Risk Assessment of LNG Carrier Pilotage Due to Secondary Pilotage Based on Improved SD

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Abstract. Ships transporting pilots in mid-flight are ships with limited maneuverability, and frequent boarding and unloading of pilots within a short distance will inevitably increase additional risks. This paper takes the secondary pilotage risk assessment of Mirs Bay Liquefied Natural Gas (LNG) carrier as the research object. Based on previous accident reports and related studies of LNG carriers, this paper uses the principles of System Dynamics (SD) and Safety Systems Engineering (SSE) to construct the Pilotageal risk assessment index system and system dynamics risk assessment model of Mirs Bay, and integrates the improved coupling theory into the model to improve the simulation accuracy of the model. Based on the conventional Pilotage risk assessment of LNG carrier, the risk coefficient, weight and coupling degree of each subsystem and index within the system were evaluated and calculated respectively, and then substituted into the model for simulation. The quantitative results of the impact of "secondary pilotage" on the Pilotage risk of LNG carrier in Mirs Bay waters were obtained.

Keywords: Secondary pilotage; Navigation risk assessment; System dynamics; Coupling theory

1 Introduction

The Dapeng Bay LNG Hub in Shenzhen is the largest and most densely distributed LNG unloading port in China, bearing the significant responsibility of supplying gas to regions such as the Pearl River Delta and Hong Kong-Macao. Ensuring the safe Pilotage of LNG vessels in the waters of Dapeng Bay is tantamount to safeguarding the energy security of the Pearl River Delta and Hong Kong-Macao regions. However, due to policy changes, LNG vessels berthing in Dapeng Bay now require an additional pilotage within a distance of less than 5 nautical miles, known as secondary pilotage. Therefore, it is imperative to assess the risks posed by secondary pilotage and provide targeted strategies for risk mitigation.

Currently, there is extensive theoretical research on ship Pilotage risk assessment, primarily based on the principles of system reductionism. This involves using probability and mathematical statistics on existing data to construct assessment system models for studying risks. Widely used research methods include Lin's probabilistic risk assessment method, Gan Haoliang's comprehensive safety assessment method [1],

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and Cai's maritime traffic risk system analysis and assessment method. Common risk assessment models include accident chain models [2], fault tree models [3], and probability models [4]. Pilotage risk assessment is a subset of ship Pilotage risk assessment, sharing similar research methods and assessment models. For instance, Fang Quangen et al. comprehensively analyzed and evaluated the pilotage risk in Shanghai Port using Formal Safety Assessment (FSA). Xuanshaoyong et al. [6] proposed an improved risk assessment method based on Bayesian theory and hybrid Pilotage traffic flow calculation. Chen Hao, Hu Shenping, and others [7] established a pilotage risk assessment model for port waters based on uncertain measure theory. However, these research methods and assessment models mainly focus on studying the risk situation at a specific time period or point in time. They lack continuity and comprehensiveness in studying the occurrence of risk incidents, and there is a shortage of universally effective methods for risk investigation, analysis, prediction, and prevention.

Compared to previous research methods, the most significant difference of system dynamics lies in its capability to conduct both dynamic analysis over time and coordination among factors. This method is highly suitable for analyzing and resolving the complex issues of ship Pilotage risk assessment in port waters, which involve multiple influencing factors, nonlinear and interactive relationships among these factors, and partial prediction of future system developments. By incorporating coupling theory into the steps of system dynamics problem-solving, not only can the relationships among risk factors be better delineated, but the degree of interaction can also be quantified using coupling measurement models. This approach addresses previous shortcomings in system dynamics assessment, such as limited research on coupling mechanisms during the evolutionary process and unscientific quantification of coupling relationships among factors. The combined application of these two research methods can provide a more scientifically rigorous quantification of the Pilotage risk associated with secondary pilotage of LNG vessels in Dapeng Bay. This would offer data support for comprehensive risk assessment studies, holding both theoretical significance and practical value.

2 Construction of an Evaluation Index System Based on System Dynamics

System Dynamics is primarily based on the principles of systems theory, incorporating perspectives and methods from control theory and information theory. It is a scientific theory used to understand and address problems in large-scale systems with complex relationships and information feedback.

The Pilotage risk assessment system in port waters is generally complex and extensive. Conventional evaluation models often struggle to clearly and accurately depict the intricate and dynamic relationships within the system, along with potential patterns of change. Therefore, this paper introduces relevant theoretical methods from System Dynamics into the assessment process. Through systematic analysis, structural analysis, the construction of causal loop diagrams, and risk evaluation models, this study aims to address the research problem at hand.

2.1 Construction of the Pilotage Risk Assessment System

Definition and System Construction of Conventional Pilotage Pilotage Risk.

The factors influencing the Pilotage risk of LNG vessels are intricate and complex. This study conducts an analysis of a substantial body of literature in the field of port Pilotage risk assessment. Based on conventional methods for assessing Pilotage risk, and considering the specific characteristics of LNG vessels and the Dapeng Bay Hub waters, the Pilotage risk assessment system is structured into three hierarchical levels. The first level is the Dapeng Bay LNG vessel Pilotage risk assessment system. The second level comprises four main factors: person factors, vessel factors, environmental factors, and management factors. The third level consists of sub-factors derived from the main factors, including competency, health status, fatigue level, and professionalism; hull strength, cargo nature, maneuverability, and equipment condition within vessel factors; hydrological conditions, wind conditions, visibility, channel conditions, Pilotage density, obstructions, and Pilotageal aids within environmental factors; Vessel Traffic Services (VTS) supervision, adequacy of emergency plans, alternation of authority, and level of teamwork cooperation within management factors. The logical tree diagram is illustrated in Figure 1.

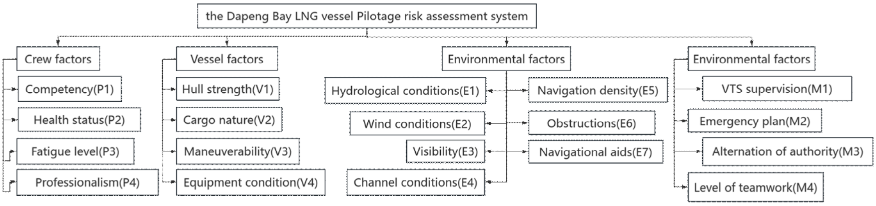

Fig. 1. The Logical Tree of the Dapeng Bay LNG Vessel Pilotage Risk Assessment System

Definition of Secondary Pilotage Pilotage Risk.

Starting from the actual situation of secondary pilotage of LNG vessels in Dapeng Bay, this study, by soliciting opinions from relevant professionals such as captains and pilots, has preliminarily identified nine risk factors directly affected by secondary pilotage: Health status, Fatigue, Maneuverability, Equipment working conditions, Traffic density, VTS supervision, Emergency plan, Power change and Team cooperation. Therefore, this paper reevaluates nine data items in the "secondary pilotage" mode.

2.2 Quantification of System Indicators

Quantification Method for Index Risk Coefficients and Weights.

Combining the risk assessment index system determined in Section 1.1, this study employs Likert scale method to quantitatively score the actual Pilotage environment in Dapeng Bay waters, LNG vessels, and crew indicators, determining the risk coefficients for each index. Utilizing SPSS software, expert survey method and Analytic Hierarchy Process (AHP) are employed to analyze and calculate the weights of each risk assessment index. Since variations in index risk coefficients within the same system do not affect the contribution of the index to the overall system, the risk coefficients of each index may vary under different Navigation modes while the weights remain unchanged.

The Quantitative Results of Indicators.

Based on the evaluation method described earlier, this study determined the risk coefficients of indicators under two different conditions: the conventional Navigation mode and the "secondary pilotage" Navigation mode. Subsequently, a questionnaire survey was conducted to determine the weights of indicators using the expert survey method. A total of 300 questionnaires were distributed to various stakeholders in the shipping industry, including LNG terminal managers, agency staff, government officials, shipowners or operators, pilots, and crew members. A total of 255 valid questionnaires were collected, and the data were analyzed to derive the weights of indicators. The risk coefficients of indicators and their corresponding weights are presented in Table 1.

Table 1. Table of Indicator Risk Coefficients and Indicator Weights

Primary Index	Secondary Index	Three-Level Index	Risk Coefficient of Conventional Pilotage	Risk Coefficient of Secondary Pilotage	Weight (%)
Risk Coefficient of Ship Pilotage Index	Person Factor	Competency(P1)	0.1	0.1	5.76
		Health Status(P2)	0.3	0.4	5.53
		Fatigue Level(P3)	0.3	0.4	6.336
		Professionalism(P4)	0.3	0.3	5.53
	Vessel Factor	Hull Strength(V1)	0.3	0.3	4.954
		Cargo Nature(V2)	0.8	0.8	5.3
		Maneuverability(V3)	0.4	0.5	5.645
		Equipment Condition(V4)	0.2	0.3	4.954
	Environment Factor	Hydrological Conditions(E1)	0.3	0.3	4.954
		Wind Conditions(E2)	Change with Time[a]	Change with Time	5.415
		Visibility(E3)	Change with Time	Change with Time	5.76
		Channel Conditions(E4)	0.3	0.3	4.954
		Navigation Den-	0.3	0.4	5.53

		sity(E5)			
		Obstructions(E6)	0.1	0.1	5.184
		Navigational Aids(E7)	0.1	0.1	5.184
	Manage Factor	VTS Supervision(M1)	0.1	0.3	4.954
		Emergency Plan(M2)	0.1	0.3	4.493
		Alternation of Authority(M3)	0.3	0.7	4.493
		Level of Teamwork(M4)	0.1	0.3	5.069

a: Due to the seasonal variations affecting wind conditions and visibility in port waters, the risk coefficients for these two indicators are represented in tabular form, as shown in Table 2.

Table 2. E2, E3 Pilotageal risk

Mouth	1	2	3	4	5	6	7	8	9	10	11	12
Wind Conditions(E2)	0.2	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Visibility(E3)	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.1	0.1	0.1

3 Study on Coupling of Pilotage Risk Systems

Research on coupling has primarily focused on fields such as computer science, social urban development, and environmental governance [5]. Fine-grained studies on risk coupling have mainly addressed aspects like mining regulation risks, corporate financial risks, and traffic control risks. In previous studies on Pilotage risk, research on the coupling mechanisms in risk evolution has been relatively weak, lacking systematic investigation into the coupling relationships among Pilotage risk factors. Therefore, this paper integrates the improved coupling model into the SD Pilotage risk assessment system, making the evaluation process more rational and the quantitative results of the model more precise.

3.1 Multifactor Coupling Theoretical Analysis of General Aviation Risk Systems

In practical scenarios, the Pilotageal risk assessment system in port waters is considerably extensive and intricate, characterized by non-linear and interactive relationships among risk factors. When a single or multiple risk factors within the system undergo changes due to external influences, it may trigger processes of evolution and alterations in the nature of other risk factors. This results in the coupling of risks during the evolution process, and overlooking these relationships often leads to less accurate assessment outcomes, causing significant discrepancies with the actual situation.

For instance, secondary piloting results in increased operational demands on vessels, intensifying the fatigue levels of the crew, consequently leading to a direct elevation in the Pilotageal risk value. Simultaneously, the heightened fatigue levels of the crew also impact their health conditions, causing an increase in the risk coefficient for this specific indicator. This, in turn, indirectly contributes to the escalation of the Pilotageal risk value, as illustrated in Figure 2.

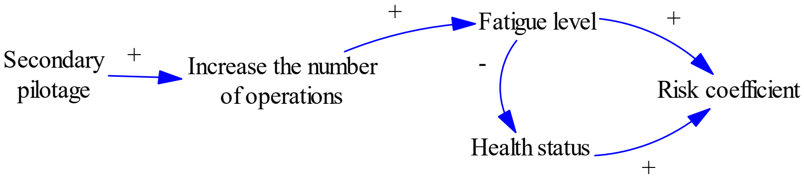

Fig. 2. P2—P3 Coupling Interaction Diagram

Hence, when analyzing the changes in risk within the system, it is insufficient to independently calculate the variations in the risk coefficients of the affected indicators. A comprehensive analysis should be conducted, considering the system and its subsystems, to quantify the impact of these influences on the evaluation system. This involves calculating the required degree of coupling for assessment.

3.2 Multifactor Coupling Measurement of Pilotageal Risk Systems

Model Selection.

Based on a cross-sectional comparison of various coupling measurement models, this paper asserts that the coupling degree model is more suitable for Pilotageal risk assessment.

1) The risk assessment indicator system constructed in the first chapter of this paper, along with the quantifiable data obtained through the expert scoring method, is equally applicable to the coupling degree model. Quantitative analysis can be directly conducted based on this indicator system and data, significantly simplifying the complexity associated with the application of the coupling degree model.

2) In Pilotageal risk assessment, the upper and lower limits of the utility function are relatively easy to determine. When vessels can navigate, the upper limit of the utility function is set to 1. In situations where adverse weather conditions or insufficient Pilotageal capacity due to factors such as channel restrictions prevent Pilotage, the lower limit of the utility function is set to 0.

Coupling Degree Calculation.

Building upon the analysis results presented in section 2.2.2, this paper calculates the coupling degree between each of the nine risk indicators directly influenced by secondary piloting and the remaining eighteen indicators.

4 Simulation-based Pilotageal Risk Assessment Using System Dynamics

4.1 Construction and Simulation of Pilotageal Risk System Dynamics Model

The previous sections have essentially completed the system analysis and some structural analysis in constructing the risk assessment system. Here, based on the professional system dynamics software Vensim PLE 7.3.5, the feedback structure will be determined, and causal loop diagrams along with the risk assessment model will be established for comprehensive evaluation.

Simulation of Pilotageal Risk System Dynamics Model.

This paper, based on the environmental conditions of Dapeng Bay and the two different types of Navigation modes for LNG ships, namely conventional Pilotage and "secondary piloting," constructs System Dynamics models for each mode. Simultaneously, to illustrate the impact of coupling factors on the overall risk value of the system, a detailed refinement is applied to the "secondary piloting" Navigation mode SD model. This refinement involves categorizing it into "secondary piloting" Navigation mode SD non-coupling model and "secondary piloting" Navigation mode SD coupling model. Ultimately, through simulation of these three models, the Pilotageal risk values under different conditions and the influence of the "secondary piloting" Navigation mode on Pilotageal risk values are determined.

Simulation of Conventional Navigation mode.

The SD model for conventional Navigation mode primarily reflects the Pilotageal risk assessment relationship for LNG ships under normal Pilotage conditions. This simulation aims to illustrate the calculation process of Pilotageal risk values under conventional Navigation mode, with model values primarily derived from historical statistical data. Based on the International Maritime Organization (IMO) Maritime Safety Committee" s Formal Safety Assessment for Liquefied Natural Gas (LNG) carriers, it is reported that the annual average Pilotageal risk value for LNG ships is 5.6*10^-2, and the occurrence of accidents during entering and leaving the port is 1/45th of the total accidents. Therefore, the annual average Pilotageal risk value during berthing and unberthing of LNG ships is 1.24*10^-3. The risk values in this paper are all calculated based on this data. Additionally, to depict the contribution of each risk indicator to the overall risk value over time, the Pilotageal risk values are cumulatively calculated monthly. The risk value for December represents the annual average risk value under the simulated conditions. In the structure of the conventional Navigation mode SD model, the risk coefficient is abbreviated as rc, the impact coefficient is abbreviated as ic, the risk value is abbreviated as vr, the time coefficient is abbreviated as tc, the adjustment coefficient is abbreviated as ac, and the weight is abbreviated as w, as shown in Figure 3.

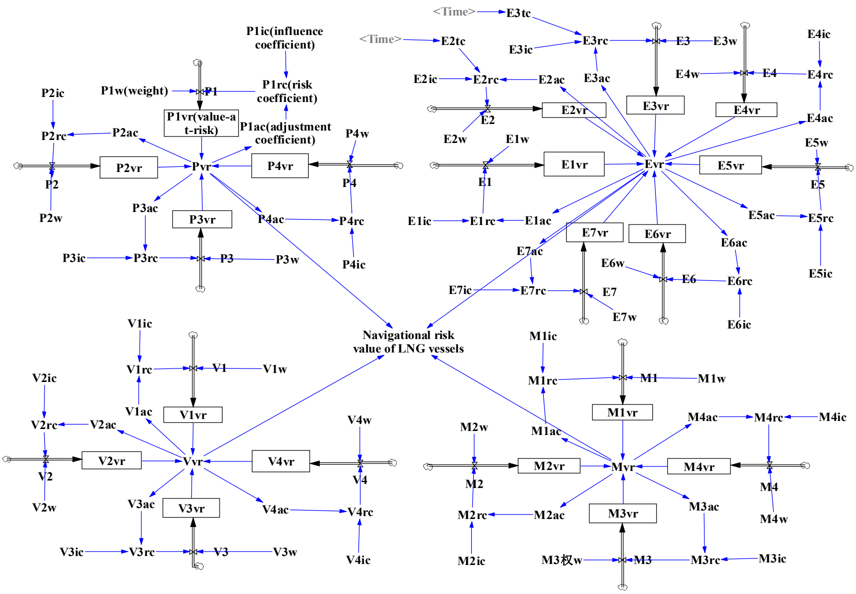

Fig. 3. SD Model for Conventional Navigation mode

Simulation of "Secondary Piloting" Navigation mode.

(1) Non-Coupling Model of "Secondary Piloting" Navigation mode in System Dynamics adds the influence parameters of "second pilotage" on indicators into the relative indicator model to simulate the direct impact on the navigation system. Among them, the second pilotage impact coefficient is abbreviated as sic, as shown in Figure 4.

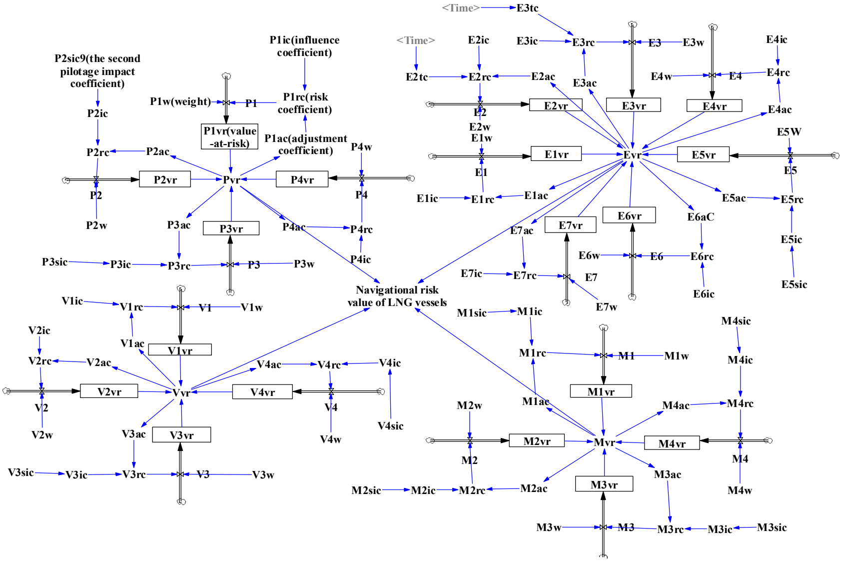

Fig. 4. Non-Coupling Model of "Secondary Piloting" Navigation mode in System Dynamics

(2) Coupling Model of "Secondary Piloting" Navigation mode in System Dynamics

Due to the extensive nature of the "Coupling Model of "Secondary Piloting" Navigation mode in System Dynamics," this paper will present an example using the crew section, as depicted in Figure 5. The other sections, including vessel, environment, and management, are also interconnected with the "Pilotageal Risk Value of LNG Ships," collectively forming the Coupling Model of "Secondary Piloting" Navigation mode in System Dynamics.

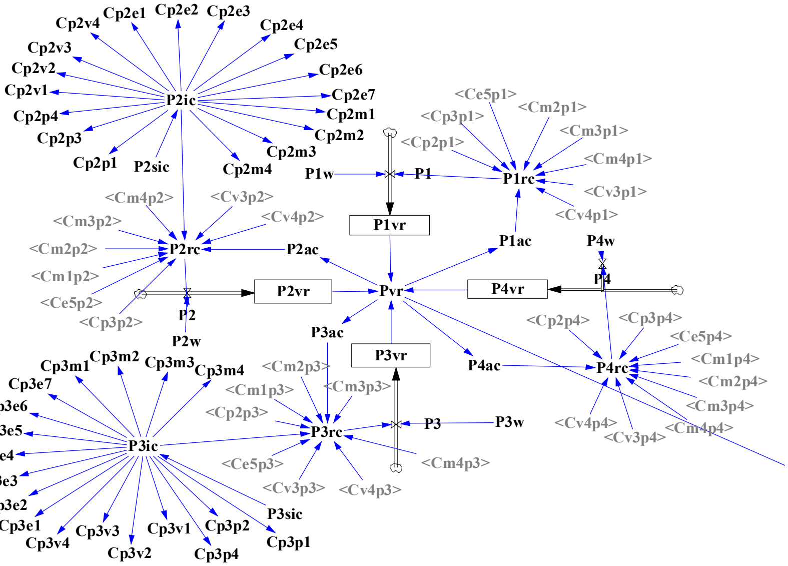

Fig. 5. Coupling Model of "Secondary Piloting" Navigation mode in System Dynamics

4.2 Simulation Results

Statistical Analysis of Results.

Based on the determination of the three models in the preceding sections, let the Pilotageal risk value for the conventional Navigation mode be denoted as α. The simulated Pilotageal risk value for the "Secondary Piloting" Navigation mode without considering the impact of coupling factors is represented as β, while the simulated Pilotageal risk value for the "Secondary Piloting" Navigation mode considering the impact of coupling factors is denoted as ω, as illustrated in Table 3 and Figure 6.

Table 3. Comprehensive Risk Value of Pilotageal Risk System

Risk Value (‰)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
α	0.05	0.10	0.16	0.21	0.26	0.31	0.36	0.41	0.47	0.52	0.57	0.62
β	0.07	0.13	0.20	0.27	0.34	0.40	0.47	0.54	0.61	0.67	0.74	0.81
ω	0.07	0.15	0.22	0.29	0.37	0.44	0.51	0.59	0.66	0.74	0.81	0.88

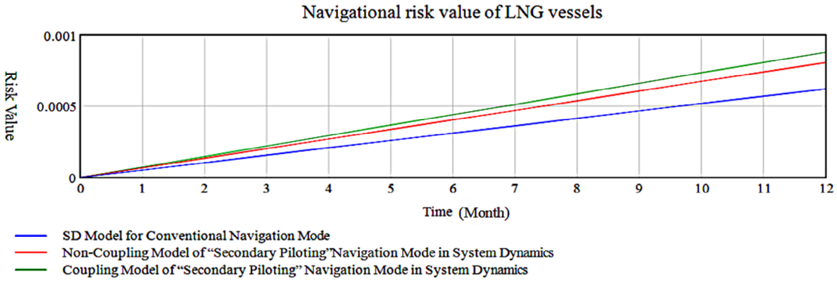

Fig. 6. Navigational risk value of LNG vessels

Analysis of Results.

1)Internationally, most countries and relevant organizations recognize the acceptable range of Pilotageal risk for LNG ships to be between 10^-6 and 10^-3 per year. Through model calculations, this paper determines that the Pilotageal risk of LNG ships entering and leaving Dapeng Bay under the conventional Navigation mode is 0.62*10^-3, significantly lower than the upper limit of the acceptable risk value (1*10^-3). This aligns with the excellent Pilotageal conditions in the Dapeng Bay area. The SD coupling model for the "Secondary Piloting" Navigation mode indicates that the Pilotageal risk value for LNG ships in Dapeng Bay after implementing "Secondary Piloting" is 0.88*10^-3, much higher than the risk value under the conventional Navigation mode and approaching the upper limit of the acceptable risk standard. Therefore, it is concluded that implementing "Secondary Piloting" goes against the principle of maintaining Pilotageal conditions in the area and should be prohibited. Instead, alternative management measures, such as reciprocal pilotage recognition and alternate pilotage, should be adopted.

2) From the simulation results, it can be deduced that, without considering the coupling effect among risk factors, the risk value of the "Secondary Piloting" Navigation mode is 30.6% higher than that of the conventional Navigation mode. When considering the coupling effect, the risk value of the "Secondary Piloting" Navigation mode is 41.9% higher than that of the conventional Navigation mode, representing an 11.3% increase compared to the scenario without considering the coupling effect. Therefore, it is established that the coupling effect has a significant impact on the calculation of the risk value for the "Secondary Piloting" Navigation mode and cannot be overlooked in research computations.

3)By integrating the results of coupling degree research with the controllability of various indicator risk coefficients in practical operations, eight indicators including competency, fatigue level, professionalism, equipment condition, navigational aids, VTS supervision, authority rotation, and teamwork cooperation were identified to have a relatively high impact on the overall system risk value and are easily adjustable. Therefore, when it is not possible to eliminate "secondary pilotage," priority can be given to the reasonable regulation of these eight indicators to ensure that the system risk value remains within an acceptable range.

5 Conclusion and Outlook

5.1 Conclusion

The research conclusions of this paper can be summarized as follows:

1) Based on the actual Pilotageal environment in Dapeng Bay and considering the unique Pilotageal conditions of "Secondary Piloting," a three-tiered, nineteen-indicator Pilotageal risk assessment system for LNG ships in Dapeng Bay was established. This lays the groundwork for the study of LNG ship Pilotage in the Dapeng Bay area.

2) A System Dynamicsmodel for the Pilotageal risk assessment of LNG ships in Dapeng Bay was established, incorporating coupling theory. Simultaneously, to enhance the applicability of the coupling measurement model to the SD model, improvements were made to the coupling calculation method for the three-level indicators in the model. The indicators requiring coupling calculation were reorganized into a subsystem, and coupling was calculated following the computation method of the second-level subsystem, providing a more concise determination of the coupling between indicators.

3)Simulation calculations were conducted using the System Dynamics model, yielding quantitative results on the impact of "Secondary Piloting" on the Pilotageal risk of LNG ships in Dapeng Bay (Pilotageal risk value of 0.88*10^-3). This provides a theoretical basis for the formulation of relevant measures to mitigate risks.

5.2 Outlook

1) The factors influencing Pilotageal risks for vessels are numerous. Despite a certain level of analysis conducted in this paper, the establishment of a three-tiered evaluation system only provides a basic framework. The intricate relationships and synergies among various influencing factors within the system could be further explored in-depth.

2) The currently available data on LNG ship accidents are limited and dated. Obtaining more recent and comprehensive statistical data would enhance the timeliness and reference value of the analysis and calculations.

Acknowledgments

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