A Quantitative Liability Risk Assessment of Oil Spills in Oil Port: The Case of the Guangdong-Hong Kong-Macao Greater Bay Area

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Abstract: To mitigate risk and enhance safety in oil port, this study proposes a method to analyze the civil liability risk and criminal liability risk of oil spills in oil port. By scenario analysis and data analysis, this study estimates the probability, spillage, casualty, actual compensation and total spill cost of each spillage scenario, including loading arm/hose rupture and hull failure when a vessel is berthing, maneuvering near a berth and moving through the port. Based on these estimated factors and the legal liability, the civil liability risk and criminal liability risk borne by the oil ports and ship owners are respectively estimated. Finally, data of an oil terminal in the Guangdong-Hong Kong-Macao Greater Bay Area are taken as a study case to verify the applicability of the proposed method. The estimated probability and consequence can help to judge which scenario would result in crime and provide reference for emergency capacity equipping, and the estimated risks are useful to loss mitigation and crime prevention. The findings and analysis reveal the low compensation ratio and the inconsistency in the incriminating standards of oil spills in China, so it is suggested to strengthen the enforcement of civil compensation and unity the incriminating standards.

Keywords: Oil port; Marine pollution; Oil spills; Quantitative risk assessment; Legal liability.

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1 Introduction

Attention on potential oil spills in oil port has increased as the oil trade has grown significantly. In 2017, China's crude oil consumption was 610 million tonnes, and its import volume reached 420 million tones (Cpy, 2018). Most of imported crude oils are transported through oil ports, except for those crude oils imported through pipelines. At the same time, tankers tend to be increasing in number and larger in tonnage. These factors have combined to weaken safety of the oil port. As a distribution center and transfer station for hazardous materials, the oil port is a place with frequent oil spills, which could result in substantial environmental and economic catastrophes and would cause great casualties, huge economic losses and irreparable environmental damage (Lam and Su, 2015; Lam and Lassa, 2017). One example is the August 1995 fire in Guangzhou port that caused by ship collision during moving to the berth and resulted in a spillage of 200 tonnes, an economic compensation of 82 million RMB (Renminbi) and pollution on tourist attractions. The increasing imports of crude oil would not only increase the probability of accidents in oil ports but also exacerbate their consequences. Therefore, it is crucial and timely to mitigate the oil spills risk of oil port.

In order to prevent and control oil spills, there are some international conventions governing compensation for oil pollution damage and clean-up costs, including the 1969 and the 1992 International Convention on Civil Liability for Oil Pollution Damage ("CLC 1969" and "CLC 1992") and the 1971 and 1992 conventions on the Establishment of an International fund for Compensation for Oil Pollution Damage ("1971 Fund" and "1992 Fund"). There is also legal regime in force in China, including Civillaw (2011) and Criminallaw (2013). According to Civillaw (2011), an enterprise who is responsible for oil spills is demanded to compensate for the total spill cost. Here, the total spill cost denotes the total cost of an oil spill, including the clean-up cost, preventive measure cost, fishery-related cost, tourism-related cost, farming-related cost, environmental damage cost and so on. According to Criminallaw (2013), an enterprise may commit a criminal act, if the oil spill causes one of the following three features: (1) the spillage is larger than 3 tones, (2) the total spill cost is more than 300 thousand RMB, and (3) there is casualty in the accident. However, there is no judicial interpretation to guide enterprises to estimate the civil liability risk and criminal liability risk. It is urgent to propose a quantitative method to assess the civil liability risk and criminal liability risk in oil port, which will guide and restrict enterprises to reduce both risks.

This paper proposes a quantitative method to estimate and analyze the civil liability risk and criminal liability risk of oil spills in oil port to reduce the oil spill risk. Here, Civil liability risk refers to the legal liability that should be borne because of the violation of civil law (Hiller, 2012), and Criminal liability risk refers to the legal liability that should be borne because of the violation of criminal law (Pollack and Reisinger, 2014). Generally, risk is the product of probability and consequence (Akyuz and Celik, 2018). In this paper, the civil liability risk is defined as the product of the probability and the compensation caused by the oil spill, and the criminal liability risk is defined as the product of the probability and the number of crimes caused by the oil spill. The number of crimes is set as 1, when the consequence constitutes a crime. Otherwise, the number of crimes is set as 0. The remainder of this paper is structured as follows: Section 2 reviews the existing literature. Section 3 introduces the method. Section 4 applies the proposed method to a case in the Guangdong-Hong Kong-Macao Greater Bay Area. Section 5 discusses the results, and Section 6 contains concluding remarks.

2 Literature review

Existing risk assessment studies can generally be categorized into the quantitative and qualitative risk assessment. Qualitative risk assessment relies on the subjective experience of evaluator, which leads to different assessment result from different evaluator (Johnson, 2016). Hence, the quantitative risk assessment is getting more and more attention (Yang et al., 2013; Zhang et al., 2020). In order to assess the risk objectively, this paper proposes a quantitative method to assess the risk of oil port.

There are three main following points in the general quantitative risk assessments: probability estimation, consequence estimation, as well as risk estimation. First, estimate the probability of each spillage scenario. Then, estimate the consequence of each spillage scenario. Finally, calculate the risk as the product of the corresponding probability and consequence, and set acceptable criterion to analyze risk and judge whether the risk is in the acceptable area.

For probability and consequence estimation, after reviewing the classical and state-of-the-art literature reviews by Li et al. (2012) and Luo and Shin (2016), it is clear that probability and consequence estimation literature can be classified into four major branches as follows: simulation model (Monteiro et al., 2020), fault tree (Fowler and Sorgard, 2000; Sihombing and Torbol, 2018) and Bayesian network (Haenninen, 2014; Jiang and Lu, 2020) approach for causation probability estimation, formula models for geometrical probability estimation (Fujii and Tanaka, 1971; Pedersen, 2010) and using historical statistical data. In order to analyze whether the general oil port and ship owner can take the liability risk and dig out the problems in current Marine pollution prevention laws, this paper assesses the liability risk in general scene. The former three methods have to consider with some detailed ship's particulars information (e.g. course over ground, speed and weight) or the expert judgment, therefore, the former three method are suitable for estimating risks in a special area, rather than in general area. The fourth method is using the industrial failure database, enterprise and supplier data history data to estimate the probability and consequence, which is more suitable in general area. Therefore, this paper chooses the fourth method to estimate the probability and consequence. Now, some foreign institutions (such as Det Norske Veritas, Dutch National Institute for Public Health and Environment, and British Health and Safety Executive) have their own failure databaseand provide some handbooks for risk assessment (Dnv, 2001; Bevi, 2009; Hse, 1978), which are widely used to calculate probability and spillage of oil spills (Ronza et al., 2006; Vilchez et al., 2011; Zhang et al., 2014). Generally, there are two main scenarios result in oil spills in oil port, including loading machine rupture and hull failure. These handbooks provide the general frequency of accidents and emergency response time in different scenarios, and the oil flow rate for hull failure. The probability in each scenario can be estimated based on the general frequency, ship traffic, berthing time, and amount and handling time of loading machine. The spillage in each scenario can be estimated based on the emergency response time and oil flow rate. However, there is no interpretation for the handling time and flow rate of loading machine. Previous studies tend to set the handling time and flow rate as the corresponding mean (Ronza et al., 2006; Zhang et al., 2014). China Maritime Safety Administration assumes the handling events were handled by only one loading machine, and the oil flow rate of loading machine equaled to the handling speed (Cmsa, 2011). Actually, the handling vessels with different tonnages would be handled by loading machines with different handling times and flow rates. Therefore, these assumptions leaded to the miscalculated probability and spillage of loading machine rupture, since the probability is proportional to the handling time, and the spillage is proportional to the oil flow rate (Dnv, 2001; Bevi, 2009; Hse, 1978). As a result, it is unable to dig out the main cause of accidents and judge which scenario would violate the criminal law, let alone provide scientific basis for civil liability risk mitigation or crime prevention. To solve this problem, this paper calculates the actual handling time of loading machine with different sizes by considering the loading machine utilization and amount, and estimates the flow rate of loading machine rupture with different sizes by considering the loading machine diameter and maximum safe flow velocity. Based on the estimated handling time and flow rate of loading machine, this paper calculates the probability and spillage of each spillage scenario according to the handbooks.

For oil spill risk estimation for oil port, existing researches tend to estimate the casualty to analyze individual and social risk (Zhang et al., 2014; Ronza et al., 2006; Vilchez et al., 2011), while leaving aside liability risk estimation. According to the civil compensation provision and incriminating standards, it can be found the key factors of civil liability risk and criminal liability risk are the compensation, total spill cost and casualty of each spillage scenario. For the casualty, Jtt1143 (2017) provides a casualty function of spillage in general situation. For the compensation and total spill cost, (Kontovas et al., 2010; Imo, 2015) regard the compensation is equated with the total spill cost, since the International Convention on Civil Liability for Oil Pollution Damage stipulates the responsible party should compensate for the total spill cost. However, the total spill cost is found to be significantly larger than the actual compensation in this paper. Therefore, this study estimates the compensation and total spill cost of each spillage scenario respectively, and discusses the civil liability risk based on actual compensation and statutory compensation, respectively. Here, the statutory compensation is the total spill cost. Some previous studies have pointed out that there is a log-linear relationship between spillage and total spill cost and a log-linear relationship between spillage and actual compensation, and deduced the corresponding regression models (Kontovas et al., 2010; Imo, 2015; Yamada, 2009). However, these deduced regression models may not be suitable for the oil spills in China, since the actual compensation and total spill cost are affected by the surroundings and policies. To estimate the total spill cost and actual compensation, this paper collects the accidents with actual compensation or total spill cost in China. This method first uses the accidents with total spill cost and spillage in China to deduce the log-linear function between spillage and total spill cost. Similarly, this method deduces the log-linear function between spillage and actual compensation, and discusses the compensation ratio in China. Then convert the spillage of each spillage scenario into casualty, actual compensation and total spill cost, and estimate the civil liability risk and criminal liability risk by considering the probability, consequence and incriminating standard. Finally, provide some guidance for mitigating civil liability risk, preventing crime and perfecting the marine pollution prevention laws by risk analysis.

From possible legal consequences, this paper proposes a quantitative method to estimate the civil liability risk and criminal liability risk of different spillage scenarios in oil port. The applicability of this method is verified by a general case of an oil terminal in the Guangdong-Hong Kong-Macao Greater Bay Area. The estimated results can be applied on perfecting the marine pollution prevention laws and guide oil ports and ship owners to reduce civil liability risk and prevent crime.

3 Methodology

This section will introduce the methodology. As shown in Figure 1, this paper just discusses the oil spills in oil port. From a general point of view, there are two basic scenarios while estimating the risk in an oil port, including loading arm/hose failure and hull failure. The initiating events of hull failure include ship-ship collision while a tanker is (dis)charging, collision and grounding during moving through the port, and ship-land collision during maneuvering near a berth. There is two-fold possibility in each spillage scenario. According to the degree of damage, loading arm/hose rupture can be divided into total and partial rupture, and the oil spill of hull failure can be divided into minor and major spills.

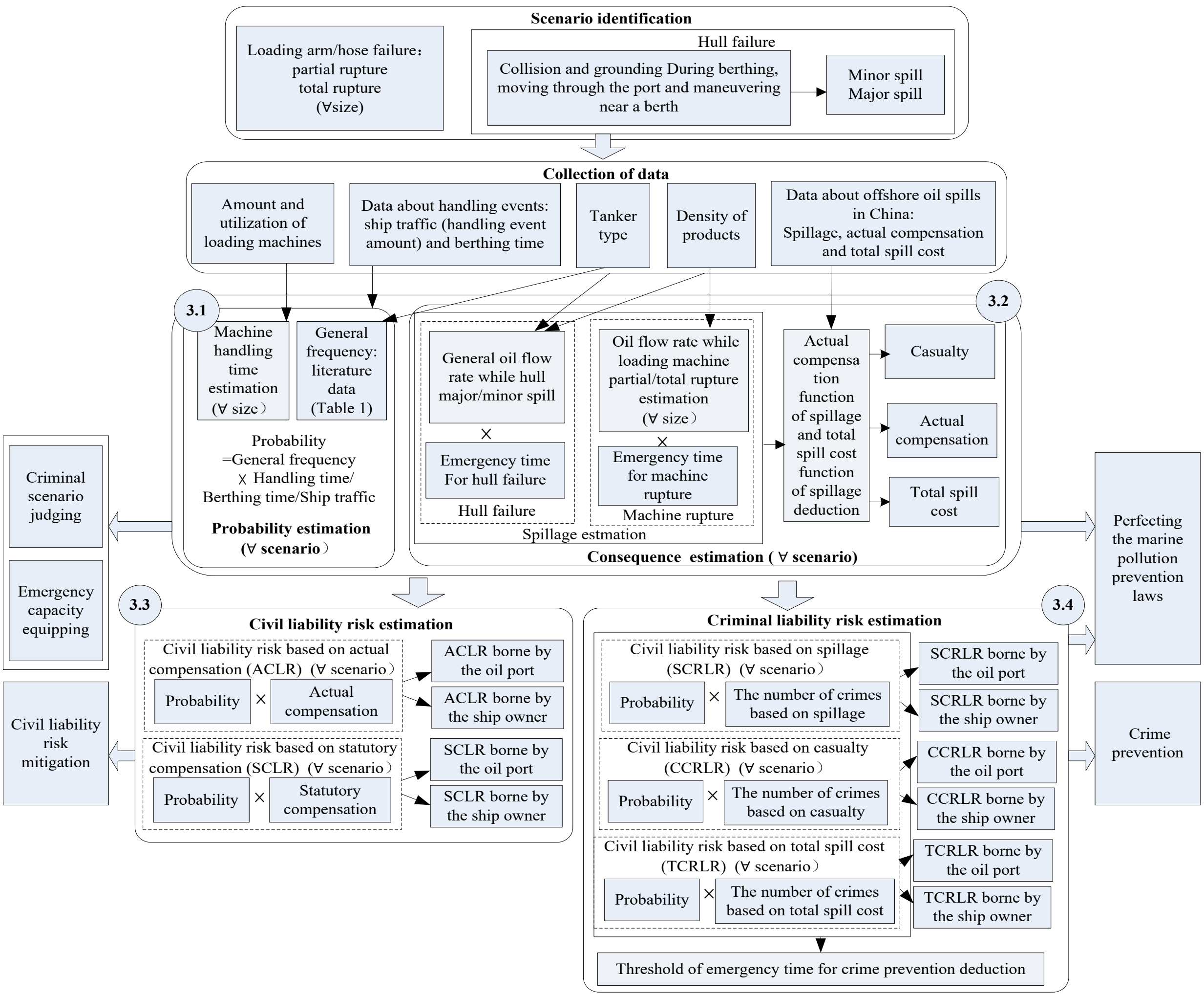


Figure 1. Overview framework of oil port quantitative liability risk analysis.

This methodology needs to collect some data, including the key inputs of spill probability and consequence estimation, as follows:

(1) Amount and utilization of the loading arm/hose with different sizes are key factors of machine rupture probability estimation. Here, the utilization can be estimated by historical statistic data, or assume the loading machine utilization equals the corresponding berth utilization, which can be objectively estimated by AIS data (Zhong et al., 2020).

(2) Data about handling events, including ship traffic (means the handling event amount) and berthing time, which is critical to calculate the probability of accident. The existing research tends to estimate the ship traffic by historical statistic data, and roughly estimate the berthing time according to the tonnage of ship(Ugurlu et al., 2015). Zhong et al. (2020) propose an accurate method to estimate this information by AIS data. The data about handling events in this paper is gained referring to the latter method.

(3) Tanker type, which affects the probability and spillage of hull failure (Yip et al., 2011), can be gained by historical records. According to the requirements of the ministry of transport, single-hull chemical ships and single-hull oil ships with DWT > 600 tonnes are prohibited from entering Guangzhou Port and other major water areas in China from January 1, 2016. Using double hull has become an irresistible trend. Therefore, the tanker hull can be assumed as double hull in the large oil port.

(4) Density of petroleum products would be used to estimate the weight of spillage. This paper sets the maximum density of all the petroleum products as the unique density.

(5) Data about offshore oil spills in China, including the spillage, actual compensation and total spill cost. This historical data is extracted from Bulletin of China Marine Disaster, Northwest Pacific Action Plan and some studies (Hui, 2000; Lao, 2003).

After scenario identification and data collection, the method consists of four key phases:

(1) Probability estimation: The probability of each spillage scenario is estimated as the product of the corresponding general frequency and traffic data (including machine handling time, berthing time and ship traffic). Here, the general frequency is provided from the handbooks (Bevi, 2009; Hse, 1978; Hsc, 1991) as shown in Table 1. The machine handling time is estimated by considering the machine utilization and machine amount.
(2) Consequence estimation: Firstly, the spillage of each spillage scenario is estimated as the product of the corresponding oil flow rate and emergency response time. Here, the oil flow rate while loading machine rupture is calculated by considering the loading machine diameter and maximum safe flow velocity in this study. Then, the actual compensation function of spillage and the total spill cost function of spillage are deduced by the data about accidents. Finally, the spillage of each spillage scenario is converted into the corresponding total spill cost, actual compensation and casualty based on the deduced functions.

(3) Civil liability risk estimation: This phase estimates the civil liability risk based on actual compensation (ACLR) and civil liability risk based on statutory compensation (SCLR) borne by the oil port and ship owners, respectively. Firstly, the ACLR in each spillage scenario is calculated as the product of the corresponding probability and actual compensation, and the SCLR in each spillage scenario is calculated as the product of the corresponding probability and statutory compensation. Then, according to the party responsible for the accidents, the ACLR borne by the oil port can be estimated by adding up the ACLRs in the spillage scenarios due to loading machine rupture, and the ACLR borne by the ship owners can be estimated by adding up the ACLRs in the spillage scenarios due to hull failure. Similarly, the SCLR borne by the oil port and ship owners can be estimated.

(4) Criminal liability risk estimation: This phase estimates the criminal liability risk based on spillage (SCRLR), criminal liability risk based on total spill cost (TCRLR) and criminal liability risk based on casualty (CCRLR) borne by the oil port and ship owners, respectively. Firstly, the SCRLR in each spillage scenario is calculated as the product of the probability and the number of crimes caused by the oil spill. Here, the number of crimes is set as 1, when the consequence constitutes a crime according to the incriminating standard based on spillage. Otherwise, the number of crimes is set as 0. Then, according to the party responsible for the accidents, the SCRLR borne by the oil port can be estimated by adding up the SCRLRs in the spillage scenarios due to loading machine rupture, and the SCRLR borne by the ship owners can be estimated by adding up the SCRLRs in the spillage scenarios due to hull failure. Similarly, the TCRLR and CCRLR borne by the oil port and ship owners can be estimated. Additionally, the threshold of emergency response time for crime prevention in each scenario is deduced based on the calculation formulae of criminal liability risk and the incriminating standard.

3.1 Probability estimation

After reviewing the literature, in the given period, the probability of oil spills in scenario i can be calculated as (Bevi, 2009; Hse, 1978; Hsc, 1991):

$$P_i = \begin{cases} f_{arm,t} \times T_{arm}^S & \text{for loading arm (with size } S\text{) total rupture during handling} \\ f_{arm,p} \times T_{arm}^S & \text{for loading arm (with size } S\text{) partial rupture during handling} \\ f_{hose,t} \times T_{hose}^S & \text{for hose (with size } S\text{) total rupture during handling} \\ f_{hose,p} \times T_{hose}^S & \text{for hose (with size } S\text{) partial rupture during handling} \\ f_{hull,b} \times T \times PM \times T_b & \text{for major spill due to hull failure during berthing} \\ f_{hull,b} \times T \times pm \times T_b & \text{for minor spill due to hull failure during berthing} \\ f_{hull,m} \times PM \times T' & \text{for major spill due to hull failure during maneuvring near a berth} \\ f_{hull,m} \times pm \times T' & \text{for minor spill due to hull failure during maneuvring near a berth} \\ f_{hull,p} \times PM \times T' & \text{for major spill due to hull failure during moving through the port} \\ f_{hull,p} \times pm \times T' & \text{for major spill due to hull failure during moving through the port} \end{cases} \quad (1)$$

Here, $f_{arm,t}$ is the general frequency of loading arm total rupture per hour during cargo handling, and $f_{arm,p}$ is the general frequency of loading arm partial rupture per hour during cargo handling. $f_{hose,t}$ is the general frequency of hose total rupture per hour during cargo handling, and $f_{hose,p}$ is the general frequency of hose partial rupture per hour during cargo handling. $f_{hull,b}$ is the general frequency of ship-ship collision during berthing, expressed per unit time and per ship passage. $f_{hull,m}$ is the general frequency of a ship-land collision while a tanker is maneuvering near a berth. $f_{hull,p}$ is the general frequency of ship-land collision, ship-ship collision and grounding per operation during moving through the port. In this method, the value of $f_{hull,m}$ is based on (Hsc, 1991), and the value of $f_{hull,p}$ is based on Hse (1978), since they make more detailed analysis. The value of general frequency of initiating event per hour (operation) in other scenarios are both based on Bevi (2009), since it is more recent. Table 1 shows the values of these general frequencies. T is the total number of ships, which have chances to collide with the handling ships, in the given period. PM is the probability of major spill under the condition of hull failure, and pm is the probability of minor spill under the condition of hull failure. PM and pm are determined by the ship type (Bevi, 2009). T_{arm}^S is the handling time of loading arm with size S in hours. T_{hose}^S is the handling time of hose with size S in hours. T_b is the berthing time in the given period in hours. T' is the handling event amount in the given period. This method assumes T as T' in the given period, since only ships entering the terminal for handling have chances to collide with the handling ships.

Table 1 The values of general frequencies of initiating event per hour (operation)

Parameter	$f_{arm,t}$ (*hour*$^{-1}$)	$f_{arm,p}$ (*hour*$^{-1}$)	$f_{hose,t}$ (*hour*$^{-1}$)	$f_{hose,p}$ (*hour*$^{-1}$)	$f_{hull,b}$ (*passage*$^{-1}$*hour*$^{-1}$)	$f_{hull,m}$ (*operation*$^{-1}$)	$f_{hull,p}$ (*operation*$^{-1}$)
Value	3×10^{-8}	3×10^{-7}	4×10^{-6}	4×10^{-5}	6.7×10^{-11}	2.2×10^{-3} (HSC, 1991)	2.5×10^{-4} (Hse, 1978)

Source: Complied by the authors based on Bevi (2009), HSC(1991)and Hse (1978)

Therefore, in a given period, the probability of oil spills in each spillage scenario can be gained by inputting the corresponding ship traffic, berthing time, handling time of loading machine and ship type into the model. Here, ship traffic, berthing time and ship type can be directly collected. The handling time of loading arm with size S in the given period l, can be estimated by:

$$T_{arm}^S = l \times U_{\text{arm}}^S \times N_{\text{arm}}^S \quad (2)$$

Here, U_{arm}^S is the utilization of loading arm with size S, and N_{arm}^S is the amount of loading arm with size S.

Similarly, the handling time of hose with size S in the given period l (denoted by T_{hose}^{S}) is:

$$T_{hose}^{S} = l \times U_{hose}^{S} \times N_{hose}^{S} \quad (3)$$

Here, U_{hose}^{S} is the utilization of hose with size S, and N_{hose}^{S} is the amount of hose with size S. The handling time of loading machine with size S in the given period l is:

$$T_{mach}^{S} = T_{arm}^{S} + T_{hose}^{S} \quad (4)$$

Therefore, with the collected data, the probability of oil spills can be estimated.

3.2 Consequence estimation

This section first estimates the spillage of each spillage scenario, and then converts the spillage into the corresponding total spill cost, actual compensation and casualty.

3.2.1 Spillage estimation

Spillage in scenario i is calculated as the product of the corresponding oil flow rate and emergency response time:

$$V_i = \begin{cases} V_{mach,t}^{S}(T_1) = \pi d_S^2 \rho v_{safe} \times T_1 / 4 & \text{for loading machine total rupture} \\ V_{mach,p}^{S}(T_1) = \pi d_S^2 \rho v_{safe} \times T_1 \times 10\% / 4 & \text{for loading machine partial rupture} \\ V_{hull}^{M}(T_2) = RM \times T_2 \times \rho & \text{for major spill due to hull failure} \\ V_{hull}^{m}(T_2) = rm \times T_2 \times \rho & \text{for minor spill due to hull failure} \end{cases} \quad (5)$$

Here, $V_{mach,t}^{S}$ is the spillage of machine (with size S) total rupture, and $V_{mach,p}^{S}$ is the spillage of machine (with size S) partial rupture. V_{hull}^{M} is the spillage of major spills from hull, and V_{hull}^{m} is the spillage of minor spills from hull. d_s is the diameter of loading machine with size S. v_{safe} is the maximum safe flow velocity, and is set as 4.5 m/s (Jts165, 2013). ρ is the density of products. RM and rm are the volume of spillage per unit time for major spill and minor spill, respectively. They are determined by the ship type (Bevi, 2009). T_1 is the emergency response time for machine rupture, and T_2 is the emergency response time for hull failure.

3.2.2 Actual compensation and total spill cost estimation

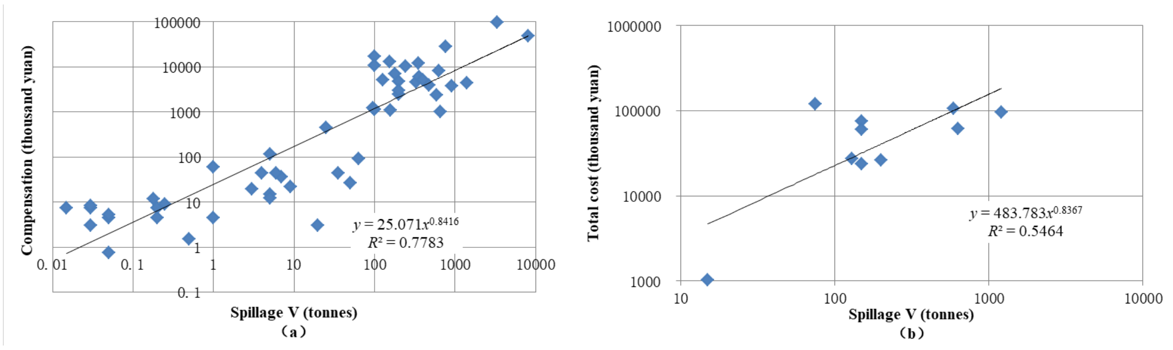
For actual compensation and total spill cost, some researchers uncover the actual compensation and total spill cost are in the log-linear relation to the spillage and build the regression models. However, actual compensation and total spill cost vary by regions, due to the different surroundings and policies. To estimate the total spill cost and actual compensation for the accidents in China, this section collects the spillage, actual compensation and total spill cost of offshore oil spills in China. In theory, the actual compensation should have equaled to the corresponding total spill cost, since the Maritime Law stipulates the responsible enterprises should compensate for the total spill cost in China. However, the total spill cost is found to be significantly larger than the actual compensation by the variance analysis of actual compensation and total spill cost for unit spillage. Therefore, this method deduces the log-linear function between spillage and actual compensation and the log-linear function between spillage and total spill cost, respectively.

This phase first converts the actual compensation and total spill cost into RMB at 2018 taking into account the inflation rate, since the collected data cover the accidents from 1975 to 2004. Secondly, the incomplete entries and outliers are removed. In this way, two datasets are gained, one of 55 spills with actual compensation and spillage for the period of 1975 – 2000, and another of 10 spills with total spill cost and spillage for the period of 1989 - 2004. Thirdly, the former dataset is used for the log-linear regression analysis between spillage and actual compensation as shown in Figure 2(a), and the latter dataset is used for the log-linear regression analysis between spillage and total spill cost as shown in Figure 2(b).The equations of the fitted model are:

$$C_{com}(V) = 25071 V^{0.8416} \quad (6)$$

$$C_{cost}(V) = 483783 V^{0.8370}$$

(7)Here, C_{com} denotes the actual compensation in RMB, C_{cost} denotes the total spill cost in RMB, and V denotes spillage in tonnes.



(a) Linear Regression of Log10(Spillage) and Log10(Actual compensation);

(b) Linear Regression of Log10(Spillage) and Log10(Total spill cost).

Figure 2. Linear Regression.

The reliability analysis of regression models is shown in Table 2.

Table 2 The reliability analysis of regression models

Models	R-squared	Significance F	P-value of Intercept	P-value of variable
Actual compensation	0.778264	1.22E-18	2.88E-38	1.22E-18
Total spill cost	0.546383	0.014573	0.027364	0.014573

All of the significance F and P-value in this study are smaller than 0.05, and the R-squared in this study are larger than those in Psarros (2009) (the R-squared is 0.507) and Yamada (2009) (the R-squared is 0.460). Therefore, the regression models are reliable.

The actual compensation of scenario i (denoted by $C_{com,i}$) and the total spill cost of scenario i (denoted by $C_{cost,i}$) can be estimated by:

$$C_{com,i} = C_{com}(V_i) \tag{8}$$

$$C_{cost,i} = C_{cost}(V_i) \tag{9}$$

3.2.3 Casualty estimation

The casualty $C_{casualty}$ can be estimated by (Jtt1143, 2017):

$$C_{casualty}(V) = \begin{cases} \dfrac{V - 30.035}{33.66} & V \geq 30.035 \\ 0 & Others \end{cases} \tag{10}$$

Here, V is spillage in tonnes. The casualty of scenario i (denoted by $C_{casualty,i}$) can be estimated by:

$$C_{casualty,i} = C_{casualty}(V_i) \tag{11}$$

3.3 Civil liability risk estimation

In this paper, the civil liability risk is defined as the product of the probability and the compensation, which means the mathematical expectation of compensation in a given period. This section discusses the civil liability risk based on actual compensation and statutory compensation (total spill cost), respectively.

Firstly, the civil liability risk based on actual compensation (ACLR) in each spillage scenario is calculated as the product of the corresponding probability and actual compensation. Then, according to the party responsible for the accidents, the ACLR borne by the oil port can be estimated by adding up the ACLRs in the spillage scenarios due to loading machine rupture, and the ACLR borne by the ship owners can be estimated by adding up the ACLRs in the spillage scenarios due to hull failure. Similarly, the civil liability risk based on statutory compensation (SCLR) borne by the oil port and ship owners can be estimated.

Based on the probability and actual compensation estimation, the ACLR in scenario i can be calculated by:

$$R_{com,i}=P_i\times C_{com,i}=\begin{cases} f_{arm,t}\times T_{arm}^S\times C_{com}[V_{mach,t}^S(T_1)] & \text{for loading arm (with size } S\text{) total rupture during handling}\\ f_{arm,p}\times T_{arm}^S\times C_{com}[V_{mach,p}^S(T_1)] & \text{for loading arm (with size } S\text{) partial rupture during handling}\\ f_{hose,t}\times T_{hose}^S\times C_{com}[V_{mach,t}^S(T_1)] & \text{for hose (with size } S\text{) total rupture during handling}\\ f_{hose,p}\times T_{hose}^S\times C_{com}[V_{mach,p}^S(T_1)] & \text{for hose (with size } S\text{) partial rupture during handling}\\ f_{hull,b}\times T\times PM\times T_b\times C_{com}[V_{hull}^M(T_2)] & \text{for major spill due to hull failure during berthing}\\ f_{hull,b}\times T\times pm\times T_b\times C_{com}[V_{hull}^m(T_2)] & \text{for minor spill due to hull failure during berthing}\\ f_{hull,m}\times PM\times T'\times C_{com}[V_{hull}^M(T_2)] & \text{for major spill due to hull failure during maneuvering near a berth}\\ f_{hull,m}\times pm\times T'\times C_{com}[V_{hull}^m(T_2)] & \text{for minor spill due to hull failure during maneuvering near a berth}\\ f_{hull,p}\times PM\times T'\times C_{com}[V_{hull}^M(T_2)] & \text{for major spill due to hull failure during moving through the port}\\ f_{hull,p}\times pm\times T'\times C_{com}[V_{hull}^m(T_2)] & \text{for minor spill due to hull failure during moving through the port} \end{cases} \quad (12)$$

Adding up the risks in the spillage scenarios due to loading machine rupture, the ACLR borne by the oil port (denoted by R_{com}^p) can be calculated by:

$$R_{com}^p=\sum_{i\in I_p}R_{com,i}=(f_{arm,t}\times T_{arm}^S+f_{hose,t}\times T_{hose}^S)\times C_{com}[V_{mach,t}^S(T_1)]+(f_{arm,p}\times T_{arm}^S+f_{hose,p}\times T_{hose}^S)\times C_{com}[V_{mach,p}^S(T_1)] \quad (13)$$

Here, I_p is the set of the spillage scenarios due to loading machine rupture, which are blamed on the oil port, generally.

Adding up the ACLRs in the spillage scenarios due to hull failure, the ACLR borne by the ship owners can be gained. Since the probability and consequence of oil spill are equal for each handling event, the risk is equal for each handling event. Therefore, the ACLR borne by ship owners for a handling event (denoted by R_{com}^h) can be calculated by:

$$\begin{aligned} R_{com}^h=\sum_{i\in I_s}R_{com,i}/T'=&(f_{hull,b}\times T_b+f_{hull,m}+f_{hull,p})\times PM\times C_{com}[V_{hull}^M(T_2)]\\ &+(f_{hull,b}\times T_b+f_{hull,m}+f_{hull,p})\times pm\times C_{com}[V_{hull}^m(T_2)] \end{aligned} \quad (14)$$

Here, I_s is the set of the spillage scenarios due to hull failure, which are blamed on the ship owners, generally.

Similarly, the SCLR in scenario i can be calculated as the product of the corresponding probability and total spill cost:

$$R_{cost,i}=P_i\times C_{cost,i}=\begin{cases} f_{arm,t}\times T_{arm}^S\times C_{cost}[V_{mach,t}^S(T_1)] & \text{for loading arm (with size } S\text{) total rupture during handling}\\ f_{arm,p}\times T_{arm}^S\times C_{cost}[V_{mach,p}^S(T_1)] & \text{for loading arm (with size } S\text{) partial rupture during handling}\\ f_{hose,t}\times T_{hose}^S\times C_{cost}[V_{mach,t}^S(T_1)] & \text{for hose (with size } S\text{) total rupture during handling}\\ f_{hose,p}\times T_{hose}^S\times C_{cost}[V_{mach,p}^S(T_1)] & \text{for hose (with size } S\text{) partial rupture during handling}\\ f_{hull,b}\times T\times PM\times T_b\times C_{cost}[V_{hull}^M(T_2)] & \text{for major spill due to hull failure during berthing}\\ f_{hull,b}\times T\times pm\times T_b\times C_{cost}[V_{hull}^m(T_2)] & \text{for minor spill due to hull failure during berthing}\\ f_{hull,m}\times PM\times T'\times C_{cost}[V_{hull}^M(T_2)] & \text{for major spill due to hull failure during maneuvering near a berth}\\ f_{hull,m}\times pm\times T'\times C_{cost}[V_{hull}^m(T_2)] & \text{for minor spill due to hull failure during maneuvering near a berth}\\ f_{hull,p}\times PM\times T'\times C_{cost}[V_{hull}^M(T_2)] & \text{for major spill due to hull failure during moving through the port}\\ f_{hull,p}\times pm\times T'\times C_{cost}[V_{hull}^m(T_2)] & \text{for minor spill due to hull failure during moving through the port} \end{cases} \quad (15)$$

The SCLR borne by the oil port (denoted by R_{cost}^p) can be calculated by:

$$R_{cost}^p=\sum_{i\in I_p}R_{cost,i}=(f_{arm,t}\times T_{arm}^S+f_{hose,t}\times T_{hose}^S)\times C_{cost}[V_{mach,t}^S(T_1)]+(f_{arm,p}\times T_{arm}^S+f_{hose,p}\times T_{hose}^S)\times C_{cost}[V_{mach,p}^S(T_1)] \quad (16)$$

The SCLR borne by ship owners for a handling event (denoted by R_{cost}^h) can be calculated by:

$$\begin{aligned} R_{cost}^h=\sum_{i\in I_s}R_{cost,i}/T'=&(f_{hull,b}\times T_b+f_{hull,m}+f_{hull,p})\times PM\times C_{cost}[V_{hull}^M(T_2)]\\ &+(f_{hull,b}\times T_b+f_{hull,m}+f_{hull,p})\times pm\times C_{cost}[V_{hull}^m(T_2)] \end{aligned} \quad (17)$$

3.4 Criminal liability risk estimation

In China, there are three standards to judge whether the oil spill as a violation of the criminal law: (1) spillage is larger than 3 tonnes, (2) total spill cost is more than 300,000 RMB, and (3) there is casualty in the accident. This section analyzes the criminal liability risk borne by the oil port and ship owners based on these three standards.

The criminal liability risk is the product of the probability and the number of crimes caused by the oil spill. The number of crimes is set as 1, when the consequence constitutes a crime. Otherwise, the number of crimes is set as 0. It can be deduced that the criminal liability risk indicates the mathematical expectation of the number of crimes in a given period.

According to the analysis above, the criminal liability risk based on spillage (SCRLR) borne by the oil port (denoted by $R_{crime}^{spillage,p}$), the criminal liability risk based on total spill cost (TCRLR) borne by the oil port (denoted by $R_{crime}^{cost,p}$) and the criminal liability risk based on casualty (CCRLR) borne by the oil port (denoted by $R_{crime}^{casualty,p}$) can be calculated by Equation 18-20, respectively:

$$R_{crime}^{spillage,p} = 1\times \sum_{i\in I_p \mid V_i>3t} P_i + 0\times \sum_{i\in I_p \mid V_i\le 3t} P_i \tag{18}$$

$$R_{crime}^{\cos t,p} = 1\times \sum_{i\in I_p \mid C_{\cos t,i}>300000\,yuan} P_i + 0\times \sum_{i\in I_p \mid C_{\cos t,i}\le 300000\,yuan} P_i \tag{19}$$

$$R_{crime}^{casualty,p} = 1\times \sum_{i\in I_p \mid C_{casualty,i}\ge 1} P_i + 0\times \sum_{i\in I_p \mid C_{casualty,i}<1} P_i \tag{20}$$

Similarly, for each handling event, the SCRLR borne by ship owners (denoted by $R_{crime}^{spillage,h}$), the TCRLR borne by ship owners (denoted by $R_{crime}^{cost,h}$) and the CCRLR borne by ship owners (denoted by $R_{crime}^{casualty,h}$) can be calculated by Equation 21-23, respectively:

$$R_{crime}^{spillage,h} = 1\times \sum_{i\in I_s \mid V_i>3t} P_i / T' + 0\times \sum_{i\in I_s \mid V_i\le 3t} P_i / T' \tag{21}$$

$$R_{crime}^{\cos t,h} = 1\times \sum_{i\in I_s \mid C_{\cos t,i}>300000\,yuan} P_i / T' + 0\times \sum_{i\in I_s \mid C_{\cos t,i}\le 300000\,yuan} P_i / T' \tag{22}$$

$$R_{crime}^{casualty,h} = 1\times \sum_{i\in I_s \mid C_{casualty,i}\ge 1} P_i / T' + 0\times \sum_{i\in I_s \mid C_{casualty,i}<1} P_i / T' \tag{23}$$

This method set the criminal liability risk to be in the acceptable areas, when the criminal liability risk is less than 0.01 per year. It is because the frequency of offshore oil spills is regarded as very low, when the frequency is less than 0.01 (Jtt1143, 2017).

To prevent crime, this section calculates the threshold of emergency response time keeping spillage less than 3 tonnes (denoted by $T_{spillage=3}$), the threshold of emergency response time keeping total spill cost less than 300,000 RMB (denoted by $T_{total\ cost=300000}$), and the threshold of emergency response time keeping casualty less than 1 (denoted by $T_{casualty=1}$), in each spillage scenario. Here,

$$T_{spillage=3} = \begin{cases} V_s^{machine-1}(3) & for\,machine\,rupture \\ V^{hull-1}(3) & for\,hull\,failure \end{cases} \tag{24}$$

$$T_{\cos t=300000} = \begin{cases} V_s^{machine-1}[C_{\cos t}^{-1}(300000)] & for\,machine\,rupture \\ V^{hull-1}[C_{\cos t}^{-1}(300000)] & for\,hull\,failure \end{cases} \tag{25}$$

$$T_{casualty=1} = \begin{cases} V_s^{machine-1}[C_{casualty}^{-1}(1)] & for\,machine\,rupture \\ V^{hull-1}[C_{casualty}^{-1}(1)] & for\,hull\,failure \end{cases} \tag{26}$$

Based on Equation 5, 9, 11 and 24-26, Table 3 shows the threshold of emergency response time of different scenarios. In Table 3, the minimum is calculated by setting ρ as 1 kg/L, RM as 360 m^3/h, and rm as 180 m^3/h, and the maximum is calculated by setting ρ as 0.6 kg/L, RM as 150 m^3/h, and rm as 40 m^3/h, since the general range of the density of oil is from 0.6 kg/L to 1 kg/L, the range of RM is from 150 m^3/h to 360 m^3/h, and the range of rm is from 40 m^3/h to 180 m^3/h (Bevi, 2009). The thresholds which are shorter than the general values are in bold face. The general emergency response time for hull failure is 30 minutes (Bevi, 2009), and the general emergency response time for mechanical failure is set as 3 minutes (Cmsa, 2011).

Table 3 The threshold of emergency response time for crime prevention

Scenario	Size	$T_{spillage=3}$(minutes)			$T_{total\ cost=300000}$(minutes)			$T_{casualty=1}$(minutes)		
		Equation	Min	Max	Equation	Min	Max	Equation	Min	Max
Machine total rupture	DN150	$0.61/\rho$	**0.61**	**1.02**	$0.11/\rho$	**0.11**	**0.19**	$12.94/\rho$	12.94	21.57
	DN200	$0.34/\rho$	**0.34**	**0.57**	$0.06/\rho$	**0.06**	**0.11**	$7.28/\rho$	7.28	12.13
	DN250	$0.22/\rho$	**0.22**	**0.37**	$0.04/\rho$	**0.04**	**0.07**	$4.66/\rho$	4.66	7.76
	DN300	$0.15/\rho$	**0.15**	**0.25**	$0.03/\rho$	**0.03**	**0.05**	$3.23/\rho$	3.23	5.39
	DN350	$0.11/\rho$	**0.11**	**0.19**	$0.02/\rho$	**0.02**	**0.04**	$2.38/\rho$	**2.38**	3.96
	DN400	$0.09/\rho$	**0.09**	**0.14**	$0.02/\rho$	**0.02**	**0.03**	$1.82/\rho$	**1.82**	3.03
	DN500	$0.05/\rho$	**0.05**	**0.09**	$0.01/\rho$	**0.01**	**0.02**	$1.16/\rho$	**1.16**	**1.94**
Machine partial rupture	DN150	$6.09/\rho$	6.09	10.16	$1.15/\rho$	**1.15**	**1.91**	$129.39/\rho$	129.39	215.65
	DN200	$3.43/\rho$	3.43	5.71	$0.65/\rho$	**0.65**	**1.08**	$72.78/\rho$	72.78	121.30
	DN250	$2.19/\rho$	**2.19**	3.66	$0.41/\rho$	**0.41**	**0.69**	$46.58/\rho$	46.58	77.63
	DN300	$1.52/\rho$	**1.52**	**2.54**	$0.29/\rho$	**0.29**	**0.48**	$32.35/\rho$	32.35	53.91
	DN350	$1.12/\rho$	**1.12**	**1.87**	$0.21/\rho$	**0.21**	**0.35**	$23.77/\rho$	23.77	39.61
	DN400	$0.86/\rho$	**0.86**	**1.43**	$0.16/\rho$	**0.16**	**0.27**	$18.20/\rho$	18.20	30.33
	DN500	$0.55/\rho$	**0.55**	**0.91**	$0.10/\rho$	**0.10**	**0.17**	$11.65/\rho$	11.65	19.41
Major spill from hull	All tonnages	$3/RM/\rho$	**0.50**	**2.00**	$0.56/RM/\rho$	**0.09**	**0.37**	$63.70/RM/\rho$	**10.62**	42.47
Minor spill from hull		$3/rm/\rho$	**1.00**	**9.00**	$0.56/rm/\rho$	**0.19**	**1.68**	$63.70/rm/\rho$	**21.23**	191.10

The threshold of emergency response time indicates the maximal emergency response time to prevent crime. Once the accident happened, the emergency response time should be kept within the threshold, otherwise the accident will violate the criminal law. Therefore, the criminal liability risk can be reduced by keeping the emergency response time less than the threshold or reducing the probability of violation.

4 Case study: GZ Terminal in the Guangdong-Hong Kong-Macao Greater Bay Area

GZ Terminal (GZT) is the one of the largest oil terminals in Nansha, which is transportation hub of the Guangdong-Hong Kong-Macao Greater Bay Area. In this terminal, the maximum berth tonnage was 80,000 tonnes, and the throughput was 3.6 million tonnes in 2018. The product with the maximum density is refined oil, so set ρ as 0.738 kg/L. Most of the handled ships are double-hull and liquid bulk tankers, so pm, PM, rm and RM are set as 0.006, 0.0015, 40 m^3/h and 150m^3/h, respectively (Bevi, 2009). The emergency response times for mechanical rupture and hull failure in GZT are 3 minutes and 30 minutes, respectively. The ship traffic is 1,324, and berthing time of ships is 18,493 h in GZT in 2018.

4.1 Probability and consequence estimation results

Input the amount and utilization of loading arm and hose with different sizes (shown in Table 4) into Equation 2-4, the corresponding handling time can be gained as shown in the 7th and 8th column of Table 4, respectively.

Table 4 The handling time of loading machine with different sizes in GZ Terminal in 2018

Size	d_s(cm)	N^S_{arm}	U^S_{arm}(%)	N^S_{hose}	U^S_{hose}(%)	T^S_{arm} (h)	T^S_{hose} (h)	T^S_{mach} (h)
DN150	15.24	15	10	6	10	13140	5256	18396
DN400	40.64	3	21	0	0	5519	0	5519

Inputting the parameters of GZT into the proposed method, the probability and consequence of oil spill in different scenarios in GZT in 2018 are summarized in Table 5.

Table 5 The probability and consequence of oil spill in different scenarios in GZ Terminal in 2018

Scale	Scenario	Size/ tonnage	Probability of oil spill P_i	Spillage V_i (tonnes)	Casualty $C_{casualty,i}$	Actual compensation $C_{com,i}$ (RMB)	Total spill cost $C_{cost,i}$ (RMB)
Total rupture	Loading arm	DN150	0.000394	**10.9**	0.0	187,184	**3,569,663**
		DN400	0.000166	**77.5**	**1.4**	975,457	**18,426,521**
	Hose	DN150	0.021024	**10.9**	0.0	187,184	**3,569,663**
Partial rupture	Loading arm	DN150	0.003942	1.1	0.0	27,165	**519,909**
		DN400	0.001656	**7.8**	0.0	141,240	**2,683,758**
	Hose	DN150	0.210240	1.1	0.0	27,165	**519,909**
Minor spill	Hull failure during berthing	All tonnages	0.000010	**14.8**	0.0	242,139	**4,600,713**
	Hull failure during maneuvering near a berth		0.017477	**14.8**	0.0	242,139	**4,600,713**
	Hull failure during moving through the port		0.001986	**14.8**	0.0	242,139	**4,600,713**
Major spill	Hull failure during berthing		0.000002	**55.4**	0.8	735,376	**13,903,275**
	Hull failure during maneuvering near a berth		0.004369	**55.4**	0.8	735,376	**13,903,275**
	Hull failure during moving through the port		0.000497	**55.4**	0.8	735,376	**13,903,275**

To illustrate oil spills as a criminal act, the spillage (≥3 tonnes), casualty (≥ 1) and total spill cost (≥ 300,000 RMB) are bolded in Table 5. It can be found: (1) based on the incriminating standard of spillage, except for loading machine (with size DN150) partial rupture, the oil spills in the other scenarios would be convicted of a crime. (2) Based on the incriminating standard of casualty, except for loading machine (with size DN400) total rupture, the oil spills in the other scenarios would not cause crime. (3) Based on the incriminating standard of total spill cost, the oil spill in every scenario would violate the criminal law.

4.2 Civil liability risk estimation results

Based on Equation 13 and 16, in 2018, the ACLR borne by GZT can be calculated as 10,223 RMB, and the SCLR borne by GZT can be calculated as 195,305 RMB. The annual income of enterprise can be checked from its annual report. Without the annual report, set and the handling income is about 17 RMB per tonne (Pcrmcpr., 2001). Therefore, the handling income can be calculated by: $17\,RMB\ per\ tonne \times Throughput = 61{,}200{,}000$ RMB. It can be found the handling income is far larger than the ACLR (accounts for 0.02% of the handling income) and the SCLR (accounts for 0.32% of the handling income).

Based on Equation 14 and 17, the ACLR borne by ship owners for a handling event can be calculated as 6 RMB, and the SCLR borne by ship owners for a handling event can be calculated as 119 RMB.

To analyze and compare the SCLRs in different spillage scenarios, this section calculates the SCLRs in different spillage scenarios and their ratios as shown in Table 6:

Table 6 The contribution of each spillage scenario to the civil liability risk based on statutory compensation.

Scenario	Hose rupture	Loading arm rupture	Hull failure during berthing	Hull failure during moving through the port	Hull failure during maneuvering near a berth
The civil liability risk based	184,354	10,951	79	16,040	141,152

on statutory compensation (RMB per year)					
Ratio	52.29%	3.11%	0.02%	4.55%	40.03%

From Table 6, it can be found that the SCLR in GZT in 2018 is mainly contributed by hose rupture and hull failure during maneuvering near a berth, which is 325,506 RMB and accounts for 92.32% of the total. The SCLR caused by hull failure during berthing is negligible, which is 79 RMB accounts for 0.02% of the total risk.

4.3 Criminal liability risk estimation results

Based on Table 5 and Equation 18-20, the annual SCRLR borne by GZT $R_{crime}^{spillage,p} = 0.023239 > 0.01$, the annual CCRLR borne by the GZT $R_{crime}^{casualty,p}$=0.000166 < 0.01, and the annual TCRLR borne by GZT $R_{crime}^{cost,p}$= 0.237421 > 0.01.

Based on Table 5 and Equation 21-23, the SCRLR borne by ship owners for a handling event $R_{crime}^{spillage,h} =$ 0.000018, the TCRLR borne by ship owners for a handling event $R_{crime}^{cost,h} = 0.000018$, and the CCRLR borne by ship owners for a handling event $R_{crime}^{casualty,h}$=0.

5 Discussion

A methodology was proposed to estimate civil liability risk and criminal liability risk in oil port. The scope of the method is restricted to loading machine rupture and hull failures during berthing, maneuvering near a berth and moving through the port.

5.1 Application of probability and consequence

The estimated probability and consequence of each spillage scenario as shown in Table 5 can be helpful to: (1) judge which scenario would result in crime (2) and provide scientific basis for emergency capacity equipping.

In Table 5, the spillage (≥ 3 tonnes), casualty (≥ 1) and total spill cost (≥ 300,000 RMB) were in bold face. It means the corresponding scenarios would violate the criminal law based on the standards of spillage, casualty and total spill cost, respectively. The spillages and the corresponding probabilities can be applied on the terminal emergency capacity equipping. The spills (with spillage < 11 tonnes) probability ($\sum_{V_{i<11\ tons}} P_i$= 0.237256) amounted for 90.64% of all the spills probability ($\sum_i P_i$= 0.261762). It means GZT could deal with 90.64% of the oil spills if GZT was capable of responding to an oil spill of 11 tonnes.

5.2 Discussion on civil liability risk and the methods of civil liability risk mitigation

From the civil liability risk estimation results (see Section 4.2), the annual the SCLR borne by GZT (195,305 RMB) only accounted for 0.32% of the handling income of GZT (61,200,000 RMB), and the SCLR borne by ship owners for a handling event is rather small (119 RMB). It indicates the civil liability risk can be afforded by the oil ports and ship owners. However, the total spill cost (statutory compensation) in each spillage scenario was rather large (519,909-18,426,521 RMB), which accounted for 0.85% - 30.11% of the annual handling income of GZT, even if the oil spill could be responded in time. It means total spill cost would be difficult to be afforded, once the oil spill happened. Therefore, it is necessary for both oil terminals and ship owners to buy insurance or fund for civil liability risk.

This paper found the critical influence factors on risk by finding the scenario with maximal contribution to the civil liability risk. From Table 6, it can be found the SCLR was mainly contributed by hose rupture and hull failure while a tanker is maneuvering near a berth, which accounted for 92.32% of the total. From Table 1, it can be found the high general frequencies of hose rupture per hour and ship-land collision while a tanker is maneuvering near a berth per operation is the main cause of high risk for these two scenarios, and the critical influences on the total risk. It means the risk can be well controlled by mitigating the general frequencies of these two scenarios. Therefore, the following measures are crucial to control and mitigate the risk: (1) reduce the utilization of hose, especially for the hose with large size; (2) ensure the quality of the hoses by strengthening the regular inspection and replacement of the hoses; (3) decrease the frequency of ship-land collision while a tanker is maneuvering near a berth by strengthening the supervision of the moving vessels in the terminal; (4) increase the emergency response speed through regular exercises.

5.3 Discussion on criminal liability risk and the methods of crime prevention

The criminal liability risk estimation results showed the risk borne by GZT was acceptable in terms of casualty, and unacceptable in terms of spillage and total spill cost. There are two ways for oil port to mitigate the criminal liability risk to be acceptable theoretically: (1) Reduce the probability of violation to be less than 0.01 per year by using loading arm to replace hose; and (2) turn the consequence of the violation into the consequence of the compliance, by reducing the emergency response time to be shorter than the threshold as shown in Table 3.

Take GZT as a case, the SCRLR could be mitigated to be acceptable in the former way. Without variation of the handling quantities, set T_{hose}^{DN150} as variable, $T_{arm}^{DN150} = 18396\,h - T_{hose}^{DN150}$ and kept the other parameters unchanged. Inputting the parameters into Equation 18, $R_{crime}^{spillage,p}$=$3.97 \times 10^{-6} T_{hose}^{DN150} +$ 0.002373. Therefore, the crime could be prevented by keeping $T_{hose}^{DN150} \leq$ 1921 h in terms of spillage. The risk also could be mitigated to be acceptable in the last way. Reduced T_1 within the threshold (0.61/ρ = 0.61/0.738 = 0.83 minutes) for the loading machine (with size DN150) total rupture as shown in Table 3. In this situation, the spillage caused by loading machine (with size DN150) total rupture and loading machine (with size DN400) partial rupture was reduced within 3 tonnes, and $R_{crime}^{spillage,p}$= 0.000166 < 0.01. The TCRLR could be mitigated to be acceptable by using loading arms to replace all hoses, while reducing T_1 within the threshold (1.15/ρ= 1.15/0.738=1.6 minutes) for the loading machine (with size DN150) partial rupture. In this situation, the total spill cost caused by loading machine (with size DN150) partial rupture was reduced within 300,000 RMB, and $R_{crime}^{cost,p}$ =0.002373 < 0.01.

From the criminal liability risk borne by ship owners for a handling event estimation results, the risk based on casualty $R_{crime}^{casualty,h}$=0, and the risks based on spillage and total spill cost $R_{crime}^{spillage,h} = R_{crime}^{cost,h} =$ 0.000018. This result was based on the assumption that the emergency time for hull failure was equal to 30 minutes and the ship type was double-hull and liquid bulk tanker. Based on Equation 1 and 5, it could be found the probability of accidents in each operation is greatly affected by the ship type, and the consequence is greatly affected by the ship type and emergency time. From Table 3, it could be deduced it is difficult to prevent crime by accelerating the emergency speed in the spillage scenarios due to hull failure. Therefore, the ship owners can only prevent crime by choosing safer ship type and controlling the operations amount. In the case, the SCRLR and TCRLR borne by a ship owner were acceptable if only the ship owner undertook less than $0.01 \div 0.000018 =$544 handling events per year.

In conclusion, both the oil port and ship owner may violate the criminal law. To prevent crime, (1) the oil port can reduce the probability of violation by using loading arm to replace hose; and turn the consequence of the violation into the consequence of the compliance by reducing the emergency response time to be shorter than the threshold. (2) The ship owner can reduce the probability of violation by choosing safer ship type and controlling the operations amount.

5.4 Problems in China's current Marine pollution prevention laws

In China, it is stipulated under the civil law that enterprises should compensate for total spill cost. However, the actual compensation tends to be far less than the total spill cost and the worldwide actual compensation actually. Figure 3 illustrated the ratio of the actual compensation to the total spill cost in China, and the ratio of the actual compensation in China to the worldwide actual compensation. Here, the actual compensation function in China ($25071 \times V^{0.8416}$ RMB) and the total spill cost in China ($483783 \times V^{0.8370}$ RMB) were deduced in Section 3.2.2, and the worldwide actual compensation function ($297165 \times V^{0.7233}$ RMB) is derived from Imo (2015) based on the oil spills in the whole world. From Figure 3, it can be found the actual compensation could only cover less than 5.4% of total spill cost in China, and is less than 25.1% the global-level actual compensation for the same spillage when the spillage is within 10,000 tonnes. Due to the lack of recent data, the collected data of the oil spills is pre-2010. Actually, since January 1, 2018, China has changed the clean-up cost (the main part of the actual compensation) to environmental pollution tax, which is levied at a rate of 14,000 to 140,000 RMB per tonne depending on the region. The new policy might make the actual compensation higher, but the tax is still less than the worldwide actual compensation and could not cover the total spill cost yet. Take the punishment standard (3 tonnes) in China as an example, the tax is $140{,}000 \times 3 = 420{,}000$ RMB, based on the upper limit of the standard of taxation (140,000 RMB per tonne). However, the tax just is 63.8% of the worldwide actual compensation ($297165 \times 3^{0.7233} = 657{,}807$ RMB), and accounts for 34.6% of the total spill cost ($483783 \times 3^{0.88367} = 1{,}212{,}992$ RMB). Therefore, it is urgent to strengthen the enforcement of civil compensation to increase the compensation ratio in China. To strengthen the enforcement of civil compensation, it is suggested to formulate the compensation standard for unit spillage, instead of the current qualitative compensation requirements.

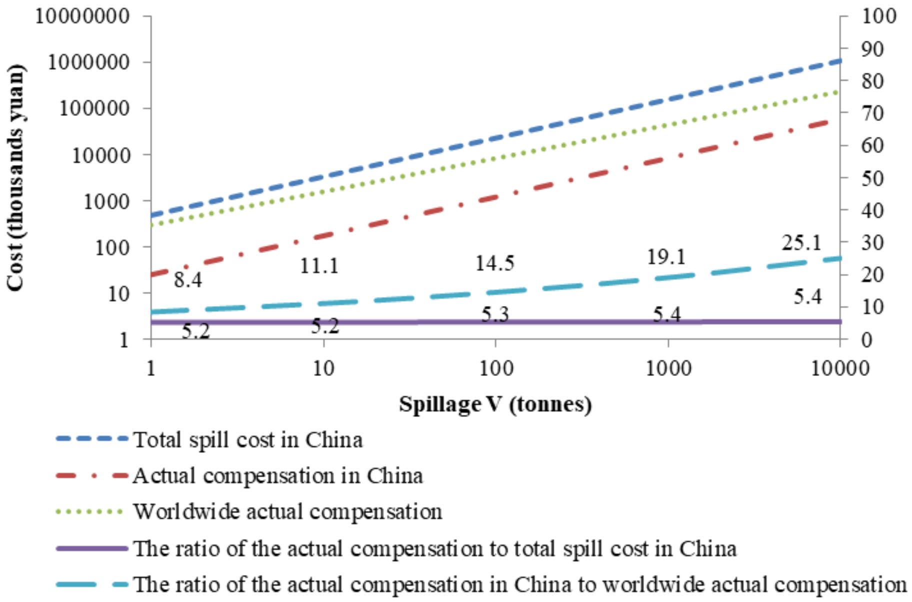


Figure 3. Comparison of compensations (in log-linear plot).

Based on the total spill cost function of spillage and the casualty function of spillage, it can be found the incriminating standards are inconsistent, since 3 tonnes spillage corresponds to 1,212,992 RMB total spill cost, and 3 tonnes corresponds to no casualty. It means the incriminating standard of casualty is the loosest, and the incriminating standard of total spill cost is the strictest. Is it necessary to unity these standards? To answer this question, the impacts of these standards on the enterprise are discussed: (1) the standard of casualty is the loosest but can play a good supporting role. This standard is easy to comply, since the corresponding emergency response time threshold is far longer than the general emergency response time in almost all scenarios (see Table 3), except for larger machine (with size ≥ DN350) total rupture and major spills from hull, whose probability is quite small. Hence, this standard could not restrict the enterprise to reduce the emergency response time or the probability of accident well. However, this standard would constrain the enterprise to build terminal in the location with low population density, and make enterprise pay more attention to the protection of personnel safety when responding to accident. (2) The standard of spillage and the standard of total spill cost are both important, but these standards should be unified. On one hand, the effects of the standard of spillage and the standard of total spill cost are irreplaceable, since the standard of spillage can guide the enterprise to prevent crime more directly, and the standard of total spill cost would constrain the enterprise to build terminal in the location with low economic density. On the other hand, without unity, these two standards might lend the enterprise to divergence when prevents the risk.

In the proposed method, we acknowledge the failure frequency of the handbook may not be suitable to the frequency in China, and the regression database for actual compensation and total spill cost lacks of recent data and is fairly sparse, which may lead to an estimation error. Unfortunately, there are few open data about oil spills in the China. In the future, it is necessary to enhance the risk accident database in China to strengthen the safety of water transportation.

6 Conclusions

From a legal perspective, this paper is aimed to propose a quantitative method to estimate and analyze the risk of oil spills in oil port, whose results have implications for oil port safety and costs management strategies as well as for policy-making. This paper has proposed a method to estimate the civil liability risk and criminal liability risk of each spillage scenario, including loading arm/hose partial/total rupture and hull failure when a vessel is berthing, maneuvering near a berth and moving through the port. Firstly, this paper estimated the probability and spillage of each spillage scenario. Secondly, the spillage of each spillage scenario was estimated by scenario analysis. Then the 65 oil spills data in China has been collected to deduce the actual compensation function of spillage and the total spill cost function of spillage, and the spillage of each spillage scenario has been converted into the total spill cost, actual compensation and casualty. Thirdly, the civil liability risk and criminal liability risk borne by the oil ports and ship owners have been determined based on the estimated probability, spillage, total spill cost, actual compensation, casualty and legal liability.

A general oil terminal in the the Guangdong-Hong Kong-Macao Greater Bay Area has been taken as a case to verify the proposed method. The results are of great significance to oil ports, ship owners and legislatures. For oil ports and ship owners, (1) the estimated probability and the corresponding spillage of each spillage scenario can not only provide reference for emergency capacity setting, but help to judge which scenario would violate the criminal law. (2) The analysis the civil liability risk in each spillage scenario showed the necessity to buy insurance or fund, and digged out the critical influence factors on risk, which is useful to risk control. (3) The threshold of emergency response time and the criminal liability risk estimation can provide advice for crime prevention. For legislatures, (1) the comparison among the actual compensation in China, the total spill cost in China and the worldwide actual compensation revealed the low compensation ratio of oil spills in China. To strengthen the enforcement of civil compensation, the government could formulate the compensation standard for unit spillage, instead of the current qualitative compensation requirements. (2) The incriminating standards were found to be irreplaceable and inconsistent. The incriminating standard based on casualty is the loosest, and the incriminating standard based on total spill cost is the strictest. Therefore, it is suggested to keep the incriminating standard based on casualty, and unity the incriminating standard based on spillage and the incriminating standard based on total spill cost to prevent enterprises from divergence when prevents the risk.

In summary, the main contributions of this paper include: (1) to the best of our knowledge, this is the first work to analyze the liability risk in oil port. Comparing with the existing methods, the proposed method details the spillage, total spill cost, actual compensation, casualty, civil liability risk and criminal liability risk of each spillage scenario. (2) Based on the oil spills data in China, this study deduces the actual compensation function of spillage and total spill cost function of spillage. (3) The results provide some guidance for mitigating civil liability risk, preventing crime and perfecting the marine pollution prevention laws.

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