Research on the External Safety Distance between Dangerous Goods Anchorage and Bridge in Inland River

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Abstract—To scientifically and reasonably evaluate the influence of dangerous goods anchorage on bridge safety, we used the quantitative risk assessment (QRA) method to investigate the external safety distance between anchorage and bridge. The accident consequence and frequency are analyzed and calculated quantitatively. The conformity of external safety distance was according to the acceptable risk standard. The results show that when the distance between the anchorage and the bridge is 942 m, the calculated risk level is unacceptable for ships. The external safety distance should be adjusted to more than 1750 m.

Keywords- Dangerous goods anchorage; Bridges; External safety distance; Quantitative risk assessment

1 INTRODUCTION

With the development of inland river transport and regional transportation facilities in China, the contradiction of safety distance between anchorage and bridges becomes increasingly prominent. For example, in one plan, the external safety distance between the dangerous goods anchorage (four anchors) and the bridge in the inland river is set at 942 m. The dangerous goods carried by anchorage ships are volatile, flammable, explosive, and toxic hazardous chemical production. Once a leak, fire, or explosion happens, ship operators and nearby ships, bridges, and wharves will be adversely affected. To evaluate the external safety distance between the anchorage and a bridge, we analyzed the consequences of fire and explosion accidents of typical dangerous cargo ships and the frequency of accidents. Furthermore, the influence of dangerous goods ships on the bridge when anchoring was investigated and calculated. The external safety distance between the anchorage and the bridge is calculated using the risk acceptability criteria.

2 ANALYSIS OF ACCIDENT CONSEQUENCES

2.1 Physical and chemical properties of transporting hazardous chemicals

The anchorage can provide anchoring services for ships of 46 surrounding wharves (berths). The cargo loaded by these ships is liquid chemicals, oils, liquefied hydrocarbons, and flammable solids. The berths served by anchorage which include one berth for loading and

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unloading liquefied petroleum gas (LPG) and two berths for butadiene. Most dangerous goods carried by ships are inflammable and explosive hazardous chemicals. The main characteristics of these goods are inflammable, explosive, toxic, volatile, thermal expansion, easy to generate static electricity, and easy to spread and flow. It is worth noting that compressed liquefied gases (LPG, butadiene, etc.) are easy to expand. The harmful of these substances are the internal reasons for the hazards such as leakage and diffusion, fire, explosion, and poisoning in the process of mooring. It is also the main reason that anchorage ship leakage accident adversely affects the bridge.

There are many kinds of different dangerous cargo carried by mooring ships in this anchorage. To further clarify the risk level of ships carrying dangerous goods, we regarded the mooring ships with different cargoes as "units" in this study. The risk factors scoring method [1] was used to select the more dangerous chemicals. The risk factors scoring method is based on five indicators: cargo type, capacity, temperature, pressure, and operation. Each item is divided into four categories: A, B, C, and D, with the scores 10, 5, 2, and 0, respectively. Finally, the risk level of the unit is evaluated by the sum of these scores. Table I shows the results of risk classification. As can be seen in Table 1, cargoes such as liquefied petroleum gas, propane, butane, and butadiene are high risk. cargoes such as naphtha and gasoline, are medium risk.

Table 1 The Result of risk factors scoring

Cargoes	**Cargo type**	**Capacity**	**Temperature**	**Pressure**	**Operation**	**Total score**	**Risk level**
Class A: LPG, propane, butane, butadiene.	10	10	0	2	0	22	High risk
Class B: Naphtha, gasoline.	5	10	0	0	0	15	Medium risk
Brimstone	10	0	0	0	0	10	Low risk

2.2 Types of accident consequences

Combined with the analysis of physical and chemical characteristics of dangerous goods carried by ships at anchorage, the toxicity of these goods is less harmful than fire and explosion. The bridge damage is caused by ship fire and explosion accidents. Personnel operation error, equipment damage, poor management, ship collision, and adverse natural conditions usually cause chemical leakage. Flammable, explosive, toxic, and harmful substances would release immediately. Additionally, the cabin and the engine room are easy to form explosive mixed gas. Once introduced the fire source, a fire explosion will happen. Depending on the storage status of the goods, the types of fire and explosion include pool fire, jet fire, flash fire, and vapor cloud explosion. Typical event trees are shown in Figures 1 and 2 [1]. For bridges, the thermal radiation and explosion shock wave generated by ship fire and explosion will have an impact on piers and vehicles passing on the bridge deck.

- The leakage of cargo carried by ship forms a liquid pool or jet, and the pool fire or jet fire occurs when introducing the fire source. The thermal radiation generated has an impact on the bridge and the passing personnel.

•The vapor cloud is formed by the leakage and diffusion of the cargo carried by ship, and the vapor cloud explosion occurs when introducing the fire source. The explosion shock wave generated will have an impact on the bridge and the passing personnel.

•An explosive mixture of gases is formed in the closed space, such as the cabin and engine room of the ship, which will explode when encountering the fire source. The resulting explosion shock wave badly affects the bridge.

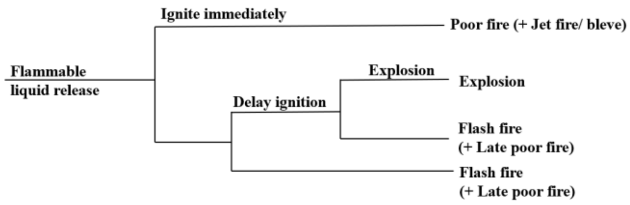

Figure 1. Leakage event tree of flammable liquid.

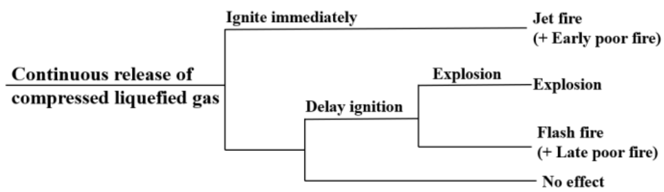

Figure 2. Leakage event tree of continuous release of compressed liquefied gas.

2.3 Loss of containment events (LOCs)

The leakage of dangerous liquid and gas directly determines the damage scope of the accident. The following two situations can occur, scenario 1: the catastrophic rupture of a ship (total leakage in an instant), and scenario 2: a certain amount of leakage in a period of time. Different scales of leakage have different consequences. Herein, we investigated the consequences of cargo leakage and cabin explosion.

1)Cargo leakage: Loading and unloading activities and external effects are analyzed for ship cargo leakage. Since the anchorage is forbidden to carry out lightering operations, this simulation only considers the influence of external effects (ship collision). Ship collision accidents are analyzed as follows [1][2][3].

•Large hole leakage (150 mm aperture) is classified as a general collision accident.

•Human collision factors include wrong human operation, intentional collision, and an accident occurring at high ship speed and near 90°. The assumed damage range is 760 mm vertically inward from the side of the cargo area, so 760 mm is selected as the breach size.

•The cargo holds completely ruptured is considered the extreme case.

2)Cabin explosion: Combustible gas mixtures in a cargo hold explosion was analyzed (LPG is assumed to be near the explosive limit).

The leakage accident events are shown in Table 2.

Table 2 Mooring Ship Leakage Accident consequence

Simulated ships type	**LOCs**		**Accident consequence**
LPG ships (Full pressure)	Large hole leakage	Leakage aperture: 150 mm.	Jet fire and vapor cloud explosion
	Local breakage	Leakage aperture: 760 mm	
	Completely ruptured	All stocks released instantaneously.	
	Cabins exploded	The cabin contains explosive mixtures of gases.	Vapor cloud explosion
Butadiene ships (Full pressure)	Large hole leakage	Leakage aperture: 150 mm.	Jet fire and vapor cloud explosion
	Local breakage	Leakage aperture: 760 mm	
	Completely ruptured	All stocks released instantaneously.	
	Cabins exploded	The cabin contains explosive mixtures of gases.	Vapor cloud explosion
Petrol ships	Large hole leakage	Leakage aperture: 150 mm.	Pool fire and toxic diffusion
	Local breakage	Leakage aperture: 760 mm	
	Completely ruptured	All stocks released instantaneously.	
	Cabins exploded	The cabin contains explosive mixtures of gases.	Vapor cloud explosion

3 QUANTITATIVE RISK ASSESSMENT

3.1 Hypothetical cases

Due to the change of the cargo and anchoring position of the mooring ship, the risks of cargo ships and mooring combinations are different. In this study, ships that carry out high-risk-level goods (analyzed in Section II) were chosen for calculating individual and social risk. In addition, according to the data of the berthing dock of ships in this anchorage, the mooring cases with high risk were listed, as shown in case 1 of Table 3. As a comparison, the conventional mooring case was listed, as shown in case 2.

Table 3 two cases for calculating risk

Cases	**The first anchor position**	**The second anchor position**	**The third anchor position**	**The fourth anchor position**
Case 1	Butadiene ships	Butadiene ships	LPG ships	Petrol ships
Case 2	Petrol ships	Petrol ships	Petrol ships	Petrol ships

3.2 Calculation of leakage frequency

The failure frequency analysis of each accident case is as follows:

•Completely ruptured accident. According to the public literature and analysis of major ship grounding/collision accidents in history [4], there is no accident case of completely ruptured. Therefore, the failure frequency value of completely ruptured was $< 10^{-8}$.

•Large-scale outflow caused by external effects. The basic accident frequency is calculated according to the following formula [5]:

$$f_0=6.7\times10^{-11}\times T\times t\times N \quad (1)$$

where *T* is the total number of ships per year on the transport route, *t* is the average duration of loading/unloading per ship (in hours), and *N* is the number of transshipments per year.

After calculation, f0=0.85×10-3. In the case of a gas carrier, f=0.025×f0=0.21×10-4. In the case of liquid cargo ships (double hull), f=0.006×f0=0.51×10-5.

The scoring factor of the management system is used to correct the leakage frequency [6]. The relevant construction standards and classification standards for full-pressure LPG ships are strict. Hence, the correction factor of LPG ships is 0.25 (management system evaluation score of 75). The correction factor of petrol ships is 1 (management system evaluation score of 50). The adjusted failure frequency is shown in Table 4.

Table 4 Adjusted failure frequency of Accident Events

Simulated ships type	LOCs		Adjusted failure frequency
LPG ships（Full-pressure）	Large hole leakage	Leakage aperture: 100 mm.	0.525×10^{-5}
	Local breakage	Leakage aperture: 760 mm	0.525×10^{-5}
	Completely ruptured	All stocks released instantaneously.	$<10^{-8}$
	Cabins exploded	Empty cabins and LPG are in explosive limit.	0.525×10^{-5}
Butadiene ships（Full-pressure）	Large hole leakage	Leakage aperture: 100 mm.	0.525×10^{-5}
	Local breakage	Leakage aperture: 760 mm	0.525×10^{-5}
	Completely ruptured	All stocks released instantaneously.	$<10^{-8}$
Petrol ships	Large hole leakage	Leakage aperture: 100 mm.	0.51×10^{-5}
	Local breakage	Leakage aperture: 760 mm	0.51×10^{-5}
	Completely ruptured	All stocks released instantaneously.	$<10^{-8}$
Methanol ships	Large hole leakage	Leakage aperture: 150 mm.	0.51×10^{-5}
	Local breakage	Leakage aperture: 760 mm	0.51×10^{-5}
	Completely ruptured	All stocks released instantaneously.	$<10^{-8}$

3.3 Number of bridge passenger

The average volume of the cross-river section of this bridge is 47616 pcu/d. The number of vehicles at the same time is ~131. When each vehicle carries 1.5 people, the number of people passing through the river is 196.5.

3.4 Risk calculation results

Individual risk and social risk were calculated using TNO RISKCURVE software. According to relevant regulations and standards [7], the value of individual risk in the bridge area should be < 3×10-7, and the value of social risk should fall into the acceptable interval.

1)Case 1: Results of individual and social risks. The results of individual risk are shown in Figure 3. The value of individual risk in the bridge area is ≥ 3×10^{-7}, which means individual risk is unacceptable.

Figure 4 is the F-N curve of social risk. It can be seen that part of the social risk curve falls in the area of maximum reduction, and further measures should be taken to reduce social risk.

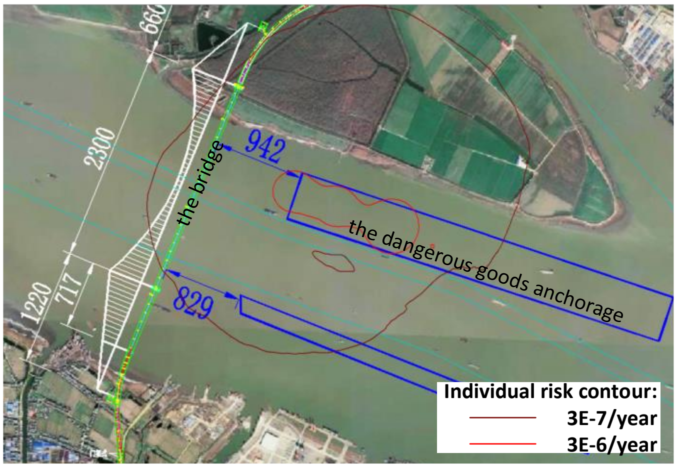

Figure 3. Individual risk contour of case 1.

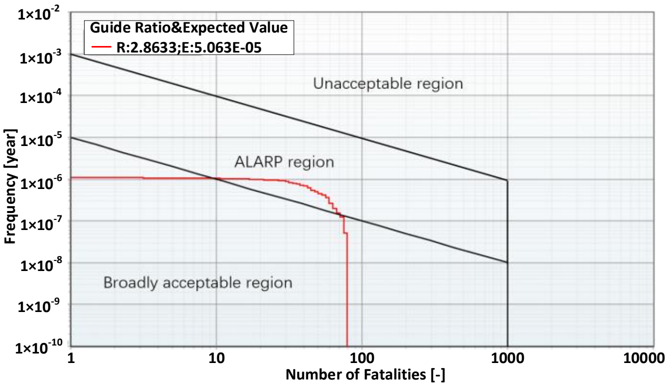

Figure 4. F-N curve of case 1.

To reduce personal and social risks, full-pressure ships carrying class A fire dangerous cargo such as butadiene and LPG should anchor as far away from the bridge as possible. When this measure is taken, the individual risk and social risk are shown in Figure 5 and Figure 6, respectively. In this case, the individual and social risks can meet the requirements. The anchorage is more than 1750 m away from the bridge.

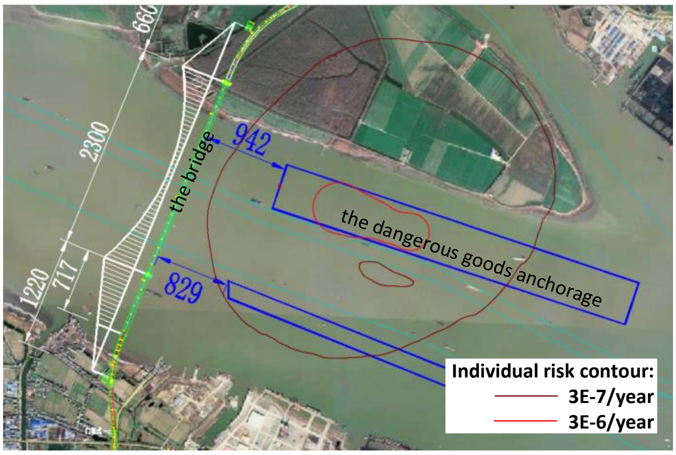

Figure 5. Results of adjusted individual risk.

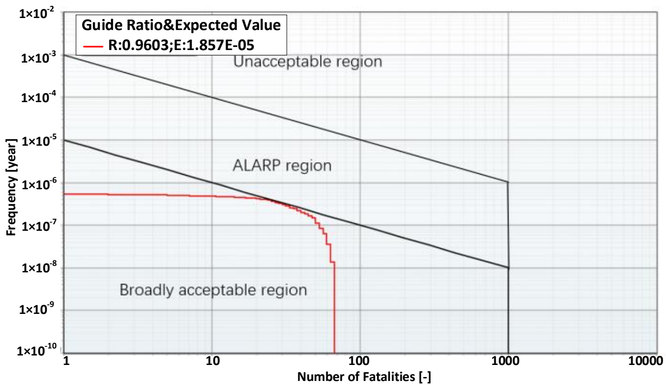

Figure 6. Results of adjusted social risk.

2)Case 2: Results of individual and social risks. Figure 7 shows the calculated result of individual risk. The individual risk value in the bridge area is < 3×10^{-7}, and the personal risk is acceptable. Due to the social risk being small, the F-N curve is not given. When the distance between the anchorage and the bridge is 942 m, the risk level of mooring petrol ships is acceptable.

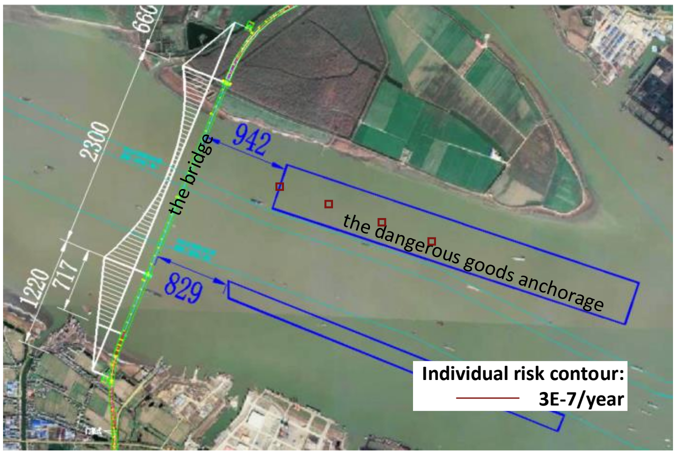

Figure 7. Individual risk contour of case 2.

4 CONCLUSIONONS

The accident risk that the anchorage may cause harm to the bridge is a ship fire and explosion accident. The common mooring combination (case 1) and the most dangerous mooring combination (case 2) were analyzed using the quantitative risk assessment. When the distance between the anchorage and the bridge is 942 m, the risk level is acceptable for anchoring petrol ships. The risk level is not acceptable when anchoring full-pressure ships with class fire dangerous cargos such as butadiene and LPG. Therefore, all pressure ships carrying class A fire-risk cargo, such as butadiene and LPG, should anchor as far away from the bridge as possible. After calculation, it should be more than 1750 m away from the bridge.

Taking safety measures to prevent and control risks and reduce safety risks:

•Full-pressure ships carrying class A fire-dangerous goods such as butadiene and LPG should be anchored as far away from the bridge as possible.

•During the anchoring period, the ship should strictly control the ignition source, implement anti-static measures, and prohibit the maintenance of ignition, washing/cleaning, and lightering.

•Bridge management establishes an emergency linkage mechanism with anchorage and drafts an emergency plan.

•Strengthen navigation management and guidance of nearby waterways. Furthermore, improving the corresponding navigation facilities and reducing the possibility of leakage caused by collision.

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