A STAMP-based Causal Analysis of the Beiyou25 Grounding Accident

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***Abstract*—The traditional risk analysis method attributes the accidents to the chain reaction of a single event, which highlights the importance of component errors for the accident consequences. With the increasing integration of social science and technology, information interaction becomes more prominent in system safety. Therefore, the Systems-Theoretic Accident Modelling and Processes (STAMP) is introduced to analysis the complex socio-technical system. It focuses on safety constraints, information interaction and process model, and deeply excavates the functions and impacts among components. The STAMP-based causal analysis is conducted in this paper for hazard identification of navigation safety during Beiwei routes in China. First, lessons are learned by analyzing the latest grounding accident of Beiyou25; Second, the problems existing in ships, wharfs, company and meteorology are thoroughly proposed based on the actual situation of the Beiwei routes to ensure the navigation safety.**

Keywords- System safety; STAMP; Safety constraint; Process model

I. INTRODUCTION

The shipping industry has been widely acknowledged as one of the high-risk industries in the world [1, 2]. Ships sailing at sea will be influenced by technical conditions, route conditions, human factors and natural conditions [3]. In such a highly complex environment, it is difficult to ensure the absolute safety of ship navigation. Once unexpected event occurs, it may be developed into accidents such as capsizing, flooding, fire, explosion, grounding and collision [4].

Complex systems often fail in complex ways [5]. For example, the shipwrecks of Eastern Star [6] and the Korean Sewol ferry [7]. are no longer a simple component failure problem, but also should be attributed to the failure of interconnection and coupling between components. Traditional accident analysis methods can discover the main causes of accidents, however, they ignore the possibility of accidents in complex systems and attribute 75-96% of accidents to human error [2, 8, 9]. The classic accident analysis methods of fault tree analysis, event tree analysis, domino accident model, Swiss cheese model [10], as well as the failure mode and effects analysis are based on linear analysis to a certain degree [11]. However, it is difficult to find the indirect relationship between components, and to find the problems in system design or operation.

From a system perspective, the human factors, social organizations, design requirements and levels of organizations can be treated as a control problem. Instead of attributing component failure to the cause of accidents, the kernel of this method attributes the failure to safety constraints. The idea of STAMP model is that accident prevention requires identifying and eliminating (or mitigating) unsafe interactions between components, namely, strengthening control and strengthening safety constraints in system development, design and operation. Based on the STAMP, the system theory process analysis method (STPA) was proposed by Nancy in 2011 [12].

The model has the following advantages in the field of maritime safety: (1) Easy to find the representative factors influence system safety from two aspects of system development and system operation. (2) Easy to understand the whole process of the accident, and further propose complete suggestions to improve the system safety. (3) Provide a more structured model for maritime field [7]. The model compensates for the defect of over-linearity in traditional accident analysis methods, and improves the analytical ability to deal with complex social-technical systems.

By introducing the STAMP model, this paper makes a causal analysis of the Beiyou25 grounding accident from the perspective of control theory. By establishing the STAMP based ship accident model, the unsafe control actions and potential hazards are identified, and the accidents causes are analyzed and reasonable safety measures are proposed.

II. STAMP-BASED RISK ASSESSMENT MODEL

In system theory, complex systems are the synthesis of various components. Meantime, the system maintains a

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dynamic balance by mutual feedback and control actions among components at different levels [13]. As shown in Figure.1, STAMP inherits the idea of system control theory and treat complex systems as hierarchical structures with multiple layers, including control layer, intermediate layer and controlled layer. Specifically, the controller receives feedback information to correct the defects, and the controlled process the superior's instructions and carries out the corresponding operation. Only when the control actions are effective, the constraints are satisfied, and the feedback information is timely, accurate and effective, can guarantee the system safety. According to the above system safety requirements, the corresponding system control defects can be divided into the following three categories: (1) Controllers take inadequate or inappropriate control actions; (2) Inadequate implementation of control actions; (3) Incorrect or missing feedback.

In the hierarchical structure of the shipping system, each organization should operate in good condition, and the hierarchical organizations should communicate with each other, timely feedback, timely amendment, and jointly assume the responsibility of navigation safety and cargo safety of the shipping industry.

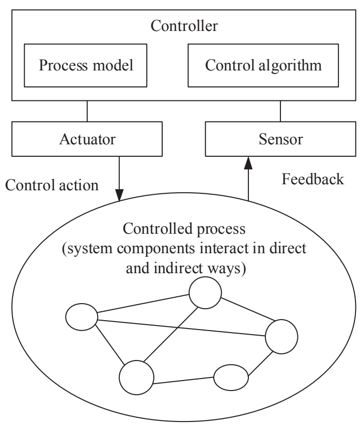

Figure 1. Basic control loop of STAMP

III. STPA RISK ANALYSIS METHOD

STPA is a system safety analysis method based on STAMP model. The method has the ability of deep exploration and comprehensive analysis, which has been widely used in aviation [14], pipeline transportation [15], railway [16], energy exploitation [5], LNG transfer safety [17] and other fields. This method identifies the unsafe control actions in top to bottom, and then finds out the safety constraints in the system. Specifically, the integrity, rationality, validity and timeliness are the premise to ensure the safe operation in system. To facilitate the understanding of the STPA method, the method is divided into the following four steps.

1) Define system hazards and associated safety constraints

The definition of system hazard is usually compared with the definition of system accident in order to clearly distinguish the difference and connection between them. In general, danger is the premise of an accident and the accident is the result of a danger. However, the existence of danger does not lead to accidents certainly. In many cases, system hazards are assessed subjectively by experts. After defining system hazards, associated safety constraints can be formulated to prevent hazards. In this paper, the relationship between hazard and accident of ship navigation is taken as an example, as shown in Table I. Figure2 gives the categories of different hazards.

TABLE I. EXAMPLES OF NAVIGATION HAZARDS AND ACCIDENTS

No.	Accident	No.	Hazard	Safety constraint
A-1	Casualty	H-1	Insufficient meteorological information	Conduct meteorological observation and report information
A-2	Ship loss	H-2	Ship operational errors	COLREGS
A-3	Environmental pollution	H-3	Seafarers' incompetence	STCW convention
		H-4	Underestimation of navigation situation	Rule of Duty of Seamen
		H-5	Lack emergency response mechanism	ISM CODE
		H-6	Fatigue handling	Rule of Duty of Seamen
		H-7	Unused Safe Speed	COLREGS

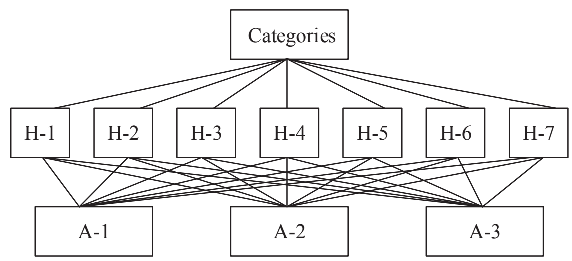

Figure 2. Hazards of grounding accidents

2) Establish safety control structure

After defining hazard and safety constraints, a typical hierarchical structure of social technology including safety control processes is established, namely, hierarchical safety control structure, divided into two basic parts: system development and system operation. Each part has several layers, feedback control loops and communication channels. Each structure represents a component of social technology system; downward connections represent control actions imposed to strengthen security constraints on the system; and upward connections represent information feedback to the controller in order to meet constraints more effectively.

3) Identify potential inappropriate control actions

After defining the system safety control structure, it is necessary to identify potential inappropriate control actions which make the system in a hazard state. Hazard state refers to the state of the system in which the defined safety constraints are violated. Four identification methods of inappropriate control are listed according to the potential dangers of unsafe control actions [8]: (1) Control action is not provided; (2) Unsafe control action is executed; (3) Control action is too early or too late executed; (4) Control action is applied for a too short or too long time period.

Improper or inappropriate control actions may cause system malfunction or interaction disorders between components. In order to ensure the integrity of the assessment, it is necessary to conduct a thorough analysis on each control action in an order manner.

4) Identify the causes of inappropriate control action

After determining the inappropriate control actions, the potential causes of accidents can be identified, which can be used to propose corresponding measures to prevent the identified hazards. STAMP works according to the risk control framework and is guided by a series of defects in the control loop. Because the accident is caused by inappropriate control actions and violation of safety constraints, the cause of the accident can be understood as control defects.

IV. STAMP-BASED ANALYSIS ON THE BEIYOU25 GROUNDING ACCIDENT

On March 23, 2019, at 1458, the passenger ship " Beiyou25" belonging to Beihai Xinyi Cruise Ship Co., Ltd,770 passengers on board, arrived at Weizhou Island from the International Passenger Terminal of Beihai Port. It was expected to berth at West Point Wharf of Weizhou Island at 14:40. However, the coastal gust of Grade 7 (According to the actual situation, gust of Grade 8) caused the ship to deviate from the channels, and ended in grounding.

A. Accident process

According to VTS, navigation aid integrated application system and video surveillance and the crew' statements, the accident process is as follows:

At 1300, " Beiyou25" carries 770 passengers from Beihai Overseas Chinese Harbor International Passenger Terminal to Weizhou Island, with 2.8m fore draft and 3.4m stern draft.

At 1435, arriving at Weizhou Oil Bridge, the speed is 15.8 knots and the course is 183 degrees. There are three people on duty at the bridge, which are the captain, the third officer and a steersman.

At 1442, arriving at Weizhou Passenger Terminal, the speed was 7.1 knots, the course was 144 degrees, the telegraph operator was the captain, the rudder was the steersman on duty, and the lookout observer is third officer.

At 1443, throwing right anchor, the anchor position is about 80m from the wharf and 250m from the Weizhou terminal vertically. Vessel speed was 5.6 knots, course was about 143 degrees, half astern starboard, midships, full starboard rudder.

At 1444, vessel speed 2 knots, course 235 degrees, wind on starboard side, stern toward wharf, 5 shackles water.

At 1446, vessel speed 0.6 knots, course 299 degrees, slow ahead starboard, slow astern port. The vessel was adjusted to the westernmost end of the wharf with the stern facing the wharf.

At 1449, the captain found it difficult to handle the ship during berthing. The starboard side of the ship swung over the south section of Ro-Ro and the berthing had failed.

At 1452, the retreat speed 1.7 knots, wind on starboard side and the ship was forced to float toward the 4 # light-buoy. The ship began dragging anchor, and the captain ordered to heave up the anchor and readjusted the berthing.

At 1453, stop starboard, slow ahead port, continued heaving up anchor.

At 1456, when the ship heaved up the anchor at 3 knots, the chief officer heard the donkey man said there was a sound of sand rubbing on the bottom of the ship.

At 1458, the ship was grounded. The captain notified the chief officer to lower the left anchor and fixed the ship to prevent the ship from drifting towards the shoal. At this time, the ship had list to starboard side about 3 degrees.

Figure 3. Track of Beiyou25 grounding accident process

B. Identification framework of hazard factors

The hazard identification framework is established by STAMP method as shown in Figure4. First, the Ministry of Transport formulates relevant laws and guidelines to ensure the safety of ship navigation, including passenger ship navigation standards, passenger ship safety and competency standards, high-speed passenger ship safety management rules and other provisions. Among these provisions, it is necessary to formulate them in accordance with the relevant requirements of International Maritime Organization (IMO). Specifically, the regional maritime bureaus are responsible for organizing and implementing.

There are two aspects in this framework: one is the system development and the other is system operation [13]. In the aspect of system development, it is necessary to carry out risk prevention and control from ship companies, risk project management, ship design and manufacture, shipyards and classification societies to ensure the safety of ships in the design stage and realize the safety of the whole life cycle.

The system operation of the shipping industries involves the supervision of the Maritime Bureau, the actual management of the ship company, the actual operation of the crew, the interaction of the external environment and the management of the wharf company.

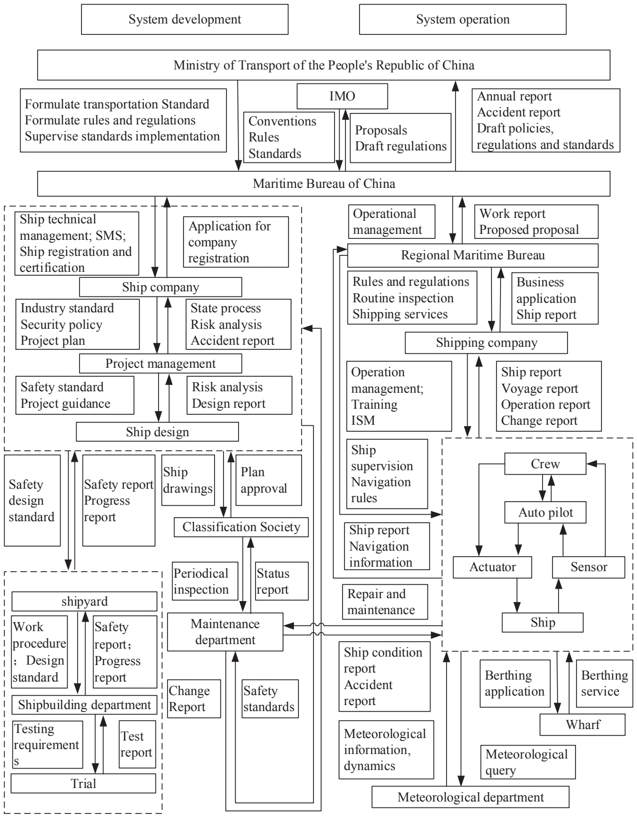

Figure 4. The risk identification framework of shipping industry

In practice, these components interact with each other. Only when each subsystem can take appropriate actions at the right time and place, can the safety of the ship navigation system be guaranteed.

C. *Hazards of meteorological warning*

The occurrence of “Beiyou25” grounding accident is closely related to bad weather. Specifically, it is mainly against safety constraints: (1) Weather monitoring means are inadequate, and it is difficult to collect local meteorological information; (2) It is difficult to meet the requirement completely that transmits the information of Meteorological Bureau. Inappropriate decision-making: imprecise meteorological information leaded to inappropriate decision-making. Inadequate control actions: failure to anticipate local bad weather.

For further analysis, meteorological departments mainly provide public meteorological services. Maritime meteorological information services are not included in the scope of public meteorological services. There is no systematic construction of meteorological basic data acquisition stations, and insufficient meteorological basic data support for maritime transportation and other fields, leading to the inability to timely, scientific and accurate forecast of severe weather in coastal waters. The public meteorological services provided by meteorological departments around the country for the whole society cannot fully meet the needs of maritime safety in terms of space scale and time accuracy. The meteorological departments of the state, provinces, cities and counties provide different levels of public meteorological forecast services. Maritime Bureau and other water traffic management departments collect information and carry out water traffic safety management according to corresponding levels of meteorological forecast information. There is no explicit regulation or guidance to improve this phenomenon, which brings some difficulties to the early warning and supervision of ship safety.

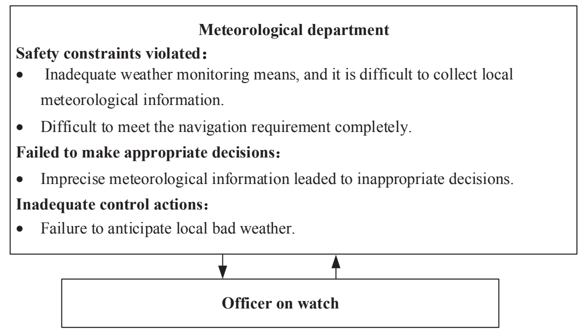

Figure 5. Identification of hazards in meteorological warning

D. *Hazards of crew maneuvering*

As shown in Figure6, the hazards of crew maneuvering mainly include four aspects, which are, violations of safety constraints, failure to make up appropriate decision, inadequate control actions and mental deficiencies.

Specifically, violations of security constraints include: (1) Failure to strictly implemented the safety standards for ship navigation. Because meteorological warning can only forecast the whole weather condition, but difficult to the local weather condition in real time. As the first person in charge of the scene, the crew should be able to feel the situation of the wind on the scene, monitor the wind situation in real time and make proper decisions; (2) When dropping anchor, the speed of the ship was too fast, the anchorage position didn't select properly resulting in dragging anchor; (3) Underestimated the possibility of ship grounding under the influence of strong wind; (4) Due to the large wind area, the ship berthing and cycling operation should be cautious; (5) The crew's maloperation during berthing.

The crew failed to make reasonable decisions in the external environment, including: (1) Lack of experience and training; (2) Lack of awareness of safety in production management; (3) High wind speed, low tide level; (4) Unfavorable daily supervision of ships.

Inadequate control actions: (1) Inadequate estimation of ship and environmental conditions; (2) Failure to stop berthing and mooring operations in time; (3) Inadequate inspection of ship grounding; (4) Improper using rudder and anchor.

Mental deficiencies include: (1) Lack of experience, inadequate estimation of the situation; (2) Driving fatigue lax; (3) Fixed operation, slow response to emergencies.

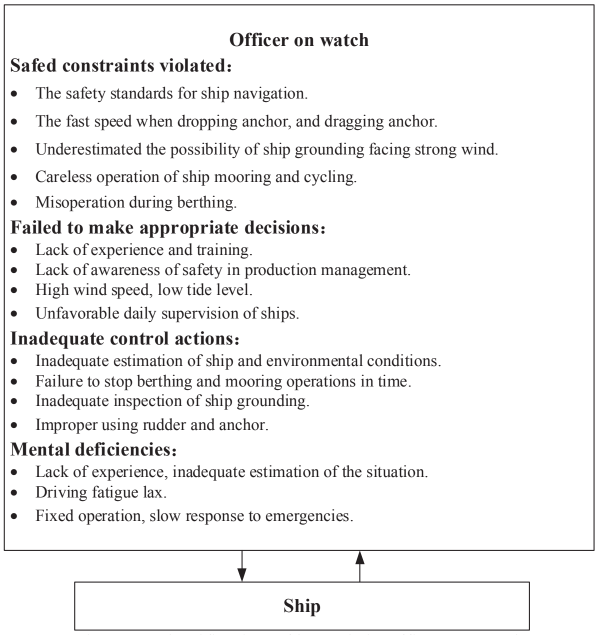

Figure 6. Identification of hazards in officer on watch

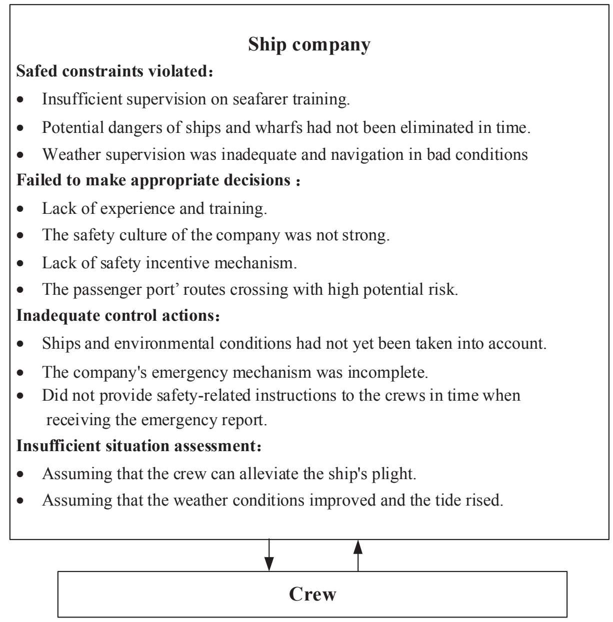

Figure 7. Identification of hazards in officer on watch

E. Hazards of ship company

As shown in Figure 7, the hazards of ship company mainly include four aspects, which are, violations of safety constraints, failure to make up appropriate decision, inadequate control actions and mental deficiencies.

Violations of security constraints include: (1) Insufficient supervision on seafarer training; (2) Potential dangers of ships and wharfs had not been eliminated in time; (3) Weather supervision was inadequate and navigation in bad conditions.

Failure to make appropriate decisions: (1) Lack of experience and training; (2) The safety culture of the company was not strong; (3) Lack of safety incentive mechanism; (4) The passenger port' routes crossing with high potential risk.

Inadequate control actions: (1) Ships and environmental conditions had not yet been considered; (2) The company's emergency mechanism was incomplete; (3) when receiving the report, the shipping company did not provide safety-related instructions to the crew in time.

Insufficient situation assessment: (1) Assuming that the crew can alleviate the ship's plight; (2) Assuming that the weather conditions improved and the tide rising.

F. Hazards of wharf and navigation environment

Based on the above identification of various hazards, the wharf management factors can be obtained by analogy, which can be divided into the following four aspects, as shown in Figure 8.

V. HAZARD CONTROL MEASURES FOR SHIP NAVIGATION

A. Enhance the public meteorological service capability of passenger transport

- In conjunction with the Meteorological Bureau, a public and professional meteorological service system should be established to meet the needs of maritime traffic safety.
- Actively create conditions for the establishment of coastal meteorological monitoring stations, coordinate and contact ships with coastal monitoring conditions to upload basic meteorological information to meteorological departments.
- To formulate and improve the ban management measures for ship navigation under severe weather conditions, and to clarify the meteorological information sources on which the maritime safety management work is based.

B. Strengthen the responsibility consciousness of enterprise safety

- Carefully implement the safety management system of shipping enterprises and the standardization system of safety production.
- Effectively strengthen safety and professional training, and constantly improve the quality of employees.
- Do a good job in equipment maintenance and hidden danger investigation.
- Strengthen the dynamic management of ship and actively explore the mode of passenger ships' dynamic management by transport enterprises.

C. Improving the competency standard of passenger crew

Passenger crew need higher abilities and qualities than ordinary cargo crew, but there is no higher standard requirement in terms of competency standards. Low standard passenger crew are difficult to meet the requirements of passenger transport safety development.

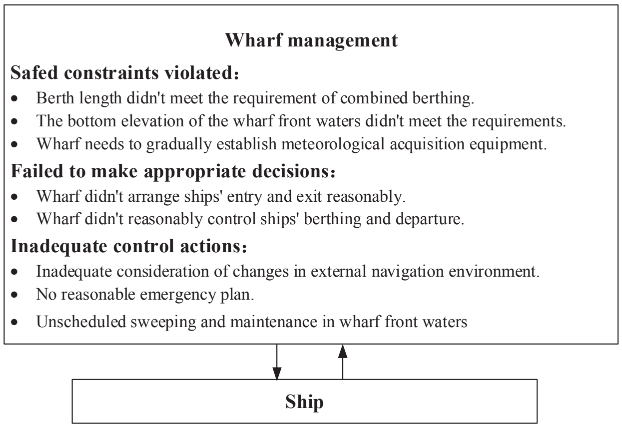

Figure 8. Identification of hazards of wharf management

- The examination and certification of seafarers are not specific to the seafarers, so the examination content, certification standards and the requirements of seafarers' competence should be improved.
- Enhance the entry threshold of passenger crew, and increase the qualification requirements of passenger crew, especially captains and engineers.
- Passenger shipping companies should strictly control the access conditions of passenger crew, select members with strong business ability, good attitude and high quality to serve on passenger ships, and supplement them with more attractive treatment.

VI. CONCLUSIONS

The STAMP model is employed to analyze the grounding accident of “Beiyou25” cruise, and the hierarchical safety control structure model is established with the STPA method. It can be concluded that: passenger ship safety system involves many industries and departments, not only the responsibilities of shipping companies, crew, safety supervision units and departments, but also the government, design departments, shipyards, shipping departments, classification societies, meteorological departments, wharfs and other departments.

Compared with the traditional methods, the STAMP can provide a more systematic and comprehensive perspective of accident analysis, and discover more problems and defects among different levels, instead of being limited to a certain angle of the accident. STAMP can use specific events for accident casual analysis, and improve the system ability to find and correct problems. Furthermore, by combining the quantitative analysis methods, STAMP can realize the quantitative study of safety control actions, and achieve the ability of qualitative and quantitative accident prevention and analysis.

In the maritime industry system, because the accidents consequences often end in tragedies, each department should perform its own duties and exchange information with each level and implement safety constraints in order to reduce the incidence of accidents.

VII. ACKNOWLEDGMENTS

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