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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