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Analysis and Control Measures of Hazardous Chemical Explosions Based on Fault Tree Analysis

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Abstract In view of the environmental and safety risks of hazardous chemical explosions in chemical enterprises, the fault tree analysis was used to establish a fault tree model of hazardous chemical explosions and comprehensively analyze the possibility of the explosions. The 34 basic events that caused hazardous chemical explosions were expounded, and the minimum cut and path sets were obtained. The structure importance of basic events were calculated. According to the minimum path sets, the basic events when the accident does not occur were determined, and combined with the sequence of structure importance, the preventive measures for hazardous chemical explosion accidents were proposed. The fault tree model intuitively clarified the correlation between the direct causes of hazardous chemical explosion accidents, and proposed directions for effectively reducing the probability of hazardous chemical explosion accidents in the chemical industry.

Key words Hazardous chemical explosions in chemical enterprises; Fault tree analysis; Preventive measures

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The chemical industry has become an important part of the global economic development and one of the pillar industries of the national economy. The development of chemicals and new materials has provided strong support for the development of major downstream industries such as energy, transportation, construction and medicine in China. At the same time, the real living standard and the demand for further improvement of the quality of life in the future have proposed more diversified and high-quality development requirements. However, the development of the chemical industry has also brought negative impacts on human beings. Among them, the wide application of hazardous chemicals with properties such as toxicity, corrosion, combustion, combustion support and explosion has increased the hidden dangers of accidents, caused the occurrence of hazardous chemical explosion accidents in chemical enterprises, and brought huge losses to the ecological environment, national life and property safety[1].

In the 10 years since 2011, there were more than 10 major hazardous chemical explosion accidents in China. Among them, in the explosion accident in Tianjin Binhai New Area on August 12, 2015, 165 people died, and 8 people missed; 798 people were injured, and the direct economic loss amounted to 6.866 billion yuan. Moreover, the accident caused 129 kinds of chemical substances to explode, burn or leak and spread, which caused varying degrees of impact on the surrounding environment[2]. In the "11.28" major explosion accident in Zhangjiakou in 2018, 24 people died, and 21 people were injured; the direct economic loss was up to 41.488 6 million yuan[3]. In the "3.21" explosion accident in Jiangsu in 2019, 78 people died, and 76 people were seriously injured; 640 people were hospitalized, and the direct economic loss reached 1 986.350 7 million yuan[4].

Therefore, in order to avoid major accidents threatening the safety of human life and property, it is necessary to actively identify and control major hazard sources, comprehensively analyze the probability of potential hazards, determine the use and disposal of different types of hazardous chemicals, identify their risks, and conduct scientific and reasonable quantitative analysis to strengthen risk management and prevention awareness. For this reason, many experts and scholars at home and abroad have carried out research on the explosion accident of dangerous chemicals. For instance, Adedigb *et al.*[5] used Bayesian network to analyze the correlation between various factors and the probability of occurrence of accidents during the transportation of hazardous chemicals. Dakkoune *et al.*[6] selected and collected 169 safety incidents during 1974 – 2014 in the French database ARIA, and found that the main cause of the accidents was human operation errors. Chen Weike *et al.*[7] analyzed the causes of 200 fire and explosion accidents in the storage and transportation of flammable and explosive chemicals, used the frequency statistics method to obtain the factors causing the accidents, and obtain 14 key factors based on the association rule model in the Apriori algorithm. Zhang Ziyan[8] used ALOHA software to simulate fire accidents caused by typical hazardous chemicals, and studied the damage scope of the accidents. The analysis results provided effective technical support for the rescue of typical hazardous chemical leakage accidents.

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In this paper, based on the theory of fault tree analysis, the major danger sources of hazardous chemical explosions in chemical enterprises were deduced, and reliable and efficient prevention and control measures for effective prevention and control of accidents were proposed.

1 Fault tree theory

1.1 Fault tree analysis method The fault tree analysis (FTA) method is one of the important methods for safety analysis, risk assessment and accident cause research. It is a graphical deduction method using mathematical logic reasoning to identify hazards, obtain the direct causes of accidents, analyze the correlation between the causes, reveal potential dangers, clarify the probability of accidents[9-10], and finally achieve the qualitative and quantitative analysis of accidents. The fault tree analysis method also plays an important role in the risk assessment of the explosion of hazardous chemicals in chemical enterprises. It can not only comprehensively expound the various causes that lead to the explosion of hazardous chemicals and their correlations, but also find out accident prevention methods according to the whole process of the occurrence and development of an accident, so as to prevent the recurrence of similar incidents.

1.2 Top events and basic events Top event (T) refers to the accident under analysis. The top event in this paper is the explosion of hazardous chemicals in chemical enterprises. The most basic cause that contributes to the occurrence of the top event is called the base event (X).

1.3 Minimum cut set and minimum path set The set of basic events that lead to the occurrence of the top event is called a cut set, namely the set of basic events that cause the occurrence of hazardous chemical accidents, and the set of the minimum basic events that cause the occurrence of the top event is the minimum cut set; the set of basic events that do not cause the occurrence of the top event is called a path set, and the set of the minimum basic events that do not cause the occurrence of the top event is the minimum path set.

2 Steps of fault tree analysis of hazardous chemical explosions and analysis of explosion cases

2.1 Steps of fault tree analysis of hazardous chemical explosions The basic process of the fault tree analysis method is generally divided into the preparation stage, the qualitative analysis stage, the quantitative analysis stage and the safety evaluation stage. Among them, the preparation stage includes being familiar with the system, investigating accidents, determining the top event and investigating the causes of accidents; the qualitative stage includes fault tree drawing and qualitative analysis[11]. In this paper, the accident of hazardous chemical explosion in chemical enterprises will be analyzed strictly following the steps of being familiar with the storage and transportation system of hazardous chemicals in an enterprise, investigating related accidents, identifying the top event, establishing an accident tree model, determining intermediate events and basic events, conducting qualitative analysis and putting forward preventive measures. The analysis steps of the accident are shown in Fig. 1.

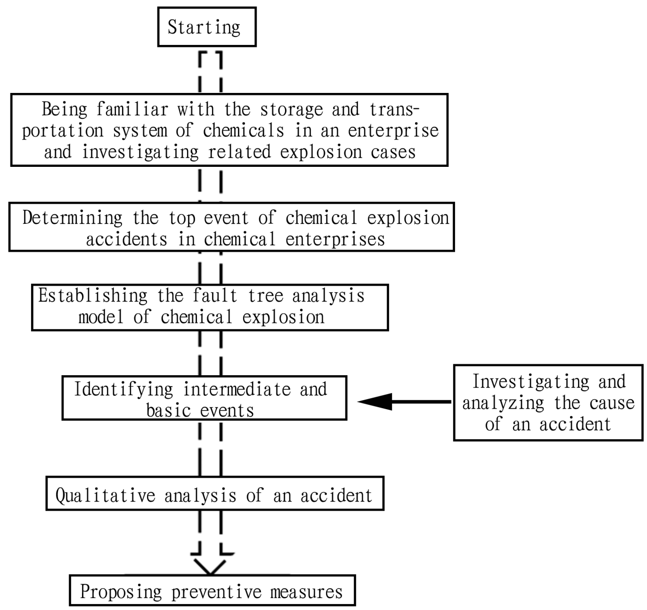

Fig. 1 Steps of fault tree analysis of hazardous chemical explosions in chemical enterprises

2.2 Analysis of explosion cases caused by chemicals On August 2, 2013, the exhaust gas treatment system of the automatic painting production line on the 3rd floor of a company in Ningbo deflagrated, and both ends of the exhaust gas treatment container set on the cement roof outside the automatic painting production line were blown open. The air inlet pipe on the upper part of the container was blown off and flew away. The air outlet pipe of the container and the "plasma exhaust gas purifier" connected to it were all blown up, and the fan at the output end was blown up and displaced. The suction pipe of the automatic painting room close to the waste gas treatment container was blasted, and the equipment of the automatic painting production line was seriously damaged. The causes of the accident are as follows: the automatic painting production line of the company's painting workshop used paints and solvents that mainly contain hazardous chemicals such as xylene, ethyl acetate and butyl acetate; since the spraying production continued for 17 h, the concentration of flammable and explosive mixed gas in the exhaust gas treatment container or YJ-L electrostatic fume purifier reached the explosion limit, or the concentration of the mixture of flammable and explosive dusts such as paint mist and combustible particles was up to the explosion limit.

At about 01:00 on June 5, 2017, a liquefied petroleum gas transport tanker in the loading and unloading area of the storage and transportation department of a petrochemical company in Linyi City leaked liquefied gas during the unloading operation, causing a major explosion and fire accident. The driver of the tank truck, who ran long distances and worked continuously, did not strictly implement the unloading regulations, and had serious operational errors when conducting the liquefied gas unloading operation at midnight. As a result, the quick-connect interface and the liquid-phase discharge pipe of the tanker could not be reliably connected, and were disconnected instantly when the liquid-phase ball valve of the tanker was opened, causing a large amount of liquefied gas in the tank to leak. The on-site personnel failed to deal with it effectively. The leaked liquefied gas gasified rapidly, spread rapidly, formed an explosive gas mixture with air to reach the explosion limit, and exploded and burned when encountering an ignition source. The continuous combustion of the liquefied gas leakage area successively led to the explosion of the tank of the leaking vehicle and the tanks of other transport vehicles parked in the loading and unloading area.

3 Analysis of hazardous chemical explosion accidents

3.1 Establishment of the fault tree model of hazardous chemical explosions According to the above analysis of the explosion accidents caused by chemicals, it is obtained that when chemicals caused an explosion accident, the high-temperature and high-pressure gas generated would expand at a high speed to form a shock wave, causing damage to the equipment and buildings in the surrounding environment to form a large number of fragments and even casualties. In addition, when the flammable material tank area or pipeline exploded, the flammable material thrown out by the explosion would cause a large-scale fire. Besides, fire and explosion could also cause secondary environmental pollution accidents. For example, excessive discharge of CO, SO_2 and particulate matter in a short period of time would seriously pollute the ecological environment of nearby areas. Therefore, in order to prevent such accidents, in the management of hazardous chemicals, enterprises should firstly isolate, separate and store them separately in accordance with relevant national regulations and different properties of hazardous chemicals to prevent explosions and fires caused by improper storage environment and material mixing; secondly, hazardous chemical storage areas should be inspected regularly, and once damage, raw material leakage and quality changes are found, they should be dealt with immediately; thirdly, it is strictly forbidden to produce open flames in production plants, tank farms, oil and chemical raw material loading and unloading areas, and appropriate firefighting equipment and personnel should be equipped with in each area[12]. In addition, it is necessary to strengthen the education and training of warehouse staff, hazardous chemical handlers and firefighters.

Therefore, from the perspective of enterprise management, there are two factors that cause the explosion of hazardous chemicals in chemical enterprises to occur. On the one hand, there are a large number of flammable and explosive dangerous chemicals; on the other hand, there is an ignition source. There are four main ways for the leakage of flammable and explosive hazardous chemicals: leakage from storage tanks, leakage from accessories or pipelines, and leakage during loading and unloading. In addition, the mixed storage and mixed release of hazardous chemicals is also one of the important factors causing explosion accidents. There are two risk factors leading to the leakage of tanks: the quality of the tank itself is not compliant, and the tank is cracked or perforated. There are five possible factors that cause leakage of accessories or pipelines: disabled valves or flanges, inadequate supplementary welding of pipelines, excessive internal pressure, long-term corrosion to make pipelines thin and failure to repair as required. Besides, an important factor that constitutes an explosion is the existence of an ignition source in the explosion system. According to the actual situation of chemical enterprises, open flames and sparks will be analyzed respectively. When the nitrification material waste is illegally stored in the confined space of an enterprise and oxygen is sufficient, it is very easy to cause the spontaneous combustion of combustible hazardous chemicals to produce open flames. In addition, illegal ignition and illegal smoking in the maintenance of personnel may cause explosions. For spark ignition sources, the causes were analyzed from electrostatic sparks, electrical sparks and mechanical sparks.

Hence, to avoid the occurrence of hazardous chemical explosions in chemical enterprises from the source, from the perspective of enterprise management, an fault tree model was established in terms of the existence of a large number of flammable and explosive hazardous chemicals and the existence of fire sources. The fault tree model is shown in Fig. 2, and the meanings of specific codes are shown in Table 1.

3.2 Qualitative analysis of hazardous chemical explosion events Hazardous chemical explosions in chemical enterprises were analyzed qualitatively. According to the above fault tree model, there were 34 initial causes that lead to hazardous chemical explosions (the top event), and X1, X2, X3, ⋯, X34 were used to represent these 34 basic events. These initial reasons were the risk factors that cause hazardous chemical explosion accidents in chemical enterprises. The structure of the fault tree is as follows:

$$\begin{aligned} T &= M1 \times M2 = (M3 + M4 + M5 + M6) \times (M7 + M8) \\ &= (X1 \cdot X2 + X3 \cdot X4 + X5 + X9 + X6 + X7 + X8 \cdot X34 \\ &\quad + X10 + X11 + X12 + X13 + X14 + X15 + X16 + X17) \times \\ &\quad (X18 \cdot X19 \cdot X20 + X21 + X22 + X23 + X24 + X25 + X26 \\ &\quad + X27 + X28 + X29 + X30 + X31 + X32 + X33) \end{aligned}$$

It does not mean that the top event will only occur if all of the above 34 basic events occur, so the collection of the above basic events that can cause the top event to occur and have the minimum number (namely the minimum cut set) was obtained by Boolean algebra and other mathematical methods.

The number of the minimum cut sets determines the possibility and danger of an event. There were 210 groups of the minimum cut sets, indicating that the possibility of the occurrence of the top event was very high. There were many basic events, and the calculation was relatively complicated; the system was relatively unstable and not conducive to analysis. Therefore, according to the dual nature, the minimum path set of this event, namely the collection of basic events with the minimum number that can prohibit the occurrence of hazardous chemical explosions, was analyzed[13]. It is concluded that the fault tree had 11 groups of the minimum path sets.

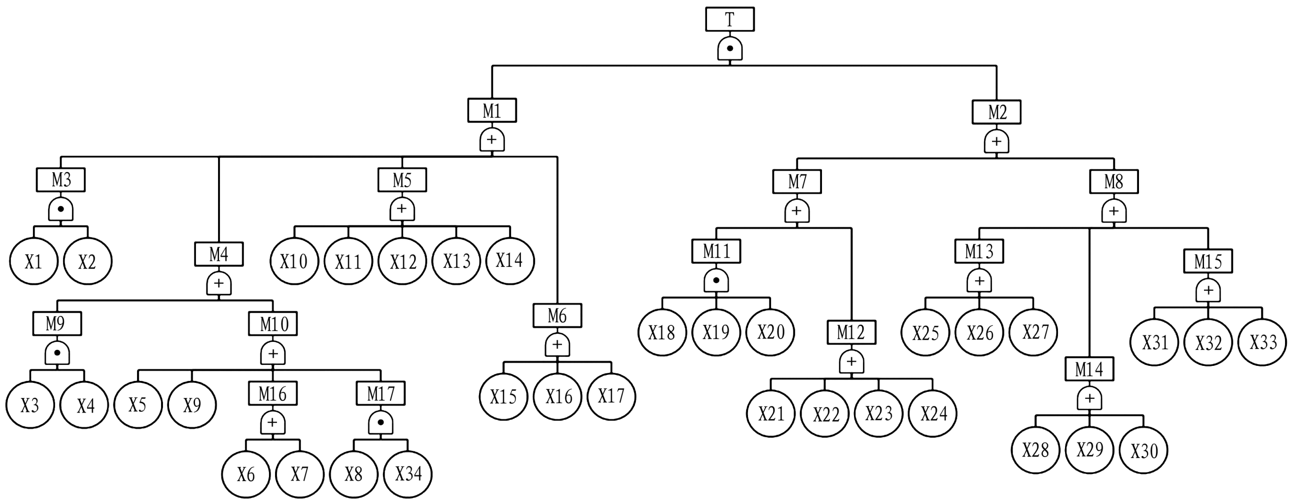

Fig. 2 Fault tree model of hazardous chemical explosion events in chemical enterprises

Table 1 List of events in the fault tree of hazardous chemical explosions in chemical enterprises

Symbol	Event type	Symbol	Event type
T	Hazardous chemical explosions in chemical enterprises	X9	The personnel fails to overhaul the problem of tanks in time
M1	Existence of a large quantity of flammable and explosive hazardous chemicals	X10	Disabled valves or flanges
M2	Existence of an ignition source	X11	Lack of supplementary welding
M3	It is strictly forbidden to store dangerous chemicals together because they can react to release heat to cause an explosion	X12	Excessive pressure in pipelines
M4	Leakage from tanks	X13	Corrosion, thinning and cracking of pipelines
M5	Leakage from accessories or pipes	X14	When there is a hidden danger of leakage in pipelines, the maintenance and management personnel fail to check and repair them as required
M6	Other ways of leakage	X15	The production equipment has not been overhauled in accordance with regulations for a long time, resulting in material leakage
M7	Open flame sources	X16	Leaking during drug loading and unloading
M8	Spark sources	X17	Leakage of combustible gases other than chemical raw materials due to failure to operate in accordance with regulations
M9	Tank quality problem	X18	Illegal storage of nitrification products and other natural hazardous chemicals
M10	Cracked or perforated tanks	X19	Sufficient oxygen
M11	Hazardous chemicals spontaneously combust to produce open flames	X20	Sealed sustainable heat environment
M12	Other types of open flames	X21	Illegal ignition during maintenance
M13	Static sparks	X22	As flammable and dangerous chemicals have been leaked, the electrical switch is triggered due to improper handling, resulting in open flames
M14	Electrical sparks	X23	Illegal smoking of personnel in a factory
M15	Mechanical sparks	X24	Machinery vehicles in a factory discharges smoke and spew flames
M16	Fatigue cracking of tanks	X25	Contacting with conductors to produce sparks during operation
M17	Corrosion cracking of tanks	X26	Producing sparks by impact and friction
X1	Mixing of materials due to personnel misoperation	X27	Being hit by lightning
X2	Turning on the device to form an explosive ability after mixing	X28	Short circuit of devices
X3	Substandard design or manufacture of tanks	X29	Ageing of equipment
X4	Equipment quality inspection or acceptance does not conform to regulations	X30	Damage to the explosion-proof device of equipment
X5	Illegal operation by personnel causes overfilling of materials to result in overpressure	X31	The grounding resistance of equipment exceeds the standard
X6	Disabled tank safety valves	X32	Excessive current
X7	Disabled tank gauges	X33	Equipment is jammed and rubbed to produce sparks
X8	Damage to corrosion coating	X34	Hazardous chemicals or external environments corrode tanks

P1 = {X1, X3, X5, X6, X7, X8, X9, X10, X11, X12, X13, X14, X15, X16, X17}
P2 = {X1, X3, X5, X6, X7, X9, X10, X11, X12, X13, X14, X15, X16, X17, X34}
P3 = {X1, X4, X5, X6, X7, X8, X9, X10, X11, X12, X13, X14, X15, X16, X17}
P4 = {X1, X4, X5, X6, X7, X9, X10, X11, X12, X13, X14, X15, X16, X17, X34}
P5 = {X2, X3, X5, X6, X7, X8, X9, X10, X11, X12, X13, X14, X15, X16, X17}
P6 = {X2, X3, X5, X6, X7, X9, X10, X11, X12, X13, X14, X15, X16, X17, X34}
P7 = {X2, X4, X5, X6, X7, X8, X9, X10, X11, X12, X13, X14, X15, X16, X17}
P8 = {X2, X4, X5, X6, X7, X9, X10, X11, X12, X13, X14, X15, X16, X17, X34}
P9 = {X18, X21, X22, X23, X24, X25, X26, X27, X28, X29, X30, X31, X32, X33}
P10 = {X19, X21, X22, X23, X24, X25, X26, X27, X28, X29, X30, X31, X32, X33}
P11 = {X20, X21, X22, X23, X24, X25, X26, X27, X28, X29, X30, X31, X32, X33}

3.3 Analysis of structure importance of basic events In this fault tree model, there were many basic events that cause the top event to occur, but the contribution of different basic events to the occurrence of the top event was not the same, that is, the structure importance of basic events is different. In order to improve the daily management of enterprises and regulatory departments and avoid accidents, the influence degree of each basic event on the top event was analyzed without considering the probability of occurrence of each basic event[14]. The formula of structure importance is as follows:

$$I_\phi(X_i) = \sum_{X_i \in P} \frac{1}{2^{n_{i-1}}} \quad (1)$$

In the above formula, $I_\phi(X_i)$ is the structure importance of basic event X_i; $X_i \in P_i$ is the minimum path set of basic event X_i belonging to P_i; n_i is the number of basic events included in the minimum path set where basic event X_i is located. The structure importance of each basic event is as follows:

I(X17) = I(X16) = I(X15) = I(X14) = I(X13) = I(X12) = I(X11) = I(X10) = I(X9) = I(X7) = I(X6) = I(X5) > I(X33) = I(X32) = I(X31) = I(X30) = I(X29) = I(X28) = I(X27) = I(X26) = I(X25) = I(X24) = I(X23) = I(X22) = I(X21) > I(X34) = I(X8) = I(X4) = I(X3) = I(X2) = I(X1) > I(X20) = I(X19) = I(X18)

4 Analysis of results and countermeasures

4.1 Analysis of fault tree results According to the calculation results of the minimum cut set, the minimum path set and the structure importance, the following results can be obtained.

(1) 210 groups of the minimum cut sets were obtained from the fault tree, which indicates that there were 210 kinds of possibilities that may induce hazardous chemical explosion accidents, and the possibility and danger of hazardous chemical explosion accidents in chemical enterprises were high.

(2) There were 11 groups of the minimum path sets, indicating that when the basic events in the minimum diameter sets do not occur, the hazardous chemical explosions in chemical enterprises will not occur, that is, the obtained minimum path sets are a necessary and sufficient condition for the hazardous chemical explosions not to occur.

(3) The analysis results of the structure importance show that the leakage of a large amount of flammable and explosive dangerous chemicals is the main reason for explosions and the key to accidents. Illegal ignition, illegal smoking, open flames, static sparks, electrical sparks and mechanical sparks caused by improper disposal are the secondary causes of accidents, and have a greater impact on the top event. In addition, tank corrosion by hazardous chemicals or external environments, substandard quality inspection or acceptance in case of substandard tank design or manufacture, turning on the device to form an explosive ability after material mixing, *etc.* are risk factors for the occurrence of an accident.

4.2 Countermeasures The number of the minimum cut sets is much larger than the number of the minimum path sets. Therefore, starting from the minimum diameter sets, countermeasures for the occurrence of hazardous chemical explosions in chemical enterprises are proposed.

(1) Risk management and control should be strengthened. According to relevant regulations, it is necessary to organize the investigation of hidden dangers of safety and environmental risks led by enterprises, regulatory units, and industry expert groups, and immediately carry out rectification actions based on the investigation results.

(2) Supervision capacity should be enhanced. A monitoring and early warning system for flammable and explosive gases, toxic and harmful gases and volatile liquids should be established, and the real-time supervision of hazardous chemical leakage in enterprises should be conducted by combining monitoring equipment and platforms and using dynamic and static supervision methods.

(3) Safety production training and education should be carried out. It is necessary to improve production process management, enterprise safety management, and safe operation, resolutely put an end to all violations of laws and regulations, and avoid fire from the source.

(4) Emergency training should be strengthened. A responsibility system should be established to further strengthen corporate emergency training and drills for personnel at different levels. As a result, when an accident occurs, enterprise managers and operators can respond effectively to minimize the damage of the accident.

5 Conclusions

(1) Hazardous chemical explosions in chemical enterprises were analyzed by using the fault tree analysis method. The fault tree model of hazardous chemical explosions was established, and the model systematically expounds the correlation of 34 basic events that induce the occurrence of the top event. The Boolean

algebra method was used to obtain 210 groups of the minimum cut sets that cause the occurrence of events, and 11 groups of the minimum path sets that do not cause the occurrence of events.

(2) The key causes of an accident and other risk sources were determined through the analysis of the structure importance.

(3) The countermeasures for hazardous chemical explosions in chemical enterprises were put forward, and the work focus and management direction of the safety management of the chemical industry were clarified.

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(5) It is the key to disaster prevention and reduction by improving the comprehensive quality and the level of prediction and early warning of prediction and forecasting personnel.

(6) The establishment of prediction and monitoring system of urban flood control and drainage is an important work to prevent rainstorm and flood disasters, which is imperative.

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