Journal of the Korean Society of Marine Environment & Safety
Research Paper
Vol. 24, No. 3, pp. 332-338, May 31, 2018, ISSN 1229-3431(Print) / ISSN 2287-3341(Online)
https://doi.org/10.7837/kosomes.2018.24.3.332

Validation of Statistical Analysis-based Aberrancy Probability Using Marine Simulations

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Abstract : *To perform the Maritime Safety Audi Scheme, 10^{-4} was constantly applied without adjustment when evaluating the proximity of the fairway. The necessity of applying the different aberrancy probabilities from the different proximity of the fairway depending on the shape of the route and the size of the ship was validated using marine simulations. Marine simulation was performed to evaluate the validity of statistical analysis-based aberrancy probability according to the different shapes of routes and ship size presented in the previous study. As results, the validity of the criterion of the statistical analysis-based aberrancy probability was confirmed by comparing with the results of simulation-based aberrancy probabilities. The results support that the aberrancy probabilities by the types of a vessel could be different based on the type and size of vessels. The results motivate that further investigation is required to find the reasonable criteria of the aberrancy probabilities for the maritime traffic safety audit according to the fairway shape and the size of the vessel.*

Key Words : *Aberrancy probability, Statistical analysis-based probability, Simulation-based aberrancy probability, Marine traffic simulation, Maritime Safety Audit Scheme*

1. Introduction

Construction of facilities such as bridges, tunnels and cables, and to develop or redevelop ports or docks significantly changes the marine environment. Therefore, the Maritime Safety Audit Scheme (MSAS) introduced the Ministry of Maritime Affairs and Fisheries (MOMAF) in 2009, to professionally evaluate the risk factors of navigation safety in the marine environment. The maritime safety audit scheme is intended to make future-oriented and safety-friendly developments by preliminarily investigating, measuring and evaluating the effects of marine development projects on ship traffic and reflecting the results in the design.

An acceptable aberrancy probability is defined as below 1.0×10^{-4} based on the closest distance between the obstacles that affect the traffic (MOMAF, 2017). However, Kim and Kwon (2017) analyzed the actual vessel tracks in the major ports of Korea and argued that aberrancy probabilities were different when the size of ships and shapes of fairways were changed.

Therefore, the purpose of this study was to validate the statistical analysis-based aberrancy probability through marine maneuvering simulation as proposed by Kim and Kwon (2017). Mokpo and Incheon ports which include both straight and curved inbound and outbound fairways were selected as marine maneuvering simulation environments, and multiple simulations were conducted to support statistical evidence of this simulation-based validation study.

2. Methods

2.1 Overview of marine simulation

Ship maneuvering simulation is a highly sophisticated technology that integrates many techniques of shipbuilding engineering, civil engineering, marine engineering, shipbuilding, computer engineering and ergonomics. The ship maneuvering simulator mathematically builds the target sea area and the target ship. By adopting a high-performance computer system, the ship maneuvering experiments perform realistic representations of various marine traffic conditions that can be controlled and reproduced.

The simulator used in this study is based on the independent performance of the ship's forces, including the hydrodynamic forces of the ship, propeller and rudder, adding the effect of the interaction between them to the single performance. The modular maneuvering model mathematical model of Yasukawa and Yoshimura (2015) was used. When experimental data was available, the necessary forces were calculated using the obtained

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data. However, if there is no experimental data, various empirical equations can be alternatively used to perform necessary calculations based on the basic characteristics of the ship.

2.2 Traffic safety assessment method

As an evaluation method, subjective evaluation and aberrancy probability reflecting the proximity of ships were evaluated for assessing marine traffic safety. The two aspects were used in the Maritime Safety Audit Scheme.

2.2.1 Aberrancy probability

The proximity assessment of the ship sets the reference point or baseline at which the marine traffic hazard is expected, and measures the proximity distance during the operation of the ship. In this study, the distance from bridge to bridge is measured from the tracks of the simulated vessel on the route when the bridge exists, and the distance from the end of the route is calculated when there is no bridge on the route. The mean and standard deviation of the calculated data were calculated using the normal distribution probability.

The aberrancy probability is obtained from the following equation (1) using the standard normal distribution formula for the ship's center distance from the reference point μ and σ, and the aberrancy probability z that the ship will hit the bridge or obstruct the route. Denote that e represents Euler's number.

$$P(z \geqq z_o) = 1.0 - \int_0^{z_o} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2} dz \qquad (1)$$

2.2.2 Subjective evaluation of navigators

As a subjective evaluation criterion of the ship operator, the safety criteria for each item is listed in Table 1, and the ship operator classifies the burden or risk due to the sea bridge in seven stages. When the subjective evaluation of the operator is more than or equal to -2.0, it is determined that it is possible to secure the safety of the traffic and the security of the passengers according to the changes in the maritime traffic environment. In this study, the subjective evaluation of the ship operators required for the criteria of the maritime invasion probability was excluded from the average of -2.0 (hazard) and below.

Table 1. Ship operator's subjective evaluation

Scale	Definitions
-3	Significant Risk
-2	Moderate Risk
-1	Minor Risk
0	Neutral
+1	Minor Safe
+2	Moderate Safe
+3	Very Safe

2.3 Marine simulation scenario

Yoon (2004) states that a ship navigating along a route should maintain sufficient distance between vessels traveling in opposite directions. Also, the ship should remain in the central lane to avoid approaching the outer limits of the waterway or route on the starboard side of the fairway. Moreover, Kim and Kwon (2017) found that ships of a small size did not feel a heavy burden about the obstacles at the center of the route or the outbound route, so aberrancy probability of the small ships were greater than 1.0×10^{-4}. Most ship operators have a much smaller value than 1.0×10^{-4} because they navigate along the center of the route unless it is in the case of interchange traffic during ship maneuvering simulations.

Therefore, the significant difference between actual vessel traffic and ship maneuvering simulation was identified. Based on the difference between practice and simulation, it was assumed that the ship proceeding along the route is on the right side if there was no other traffic (Fig. 1) when the simulation was performed. The first case proceeded along the center of the course, the second case was conducted between the center of the course and the right outer edge of the course, and the third was navigated close to the outer course of the course (see Route 1, Route 2 and Route 3 in Fig. 1). A single ship navigated through the fairway, with control of ship's speed, intended heading, and alteration of ship's course were determined by the ship navigator.

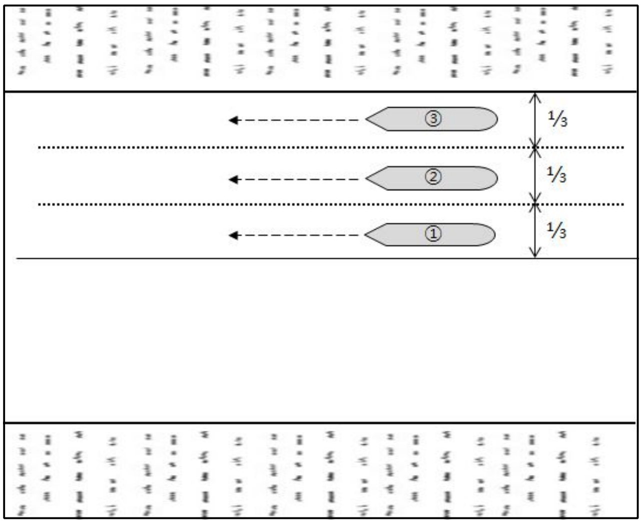

Fig. 1. Proceeding scenario of ship on channel.

In this study, the same ship model that was applied in Kim and Kwon (2017)'s preliminary study when conducting ship maneuvering simulation. The details of the applied vessel model are shown in Table 2. The target vessel can be expressed in deadweight tonnage (DWT) as the gross tonnage (GT) by using the relation of Equation (2) presented in the Port and Fishing Design Standard Commentary (MOMAF, 2014).

$$\text{Cargo Ship : } GT = 0.529 \ DWT \quad (2)$$

Table 2. Details of target vessels

Target vessels	L.O.A [m]	Breadth [m]	Draft [m]
1,000 DWT	69.2	11.2	3.8
5,000 DWT	91.5	15.5	6.0
30,000 DWT	181.0	26.0	9.7
100,000 DWT	245.0	39.3	15.1

Park et al. (2013) found that subjective risk could vary with maneuvering experience. Therefore, in order to ensure the objectivity of the ship operator performing the ship maneuvering simulation, the ship maneuvering simulation was carried out by classifying the boarding career as being less than five years, five to ten years, and ten years or more as shown in Table 3.

Table 3. Ship operator's maneuvering experience

Group	Onboard Career	Person
1	< 5 year	20
2	5 year - 10 year	4
3	10 year <	4

Although there is no solid idea how many ship maneuvering simulations should be performed Jung (2014) insisted that the ship maneuvering simulation should be performed at least five times. In this experiment, the number of executions of ship maneuver simulation is divided into day and night according to ship size as shown in Table 4, and was performed a total of 54 times, nine times each. According to the traffic conditions, the simulation with Route 1 was carried out in B bridge, Route 2 in C bridge, and Route 3 in A bridge. The ship operators participated in the missions one by one.

Table 4. Frequency of simulation scenarios

Target vessels	Time	B Bridge (#1 Fairway)	C Bridge (#2 Fairway)	D Bridge (#3 Fairway)
1,000 DWT	Day	9 times	9 times	9 times
	Night	9 times	9 times	9 times
5,000 DWT	Day	9 times	9 times	9 times
	Night	9 times	9 times	9 times
30,000 DWT	Day	9 times	9 times	9 times
	Night	9 times	9 times	9 times
100,000 DWT	Day	9 times	9 times	9 times
	Night	9 times	9 times	9 times

2.4 Marine simulation environment

Based on the technical standards for the Maritime Safety Audit Scheme, the natural environmental conditions are applied to the most difficult conditions in maneuvering. The wind direction of the simulation target sea area was applied to the NW series which appeared most in the sea area, and the wind speed was set to 27 knots. In the target area, the tide is the most disadvantageous to the ship's traffic, the strongest tide is applied to the port of entry and departure.

2.4.1 Straight fairway with a bridge

The simulation scenario of the ship entering and leaving the Incheon Bridge is shown in Fig. 2. For the port of entry, the simulation was completed after passing the Incheon Bridge along the right route of the port of entry, starting 1 mile off the south of Incheon Bridge. For ships departing from Incheon Bridge, it started from 1 mile off the north of Incheon Bridge and ended after passing Incheon Bridge along the right route of the departure route.

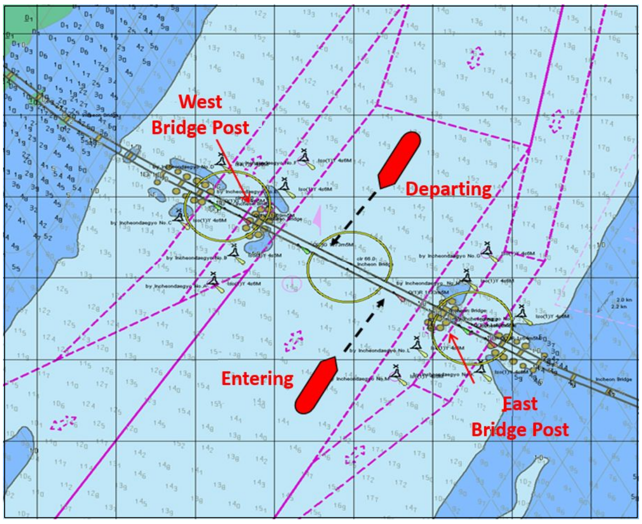

Fig. 2. Incheon bridge traffic scenario.

2.4.2 Curved fairway with a bridge

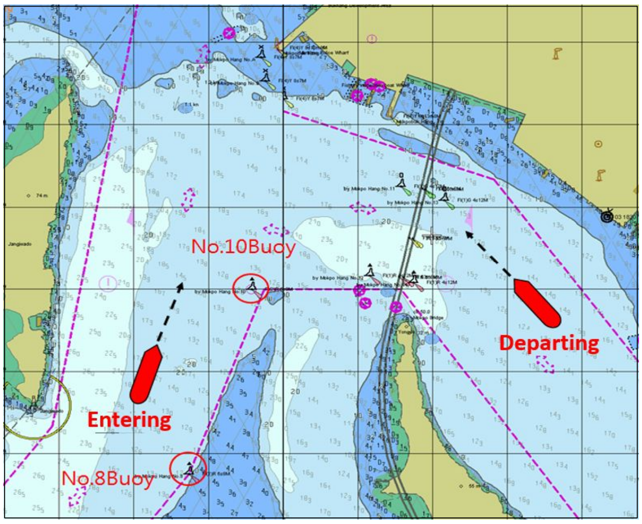

Fig. 3. Mokpo bridge traffic scenario.

The simulation scenario of the ship entering and leaving the port of Mokpo Bridge is shown in Fig. 3. In the case of the vessel at the port of entry, the initial position started from No. 8 Buoy, made a detour around No. 10 Buoy on the starboard, passed through Mokpo Bridge, and entered the straight route. For the departing vessel, the simulation was terminated when it passed through Mokpo Bridge, turned left, passed by No. 10 Buoy and started from 1 mile before the right side of Mokpo Bridge.

2.4.3 Straight fairway without a bridge

The simulation scenario configuration in the Incheon East fairway is shown in Fig. 4. The initial location of the Incheon East fairway started from the beginning of the Incheon East fairway, followed by the bypass at the starboard side, and the simulation was terminated after passing by No. 2 Buoy along the straight route.

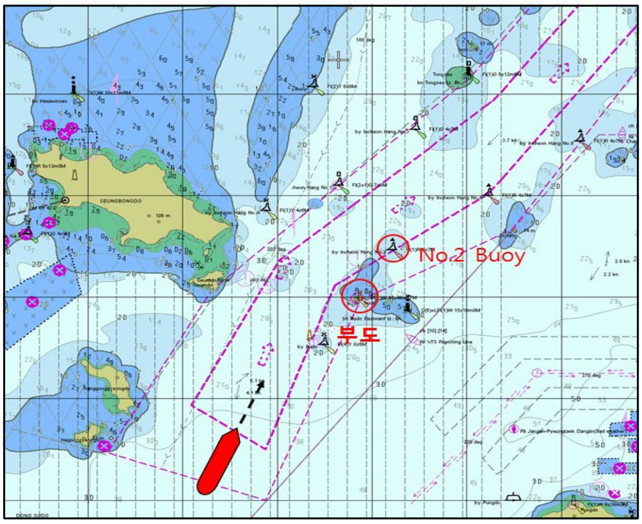

Fig. 4 Inchon east channel traffic scenario.

2.4.4 Curved fairway without a bridge

The simulation scenario composition in Mokpo-gu is shown in Fig. 5. In the case of a ship moving from Mokpo port to Mokpo port, the initial position started from No. 2 Buoy, and the other side was on the starboard side. The simulation at Mokpo-gu was divided into 1,000 DWT class, 5,000 DWT class and 30,000 DWT class according to ship size. A total of 112 simulations were conducted 54 times at three scenarios according to the traffic conditions.

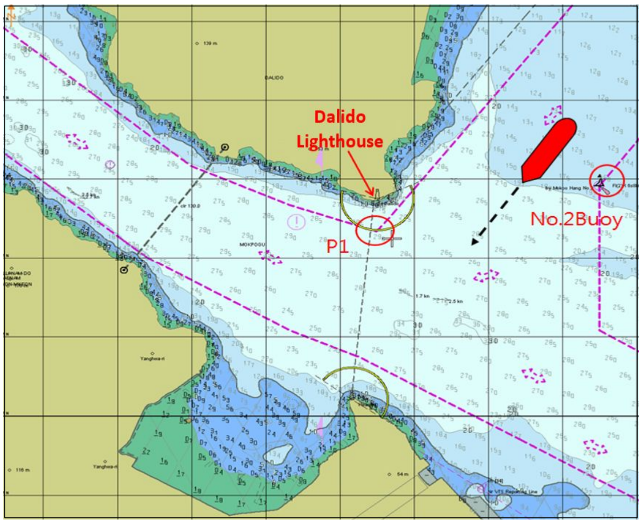

Fig. 5. Mokpo channel traffic scenario.

3. Results of Aberrancy Probability and Discussions

3.1 Results of aberrancy probability

3.1.1 Straight fairway with a bridge

As a result of the simulation of the proximity distance and the aberrancy probability for the vessels entering Incheon Bridge, the aberrancy probability were less than 10^{-4} for Routes 1 and 2 but greater than 10^{-4} for Route 3. For ships departing Incheon Bridge, the aberrancy probabilities of Routes 1 and 2 were less than 10^{-4}, and Route 3 was more than 10^{-4}.

Subjective evaluation of the Incheon Bridge simulation participants showed that the average route of safety was +2.7 in the A route of Incheon Bridge whereas in slightly safe in the route of B (+1.7). However, in the case of the C route, the evaluation criteria for the 30,000 DWT class and the 100,000 DWT class ship were not satisfied, and the other ships satisfied the evaluation criteria. For departing vessels, safety was averaged (+2.6) on Route 1 and slightly safe (+1.6) on Route 2. In the case of vessel C, it was evaluated that for ships of 30,000 DWT and 100,000 DWT, the criterion of -2.0 or less was not satisfied.

Comprehensive assessment including subjective evaluation showed that the probability of passage incidence was different according to vessel size at the port of entry and departure. The value was less than 10^{-2} in less than 5,000 DWT and less than 10^{-3} in more than 30,000 DWT.

3.1.2 Curved fairway with a bridge

As a result of the simulation of the proximity distance and the aberrancy probability for the ships entering Mokpo Bridge, the aberrancy probability was found to be less than 10^{-4} for Routes 1, 2, and 3 for all ships. Simulation results of the proximity distance and the aberrancy probability for the ship departing from Mokpo Bridge showed that the aberrancy probability for Route 1 and Route 2 were less than 10^{-4} and 10^{-4} or more for Route 3.

As a result of the subjective evaluation of Mokpo Bridge simulation participants, navigators felt that Mokpo Bridge was safe (+2.5) on Route 1 and slightly safe (+0.8) on Route 2. However, the subjective evaluation of the ship on the Route 3 of 30,000 DWT did not meet the evaluation criteria of -2.7, whereas the other ships satisfied the evaluation criteria. In the case of departing vessels, average safety (+2.3) was found on Route 1 and slightly safe (+0.8) on Route 2, but it was the same as the result on entry for Route 3.

The comprehensive evaluation including subjective evaluation showed a value of 10^{-2} and 10^{-3} or more at the entrance and departure of 1,000 DWT and 5,000 DWT respectively, 10^{-4} at the entry of 30,000 DWT, and 10^{-4}, respectively.

3.1.3 Straight fairway without a bridge

As a result of the simulation of the proximity distance and the aberrancy probability according to the size of the vessel, the probability of the passage invasion according to the size of the vessel was less than 10^{-4} only in Route 1 and the value 10^{-4} or more in Route 3 respectively.

As a result of evaluating the risk perceived by the ship operator on a 7 - point scale, it was safe (+2.8) in Route 1 and slightly safe (+1.4) in Route 2. However, it was -2.5 and -2.9 for the 30,000 DWT and 100,000 DWT vessels of the Route 3, respectively.

Comprehensive assessment including subjective assessment, except for those where the subjective evaluation result of the ship operator is less than -2.0 among the aberrancy probability to Routes 1, 2, and 3, greater than 10^{-3}.

3.1.4 Curved fairway without a bridge

Simulation results of the proximity distance and the aberrancy probability for ships entering Mokpo port from Mokpo port resulted in less than 10^{-4} chance of aberrancy in ships less than 5,000 DWT. On the other hand, 30,000 DWT vessels have a very high risk of less than 10^{-4} in Route 1 and 10^{-1} in Route 3,

As a result of evaluating the danger perceived by the ship operator in Mokpo-gu, the average score of safety on Route 1 was +2.4 and the safety of Route 2 was slightly safe (+1.4). However, it was -2.2 when it was navigated on Route 3 in the ship of 30,000 DWT class, and it did not satisfy the evaluation standard of -2.0 or more.

Comprehensive assessment including subjective assessment is performed in the case where the aberrancy probability including the value of -2.0 or more is less than 5,000 DWT, except for the item where the subjective evaluation result of the ship operator is -2.0 or less among the aberrancy probabilities of Route 1, 10^{-2} or more, and more than 30,000 DWT or more.

3.2 Discussion

Table 5 compares the results of simulations performed on straight and curved routes with and without bridges on the fairways. The simulation results show that the aberrancy probability including only the value of -2.0 or more, in which the ship operator feels relatively safe, excluding the items whose subjective evaluation result is -2.0 or less.

The aberrancy probabilities in the straight line with bridges were 2.6×10^{-2}, 8.6×10^{-3} and 8.1×10^{-4} at 1,000 DWT, 5,000 DWT, and 30,000 DWT, respectively. The values of 1.7×10^{-2}, 5.1×10^{-3} and 5.8×10^{-4} were also shown in the curved route, showing that the marine invasion probability 10^{-2}, 10^{-3}, 10^{-4} presented in this study did not deviate significantly.

The aberrancy probability through the curved route without bridges was 2.0×10^{-1}, 4.4×10^{-2}, 7.3×10^{-3} at 1,000 DWT and 5,000 DWT, and 30,000 DWT, and the values are almost identical to the statistical analysis-based aberrancy probabilities. Also, the values of 4.4×10^{-2} and 7.3×10^{-3} at 5,000 DWT and 30,000 DWT were higher than those of 10^{-3} and 10^{-4}, respectively. The result shows that the ship's track deviates significantly from the autonomous navigation of the ship operator in the relatively wide route, which is higher than the suggested value.

Based on these results, it can be seen that the results of the study using the ship maneuvering simulation and the aberrancy probability presented in the previous study were not significantly different to the simulated results. The results support that the statistical analysis-based aberrancy probabilities (Kim and Kwon, 2017) were acceptable through reasonable evidence from the simulation-based aberrancy probabilities.

Table 5. Comparison of suggested values and simulation value

Fairway of marine bridge				
Fairway	Suggest values		Simulation value	
Straight lane	<1,000GT	1.0×10^{-2}	1,000DWT	2.6×10^{-2}
	1,000-3,000GT	1.0×10^{-3}	5,000DWT	8.6×10^{-3}
	3,000GT<	1.0×10^{-4}	30,000DWT	8.1×10^{-4}
Curved lane	<1,000GT	1.0×10^{-2}	1,000DWT	1.7×10^{-2}
	1,000-5,000GT	1.0×10^{-3}	5,000DWT	5.1×10^{-3}
	5,000GT<	1.0×10^{-4}	30,000DWT	5.8×10^{-4}
Fairway of common				
Fairway	Suggest values		Simulation value	
Straight lane	<5,000GT	1.0×10^{-3}	5,000DWT	4.4×10^{-2}
	5,000GT<	1.0×10^{-4}	30,000DWT	7.3×10^{-3}
Curved lane	<1,000GT	1.0×10^{-1}	1,000DWT	2.0×10^{-1}
	1,000-10,000GT	1.0×10^{-2}	5,000DWT	4.4×10^{-2}
	10,000GT<	1.0×10^{-3}	30,000DWT	7.3×10^{-3}

4. Conclusion

In the evaluation of proximity according to the Implementation Guideline for Maritime Safety Audit Scheme, 10^{-4} has been constantly applied without adjustment. In this study, the necessity of applying the different aberrancy probabilities depending on the shape of the route and the size of the ship was validated using marine simulations.

In the Maritime Safety Audit Scheme, the criteria for the aberrancy probability is specified to be less than 10^{-4}. However, objective and reasonable grounds are not clear for applying the same criteria for all marine vessels. In this study, ship maneuvering simulation was performed to evaluate the validity of statistical analysis-based aberrancy probability according to the type of route and ship size presented in the previous study.

As a result of comparison between the statistical analysis-based aberrancy probability and the simulation-based aberrancy probability, the validity of the criterion of the statistical analysis-based aberrancy probability was confirmed.

Based on the actual tracks of the passing vessels, it was found that the aberrancy probabilities by the types of vessel were different according to the type and size of vessels. Therefore, further investigation is required to set reasonable criteria for the aberrancy probabilities for the Maritime Safety Audit Scheme according to the fairway shape and the size of the vessel.

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Received : 2018. 04. 30.
Revised : 2018. 05. 23. (1st)
: 2018. 05. 27. (2nd)
Accepted : 2018. 05. 29.