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Safety distance assessment of industrial toxic releases based on frequency and consequence: A case study in Shanghai, China

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ABSTRACT

A case study on the safety distance assessment of a chemical industry park in Shanghai, China, is presented in this paper. Toxic releases were taken into consideration. A safety criterion based on frequency and consequence of major hazard accidents was set up for consequence analysis. The exposure limits for the accidents with the frequency of more than 10^{-4}, 10^{-5}–10^{-4} and 10^{-6}–10^{-5} per year were mortalities of 1% (or SLOT), 50% (SLOD) and 75% (twice of SLOD) respectively. Accidents with the frequency of less than 10^{-6} per year were considered incredible and ignored in the consequence analysis. Taking the safety distance of all the hazard installations in a chemical plant into consideration, the results based on the new criterion were almost smaller than those based on LC50 or SLOD. The combination of the consequence and risk based results indicated that the hazard installations in two of the chemical plants may be dangerous to the protection targets and measurements had to be taken to reduce the risk. The case study showed that taking account of the frequency of occurrence in the consequence analysis would give more feasible safety distances for major hazard accidents and the results were more comparable to those calculated by risk assessment.

1. Introduction

The rapid growths of the chemical and petrochemical industries had been a major driving force of the Chinese economy in the last decade. Over 60 national or provincial chemical industry parks (CIP) had been authorized till 2005, while the number of CIPs in operation or under development was over 300. Some chemical plants or CIPs were built in or close to the urban areas, and some others built in rural areas have been gradually surrounded by populated areas due to limited land resources and rapid urbanization. In an environmental risk review of 7555 chemical and petrochemical plants nationwide in China in 2006, the State Environmental Protection Administration (SEPA) found that 2489 are close to cities or in densely populated areas [1]. Environmental risks posed by such geographical distribution of chemical plants have emerged gradually with the soaring environmental pollution incidents. For example, about 150,000 people were evacuated during the chlorine leaking accident on 16 April 2004 in the Tianyuan Chemical Plant in Chongqing City in southeast China. The public have been aware of such environmental risks. A P-xylene (PX) project in the Hai-cang District of Xiamen City, Fujian Province, was halted in 2007 due to intensive opposition from the public. The main public opposition to the project was that the site was too close to residential areas, and the debate focused on the answer to the question "how close is too close?" There are no special regulations on the safety distances of chemical plants based on the impacts of major accident hazards in China so far. The increasing environmental pollution accidents and public opposition cases to hazard sources evidenced the need to give more emphasis on the control of major accident hazards and to improve safety distance regulations for the siting of major hazard installations or the land-use planning in risky areas.

Safety distance has already been an important measurement for the hazard control of chemical plants, which usually means to have some space between the hazardous installation and different types of targets. The European Industrial Gases Association (EIGA) defines the safety distance as the minimum separation between a hazard source and an object (human, equipment or environment) which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident [2]. In the Safety Standard for Explosives, Propellants, and Pyrotechnics of NASA [3] separation of explosive locations is required to minimize explosive hazards. In the European Council's Seveso II Directive (96/82/EC), it is required that land-use and/or other relevant policies applied in the member states to take account of the need, in the long term, to keep a suitable distance between residential areas, areas of substantial public use or areas of particular natural interest or sensitivity and establishments presenting such hazards. Different safety criteria for land-use planning have been developed in the member

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states after more than 10 years of the implementation of Seveso II Directive [4,5].

1.1. Quantification of safety distances

Quantification of safety distances is often done by consequence analysis and/or risk assessment. The consequence analysis focuses on the consequences of conceivable accidents without quantifying the likelihood of these accidents [6]. The worst-case scenario is usually the reference scenario in this approach. The safety distance calculated tends to be very large when a fairly high inventory is involved [7]. The main criticism against this approach usually focuses on its ignorance of the frequency of the accidents [6]. Risk assessment takes the likelihood of occurrence into account, as well as the population distribution. In this sense the risk based approach is better than the consequence based approach. However the risks of all the reference scenarios are summed up and little emphasis is given to the consequence of a single scenario in the risk based approach. Therefore, the safety zone set by this approach provides poor protection on the public safety in a determinate scenario like the worst-case scenario. Thus the two approaches are sometimes used together to determine the safety distances of hazard installations. One of the barriers in applying the hybrid of the consequence and the risk based approaches consists of the difficulty to deal with the inconsistency of the safety distances for high-impact and low-frequency accidents calculated by these two approaches. So the balance of the weights of the consequence and the likelihood of occurrence is a puzzle in the siting of major hazard installations.

1.2. Safety criteria

Safety criteria for the public area are necessary for the determination of the safety distance. Exposure concentrations, individual and societal risks are the most popular indicators of the offsite impact. The exposure concentration limits are usually derived from human or animal toxic exposure data. The French land-use planning criterion applied in 1990s adopted LC1 (lethal concentration which causes mortality of 1% of the exposed population) to identify the hazard zone corresponding to the beginning of irreversible heath effects and Immediately Dangerous to Life and Health limit (IDLH) as the threshold concentration to identify the hazard zone where the lethal effect occurs[5,6]. Besides LC1 and IDLH, some other databases for toxic effects were used: Acute Exposure Guideline Levels (AEGL), Emergency Response Planning Guideline (ERPG), Temporary Emergency Exposure Limit (TEEL), Acute Exposure Threshold Levels (AETL) [8–15]. The standards on acceptable or tolerable risks are usually based on the risk statistics as well as the economy development level and the public value concept. Therefore the criteria are different from each other to some extent. For example, the maximum individual risk of death in cases of existing major hazard sites in the Dutch land-use planning criterion is 10^{-5} per year [6,16]. And for a single new risk source a maximum tolerable individual risk of death of 10^{-6} per year has been adopted, which is an increase of the risk of death in everyday life by one percent. The acceptable criterion of individual risk for the land-use planning in the United Kingdom is defined in three levels [17,18]. The maximum limit, which is for low density areas, is 10 in a million per year; for most of the public, the risk of death should not exceed 1 in a million per year; for areas with highly vulnerable people like schools, hospitals and old person's accommodation, an individual risk exceeding 0.3 in a million per year is not acceptable. The criterion of societal risk adopted in the Netherlands is $10^{-3}/N^2$, N being the number of fatalities, while in the United Kingdom it is proposed that the risk of an accident causing the death of 50 people or more in a single event should be regarded intolerable if the frequency is estimated to be more than one in five thousand per annum. The slope of −1 for the FN curve is adopted.

Various approaches can give incomparable safety distances. Christou et al. [19] suggested that there may be significant differences between the safety zones calculated by the consequence analysis and risk assessment and also between the safety zones found through calculations and by expert experiences. Such differences can be significantly large for high-impact and low-frequency hazards, i.e. the hazard zone derived by consequence analysis may be much larger than that given by risk assessment which takes the frequency into account. So when major hazards of very low frequency are taken into account in the siting of or the land-use planning in the vicinity of major hazard sources, it is usually very difficult to draw a proper conclusion which are acceptable both for the developer and the public.

Efforts have been taken to balance the weights of the frequency of occurrence and the consequence in the safety distance assessment. Health and Safety Executive (HSE) of the United Kingdom suggests using the dangerous toxic loads SLOT (Specified Level of Toxicity) and SLOD (Significant Likelihood of Death) in the safety reports [20]. Such method takes the exposure duration into account and gives a better estimation of the hazard zone than that uses only the toxic concentration footprint. Without taking the likelihood of occurrence into account, the safety distance based on the dangerous toxic load, however, may be still much larger than the estimation based on risks for the high-impact and low-frequency accidents. Italy adopts a hybrid criterion that takes into account the frequencies as a mitigation factor for the damage zones, identified using a consequence-oriented approach [5]. A risk matrix is used to combine four probability classes with four effect areas. Each combination is associated to the compatible land-use patterns. The new land-use planning criterion in France combines probability, severity and time requirements for evacuation of buildings [21]. Such criterion is not applicable yet in China due to various reasons. For example, the time requirements for the large-scale offsite emergency response is about 30–60 min according to some local requirements on emergency response planning. Taking 30–60 min as the time to get to shelter, the safety distances found through consequence analyses are usually close to the distances calculated without such time requirement.

1.3. Safety distance regulations in China

There are some official safety distance requirements in China. Decree No. 10 of the State Administration of Work Safety and State Administration of Coal Mine Safety of China [22] requires that major hazardous chemical production and storage installations should be kept away from the sensitive places and areas protected by laws, regulations and standards. According to the General Principle of Safety Assessment for Phosgene and its Products Plant [23], the distance between phosgene and its products plant and the sensitive areas in the downwind of the most frequent wind direction should be no less than 2000 meters. Such requirements however were almost set on the basis of expert experiences without taking the scale of the hazard installation into account. And the risk control of hazard installations has not been taken account of in land-use planning, and it remains the concern of safety production and environmental protection authorities. LC50 (lethal concentration which causes mortality of 50% of the exposed population) is widely used in China to identify the hazard zone corresponding to the beginning of the lethal effects [24–26]. Since no official database of LC50 is yet available, LC50 data from different researches were used in the relevant researches. The Chinese environmental risk assessment guideline (HJ/T 169-2004) [24] also suggests to identify the death zone with the mortality of 50% of the exposed population which can be calculated through the probit equation. The risk

Table 1
Safety criterion based on frequency and consequence.

Safety Level	Frequency (per year)		Description of the consequence	Consequence indicator
I	Frequent Probable Occasional	$>10^{-2}$ 10^{-3} to 10^{-2} 10^{-4} to 10^{-3}	Irreversible health effects	Mortality of 1% or SLOT
II	Remote	10^{-5} to 10^{-4}	Significant likelihood of death	Mortality of 50%, or SLOD
III	Improbable	10^{-6} to 10^{-5}	Highly significant likelihood of death	Mortality of 75% or 2×SLOD
IV	Incredible	$<10^{-6}$	–[a]	–

[a] Incredible scenarios are ignored in the safety distance assessment by consequence analysis regardless of their impacts.

of the maximum credible accident of a hazard installation should not exceed the statistical value for the corresponding industry as required by HJ/T 169-2004. For the chemical industry, the maximum risk of death in a single accident is usually restricted to be 8.33×10^{-5} in China [27]. There are no other requirements on the risk arising from the hazard installations in China now.

This paper presents a case study on the safety distance assessment of a chemical industry park in Shanghai, China. The study focused on the hazard contribution of toxic releases. Risk assessment and consequence analysis were both done for the calculation of safety distance. A safety criterion based on frequency and consequence of major hazard accidents was set up for consequence analysis.

2. Method

The safety distance in this study was the minimum space between the hazard sources in a CIP and densely populated area. The aim of the study was to evaluate the risk on the public safety posed by the hazard sources and identify the hazard zone of the CIP. Both consequence assessment and risk analysis were done to calculate the safety distance. Major accidents were identified referring to the TNO purple book [28]. Meteorological data of the past three years measured in the vicinity of the CIP were used in the risk analysis. Based on the statistics of the meteorological data, average wind of 3.2 m/s under neutral stability and low wind of 1.5 m/s under stability F were used as reference meteorological conditions for consequence analysis. Population distribution in the study area was interpreted from aerial photos. The individual risk criterion of HSE for developments used by highly vulnerable people was adopted in

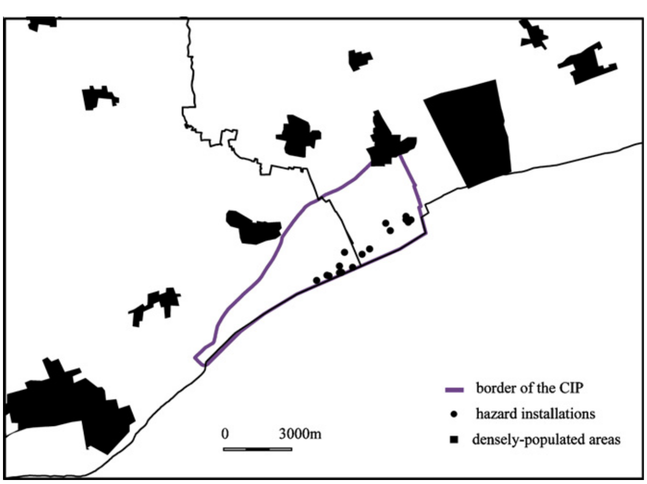

Fig. 1. Map of the hazard installations and the densely populated areas. The border of the CIP was marked by a broad line, the existing hazard installations inside the study area were marked small dots, and the densely populated areas were marked by black polygons.

the risk assessment, as well as the HSE societal risk criterion. A new safety criterion for the consequence assessment was set up in this study to improve the comparability of the results of risk assessment and consequence analysis.

The safety criterion, as shown in Table 1, is based on the frequency and consequence of the accidents. The main aim of applying the new safety criterion is to provide better protection against frequent accident hazards and correspondingly less protection against the hazard of very low frequency. Taking account of the increasing siting difficulty of chemical plants due to limited land resources and rapid urbanization in China, the implementation of such criterion can encourage the developers to improve the production system or the safety system to reduce the accident frequencies and increase the siting attainability.

The worst-case scenario is usually adopted in the consequence based approach. But when the frequency of occurrence is taken into account in the consequence based approach, a set of pre-selected scenarios of different consequences and frequencies have to be considered. The reference scenarios identified in the risk assessment were also used in the consequence analysis.

As shown in Table 1, four safety levels for the accidents were defined combining six frequency levels and three consequence levels in the new safety criterion. Accidents of Safety Level I (SL-I) were defined to be those occur once in ten thousand years or more frequently, accidents of Safety Level II (SL-II) were the remote accidents with the frequency of 10^{-5}–10^{-4} per year, accidents of Safety Level III (SL-III) were the improbable accidents with the frequency of 10^{-6}–10^{-5} per year. Accidents with the frequency of less than 10^{-6} per year were considered incredible and ignored in the safety distance assessment by consequence analysis regardless of their impacts. The exclusive zone for a SL-I accident corresponds to the area with irreversible health effects or worse, the exclusive zone for a SL-II accident corresponds to the area with significant lethal effects or worse, and the exclusive zone for a SL-III accident corresponds to the area with highly lethal significant effects or worse.

Two indicators of accident consequence were adopted, i.e. the dangerous toxic load [20] and the mortality calculated through the probit Eq. (1) with the toxic data suggested by HJ/T 169–2004.

$$Y = A + B \ln(C^n \times t) \quad (1)$$

where Y is the probit value, A, B and n are the specific toxic data for chemicals, C is the exposure concentration, and t is the exposure time. When the dangerous toxic loads and the toxic data for the mortality calculation of a chemical species are both available, two safety distances were calculated and the larger one should be accepted. More specifically, mortalities of 1%, 50% and 75%, as well as the toxic loads of SLOT, SLOD and twice of SLOD, were adopted as the threshold values for the SL-I, SL-II and SL-III accidents respectively. When toxic data were not available to calculate the mortality, a default approach of simply multiplying SLOD by a factor of 2 was taken to calculate the toxic load for the SL-III accidents. The multiplying factor is approximately equal to the result of dividing the

Table 2
Accident scenarios.

Scenario ID	Installation	Containment	Scenario description	Frequency (events/year)
1-1[a]	Phosgenation vessel	Phosgene	Rupture	8.00×10^{-6}
1-2	Canned submersible pump	Phosgene	Rupture	3.00×10^{-7}
1-3	Pipeline	Phosgene	Rupture	1.80×10^{-6}
2-1	Storage tank	Phosgene	Rupture	3.00×10^{-6}
3-1	Pipeline	Phosgene	Leakage from a hole	5.10×10^{-5}
3-2	Pipeline	Phosgene	Rupture	1.00×10^{-5}
3-3	Pipeline	Phosgene	Rupture	3.90×10^{-6}
3-4	Pipeline	Phosgene	Rupture	4.00×10^{-6}
4-1	Pipeline	Phosgene	Leakage from a hole	2.40×10^{-5}
4-2	Pipeline	Phosgene	Rupture	4.80×10^{-6}
4-3	Pipeline	Phosgene	Rupture	2.60×10^{-6}
5-1	Pipeline	Phosgene	Leakage from a hole	1.10×10^{-6}
5-2	Pipeline	Phosgene	Leakage from a hole	4.60×10^{-6}
5-3	Pipeline	Phosgene	Leakage from a hole	3.00×10^{-6}
5-4	Pipeline	Phosgene	Rupture	2.50×10^{-7}
6-1	Pipeline	Phosgene	Leakage from a hole	5.60×10^{-6}
6-2	Pipeline	Phosgene	Rupture	4.80×10^{-7}
6-3	Pipeline	Phosgene	Leakage from a hole	2.80×10^{-6}
8-1	Storage tank	Chlorine	Rupture	2.00×10^{-6}
8-2	Pipeline	Chlorine	Outflow from a leak with an effective diameter of 10% of the nominal diameter	7.69×10^{-4}
8-3	Pipeline	Chlorine	Rupture	6.59×10^{-6}
9-1	Storage tank	Ammonia	Overpressure release from the relief valve	1.00×10^{-6}
9-2	Storage tank	Ammonia	Leakage from the pipe joint	3.50×10^{-5}
9-3	Pipeline	Ammonia	Leakage from a hole	4.50×10^{-5}
9-4	Pipeline	Ammonia	Rupture	8.90×10^{-6}
9-5	Pipeline	Ammonia	Leakage from a hole	6.00×10^{-4}
9-6	Pipeline	Ammonia	Rupture	1.20×10^{-4}

[a] The number before the hyphen is the index of the chemical plants, and the number after the hyphen is the index of the accident scenarios identified for a chemical plant.

toxic loads corresponding to the mortality of 75% by the toxic loads corresponding to the mortality of 50%. Here the toxic load is the $C^n t$ in Eq. (1) calculated with the toxic data in HJ/T 169-2004.

3. Results and discussion

3.1. Description of the case

The case was the safety distance assessment of a CIP in the coastal area in Shanghai. There were nine chemical plants in this CIP which transport, store or deal with ammonia, chlorine and phosgene. The locations of hazard sources in these chemical plants are marked by small dots in Fig. 1. The locations of the CIP and the densely populated areas are also shown in the figure. Colleges and centralized residential areas in towns were identified to be areas to be protected. The major hazard sources were close to some densely populated public areas. And the minimum distance between the

Table 3
Safety distances based on different exposure limits.

Scenario ID	Safety Level	Safety distance (m)					
		SLOT	SLOD	2 × SLOD	1%	50%	75%
9-6	I	1,360	940	730	2940	900	530
8-2	I	2,090	1,240	970	2,090	640	490
9-5	I	430	310	260	820	300	100
8-3	II	7,900	4,690	3680	7,900	2,420	1720
9-3	II	960	670	520	2,090	640	410
4-1	II	550	300	220	290	220	180
9-1	III	16,010	10,900	6930	11,620	10,080	4470
9-4	III	9,270	6,500	5080	15,580	6,230	2130
8-1	III	10,700	6,370	5010	10,690	3,290	2340

Table 4
Safety distances for all the scenarios.

Scenario ID	Safety Level	New criterion (m)	LC50 (m)	SLOD (m)	Scenario ID	Safety Level	New criterion (m)	LC50 (m)	SLOD (m)
1-1	III	0[a]	2030	0	6-1	III	0	0	0
1-2	IV	–[b]	920	680	6-2	IV	–	2520	0
1-3	III	410	2220	670	6-3	III	880	4160	1670
2-1	III	2000	4680	3400	7-1	III	240	1420	340
3-1	II	260	360	260	7-2	III	480	990	730
3-2	III	570	1600	920	8-1	III	5010	2150	6370
3-3	III	430	2140	610	8-2	I	2090	470	1240
3-4	III	1010	3210	1650	8-3	II	4690	1580	4690
4-1	II	300	480	300	9-1	III	6930	16190	10900
4-2	III	740	1890	1190	9-2	II	0	0	0
4-3	III	0	7400	2340	9-3	II	670	930	670
5-1	III	0	0	0	9-4	III	5080	8180	6500
5-2	III	0	0	0	9-5	I	820	430	310
5-3	III	0	0	0	9-6	I	2940	1310	940
5-4	IV	–	3610	0					

[a] Safety distances of zero indicate that the concentration or toxic load in the domain were lower than the concerned exposure limits.
[b] Safety distances were not calculated for the accidents of Safety Level IV.

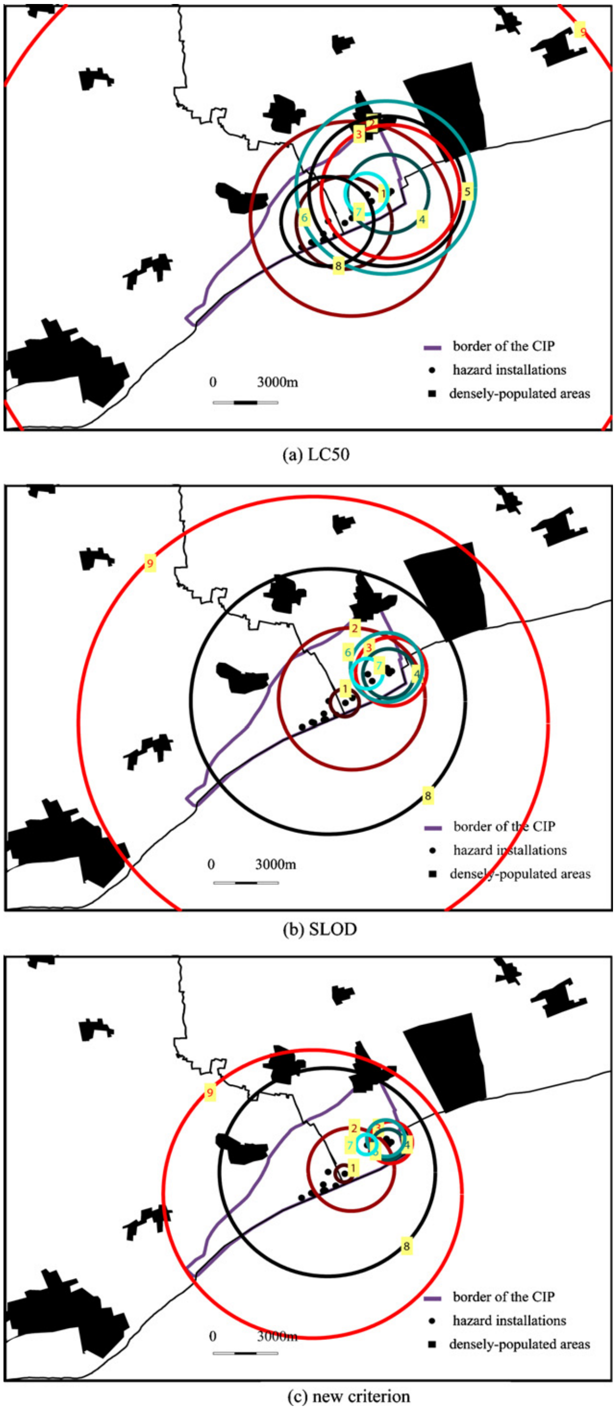

Fig. 2. Safety distances based on LC50, SLOD and the new safety criterion. The radiuses of the hazard zones are the corresponding safety distances. The digital markers correspond to the indices of the nine chemical plants.

residential areas and the hazard sources was about 2.5 km. While the public in these densely populated areas were posed to the risk arising from the CIP, the comprehensive environment of the CIP was still attracting more and more investments. So it was urgent to evaluate the external safety of the CIP and set a proper safety criterion for future development.

The accident scenarios compiled by Environmental Resources Management China are presented in Table 2. Twenty nine accidents were found to be major accidents.

3.2. Consequence analysis results: comparison of different criteria

The safety distances based on different exposure limits are shown in details in Table 3. The numbers of the SL-I, SL-II and SL-III scenarios found in this case were 3, 5 and 18 respectively. Due to limited space, only three scenarios of each safety level which have the most severe impacts among the scenarios are presented in the table.

The safety distances based on SLOD and mortality of 50% for the SL-I and SL-II scenarios were smaller compared to those of the SL-III scenarios. This indicates that low-frequency accidents tend to have higher impact than high-frequency accidents.

Table 4 shows the final results of consequence analysis of all scenarios. The safety distances calculated with LC50 and SLOD are also given. We can find from Table 4 that some of the footprints of LC50 reach more than 10 km. As the demand of urbanization in China still keeps growing fast, it is impossible to keep a safety distance of 10 km in the developing areas. As a result of applying the new safety criterion, the final safety distances of the SL-I scenarios were larger than the results based on the unique safety criterion like SLOD or mortality of 50%, and most of the final safety distances of the SL-III scenarios were smaller than the results based on the unique safety criterion. Some safety distances of the SL-III scenarios based on the new criterion were higher than those based on LC50, like Scenario 8-1. It is worthy of mention that such increase is not the result of the application of the tiered criteria, but the result of substituting the exposure limit LC50 with SLOD. As shown in Table 4, the safety distances base on LC50, SLOD and the new criterion were 2150m, 6370m and 5010m respectively.

After the calculation of safety distances for all the scenarios in Table 2, the safety distances for the nine chemical plants were determined. Fig. 2 shows the safety distances for these plants, in which the results based on LC50 and SLOD are also given for comparison. As mentioned above, the safety distances based on LC50 were usually larger than that based on the new safety criterion. This was also true for the comprehensive results for the chemical plants. Four of the hazard zones based on LC50 (Fig. 2a) were too large that several densely populated areas were covered by them. The largest circle covered almost all the densely populated areas in the vicinity of the CIP. The maximum safety distance based on SLOD (Fig. 2b) was smaller compared to that based on LC50. Two of the hazard zones in Fig. 2 would cover some populated areas. Most of the hazard zones based on SLOD were smaller than those based on LC50.

As discussed above, some of the hazard zones based on the new criterion were be larger than those based on SLOD from the point of view of a single scenario. But the hazard zones for the chemical plants based on the new criterion (Fig. 2c) were almost smaller than those based on SLOD. That was because the weight of those high-impact and low-frequency scenarios was still decisive in the comprehensive evaluation on the basis of the chemical plants, although the exposure limits for them were increased according to the new safety criterion.

3.3. Safety distance based on consequence analysis and risk assessment

The consequence analysis based on the new safety criterion indicates that the hazard sources in chemical plants No. 8 and No. 9 may be a threat to the public safety. Individual and societal risks were assessed taking account of all the major accident scenarios of the hazard installations in the CIP. All the risks of death of the maximum credible accidents were smaller than 8.33×10^{-5}. The individual risk contour is shown in Fig. 3a and the societal risk of the existing installations in Fig. 3b. The hazard zone corresponding to the individual risk of 3×10^{-7} per year will not reach the densely populated areas around the CIP, and the FN curve for the existing

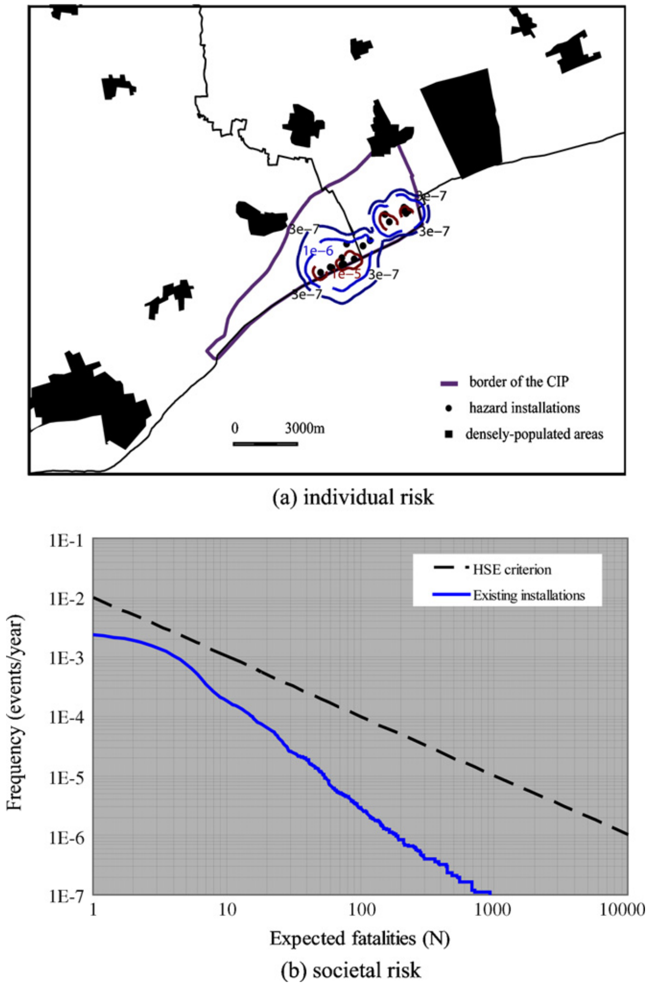

Fig. 3. Risks arising from the hazard installations.

hazard installations lied below the criterion line which indicates the acceptability of the societal risk arising from the CIP.

3.4. Discussion

Safety distance does not mean to provide protection against the catastrophic hazards. Such concept is partially realized by the new safety criterion. If a catastrophic accident is believed to occur once or less in ten million years, it will be ignored in the safety distance assessment, otherwise it should be taken into account in the assessment. It is not safe to exclude all catastrophic accidents like Scenarios 9-1 and 8-1 in the safety distance assessment due to their large hazard zones based on LC50 or SLOD or even the new safety criterion.

Although the hazard zones in Fig. 2c and Fig. 3a are still very different, the hazard zones based on the new safety criterion (Fig. 2c) are more comparable to the results based on the risks (Fig. 3a) than those based on LC50 or SLOD. Furthermore, the meaning of the discrepancies between the results in Fig. 2c (new criterion) and Fig. 3a (individual risk) are different compared to the meaning of the discrepancies between the results in Fig. 2a (LC50) and Fig. 3a (individual risk). Comparing the results in Fig. 2a and Fig. 3a, people tend to prefer the results based on the risks and doubt on the acceptability of the results by consequence analysis, because the latter suggests providing protection on the major hazards of very low frequency. The comparison of Fig. 2c and Fig. 3a, however, indicates that measurements should be taken to decrease the masses or the frequencies of the catastrophic spills from the two plants that have very large hazard zones based on the tiered safety criterion. When the frequencies are considered in the consequence analysis, the consequence analysis may help to find out the real threat to the public safety.

4. Conclusions

With the rapid development of the economy and the chemical industry in China, risks arising from hazard chemical installations are attracting more and more public attention. It is very important to improve the risk control of the chemical industry due to the increasing environmental pollution accidents. Safety distance is an effective way to control the risk. The most popular approaches for the safety distance assessment are consequence analysis and risk assessment. But the results for major hazard accidents based on these two approaches may be of large discrepancy, mostly due to the low frequency of the high-impact accident scenarios.

A case study on the safety distance assessment of a chemical industry park in Shanghai, China, was presented in this article. The aim of the study was to evaluate the risk on the public safety posed by the hazard sources and identify the hazard zone of the CIP. A safety criterion based on frequency and consequence of major hazard accidents was set up for consequence analysis. Four safety levels for the accidents were defined combining six frequency levels and three consequence levels in the criterion. The exposure limits for the accidents with the frequency of more than 10^{-4}, 10^{-5}–10^{-4} and 10^{-6}–10^{-5} per year were mortalities of 1% (or SLOT), 50% (SLOD) and 75% (twice of SLOD) respectively. Accidents with the frequency of less than 10^{-6} per year were considered incredible and ignored in the safety distance assessment by consequence analysis regardless of their impacts. The safety distances derived by consequence analysis for accidents with the frequency of less than 10^{-5} per year (or more than 10^{-4} per year) were smaller (or larger) than those calculated based on LC50 or SLOD. Since most of the accident scenarios identified in the case study were at the frequency of 10^{-6}–10^{-5} per year, the final safety distances based on the new criterion were almost smaller than those based on LC50 or SLOD. The following conclusions can be drawn from this study:

1) The combination of the results of consequence analysis and risk analysis showed that the hazard installations in two of the chemical plants in the CIP may be dangerous to the protection targets. Such chemical plants had to reduce the inventory or the frequency of those catastrophic spills.
2) Taking account of the frequency of occurrence in the consequence analysis would give more feasible safety distances for major hazard accidents and the results were more comparable to those calculated by risk assessment.
3) Since the safety distance may decrease with the frequency of occurrence, applying the new safety criterion will encourage the developers to improve the risk prevention system and reduce the frequency of high-impact accidents.

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References

[1] Ministry of Environmental Protection of the People's Republic of China, SEPA publicized the result of the environmental risk review of chemical

and petrochemical plants nationwide (in Chinese), General News No. 52, http://www.mep.gov.cn/xcjy/zwhb/200607/t20060711_78331.htm, 2006.
[2] EIGA, Determination of safety distances, IGC Doc 75/07/E, http://www.eiga.org/pdf/Doc 75 07 E.pdf, 2007.
[3] NASA, Safety standard for explosives, propellants, and pyrotechnics, NSS 1740.12, 1993.
[4] C. Basta M. Struckl, M. Christou, Overview of roadmaps for land-use planning in selected member states. Report No. EUR 23519 EN, http://mahbsrv.jrc.it/downloads-pdf/Roadmaps-2008.pdf, 2008.
[5] V. Cozzani, R. Bandini, C. Basta, M.D. Christou, Application of land-use planning criterion for the control of major accident hazards: a case-study, J. Hazard. Mater. A136 (2006) 170–180.
[6] M.D. Christou, S. Porter, Guidance on land use planning as required by Council Directive 96/82/EC (Seveso II). Report No. EUR 18695 EN, http://mahbsrv.jrc.it/downloads-pdf/Landuse2.pdf, 1999.
[7] A. Marangon, M. Carcassi, A. Engebo, S. Nilsen, Safety distances: definition and values, Int. J. Hydrogen Energy 32 (2007) 2192–2197.
[8] NOISH, Documentation for Immediately Dangerous to Life or Health Concentrations (IDLH): NIOSH Chemical Listing and Documentation of Revised IDLH Values (as of 3/1/95), http://www.cdc.gov/niosh/idlh/intridl4.html, 1994.
[9] United States Environmental Protection Agency, ALOHA user's manual, http://epa.gov/OEM/docs/cameo/ALOHAManual.pdf, 2007.
[10] United States Environmental Protection Agency, The development of Acute Exposure Guideline Levels (AEGLs), http://www.epa.gov/oppt/aegl/, 2005.
[11] American Industrial Hygiene Association, Current AIHA ERPGs, http://www.aiha.org/1documents/Committees/ERP-erpglevels.pdf, 2007.
[12] United States Environmental Protection Agency, Risk management program guidance for offsite consequence analysis, EPA 550-B-99-009, 1999.
[13] D.K. Craig, J.S. Davis, D.J. Hansen, et al., Derivation of Temporary Emergency Exposure Limits (TEELs), J. Appl. Toxicol. 20 (2000) 11–20.
[14] M.T. O'Mahony, D. Doolan, A. O'Sullivan, M. Hession, Emergency planning and the Control of Major Accident Hazards (COMAH/Seveso II) Directive: an approach to determine the public safety zone for toxic cloud releases, J. Hazard. Mater. 154 (1-3) (2008) 355–365.
[15] M. Wood, A. Pichard, U. Gundert-Remy, S.M. Christianus de Rooij, Tissot, The AETL methodology as a potential solution to current challenges associated with the development and use of acute exposure levels in Seveso II applications, J. Hazard. Mater. A133 (2006) 8–15.
[16] B.J.M. Ale, Tolerable or acceptable: a comparison of risk regulation in the United Kingdom and in the Netherlands, Risk Anal. 25 (2) (2005) 231–241.
[17] Health and Safety Executive, Reducing risks, protecting people: HSE's decision-making process. HSE BOOKS, http://www.hse.gov.uk/risk/theory/r2p2.pdf, 2001.
[18] Health and Safety Executive, PADHI—HSE's land use planning methodology, http://www.hse.gov.uk/landuseplanning/padhi.pdf, 2006.
[19] M.D. Christou, A. Amendola, M. Smeder, The control of major accident hazards: the land-use planning issue, J. Hazard. Mater. 65 (1999) 151–178.
[20] Health and Safety Executive, Assessment of the dangerous toxic load (DTL) for specified level of toxicity (SLOT) and significant likelihood of death (SLOD), http://www.hse.gov.uk/hid/haztox.htm, 2007.
[21] B. Cahen, Implementation of new legislative measures on industrial risks prevention and control in urban areas, J. Hazard. Mater. 130 (2006) 293–299.
[22] State administration of work safety and State administration of coal mine safety, Measures for the implementation of hazardous chemical manufacturing license (Decree of State Administration of Work Safety and State Administration of Coal Mine Safety of China No. 10), 2004 (in Chinese).
[23] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ), General principle of safety assessment for phosgene and its products plant (GB 13548-92), 1992 (in Chinese).
[24] Ministry of Environmental Protection of the People's Republic of China, Technical guidelines for environmental risk Assessment on projects (HJ/T 169-2004), 2004.
[25] J. Du, Analysis on the leaking process of toxic gases from chemical accidents and determination of the risky area (in Chinese), Chin. Saf. Sci. J. 12 (6) (2002) 55–60.
[26] Z. Jia, G. Jing, Q. Zhang, Analysis on the diffusion of toxic gases from gas explosion and the determination of risk area (in Chinese), Chin. Saf. Sci. J. 17 (1) (2007) 91–95.
[27] E. Hu, Techniques and methods for environmental risk assessment (in Chinese), Chinese Environmental Science Publishing House, Beijing, 1999.
[28] Committee for the Prevention of Disasters, Guidelines for Quantitative Risk Assessment (Purple Book CPR 18E), Hague, 1999.