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Discussions

Risk assessment study of fire following earthquake: a case study of petrochemical enterprises in China

J. Li[1,2], Y. Wang[1,2], H. Chen[1,2], and L. Lin[1,2]

[1]Key Laboratory of Environmental Change and Natural Disaster of MOE, Beijing Normal University, No.19, XinJieKouWai St., HaiDian District, 100875, Beijing, P. R. China
[2]Academy of Disaster Reduction and Emergency Management, Beijing Normal University, No.19, XinJieKouWai St., HaiDian District, 100875, Beijing, P. R. China

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Correspondence to: Y. Wang (wy@bnu.edu.cn)

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Abstract

After an earthquake, the fire risk of petrochemistry enterprises is higher than that of other enterprises as it involves production processes with inflammable and explosive characteristics. Using Chinese petrochemical enterprises as the research object, this paper uses a literature review and case summaries to study, amongst others, the classification of petrochemical enterprises, the proportion of daily fires, and fire loss ratio. This paper builds a fire following earthquake risk assessment model of petrochemical enterprises based on a previous earthquake fire hazard model, and the earthquake loss prediction assessment method, calculates the expected loss of the fire following earthquake in various counties and draws a risk map. Moreover, this research identifies high-risk areas, concentrating on the Beijing-Tianjin-Tangshan region, and Shandong, Jiangsu, and Zhejiang provinces. Differences in enterprise type produce different levels and distribution of petrochemical enterprises earthquake fire risk. Furthermore, areas at high risk of post-earthquake fires and with low levels of seismic fortification require extra attention to ensure appropriate mechanisms are in place.

1 Introduction

Petrochemical enterprises produce products under complex process conditions and can be described as having the following characteristics: airtight environments, high-temperatures, high-pressure, deep cooling and pipelining in most cases, and involve raw materials and products that are inflammable, explosive, toxic, and corrosive. Further, such processes are prone to catch fire in daily production because of a number of factors including operation errors and equipment failure.

After a destructive earthquake strikes, fires are likely to occur in petrochemical enterprises with the leakage of inflammable and explosive substances, ignited by friction sparks or open flames as a result of earthquake damage to workshops, equipment, containers, and other structures. For example, during the Tangshan Earthquake in

China in 1976, a fire occurred in a synthetic fat factory in Tianjin, which totally destroyed the workshop after the sudden explosion of the synthetic tower resulting from a rise in temperature and pressure due to a power failure after workshop frames collapsed. A fire also broke out in a chemical plant in Hangu because of the spontaneous combustion of silicon dichloride following pipeline equipment damage with the collapse of buildings. Furthermore, a fire started in a factory in Hangu when a violent shake threw glycerin into a strong oxidant potassium permanganate and caused a chemical reaction (Business Community, 2008). During Japan's 2011 earthquake, numerous fires started in refineries in cities such as Sendai and Chiba, leading to a significant interruption of factory production (Sohu News, 2011a; Sohu News, 2011b). Therefore, post-earthquake fires (secondary fires) constitute the greatest threat and harm to petrochemical enterprises (Hui and Jiang, 2002). In 1976, fires in petrochemical enterprises accounted for 24 % of the total post-earthquake fires in Tianjin as a result of the Tangshan Earthquake in China (Business Community, 2008).

The total output value of the Chinese petrochemical industry makes up more than 12 % of the gross industrial output value (China Petroleum & Chemical Industry Association, 2009). However, in terms of site selection, petrochemical enterprises' main concern is given to raw materials, product transport, and industrial basis, with little or no consideration for earthquakes. For example, a great many petrochemical enterprises, such as the Jianfeng enterprise, Youxin chemical plant, Hongda chemical plant, and Huafeng phosphorus chemical plant, are located along the Longmenshan Mountain fault belt where the Wenchuan Earthquake occurred in 2008. Furthermore, the layout of most petrochemical enterprises significantly increases post-earthquake fire hazards.

From the perspective of the post-earthquake fire causing mechanism of petrochemical enterprises, by summarizing the regular pattern of general fire occurrence in different types of enterprises, this paper can build a petrochemical enterprise post-earthquake fire risk assessment model based on the post-earthquake fire risk model put forward by Zhao Zhendong (Yu et al., 2003; Zhao et al., 2003) and earthquake loss prediction assessment methods. A macro analysis will follow, with comments on

the post-earthquake fire risk of Chinese petrochemical enterprises, and thus this paper can provide a scientific basis for regional economic development and industrial planning.

2 Previous research

Currently, the most common analysis model to determine the rate of post-earthquake fires is the empirical statistics regression model. Its aim is to find the expression between the post-earthquake fire rate and post-earthquake fire factors using a regression analysis method based on statistics regarding historical earthquake damage.

Kawasumi (1961) and Mizuno (1978) performed the statistical regression analysis with historical earthquake secondary fire data and obtained the relation between the outbreaks of fires and the damage of buildings, named Kawasumi's model and Mizuno's model respectively. Kobayashi (1984) studied that the fire outbreak rate is in relation with the seismic intensity. And he found in the case of earthquakes of less or equal to intensity 6, the fire outbreak rate of total fires may not exceed 2.0×10^{-4}, and of chemical fires may not exceed 0.5×10^{-4}; But in the case of earthquakes of more or equal to intensity 7, the fire outbreak rate is difficult to be estimated due to lack of data. Scawthorn put forward a regression model (Scawthorn, 1986; Scawthorn, 1996; Scawthorn et al., 1981), looking for a relationship between post-earthquake fire rates and earthquake intensity on the basis of collecting and analyzing data on 20th century post-earthquake fires in the United States. His results have been applied to the software package HAZUS developed by the Federal Emergency Management Agency (FEMA) to assess loss under the affect of multiple disasters, and to predict the number of post-earthquake secondary fires in the United States.

In studying the fire after the Northridge earthquake in California, Trifunac and Todorovska (1997, 1998) found that fire ignition rate models correlated with site intensity, peak horizontal ground velocity, the number of red-tagged buildings, and breaks in water pipes. Based on the Monte Carlo simulation and physics-based

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fire-spread/evacuation simulation, Nishino at el. (2012) considered a number of factors (number and location of fire outbreaks, firefighting at the initial stages, weather, earthquake-related structural damage to buildings, initial evacuee locations, and the obstruction of roads) to simulate the burn-down risk and fire-fatality risk after an earthquake. Zhao (2010) built an integrated software system for the dynamic simulation of fires following an earthquake based on GIS; fire ignition, fire-spread, and fire-suppression were also considered in this system.

Tanaka (2012) studied the characteristics and problems of fires following the Great East Japan earthquake in March 2011, and he classified post-earthquake fires into three types: conventional types of fires unrelated to tsunami waves, conflagrations in coastal areas inundated by the tsunami, and the peculiarities of tsunami-related fires. Fire characteristics are different from fire types. Fire ignition rates should be documented to determine the relative occurrence of gas, electrical, chemical and other types of fires (Trifunac and Todorovska, 1997).

The DOW Fire & Explosion Index method and the ICI MOND method (Cai et al., 2009; Wang and Xu, 2009) have been adopted in petrochemical enterprise fire safety assessment studies for the quantitative study of the degree and loss of chemical fire risk on the basis of previous accident statistics, material potential energy, and the situation of current safety measures.

However, in view of there being relatively few studies on post-earthquake fires in petrochemical enterprises, Xu et al. (2002) presented methods to calculate the petrochemical enterprise post-earthquake fire probability via research on the relationships among the probability of petrochemical enterprise post-earthquake secondary fires, level of combustible hazard classification, and the level of equipment damage from earthquakes. Chen (2010) researched the risk of industrial enterprise secondary accidents in a natural disaster, based on energy transfer and fire dynamics energy theories, combined with the Hazard and Operability Analysis (HAZOP) method.

3 Mechanism and assessment models of petrochemical enterprise fire following earthquake

Figure 1 shows the post-earthquake fire causing mechanism of petrochemical enterprises. The earthquake first damages workshops and equipment (this loss is called earthquake direct loss) in petrochemical enterprises, then triggers the leakage of flammable, explosive, toxic, and corrosive objects, which result in fire once they meet with an open flame or a spark caused by friction of some kind. Furthermore, the earthquake can cause damage to fire-fighting facilities, pipelines, and roads, which reduces fire-fighting capacity. Thus, it accelerates the spread of fire and fire loss is greater (loss is referred to as fire loss). The sum of the above two losses is the total loss of the fire following earthquake.

According to the above analysis, the calculation formula of post-earthquake fire total loss EFL is shown as expression (1), where EL denotes the direct loss of the earthquake and FL the fire loss.

$$\mathrm{EFL} = \mathrm{EL} + \mathrm{FL}. \tag{1}$$

It is necessary to classify the earthquake fire loss according to the petrochemical enterprise types that are susceptible to fire. The calculation formula of the direct earthquake loss EL in a certain petrochemical enterprise is shown in expression (2).

$$(\mathrm{EL}_{R_i})_k = \sum_{j=1}^{5} P\left(D_j|R_i\right) \cdot I_{D_j} \cdot W_K. \tag{2}$$

In expression (2), D_j refers to the damage level and $P(D_j|R_i)$ to the probability of the damage level D_j with the seismic ground motion parameter R_i. Furthermore, I_{D_j} denotes the earthquake loss ratio of the damage level D_j, k is the petrochemical enterprise type, and W_k the total fixed assets of k-type petrochemical enterprises.

The calculation formula of a petrochemical enterprise's fire loss FL is shown in expression (3).

$$(\mathrm{FL}_{R_i})_k = \frac{1}{C} \cdot \sum_{j=1}^{5} P\left(D_j|R_i\right) \cdot P(F)_k \cdot I_f \cdot W_k^{'}. \quad (3)$$

In expression (3), *1/C* stands for safety measure failure coefficients, $P(F)_k$ for the post-earthquake fire occurrence probability of k-type petrochemical enterprises, I_f for the fire loss ratio, and W_k' for the value of k-type petrochemical enterprises before the fire occurs.

Where a fire occurs after an earthquake, W_k' stands for the surplus value after the earthquake damage, as shown in expression (4).

$$W_k^{'} = W_k - \mathrm{EL} \quad (4)$$

In terms of the DOW Fire & Explosion Index assessment method, because process control, physical isolation, and fire prevention measures can reduce fire loss, security compensation coefficient C is usually adopted to revise the index to ensure that the final loss assessment value better conforms to reality. An earthquake often reduces the local fire-fighting capacity, thus aggravating fire loss. In this case, the safety measure failure coefficient *1/C* can be used to revise fire loss when fire-fighting capacity has been reduced because of the earthquake.

Consulting the best safety measure compensation coefficient in the DOW Fire & Explosion Index assessment method, C is established: $C = 0.489$ and $1/C = 2.05$.

4 Macro risk assessment of China petrochemical enterprise fire following earthquake

4.1 Earthquake hazard probability $P\ (D_j|R_i)$ and loss ratio I_{D_j}

The 2000 seismic ground motion zonation map (Peng et al., 2004) of China has seven levels: < 0.05 g, 0.05 g, 0.10 g, 0.15 g, 0.20 g, 0.30 g and ≥ 0.40 g, according to the seismic peak ground acceleration (PGA) in each region and the 10 % of probability of exceedance in the class (medium hard) site over 50 yr.

Earthquake loss assessment in China classifies the damage levels of buildings into five levels: collapse, serious damage, medium damage, slight damage, and basically intact. Further, the assessment also provides (based on historical earthquake damage and experimental data) the probability $P(D_j|R_i)$ and loss ratio I_{D_j} corresponding to different damage levels (Earthquake loss prediction research team of China Earthquake Administration, 1990; Institute of Engineering Mechanics, 2005).

As industrial factory buildings are the main assets of petrochemical enterprises, this paper takes the factory building loss ratio as the earthquake loss ratio I_{D_j} of petrochemical enterprises. In expression (2), the I_{D_j} is the loss ratio of petrochemical enterprises suffering from different degrees of seismic damage, and its range refers to the industrial factory building damage loss ratio in post-earthquake field works–part 4: assessment of direct loss (GB/T 18208.4-2005) (Institute of Engineering Mechanics, 2005), as shown in Table 1.

4.2 Petrochemistry enterprise classification k and asset value W_k

A post-earthquake fire is subject to uncertainty due to numerous factors including the existence of combustibles, flammability of combustibles, and earthquake damage levels. Production equipment, technological processes, raw materials, and semi-finished and final products vary among petrochemical enterprises, which result in different fire probabilities.

In accord with the Industrial Classification For National Economic Activities (GB/T 4754-2011) (National Bureau of Statistics of China, 2011), this paper divides petrochemical enterprises into four types: PE_1, oil, natural gas drilling, petroleum processing, coking and nuclear fuel processing enterprises; PE_2, chemical raw materials and chemical product manufacturing enterprises; PE_3, chemical fiber manufacturing enterprises; PE_4, rubber and plastic product manufacturing enterprises.

Considering the complexity of the value components of petrochemical enterprises and the availability of data, the fixed asset value is taken as its total value W_k.

The fixed asset data W_k for the four types of petrochemical enterprises was sourced from China's 2008 economic census data [9], with the province as the basic statistical unit. In view of the lack of related county or city data regarding the fixed assets of petrochemical enterprise, this paper assigns province-level values for fixed assets to all cities and counties according to the industry output value ratio of every city or county to the whole province. Therefore, the distribution of the fixed assets of petrochemical enterprises for counties or cities is obtained in this paper. Figure 2 shows the distribution of the fixed assets per unit area of petrochemical enterprises.

4.3 Fire hazard probability of different types of petrochemical enterprises

The fire occurrence probability $P(F)$ of petrochemical enterprise depends on the probability $P(C)$ of leakage and diffusion of flammable materials in factories, the probability $P(S)$ of ignition, and the fire proportion F_k of the petrochemical enterprise, as shown in expression (5) below.

$$P(F)_k = P(C) \cdot P(S) \cdot F_k \tag{5}$$

Table 2 shows the data (Yu et al., 2003; Zhao et al., 2003) from Zhao Zhendong et al. on the basis of historical data, that is, the probability $P(C_j|D_j)$ of leakage and diffusion and the probability $P(S_j|D_j)$ of petrochemical enterprise fire occurrence at different levels of earthquake damage.

F_k is the daily fire occurrence proportion of petrochemical enterprises. Fire hazard probability varies among petrochemical enterprises because the chemical substances used in their production processes and the flammable materials in the factory buildings have different characteristics and are stored in various quantities (Sinopec Group, 2008; The Ministry of Public Security of PRC, 2006). Therefore, this paper uses F_k to adjust their fire hazard probability.

On account of the lack of official statistics regarding fires in petrochemical enterprises, this paper calculates F_k by collecting data on 233 fires at petrochemical enterprises in China from January 2005 to July 2011; the data were sourced from China's most authoritative fire protection websites (China's online fire protection website and the Huicong fire protection website) (China Fire Protection Website, 2005–2011; Huicong Fire Protection Website, 2005–2011). According to the China Fire Services, the incidence of petrochemical enterprise fires was 579, 429, 532, 382, and 349 (Fire Department of the Ministry of Public Security of PRC, 2006–2010) for the year 2005, 2006, 2007, 2008, and 2009, respectively. The 233 records are in accord with the minimum sample size demand of the sample survey.

According to enterprise types, this paper divides the above fires into four categories: PE_1, PE_2, PE_3, and PE_4, and calculates daily fire proportion for each category. The results are shown in Table 3; for PE_2, the fire proportion of chemical raw materials and chemical product manufacturing enterprises is higher than for the other categories.

4.4 Fire loss ratio l_f of petrochemical enterprises

Considering the availability of data, this paper simplified the calculation of petrochemical enterprise fire loss ratio l_f by the average loss ratio, that is, the ratio of the average fire loss value to the average fixed asset value of petrochemical enterprises, as shown in expression (5) below.

$$l_f = \frac{L_f}{W} \tag{6}$$

In this expression, l_f refers to the petrochemical enterprise daily fire loss ratio, L_f to the petrochemical enterprise daily fire average loss value, and W to the average fixed asset value of a single petrochemical enterprise.

According to the average fixed asset value of petrochemical enterprises (Leading Group Office of the Second China Economic Census of the State Council, 2010)and petrochemical enterprise fire economic loss data (Fire Department of the Ministry of Public Security of PRC, 2006–2010) in 2008, the petrochemical enterprise daily fire loss ratio $l_f = 0.001$.

5 Fire following earthquke risk of petrochemical enterprises for China's counties

The seismic ground motion zonation map can help identify the level of seismic ground motions R_i in each county and then obtain the $P(D_j|R_i)$ and l_j. With the above loss ratio and fixed asset value, and expressions (1), (2), (3), and (4), the post-earthquake fire expected loss value of the four types of petrochemical enterprises in various counties can be calculated, as shown in Fig. 3a, b, c, and d. Figure 3e shows a post-earthquake fire risk map of China's petrochemical enterprises, showing the loss value of the four types of petrochemical enterprises.

In each picture in Fig. 3, the colors, from dark to light show the post-earthquake fire risk from high to low. Figure 3e shows that the high-risk post-earthquake areas are mainly distributed in central China, including the Beijing-Tianjin-Tangshan region, Shandong, Jiangsu, Zhejiang provinces, and parts of Henan, Shanxi, Shaanxi, Sichuan, Yunnan, Xinjiang, and Guangdong provinces. Cause analysis shows, because of the post-earthquake fire risk chain, that high-risk areas of petrochemical enterprises are closely related to the distribution of seismic fault belts. For example, northern China, containing the north-south seismic belt, has historically experienced significant earthquakes and has a relatively high risk. In contrast, there is a close correlation between risk levels and output value of petrochemical enterprises. For example,

the risk in Shandong and Jiangsu provinces is the highest because the petrochemical industry there is flourishing. In those two provinces, the total amount of fixed assets of large-scale (over 5 million RMB in annual sales) petrochemical enterprises accounted for over 10 % of all petrochemical production in 2008, and ranked first and second in China.

From the perspective of the specific risk distribution of the four types of petrochemical enterprises, as the fixed asset value of PE_1 and PE_2 enterprises are relatively high, so too are the corresponding risk levels, as shown in Fig. 3a and b. In contrast, the risk levels of PE_3 and PE_4 enterprises are relatively low, as shown in Fig. 3c and d. The distribution of high-risk areas for all types of petrochemical enterprises is basically the same as the distribution in Fig. 3e.

The above expected loss is calculated in county unit, and if the expected loss in county is added up to the province unit, the result is shown in Table 4, which is the top ten expected loss of earthquake-fire for provinces. The high loss areas are mainly concentrated in the Bohai Rim (Tianjin, Beijing, Shandong, Hebei, Liaoning), the Yangtze River Delta (Shanghai, Jiangsu) and Shanxi-Henan-Shaanxi Region. But there are large differences between provinces in four type enterprises, and the provinces should adopt different risk prevention measures according to their own development features of the petrochemical industry. For example, Shandong should pay attention to PE_1 and PE_2 earthquake-fire prevention, however, Shanghai and Jangsu only need focus on PE_2.

6 Discussion

The seismic ground motion zonation map is used to determine the seismic fortification of buildings in China. The seismic PGA = 0.05 g is the minimum seismic fortification level, and PGA < 0.05 g is the non-seismic fortification area. Using GIS software layer calculation functions, areas of PGA < 0.05 g can be extracted from the seismic ground motion zonation map and areas with a local expected loss per unit above 20 000 RMB [see Fig. 3(e)]; the two areas can then be added together using GIS superposition to show where the two meet, as shown in Fig. 4.

The black areas in Fig. 4 show regions with low-level seismic fortification and a high risk of petrochemical enterprise post-earthquake fires; these areas are mainly distributed in the southern Shandong Peninsula, southern Jiangsu Province, and along the coast of the Hangzhou Bay and the Pearl River Delta.

In accordance with the post-earthquake fire risk assessment results, the post-earthquake fire loss value per unit area is at a higher level in the above areas, where fire risk is often ignored because of the lower levels of seismic fortification. Accordingly, the level of fire protection construction in petrochemical enterprises is especially important in these areas; on the one hand, an appropriate emergency disaster plan should be formulated, and on the other, seismic standards should be taken into consideration when petrochemical enterprises undertake the construction of fire protection equipment and pipelines to ensure appropriate fire protection in an earthquake.

7 Conclusions

The risk of fire is high for petrochemical enterprises, especially when buildings, chemical equipment, and fire-fighting capacity are damaged in an earthquake. This paper, based on the seismic ground motion zonation map, calculated the expected loss in a post-earthquake fire for four types of petrochemical enterprises in counties in China. The analysis focused on the probability of flammable material leakage and diffusion, ignition source, and fire proportion of petrochemical enterprises.

Areas with a high risk of post-earthquake fires have a wide distribution in the Beijing-Tianjin-Tangshan region; Shandong, Jiangsu, and Zhejiang provinces; and in a number of counties in Henan, Shanxi, Shaanxi, Sichuan, Yunnan, Xinjiang and Guangdong. The risk of petrochemical enterprises requires extra attention and measures in some areas, especially where the level of seismic fortification is low.

In view of the available data, the calculation of some of the parameters used in this paper was conducted in a simplified way. Thus, further study is required to conduct a more precise risk assessment, including a more detailed classification based on petrochemical enterprise production processes, and the effect of varying earthquake intensities on chemical equipment, fire probability, and diffusion probability for all types of petrochemical enterprises.

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Table 1. Industrial factory building damage loss ratio.

Collapse	Serious damage	Medium damage	Slight damage	Basically intact
81–100 %	46–80 %	17–45 %	5–16 %	0–4 %

Source: Post-earthquake field works–part 4: assessment of direct loss (GB/T 18208.4-2005)

Table 2. Probability of leakage, diffusion, and fire occurrence of inflammable material.

	Collapse	Serious damage	Medium damage	Slight damage	Basically intact
Leakage, diffusion $P(C_j \vert D_j)$	0.97 (0.94–1.00)	0.89 (0.84–0.94)	0.80 (0.75–0.84)	0.68 (0.60–0.75)	0.50 (0.40–0.60)
Fire occurrence $P(S_j \vert D_j)$	0.97 (0.94–1.00)	0.89 (0.84–0.94)	0.80 (0.75–0.84)	0.68 (0.60–0.75)	0.50 (0.40–0.60)

Source: Zhao et al. (2003).

Table 3. Daily fire proportion for petrochemical enterprises.

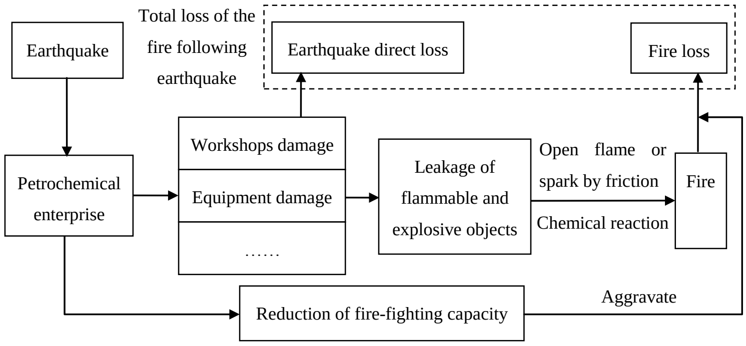
Enterprise type	PE_1	PE_2	PE_3	PE_4
Daily fire proportion	0.171	0.438	0.129	0.262

Source: Authors

Table 4. The top ten expected loss of earthquake-fire for provinces.

Province name	Expected loss (unit: ten thousand RMB)				
	PE1	PE2	PE3	PE4	Total
Tianjin	13 995.60	4107.67	57.05	2619.64	20 779.97
Beijing	5786.72	2927.80	52.41	1006.52	9773.45
Shanghai	739.14	2183.59	65.43	662.38	3650.54
ShanDong	1055.01	1101.85	55.18	367.98	2580.01
Hebei	1162.63	743.13	37.59	242.28	2185.62
Jiangsu	182.90	1264.73	294.60	383.13	2125.36
Henan	845.04	1003.48	76.15	198.14	2122.82
Shanxi	1369.62	690.46	0.85	41.18	2102.12
Shaanxi	1854.04	184.46	0.31	16.40	2055.22
Liaoning	926.71	576.29	35.71	209.19	1747.89

Source: Authors



Source: Authors

Fig. 1. Post-earthquake fire causing mechanism of the petrochemical enterprises.

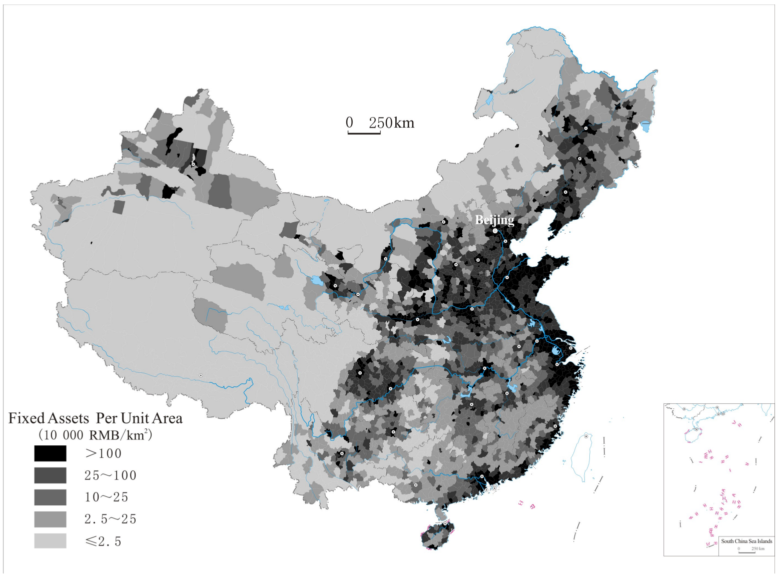


Fig. 2. Fixed assets per unit area of petrochemical enterprises.

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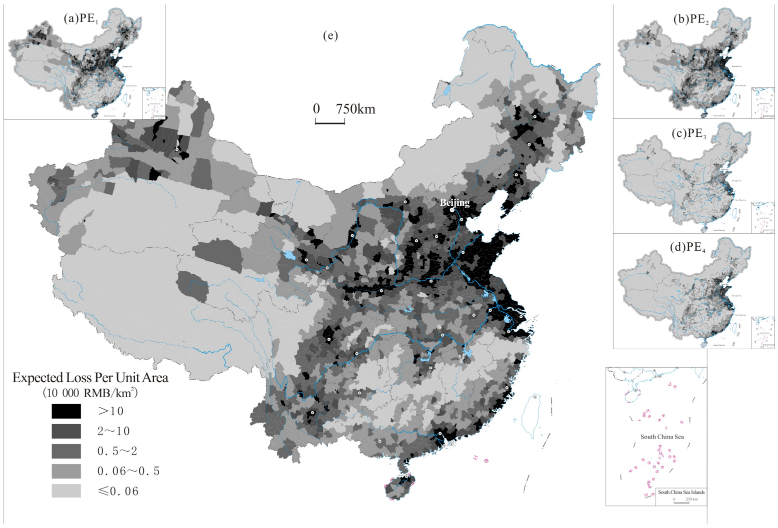

Fig. 3. Earthquake-fire risk map of petrochemical enterprises.

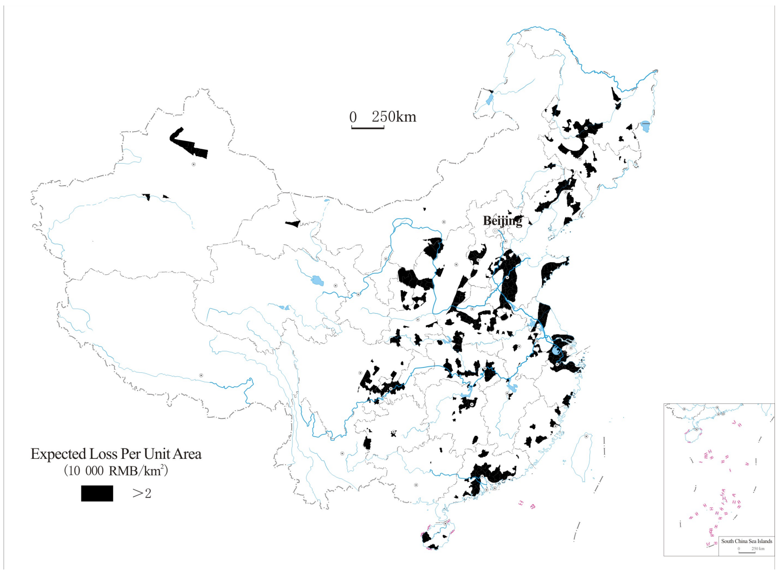

Fig. 4. Expected loss per unit area above 20 000 RMB in seismic PGA < 0.05 area.

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