A Novel Through Capacity Model for One-way Channel Based on Characteristics of the Vessel Traffic Flow

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ABSTRACT: Vessel traffic flow is a key parameter for channel-through capacity and is of great significance to vessel traffic management, channel and port design and navigational risk evaluation. Based on the study of parameters of characteristics of vessel traffic flow related to channel-through capacity, this paper puts forward a brand-new mathematical model for one-way channel-through capacity in which parameters of channel length, vessel arrival rate and velocity difference in different vessels are involved and a theoretical calculating mechanism for the channel-through capacity is provided. In order to verify availability and reliability of the model, extensive simulation studies have been carried out and based on the historical AIS data, an analytical case study on the Xiazhimen Channel validating the proposed model is presented. Both simulation studies and the case study show that the proposed model is valid and all relative parameters can be readjusted and optimized to further improve the channel-through capacity. Thus, all studies demonstrate that the model is valuable for channel design and vessel management.

1 INTRODUCTION

Channel-through capacity is described as the maximum number of vessels passing a particular channel per unit time. It is not only an important parameter to measure port workload and port throughput capacity, but also a reference indicator for vessel traffic management and port channel design. Besides, channel-through capacity is of great significance to channel and port operating condition assessment (Yeo et al. 2007, Yang et al. 2016), channel efficiency optimization (Davis et al. 1980) and ship navigation risk evaluation. In recent years, people have been paying more attention to water transportation and the demand for navigational risk reduction and waterway operation efficiency improvement has been increasing. Thus, the research for channel-through capacity becomes more and more realistically significant.

Currently, there are mainly three types of methods to carry out the research on channel-through capacity: Static Calculation Method (SCM), Dynamic Evaluation Method (DEM) and Model Simulation Method (MSM). SCM, based on ship domain model theory (Fujii & Tanaka 1971, Elisabeth & Goodwin 1975), is a geometric analysis method in which some correction coefficients can be selected according to previous experiences and then an empirical formula can be set up to calculate the channel-through capacity at different water conditions. With the research becoming in-depth, ship-following theory (Zhu & Zhang 2009) and other research methods have gradually been infiltrated into this calculation method. Some scholars, with consideration of the real condition of channels, have also explored the calculation method by expanding the channel-through capacity measurement not only for specific waters like channel and port (Wang et al. 2015), but

also for any applicable place of navigation (Liu et al. 2016). SCM is a quantitative analysis method; the advantage of SCM is that the output is visual, and it is especially good for analyzing the result of simple channel conditions.

DEM, based on analysis of dynamic characteristics of channel operation, helps establish a queuing model applicable to a certain channel with the statistics and studies of vessel arrival & service time and evaluate channel-through capacity dynamically by such parameters as stand-by time, stand-by queue length and stand-by probability (Mavrakis & Kontinakis 2008, Zhou et al. 2013). Typically, this method can reflect stochastic characteristics of vessel traffic and together with vessel traffic simulations can also be used to assess channel congestion (Gucma et al. 2015) and to check the stability of port service system which determines whether the port channel capacity meets the requirement of port operation, thus helping put forward a system optimization scheme based on the above estimation.

SMM, based on analysis of characteristics of vessel traffic flow and channel system, is a method conducive to build some sub-models such as vessel model and channel model so that the whole vessel navigation process can be simulated in a certain simulation environment and then a simulation model for channel-through capacity can be established after taking multiple rounds of simulation tests (O'Halloran et al. 2005, Qu & Meng 2012). Some relative studies have also further explored dynamic linkages between certain influencing factors and channel-through capacity. For example, Almaz & Altiok (2012) analyzed the change of channel-through capacity with navigable channel depth, vessel arrival rate, vessel's scale and other factors through the established simulation model. SMM can reflect the actual operation condition of the channel, describing rather accurately the influence of those dynamic changes when vessels are navigating in the channel on channel-through capacity. In addition, the method is often used to decide and select the optimal channel route (Gucma et al. 2015).

At present, in the research of channel-through capacity, SCM aims to calculate the maximum number of vessels passing through a certain channel section within a certain time. Channel length is not concerned and correction coefficients are mostly used. But the data collection of SCM is subjective and random and the influence of each factor on channel-through capacity cannot be accurately reflected just by using correction coefficients to correct the calculation formula of channel-through capacity. DEM generally focuses on channel-through capacity of port system which is actually about whether the number of port berths is enough. One-way Channel-through capacity channel is rarely mentioned and the method is mainly about qualitative analysis. SMM provides neither due consideration of the interaction among vessels nor easy access to discovering factors and the impact mechanism influencing channel-through capacity, thus failing to unveil essential laws.

Due to limitations of above traditional research methods, this paper intends to establish a brand-new mathematical model for channel-through capacity. In this model, a one-way channel is taken as the main study object and such parameters as channel length, vessel safety distance, vessel velocity and velocity difference in different vessels which are all related to vessel traffic flow are concerned. Based on this model, a theoretical calculating mechanism of channel-through capacity for one-way channel can be discovered.

2 VESSEL TRAFFIC ANALYSIS

To present the circumstances of channel traffic flow, a series of indexes are employed for analysis. In this part, with the concept of vessel traffic flow (VTF) being firstly proposed, a vessel traffic flow model and theories of mutual interference between vessels are both explored to illustrate the issue of one way channel-through capacity.

2.1 *Vessel Traffic Flow Model*

Vessel traffic flow (VTF) has been defined as the overall dynamic characteristics of continuous vessels that navigate in the same direction along a channel (Wu & Zhu 2004). Main parameters of vessel traffic flow are vessel arrival rate, vessel velocity, and so forth.

Vessel arrival rate (VAR) refers to the number of vessels arriving at the entrance of the channel per unit time. VAR is closely related to the total number of passing vessels and the degree of congestion of the channel. Vessel velocity (VV) considers two issues of vessel traffic flow, the velocity distribution range and the average velocity. Any change of two factors will instantaneously influence the VTF state and analysis of these two parameters helps guide the implementation of vessel traffic management. Some researches before this one have proved that typical parameters of vessel traffic flow obey certain distributions. In general, VAR complies with the Poisson distribution, and vessel velocity (VV) obeys the Normal distribution.

Besides the above two indexes, ship domain (SD) is another important parameter related to VTF. SD is presented for the effect of vessels on the environment. Here the concept of environment includes other vessels, channel situation and other options that directly or indirectly influence the safety of vessels. Hence, SD should be noted at all time to keep the minimum safety distance between two vessels and to improve channel passing efficiency. Vessel interval, a sub-concept of ship domain (SD), refers to the area where other vessels are avoided from entering for the reason of safety (Fujii & Tanaka 1971, Elisabeth & Goodwin 1975). The size of ship domain (SD) is closely related to such aspects as traffic density, visibility, vessel velocity, vessel type etc. For instance, high seas usually take 2 miles as a standard reference for vessel collision avoidance.

Having described the main parameters, the next step is to discuss the distribution regulation of VAR and VV. In order to solve the problem, a case study of Xiazhimen Channel is conducted in this paper to analyze characteristic s of vessel traffic flow. As shown in Figure 1, Xiazhimen Channel, located

between Taohua Island and Xiazhimen Island, is a typical one-way channel with high traffic density. With an overall length of about 7 miles, the navigation condition of the channel is quite restrictive. The hydrological conditions of this channel are superior owing to the remarkable target for vessel location, enough water depth, clear navigation signal and small waves.
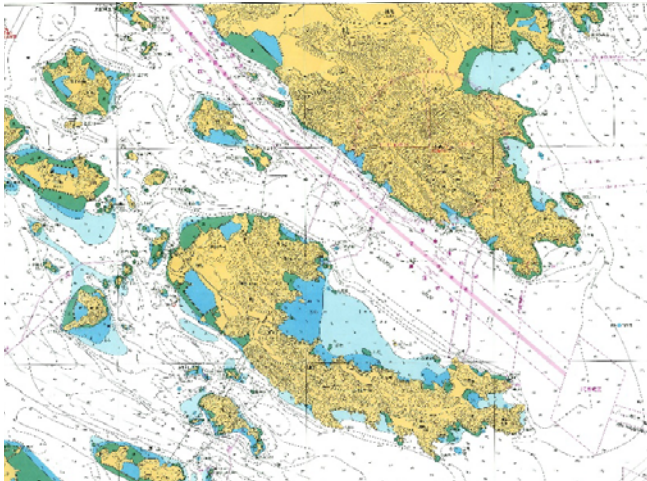

Figure 1. Xiazhimen Channel

By using the Matlab software, this case study analyzes, fits and tests the AIS data for the vessel traffic in Xiazhimen Channel collected from March 24 to 29, 2015. According to the data statistics and distribution test, the VAR at the entrance of the channel follows the Poisson distribution with an average of two vessels per hour and the VV of the vessel traffic flow follows the Normal distribution in which the average velocity is 10 knot and the standard deviation is 1.8, as shown in Table 1.

Table 1. Typical parameters of vessel traffic flow in Xiazhimen Channel

Typical parameters	Distribution types	expression model	unit
Vessel arrive rate	Poisson distribution	POISS(2)	ship/h
Vessel velocity	normal distribution	NORM(10,1.8)	kn/h

2.2 Mutual Interference between Vessels

Vessel-vessel interference means that one vessel as a give-way vessel or a following vessel in a one-way channel (or straight channel) needs to make necessary adjustments to its velocity to ensure sufficient safety clearance for avoiding collision situations when its velocity is greater than that of the consecutive front vessel and when the interval distance between them is close to the minimum safety distance.

Via brief analysis of the interaction mechanism of vessels, vessel-vessel interference can be divided into two forms: direct interaction and indirect interaction. Figure 2 demonstrates the interference analysis between two consecutive vessels. The velocity of vessel S_i and S_j is set to V_1 and V_2 respectively. After a period of time represented as t_1 when the front vessel S_i has sailed for a known distance marked as D_{ij}, it begins to enter the channel. According to ship domain theory, D_{ij}, the interval distance between two vessels should be greater than the minimum safety distance d_0 so that there will be no collision risk between these two vessels. Otherwise, vessel interaction will exist and when it becomes effective, some preventive measure should be taken.

The velocity difference can be concluded as three situations, stable，negligible and intolerable. At the stable situation when V_1 equals V_2, the distance between two vessels remains unchanged. The negligible situation means that V_1, the front vessel velocity, is higher than V_2, the following vessel velocity. Therefore, the distance between two vessels will gradually increase.
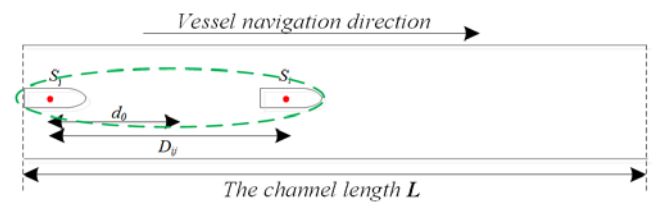

Figure 2. Interference between two consecutive vessels.

In the above two situations, there is no interaction between two vessels, hence no measures need to be taken to avoid collision. But at the intolerable situation when the front vessel velocity V_1 is smaller than V_2, the velocity of the following vessel, if the following vessel continues catching up the front vessel, the interval distance between two vessels will approach to the minimum safety distance, which will threat vessels' safety. Assuming that the interval distance between two vessels reaches the minimum safety distance at a certain time t_2 when the front vessel exits the channel, vessel-vessel interference will reach the maximum. According to the collision regulation, deceleration should be taken by the following vessel to avoid collision. The process above explains direct interference between two vessels.

Based on the direct interaction analysis, another interference mechanism, the interaction between a series of vessels sailing in the channel is studied to explore indirect interaction. There is an impact chain among these vessels which passes on from one to another and stops only when the chain is broken. This impact chain illustrates indirect interaction. In Figure 3, there are a series of vessels S_1, S_2, S_3 in the channel, and the level of vessel velocities are $V_1 < V_2 < V_3$. At the time shown in Figure 3, the interval distance between vessel S_1 and vessel S_2 reaches the minimum safety distance due to the velocity difference. In order to ensure navigational safety, S_2 will decelerate and this operation will continually impact later vessels, accelerating the process of shortening the interval between S_2 and S_3. Then S_3 will reduce its velocity to avoid collision risk. Hence, S_1 has an indirect interference on S_3 through the transition from S_2. This interaction chain not only reduces the number of vessels through the channel per unit time but also raises the channel congestion apparently.
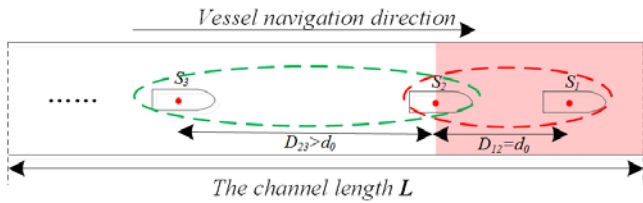
Figure 3. A chain reaction of multiple vessels interference.

To confirm the influence of vessel-vessel interference on the vessel traffic, an experiment for vessel-vessel interaction in a one-way channel is implemented in the Matlab software. Obviously, this procedure has some limitations, as it is based solely on instantaneous deceleration criteria and, above all, it neither includes other parameters except for channel length, vessel number and vessel velocity nor considers the difference between vessels except for vessel velocities and time when vessels enter the channel. The experiment explores only the relation between vessel-vessel interaction and vessel traffic flow.

According to the difference of velocity, the experiment is conducted under three circumstances: 1) Four vessels enter the channel in accordance with the velocity changing from small to large; 2) Four vessels enter the channel with randomly distributed velocity; 3) Four vessels enter the channel in accordance with the velocity changing from large to small. The simulation results of the three cases are shown in Table 2.

Table 2. Data comparison of the vessel-vessel interference.

Vessel initial velocity	Vessel final velocity	Time of all vessels through the channel
$V_1=10, V_2=9.5$ $V_3=9, V_4=8.5$	$V_1=10, V_2=9.5$ $V_3=9, V_4=8.5$	2533
$V_1=9.5, V_2=10$ $V_3=8.5, V_4=9$	$V_1=V_2=9.5$ $V_3=V_4=8.5$	2607
$V_1=8.5, V_2=9$ $V_3=9.5, V_4=10$	$V_1=V_2=V_3=V_4=8.5$	2656

With reference to the results shown in Table 2, the following observations can be made: in the first case, there is no need for any vessel to slow down, and the time required for four vessels to pass through the channel is the shortest. In the last case, S_2, S_3, S_4 need to take a proper decelerating reaction, and the time required for all vessels to pass through the channel is the longest. It can be observed that vessel-vessel interference has hindered the smoothness of the traffic flow and increased the time required for the same number of vessels to leave the waterway, which indirectly effects the channel-through capacity.

3 CHANNEL-THROUGH CAPACITY MODEL

In this part, to simplify vessel traffic system some assumptions for a calculation model of channel-through capacity are put forward. After that, based on ideal channel-through capacity, a brand-new mathematical model is established, which can manifest the relationship between some parameters of vessel traffic and channel-through capacity.

3.1 Model Assumptions

The operation process of vessel traffic system in the channel mainly includes two parts: the channel environment model and vessel traffic flow model, working together to show a real environment of vessel traffic system. Here in order to describe and analyze the relevant problem conveniently, some optimizations and assumptions are made for the calculation model, which is described fully as follows.

Channel environment designing is one foundation process for vessel traffic system analysis. It includes many sub factors such as channel length, width, water depth, bending radius, tide and etc. This paper focuses on one-way channels, hence the channel model is simplified by regarding channel length L as the main parameter. Channel length will not restrict vessels' normal operation. In the design process, a straight channel where there is no turn or intersection interference is chosen. Meanwhile, channel depth ensures the normal navigation for all vessels and the effect of tide is eliminated in this model. Lastly, vessels are allowed to sail only at the same direction and overtaking is forbidden in the channel.

With a reasonable channel environment model being designed, vessel traffic flow can be introduced as a main object to be considered later. The main parameters of vessel traffic flow include velocity, density, vessel arrival rate, vessel interval and etc. Generally speaking, the evaluation and calculation of traffic flow can intuitively reflect the vessel navigation state and the navigation environment of the channel. Here, considering all characteristics of one-way channel, ship domain needs to be highlighted. In this research, a navigational environment with neither overtaking vessels nor restrictions on the width of the channel is built. All vessels at trailing condition form a queue in the channel and there is no approaching danger from port side and starboard side. Therefore, according to the general situation of traffic flow and the actual demand of the model, the traffic flow model provides the following assumptions:

1 All vessels at stand-by condition are allowed to enter the channel immediately.
2 Vessels shall enter the channel according to the FCFS (First come, first serve) mode, which means that vessels are ordered to enter waterways merely by their arrival time.
3 The vessel velocity will remain steady during the whole voyage if there is no interference from other vessels.
4 Overtaking and head-on situation are forbidden in the channel, and safety interval, the distance between the front vessel's stern to the second vessel's fore is harnessed as the index of navigation safety.

3.2 Establishment of a Computational Model

According to the concept of channel-through capacity, the maximum number of vessels passing through the channel during a period of time, defined as C, together with channel length, navigation velocity and safety distance between the front and second vessel forms a relationship which can be described via the following function: $C=f(L, V, d_0)$. This part of the

study analyzes the microscopic characteristics of vessel traffic flow, and then finds the final function based on the geometrical relationship between vessels.

3.2.1 *Ideal channel-through capacity*

Ideal channel-through capacity studies the maximum number of vessels that can pass through the section of channel in unit time under a certain condition in which both channel conditions and traffic conditions are in ideal state, and vessels are a kind of standard ones with same technical performance and navigation parameters. In addition, vessels need to enter the channel consecutively with the distance between two adjacent vessels larger than the minimum safety distance (Dong et al. 2007). In this case, when navigating in the channel, vessels have no opportunity to overtake, but only to follow the trail until exiting the channel. Based on the theoretical channel-through capacity, the channel-through capacity in an ideal condition is analyzed.
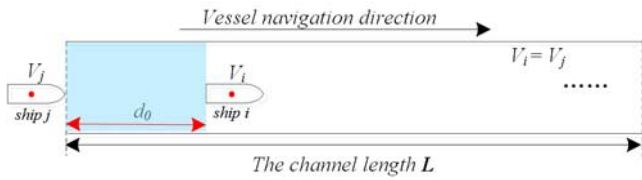

Figure 4. The analysis schematic diagram of ideal channel-through capacity.

In Figure 4, two vessels constitute a basic unit. It is assumed that arriving vessels navigate with the same velocity and enter the channel in a continuous manner. In order to ensure the safety of navigation, the distance between the front vessel S_i and the second vessel S_j should be clarified. When the front vessel is navigating in the channel, the second vessel is allowed to enter the channel only when the path of the front vessel is bigger than the minimum safe distance d_0. According to the above procedure, a traffic flow queue is created. It is an orderly management in which each vessel keeps the minimum safety distance to enter the channel. The time interval T_{ij} can be easily concluded as the following formula:

$$T_{ij} = d_0 / V \tag{1}$$

In this formula, the vessel velocity is a constant number. The vessel enters the waterway at a certain time interval T_{ij}, so the number of vessels entering the channel per hour is shown as follows:

$$C = 3600 \times V / d_0 \tag{2}$$

In formula (2), units of d_0 and V are expressed by meter and meter per second respectively.

3.2.2 *Channel-through capacity analysis model*

Objectively, there is a velocity difference for two adjacent vessels when they reach the channel. The velocity difference between two vessels exerts direct influence on channel-through capacity. If the velocity of the second vessel is smaller than that of the front one, the distance between two vessels increases gradually, which guarantees that two vessels can always meet the requirement of the minimum safety distance in the navigational state. Conversely, if the second vessel velocity is greater than that of the front one, the distance between two vessels decreases gradually until collision danger arises.
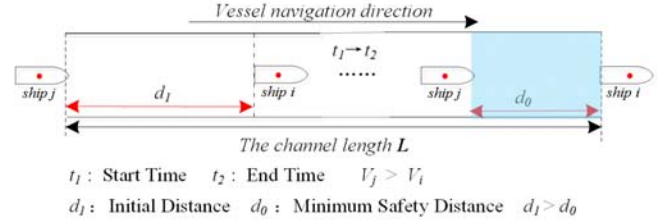

Figure 5. Analysis of vessels' distance variation under different velocity.

As shown in Figure 5, when the front vessel velocity is smaller than the second vessel velocity, in order to ensure that the distance between S_i and S_j meets the minimum safety distance requirement marked as d_0 during the whole period when two vessels are navigating in the channel, the initial distance d_1 between two vessels needs to be recalculated. Under the circumstance when the minimum safe distance between the front and second vessel can be guaranteed, each vessel is capable of maintaining a constant velocity in the navigation. The size of d_1 can be deduced from vessel velocity and channel length, as shown in the following formula:

$$d_1 = (V_j - V_i) \times L / V_j + d_0 \tag{3}$$

When the front vessel velocity is greater than or equal to that of the second one, the minimum safe distance d_0 can be chosen as the initial distance between two vessels.

In consideration of the above two situations, for the first situation when the front vessel velocity is greater than that of the second one, the probability of this situation occurring is P_1. In the second situation when the velocity of the first vessel is smaller than that of the second one, the probability is indicated as P_2. In order to find out the distribution rule of the initial distance, the concept of initial interval expectation is proposed. The calculation formula is shown as follows:

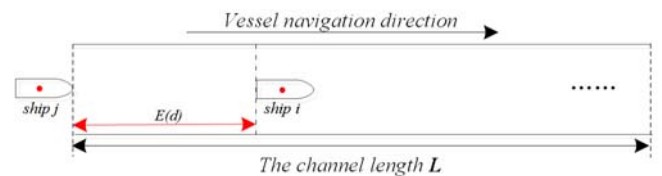$$E(d) = P_1 \times d_0 + P_2 \times d_1 \tag{4}$$

Figure 6. Analysis of channel through capacity based on vessel velocity difference.

The average initial distance of successive vessels entering the channel is replaced as initial interval expectation $E(d)$ in Figure 6. Obviously, if the distance between the front vessel and the channel entry terminal is $E(d)$, the second vessel has no restriction to enter, and then this step is repeated gradually. With combination of equations (2) ~ (4), the channel-through capacity can be expressed as follows:

$$C = \frac{3600 \times \overline{V}}{E(d)} = \frac{3600 \times \overline{V}}{d_0 + P_2 \times (V_j - V_i) \times L / V_j} \quad (5)$$

Under the realistic navigational environment, the initial velocity of different vessels entering the channel distributes in a certain value yet within a nominated range, the distribution of vessel velocity is similar to that of a Normal distribution. Here the assumed certain value is indicated as μ and the standard deviation is as σ, therefore, the initial velocity V can be replaced as $N(\mu, \sigma^2)$. With the increase of σ, the possibility of the velocity difference getting greater will increase, which means that $P_2 \times (V_j - V_i)$ will increase. Similarly, with the decrease of σ, the possibility of the velocity difference getting greater will decrease and so will the value of $P_2 \times (V_j - V_i)$. Obviously, there is a kind of certain correlation between $P_2 \times (V_j - V_i)$ and σ, which can be simplified as $(V_j - V_i) \propto \sigma$. In addition, V_j is positively correlated with V, which can be formulated as $V_j \propto V$.

With simplification, the formula of channel-through capacity can be concluded as:

$$C = \frac{3600 \times \overline{V}^2}{d_0 \times \overline{V} + k_3 \times \sigma \times L} \quad (6)$$

In formula (6), channel-through capacity C is effected by average velocity V, standard deviation σ, channel length L, and safe distance d_0. k_3 represents a constant and can be obtained by simulation afterwards. In order to intuitively reflect the relationship among channel-through capacity, standard deviation σ and channel length L, the formula is further simplified by taking d_0 and V as the fixed value:

$$C = \frac{k_1}{k_2 + k_3 \times \sigma \times L} \quad (7)$$

In formula (7), both k_1 and k_2 represent a constant and can be obtained by numerical input.

4 SIMULATION EXPERIMENT ANALYSIS

In this part, a simulation scene is firstly designed. Then some simulation experiments are conducted to further explore the proposed calculation model and verify the reliability of the model. Finally by analyzing simulation results, it can be found that the calculation model is reasonable to some extent.

4.1 Simulation Scene Design

The invented simulation model contains two parts: the vessel model and the channel environment model. The vessel model contains three sub-modules which are the vessel generation module, the vessel motion module and the vessel decision-making module. In the vessel generation module, some parameters such as vessel arrival regularity and vessel interval are necessary. These input data for vessel generation model have been concluded from the statistical analysis of the vessel traffic flow at Xiazhimen Channel. The vessel motion module is mainly used to show navigational performance of vessels in the channel. Lastly, the working mechanism for vessel decision-making model is employed to compare the real-time interval and the minimum safety distance. The channel model is designed to limit vessels' navigation by primarily setting up external parameters such as the channel situation and hydrological conditions, all of which are taken from the statistics provided in the study of Xiazhimen Channel.

Apart from some of conditions having been put forward in chapter 3.1, more limitations of the vessel traffic flow model for future analysis are given as follows:

1 Each vessel is considered separately as an object. No interference except vessel interval requirements is involved.
2 In the channel, the movement of the vessel is modeled in one dimension only. Besides, vessels move linearly along the direction of traffic flow.
3 Once vessel velocity changes, the change is completed flashily. After deceleration, the velocity of the following vessel will be the same as that of the front one.

During the simulation of the vessel navigating process, to set up the simulation scenario, the following five parameters are concerned: channel length L, vessel minimum safety distance d_0, average velocity V, velocity standard deviation σ and vessel arrival rate λ. In the design of channel environment, the average velocity V and the vessel minimum safety distance are considered as two significant constants while the rest of the parameters are variables. In each simulation experiment, Mont Carlo simulation method is adopted to obtain an evaluation parameter for channel-through capacity with reference to the number or quantity proportion of all the deceleration vessels achieved by changing vessel arrival rate. Based on the statistical analysis of the vessel traffic situation at Xiazhimen Channel, it is assumed that the minimum vessel safety distance is around 1000m, the average velocity is about 10 knots and the standard deviation is speared within the range from 1 knot to 3.7 knot. Besides, when the value of λ is more than 25, the proportion of the number of deceleration vessels is more than 95%, which means the λ more than 25 is insignificant. Therefore, in the experiment, λ varies from 1 to 25. Consequently, four research programs can be designed, as listed in table 3.

Table 3. Experiment program design.

Parameters	L(nm)	σ	V(kn)	d_0 (m)	λ
Example 1	6	1.5	10	1000	variable (1~25)
Example 2	6	2	10	1000	variable (1~25)
Example 3	10	1.5	10	1000	variable (1~25)
Example 4	10	2	10	1000	variable (1~25)

When the proportion of the number of deceleration vessels reaches 80% in one day, the stand-by time for each vessel will significantly increase and the channel will be overcrowded. In this situation, 80% of the number of deceleration vessels per day can be regarded as a reasonable number representing the channel-through capacity.

4.2 Simulation Results Analysis

Based on the above mentioned experimental scenario, the large data of statistical averages in the same experimental scenario is taken as the effective output of the experiment by Mont Carlo principle. This part of the paper focuses on the change of some parameters accompanied with the continuous change of vessel arrival rate.

Referring to the channel-through capacity equation having been mentioned in chapter 3.2, parameters k_1 and k_2, related to the average velocity and the minimum safety distance, can be obtained by calculation. However, the constant number k_3 needs to be further studied by the simulation analysis. Specific vessel arrival rate will be gained to calculate parameter k_3 in the calculation model and then by comparing and analyzing k_3 within multiple experimental scenarios, reliability and stability of the calculation model for channel-through capacity can be verified. Figure 7 shows the relationship between vessel deceleration proportion and vessel arrival rate under different experimental scenarios. In the figure, the channel-through capacity for each experimental scenario is pointed out with marks.

It can be observed from Figure 7 that the simulation experiment has verified the relation of channel-through capacity and the velocity standard deviation, the channel length. When channel length remains constant, the velocity standard deviation is larger, while the channel-through capacity is smaller. When standard deviation is constant, the channel length is longer, while channel-through capacity is smaller. The variation trend of the simulated channel-through capacity with the variation of channel length and the velocity standard deviation is consistent with the calculation model of channel-through capacity, which indicates that the calculation model has a certain degree of credibility. Considering results of all the analyses above, the following measures can be taken to improve channel-through capacity. On the one hand, if channel length is reduced to decrease the possibility of interference between vessels, channel-through capacity will increase. On the other hand, if vessel velocity entering the channel is controlled in a relatively concentrated range, that is, when the velocity difference is small, channel-through capacity can also be improved.
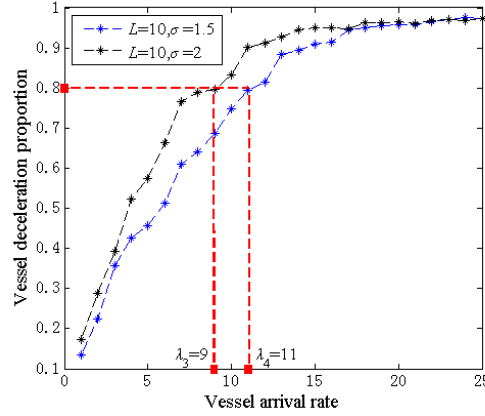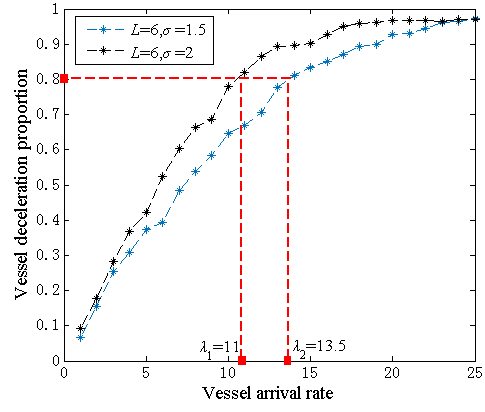

Figure 7. Simulation analysis of the channel through capacity.

The value of k_3 for the four groups of experimental conditions can be obtained by applying channel-through capacity in simulation to the calculation model, which is 0.223, 0.3076, 0.2461 and 0.2855 respectively. It can be seen that the fluctuation range of k_3 is not large and the mean variance is 0.001089. Therefore, it can be predicted that the value of k_3 tends to be a stable interval in the case that the channel length or the standard deviation of the vessel velocity is different, which indicates that the rationality of the model derivation is in a relatively acceptable range.

5 CONCLUSIONS

Based on the characteristics of vessel traffic flow and vessel-vessel interference analysis, this paper presents a calculation model of channel-through capacity. A set of simulation experiments are designed to verify the rationality of the calculation model. The results show that the data of the calculation model can match up with the simulation data to a certain extent. Meanwhile, the calculation model clearly characterizes the relation of channel-through capacity and vessel velocity, channel length. For a particular one-way channel, characteristics of vessel velocity can be analyzed by means of data acquisition and probability statistics. Based on that, the value of k_3 of the calculation model can be obtained by simulation fitting. With further experiences, it will be of great theoretical significance to guide the calculation of channel-through capacity. In addition, the model can

provide certain scientific basis and decision-making support for relevant departments to determine the velocity limit standard and to improve its management level.

However, the research results of this paper are just rudimental and preliminary, and there are still many places worthy of further study. In the process of model derivation, in order to simplify the calculation and to facilitate the analysis, the velocity difference between two adjacent vessels is assumed to be linear with the velocity standard deviation, which results in the fluctuation of k_3 to some extent. The follow-up work will mainly discuss the scientific issues of k_3 in the calculation model, and continue to modify and optimize the derivation process of the model. Further studies on the problem of k_3 under complex conditions such as the intersection of vessels, tide navigation and so on will also be expected.

ACKNOWLEDGEMENTS

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