Article

Quantitative Analysis of Influencing Factors on Changzhou Ship Lock Capacity

Quanbo Xin 1,2, Yong Wang 3, Ming Zhang 1,2,* Ruixi Wang 1,2 and Yongchao Wang 1,2

1 Tianjin Research Institute for Water Transport Engineering, Ministry of Transport of the People’s Republic of China (M.O.T.), Tianjin 300456, China; giser_xqb@163.com (Q.X.); wangrx@tiwte.ac.cn (R.W.);
wangyongchao_ocean@163.com (Y.W.)
2 National Engineering Research Center of Port Hydraulic Construction Technology, Tianjin 300456, China
3 Port and Channel Development Center of the Guangxi Zhuang Autonomous Region, Nanning 530029, China;
w13457996329@163.com
* Correspondence: kfzhangming@163.com

Abstract: The Changzhou ship lock is approaching its capacity limit. In order to quantitatively analyze the influencing factors that restrict the capacity of the Changzhou ship lock, this study proposes an influencing factor analysis method based on principal component analysis (PCA). This method estimates the confidence interval of ship passing time by fitting a lognormal distribution curve, eliminates redundancy in navigability data by combining the hydrological data and cargo load data, and quantitatively analyzes the influencing factors of ship lock capacity under saturated operating conditions. The results show that the influencing factors of Changzhou ship lock capacity are classified according to their influence contribution rate as minimum water depth above the lock sill, operation direction, ship dimensions, draft, loading capacity, and actual load. The research results can provide a theoretical basis for improving the ship lock capacity and have application value for lock scheduling management.

Keywords: Changzhou ship lock; ship lock capacity; AHP; PCA; lognormal distribution

1. Introduction

A ship lock is a crucial navigation facility designed to overcome concentrated water level differences, enabling the passage of vessels and serving as pivotal nodes in inland waterway transportation [1,2]. With the rapid development of the water transportation industry, freight demand has been increasing annually, revealing the growing issue of insufficient ship lock capacity [3]. For instance, the Three Gorges Lock experienced an early saturation of its designed capacity by 19 years. The overloading has become a norm, leading to substantial vessel backups [4,5]. The Changzhou Hydraulic Complex, as the final cascade lock on the main shipping route of Xijiang River, represents the “throat” of this golden waterway. In 2019, its freight volume surpassed that of the Three Gorges Lock for the first time, ranking it as the world’s busiest natural waterway. In recent years, it has approached saturation, and the inadequate Changzhou ship lock capacity has become a bottleneck restricting the development of Xijiang River’s golden waterway [6]. Investigating the influencing factors of the ship lock capacity can provide a theoretical basis for optimizing ship lock scheduling, which would help unleash potential throughput and alleviate congestion at the ship locks [7].

Scholars have extensively studied the factors affecting the ship lock capacity through methods such as formula calculation [8,9], factor evaluation [10,11], simulation [12–16], and the analytic hierarchy process (AHP) [17–20]. The “Code for Master Design of Shiplocks” provides a formula for calculating ship lock capacity [21]; however, most of the factors involved in the calculation are statistical data, which do not offer a direct representation of the influencing factors on ship lock capacity [22,23]. According to the elements involved...
in ship lock passage, the influencing factors of ship lock capacity can be divided into ship lock influencing factors, ship influencing factors, management factors, and environmental influencing factors [17]. Ding Tao et al. analyzed the factors affecting the cargo handling of the Three Gorges Ship Lock based on ship tonnage changes, focusing on three aspects: ship lock, ship, and the organization of ship lock operation [24]. Based on the measured hydrological data and model test results of the Changzhou ship lock, Rongyou Pan et al. observed that a decrease in water level leads to an overall downward trend in the tonnage of navigable ships through the ship lock [6]. Quantitative analysis of ship lock capacity mostly employs simulation and AHP. Peng Liao et al. established a traffic simulation model for single-level, inland multi-lane ship locks, incorporating traffic operation rules to quantitatively analyze the operational status and maximum ship lock capacity under various conditions [12–15]. Based on AHP, Duoyin Wang et al. constructed a hierarchical structure model for the influencing factors of ship lock capacity, determining the weight values of each factor [17]. Shaoyue Shi integrated fuzzy logic, AHP, and technique for order preference by similarity to an ideal solution (TOPSIS) to create a decision-making model that aids in improving ship lock capacity, mitigating potential biases that may arise from the AHP alone [18–20].

The factors influencing ship lock capacity are numerous, and existing studies have analyzed these factors from various perspectives. However, there are still some shortcomings in the quantitative analysis of ship lock capacity. They are specifically manifested in the following aspects: (1) Existing studies primarily focus on importance judgments or weight analysis, with less emphasis on the quantitative analysis of these factors. (2) Quantitative analyses are mostly based on simulation and AHP, with data derived from simulations or surveys lacking analysis based on enormous real data, thus compromising credibility. (3) Existing studies predominantly focus on the normal conditions of ship locks, whereas the constraints under saturated operation are the key to breaking through the bottleneck of ship lock capacity.

To quantitatively analyze the factors affecting the Changzhou ship lock capacity, utilizing the real hydrological observation data and ship lock passing data from the Changzhou ship lock, this paper proposes an analytical method based on principal component analysis (PCA). We estimated the confidence interval for normal navigation by fitting the passing time of ships to a lognormal distribution, and eliminated redundant data that do not meet navigability criteria by comparing the relationship between hydrological data and cargo load data. Then, we analyzed the primary factors influencing ship lock capacity and their respective contribution rates.

2. Study Scope and Data
2.1. Study Scope

The Changzhou Hub is located in the lower reaches of the Xun River, a main tributary of the Pearl River system, and serves as the final planned cascade in Guangxi. It is a crucial waterway transportation artery connecting Guangxi and Guangdong provinces [25]. The first lane and second lane of the Changzhou ship lock were completed and opened in 2007, while the third lane and fourth lane were completed and opened in 2015. The first lane is designed for 2000-tonnage vessels, with effective dimensions of 200 m in length, 34 m in width, and a minimum water depth at the sill of 4.5 m. The second lane is designed for 1000-tonnage vessels, with effective dimensions of 185 m in length, 23 m in width, and a minimum water depth at the sill of 3.5 m. The third lane and fourth lane are designed for 3000-tonnage vessels, with effective dimensions of 340 m in length, 34 m in width, and a minimum water depth at the sill of 5.8 m [26]. The upstream maximum navigable water level of the Changzhou ship lock is 25.79 m, and the downstream maximum navigable water level is 25.70 m. The maximum lock water head of the first lane and second lane is 16.05 m, with the upstream minimum navigable water level at 18.6 m, and the downstream minimum navigable water level at 4.55 m. The maximum lock water head of the third lane and fourth lane is 17.28 m, with the upstream minimum navigable water level at
18.6 m, and the downstream minimum navigable water level at 3.32 m. The designed annual one-way capacity of the Changzhou ship lock is 136 million tons, which satisfies the passage conditions for most types of vessels. Water level stations are established in the upstream and downstream approach channels to obtain real-time water level changes. The layout of navigation facilities at the Changzhou ship lock is shown in Figure 1.

![Figure 1. The layout of navigation facilities at Changzhou ship lock.](image)

Since the construction and operation of the Changzhou ship lock, the cargo volume has increased annually and is exhibiting a rapid growth trend. It surpassed the designed annual one-way capacity in 2019 and operated at near-saturation levels, as shown in Figure 2. Due to factors such as river erosion, channel dredging, and artificial sand mining, the riverbed downstream of the hub has been eroded, leading to a decrease in water levels. The water level difference between the upstream and downstream of the first lane and second lane exceeds the designed maximum operating head, significantly reducing the navigation guarantee rate. During low-water periods, when water volumes are insufficient, the ship lock capacity is severely impacted; large-scale navigation delays and blockages occur frequently, with the repercussions extending to the main lane of the Xijiang River [6].

### 2.2. Data Sources

The data include the ship passing data of the entire Changzhou ship lock in 2020 and the hydrological monitoring data during the same period.

The ship passing data were sourced from the Guangxi Xijiang Ship Lock Joint Dispatch Center. Each ship’s single passing is recorded as one record, amounting to over 140,000 records in total. The detailed data content is presented in Table 1. The ship lock sill is the minimum water depth above the lock sill of each ship lock lane. The ship weight refers to the weight of the ship when it is unloaded, the ship actual load is the weight of the ship after it is loaded with cargo, and the ship approved load is the maximum load value approved by the ship lock dispatch personnel. The “Passing Time” refers to a series of time points between “report time” and “departure time”. The “report time” refers to the time at which a ship submits its ship passing registration after arriving in the designated waiting area, while the “departure time” is the time at which the ship lock gates close after the ship...
has exited the ship lock chamber. The time difference between report time and departure time is the duration of the ship’s lockage.

![Graph](image_url)

**Figure 2.** Changes in cargo volume of Changzhou ship lock over the years. The data is from the navigation statistics of the Pearl River Administration of Navigational Affairs.

**Table 1.** Detailed data content.

<table>
<thead>
<tr>
<th>Data Name</th>
<th>Data Content</th>
<th>Data Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship Passing Data</td>
<td><strong>Ship Name</strong></td>
<td>/</td>
</tr>
<tr>
<td></td>
<td><strong>Ship Lock Lane</strong></td>
<td>first lane, second lane, third lane, fourth lane</td>
</tr>
<tr>
<td></td>
<td><strong>Ship Lock Sill</strong></td>
<td>minimum water depth above the lock sill</td>
</tr>
<tr>
<td></td>
<td><strong>Operation Direction</strong></td>
<td>up or down</td>
</tr>
<tr>
<td></td>
<td><strong>Ship Dimension</strong></td>
<td>ship length, ship width</td>
</tr>
<tr>
<td></td>
<td><strong>Ship Draft</strong></td>
<td>reported draft depth, unit: meters</td>
</tr>
<tr>
<td></td>
<td><strong>Ship Load</strong></td>
<td>load capacity, approved load, actual load, unit: ton</td>
</tr>
<tr>
<td></td>
<td><strong>Goods Type</strong></td>
<td>coal, containers, corn, empty, etc.</td>
</tr>
<tr>
<td></td>
<td><strong>Passing Time</strong></td>
<td>report time and departure time</td>
</tr>
<tr>
<td></td>
<td><strong>Travel Place</strong></td>
<td>Start Place and Arrival Place</td>
</tr>
<tr>
<td>Hydrological Monitoring Data</td>
<td><strong>Data Time</strong></td>
<td>data release time</td>
</tr>
<tr>
<td></td>
<td><strong>Upstream Water Level</strong></td>
<td>water level value collected by monitoring stations, unit: meters</td>
</tr>
<tr>
<td></td>
<td><strong>Downstream Water Level</strong></td>
<td>water level value collected by monitoring stations, unit: meters</td>
</tr>
<tr>
<td></td>
<td><strong>Inflow Volume</strong></td>
<td>calculated volume value, unit: m³/s</td>
</tr>
<tr>
<td></td>
<td><strong>Outflow Volume</strong></td>
<td>calculated volume value, unit: m³/s</td>
</tr>
</tbody>
</table>

The hydrological monitoring data were obtained from the daily water level observations at the upstream and downstream water level stations of the Changzhou ship lock. The water level stations released real-time water level data at 8:00 and 16:00 daily, from which flow volume was calculated based on the relationships between water level and flow volume. The data included data time, upstream water level, downstream water level, inflow volume, and outflow volume. Considering the minimal diurnal fluctuations in water levels, the data at 8:00 were used for the daily hydrological analysis.

3. Methods
3.1. Estimate Confidence Intervals Based on Lognormal Distribution

Factors such as lock water filling and emptying time in the upstream and downstream ship locks, ship lock scheduling strategies, ship lock chamber scheduling rules, and ship maneuvering are significantly influenced by human factors. For an individual ship passage,
these factors have a certain degree of randomness and dominance, which directly affects the analysis results of ship lock capacity. In terms of analyzing the constraints under saturated operation, abnormal navigation records caused by human factors are considered noise data. Removing the noise data and ensuring that the input data truly reflects the ship passing situation under saturated operation is a prerequisite for analyzing the constraints on ship lock capacity.

To visually identify the distribution pattern of ship passing time, a histogram was created for ship passing time. The horizontal axis represents the passing time, in 10-min intervals, while the vertical axis indicates the probability of lockage durations occurring within each interval. The statistic results are shown in Figure 3. It can be observed that the passing time exhibits a distinct lognormal distribution, with values relatively concentrated and a shape similar to the normal distribution, but with a tail extending noticeably to the right. The passing time has a possibility of greater upward fluctuation and a smaller downward fluctuation, which can well explain the right-skewed nature of the lognormal distribution.

![Figure 3. Probability density distribution of ship passing time.](image)

Assuming the ship passing time \( x \) follows a lognormal distribution, its density distribution function \( p(x) \) is given by Equation (1), and the mathematical expectation \( E(X) \) and variance \( D(X) \) are given by Equations (2) and (3), respectively. The cumulative distribution function \( F(x) \) is given by Equation (4).

\[
p(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right) \tag{1}
\]

\[
E(X) = \exp(\mu + \sigma^2/2) \tag{2}
\]

\[
D(X) = \left(\exp(\sigma^2) - 1\right) \exp(2\mu + \sigma^2) \tag{3}
\]

\[
F(x) = \frac{1}{2} \left\{ 1 + \text{erf}\left[\frac{\ln x - \mu}{\sqrt{2\sigma^2}}\right] \right\} \tag{4}
\]

Parameters \( \mu \) and \( \sigma \) are crucial for accurately fitting the lognormal distribution. SciPy is an open-source Python algorithm library and mathematical toolkit, with the sub-module "stats" containing various statistical analysis functions for describing and analyzing the
statistical properties of data. The “lognorm” function can perform maximum likelihood estimations on observed values to fit the parameters of lognormal distribution, yielding parameter estimates of $\mu = 0.83$ and $\sigma = 0.44$.

Considering that an exceptionally long or short ship passing time may be due to a dominant factor, such as large ships being delayed due to unsatisfactory water levels, or one-time lockage ignoring the impact of lock scheduling and ship types, these lockage data are not representative and do not accurately reflect the navigation conditions under saturated operation. Using data within a confidence interval as the research subject facilitates a more accurate analysis of the factors influencing lockage under saturated operation. Therefore, based on the cumulative distribution function (Equation (4)), the confidence interval for ship passing time falling within the cumulative distribution interval of $[5\%, 95\%]$ is calculated to be $[2.83 \text{ h}, 37.01 \text{ h}]$.

3.2. Eliminate Navigability Data Redundancy Based on Hydrological Analysis

The shipping industry on the Xijiang River exhibits distinct seasonal characteristics, with the low-water period typically occurring from September to the following April, and the flood season from May to August each year. Due to influence of climatic and geographical factors, the flood season may arrive earlier or later by 1–2 months in some areas. During the low-water period, reduced precipitation and the need to dilute salinity lead to insufficient shipping base flows. Additionally, factors such as riverbed erosion, channel regulation, and hydroelectric power generation severely constrain the Changzhou ship lock capacity [6]. For ship passing data that do not meet navigability conditions, hydrological factors play a decisive role in influencing the ship lock capacity, which affects the analysis of influencing factors.

To address this situation, ship passing data and hydrological monitoring data are compared on a unified time scale, and periods that do not meet navigability conditions are identified through custom query filters. The specific steps are illustrated in Figure 4. Firstly, preprocess the ship passing data and hydrological monitoring data to obtain daily cargo volume data and daily water hydrological data. Secondly, for daily hydrological data, calculate the time periods when the upstream water level is below the minimum navigable level, the downstream water level is below the minimum navigable level, the water level difference between upstream and downstream exceeds the maximum lock water head [27], and the water level difference is below the normal range. For daily cargo volume data, identify periods when the cargo volume is significantly below normal, typically due to temporary navigation suspensions caused by equipment maintenance, water accidents, or extreme weather. Then, merge the two sets of time periods, considering that non-navigable conditions affect normal navigation not just at a single point in time, but also in neighboring periods. Combining adjacent time periods improves the continuity and accuracy of the data. Finally, plot daily cargo volume data, daily water hydrological data, non-navigable conditions, and the corresponding time intervals on a unified time axis to visually present the analysis results and conduct a detailed analysis of the extracted data.

3.3. Analyze Factors Based on Principal Component Analysis (PCA)

PCA is a data analysis method that transforms multiple variables into a smaller number of comprehensive variables through variable transformation. Its essence is to seek comprehensive substitutes for correlated variables based on the correlation of the original variables [24,28–32]. Each principal component is a linear combination of the original variables, mutually independent and retaining most of the information of the original variables. For a single ship passage event, the factors that affect ship passing time are independent of each other, and multiple factors collectively affect ship passing time. PCA can identify factors with a significant impact from numerous factors and conduct a quantitative analysis, which is crucial for analyzing the factors.

A total of 11 variables were collected from the ship lockage data: ship lock sill, operation direction, ship length, ship width, ship draft, ship weight, approved load, actual
load, goods type, starting place, and arrival place. Among these, the operation direction has an independent and dominant impact on ship lock capacity. The goods type has a relatively small impact on ship lock capacity. The impact of starting and arrival places on the single-level ship lock capacity can be ignored.

**Figure 4.** The process of eliminating navigability data redundancy.

PCA is aiming to screen out important variables where highly correlated variables are orthogonally transformed into new variables, thereby losing their original meaning [33]. To make the extracted variables more concise and clear, a correlation analysis was first conducted on a large amount of ship passing data to filter out significantly correlated variables, from which representative variables were selected.

For the selected variables, the steps for quantitative analysis based on PCA include the following:

1. Assume there are m data samples and n variables, the corresponding data matrix is $R$, where each column represents a ship passing record and each row represents the variables to be analyzed.

   $$ R = \begin{pmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{pmatrix} \quad (5) $$

2. Normalize $R$ to matrix $X$, where $\bar{r}_i$ and $s_i$ are the mean and standard deviation of the i-th row, respectively.

   $$ x_{ij} = (r_{ij} - \bar{r}) / s_i $$

   $$ X = \{x_{ij}\}_{ij} $$

   (6)  

   (7)
3. Calculate the covariance matrix $D(X)$ of matrix $X$.

$$
D(X) = \begin{pmatrix}
\text{Cov}(X_1, X_1) & \cdots & \text{Cov}(X_1, X_n) \\
\vdots & \ddots & \vdots \\
\text{Cov}(X_n, X_1) & \cdots & \text{Cov}(X_n, X_n)
\end{pmatrix}
$$

(8)

4. Calculate the eigenvalues $(\lambda_1, \lambda_2, \cdots, \lambda_n)$ and eigenvectors $(x_1, x_2, \cdots, x_n)$ of $D(X)$, arrange the eigenvalues in descending order, and calculate the variance contribution rate $s_i$ corresponding to each eigenvalue $\lambda_i$

$$
S_i = \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i}
$$

(9)

5. Assume the $k$-th eigenvalue is $\lambda_k$, and calculate the cumulative variance contribution rate $Y_k$

$$
Y_k = \sum_{i=1}^{k} s_i
$$

(10)

6. PCA represents new variables using linear combinations of $n$ original variables. The eigenvalue $\lambda_k$ serves as the weight coefficient for each variable. By discarding eigenvalues with low variance contribution rates and selecting $k$ principal components that can significantly represent the original variables, the dimensionality of the data is reduced. Typically, $k$ variables with a cumulative variance contribution rate reaching 85% are chosen as the principal component variables.

4. Results and Discussion

4.1. Analysis of Hydrological Influencing

To accurately extract the time periods that meet the normal navigable conditions of ships for the ship lock, a concurrent comparison was made between the daily hydrological data and the daily cargo volume data for 2020. The analysis results of the non-navigable time intervals are presented in Figure 5, which reveals the following observations:

1. During the low-water period, the downstream water level persistently remained below the minimum navigable level, and the water level difference between upstream and downstream exceeded the maximum lock water head, leading to a sharp decrease in cargo volume. Particularly due to the low downstream water level at the end of January, the ship lock nearly came to a standstill.

2. The Xijiang River entered the low-water period from November, with the downstream water level and the water level difference approaching navigational design limits, placing significant pressure on navigational safety. In mid-November, the water level was too low, severely affecting cargo volume. As conditions improved slightly in December, coupled with strong demand for water transportation, cargo volume saw a rapid rebound, resulting in an overall increase for the month.

3. A flood occurred in mid-June, with the downstream water level nearly equal to the upstream water level, making it unsuitable for navigation. Additionally, due to reservoir water control, the downstream water level frequently fell below the minimum navigable level, impacting ship navigation.

The analysis above validates the effectiveness of the method for eliminating navigability data redundancy, and also reveals that there is still room for improvement in the Changzhou ship lock capacity. Firstly, because there is a strong demand in December, it is necessary to further optimize ship lock scheduling and ensure a sufficient base flow for the channel to enhance ship navigation efficiency; secondly, during the flood period, water levels are ample and conditions are favorable, and ship passing remains generally...
stable, but there is a significant gap between the actual load and the approved load of ships, indicating that shipping potential is not being fully unleashed.

Figure 5. Comparison of the daily hydrological data and the daily cargo volume data during the same period.

4.2. The Result of Principal Component Analysis

The results of the correlation analysis of the influencing factors are shown in Figure 6. There is a strong correlation between ship length, ship width, ship weight, and ship approved load. Referring to the hierarchical structure model proposed by Duoyin Wang about the definition of influencing factors of the ship [17], ship dimension is used to represent ship length and ship width, while ship loading represents ship weight and ship approved load. Therefore, the final analysis variables are ship lock sill, operation direction, ship dimension, ship draft, loading capacity, and ship actual load.

PCA was conducted on the above six variables. The eigenvalues and corresponding contribution rates and cumulative contribution rates are presented in Table 2, with a scree plot shown in Figure 7. From the scree plot, it can be seen that the cumulative contribution rate of the first three variables reaches 92%. From the fourth variable onward, the eigenvalues begin to stabilize. Considering the complexity of factors affecting ship lock capacity, the top four variables in terms of contribution rate, namely ship lock sill, operation direction, ship dimensions, and ship draft, are selected as the main influencing factors of ship lock capacity.

Table 2. The eigenvalues and corresponding contribution rates and cumulative contribution rates.
approved load. Therefore, the final analysis variables are ship lock sill, operation direction, ship dimension, ship draft, loading capacity, and ship actual load.

Figure 6. The correlation analysis of the influencing factors.

PCA was conducted on the above six variables. The eigenvalues and corresponding contribution rates and cumulative contribution rates are presented in Table 2, with a scree plot shown in Figure 7. From the scree plot, it can be seen that the cumulative contribution rate of the first three variables reaches 92%. From the fourth variable onward, the eigenvalues begin to stabilize. Considering the complexity of factors affecting ship lock capacity, the top four variables in terms of contribution rate, namely ship lock sill, operation direction, ship dimensions, and ship draft, are selected as the main influencing factors of ship lock capacity.

Figure 7. The scree plot of influencing factors.

4.3. Comparison with the AHP

To validate the effectiveness of the proposed method, it was compared with the commonly used AHP [17,18]. The specific steps for establishing the hierarchical structure model and calculating the index weights are not elaborated upon here.

Qualitatively, the AHP method determines its relative importance by designing a survey questionnaire and experts scoring. Although experts have rich experience and can ensure the authority of statistical results, the determination of factor weights has a certain degree of subjectivity. The AHP identified the significant factors affecting ship lock capacity as lock operation water level, the level and sill of locks, effective lock dimensions, ship
dimensions, and loading coefficient. This is largely consistent with the results obtained by the principal component analysis method.

Quantitatively, the AHP calculated the comprehensive weights of influencing factors, providing a comparison of their importance. It highlighted the need to focus on the lock operation water level, ship dimensions, and loading coefficient when enhancing the existing ship lock capacity. In contrast, the PCA provided the contribution rates of influencing factors, emphasizing the importance of ship lock sill, operation direction, ship dimensions, and ship draft.

Upon analysis, the primary reason for the differences in the research results is that the two methods were applied to different research subjects. AHP was applied to the Three Gorges ship lock, while the PCA was applied to the Changzhou ship lock. The specific manifestations are as follows:

1. The Changzhou ship lock is a four-lane ship lock with significant differences in the designed single-way capacity of each lane, while the Three Gorges ship lock is a double-lane ship lock with the same designed single-way capacity. This is why the lock sill is the primary influencing factor for the Changzhou ship lock capacity.

2. Comparing the briefing on the Three Gorges ship lock’s navigation situation, issued by the Yangtze River Three Gorges Navigation Administration, with the briefing on the Changzhou ship lock’s navigation conditions, issued by the Pearl River Administration of Navigational Affairs. MOT, it was found that the cargo volume through the Three Gorges ship lock was nearly balanced between upstream and downstream, whereas the Changzhou ship lock had a significantly lower upstream cargo volume compared to downstream. This is why operation direction became a primary influencing factor for the Changzhou ship lock capacity.

3. The AHP focuses on analyzing the factors affecting ship lock capacity under comprehensive navigation conditions, with the lock operation water level being the primary factor. The PCA focuses on analyzing the factors affecting ship lock capacity under saturated operation conditions and eliminates the impact of abnormal navigation data, such as insufficient operation water level.

It is evident that although there are differences in the analysis results between the two methods, these differences are in line with the actual conditions of different ship locks, indirectly verifying the effectiveness of the methods.

5. Conclusions

Insufficient water level, ship lock maintenance, abnormal weather, and power station discharge seriously affect ship passage and even cause ship navigation delays. They play a dominant role in the influencing factors of ship lock capacity. The ship passing data that do not meet the navigability conditions cannot accurately reflect the navigation situation of ships in saturated operating conditions. To quantitatively analyze the factors constraining the Changzhou ship lock capacity, an analysis method based on PCA was proposed based on the hydrological observation data and ship passing data from the Changzhou ship lock in 2020. The influencing factors of Changzhou ship lock capacity under saturated operation were analyzed, and the contribution rates of each influencing factor were obtained. The main conclusions are as follows:

1. The confidence interval estimation method, based on lognormal distribution, and the navigability data redundancy elimination method, based on hydrological analysis, can extract ship lock operation data that meets navigability conditions, which is a prerequisite for analyzing the factors affecting the ship lock capacity under saturated operating conditions.

2. Based on PCA, we obtained the contribution rates and cumulative contribution rates of each influencing factor, and took the influencing factors with cumulative contribution rates exceeding 90% as the primary influencing factors. By comparing the contribution rates of influencing factors, it was determined that the primary factors affecting the
Changzhou ship lock capacity are lock sill, operation direction, ship dimensions, draft, loading capacity, and actual load.

3. The results obtained by the PCA method are superior to those obtained by the AHP method in analysis of influencing factors of ship lock capacity, which can provide a theoretical basis for improving the ship lock capacity. In qualitative analysis, the data used in the AHP method mostly comes from expert survey questionnaires, which inherently introduces a degree of subjectivity. In contrast, the PCA method, based on enormous real data, leads to more reliable analysis results. In quantitative analysis, the AHP calculates comprehensive weights of influencing factors, reduces the biases arising from data subjectivity through mathematical calculations, and provides a comparative assessment of importance only. However, the PCA method is based on the analysis of enormous real data and provides the contribution rates of each influencing factor. As the amount of data increases, the accuracy of the analysis results is higher.

Based on the above analysis, we propose a set of measures to enhance the ship lock capacity, including hydrological monitoring and forecasting, optimization of lock scheduling, automation upgrades, and structural modifications. Additionally, apply predictive maintenance strategies to reduce unexpected downtime. The next research focus is to verify the applicability of the method proposed in this paper on other ship locks and extend it to investigate the influencing factors on the capacity of multi-level and multi-lane ship locks.

Author Contributions: Conceptualization, Q.X.; methodology, Q.X. and Y.W. (Yongchao Wang); software, Q.X. and R.W.; validation, Q.X. and M.Z.; formal analysis, Q.X.; investigation, Q.X. and M.Z.; resources, Y.W. (Yongchao Wang) and M.Z.; data curation, Q.X. and R.W.; writing—original draft preparation, Q.X.; writing—review and editing, Q.X. and Y.W. (Yongchao Wang); visualization, Q.X.; supervision, Y.W. (Yongchao Wang); project administration, Y.W. (Yong Wang); funding acquisition, M.Z. and Y.W. (Yong Wang). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key R&D Program of China (Grant No. 2023YFB2603800), the Guangxi Key Technologies R&D Program (Grant No. GK-AB22080106), the Key Scientific Research Program of Transportation Industry (Grant No. 2021-MS6-156), and the Fundamental Research Funds for the Central Public Welfare Research Institutes (Grant No. TKS20210305).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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

References


**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.