Risk assessment of dangerous goods areas in ports

Wu Jing[a, b*] , Chen Fengyun[b], Hu Yuchang[b], Wang Guobo[b], Xu Liansheng[b], Mao Xianling[c]
[a] North China Electric Power University, Beijing 102206, China
[b]China Waterborne Transport Research Institute, Beijing 100088, China
[c]Beijing Institute of Technology, Beijing 100081, China

Abstract: Regional quantitative risk assessment has been widely applied to the port area containing dangerous goods tanks, but has been rarely used in the dangerous goods terminals where some dangerous goods vessels often berths. By considering the risk characteristics of dangerous goods areas in ports, consisting of goods at the terminal and in tanks, this study proposes a regional quantitative risk assessment framework. This framework was applied to the Daxie port in China as a case study. The results showed that the regional risk was within acceptable limits, and the priority risk management measures should be taken in the Daxie Petrochemical Company, the Shihua Company, and Fuzhu Village, which contributed most to regional societal risk. Our study indicates that the risk posed by dangerous goods at terminals and in the water in front of the terminals should be examined as well.

Keywords: Regional quantitative risk assessment; Individual risk; Societal risk; Terminal; Tank

I. INTRODUCTION

The dangerous goods area in a port (DGAP) is where dangerous goods companies are arranged in a centralized manner in ports and the serious safety production accidents may occur to threat the safety of the companies and the surrounding environment [1]. DGAP has become crucial for risk prevention and the safety of the Yangtze River waterway. In recent years, the volume of dangerous chemicals transported along the Yangtze River has increased at an average annual rate of 10%. Thus, safety management of the river's waterway faces significant challenges.

Risk assessment has been widely studied, and its basic theory and method have matured as a result [2–4]. Many software companies have developed professional software packages to reduce computations and simplify the calculation processes, such as SAFETI (developed by the Norway Classification Society), and RISKCURVES (developed by the Netherlands Organization for Applied Scientific Research). However, few studies have addressed port risk assessment, and most have focused on the loading and offloading of liquefied natural gas [5–9]. In China, risk assessment has been widely applied to chemical industry parks but rarely to ports [10–17]. Research on ports has often focused on the dangerous goods tank area, and has rarely considered the characteristics of the risk posed by dangerous goods terminals. Moreover, the newly released "Guidelines for Safety Risk Assessment in Dangerous Goods Areas in Ports" do not consider the risk of the dangerous goods terminal [1].

In this study, we propose a regional quantitative risk assessment (QRA) framework for DGAP consisting of a dangerous goods' terminal area and a dangerous goods' tank area. We then applied this framework to a case study. The proposed risk assessment framework provides a theoretical basis for risk management in DGAP.

II. QRA FRAMEWORK FOR DGAP

A. General Procedure

The general procedure of the QRA Framework of DGAP is shown in Fig. 1. A qualitative analysis is first conducted to determine the causes of and scenarios involving accidents. Quantitative calculations are then made to determine the frequency and consequences of accidents. By comparing the quantitative results with acceptable standards, we can obtain the results of the assessment and use them to propose measures to reduce or mitigate risks.

* E-mail: wujing.108@wti.ac.cn

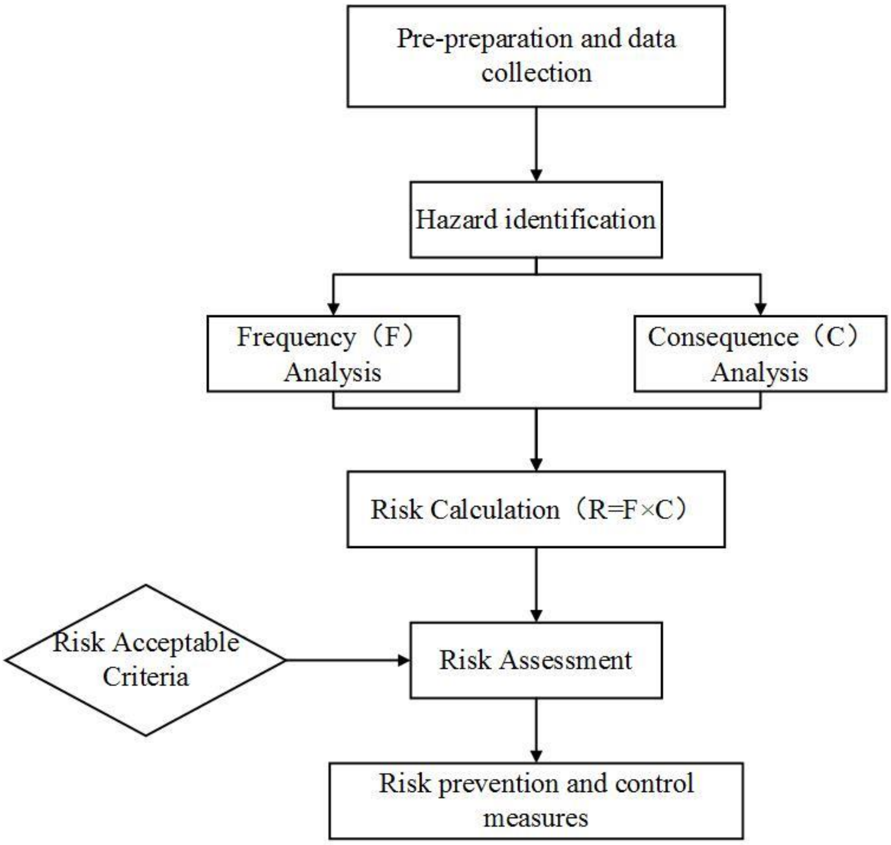


Fig. 1: General procedure for the QRA Framework of DGAP

B. Basic Data Collection

The basic data included meteorological conditions, population distribution data, and basic information and operating conditions for the storage and transportation equipment in DGAP.

The meteorological conditions included atmospheric temperature, humidity, wind direction, wind speed, and the joint frequency of atmospheric stability.

The population distribution data referred to the population during the day and at night in each functioning area of every dangerous goods company, and each surrounding area. The functioning areas of the dangerous goods company often include the terminal area, tank area, office area, dormitory area, guard room, and electric control room.

The basic information of and operating conditions for the storage and transportation equipment included a) volume capacity, types of goods, operating pressure, and operating temperature for each tank; b) the height and area for each cofferdam; and c) the tonnage and type of goods for each terminal.

C. Failure Scenario Selection

The storage and transport equipment included the tank, the vessel docking at the port, and the loading arms/hose. We chose three failure scenarios for the tank: a) complete break, b) the leakage of all stocks for 10 min, and c) the leakage of a 10-mm aperture. We chose two failure scenarios for the loading arms/hoses: a) complete break, and b) the leakage of an aperture with a maximum value of 50 mm.

D. Determining Frequency of Basic Failure

The methods used to determine the basic failure frequency of different storage and transportation equipment were different.

a. Basic failure frequency of tank

Tanks are generally classified into normal pressure tanks and pressure tanks according to the operating pressure of the stored cargo. The basic failure frequencies of both are shown in Tables 1 and 2.

Table 1: Basic failure frequency of normal pressure tanks (cited from [2])

Failure Scenario	Basic failure frequency /y^{-1}
Complete break	5×10^{-6}
The leakage of all stocks for 10 minutes	5×10^{-6}
The leakage of 10 mm aperture hole	1×10^{-4}

Table 2: Basic failure frequency of pressure tanks (cited from [2])

Failure Scenario	Basic failure frequency /y^{-1}
Completely break	5×10^{-7}
The leakage of all stocks for 10 minutes	5×10^{-7}
The leakage of 10 mm aperture hole	1×10^{-5}

b. Basic failure frequency of vessel

The basic failure frequency f_0 of the vessel can be calculated according to this formula (cited from [2]):

$$f_0 = 6.7\times1\times10^{-11}\times T\times t\times N \tag{1}$$

where T is the number of vessels per year at the port, t is the average loading and unloading times per vessel in hours, and N is the number of instances of loading and unloading per year.

c. Basic failure frequency of loading arm/hose

The loading and unloading processes involve the tank and the transport unit (tanker or vessel). The relevant activities involve the loading arm/hose for liquid goods, the emergency shut-off valve for liquid transport, the pump, and the instrument for measuring liquid level, pressure, and temperature. Table 3 lists the basic failure frequency of the loading arm/hose.

Table 3: Basic failure frequency of the loading arm/hose (cited from [2])

Failure Scenarios	The basic failure frequency of loading arm/h^{-1}	The basic failure frequency of loading hose/h^{-1}
Completely break	3×10^{-8}	4×10^{-6}
Diameter of 10% diameter or maximum 50mm aperture leakage	3×10^{-7}	4×10^{-5}

E. Risk Calculation Model

In the QRA method, risk R is described in Eq. (2). In this equation, f_i is the probability of an accident and c_i the expected consequence of the event:

$$R = \sum_i (f_i \times c_i) \tag{2}$$

Individual risk and societal risk are the core quantitative indices of the QRA model for DGAP. Individual risk measures the risk of loss of life, usually expressed by an individual risk contour [18]. Societal risk determines the total impact of an accident on society, usually expressed by the societal risk curve (F–N curve) [18]. Moreover, a societal risk contribution map should be complied to analyze the spatial distribution of regional societal risk, which can help identify high-risk areas and provide scientific support for emergency capacity allocation, and regional security planning and layout. Details about the societal risk contribution map was described by Wu et al. [10].

F. Risk Acceptance Criteria

a. Individual Risk

For workers working at companies that handle dangerous goods, we recommend adopting an unacceptable risk value of higher than 1×10^{-3} per year and a negligible value lower than 1×10^{-5} per year, as recommended by the British Petroleum Company.

For other people in important target areas and sensitive places in such companies, we recommend adopting a negligible risk value of lower than 3×10^{-7} per year, as described in the addendum to "Measures for the supervision and administration of major hazard installations of dangerous goods at ports (Trial)" [18].

b. Societal Risk

We recommend using the ALARP rule (as low as reasonably practicable) as the accepted principle for societal risk, described in the addendum to "Measures for the supervision and administration of major hazard installations of dangerous goods at ports (Trial)" [18], as shown in Fig. 2.

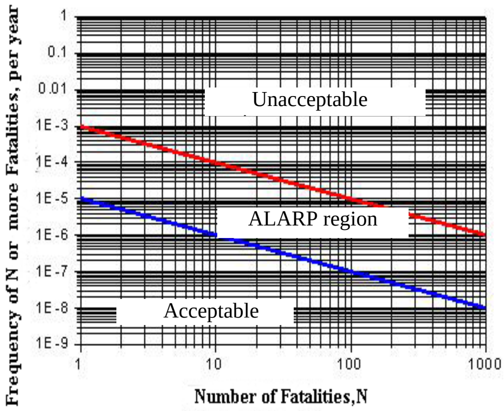


Fig. 2: F–N standard curve for societal risk

III. CASE STUDY ON QRA for DGAP

A. Study Area

The Daxie Port is located in the middle of the coastline of Mainland China, northeast of Beilun District, Ningbo City, in Zhejiang Province. It is a "T"-type meeting point of the golden coastline and the golden waterway of the Yangtze River. Daxie Island covers 30.84 km^2, and has a coastline ~26 km long. It houses three major industries: chemical, port logistics, and energy transfer. It has a total of 21 dangerous goods' terminals and 208 dangerous chemical tanks, with the highest reserve of 3.6 million m^3. There were more than 100 species of dangerous goods at the time data were collected. We selected the relatively independent northeast coastal area of Daxie Port as case study for risk calculation and analysis (see Fig. 3).

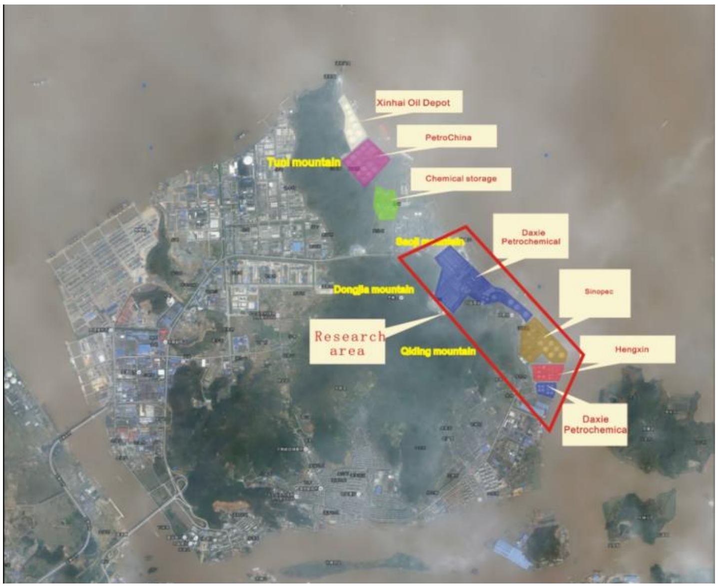


Fig. 3: Distribution of major hazards in Daxie port area

B. Meteorological Conditions

The joint frequency distributions of wind speed and atmospheric stability along different wind directions were calculated (see Table 4) using the method presented in the TNO Purple Book, described by Wu (2007) in detail [10]. A wind rose diagram is shown in Fig. 4. Moreover, we collected the annual average of the meteorological data, including the ambient temperature (17.5 ℃), atmospheric pressure (1016.1 hPa), and relative humidity (76%).

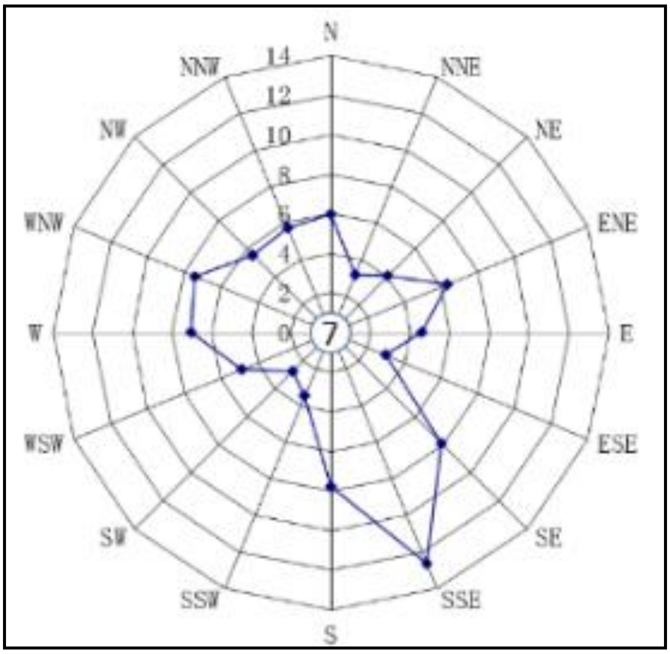


Fig. 4: Local wind rose diagram

Table 4: The joint frequency distributions of wind speed, wind direction, and atmospheric stability in Daxie port

Wind direction	Meteorological classification								
	Daytime				Night				Total
	B 1.5 m/s	D 1 m/s	D 3 m/s	D 7 m/s	B 1.5 m/s	D 1 m/s	D 3 m/s	D 7 m/s	
N	0.28	2.94	0.85	0.00	0.00	2.28	2.28	0.00	6.41
NNE	0.38	1.47	0.47	0.00	0.00	0.73	0.73	0.00	3.36
NE	0.19	2.18	0.38	0.05	0.00	1.40	1.40	0.00	4.35
ENE	0.28	2.13	1.90	0.00	0.00	2.02	2.02	0.05	6.80
E	0.09	1.57	0.85	0.05	0.00	1.92	1.92	0.05	4.95
EES	0.00	0.85	0.43	0.00	0.00	1.66	1.66	0.00	3.25
ES	0.14	2.89	1.00	0.00	0.00	4.04	4.04	0.00	8.59
ESS	0.38	2.66	2.47	0.00	0.00	6.89	6.89	0.00	13.79
S	0.38	1.14	0.85	0.00	0.00	5.65	5.65	0.00	8.59
SWS	0.09	0.62	0.24	0.00	0.00	2.69	2.69	0.00	3.85
WS	0.05	0.95	0.05	0.00	0.00	1.97	1.97	0.00	3.01
WWS	0.05	2.18	0.19	0.00	0.00	2.64	2.64	0.00	5.27
W	0.14	2.89	1.09	0.00	0.00	2.80	2.80	0.05	7.65
NWW	0.14	2.13	1.42	0.00	0.00	2.80	2.80	0.00	8.10
NW	0.19	2.47	1.09	0.00	0.00	1.87	1.87	0.00	5.98
NNW	0.24	2.61	1.90	0.00	0.00	0.88	0.88	0.00	6.04
Total	3.04	31.69	15.18	0.09	0.00	42.23	42.23	0.16	100.00

C. Population Distribution

We collected the population distribution data for six dangerous goods' companies operating in the Daxie port over two periods (day and night). Moreover, the population distribution data for the surrounding companies and villages were collected, and are listed in Tables 5 and 6.

Table 5: Population distribution of major dangerous goods' companies (person)

Company Name	Terminal Area		Tank Area		Office Area		Guard Room		Other area	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
PetroChina	/	/	8	8	32	8	3	2	/	/
Xinhai	/	/	20	5	21	2	3	2	1	1
Chemical storage	/	/	9	4	28	2	3	2	/	/
Sinopec	/	/	11	8	18	2	4	4	4	4
Daxie Petrochemical	6	6	10	5	85	22	13	13	36	21
Hengxin	3	0	10	2	7	1	1	1	3	3

Table 6: Population distribution of other surrounding companies and villages (person)

Location	Population Distribution	
	Day	Night
Saling	110	36
Fuzhu Village	816	816
Shihua	50	25
Kingmayer Steel Pipecompany	30	5
Guanwai	40	5
Fuji	120	80

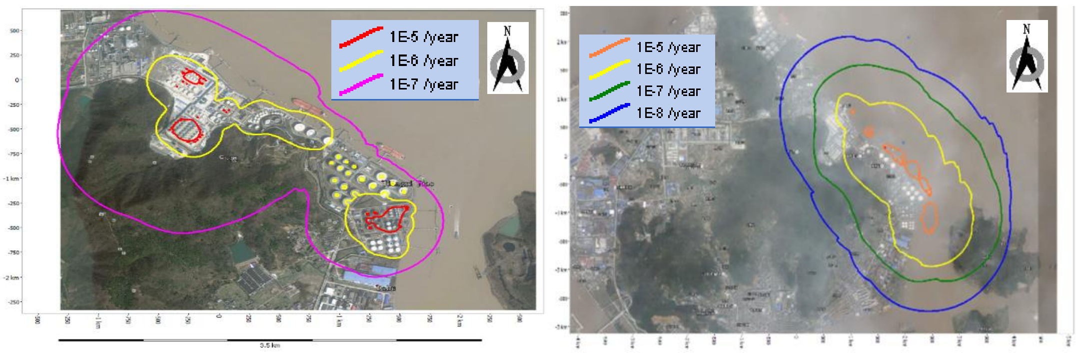
D. QRA Results

There were four dangerous goods' companies with a total of 168 dangerous goods' tanks and 10 dangerous goods' terminals in this DGAP. The risks of leakage, fire, explosion, and poisoning under the typical failure scenario were assessed for the dangerous goods' terminal and the dangerous goods' tank areas. Regional individual risk contours, regional societal risk F–N curve, and societal risk contribution map are shown in Figures 5–8.

The regional individual risk contours for the dangerous goods' tank and the dangerous goods' terminal areas both show that the risk to personnel both inside and outside the four dangerous goods' companies in the DGAP was acceptable. It can also be seen that the risks of the tank area and the dangerous goods' terminal area were of the same order of magnitude.

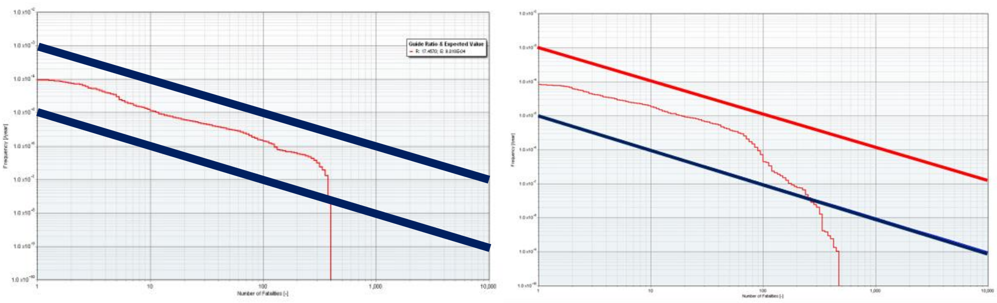
The regional societal risk of this DGAP was within the ALARP range for both the dangerous goods' tank area and the dangerous goods' terminal area. That means that if economic conditions permit, risk prevention and control measures should be implemented to minimize regional societal risk.

The societal risk contribution map and cumulative contribution of the four companies over regional societal risk show that both the dangerous goods' tanks and the dangerous goods' terminals contributed most to regional societal risk. Of these, the cumulative contributions of the dangerous goods' tanks of the Daxie Petrochemical Company (at 62.86%) and the dangerous goods' terminal of Shihua Company (52.81%) were the highest, mainly owing to the intensive population distribution around both. If economic conditions permit, risk prevention and control measures should be first implemented to these two areas. Moreover, more attention should be paid to Fuzhu Village because of its large population and major contribution to societal risk.



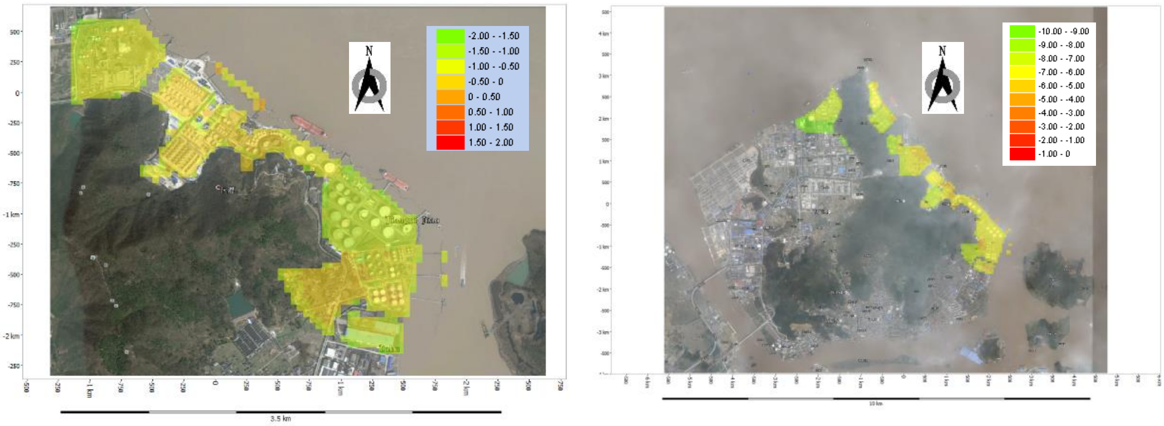
(a) Dangerous goods' tank area **(b) Dangerous goods' terminal area**

Fig. 5: Regional individual risk contours



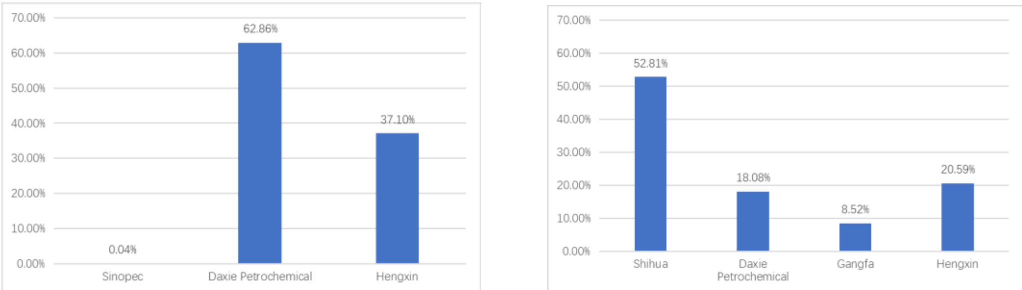
(a) Dangerous goods' tanks area **(b) Dangerous goods' terminal area**

Fig. 6: F–N curve of regional societal risk



(a) Dangerous goods' tanks area **(b) Dangerous goods' terminal area**

Fig. 7: Contribution map of societal risk



(a) Dangerous goods' tanks area **(b) Dangerous goods' terminal area**

Fig. 8: Cumulative contributions of four companies to regional societal risk

IV. CONCLUSIONS

In this study, we proposed a QRA framework for DGAP containing the general procedure, basic data collection, failure scenarios' selection, determination of the basic failure frequency, a risk calculation model, and risk acceptance criteria. This framework was applied to Daxie port for assessment. The results show that the regional individual risk and regional societal risk of this DGAP in Daxie port were within acceptable ranges. Considering the spatial distribution and cumulative contribution sources of regional societal risk, if economic conditions permit, risk prevention and control measures should be prioritized and implementation for dangerous goods' tanks of Daxie Petrochemical Company, the dangerous goods' terminal of Shihua Company, and Fuzhu Village. The results also indicate that the risk posed by the dangerous goods' terminal area should be attended to as much as the risk of the dangerous goods' tank area.

ACKNOWLEDGMENT

This research was funded by the National Key Technology Research, the Development Program of the Ministry of Science and Technology of China (2015BAG20B01; 2015BAG20B04), and the National Natural Science Foundation of China (41501561; 61772076).

REFERENCES

[1] Ministry of Transport of the People's Republic of China. *"Guidelines for Safety Risk Assessment in Concentrated Areas of Dangerous Goods Areas in Ports"*. http://www.gov.cn/xinwen/2017-06/17/content_5203364.htm，2018.3.20.

[2] National Institute of Public Health and the Environment (RIVM). *"Reference manual bevi risk assessments introduction"* [M]. Bilthoven, the Netherlands, 2009.

[3] Khan I. Khan, Abbasi S.A., *"Risk Analysis of a Typical Chemical Industry Using ORA Procedure"*. Journal of Loss Prevention in the Process Industries, 14(1): pp. 43─59, (2001).

[4] Bottelberghs P.H. *"Risk Analysis and Safety Policy Developments in the Netherlands"*. Journal of Hazardous Materials, 71(1─3), pp. 59─84, (2000).

[5] Fuentes-Bargues, J. L., M. C. Gonzalez-Cruz, C. Gonzalez-Gaya and M. P. Baixauli-Perez. *"Risk Analysis of a Fuel Storage Terminal Using HAZOP and FTA."* International Journal of Environmental Research and Public Health, 14(7), pp. 26, (2017).

[6] Martins, M. R., M. A. Pestana, G. F. M. Souza and A. M. Schleder. *"Quantitative Risk Analysis of Loading and Offloading Liquefied Natural Gas (LNG) On a Floating Storage and Regasification Unit (FSRU)."* Journal of Loss Prevention in the Process Industries, 43, pp. 629─653, (2016).

[7] Yeo, C. T., J. Bhandari, R. Abbassi, V. Garaniya, S. H. Chai and B. Shomali. *"Dynamic Risk Analysis of Offloading Process in Floating Liquefied Natural Gas (FLNG) Platform Using Bayesian Network."* Journal of Loss Prevention in the Process Industries, 41, pp. 259─269, (2016).

[8] Shebeko, Y. N., I. A. Bolodian, V. P. Molchanov, Y. I. Deshevih, D. M. Gordlenko, I. M. Smolin and D. S. Kirillov. *"Fire and Explosion Risk Assessment for Large-Scale Oil Export Terminal."* Journal of Loss Prevention in the Process Industries, 20(4─6), pp. 651─658, (2007).

[9] Alyami, H., P. T. W. Lee, Z. L. Yang, R. Riahi, S. Bonsall and J. Wang. *"An Advanced Risk Analysis Approach for Container Port Safety Evaluation."* Maritime Policy & Management, 41(7), pp. 634─650, (2004).

[10] Wu, J., et al., *"Quantitative Risk Assessment Method for Regional Port Major Hazard Installations and Its Application"*. 2017 4th International Conference on Transportation Information and Safety, pp. 890-894, (2017).

[11] Shen Yu. *"Chemical Industry Area Quantitative Risk Assessment Method and Its Application"*. Safety Health & Environment, 12(6), pp. 37─39, (2012).

[12] MA Yuepeng , LI Zhuxia , NI Kai, YANG Liu. *"A Quantitative Chemical Industry Area Risk Assessment Model"*. Journal of Safety and Environment, 12(5), pp. 239─242, (2012).

[13] Zhou Yafei, Liu Mao. *"Risk Analysis of Major Accidents in Chemical Industry Areas"*. Journal of Disaster Prevention and Mitigation Engineering, 31(1), pp. 68─74, (2011).

[14] Wu Zongzhi, Duo Yingquan, Wei Lijun , Guan Lei. *"Quantitative Area Risk Assessment Method and its Application in Land Use Safety Planning for Major Hazard Installations"*, Engineering Science, 8(4), pp. 46─49, (2006).

[15] Ma Kewei, Zhu Jianxin, Bao Shiyi. *"Research on Quantitative Risk Assessment in Chemical Park Based on Domino Effect Model"*. Journal of Zhejiang University of Technology, 39(1), pp. 29─33, (2011).

[16] Sun Dongliang, Jiang Juncheng. *"Discussion on the Several Problems in Quantitative Risk Analysis of Chemical Industry Park"*. Industrial Safety and Environmental Protection, 39(1), pp. 29─33, (2010).

[17] Jia Wei, Zhu Jianxin, Gao Zengliang, Bao Qifu. *"The Method of Quantitative Area Risk Assessment and Its Application in Chemical Industrial Park"*. China Safety Science Journal, 19(05), pp. 140─146, (2009).

[18] Ministry of Transport of the People's Republic of China. *"Acceptable Risk Value [EB/OL]"*. http://www.mot.gov.cn/xiazaizhongxin/ziliaoxiazai/201510/P020151013 509893367324.doc，2013.5.2.