Towards resilience in water transport systems: A lesson learned from *Eastern Star*

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ABSTRACT

The cruiser Eastern Star accident is a catastrophic accident in water transportation industry. The accident has originated from both natural and human-induced causes. This type of complex causation constitutes a pervasive threat to a broader range of human activities rather than the single case of Eastern Star. The present paper offers an in-depth reflection on the Eastern Star accident through analysis by conventional methods. A first objective is to identify issues in the water transport system. A comparative study is performed to find how the different methods can help to improve safety in unexpected or unknown disruptions for the water transport system, steering towards the concept of resilience as more pertinent from the perspective of safety engineering. Difficulties and challenges in the current paradigms of risk and resilience are delineated at both the operational and theoretical levels, with respect to the specificities of water transport. To articulate the relationship between resilience and risk assessment, this paper proposes a resilience-modulated risk model for integration in the practical sense.

Keywords: Resilience, System Safety, Accident Analysis, Resilience-modulated Risk Model, Eastern Star Accident

1. INTRODUCTION

Water transport rests on a traditional industry that dates back to the most ancient human activities. Despite the fast socio-technical evolution of the world, waterways remain the essential means of material and goods transportation, accounting for over 90% of the world's trade (*1*). During its long course of development, waterway transportation has been always considered potentially hazardous and dangerous, as witnessed by the numerous maritime accidents. In view of this, much attention has been devoted to the risk/safety analysis of waterway transportation systems (*2*). Accident analysis, as the other side of the coin, has equally received attention from the scientific and technical community.

In the literature, research on pre-accident and post-accident analysis has appeared extensively (*3,4*). For the majority of the pre-accident studies, the risk-based perspectives and methods dominate (*5*); for the post-accident studies, statistics and field data are exploited to recognize the patterns of accident causation and development, for finding indications for accident prevention (*6*).

On the other hand, the development of technology can change the study of risk and accident analysis. With abundance of sensing equipment on board of modern systems, accurate and numerous data can be collected to support the formulation of risk models; big data and enhanced computing capacity offer opportunities to uncover accident-related knowledge (*7*).

For example, on the basis of contemporary surveillance technology for maritime safety, e.g., AIS (Automatic Identification System), VTS (Vessel Traffic Service), ARPA (Automatic Radar Plotting Aid) (*8*), different types of early warning systems are designed and implemented for maritime safety administration. Employment of these early warning systems is a most tangible way to convey risk information to users (*9*).

Despite the progress in the risk/accident analysis capabilities, there seems to be no concrete translation of this into improvements in accident prevention. Severe accidents in water transport (e.g., Costa 2012, Sewol 2014) have still occurred. These catastrophes call for further advancements and their implementation in practice. This will be highlighted in this paper.

The rest of the paper is structured as follows: section 2 introduces the main features, specifics of water transport systems; section 3 provides the details of the Eastern Star accident; section 4 introduces a resilience-based study of the accident; section 5 proposes a resilience-modulated risk model to overcome some difficulties of the traditional methods; section 6 concludes the work and summarizes the contributions of the paper.

2. THE WATER TRANSPORT SYSTEM AND ITS CHARACTERISTICS

The safety of a system is strongly related to the characteristics of the system, including components, structures, functions and their associated dynamics. As for water transport system (WTS):

(1) It generally consists of four major components, namely the navigational environment(I), the ships(II), the administration(III), and the humans (IV). Except for the environmental component, the other components of the system are *human-intensive* where the interactions between the human and the software/hardware elements of the system are closely interweaved. The *human-intensiveness* of water transport also means that the decisions and actions from some key individuals can strongly influence the overall situation of the system and its evolution.

(2) The ship in the water transport is a highly *autonomous* system, whose behavior is largely determined by the humans (i.e., the crews) who have direct control over it. Each ship can be regarded as an entity, which can make decisions and responds to external changes with actions that are considered most beneficial.

(3) The ship-shore, ship-ship interactions make it a *loosely coupled* system, in which the controls or instructions among the parties undergo substantial uncertainty in terms of time lag and execution outcomes. Instructions for the ship operation are subject to the crew's judgments before being executed.

(4) The ships within a water area can form a *self-organized* network of autonomous elements. The communication over the network involves reciprocal real-time coordination and emergent behaviors. For a ship in trouble, nearby ships are a potential source for mitigating the incident and minimizing the losses.

These characteristics lead to some salient differences between the water transport system and other critical infrastructures (CIs), such as power grids, oil and gas pipelines etc(*10*):

(1) The components of WTS are moving across a large spatial domain.

(2) The human-system relation in WTS is a dominant property, and the actions of the humans have strong impacts on the overall behavior of the system.

(3) WTS involves multi users with multiple roles, and coordination is complicate and uncertain. This can give rise to quite opposite situations, e.g., cooperation or conflict in terms of user behavior.

(4) The performance of the WTS is extremely sensitive to variable environmental factors, i.e., meteorology and hydrology.

The safety of the CIs has been studied extensively in the literature(*10*).While methods and results from these studies can be potentially transferred to address the safety problems in WTS, the aforementioned specific characteristics of WTS require a domain-specific approach to safety enhancement therein.

3. THE EASTERN STAR ACCIDENT

3.1. Recent Accidents in WTS

Studies of accidents in WTS provide a way to understand the causes, errors and related measures for accident precaution. This also helps the development of the methodology for pre- and post- accident analysis.

Research on the Costa Concordia accident occurred in 2012 has compared it to the TITANIC accident in 1912 (*11*), although the loss caused by Costa is much less. Two years after, the capsizing of Sewol in 2014 again sparked the interest for augmented safety knowledge (*12*). In 2015, the accident of the inland passenger ship, *Eastern Star,* has once more poses questions and challenges to the theory and practice of safety in water transport.

3.2. Sketch of The Eastern Star Accident

3.2.1. A Brief Review of The Accident

The Eastern Star is a cruise ship, which operates itineraries along the Yangtze River, featuring the Three Gorges sightseeing. The length of the ship is 76.5 meters, the beam 11 meters, and the capacity 534 passengers.

On 28th May, the Eastern Star departed from Nanjing at 1300 hours (GMT+8,the same below),with destination Chongqing in the upper reaches of the Yangtze River. At 1930 hours on 1st June, the ship entered the Jian Li waters with heading nearly to the north. At this time of the trip, the regional waterway was being struck by a severe rainstorm. The Eastern Star rushed into the central area of the strong convection at 2119 hours, when it was hit by fierce northwest linear gale to the port. The ship swerved to the port during 2120 to 2121 hours, with heading jerked from 23° to 342°, aiming to counteract the gale. Approximately at 2132 hours, the ship capsized to the starboard within 1 minute and was drifting downstream afterwards. The last AIS signal was broadcasted at 2131 hours, at 29°42'N, 112°55'E.

The *Changhang Jiangning*, a RORO ship whose route was similar to that of Eastern

Star, had some short communication with Eastern Star via VHF when both of the ships set about taking actions to cope with the harsh storm. Changhang Jiangning managed to anchor steadily against the wind at 2123 hours. At that time, Eastern Star overtook it and ran into its doom. The trajectories of Easter Star and Changhang Jiangning are sketched in Fig.1.

The accident resulted in 442 life losses, making it the most fatal maritime accident in China since 1949. Only 12 persons on board survived, including the master and chief engineer officer.

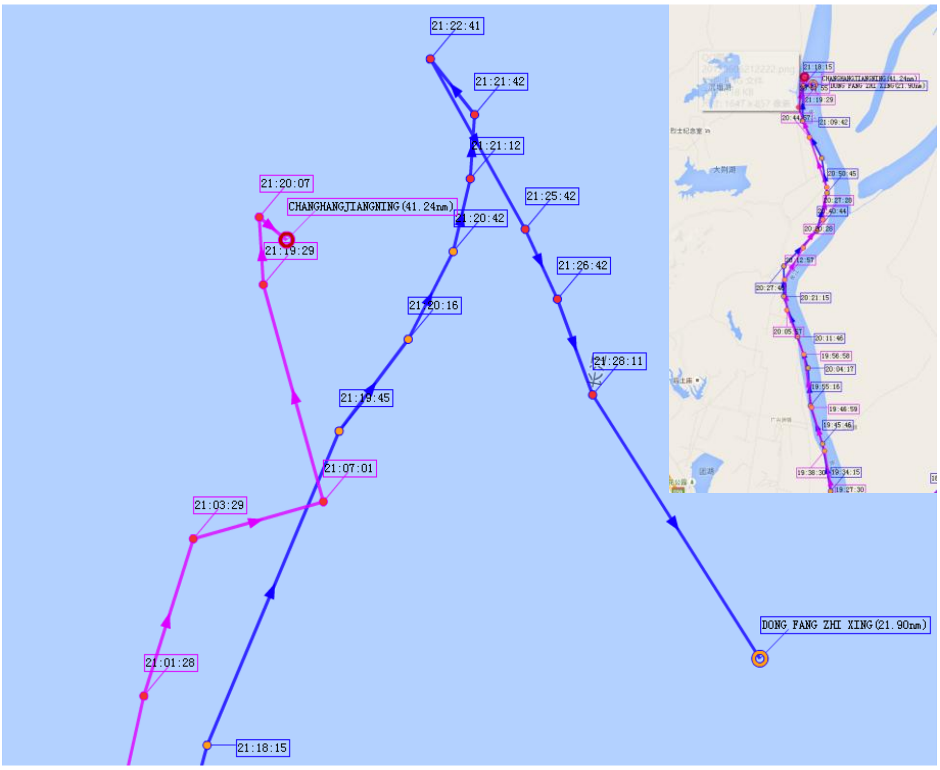

FIGURE 1 Trajectories of *Easter Star* and *Changhang Jiangning*

3.2.2. The Facts in The Accident Context

The following Table 1 summarizes the referential facts that are considered credible during the accident. The event list has been drawn from the auxiliary resources that are traceable for the follow-up accident analysis.

TABLE 1 THE FACTS PRESENTED IN THE ACCIDENT CONTEXT

#	Time	Event	Remarks/Auxiliary Information
1	13:00,28th May	Departs from Nanjing, sailing upstream towards Chongqing.	Most passengers are senior citizens; the ship berths at each scheduled scenic site for a period in the daytime and sails without stay at night.
2	11:44,1st June	Departs from Chibi heading for Jingzhou, the next scenic site.	A companion ship, *Sightseeing 6*, departs from Chibi at around 9:00-10:00, a few hours ahead of the Eastern Start, and the ship barely escapes the catastrophe by timely taking the preventive action of anchoring in Jianli.
3	17:26,1st June	Jingzhou MSA(Maritime Safety Administration, the government body) releases on its website the early warning about the regional storm in its administrative zone.	The Eastern Star sinks before she can reach the region of Jingzhou MSA.
4	21:11,1st June	Jianli MSA starts a rolling broadcast of the storm warning.	The Eastern Star is already in trouble at the time, even if the ship had the chance of receiving the VHF signal in the harsh environment.

5	21:23,1st June	Changhang Jiangning tries to anchor against the wind.	The Eastern Star overtakes the Changhang Jiangning as the latter slows down to anchor. Shortly afterwards, the Eastern Star speaks to Changhang Jiangning via VHF that she is going to anchor *behind* Changhang Jiangning, meaning that she may tend to withdraw from the storm ahead.
6	21:24,1st June	The ship begins to move backwards under the pressure of the northwest gale.	Although the heading is pointed to the northwest to move against the gale to find a chance to anchor, the ship is actually blown backwards to the southeast.
7	Around 21:32, 1st June	The Eastern Star capsizes to the starboard within 1 minute.	The Eastern Star is drifting downstream after her capsizing, with a small part of the hull bottom hovering above water.
8	22:13, 1st June	The ship *Tonggonghua 666* notices the cry for help of two drowning passengers in the Yangtze river, and reports to the Yueyang MSA.	MSA's patrol boat *12215* sets out to rescue the drowning passengers.
9	23:17, 1st June	An early warning message appears on the website of Yueyang MSA about the storm, warning that the state of alert begins at 22:00.	This early warning message comes nearly 2 hours after the accident, albeit useful for other ships.
10	23:50,1st June	Jingzhou MSA rescinds the early warning it dispatches at 17:26	At this time, the convective weather in this region attenuates.
11	23:50-24:00, 1st June	3 passengers and 4 crew members are rescued by patrol boat 12215.	At this time, the MSA finally learns and confirms the sinking of Eastern Star.
12	Morning, 2nd June	Large scale emergency forces across the country are mobilized to undertake the rescue.	The national leader arrives at the spot; all the needed resources are being scheduled; massive military troops assemble in Jianli to lead the rescue operations.
13	07:30,2nd June	The Three Gorges Reservoir reduces its discharge rate from 17200m^3/s to 7000m^3/s per the request of search & rescue command center.	The water level near the sunken ship descends by 3 meters in the next few days, which is instrumental to the rescue operation.
14	Afternoon, 2nd June	Two survivors are rescued by a military diver from the cabins of the capsized ship immersed in water.	The passenger and the crew members are the last to be saved among the 12 survivors, and perhaps the most suffering from despair and horror.
15	07:00,5th June	The sunken ship is overturned to the normal attitude.	The top deck emerges out of water.
16	18:35,5th June	The whole hull is uplifted out of water.	The main part of rescue is complete at the time.

Besides these events occurring directly during the context of the accident, some related background information is also revealed as follows:

Background fact 1: The ship was built in 1994 and the original capacity of passengers was 584, with a length of 66 meters and a beam of 11meters. The ship underwent a major rebuilding in 1997, when the length was extended by 11 meters and the bow was changed from flat to sharp. In 2008, after another rebuilding, the final capacity was adjusted to 534.

Background fact 2: The rebuilding also changed the layout of the passenger cabins, as is plotted in Fig.2. And even if the sliding window is opened to its maximum, the open area is only 1/3-1/2 of the total window area and is further substantially blocked by the headboard of the upper bed.

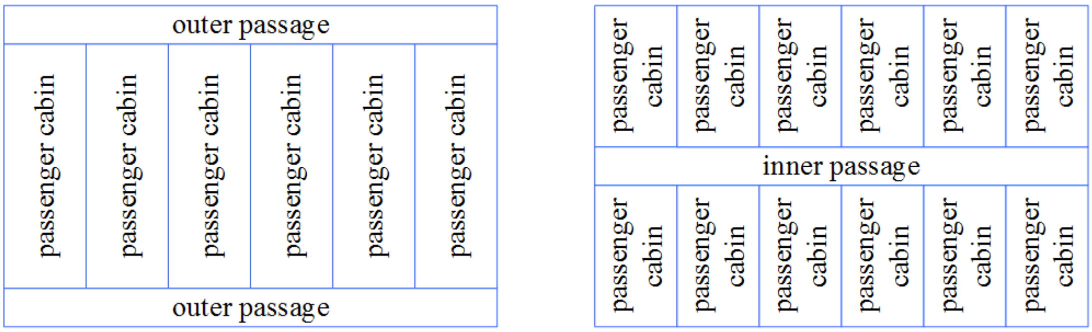

FIGURE 2 Cabin layout before and after the rebuilding in 1997

Background fact 3: The master has rich experience in navigation in Yangtze River. He has been captaining Easter Star since 2007, and the performances of himself and his team are exceptional in the cruise company.

Background fact 4: The waterway where the accident took place is in good conditions, and prior accident statistics do not indicate that this section of waterway is dangerous.

Background fact 5: The Eastern Star is not equipped with VDR (Voyage Data Recorder) and GMDSS(Global Maritime Distress and Safety System), which means that the data inside the ship is untraceable and the ship cannot automatically send out alarm messages in case of distress.

4. THE RESILIENCE STUDY OF THE EASTERN STAR

4.1. System Safety from The Perspective of Resilience

Research on resilience has growing interest recently. The early usage of the concept dates back to ecology studies on large population of species and long cycles of evolution (*13*). Researchers in other disciplines find its conceptual significance in system safety. Hollnagel et al. (*14*) conceptualize resilience as a phase transition of adaptation to the adverse situation that comprises anticipating, monitoring, responding, and learning.

The most significant shift that resilience analysis offers from traditional risk analysis lies in the holistic thread of the former for adverse event responding. In fact, the reaction and recovery stages are little considered in conventional risk studies while the resilient places emphasis on these.

4.2. Resilience in Water Transport Systems

There are diverse and domain-specific definitions for resilience (*15*). These definitions differ in literal expression, but somehow overlap in meaning. Considering two typical mindsets of resilience understanding, the first one includes anticipating, monitoring, responding, and learning (AMRL) (*14*), the other includes the capability of absorption, adaptation and restoration(AAR) (*15*).The suitability of these properties for the water transport context is summarized in Table 2.

TABLE 2 TWO TYPICAL DEFINITIONS FOR RESILIENCE AND THEIR INTERPRETATION IN WATER TRANSPORT

Key Properties	General Meaning	Possible interpretation in WTS
anticipating	Imagining what to expect	Humans (crew, shore-side administrative personnel, and passengers) in the system are aware of the potential adverse event.
monitoring	Knowing what to look for	Safety indicators derived from surveillance signals or various sensor data (hydrological, meteorological) are under close observation
responding	Knowing what to do, being capable of doing it	Humans in the system are able to take right actions to deal with a factual adverse event

learning	Knowing what has happened	Humans in the system know the current situation and draw lessons from the past events
absorption	Damping the negative impact of the adverse event	Humans in the system take remedial measures to mitigate the adverse event
adaptation	Making intentional adjustment to come through a disruption	Key components in the system (i.e., humans, ships, equipment and administration) are revised to better withstand the adverse event
restoration	Returning to the normal state	The ships in trouble survive, or the search and rescue (SAR) operation is complete

We can see from Table 2, that both ARML and AAR show some points of little relevance when directly applied to water transport, as can be summed up as follows:

ARML does not fully characterize the recovery process. It is worth noting that, in water transport, there can be loss or damage caused by the disruption, even if the system is undergoing recovery.

The *absorption* in AAR is more related to the physical properties of an individual ship instead of the organizational or administrative mechanism at the transportation administration level.

The *adaptation* in AAR usually means making adjustments towards some types of adverse events with clear and stable patterns. Hence *adaptation* makes less sense when a ship has to confront unforeseen disruptions, unless there are some types of prolonged threats that occur regularly.

To obtain a more specific description of resilience for water transportation, the following presumptions are supposed to be observed:

Ships are at the core position of water transport safety. Whatever types of accidents in water transport may occur, they must be firstly related to ships, though the damage or losses are not limited to the ships themselves.

With regard to the *human-intensive* nature of water transport system, onboard operation and shore-side administration are the determinants of safety.

The quality, or the effectiveness of operation and administration depend on several factors, including the individual's knowledge, capability maturity, and the management mechanism at the higher level.

In light of these observations, the resilience model should be revised for application to WTS with respect to the features, which can be referred to as PMRL (*preparedness-mitigation-recovery-learning*), as follows:

Preparedness: The preventive measure and the shadow resources that can be potentially employed in case of known hazards.

Mitigation: Minimizing the loss and damage after the occurrence or hazard, or taking proper precautions when the imminent hazard is sensed.

Recovery: Returning to the normal state.

Learning: Formalized and institutionalized measure to be adopted to prevent similar accidents in future navigation.

4.3. Resilience Analysis of the Eastern Star Case

4.3.1. Critical Functionality Curves

We adopt the CFC (Critical Functionality Curve)to analyze the resilience characteristics of the Eastern Star (*16*). Critical functionality is equivalently called *system level delivery* or *figure-of-merit* by other authors (*17*).

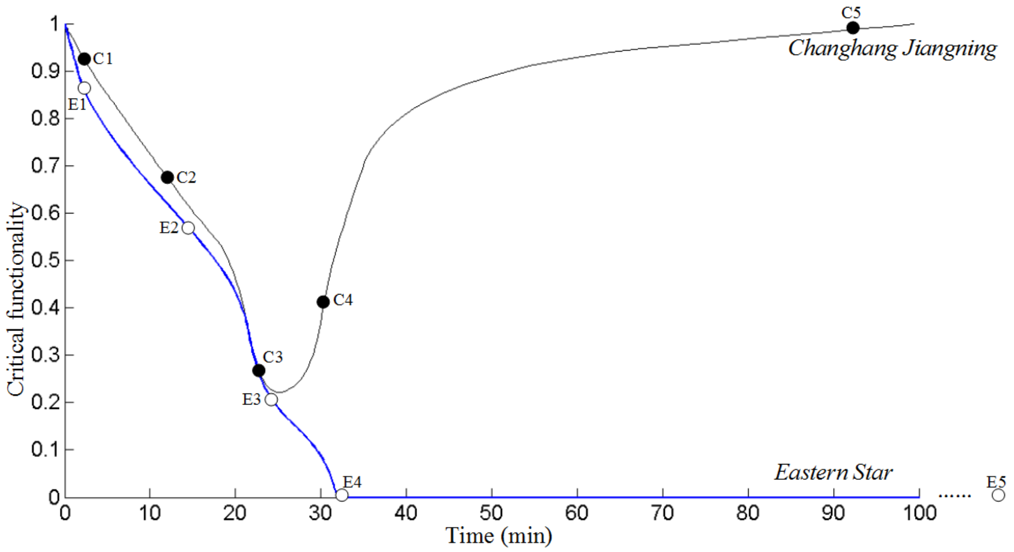

FIGURE 3 Comparison of Eastern Star and Changhang Jiangning CFCs

Fig. 3 represents *conceptual* CFCs for the Eastern Star and Changhang Jiangning ships. Some key events are listed for the trajectory of the accident/incident evolution. The horizon axis is the time (in minutes) from the 2100 hours on June1.

E1:At 21:03, the crew of Eastern Star noticed the thunder and rain up ahead.
E2: At 21:15, the Eastern Star encountered the squall line.
E3: At 21:24, the Eastern Star was held back by the strong northwest wind.
E4: At 21:32, the Eastern Star capsized.
E5: At 23:50, the MSA confirmed this accident.
C1: At 21:03, the crew of Changhang Jiangning noticed the thunder and rain up ahead.
C2:At 21:15, the speed of Changhang Jiangning slowed down to compromise to the strong wind.
C3: At 21:23, the Changhang Jiangning was held back by the strong northwest wind.
C4:At 21:33, the Changhang Jiangning anchored steadily.
C5:At 22:40,as the convective weather attenuated, the Changhang Jiangning weighed anchor and proceeded.

The two ships have similar CFC before 21:23 due to the fact that both of them rushed into the center zone of the storm. Nevertheless, the SCNWP of Changhang Jiangning is 20% higher than that of Eastern Star, and this difference in ship structure matters in the consequence and determines the latter part of the two curves after 21:23.

4.3.2. A layered View of Resilience for WTS

CFC provides an intuitive way to reflect the performance change spanning the whole process of the accident, which can be regarded as the *shell* of the resilience model. Furthermore, to obtain an insight into the mechanism of the resilience in WTS, a layered model is drawn in Fig. 4 to illustrate the logic of resilience.

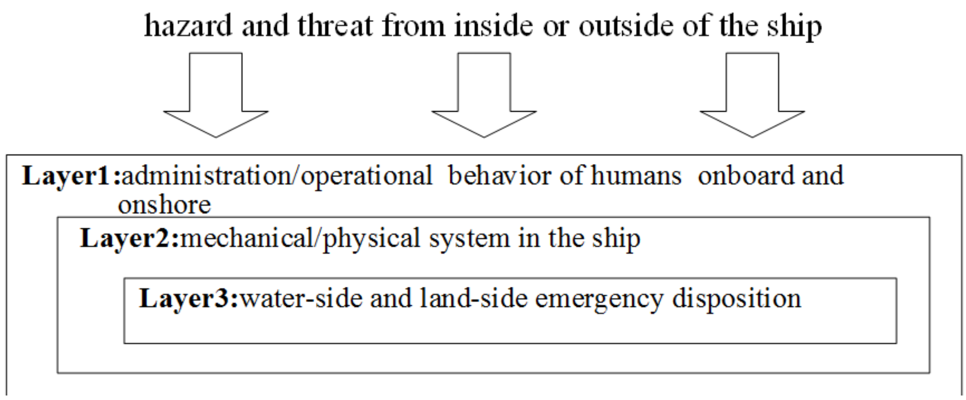

FIGURE 4 The logic of resilience against simple accident in WTS

Besides the Eastern Star accident, the three-layered model can be generally applied to other types of accidents in WTS. In the case of Eastern Star, the hazard/threat came from the outside, i.e., the squall line weather; in other cases, the hazard/threat can come from the inside, e.g., an accident to the LPG/LNG tanks on board.

In the layered model of resilience, each layer provides its own capacity of resilience. If the upper layer does not withstand the hazard, the lower layer will be exposed to the hazard and its resilience property can allow continuing to resist. Fig.5 illustrates three CFCs that implicate the different levels of “bouncing back”. Intuitively, the degree of convexity reflects the intensity of the disruption, given the resilience capability of the WTS.

As for the case of Eastern Star, Table.3 summarizes the meaning of *preparedness*, *mitigation* and *recovery* for all three layers of the model. The interpretation is delineated in general sense as well as for the specific case of Eastern Star. The *learning* aspect of resilience is not included in the table, because its principles are applicable to all layers, i.e., updating the knowledge to enhance the overall resilience capability to future disruption.

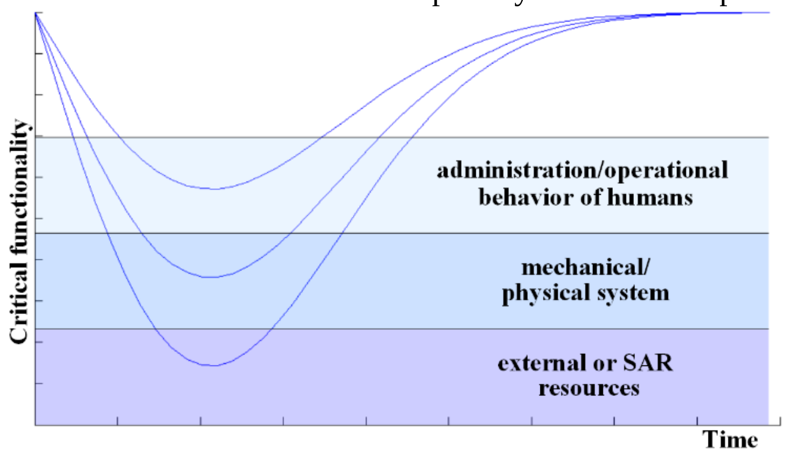

FIGURE 5 System resilience reflected by the degree of CFC convexity

TABLE 3 RESILIENCE FOR LAYER 1 TO LAYER 3

		Guideline of practice in the view of resilience	***What is supposed to happen in the Eastern Star case***	***What actual happened in the Eastern Star case***
Layer1	*Prepared-ness*	Awareness of the threats and keeping the ships from the potential threat with reasonable safety margins.	Both the crew and the MSA are fully aware about the major threats to the cruiser ship.	The crew underestimates the severity of the storm.
	Mitigation	By perception of the adverse situation, the mechanisms in administration/operation intervene in time and take effective guard measures to prevent the anomalies from aggravating.	The destructive effect of the storm is recognized by the ship and the MSA, and the decision of immediate anchoring is made to hold Eastern Star.	Navigation is not stopped in time.

	Recovery	The detected anomalies are defused or the hazardous situation is resolved.	The ship is allowed to proceed when the storm tends to ease.	
Layer2	*Prepared-ness*	The physical system of the ship is designed to sustain a certain degree of disruption, such as collision, wind, fire, pressure, loss of power, etc.	The design/rebuilding of the ship sticks to the stringent standards.	The inspection of the ship building is not rigidly conducted.
	Mitigation	The strikes on the ship can be alleviated by the facility/equipment onboard (e.g. ballast) and human's maneuvering tactics.	The SCNWP of the ship is high enough to withstand the storm.	The ship capsizes in short time.
	Recovery	The ship sustains the conventional strikes.	The ship manages to survive in the tough environment.	
Layer3	*Prepared-ness*	Emergency plans are supported by technical systems and well-deployed emergency resources.	The crew and the shore-side administration are alert in detecting distress.	The accident is unexampled in the history of WTS in inland river, there is lack of experience and cognition about such an accident.
	Mitigation	Timely on-site emergency operation can lower the loss and damage to the minimum.	Fast emergency response and SAR operation is started.	It takes nearly 2.5 hours to know and confirm the accident.
	Recovery	The negative post-accident impact decays rapidly.	The SAR operation is conducted as scheduled.	The post-disaster SAR activity is strong and valuable, 2 out of 442 persons are rescued by the operation.

5. INTEGRATING RISK AND RESILIENCE APPROACH IN WTS

5.1. Integration of Resilience and Risk in WTS

5.1.1. Relationship of Risk and Resilience in WTS

The previous discuss leads to a realistic problem: is resilience a methodology superior to the current risk study? Or at least, can resilience study help to facilitate the current risk analysis in WTS?

The above question amounts to articulating the relationship between the two paradigms. In one of the ETH's report (*18*), the opinions about the risk-resilience relationship can fall into three categories: resilience is (1) the goal of risk; (2) part of risk management; (3) alternative to risk management. From the angle of critical infrastructure protection, most practitioners adopt the first or second perspective on the risk-resilience relationship. The idea behind is that the current edifice of risk management has been deep rooted in the mindset of practitioners, and a radical shift from risk management to resilience would put many established practice into question.

In WTS, there are numerous works of research and applications in the risk analysis (*19*).On the contrary, the research on resilience is very limited (*20*). This situation partially demonstrates the lag between the general and the domain-specific in resilience studies. In what follows, we again *assume* that risk assessment is applicable to Eastern Star as if we were at the time before the accident.

As in the case of the Eastern Star accident, though the main cause can be ascribed to human factors, other causes can be gleaned as follows:

(1) The early warning mechanism is poor;

(2) The ship-shore communication is poor;

(3) The physical safety (e.g., SCNWP)is sacrificed for the economical need;

(4) The executing of itinerary contract is given high priority;

(5) The alarm system is inadequate.

According to the typical risk studies on water transport, risk assessment usually focuses on the hazard-related impacts, while *taking for granted* that the implementation of safety mechanism is sound. However, of the above five items, (1) and (2) relate to the defects of maritime administration,(3) relates to defects of ship inspection administration; (4)relates to the safety culture of the industry, (5) usually exceeds the consideration of risk assessment, which does not concern post-accident reaction. These factors can largely be attributed to the implementation of safety measures, and thus, they are less likely to have been taken into account in the formal risk assessment in the light of prior studies.

The Eastern Star case brings insight into a typical predicament we have to confront. On one hand, the operational feasibility of FSA is relatively weak, as discussed in section 4.4; on the other hand, some of the factual causal elements might be overlooked by the current risk assessment in WTS.

This indicates two problems in the present risk assessment in WTS, namely

(1) Lack of clear objective for the implementation of risk assessment;

(2) Lack of methodology to manage the residual risk.

By "residual risk", we refer to the fact that any risk analysis can only cover a small portion of factors in the real-world system and the uncovered part is still prohibitively complex.

Regarding to the explication of the resilience in WTS (Table 3), resilience offers a promising framework to address these difficulties by building a holistic risk management. In this sense, resilience is not a method superior to risk assessment, but an evolutional mechanism that can capsule the traditional risk assessment into a setup of continuum. This continuum can help to weave a more cohesive logic for the actors/stakeholders to react in the potentially adverse condition.

5.1.2. Resilience-modulated Risk Model in WTS

A resilience-modulated risk model for WTS is here delineated from the engineering and practical perspective:

(1) Resilience is carried by recursive risk assessments;

(2) The risk assessment is updated in *real time*;

(3) Compound risk assessment is conducted towards a portfolio of potential hazards with the corresponding description/explanation of scenarios;

(4) The decision objective is set by the requirement of global resilience.

Fig. 6 illustrates the model by micro-view (a) and macro-view (b). In (a), the risk assessment unit is the elemental block to study the system behavior. In practice, the risk assessment and decision making are implemented conjunctly by humans onboard (i.e. the crew) and onshore (i.e. the MSA staffs).

In (b), the two resilience curves represent the expected and the actual trajectory of the system performance. The expected resilience sets the objectives for the assessment unit in real time so that the optimal decision can be made. However, the actual system performance is subject to the uncertainties and the residual risk. In this manner, the modulation of resilience can orient the design and development of WTS.

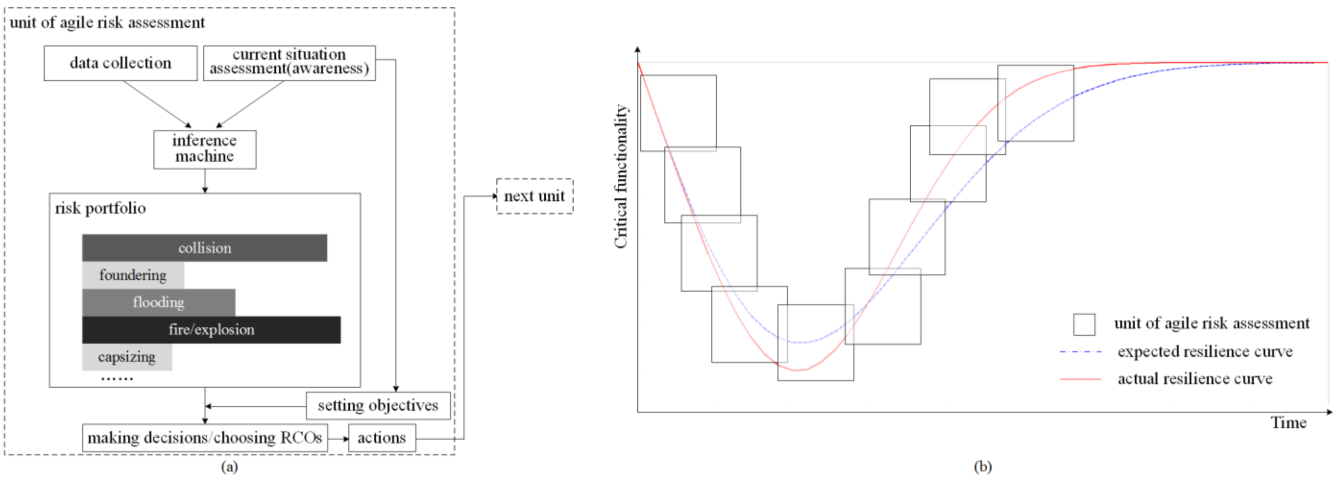

FIGURE 6 The risk-resilience relationship in WTS

5.2. Strategies and Design to Support Better Resilience in WTS

5.2.1. Making Risk Analysis More Meaningful

The resilience study aims at tracking/shaping the dynamic characteristic of the system safety. In this point, resilience is regarded as an emergent property of what an engineering system does, rather than a static property the system has (*21*).To this end, system operation should be scrutinized on an ongoing basis (*22*), which places more emphasis on the actions taken to react to adverse events.

The current theoretical study on risk tends to have more sophisticated insights than the conventional binary understanding, i.e., the likelihood and the consequence. These new insights include uncertainty, the strength of evidence, available knowledge etc. This is one important side of the problem. Nonetheless, there is still a shortage of research on risk-based decision making to fully embark on resilience, as resilience in WTS calls for a full suite of concrete decisions and precautious measures to make the result of risk assessment more meaningful.

In WTS, the performance of the system is largely determined by the operations undertaken by the actors/stakeholders, hence, from the perspective of resilience, it is the risk-informed decision making that really matters, in which the global resilience designates the reference for the objectives. Furthermore, the decision-making is another problem full of uncertainty and subjective factors, which involves the behavioral stability and continuity of the human or organizations.

5.2.2. Specific Considerations for Human Factors and Organization Resilience

As has been illustrated in Fig. 3, the resilience curve of Eastern Star hits the horizon axis and never bounces back. It has also been discussed that, the Eastern Star is a typical accident caused by human errors and organizational factors. Since it is widely accepted that as high as 70% of the accidents are caused by human factors, the Eastern Star is another instance to validate this allegation. As for the organizational factors, it can be seen that the organizational resilience entirely collapses, regarding the behavior of the crew and the MSA staff.

The *human-intensiveness* of WTS means that the performance of the system is highly dependent upon some “key” persons. This entails a subtle mechanism to function: on one hand, the key individuals should be allowed adequate autonomy to make their own decisions and judgements; on the other hand, the anomalies of decisions or behaviors should be detected and prevented. To fulfill these requirements, human reliability and organizational resilience should be fully taken into account.

It is understandable that the individual behavior of humans and the institutionalized behavior of an organization give rise to another level of risk, which is different from the conventional risk factors that are directly related to disruptions, and is usually not addressed in the standard risk analysis. The Eastern Star tragedy witnessed the total failure of human reliability and organizational resilience, and this strongly reminds the realistic weak point: while the recent study pays more attentions to the "outside" risk of potential hazard, the actors/stakeholders' own capability of implementation and execution of the countermeasures is even more fundamental.

5.2.3. Towards Resilience in WTS

One can hardly prescribe a complete list of "things to do" to swiftly reach the resilience in WTS. To make the problem tractable, we summarize the major lessons that can be learned from the Eastern Star case, with respect to different socio-technical levels.

(1) At the technical level: The WTS calls for a dynamic risk assessment guided by clear decision objectives and action plans for every actors/stakeholders (e.g. the crew and the MSA staff). Risks are evaluated on an ongoing basis and are constantly updated by the current situation awareness, exploiting also monitored data and information.

It is also proposed that a discrete risk spectrum (poly-hazard) should be derived by the pattern recognition from promiscuous sensor data or ad-hoc information. In another word, risk assessment is not bound to any predefined scenario. Rather, the hazardous scenarios are implied from the data by recognition scheme combined with subjective knowledge. In this way, a wide range of anomalies can be processed while we need not exhaust all the possibilities of specific scenarios.

(2) At the human and management level: The WTS calls for a strong implementation mechanism to fulfill the execution of safety-related practice. Human reliability and organization resilience are among the most important factors. The competence and stability of individuals determines the quality of decision or operation, and the group performance of the organization determines the overall capability of achieving the objectives as good as possible amidst individual failures or emergent strain. The capability maturity of individuals and organizations should be maintained by systematic training. A safety culture should be fostered to promote a safe organization.

(3) At the socio-economic level: The WTS calls for a good balance between economical effectiveness and safety soundness. Any safety problem should be discussed and solved on the premise of a given social and economic condition. In the case of the Eastern Star, the profit-driven actions undermine the safety of the ship. This highlights the consciousness of the practitioners that the bottom line of safety requirements should be stringently observed.

6. CONCLUTIONS

In this paper, we carry out an empirical study on the Eastern Star accident to discuss the essential causes and draw relevant insights for the safety in WTS. Typical conventional accident models and risk-based analysis have been considered to look at the accident from multiple angles. This paper also considers some of the recent buzzwords such as black swan, unknown unknowns, etc. for reference. We find that the most challenging problem may be: What will these methodologies bring forth for the decision-makers when no accident occurs? Hence, there is an impassable gulf to know something about the future disruption. In this regard, this paper favors resilience as a more practical paradigm to enhance the capability of dealing with the undesired and unexpected events.

By making an in-depth comparative study on the risk and resilience, this paper employs resilience as an effectual methodology to strengthen the safety in waterway transportation. This maintains that the current risk assessment should be conducted in an ongoing manner to account for continuity and dynamics of the system. With this regard, risk is represented as a discrete spectrum by pattern recognition of the real time data available.

The Eastern Star accident is a catastrophe that will have long-last impact on the safety research in water transport. What makes it an unforgivable tragedy to the public opinion is that, unlike other disasters caused by natural forces, the Eastern Star accident is a tragedy that could have been avoided. This paper uses this accident as a case study, and performs qualitative and quantitative modeling enlightened by the idea of resilience, the results may shed light on other transport modes as well as water transport, aiming to engineer a safer mobility.

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