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The Storage Tank Explosion Damage and the Effectiveness of Control Measures in the Chemical Industrial Parks of Smart Cities

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Abstract: Safety is one of the goals of a smart city. To study storage tank explosion damage in a city's chemical industrial parks, determine the position of control measures according to the situation, and realize the analysis of the measured utility, we proposed the area damage probability importance distribution. In this way, the prediction and prevention of risk in chemical industrial parks can be achieved intelligently. The concept of area damage probability importance distribution was given, and the utility analysis method of the control measures for storage tank explosion accidents was put forward. It is concluded that the area damage probability importance distribution represents the change degree of damage probability: that is, the damage degree of storage tank explosion in a chemical industrial park. The control measures for a storage tank explosion can be set up in varying positions, as the explosion damage is mainly caused by shock waves; the blast walls are selected as the measure set, and the calculation method for the area damage probability is modified. By comparing the calculated area damage probability distribution before and after, evaluation of the control measures' effectiveness can be achieved. Finally, the flow chart of the algorithm is given. The example analysis shows that the calculation process and analysis results meet the design requirements of the algorithm. The effectiveness of the method, the distribution characteristics, and the significance and function of the importance distribution of damage probability are discussed. This provides an effective method for smart cities to predict and prevent the impact of an explosion at chemical industrial parks.

Keywords: safety system engineering; chemical park safety; explosive evolution; area damage probability; importance distribution; control measures; utility analysis

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1. Introduction

The chemical industry is the basic industrial pillar of the national economy, and it also holds the main position for the transformation of old and new kinetic energy for the industrial industry. The chemical industry is related to the development of all walks of life; as one of the most important raw materials, chemicals are widely used in various industrial fields. However, there are some problems in the safety status of chemical industrial parks. On the one hand, the planning and layout of such parks are unreasonable, and the large number of enterprises in the park and their dense distribution lead to a sharp increase in high-risk materials, devices, production, storage, and operations,

which increase the safety risk of production. At the same time, the area of these parks is very large, and the consequences of an accident are very serious. On the other hand, densely populated city construction land in some areas is tight, the planning of chemical industrial parks cannot adapt to this state of affairs, and the possibility of safety accidents increases. People attach great importance to the safety of chemical industrial parks, but the safety problem of chemical industrial parks and ensuring the safety of production still need to be solved through systematic research. A variety of monitoring and monitoring equipment is installed, especially in a smart city, which guarantees safe production in chemical industrial parks.

The safety of chemical industrial parks in city areas mainly depends on the condition of the storage tanks themselves and on the disaster prevention and reduction control measures. The former is related to the design of chemical industrial parks, including storage materials, storage tank materials, their volume and shape, the relative position of storage tanks, etc. The latter pertains to the disaster prevention and mitigation measures and devices set up based on storage tank planning. The former considers the distribution of storage tanks in chemical industrial parks from the perspective of production. The latter aims to set up measures to ensure the safety of the park. For chemical industrial parks in cities, especially for existing chemical industrial parks, the selection and setting of disaster control measures are important ways to study and guarantee safety. These situations, parameters, and controls cannot be separated from the basic conditions provided by the smart city.

To study and determine the appropriate location for the implementation of accident control measures in chemical industrial parks and achieve the safety goals of a smart city, a scheme is proposed to firstly calculate the area damage probability importance distribution; then, we selected locations of greater importance in which to set control measures, and finally, we analyzed and evaluated the utility of these control measures. The calculations of tank explosion damage probability, damage probability distribution, tank explosion damage evolution processes, and area damage probability distribution were completed in the preliminary work, which is briefly described here. Based on the concept of smart cities, the paper focuses on the importance distribution of area damage probability and the utility cell of control measures. Based on the concept of smart cities, this paper aims to provide an effective method for selecting the appropriate location for accident control measures in chemical industrial parks.

The main contributions of our work are as follows:

The concept of area damage probability importance distribution is proposed.

The utility analysis method of control measures for storage tank explosion accidents is presented.

We consider that the area damage probability importance distribution represents the change in the degree of damage probability: that is, the degree of damage caused by a storage tank explosion.

This study is organized as follows. Section 2 covers related works; Section 3 introduces the disaster characteristics of chemical industrial parks and smart cities; Section 4 covers the theoretical basis; Section 5 outlines our proposed method; Section 6 presents the simulations and results; and Section 7 discusses the conclusions and future work.

2. Related Work

At present, there has been considerable research on production accidents and safety measures in chemical industrial parks. Shuangshuang et al. [1], combined with study of the current situation of purge gas treatment and emissions in the coal chemical industry, proposed a new method for the explosive utilization of purge gas in the coal chemical industry. Nurzailyn et al. [2] believed that it was necessary to conduct risk assessment research related to explosions to forecast the consequences of a potential explosion. Haixia et al. [3] constructed the Jiangsu chemical risk prevention index system from three dimensions of risk source intensity, receptor vulnerability, and risk prevention ability. Zakrzewska

et al. [4] proposed a new method to produce sustainable and innovative foam, and they studied the effects of combustion performance and thermal stability. Sheng et al. [5] proposed a real-time fire situational awareness (FSA) method based on UAVs to capture the spatio-temporal evolution characteristics of fires and predict the development trend of fire-related accidents. Gonyora et al. [6] used quantitative data analysis methods to explore the relationship between participants' perception of human and organizational factors, maintenance and accidents. Guo et al. [7] proposed a multi-task learning model, namely robust progressive hierarchical extraction, to systematically predict the accident risk category, risk possibility and risk severity. Ebrahimi et al. [8] proposed a nonlinear accident quantitative analysis method that combines the system theory accident model and process (stamp) with the decision test and evaluation laboratory (DEMATEL) and fuzzy logic. He et al. [9] proposed an evacuation path-planning method, which is helpful to optimize the emergency management of multi-hazard accidents and provide guidance for strengthening safety and loss prevention in the chemical industry. Kamran et al. [10] provide a comprehensive and practical method for assessing and managing the risks related to the domino effect in chemical storage tanks by integrating BT, spa and multi-agent dynamic analysis and simulation. Yalcin et al. [11] believed that in the chemical industry, human factors of organization and operation have a significant impact on accidents. Due to the influence of various factors, chemical accidents can occur in various industrial operations. Yuanyuan et al. [12] believed that it was challenging to apply quantitative risk assessment (QRA) to domino accident assessment owing to the uncertainty of the accident escalation process. Bjorheim et al. [13] believed that since the chemical and process industries are very likely to cause personal injury and environmental pollution, objective standards and methods are needed to support plant operators to make decisions and optimize the investment in safety measures. Afube et al. [14] pointed out that correctly identifying hazards and creating a safe working environment are the main challenges facing the management of many industries today. Vianello et al. [15] pointed out that the high complexity of chemical and petrochemical plants determines the complex safety management of these facilities. Therefore, it is necessary in order to find innovative solutions to ensure the prevention of process equipment failure and containment loss.

These studies have their characteristics and have investigated, controlled, and prevented accidents in chemical industrial parks through various theories, methods, and technologies. However, these studies did not focus on the strategic placement of accident prevention measures within the park; instead, they concentrated solely on the accidents and the outcomes of the measures. It is evident that the effectiveness of these control measures placed in different areas of the park is not consistent. If the measure is distant from the accident source, it may not be fully effective; if the distance is too close, the control effect may not be ideal. Furthermore, these studies did not consider the functionalities and capabilities of established smart cities. Despite the abundance of monitoring systems in smart cities, they lack the necessary intelligent methods for analyzing the explosion process in chemical industrial parks. It is essential to conduct an analysis of explosion control measures and their efficacy based on these intelligent analytical methods. The author emphasizes the importance of selecting appropriate accident control measures but stresses that determining the correct location for these measures is even more crucial. This will help maximize the effectiveness of the control measures and achieve the optimal control outcome. Ultimately, this will enable smart cities to enhance their capabilities in preventing, analyzing, and managing chemical industrial park explosions.

3. Disaster Characteristics of Chemical Industry Park and Smart Cities

The chemical industry is an essential pillar of the national economy, supplying raw materials for various industries. It plays a crucial role in construction, electronics, household goods, agriculture, paper packaging, automobiles, medical treatment, and energy. The industry continuously promotes research and development (R&D) and the application of new materials, processes, and technologies, enhancing product quality and driving

industrial upgrading and transformation. It also generates numerous employment opportunities for labor-intensive and technology-intensive sectors, fostering the growth of related industries. Consequently, the chemical industry is a key sector in China. Chemical industry parks serve as vital platforms for industry development. Through centralized planning, resource integration, and optimized layout, they create a conducive environment for chemical enterprises. Centralized environmental management and unified safety supervision help mitigate environmental pollution and safety incidents, ensuring the industry's safe production.

There are also some evident issues in the chemical industry park. Some chemical industry parks lack scientific foresight in the initial planning stage, resulting in unreasonable park layouts. Chemical enterprises are too concentrated and lack sufficient safety distance, which can lead to severe consequences in case of accidents. The chemical industry park involves the storage and production of a large number of flammable, explosive, toxic, and harmful substances, making it prone to safety accidents. Inadequate investment in infrastructure and public works construction has resulted in problems with water supply, power supply, and gas supply in the park. Management involves multiple departments and levels, requiring the coordination of resources and efforts from all parties. There is a shortage of management and technical personnel with professional knowledge of the chemical industry in terms of talent and technology. Although the aforementioned problems are diverse, they can lead to failures, accidents, and even disasters when they occur. Therefore, the safety of chemical industry parks has always been a core concern and an insurmountable red line in chemical production.

The chemical industry park is prone to safety accidents due to the aforementioned issues, which may lead to a series of accidents or even disasters. Disasters in chemical industry parks have distinct characteristics. The chemical industry park has attracted a large number of chemical enterprises, involving a significant amount of flammable, explosive, toxic, and harmful substances as well as numerous hazardous sources. If the production and storage devices or pipelines are damaged, they may leak and cause fire, explosions, and poisoning accidents. Thermal radiation, shock waves, and poisoning can cause widespread harm to human beings, leading to significant casualties and property damage. Chemical industry park disasters often involve multiple levels of disaster chains. There may be a cause-and-effect relationship between natural factors and industrial factors, triggering a chain reaction of disasters. The degree of damage and the time of action are higher than those of a single disaster, resulting in a secondary disaster with increased risk. The fire hazards in the chemical industry park are complex, encompassing storage, production, abnormal temperatures, etc. Due to the facilities being situated in different functional areas, they may be inadequately maintained, mismanaged, or affected by natural disasters. Once a disaster occurs, it may spiral out of control. These are the challenges confronting the safety of the chemical industry park and the reasons why solving the disaster problem is complex. In conclusion, the issues include disaster perception, data monitoring, disaster analysis, evolution mechanisms, prevention and prediction, emergency response, and more. Intelligent theories and methods offer a viable solution to address the aforementioned problems.

In the smart city, intelligent technology monitors and analyzes the safety risks of the chemical industry park in real time by establishing a safety risk perception mechanism and using intelligent technologies such as the Internet of Things and big data to realize rapid and accurate quantitative risk impact and risk early warning. With the help of intelligent algorithms and models, the safety situation of the chemical industry park is evaluated and predicted in real time to prevent the expansion and escalation of disasters and accidents. Establishing an intelligent emergency platform to realize information sharing and real-time data collection solves the information processing problems of traditional emergencies and optimizes the emergency command and decision-making process to improve efficiency and accuracy. Through the Internet of Things perception and big data analysis, real-time monitoring and early warning of environmental quality in the chemical industry park

are achieved. By applying GPS, GIS, and other technologies, dynamic monitoring and the management of dangerous chemical vehicles and logistics can be realized in real time. It is evident that using intelligent technology in disaster research of the chemical industry park is feasible; simultaneously, considering the high integration of equipment, information, and data in the chemical industry park, information automation is suitable for the construction and application of intelligent systems. Therefore, the use of intelligent theory and technology to study the disaster problem of chemical industry parks is gradually increasing. This also provides a guarantee for the safety of the chemical industry park in the smart city. In particular, research on the tank explosion process in the chemical industry park relies more on intelligent analysis technology to determine control measures and ensure the safety of the chemical industry park.

4. Theoretical Basis

This section introduces the tank explosion damage probability, damage probability distribution, damage evolution process, and determination method of area damage probability distribution resulting from storage tank explosion. This is the basic concept and calculation methods that are essential for ensuring the safety of chemical industrial parks in smart cities. Within the context of a smart city framework, the potential explosion process of storage tanks in chemical industrial parks can be described and simulated to meet the safety objectives of real-time analysis, prediction, and early warning of storage tank explosion risks in smart cities.

4.1. Tank Explosion Damage Probability

The evolution of storage tank explosion damage in chemical industry parks in smart cities is considered as the main line, and the derivation process is studied by the interaction of shock waves generated through storage tank explosion overpressure. Initially, the chemical industry park grid is divided [16,17], and explosion damage probability distribution is represented by a gridding matrix. The storage tank vapor cloud explosion used TNT equivalent W_{TNT} to estimate the instantaneous explosion shock wave. Various parameters of shock waves are expressed by proportional distances $z_e = r/{W_{TNT}}^{1/3}$. So, the overpressure Δp is a function of normal pressure p_0, as shown in Equation (1). The detailed derivation process of Equation (1) can be found in reference [18]

$$\Delta p = p_0 \frac{1616[1 + (\frac{rQ_{TNT}}{8.1\alpha W_f Q_f})^2]}{\sqrt{1 + (\frac{rQ_{TNT}}{0.0864\alpha W_f Q_f})^2}\sqrt{1 + (\frac{rQ_{TNT}}{0.576\alpha W_f Q_f})^2}\sqrt{1 + (\frac{rQ_{TNT}}{2.43\alpha W_f Q_f})^2}} \quad (1)$$

where: α is the vapor cloud equivalent coefficient, 0.02–14.9%, the value is 4%; W_f is the total mass of fuel in the vapor cloud, Kg; Q_f is the combustion heat of the combustible substance, KJ/kg; Q_{TNT} is the explosion heat of the combustible substance, the value is 4120–4690 KJ/kg; r is the distance between the measuring point and explosion source, /m; Δp is the explosion overpressure peak at r, Pa; and P_0 is the surrounding environment pressure, Pa.

Let X be the width boundary of the chemical industry park, /m; $x \in \{0, 1, \ldots, X\}$ represents the coordinates of the mesh width edge division; Y is the height boundary of the chemical industrial park, /m; $y \in \{0, 1, \ldots, Y\}$ represents the coordinates of the grid height edge division. Then, the chemical industry park can be represented as $Z_{X \times Y}$ (hereinafter referred to as Z). $O = \{o_1, \ldots, o_N\}$ represents the storage tanks set, N is the number of storage tanks set, and $n \in [1, N]$, o_n is the nth storage tank. The distance $r_{x,y}$ between each position x, y and o_n is expressed as Equation (2). The overpressure of the o_n explosion in the Z area is ΔP_{o_n}, which is expressed as Equation (3).

$$r_{x,y} = r(x, y) = \sqrt{(x_n - x)^2 + (y_n - y)^2} \quad (2)$$

$$\Delta P_{o_n} = F_{\Delta p}(x_n, y_n, P_o, \alpha, W_f, Q_f, Q_{TNT}) \tag{3}$$

Let the damage probability expression o_n be $q_{o_n} = F_q(x, y, L, \Delta P_{o_n})$.

The calculation equations can be obtained according to the damage probability model [19,20]. The explosion of the storage tank o_n causes a shock wave to any position (x, y) in the Z area, and the damage probability of the tank at that position is q_{o_n}, which is expressed as Equation (4). L indicates the pressure vessel type, $L = 1$ is normal pressure, and $L = 2$ is high pressure.

$$q_{o_n} = \begin{cases} F_q(x, y, 1, \Delta P_{o_n}), L = 1 \\ F_q(x, y, 2, \Delta P_{o_n}), L = 2 \end{cases} \tag{4}$$

The basic information and parameters are readily available due to the robust monitoring and communication capabilities of the smart city.

4.2. Damage Probability Distribution

The probability of tank damage at all grid positions (x, y) caused by a tank o_n explosion is expressed by a grid matrix, damage probability distribution $P(o_n, Z)$. It can be abbreviated as P_{o_n}. P_{o_n} is the $X \times Y$ n matrix, and the element value is $q_{o_n} = F_q(x, y, L, \Delta P_{o_n})$, so $P_{o_n} = F_q(x, y, L, \Delta P_{o_n})$, $x \in [0, 1, \ldots, X]$, $y \in [0, 1, \ldots, Y]$. For N tanks in Z, $P_O = [P_{o_1}, P_{o_2}, \ldots, P_{o_N}]$. This represents the damage probability distribution caused by all tanks in this area.

4.3. Damage Evolution Process

Next, we determined the tank explosion damage evolution process. Let o_n be the detonation tank, $o_n \in O$; other storage tanks are represented by $o_i \in O (i \neq n)$. The maximum damage probability to all remaining tanks from the explosion is $Max\{q_{o_n \to o_i}\}$, where $q_{o_n \to o_i}$ is the damage probability caused by o_n explosion to o_i at the (x_i, y_i) position, and o_i is the tank most likely to continue to explode. o_n Remove o_n from the set where $O = O/o_n$ is O, and add objects o_n sequentially in the set of $\overline{O} = \overline{O} \cup o_n$ for $\overline{O}$. Determine the steps of the evolution process as follows. Set o_n as the detonation tank for the first time, $Q_1 = Max\{q_{o_n \to o_i}\}, \overline{O} = o_n \cup o_i, O = O/o_i, n = i$. The damage probability of other tanks is traversed under the influence of o_n, $Q_2 = Max\{Q_1 + (1 - Q_1)q_{o_n \to o_i}\}, \overline{O} = \overline{O} \cup o_i$, $O = O/o_i, n = i$, using the intermediate process strategy. The damage probability of the last two tanks is determined under the influence of o_n for the $N - 2$th time, $Q_{N-2} = Max\{Q_{N-3} + (1 - Q_{N-3})q_{o_n \to o_i}\}, \overline{O} = \overline{O} \cup o_i, O = O/o_i, n = i$; for the $N - 1$th time, $Q_{N-1} = Max\{Q_{N-2} + (1 - Q_{N-2})q_{o_n \to o_i}\}, \overline{O} = \overline{O} \cup o_i, O = \phi$, stop. Finally, $\overline{O}$ is the set of tank explosion sequences in which o_n is the maximum damage probability of the detonation tanks, and $Q = [100\%, Q_1, Q_2, \ldots, Q_{N-1}]$ is the corresponding damage probability set. By setting different tanks as the detonation tank, N sequences of explosion evolution can be compared to determine the most unfavorable sequence of explosion.

4.4. Damage Probability Distribution of the Most Unfavorable Area

The order $\overline{O}$ of the most unfavorable damage evolution process and the corresponding damage probability Q are determined. Let $\overline{O} = [o_1, o_2, \ldots, o_N]$, $Q = [100\%, Q_1, \ldots, Q_{N-1}]$ and $P_O = [P_{o_1}, P_{o_2}, \ldots, P_{o_N}]$. Then, the area damage probability distribution of the most unfavorable explosion evolution is shown in Equation (5).

$$P_Z^{o_1} = \{P_Z^{o_1}(x, y) = \sum_{i=1}^{N} Q_i P_{o_i}(x, y) | x \in \{0, 1, \ldots, X\}, y \in \{0, 1, \ldots, Y\}\} \tag{5}$$

Equation (5) represents the superposition and sum of the product of all tank damage probabilities and the tank damage probability distribution caused by their damage, which forms the area damage probability distribution after the most unfavorable tank explosion damage process. Through the area damage probability distribution, the smart city can

obtain the changes in the area damage probability distribution with the help of changes in basic data. This is also the fundamental mathematical model for enabling smart cities to ensure the safety of chemical industrial parks.

The above parts are referred to in the literature [18]. We consider that the area damage probability importance distribution represents the degree of change in damage probability, specifically the extent of damage from a storage tank explosion in chemical industrial parks. Based on this assumption, we conduct the following research.

5. Proposed Method

5.1. Area Damage Probability Importance Distribution

The area damage probability importance distribution is the change degree of damage probability at all locations in the area during the tank explosion damage evolution process. Due to the different relative positions of storage tanks, the damage probability differs at different positions. Locations with significant variations indicate a greater impact on the area damage probability distribution. Conversely, locations with minimal changes have little effect on the change in area damage probability distribution. This concept introduces the notion of area damage probability importance, which varies across locations. It represents an importance distribution in chemical industrial parks, which is known as the area damage probability importance distribution. Through the distribution calculation method, a smart city can obtain the real-time damage probability importance distribution in chemical industrial parks, enabling the control of safety in these areas.

For a location in chemical industrial parks $(x, y)(x \in [1, \cdots, X], y \in [1, \cdots, Y])$, the importance of damage probability is comprehensively calculated by vector sum, as shown in Equation (6).

$$I_Z^{o_1}(x, y) = \sqrt{\left(\partial P_Z^{o_1}(x, y)/\partial x\right)^2 + \left(\partial P_Z^{o_1}(x, y)/\partial y\right)^2} \tag{6}$$

where $P_Z^{o_1}(x, y)$ is the explosion damage probability at the (x, y) position, o_1 is the detonation tank (the most adverse process) during the tank explosion damage evolution process, and Z is the chemical industry park.

In Equation (6), $\partial P_Z^{o_1}(x, y)/\partial x$ represents the change degree of damage probability in the x direction of the park, which is the importance of the x direction; $\partial P_Z^{o_1}(x, y)/\partial y$ represents the change degree of damage probability in the y direction of the park, which is the importance of the y direction. The damage probability importance of position (x, y) in the x and directions is $I_Z^{o_1}(x, y)$. For Z, the damage probability importance distribution is shown in Equation (7).

$$I_Z^{o_1} = \left\{ I_Z^{o_1}(x, y) \middle| x \in \{0, 1, \ldots, X\}, y \in \{0, 1, \ldots, Y\} \right\} \tag{7}$$

$I_Z^{o_1}$ is a $X \times Y$ two-dimensional matrix. The element in case y of the row x is $I_Z^{o_1}(x, y)$. Finally, the area damage probability importance distribution $I_Z^{o_1}$ is obtained. The area damage probability importance distribution plays a crucial and significant role. It signifies the degree of change in damage probability at each location within the area. These locations are vital for considering personnel evacuation, constructing structures, disaster prevention and reduction measures, or facility structures, particularly in preventing the disaster evolution process caused by storage tank explosions. They serve as a key reference for smart cities aiming to enhance safety in chemical industry parks. Accident control measures are implemented in locations where the area damage probability is of greater significance, effectively mitigating the impact of accidents. This is because locations with high damage probability importance correspond to areas with significant variations in damage probability. Implementing control measures in these areas can substantially reduce the likelihood of increased damage probability. Therefore, the optimal placement of control measures can be determined based on the distribution of area damage probability importance. This method offers an intelligent approach for making safety decisions in smart cities.

5.2. Effectiveness Analysis of Control Measures

In smart cities, various measures are implemented to control accidents in chemical industrial parks, relying on a robust monitoring and communication infrastructure. These measures must be carefully evaluated, taking into account their type, impact, and placement within the park. The effectiveness of each measure is closely tied to its specific characteristics with particular emphasis on its location. The primary objective is to optimize the effectiveness of these measures. Therefore, when the effectiveness of the measures is predetermined, selecting the most suitable locations for their implementation becomes a critical concern.

The area damage probability importance distribution obtained in the previous section is a method for selecting the appropriate location for measures. The location with the highest importance indicates where control measures should be implemented. Since the importance of area damage probability is being studied, the foundation is the tank explosion damage probability. The primary issue is the shock wave generated by the overpressure from the storage tank explosion. Therefore, blast walls are selected as a measure to mitigate the damage. Blast walls can withstand the explosion shock wave and confine the explosion damage within a specific area. Blast walls come in various types such as reinforced concrete blast walls, steel blast walls, section steel blast walls, brick blast walls, flame-retardant blast walls, and military special riot walls. Reinforced concrete blast walls are securely connected at the intersection of steel bars with a typical wall thickness ranging from 30 to 1000 px. Blast walls should be capable of withstanding impact pressures of thousands or even megapascals. It is essential to place suitable blast walls between explosive hazardous devices and non-explosive hazardous devices as well as between different explosive hazardous devices.

The impact pressure that the blast walls can withstand is P_K/Kpa. At the same time, it is believed that the overpressure value of the blast walls on the shock wave directly decreases the pressure, so the damage probability after the explosion shock wave passes through the blast walls is $q_{o_n}^K$. The damage probability distribution, the damage evolution process of tank explosion, and the area damage probability distribution are recalculated by using $q_{o_n}^K$.

The area damage probability of the location (x, y) after the installation measures (blast walls) are implemented is $P_{ZK}^{o_1}(x, y), x \in [1, \cdots, X], y \in [1, \cdots, Y]$. According to the damage probability model [19,20], we can calculate the destructive action of a normal pressure vessel when the pressure exceeds 22 KPa, as shown in Equation (8); and the destructive action of a high-pressure vessel occurs when the pressure exceeds 17 KPa, as shown in Equation (9). Following the method outlined in Sections 4.1 and 4.2, the $P_{ZK}^{o_1}(x, y)$ after the implementation measures are recalculated. The blast walls are set at the position with a larger value in the area damage probability importance distribution $I_Z^{o_1}$. Considering the impact of explosion shock waves, the blast walls are arranged in a ring around the storage tank. The equation for calculating the damage probability of the inner area of the blast walls remains unchanged, while the area damage probability of the outer area is determined using Equations (8) and (9).

$$q_{o_n} = \begin{cases} \left(-18.96 + 2.44 \ln\left(\Delta P_{o_n}(x, y) - q_{o_n}^K\right)\right)/100, \Delta P_{o_n}(x, y) \geq 22\text{KPa} \\ 0, \Delta P_{o_n}(x, y) < 22\text{KPa} \end{cases} \tag{8}$$

$$q_{o_n} = \begin{cases} \left(-42.44 + 4.33l \ln\left(\Delta P_{o_n}(x, y) - q_{o_n}^K\right)\right)/100, \Delta P_{o_n}(x, y) \geq 17\text{KPa} \\ 0, \Delta P_{o_n}(x, y) < 17\text{KPa} \end{cases} \tag{9}$$

There are various methods to assess the effectiveness of control measures, which can be evaluated using the criteria outlined in Equation (10).

$$E_{ZK}^{o_1} = \left\{ E_{ZK}^{o_1}(x, y) \middle| \begin{array}{l} E_{ZK}^{o_1}(x, y) = P_Z^{o_1}(x, y) - P_{ZK}^{o_1}(x, y) \\ , x \in [1, \cdots\cdots, X], y \in [1, \cdots\cdots, Y] \end{array} \right\} \tag{10}$$

In Equation (10), $E_{ZK}^{o_1}(x,y)$ represents the reduction in damage probability at the (x,y) position after the implementation of control measures. Here, $P_{Z}^{o_1}(x,y)$ without taking measures is generally greater than $P_{ZK}^{o_1}(x,y)$ after taking measures in all locations of the park. $E_{ZK}^{o_1}$ is a $X \times Y$ matrix, where each positioning element has a value of $E_{ZK}^{o_1}(x,y)$. The larger $E_{ZK}^{o_1}(x,y)$ is, the better the effect of protective (blast walls) measures are at the (x,y) position. Of course, there are many methods to analyze the effectiveness of control measures. Generally, different algorithms are designed according to different purposes, and the above method is just one of them.

5.3. Algorithm Flow

Figure 1 illustrates the complete flow of the algorithm described above.

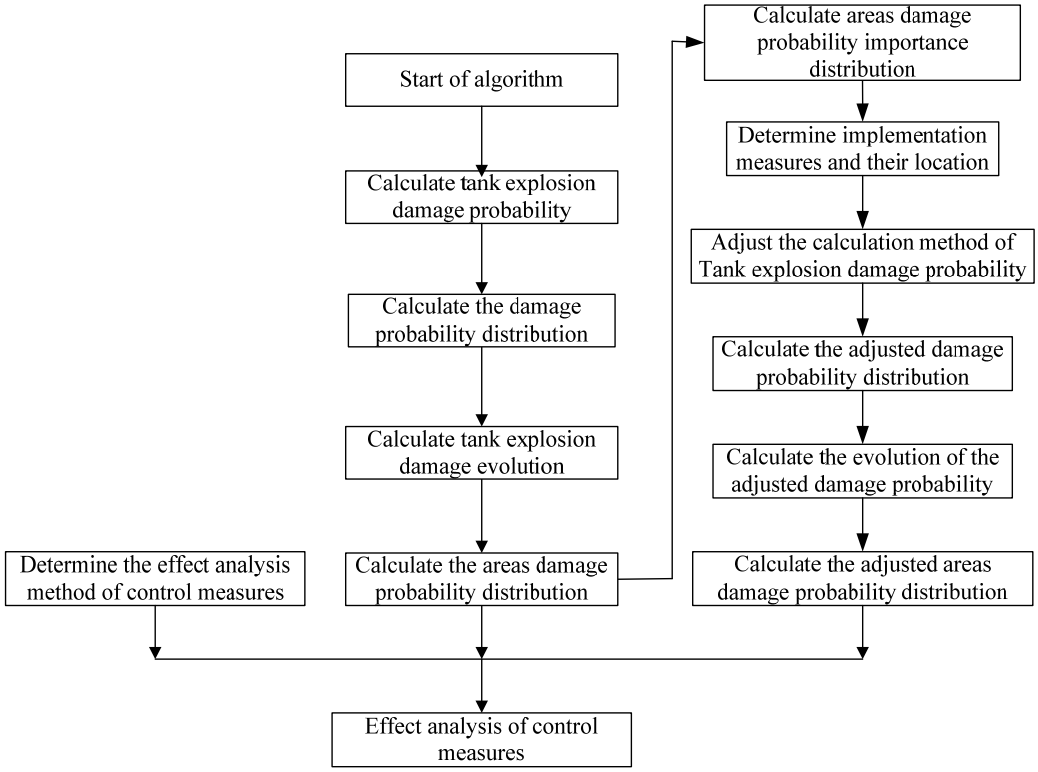


Figure 1. Algorithm flow chart. Note: The arrows in the figure are the analysis process.

The above process provides two intelligent analysis methods: one is the analysis method of area explosion damage in chemical industrial parks, and the other is the analysis method of the effectiveness of control measures. The former allows the smart city to analyze and determine the risk situation of the chemical industrial parks in real time, while the latter enables the smart city to proactively formulate the best safety measures.

6. Simulations and Results

6.1. Basic Situation

Taking a chemical industrial park as an example, Table 1 shows the physical parameters and relative positions of four storage tanks $O = \{o_1, o_2, o_3, o_4\}$ within the chemical industrial parks. The chemical industrial park is 1000 m $\times$ 1000 m area, $x \in \{0, 1, \ldots, 1000\}$m, $y \in \{0, 1, \ldots, 1000\}$m.

According to the analysis method of the damage evolution process of a storage tank explosion, the most unfavorable evolution process is determined. The calculation process has been outlined in the literature [21], which is briefly summarized here. Refer to the detailed process in the literature [21].

Table 1. Material parameters stored in storage tanks.

Storage Tank	Matter	*x*/m	*y*/m	Volume/m^2	Density Kg/m^3	Object Combustion Heat Q_f/KJ/Kg	Type
o_1	gasoline	200	800	1000	730	41,868	high pressure
o_2	diesel oil	900	100	2000	850	40,320	normal pressure
o_3	ethanol	700	700	900	800	22,890	high pressure
o_4	ethanol	500	450	1500	800	22,890	high pressure

6.2. Evolution Process

Set tank 1 as the detonation tank. $o_n = o_1, o_i \in \{o_2, o_3, o_4\}, \overline{O} = \{o_1\}, O = \{o_2, o_3, o_4\}$, $q_{o_n \to o_2} = 13.19\%$ is the probability of damage caused by o_n o_1 to o_2.$q_{o_n \to o_3} = 3.15\%$, $q_{o_n \to o_3} = 5.12\%$, $Q_1 = Max\{13.19\%, 3.15\%, 5.12\%\} = q_{o_n \to o_2}$, and $\overline{O} = o_1 \cup o_2 = \{o_1, o_2\}$, $O = \{o_3, o_4\}, Q_1 = 13.19\%$. The second comparison (evolution) process is $\overline{O} = \{o_1, o_2\}, O = \{o_3, o_4\}, o_n = o_2, o_i \in \{o_3, o_4\}$, $Q_2 = Max\{Q_1 + (1 - Q_1)q_{o_2 \to o_3}, Q_1 + (1 - Q_1)q_{o_2 \to o_4}\}$, among $q_{o_2 \to o_3} = 3.53\%$, $q_{o_2 \to o_3} = 3.88\%$. $Q_2 = Max\{16.25\%, 16.56\%\} = q_{o_2 \to o_4}$, $\overline{O} = \overline{O} \cup o_4 = \{o_1, o_2, o_4\}, O = \{o_3\}, o_n = o_4, o_i \in \{o_3\}$. $Q_3 = Max\{Q_2 + (1 - Q_2)q_{o_4 \to o_3}\}, q_{o_4 \to o_3} = 6.45\%$, $Q_3 = 16.56\% + (1 - 16.56\%) \times 6.45\% = 21.94\%$. The maximum damage probability sequence of the storage tank when the storage tank o_1 detonates is $\overline{O} = \{o_1, o_2, o_4, o_3\}$, while the corresponding damage probability is $Q = \{100\%, 13.19\%, 16.56\%, 21.94\%\}$. The process of analyzing the remaining tanks as initial explosion tanks is the same. The damage evolution process of the four storage tanks as initial explosion tanks is shown in Figure 2.

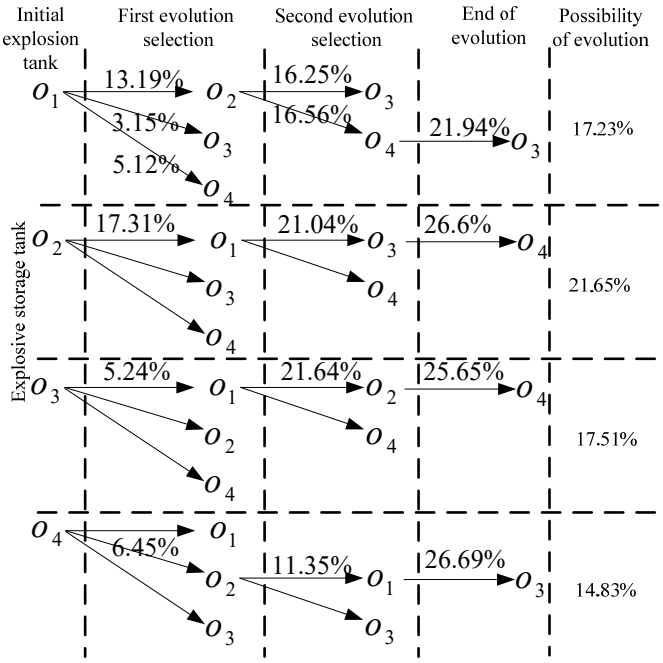


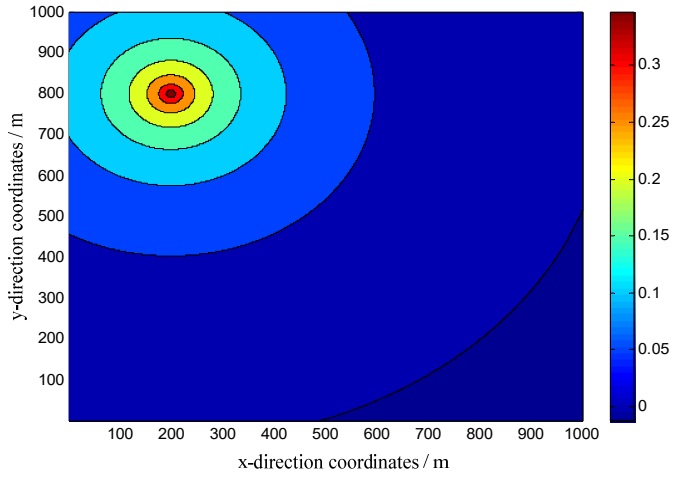
Figure 2. Damage evolution process of four tanks after explosion.

6.3. Worst Case Identified

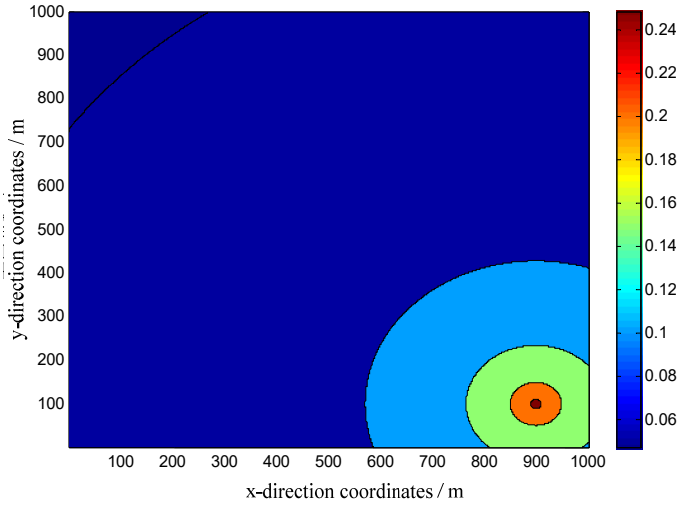
It can be seen from Figure 2 that the most unfavorable storage tank explosion damage evolution process occurs during the o_2 initiation. Of course, other methods of determining the most unfavorable evolution can also be constructed according to the need. Then, we calculated the area damage probability distribution as shown in Equation (11).

$$\begin{aligned} &P_Z^{o_2}(x, y) \\ &= P_{o_2}(x, y) + 17.31\% \times P_{o_1}(x, y) + 21.04\% \times P_{o_4}(x, y) + 26.6\% \times P_{o_3}(x, y) \end{aligned} \tag{11}$$

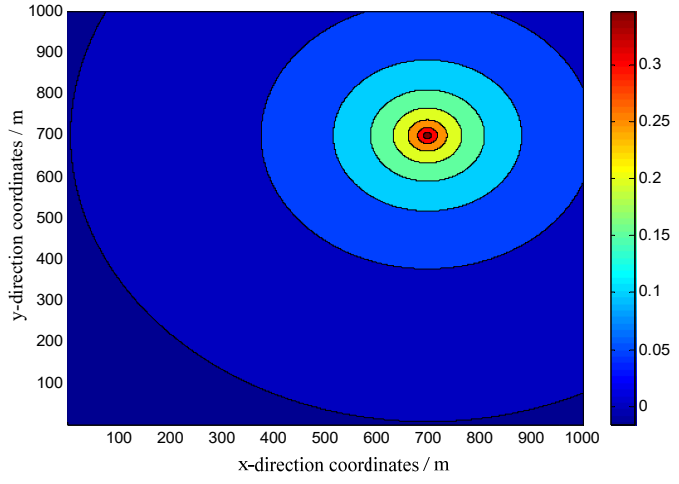
According to Equation (11), the damage probability distribution of each tank required for calculation is shown in Figure 3. Since this part is not in the middle of the paper, the resulting figure [21] is directly introduced.



(**a**) O_1 high pressure

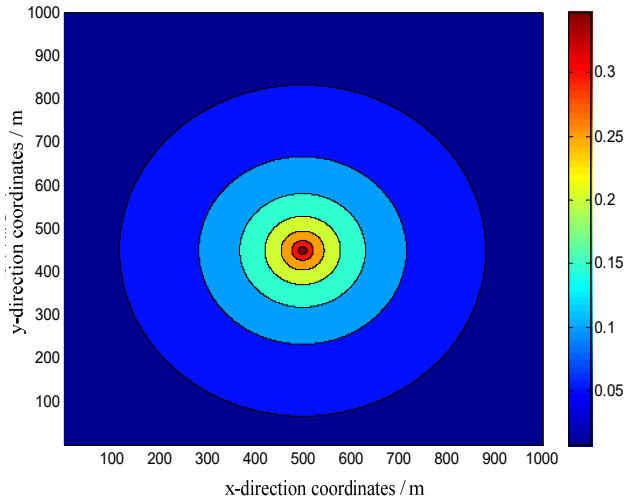


(**b**) O_2 normal pressure



(**c**) O_3 high pressure

Figure 3. *Cont.*



(**d**) O_4 high pressure

Figure 3. Damage probability distribution caused by the explosion of each storage tank. Note: the color scale on the right-hand side of the figure represents damage probability without unit % (legend unit 1).

The $P_Z^{O_2}(x, y)$ of area damage probability distribution under the most unfavorable conditions is finally obtained, as shown in Figure 4 (legend unit %).

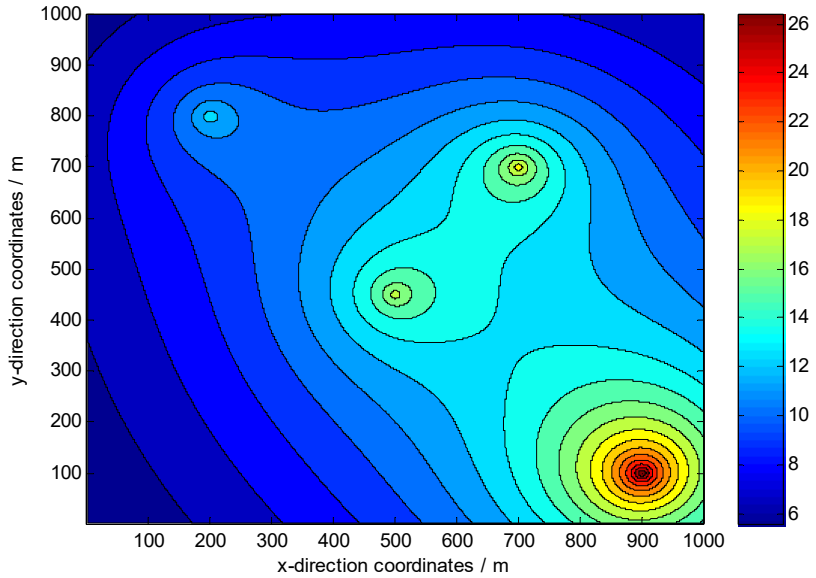


Figure 4. Area damage probability distribution in the most unfavorable state (legend unit %).

6.4. Importance Distribution and Effectiveness Analysis of Measures

The damage probability importance distribution in the x direction and y direction was calculated in Figures 5 and 6, respectively.

In Figures 5 and 6, the damage probability importance distribution in a single direction has little change, and the gray dividing line of different colors only divides the whole area into two parts. It also shows that the area damage probability distribution does not change much in most areas, and it only changes greatly at the gray boundary of different colors. By considering the storage tank's location, it becomes apparent that the gray dividing line in the figure connects the boundaries of the primary affected areas resulting from the storage tank explosion. Moreover, the distribution areas and dividing lines of damage probability

importance vary across different directions. This variation is a result of the algorithm design and also reflects the evolving process characteristics of a storage tank explosion.

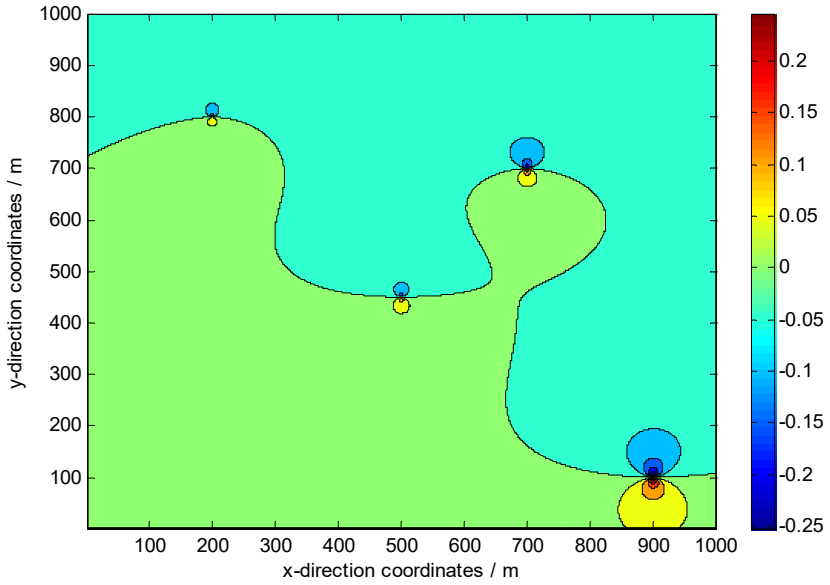


Figure 5. Damage probability importance distribution in the *x*-direction (legend unit 1).

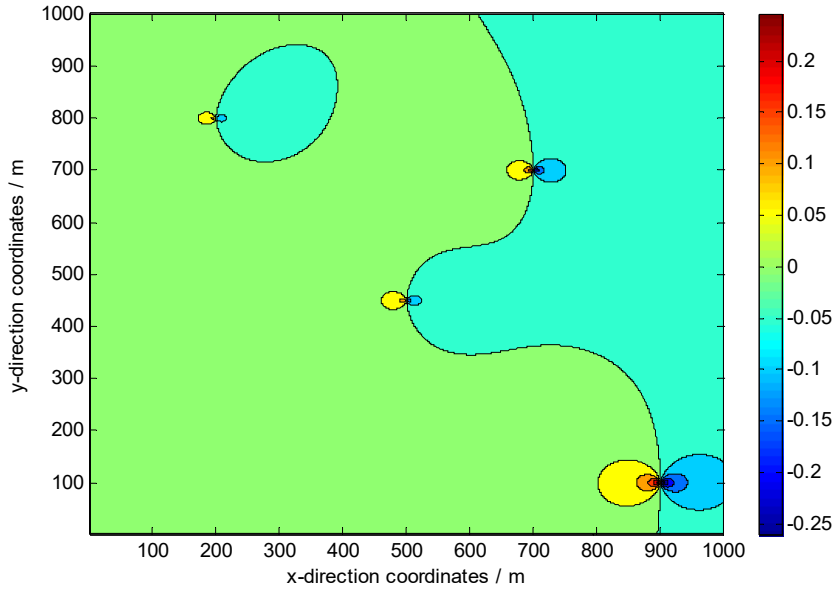


Figure 6. Damage probability importance distribution in the *y*-direction (legend unit 1).

The overall area damage probability importance distribution $I_Z^{o_1}$ calculated from Equation (6) is shown in Figure 7.

Contour lines are utilized to represent the importance value in the figure. The contour lines for the storage tank position are densely packed, indicating intense explosion effects in these areas, making them unsuitable for blast wall installation. Consequently, blast walls are positioned where the damage probability importance changes first: at the outermost explosion site of the chemical industrial parks and the storage tank explosion site. The blast walls are arranged in an arc centered on the storage tank and can withstand shock waves with an overpressure of 10 KPa. By referring to Equations (8) and (9) in Section 5.2, the area damage probability is recalculated post-implementation, as depicted in Figures 1 and 8. Figure 8 closely resembles Figure 4, illustrating the area damage probability distribution after the measures are in place, which is calculated according to the evolution process

of the storage tank explosion damage under the most unfavorable conditions shown in Figure 4. The area damage probability distributions within the blast walls remain constant due to the algorithm settings. Otherwise, Equations (8) and (9) are employed to compute the area damage probability distribution. However, distinguishing differences in the area damage probability map is challenging, hindering the demonstration of blast walls' control effectiveness. Therefore, the method proposed in Section 5.2 for analyzing the effectiveness of control measures is utilized to describe the accident control effectiveness of the measures. By utilizing Equation (10), along with Figures 4 and 8, the effectiveness of the measures' implementation is assessed, and Figure 9 is generated to display the distribution of damage probability reduction following the implementation of the measures.

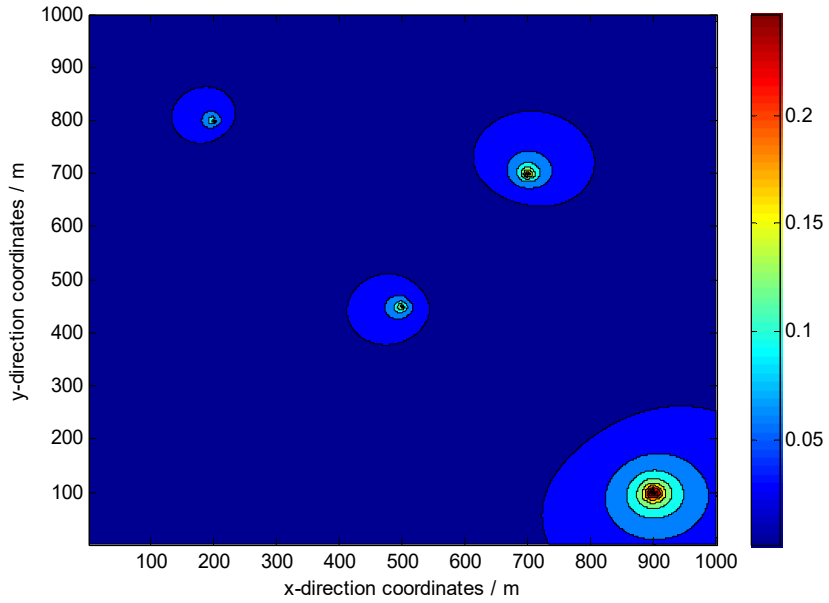


Figure 7. Overall damage probability importance distribution $I_Z^{o_1}$ (legend unit 1).

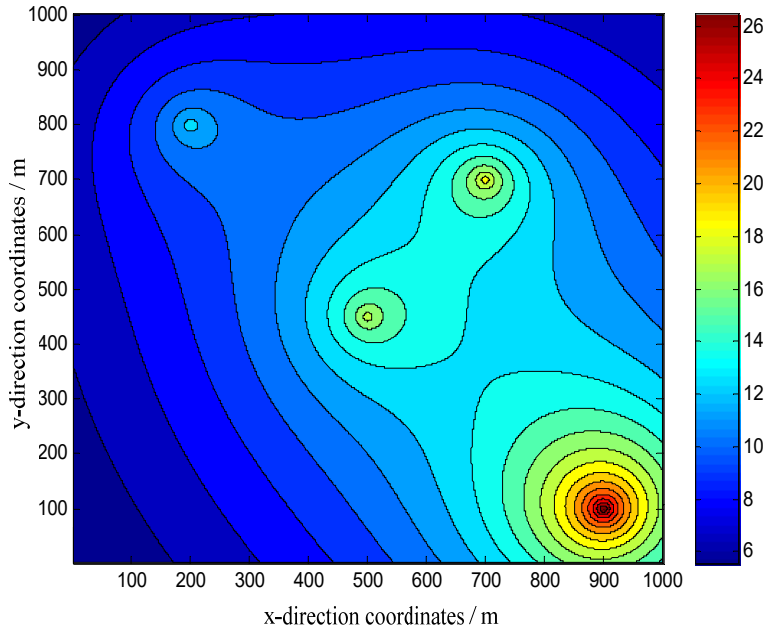


Figure 8. Area damage probability after implementation of measures (legend unit %).

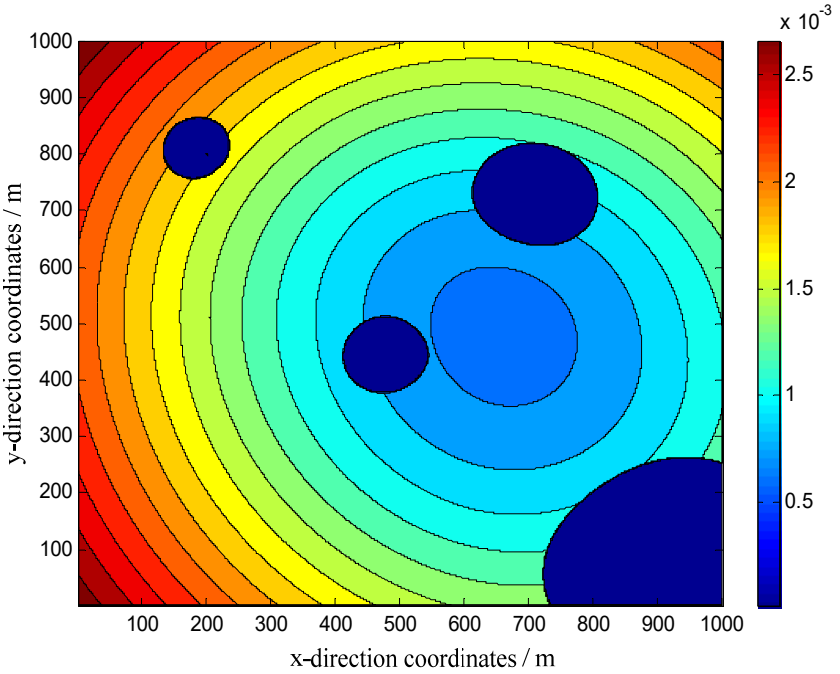


Figure 9. Reduction distribution of damage probability after implementation of measures (legend unit %).

Figure 9 illustrates the effectiveness of blast wall measures and their strategic placement based on the damage probability importance. The damage probability remains unchanged inside the blast walls, resulting in a 0 difference in damage probability within them. Outside the blast walls, the probability of damage to storage tanks decreases to varying extents. Notably, Figure 9 demonstrates a significant reduction in damage probability at the periphery of chemical industrial parks with a smaller decrease toward the center. This is due to the continued calculation of damage probability distribution within the blast walls in their original state, creating a relatively uniform change in damage probability. The flat area of explosion damage probability between the three storage tanks in the lower right corner of Figures 4 and 8 represents a transitional zone between the peak values of damage probability at these locations. This area remains consistent regardless of using the original or modified damage probability calculation method, showing a minimal change in damage probability. Figure 9 further highlights a pattern of reduced damage probability inside and increased probability outside. The placement of blast walls and the effectiveness analysis method prove to be successful, underscoring the importance of studying the distribution of damage probability in the area.

The paper proposes that the area damage probability distribution importance is that it enables investigating the distribution of the final formation of the damage evolution process of a storage tank explosion in the park. The most variable position corresponds to the most critical situation. These positions should be where control measures are implemented to achieve better effectiveness. Effective accident control measures, distribution calculation methods, and evaluation methods can be developed by combining the importance of distribution with other objectives.

Therefore, the method proposed in this paper aims to provide real-time parameters using robust monitoring capabilities to enable an intelligent analysis of damage probability in chemical industrial parks. It can dynamically assess the impact of all control measures based on the evolving actual situation and intelligently and proactively determine the optimal control measures scheme. This method and technology are effective for smart cities to manage and ensure the safety of chemical industrial parks, forming the foundation for ensuring city safety. These implications are crucial for smart cities themselves, especially concerning city safety.

7. Conclusions

Based on the characteristics of a smart city, this paper studies the damage probability importance distribution in a chemical industry park and evaluates the effectiveness of control measures. We posit that the area damage probability importance distribution represents the change degree of damage probability, that is, the damage degree of storage tank explosions. The primary conclusions drawn from this study are as follows:

(1) The concept of area damage probability importance distribution is proposed. The area damage probability importance distribution refers to the degree of change in damage probability at all locations within the areas during the damage evolution process of a tank explosion. By deriving the damage probabilities in two directions within the area, the degree of their change is determined. Subsequently, by combining the changes in both directions through vector addition, the overall change indicates the damage probability importance, and the importance distribution is then established by considering the entire area. Importance distribution plays a crucial role in personnel evacuation, building construction, disaster prevention, and mitigation measures, serving as the foundation for conducting safety analyses in smart cities.

(2) The utility analysis method for controlling storage tank explosion accidents is introduced. By analyzing the area damage probability importance distribution, the locations where the probability distribution locations are identified. Blast walls are chosen as control measures based on blast wave characteristics. Following the implementation of these measures, the calculation method for area damage probability is adjusted, and the area damage probability distribution is recalculated. A comparison is made between the original and modified area damage probability distribution, using the control measures. The algorithm flow is provided, allowing smart cities to compare different accident control schemes and select the most suitable measures intelligently.

(3) The algorithm flow is illustrated through an example. The area explosion damage probability of four storage tanks and the configuration of blast walls are used as examples to calculate the damage probability importance distribution. Based on the original area damage probability distribution with the area damage probability distribution after the measures, the damage probability reduction distribution was determined using the effectiveness analysis method. The method's effectiveness, distribution characteristics, and the damage probability importance distribution in ensuring smart city safety are explained.

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