efficient navigation of waterways.

Keywords: operating forces characteristics; sector gate; prototype testing; reverse head; normal head

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Citation: Zhang, S.; Wang, X.; Ma, H. Operating Force Characteristics of Sector Gates Based on Prototype Testing. *Water* **2024**, *16*, 762. https://doi.org/10.3390/w16050762

Academic Editor: Giuseppe Pezzinga

Received: 15 February 2024
Revised: 29 February 2024
Accepted: 29 February 2024
Published: 3 March 2024

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1. Introduction

Navigation locks, as an essential infrastructure for navigation, are widely utilized to facilitate the smooth passage of vessels through waterways with varying water levels, including canals, natural rivers, and tidal rivers [1,2]. Vertically hinged sector gates are commonly used as lock gates in seaports and estuarine areas due to their ability to open and close under water flow and hydrostatic loads, as well as their capacity to withstand reverse head conditions [3,4], which address tidal-induced water level fluctuations. The use of sector gates in design and engineering dates back to 1924 when Swedish engineers successfully implemented them at the upper and lower gates of the Södertälje Canal Lock near Stockholm [1,4–6]. According to recent statistics from a survey of over 300 lock gate types in mainland China, sector gates have become the second most widely used gate type after miter gates. This is particularly true in the tidal reaches of the Yangtze River, where they are used to accommodate seasonal and tidal variations in water levels [7]. Additionally, the skin plates and trusses of sector gates create zones for dissipating collision forces, which can absorb the impact loads of vessels. The bent skin plates only experience localized loads, unlike miter gates which experience global compression. This preserves the overall stability of the lock gate system [1,8]. Engineers have adopted sector gates due to their low-damage characteristic following vessel impact [9]. The United States and Canada have embraced the design concept of sector gates when integrating lock gates with urban landscapes. This is exemplified by projects such as the Chicago Harbor Lock [10] and No. 7 Welland Canal Lock [11].

The utilization of hydraulic cylinders for gate operation presents notable advantages and has emerged as the predominant method for driving newly constructed large-scale sector gates, such as the Yuxi Lock [7] and the IHNC Surge Barrier Project [1]. Their precise control capabilities facilitate the effortless operation of gates across varying dimensions, while their efficiency and adaptability ensure swift responsiveness to gate operational commands [12]. In contrast to traditional gear-driven mechanisms, hydraulic cylinder driven systems obviate the need for gear transmission components, thereby mitigating maintenance costs and reducing the risk of system failures [13,14]. Furthermore, hydraulic cylinder operation exhibits enhanced smoothness, precision, and stability, thereby augmenting operational efficiency and adaptability. Notably, it necessitates lesser operating force for gate motion [14]. Research conducted by Buzzel suggests that hydraulic cylinder systems effectively dampen small oscillations of the gates compared to traditional mechanical driver systems, ensuring seamless and accurate gate movements [15]. Additionally, investigations by Haehnel underscore the influence of factors such as the layout of horizontal and vertical beams in the gate structure, the configuration of the gate lips on both sides of the gate leaf, the design of seals, and the geometric dimensions of the gate recesses accommodating sector gates on gate operation [8,16]. The selection of hydraulic cylinders is closely related to the above factors [16].

Excessive reverse head can cause sector gates to stall at small opening or damage the hydraulic cylinder system during extreme operating conditions. Incidents and accidents have occurred in the initial operations of locks such as Bayou Boeuf Lock, Freshwater Lock, and Calcasieu Lock in the United States [17]. Therefore, analyzing the operating force characteristics and influencing factors of sector gates is particularly important. The common approach to this issue is constructing physical models for experimental research. The U.S. Army Engineer Waterways Experiment Station has conducted extensive experiments on this matter [11,18–20]. Oswalt [17] established a 1:20 scale model to reduce the gate operating force under forward head conditions. This was achieved by removing the skin-plate lip closure, extending the panels, or combining both methods. Additionally, the operating force under reverse head conditions was reduced by shortening the lengths of accessories such as seal supports. Harrold [6] made changes to the design of center and side seals as well as the shape of the gate recess. These changes aimed to reduce operating forces by smoothing the flow of water along the gate sides during the opening and closing processes, avoiding the direct impact of the water flow on the gate axis. The studies mentioned above were conducted in locks with gate filling and emptying in very low lift. However, the lock upgrade project for the Inner Harbor Navigation Canal in New Orleans utilized sector gates at higher head differentials for deep-draft vessels, resulting in satisfactory hydraulic conditions within the lock chamber and desirable filling and emptying times [18].

In early studies, the operating force was measured by load cells and the signal was transmitted to direct-writing recorders [6,17]. The accuracy of data collection has been optimized with the continuous updating and improvement of electronic control devices such as pressure sensors. Wu et al. [21] carried out physical model experiments to analyze the operating force of sector gates under different water level combinations in tidal river with automated equipment. The critical conditions for lock operation were determined based on the maximum design value of the operating force and hydraulic conditions of the waterway. Zhu [22] added additional criteria, including flow patterns, maximum lateral flow velocity, and maximum longitudinal flow velocity, to refine the critical conditions for tidal differences, building upon Wu's research. Wang [23] investigated pulsating pressure on plate during small opening. Guo [24] supplemented the study by focusing on flow conditions inside the lock chamber for sector gates with asymmetric openings under special circumstances. Prototype testing, compared to physical model experiments, provide more direct and accurate data as they are not affected by scale effects. Hydraulic forces and friction were found to be much greater than expected during prototype testing at different gate openings and head differentials [19]. Prototype testing effectively complements friction values that cannot be measured in physical model experiments. Currently, prototype testing is widely applied in newly constructed sector gates, such as at Dalu Lock and Yuxi Lock. The test data provide crucial support for the design of lock gate hydraulic systems in the future [7,25].

The previous studies analyzed the practical engineering applications of sector gates, primarily focusing on the operational status of the gates, whether the output force by hydraulic cylinders is sufficient for gate operation, and the hydraulic characteristics of the current within the chamber. Previous research emphasized macroscopic requirements for manipulating sector gates, but there is a lack of reports on the changing characteristics and causes of force during gate operation, as well as the analysis of influencing factors of operating force. Additionally, there is a lack of clear standards and guiding documents to the operating forces under different conditions. Therefore, conducting specific analyses and studies on the nature of output force by hydraulic cylinders during operation is crucial and necessary. To address this gap, the purpose of this study is to investigate the effects of head differentials and flow velocities on the operating forces of sector gates through prototype testing. This study aims to analyze the characteristics of operating forces for the gates during both flowing and still water conditions. Relevant design considerations for operating drive devices are proposed based on the testing results.

This paper is organized as follows. Section 2 introduces the principles, methods, and contents of prototype testing for hydraulic cylinder systems of sector gates. Section 3 presents the testing results, analyses the effects of influencing factors such as forward and reverse head conditions, head differentials, and flow velocities on the operating forces of sector gates, and reveals the characteristics of operating force variations during the opening and closing processes. Section 4 discusses the significance of the results and outlines avenues for future research. Finally, Section 5 presents the conclusions.

2. Methodology

2.1. Theory of Testing

The hydraulic cylinders directly control the opening and closing of sector gates. An integrated system is used to precisely control the oil pressure pumped to achieve speed control of the gate during operation. The real-time oil pressure in both the rod and head ends of the hydraulic cylinder is monitored during prototype testing to accurately calculate the numerical value of the output operating force. The force of the cylinder can be expressed as follows [26,27]:

$$\mathrm{F_{th}} = \mathrm{P} \times \mathrm{A}, \tag{1}$$

where F_{th} is the force of the cylinder, kN; P is the nominal pressure acting on the surface of the piston, MPa; and A is the effective cross-sectional area of the piston, mm^2.

The mechanical force transmitted by the rod is the difference between the effective force in the rod end and the effective force in the head end. It is expressed as follows [26]:

$$\mathrm{F_{output}} = \mathrm{F_R} - \mathrm{F_H} = \mathrm{P_R} \times \left(\mathrm{D}^2 - \mathrm{d}^2\right) \times \frac{\pi}{4} - \mathrm{P_H} \times \mathrm{D}^2 \times \frac{\pi}{4}, \tag{2}$$

where F_{output} is the output mechanical force, kN; F_R and F_H represent the forces output from the rod end and the head end, respectively, kN; P_R and P_H are the nominal pressures in the rod end and the head end, respectively, MPa; D and d are the inner diameters of the head and the rod, respectively, mm; and π is the ratio of the circumference to the diameter, and for calculation purposes, it is commonly taken as a constant, approximately equal to 3.14.

When collecting data, pressure sensors acquire pressure electrical signals instead of directly measuring the pressure in the rod and head ends. Therefore, it is necessary to convert the electrical signals into pressure values. The output mechanical force transmitted by the rod can ultimately be expressed as follows:

$$\mathrm{F_{output}} = \mathrm{V_R} \times \alpha \times \left(\mathrm{D}^2 - \mathrm{d}^2\right) \times \frac{\pi}{4} - \mathrm{V_H} \times \beta \times \mathrm{D}^2 \times \frac{\pi}{4}, \tag{3}$$

where V_R and V_H represent the electrical signals from the rod and head ends, respectively, mV; and α and β are the conversion coefficients between pressure and voltage for the rod and head ends, respectively.

2.2. Research Sample and Data Collecting Method

This study focused on the Jianbi Lock situated at the junction of the Yangtze River and the Beijing–Hangzhou Grand Canal, two vital waterways. The northern side of the lock connects to the inland waterway, while the southern side faces the Yangtze River. Notably, the water level on the Yangtze River side experiences two tidal cycles daily, resulting in reverse head exerting pressure on the sector gates. For the prototype testing, the sector gate on the inland waterway side was selected as the research sample, while the sector gate on the Yangtze River side remained open to maintain continuous connectivity between the chamber water level and the Yangtze River water level. Figure 1a illustrates the relative positions of the upstream and downstream gates, as well as the overall layout of the navigation lock.

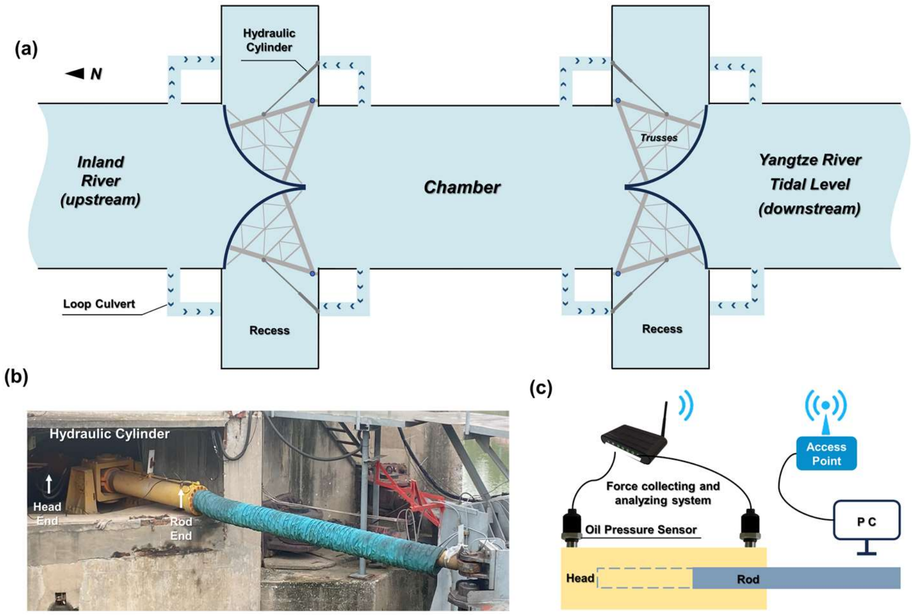

Figure 1. Schematic view of the research area. (**a**) Overview of the navigation lock, including the relative positions of the sector gates, river channels, chamber, and loop culverts. (**b**) Actual photo of the hydraulic cylinder, with white arrows indicating the rod and head ends. (**c**) Schematic diagram of the arrangement of the force testing system.

The operating forces exerted by the hydraulic cylinders are measured using oil pressure sensors. These sensors were installed at both the rod ends and head ends of the hydraulic cylinders for the two gates on the inland waterway side. The sensors have a rated range of 0–15 MPa. The relative positions of the sensors and the hydraulic cylinders are shown in Figure 1b. Calibrating the sensors is essential and critical prior to formal testing. The sensors were tested under five different pressure gradients, and based on the test voltage values, the conversion coefficients (α and β) for the rod and head ends of the hydraulic system of the west inland-side sector gate were determined to be 1.1977 and 0.5821, respectively, while for the east gate, they were 0.5730 and 0.7058, respectively. Since the hydraulic cylinders were operating normally before the test and the oil pressure was present in the cylinders, the sensors needed to be reset before installation. After resetting, they should be installed at both ends of the rod and the head. The sensors were not recalibrated during the operation of the sector gates under varying water level conditions and operational states. The sensor settings remained unchanged throughout the entire testing process.

Table 1 presents specific parameters of the hydraulic system, noting that the maximum design value of the operating force is 300 kN. Due to the river channel dividing the east and west banks, a wireless connection layout was chosen for the experiments. The oil pressure sensors were connected directly to both the rod and head ends through threaded openings, and they interfaced with a waterproof dynamic force collecting and analyzing system (China Donghua DH5908L, Jingjiang, China), which is skilled at quantitatively analyzing the electrical signals (see Figure 1c). The system has its own power supply and can transmit signals wirelessly over short distances. This allows data to be received on a computer by connecting to an access point. The delay in data transmission during on-site testing was considered acceptable. Additionally, three water level gauges were installed to monitor the water depths. One was placed on the upstream inland river side, another in the middle of the chamber, and the third on the downstream Yangtze River side. Survey-style acoustic Doppler current profilers (USA TRDI StreamPro ADCP, San Antonio, TX, USA) were used to monitor flow velocity within the chamber.

Table 1. Specifications of the hydraulic cylinder system.

Parameter	Value
Design value of the operating force	300 kN
Maximum working pressure	13 MPa
Maximum stroke	3.80 m
Cylinder diameter	250 mm
Piston rod diameter	180 mm

2.3. Validation

Before the formal prototype testing, conducting preliminary experiments to validate the accuracy of the hydraulic cylinder's output force and ensure the correctness of the force variation trend is essential. This practice aids in detecting any anomalies in the data and allows for timely corrections and recalibrations, thereby ensuring the accuracy and reliability of the test results. Multiple opening and closing operations under different water level conditions, including zero head and large head differentials, were tested at this stage. The preliminary experiment results suggest a consistent variation trend in the operating force of the two gates on the inland waterway side, with similar force values observed. Moreover, the data exhibit good reproducibility, with force values changing in accordance with the gate operational status. This reveals the reliability and accuracy of the testing method.

2.4. Experimental Conditions

This study aimed to determine the influence of different head differentials and flow velocities on the operating force characteristics of sector gates. Moreover, the differences in operating force characteristics between forward and reverse head conditions were analyzed. The valves in the upstream and downstream loop culverts remained closed, while the sector gates on the Yangtze River side remained open, maintaining communication between the chamber and the Yangtze River. Ten different head differentials were selected, covering both forward normal head conditions (with differentials ranging from 8.0 cm to 23.0 cm) and reverse head conditions (with differentials ranging from 15.0 cm to 70.0 cm). Additionally, two kinds of level combinations of still water for opening and closing operations were also selected. Twelve different flow velocities were also chosen, ranging from 0.2 m/s to 1.05 m/s for the normal flow from the inland river to the Yangtze River, and from −0.45 m/s to −1.86 m/s for the reverse flow from the Yangtze River to the inland river. Head differentials were assigned positive values when the upstream water level was higher than the downstream level. Similarly, positive values were assigned to flow velocities when the flow was directed downstream. Conversely, negative values were assigned in the opposite scenarios. Table 2 presents the specific parameters for each condition.

Table 2. Specific parameters of the experimental conditions.

Run	Water Level (m)			Variable Value	Operating Order	Notes
	Yangtze River	Chamber	Inland River			
RH-1	4.360	4.283	4.280	−0.3 cm	Open	Still water
RH-2	4.020	4.000	3.870	−15.0 cm		Reverse head
RH-3	4.580	4.580	4.360	−22.0 cm		
RH-4	4.120	4.110	3.820	−30.0 cm		
RH-5	4.310	4.300	3.950	−36.0 cm		
RH-6	4.600	4.580	3.900	−70.0 cm		
NH-1	4.350	4.297	4.300	0.3 cm		Still water
NH-2	3.860	3.850	3.940	8.0 cm		Normal head
NH-3	3.800	3.815	3.890	9.0 cm		
NH-4	3.820	3.760	3.890	13.0 cm		
NH-5	3.650	3.750	3.820	17.0 cm		
NH-6	3.600	3.780	3.830	23.0 cm		
NF-1	3.920	3.910	3.900	−0.15 m/s	Close	Reverse flow
NF-2	3.960	3.960	3.950	−0.48 m/s		
NF-3	4.040	4.010	3.980	−1.00 m/s		
NF-4	4.650	4.630	4.610	−1.40 m/s		
NF-5	3.980	3.940	3.930	−1.74 m/s		
NF-6	4.110	4.000	3.980	−1.86 m/s		
PF-1	3.770	3.825	3.835	0.20 m/s		Normal flow
PF-2	3.680	3.700	3.720	0.40 m/s		
PF-3	3.760	3.810	3.810	0.60 m/s		
PF-4	3.770	3.795	3.810	0.71 m/s		
PF-5	3.680	3.720	3.723	0.90 m/s		
PF-6	3.610	3.638	3.640	1.05 m/s		

3. Results

3.1. Operating in Still Water

In still water, the depth within the chamber is the constraint on the force required for gate manipulation. During the prototype testing of operating force in still water, the opening and closing processes maintain an approximately uniform depth within the chamber. Harrold's study on the operating forces of sector gates at Algiers Lock found that the pintle torque required for gate operation remains constant, regardless of whether the gate runs with variable acceleration or at a constant speed [6]. Figure 2 shows the duration curves of operating forces in opening and closing at constant speed under still water.

During the opening process, tension dominates, while during the closing process, pushing force dominates. Based on the magnitude and trend of the operating force, the gate opening process is classified into four stages: the initial, the small opening, the low-force operation, and the final stage. In the initial stage, the operating force is relatively higher due to friction from the side seals and friction between the top and bottom pintles [28]. In addition, at the beginning of the opening process, the gate tends to close due to its small opening [6,17], so a second peak force occurs in the small opening stage. In the low-force operation stage, the gate operates steadily with the force of approximately 18 kN, to overcome the friction from the bottom seals. It can be inferred that the friction from the bottom seals remains constant throughout the operation. As the gates approach the recesses during closing, the forces enter the final stage and experience the final peak due to compression and collision. During the closing process, there are only three stages, and compared to the opening process, the gate can still operate smoothly with low operating force in the small opening stage, without sudden fluctuations or changes in the force curve. The average operating force during the low-force operation stage for both opening and closing is 16.71 kN and 16.37 kN, respectively, indicating similar force requirements for both operations. In contrast to the gates operating under flowing conditions, the overall trend of the operating force variation during still water operation is simpler. Therefore, for gates operating under such conditions, the focus during the design phase should be primarily on the operating force required to overcome the friction of the bottom seals, side seals, and top and bottom pintles.

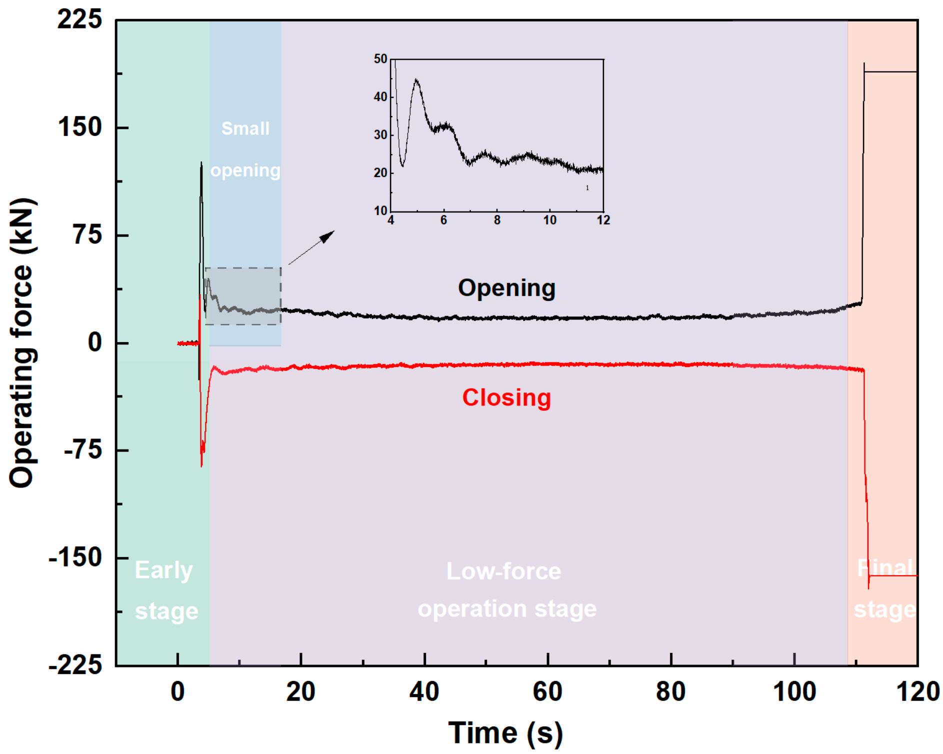

Figure 2. The division of operating force during the opening and closing of sector gates in still water.

3.2. Opening under Flowing Conditions

3.2.1. Opening Force Characteristics

The operating forces acting on the sector gate during the opening process were tested at various head differentials. Before the sector gate opens, the water levels on both sides of the gate remain stable, ensuring a sustained head difference without any flow. The gate maintained a constant speed throughout the tests. Normal head conditions were tested at 8 cm, 9 cm, 13 cm, 17 cm, and 23 cm, while reverse head conditions were tested at −15 cm, −22 cm, −30 cm, −36 cm, and −70 cm. Tension forces are represented as positive values, while pushing forces are negative. The opening force data are presented graphically in Figure 3.

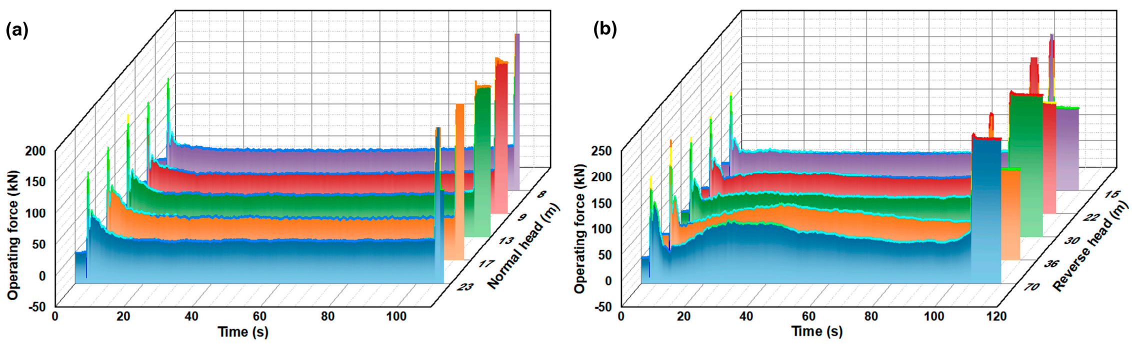

Figure 3. The duration curves of the operating force for opening the sector gates under various head differentials. (**a**) Normal head conditions; (**b**) reverse head conditions.

Figure 3 shows that the duration curves of the operating forces have common characteristics. Instantaneous peak tensile forces occur at the beginning and end of the gate opening, with significantly lower forces required during the opening process, under both normal and reverse head conditions. When the normal head differential is 8.0 cm, the operating force at the moment of gate opening is 130.46 kN, while at the instant of full opening, it reaches 252.16 kN, with a peak force during the opening process of 20.93 kN. As the normal head differential increases to 23.0 cm, the aforementioned forces become 148.51 kN, 234.10 kN, and 43.61 kN, respectively. In the case of reverse head with a 15.0 cm head differential, the force required at gate opening is 138.28 kN, increasing to 256.74 kN at full opening. During the opening process, the force peaks at 30.16 kN. With a head differential of 70.0 cm, the above forces become 148.51 kN, 234.10 kN, and 43.61 kN, respectively. In summary, the operating force at the instant of gate opening typically falls between 130 and 150 kN, while at full opening, it ranges from 220 to 257 kN, with minimal variation based on the head differential. The peak operating force during opening increases with the head differential under normal head conditions, averaging a 1.51 kN increase per 1 m rise in head differential. Similarly, for reverse head conditions, there is a comparable trend, with an average increase of 1.13 kN per 1 m rise in head differential, slightly lower than the normal head condition.

After reaching the peak operating force when the gate opens under normal head conditions, a second peak appears on the curve. This peak indicates that the force phase is required to overcome the flow resistance when the gate is partially open. Subsequently, the operating force gradually decreases and remains at a lower level from 20 s to ~105 s during the opening process. In contrast, when opening the gate with flowing water under reverse head conditions, the operating force returns to near zero levels after the initial peak. The second peak occurs between 10 s and ~60 s in the opening process. Therefore, the primary difference between them lies in the timing of the second peak. In the reverse head condition, the peak occurs later compared to the normal head. That is to say, during the gate opening process, the gate reaches a larger opening at the moment of maximum flow resistance under reverse head than normal head.

3.2.2. Division of Opening Force Intervals

Figure 4 shows the duration curves of the operating forces during the gate opening at constant speed under flowing conditions. Following the same categorization method for the still water conditions, the opening process under the normal head is divided into initial, small opening, low-force operation, and final stages.

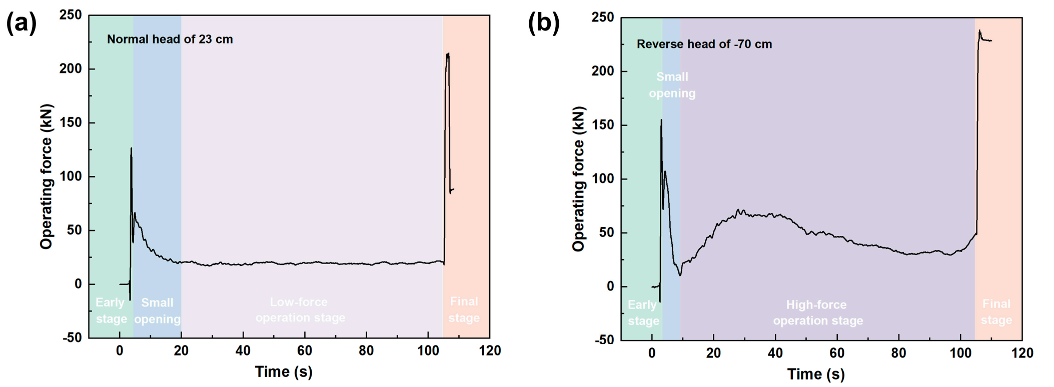

Figure 4. The division of opening force under flowing conditions. (**a**) Normal head of 23 cm; (**b**) reverse head of −70 cm.

In the small opening stage under normal head, a force peak occurs due to the gate gap flow, which tends to close the gate, requiring increased hydraulic pressure to open the gate [6]. Furthermore, the duration of force reduction in this stage is slightly longer than the reverse head. The peak force in the small opening stage is positively related to the head differential, showing a strong linear relationship, with a coefficient of determination of 0.902 (blue points in Figure 5). Conversely, during the opening process of the reverse head, the low-force operation stage is supplanted by the high-force operation stage. Comparing Figure 4a,b, it is evident that there is a significantly higher peak force during reverse head opening compared to the same period under normal head, which occurs at the opening ratio of approximately 20–30%. Since the frictional force of the bottom water is constant, the variation in operating force during this period is primarily due to flow resistance. The resistance includes not only the force caused by the gate gap flow at the center of the chamber, but also the flow around the gate in recess [6,20]. As the opening ratio increases, the head difference between the two sides of the gate decreases, resulting in a gradual reduction in force during the later stages of high-force operation. The peak force during this stage is positively correlated with the head differential and exhibits a strong linear relationship, with a coefficient of determination of 0.994 (red points in Figure 5). In summary, both the magnitude and direction of the head differential play a critical role in determining the operating force during opening under flowing conditions.

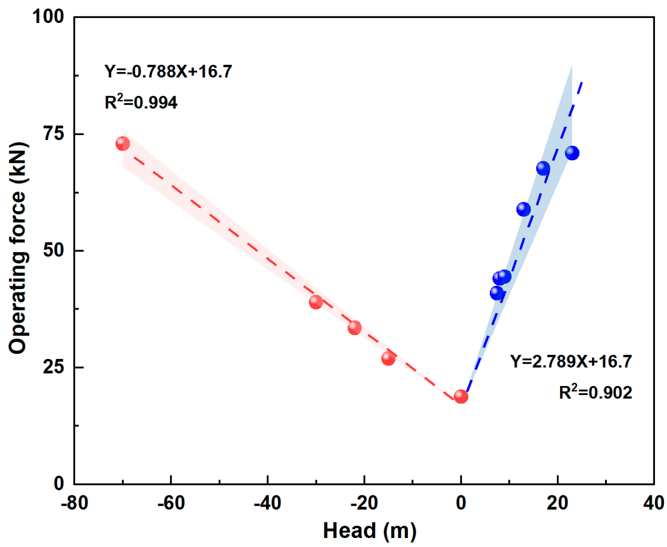

Figure 5. The relationship between head and operating force during gate opening under flowing conditions (red points represent peak forces during the high-force operation stage, while blue points represent peak forces during the small opening stage; the red and blue areas represent the 95% confidence band).

3.3. Closing under Flowing Conditions

3.3.1. Closing Force Characteristics

The experiment also analyzed the operating forces of the sector gate during the closing process under different flow velocities in the chamber. The focus was on the temporal variation of these forces. The primary objective of this phase of the experiment was to compare and analyze the differences and variations in the force characteristics under flowing conditions. The velocities of the normal flow downstream (from the inland river to the Yangtze River) were set at gradients of 0.20 m/s, 0.40 m/s, 0.60 m/s, 0.71 m/s, 0.90 m/s, and 1.05 m/s, while upstream reverse flow velocities had gradients of −0.15 m/s, −0.48 m/s, −1.00 m/s, −1.40 m/s, −1.74 m/s, and −1.86 m/s, respectively. The closing force data are presented graphically in Figure 6.

Similar to the gate opening operation, the operating force during the closing process exhibits peaks at the beginning and end, with relatively smaller pushing forces throughout the process (Figure 6). During normal flow, the operating force remains at a low level after the peak thrust at the moment of gate closure until the sector gate approaches partial closure, at which point it gradually increases. The duration and trend of the operating force in reverse flow are generally similar to those described above, but with a higher pushing force requirement in the small opening stage.

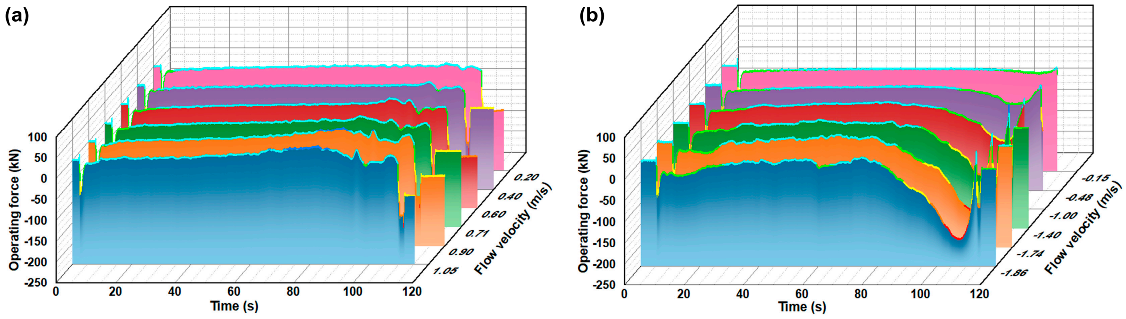

Figure 6. The duration curves of the operating force for closing the sector gates at different flow velocities. (**a**) Normal flow; (**b**) reverse flow.

When the water flows downstream and hits the skin plate at a velocity of 0.20 m/s, the initial pushing force during closure is 71.29 kN, reaching a peak force of about 2.48 kN during the closing process, and ending with a pushing force of 130.87 kN at full closure. With an increase in flow velocity to 1.05 m/s, these forces rise to 72.05 kN, 33.87 kN, and 192.25 kN, respectively. On the other hand, when the water flows upstream and strikes the trusses at a velocity of −0.15 m/s, the initial pushing force during closure measures 82.50 kN, peaking at around 18.07 kN during the closing process, and concluding with a pushing force of 109.02 kN at full closure. With an increase in flow velocity to −1.86 m/s, these forces reach 85.23 kN, 186.78 kN, and 112.86 kN, respectively. The initial force applied during closure remains relatively consistent, ranging from 70 to 85 kN, and is not significantly impacted by changes in flow velocity. However, when the flow hits the skin plates at the instant of full closure, a greater force of 130 kN to 195 kN is required. On the other hand, when the flow strikes the sector gate trusses, the force at the end of closure is slightly lower, approximately 108 kN to 115 kN. The force required to close the gate increases with the flow velocity, especially when the flow hits the trusses. Moreover, an increase of 1.71 m/s in the velocity of the reverse flow results in a highly sensitive peak pushing force that increases by a factor of 8.3.

3.3.2. Division of Closing Force Intervals

Figure 7a,b illustrate the distribution of operating forces during gate closing under flow conditions for both normal and reverse flows. The forces for both flow directions are divided into four stages: initial, low-force operation, small opening, and final stage.

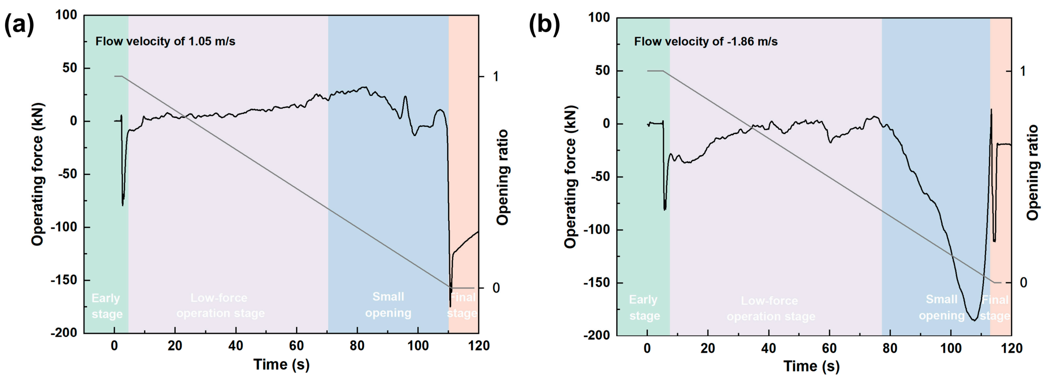

Figure 7. The division of closing force under flowing conditions. (**a**) Normal flow, flow velocity of 1.05 m/s; (**b**) reverse flow, flow velocity of −1.86 m/s.

A notable difference in force application between the two flow directions is observed primarily during the low-force operation stage. In the case of reverse flow, a pronounced peak in the push force occurs in the small opening stage. As the gate approaches closure, the decreasing opening results in increased flow resistance, requiring more force to close. A similar increase in pushing force toward the end of the closure is also observed for normal flow, although the magnitude of the force is significantly lower compared to reverse flow. This difference occurs because, unlike the transverse forces exerted by the flow as it strikes the skin plate, the flow passing through the recesses in the gate structure tends to facilitate gate opening. Consequently, hydraulic cylinder systems require additional output force to counteract this tendency. The gate operation in both flow directions during the low-force operation stage is smooth, the flow direction having a limited influence on the forces during this stage. In addition, during the small opening stage, the peak pushing force shows a positive correlation with the absolute value of the flow velocity, which shows a good fit with a quadratic polynomial function, with a coefficient of determination reaching 0.987 (Figure 8). Statistical analysis indicates that when the flow impinges on the trusses, the maximum operating force during the entire closing process occurs at gate opening ratios of 5–10%. When designing sector gates that frequently operate under reverse flow conditions, special attention should be paid to the operating forces during this phase, as they affect the selection of hydraulic cylinder systems. In summary, flow velocity is a critical factor influencing the closing forces under flowing conditions. While different flow directions have only a moderate effect on the forces during the small opening stage, there is little variation in the other three stages.

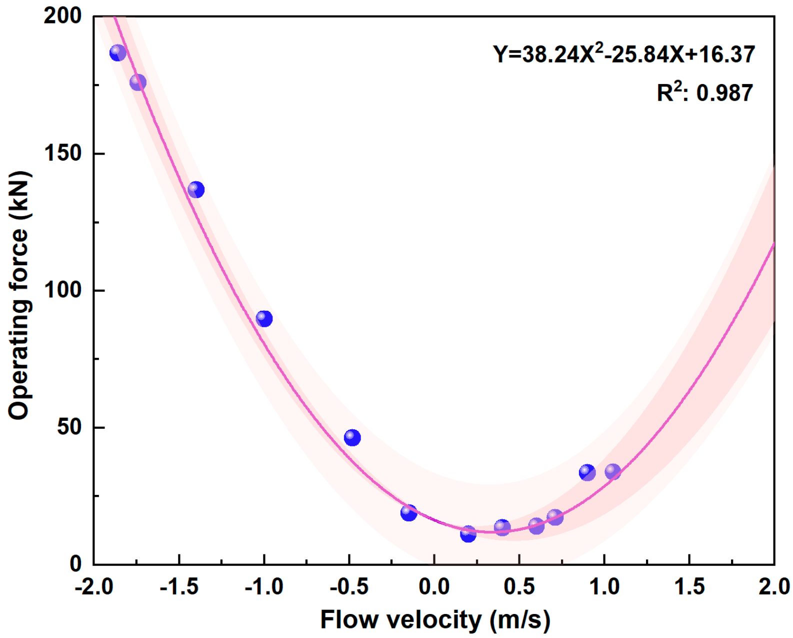

Figure 8. The relationship between peak force and flow velocity during the small opening stage (the dark pink area represents the 95% confidence band, and the light pink area represents the 95% prediction interval).

4. Discussion

The most common method for evaluating the operating force of sector gates is through tension load cells in physical models. This approach, validated through prototype testing by the United States Army Corps of Engineers, has revealed that simulating hydrodynamic loads in physical models is generally accurate [17,20]. However, frictional forces often exceed expected values, sometimes doubling the original design estimates [20]. To date, there is no precise method for estimating gate operating forces. The highlight of this paper is the analysis of operating force characteristics under different influencing conditions and operational states through prototype testing. The core of this analysis lies in examining variations in operating force under different heads and flow velocities.

The characteristics of opening force under flowing conditions can serve as initial design guidelines for newly constructed sector gates. By extrapolating from the operating force of similar-sized locks in still water, estimates can be made for the operating force required to open gates under various water level combinations and differing head differentials. In practical lock operations, gates are often opened preemptively during the final stages of filling or emptying with the head differentials [21]. This allows water to flow through the gate gap, aligning the water level in the chamber with that of the navigation channel and thereby enhancing navigation efficiency [25]. This operational approach places specific demands on the driving capacity of hydraulic cylinders. The research into the characteristics of gate opening under flowing conditions offers scientific support in this regard.

Furthermore, in some river sections with minimal water level differences due to tidal influences, locks may allow vessels to pass freely with gates fully open. However, since it is necessary to close the gates before the tide rises to restore normal lock operations, the closing force becomes a crucial safety factor for this operational method. For example, the critical flow velocity of Nantong Lock in this operational method is 2.0 m/s [21,22]. The lock near the mouth of the Yangtze River faces a significant operational challenge during flood seasons when rapid tide rises occur. Thus, the relationship between flow velocity and the closing force under flowing conditions also has significant implications for the practical operation of locks.

However, several limitations still exist in our study. For instance, further research is needed to analyze the flow fields around the gate area during movement and the assessment of hydrodynamic loads around the gates for understanding the operating force. Moreover, more equipment and sensors will be employed for force analysis, such as aerial photography devices and time-lapse photography techniques. The influence of the shape of seals and gate noses will be considered in the force analysis.

5. Conclusions

In recent years, sector gates have been widely used in lock gates at tidal estuaries due to the ability to work under bidirectional water head and operate effectively in flowing water. The hydraulic cylinder system plays a key role in ensuring the normal operation of sector gates, which serves as a fundamental prerequisite for facilitating efficient and orderly navigation. Therefore, studying the operating force characteristics of hydraulic systems is of great practical value in ensuring the safe and efficient operation of lock gates.

In this study, prototype tests of hydraulic cylinder systems were conducted to analyze the operating force characteristics under still water conditions. This study also investigated the effect of varying head differentials on the operating force during gate opening under both normal and reverse heads. In addition, the characteristics during gate closing were analyzed under flowing conditions with different flow rates and directions. Subsequently, comparisons and analyses were made on the duration processes of the operating force under different conditions. Finally, based on the characteristics and features of the operating force, important considerations for the design and selection of hydraulic cylinder systems were proposed. The conclusions can be summarized as follows:

- The prototype testing of hydraulic cylinder systems can be effectively applied to the research of operating force characteristics. It provides the most direct and accurate scientific data, which provides excellent insight into the operating and force characteristics of sector gates.
- The operating force during gate opening under still water conditions can be divided into four stages: initial stage, small opening stage, low-force operation stage, and final stage. During gate closing, there are only three stages: initial stage, low-force operation stage, and final stage. The operating force during the low-force operation stage remains relatively constant for both opening and closing, and the frictional resistance from the bottom seal remains stable throughout the operation process.
- The magnitude and direction of the head are the main factors influencing the operating force during gate opening under flowing conditions. The opening process under

normal head includes the initial stage, the small opening stage, the low-force operation stage, and the final stage, while under reverse head it includes the initial stage, the small opening stage, the high-force operation stage, and the final stage.

- The peak force for gate opening during the small opening stage under normal head and the high-force operation stage under reverse head are both linearly correlated with the head differential, with coefficients of determination of 0.902 and 0.994, respectively.
- Flow velocity is the key factor influencing the operating force during gate closing under flowing conditions. The force process includes the initial stage, the low-force operation stage, the small opening stage, and the final stage. During the small opening stage, when the trusses are impacted by flowing water, the operating force is significantly higher, and the peak force is parabolically correlated with flow velocity, with a coefficient of determination of 0.987.

Author Contributions: Conceptualization, S.Z.; Methodology, S.Z. and X.W.; Validation, X.W. and H.M.; Investigation, S.Z. and X.W.; Data Curation, S.Z. and H.M.; Writing—Original Draft Preparation, S.Z.; Writing—Review and Editing, S.Z. and X.W.; Visualization, S.Z.; Supervision, X.W.; Project Administration, X.W.; Funding Acquisition, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Nanjing Hydraulic Research Institute Foundation Project (Y123004).

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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