Impact of Navigational Safety Level on Seaport Fairway Capacity

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In this paper, the definition of seaport fairway capacity, considering port service level, is given by referring to both road and inland waterway capacity combined with the features of coastal fairways. In view of the navigation environment and ships' behaviour, the safety distance of ships entering and leaving a seaport is chosen as an overall index to evaluate the navigational safety level of a fairway. Based on the ship-following theory, an Arena-based seaport operating system simulation model is constructed to analyse the impact of safety level on seaport fairway capacity. For different navigational safety levels (i.e., minimum, general and adequate), seaport fairway capacity corresponding to different service levels and navigation durations is obtained. The results show that fairway capacity varies with safety level for a given port service level, and the lower the safety level is, the higher the fairway capacity is. Finally, a recommended navigational safety level and its associated fairway capacity are given to provide a theoretical foundation for fairway design and management.

1. INTRODUCTION.   The vigorous development of the shipping industry together with the continuous increase of shipping traffic flow in coastal fairways brings higher requirements on the capacity and safety level of these fairways. At present, many indicators are adopted to measure the safety level of ships in coastal fairways, such as the waiting time of ships, the number or probability of ship collisions, etc, among which the safety distance between ships sailing in the same direction is an important parameter in the domain of ship safety management. Being closely related to a fairway's physical conditions, ship manoeuvrability and natural conditions, safety distance directly influences fairway capacity. Because a large safety distance guarantees navigation safety to some extent, but leads to longer waiting times when a ship enters a seaport, this may fail to make the most efficient use of the fairway. Moreover a small safety distance cannot meet ships' normal collision avoidance needs, especially for large ships, and can be a major contributory cause of maritime traffic accidents.

Often several times the length of the ship or a significant time interval are used as a safety separation. For example, Tianjin Port requires safety distance to be at least six times the length of the ship. Yangtze Estuary Deepwater Channel requests an interval of no less than six minutes for ships sailing in it. These methods based on experience are easy to operate, but result in a rough value without sufficient consideration of relationships between the fairway capacity and safety level. Therefore, studying the safety level of ships sailing in coastal fairways is important to ensure navigation safety, scientifically manage the process of ships entering and leaving seaports, and to improve fairway capacity.

Existing research on safety of ships sailing in fairway mostly focus on analytical expressions (Kijima and Furukawa, 2003) and navigational safety assessment. Pietrzykowski (2008) proposed a method of navigational safety assessment by using the ship's fuzzy domain, which made use of artificial intelligence. Kujala et al. (2009) studied the risk of ship collisions by theoretical modelling. Only a few papers have studied the indicators of navigational safety level. For example, Pietrzykowski (2007) proposed the probability of ships' collision as an indicator of navigational safety level in a ship encounter situation in the open sea, which takes into account a current navigational situation as well as possible occurrence of undesired events in vessel movement.

Research integrating fairway capacity and safety level together are largely confined to inland fairways. For example, Dong et al. (2007) and Chen and Guo (2008) employed an inland ship three-dimensional domain model and ship domain model of bridge water area respectively, to amend theoretical calculation formulae of inland fairway capacity. Based on ship-following theory, Zhu and Zhang (2009) presented the functional relationship between headway and speed, obtaining a calculation model of inland fairway capacity. However, for coastal fairways, taking their complexity and randomness into account, researchers generally use a simulation approach. Nam et al. (2002), Song et al. (2010) and Wang et al. (2013) mainly focused on some key parameters of seaport production, such as the number of fairway lanes, navigation duration, and handling efficiency, ignoring the evaluation of navigation safety level and its impact on fairway capacity.

Overall, this review of literature shows that advances have been confined to inland fairways without considering the complexity and random factors in the coastal fairway system. This paper builds a simulation model based on the analysis of influencing factors of fairway's sailing risk to calculate the impact of safety level on seaport fairway capacity. In the rest of the paper, we first introduce some relevant theories, such as coastal fairway capacity definition and ship-following theory, then in Section 2 we present the calculation formula of safety distance of ships sailing through the fairway under different safety levels. After that, a simulation model of a seaport operating system is constructed and validated in Section 3. Numerous simulation experiments are carried out in Section 4 to study the relationships between navigation safety level of ships and fairway capacity. Section 5 presents a numerical study. Finally we conclude the paper in Section 6.

2.   RELEVANT CONCEPTS AND THEORIES

2.1.   *Coastal fairway capacity definition.*   At present, there is a lack of systematic and theoretical research on coastal fairway capacity, and no scientific definitions. For
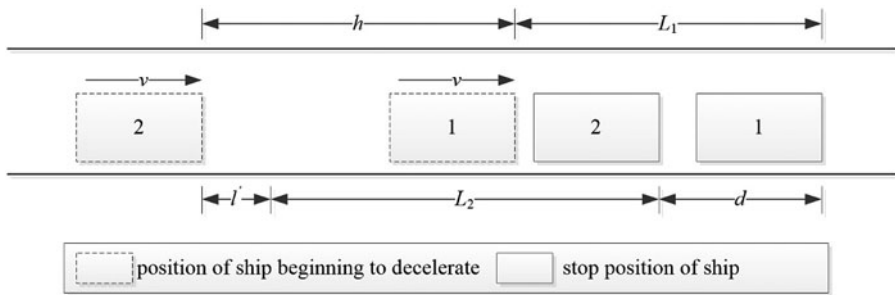
Figure 1. Ship-following model.

inland waterways, the definition of throughput capacity is the total tonnage or number of ships going through the waterway under normal status during a specific time period (Yu and Ren, 1985). Road capacity is the maximum number of vehicles that can travel on a road during a specific time period. However, for coastal fairways, the capacity is influenced not only by the natural conditions, navigation rules, and fairway dimensions etc., but also by the operation and management of the port and the port's service level. So, combining with the characteristics of coastal fairways, and referring to the definitions of throughput capacity in road, inland river and marine traffic engineering (Wu and Zhu, 2004), we define seaport fairway capacity for a given fairway of a certain seaport under normal operating status as the total annual tonnage of ships going through it at a specified port service level (Guo, et al., 2010).

Fairway capacity is one of the metrics of a fairway's load performance limits, and should reflect the service quality of the fairway for ships. $S = $ AWT/AST is introduced as the evaluation indicator of port service level (United Nations, 1985). AWT refers to ships' Average Waiting Time including the time waiting for both fairway and berth, and AST is the Average Service Time of ships at berth. The smaller the value of S is, the higher the port service level is.

2.2.   *Ship-following theory.*   Initially applied to road traffic engineering, following theory mainly simulates the driving state of a vehicle following another one ahead on a single lane (Zheng et al., 2003). Similarly, there is a buffer area around each ship when it sails in the fairway. When the traffic density of the fairway reaches the maximum capacity, the safety distance is the minimum distance between ships sailing in the same direction to avoid collision. Safety distance, the minimum distance to ensure navigation safety, is an important indicator of the safety level of the fairway, which directly affects the fairway's traffic volume.

Referring to the car-following theory, we put forward a ship-following model based on the special traffic environment (narrow waters) and collision avoidance characteristics of the coastal fairway, to simulate the stop process of ships sailing in the same direction in case of an emergency, as shown in Figure 1.

It can be seen from Figure 1 that the ship's theoretical safety distance h can be calculated as follows:

$$h = l' + d + L_2 - L_1 \tag{1}$$

where l' is the following ship's sailing distance within the reaction time of the officer of the watch (m), and it equals the product of sailing speed v and reaction time t_r; d
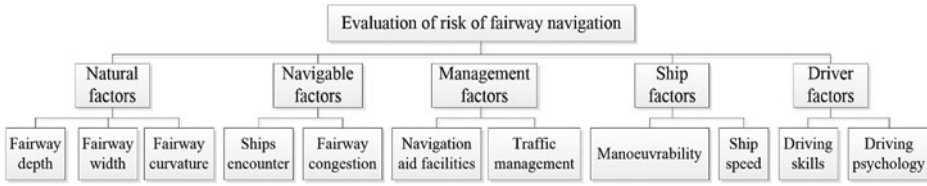
Figure 2. The influencing factors of a fairway's sailing risk.

represents the headway of the ships after they stop (m); L_1 and L_2 are the braking distance of the leading and following ships, respectively (m).

Equation (1) indicates that a ships' theoretical safety distance is related to the ship speed, reaction time of the driver, braking performance and ship length.

2.3.   *Safety level of a coastal fairway.*   Safety level of a coastal fairway, an overall evaluation of risk of navigation environment in fairway waters based on investigating ship's behaviour, is influenced by many factors (Wu and Zhu, 2004) (see Figure 2). The safety distance of ships entering and leaving port is an important quantitative indicator reflecting the safety level of a fairway with a comprehensive consideration of various factors. Different safety distances correspond to different safety levels of fairway.

According to the ship-following model and different combinations of the braking performance of the leading and following ships, expressions of safety distance under different safety levels can be obtained by Equation (1):

(a)   Minimum Safety Level (MSL): reflects the stopping process of ships in ideal conditions, that is, braking distances of the leading and following ships are the same ($L_1 = L_2$), and the corresponding expression of safety distance is:

$$h = l' + d \tag{2}$$

(b)   General Safety Level (GSL): reflects the stopping process of ships in normal conditions, that is, the leading ship stops suddenly while the following ship inertially stops ($L_1 < L_2$, $L_1 \neq 0$), and the corresponding expression of safety distance is the same as Equation (1);

(c)   Adequate Safety Level (ASL): reflects the stopping process of ships in the most unfavourable conditions, that is, the leading ship has a sudden braking and stops instantly compared to scenario (b) ($L_1 < L_2$, $L_1 = 0$), and the corresponding expression of safety distance is:

$$h = l' + d + L_2 \tag{3}$$

In other conditions ($L_1 > L_2$), the headway of the ships tends to increase, and these scenarios do not need to be considered.

To satisfy the requirement of traffic safety, Equations (1), (2) and (3) provide the definitions of safety distance and conceptually present an objective scale for
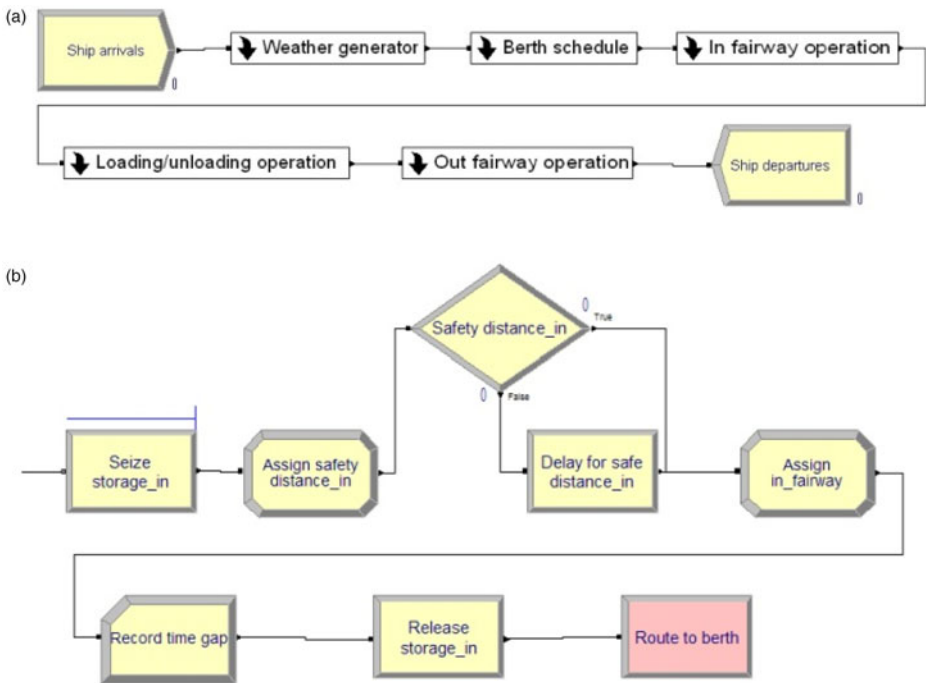
Figure 3. An Arena-based seaport operating system simulation model. (a) The top-level view of the model. (b) Modules (*In fairway operation*) for controlling safety distance.

determining a fairway's safety level. From MSL to ASL, the safety distance has an increasing trend.

3. SEAPORT OPERATING SYSTEM SIMULATION MODEL

3.1. *Model construction.* Under the influence of random factors such as ship arrivals, handling efficiency and berth condition, a seaport operating system is a typical stochastic service system with multi-level queuing. The approach of simulating seaport systems using computer simulation technology has been widely accepted (Nam et al., 2002). In accordance with the characteristics of a ship entering port, this paper constructs an Arena-based seaport operating system simulation model, which includes seven sub-models: *Ship arrivals, Weather generator, Berth schedule, In fairway operation, Loading/unloading operation, Out fairway operation* and *Ship departures*. The top-level view of the model is shown in Figure 3(a).

Taking the import process as an example, the ship arrives with a number of containers following a kind of probability distribution which the user could define. The ship is assigned its attributes (tonnage, speed) by user or random when it is created by the *Ship-arrivals* module. Then in the *Weather generator* sub-model, we can input the distribution of days that the port cannot work due to the weather, such as high winds or heavy rainstorms. After that the ship goes through the fairway and waits for berthing at the anchorage in the *Berth schedule* sub-model. When a berth is empty, a ship with the same tonnage will go to berth through the *In fairway operation* sub-model, and the
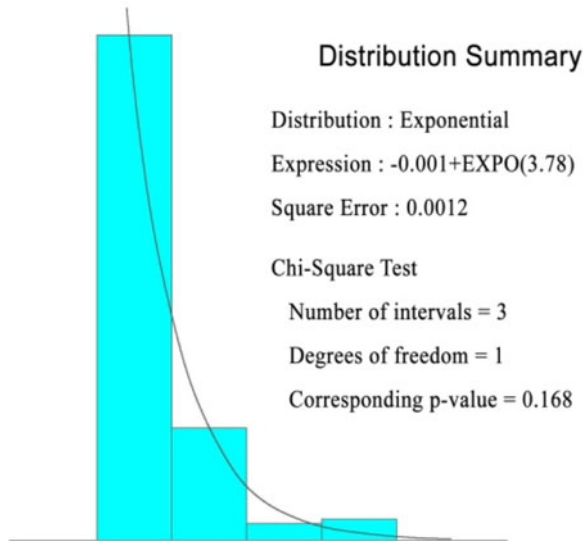
Distribution Summary

Distribution : Exponential

Expression : -0.001+EXPO(3.78)

Square Error : 0.0012

Chi-Square Test

   Number of intervals = 3

   Degrees of freedom = 1

   Corresponding p-value = 0.168

Figure 4. Fit test of ships' arrival time intervals.

containers of the ship will be handled by quay cranes in the *Loading/unloading oper-ation* sub-model. After all the handling work, the ship leaves the berth though the *Out fairway operation* sub-model, and then the vessel leaves the port through the *Ship departures* module.

Modules depicting safety distance belong to the sub-models of *In fairway operation* and *Out fairway operation*. Here the sub-model of *In fairway operation* is outlined, see Figure 3(b).

Step 1: ships judge the safety distance in turn through *Seize storage_in* module.

Step 2: ships' required safety distances are calculated in *Assign* module.

Step 3: the required safety distance is contrasted with the current headway. The ship will wait in the *Delay* module until the headway is larger than the safety distance.

Step 4: after recording the simulation information in *Record* module, ships release *storage_in* resource through *Release* module, and enter fairway through *Route* module.

3.2. *Model verification.*   One month's actual operational data of a container terminal was collected to validate the proposed model. *Arena Input Analyzer* was used for fit test of ships' arrival time intervals, see Figure 4. Chi-square goodness of fit test *p* equals $0·168$ ($>0·10$) indicating that the data obey a negative exponential distribution.

Once the arrival distribution and seaport characteristics were input into the simulation model, we ran it and obtained the results listed in Table 1. Compared with the real statistics, the maximum relative error is below 15%, which indicates that the model is reliable and can well reflect actual operating status of the seaport system.

Table 1. Simulation results of model validation.

Item	Quantity of ships arrival	AWT (h)	AST (h)	Average berth occupancy rate (%)
Simulation results	224	2·59	9·52	50·68
Actual data	223	2·99	10·04	51·85
Relative errors	0·45%	13·38%	5·18%	2·26%

4. NAVIGATIONAL FAIRWAY CAPACITY ANALYSIS

4.1. *Model assumptions.* The following assumptions are made in our model:

(a) Berths: due to the differences among combinations of berths in various port area, in this model, we assume the quantity of berths at different scales are consistent with the proportion of existing containerships when the size of the seaport increases (Guo et al., 2010).

(b) Fairway: according to the statistics, the length of existing coastal fairways in China tends to be no more than 15 km, and increases with the growing of port scale, some even reach 40 km (Wang et al., 2013). Therefore, lengths of fairway from 10 to 30 km are used in this model.

(c) Ships: Poisson probability distribution of ships' arrival time intervals is employed. Ship types and tonnages are determined by referring to the proportion of global containerships in operation and relevant provisions of seaport design (Guo et al., 2010). Also, we assume the fairway is one-way and ship speed ranges from 5 to 8 knots based on survey (Wang et al., 2013); the braking performance is estimated referring to the *Lovett and Topley* formula (Hong, 2007).

(d) Natural conditions: hydrological and meteorological conditions are supposed to be stable when ships sail in the fairway. Due to bad weather, the seaport operates only on 325 days randomly distributed in a period of one year. Ships constrained by tidal height for entering and leaving port are not taken into account.

(e) Rules of fairway usage: the leaving port process takes priority over entering port process in this model. Ships' entering and leaving port is always in accordance with the "first come first served" rule.

4.2. *Safety distance calculation.* Based on the ship-following model, safety distances under various safety levels are associated with ships' speed and characteristics. To facilitate the model input, we turn theoretical Equations (1) to (3) into analytical formula. L_1 and L_2 are estimated referring to the *Lovett and Topley* formula (Hong, 2007), respectively.

$$L_1 = 0.0121 \frac{\Delta v^2}{R_v} \tag{4}$$
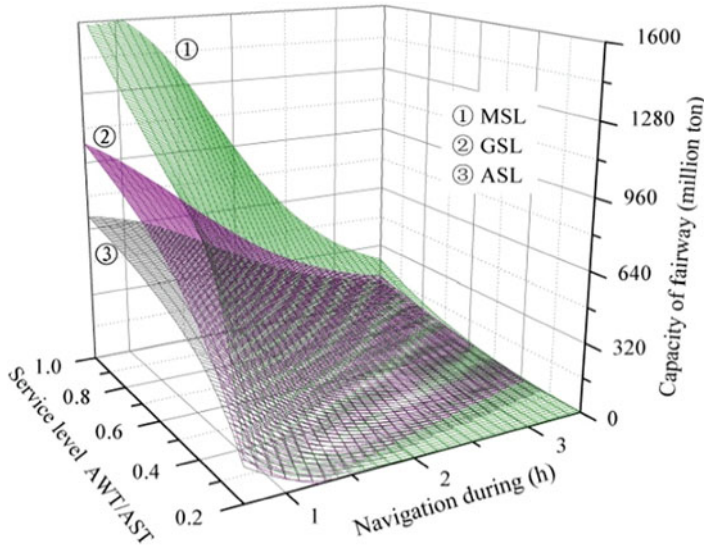
$$L_2 = 0.024 Cv \tag{5}$$

Figure 5. Relationships between fairway capacity, service level and fairway length under different safety levels.

where Δ means ship's displacement; R_v represents the resistance of the ship at the speed of v; C is the time needed for halving the speed; other symbols have the same meaning as mentioned above.

Then we get the analytical formula of safety distance under various safety levels

$$h = \begin{cases} vt_r + d \ldots \ldots \text{MSL} \\ vt_r + d + L_2^f - L_1^l \ldots \ldots \text{GSL} \\ vt_r + d + L_2^f \ldots \ldots \text{ASL} \end{cases} \tag{6}$$

where L_1^l stands for the crash stopping distance of the leading ship and L_2^f represents the inertial stopping distance of the following one.

4.3.   *Result analysis.*   Figure 5 shows the three-dimensional relationship between fairway capacity, service level and fairway length under different safety levels (MSL, GSL and ASL). Here, fairway length can be represented by navigation duration; that is, the ratio of fairway length and ship speed.

Through nonlinear regression analysis of the above-mentioned data, we can get the formula of fairway capacity corresponding to various service levels and navigation duration

$$T = \alpha_1 + \alpha_2 t + \alpha_3 S + \alpha_4 t^2 + \alpha_5 S^2 + \alpha_6 tS \tag{7}$$

where T is the fairway capacity; t and S represent the navigation duration and the port service level (AWT/AST), respectively; $\alpha_1, \alpha_2, \ldots, \alpha_6$ are fitting parameters. Table 2 lists the fitted values and its goodness.

The figure and fitting formula show that different safety levels correspond to different fairway capacities. Under the same safety level, fairway capacity increases with the reduction of navigation duration or port service level.

Table 2. Fitted values and goodness.

Safety level	α_1	α_2	α_3	α_4	α_5	α_6	R^2
MSL	286·17	−1001·76	3816·4	334·54	469·75	−1463·8	0·93
GSL	121·97	−499·82	2315·8	110·71	−680·2	−377·72	0·98
ASL	70·19	−324·47	1758·3	47·13	−779·4	−129·82	0·97

Table 3. Parameters of different berths.

Berth tonnage/10 000DWT	0·5	1	2	3	5	7	10
Berth quantity	1	2	3	2	2	1	1

5. CASE STUDY

5.1. *Parameter settings.* A seaport with 12 container berths is used as a simulation case. Berths' tonnage and quantity are presented in Table 3. The fairway is 20 km long, one-way traffic, and its speed limit is 6 knots. The safety distance between two ships is controlled to be six times length of the following ship (that is, $\lambda = 6$, see Equation (8)). This seaport does not operate on 40 days per year.

$$\lambda = \frac{h}{LFS} \tag{8}$$

where λ is the conversion coefficient of safety distance; h represents the safety distance (m); LFS is the length of the following ship (m).

5.2. *Fairway capacity comparison.* According to the regression analysis above, regression value of fairway capacity under various service and safety levels of the seaport can be computed by Equation (7), and the results are listed in Table 4. Simulation values of fairway capacity under four above-mentioned safety levels are shown in Table 4 and Figure 6.

5.3. *Impact of safety level on fairway capacity.* According to Figure 6, in different ranges of S (AWT/AST), safety level has different effects on fairway capacity:

(a) S located in [0·2, 0·4]: capacities of fairway under four safety levels almost have no difference, that is, variations of safety levels have less effect on fairway capacity.

(b) S located in [0·4, 0·6]: with the increase of S, curve bunches are divided into three tendencies. Curve 1 sharply ascends while both curve 3 and 4 slowly increase. The degree of the safety levels' effects all increases to a certain extent.

(c) S located in [0·6, 1·5]: curve 3 and 4 begin to separate, but the separation degree is small. When S reaches 1·5, the increase of curve 4 is only 4% larger than that of curve 3, indicating that the capacity of fairway under ASL is very close to the present situation.

In conclusion, fairway capacity varies with safety level for a given port service level. Maximum and minimum capacities of fairway correspond to MSL and ASL,

Table 4. Comparisons of fairway capacity under different computing methods (million tons per year).

| No. | Safety level | Port service level value (AWT/AST) | | | | | |
| | | 0·4 | | 0·5 | | 0·6 | |
		RV	SV	RV	SV	RV	SV
1	MSL	115	133	275	269	445	440
2	GSL	127	120	229	216	318	317
3	ASL	124	113	206	188	273	264
4	Present ($\lambda = 6$)	–	115	–	194	–	274

Note: RV and SV mean Regression Value and Simulation Value, respectively.
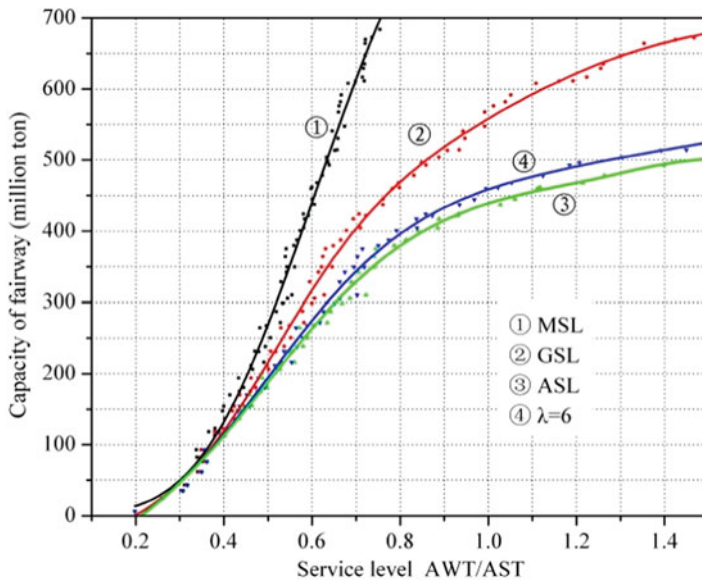

Figure 6. Relationships between fairway capacities and port service levels under different safety levels.

respectively. In other words, under the same conditions, to the specified port service level, the lower the safety level is, the larger fairway capacity is. It also shows that port service level and navigation safety level are two important factors in determining the capacity of the fairway.

5.4.   *Safety level recommendation.*   The safety distance between ships sailing in the same direction under different safety levels is associated with ship speed and properties of the leading and following ships. For a given ship speed of 6 knots, Figure 7 shows how the conversion coefficient of safety distance varies with LLS (Length of Leading Ship) and LFS (Length of Following Ship) for different safety levels.

Based on the comprehensive analysis of Figure 6 and 7 as well as the consideration of the impact of ship dimensions, controlling safety distance at six times the length of ship is to some extent reasonable. The corresponding fairway capacity is superior to
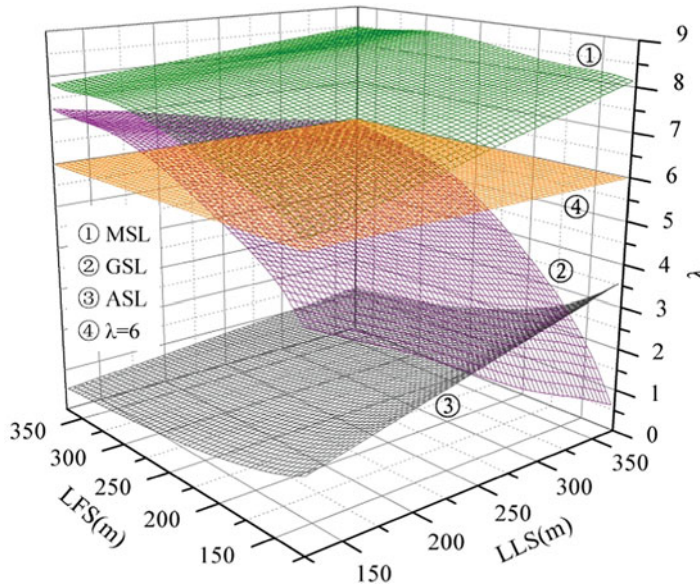
Figure 7. Ship's safety distance for different safety levels (v = 6kn).

Table 5. Capacities of fairway under different safety levels (million tons per year).

Safety level	Port service level AWT/AST			
	0·4	0·5	0·6	0·7
Present ($\lambda = 6$)	115	194	274	343
MSL	133 (−13·6%)	269 (−27·7%)	440 (−37·7%)	613 (−44·0%)
GSL	120 (−4·2%)	216 (−9·9%)	317 (−13·4%)	404 (−14·9%)

Note: the values in parentheses represent the relative decline ratios.

that of ASL under the same conditions. However, as for its essence, the existence of safety distance is to reduce collision probability between the following and leading ships. Ignoring the characteristics of the leading ship's type and movement, and only from the point of the following ship, it is easy to impose a safety area too large for some combinations of ship types (small-size ship follows large-size ship), or too small in other combinations (small-size ship leads large-size ship). It not only prevents the optimisation of fairway capacity to some extent, but also causes economic losses for both port and ship sides, and may even threaten navigation safety of large-size ships. It can be seen from Figure 6 that when S is less than 0·4, the capacities of fairways under different safety levels have almost no difference; when S is more than 0·7, the capacities increase slowly. So, in Table 5, we only consider the capacities of fairway under the service level between 0·4 to 0·7.

In Table 5, three safety levels that are derived on the basis of ship-following theory take account of many factors, and can be used to optimise the organisation of ships entering and leaving port. After comprehensively comparing each safety level and

its related fairway capacity, the safety distance corresponding to GSL is recommended to meet the requirements that ensure the safety of ships sailing as well as achieving full capacity of a fairway.

5.   CONCLUSION.   Based on the ship-following theory, this paper introduces a new computing method of safety distance under various safety levels. An Arena-based seaport operating system simulation model is constructed to study the effect of safety level on fairway capacity. The analytical formula of safety distance and fairway capacity are presented. For a given port service level, fairway capacity varies with safety level, and the lower the safety level is, the higher the fairway capacity is. Results from the simulation experiments show that controlling safety distance at six times the length of ship is to some extent reasonable. The corresponding fairway capacity is superior to that of ASL under the same conditions. However, it is easy to impose a safety area too large in some combinations of ship types. So, after comprehensively comparing each safety level and its related fairway capacity, the safety distance corresponding to GSL (General Safety Level) is recommended to meet the requirements that ensure the safety of ship sailing as well as achieving full capacity of the fairway.

Further research on the issue could proceed in several directions. For example, additional simulation experiments that consider more scenarios could be performed, such as ship collision. Future effort could also be devoted to combining a simulation model with an optimal mathematical model to solve the problem.

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