CHEMICAL ENGINEERING TRANSACTIONS

VOL. 90, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Aleš Bernatík, Bruno Fabiano

ISBN 978-88-95608-88-4; **ISSN** 2283-9216

DOI: 10.3303/CET2290135

Coping with Flood Natech Events: a Safety Framework to Make Chemical Clusters More Resilient

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Industrial accidents triggered by natural disasters (Natech events) pose huge threats to chemical clusters. Flood is a significant cause of Natech events, the interactions between flood and chemical installations may lead to complex accident scenarios. However, the chemical clusters are often not well prepared for flood Natech events due to the lack of guidance on how to implement prevention and mitigation measures. In this paper, the characteristics of flood Natech events are firstly discussed, which provide a clear understanding of accident evolution. Based on the review of several Chinese standards related to flood prevention in chemical clusters, corresponding requirements are summarized. The requirements mainly focus on the planning and design stages. To cope with flood Natech events in a long-term vision, a comprehensive safety framework for chemical clusters is proposed in this article considering a resilient viewpoint, in which different roles of government, chemical cluster, and chemical plant are discussed. Moreover, three sub-models are divided to manage safety measures before, during, and after accidents, contributing to improving the resisting ability, adaptability, and recoverability of chemical clusters to flood Natech events, respectively.

1. Introduction

Clustering development as an efficient way to integrate the chemical industrial chain and to enhance economic benefits has been adopted worldwide. However, large inventories of hazardous materials are concentrated in chemical clusters, potentially increasing the risk of catastrophic events. As opposed to the technological accidents due to conventional causes (malfunctioning of a process, human error, internal defects), those triggered by natural events (so-called Natech events) have been recognized and emphasized by scholars and practitioners of process safety (Reniers et al., 2018). Natech events could result in very severe consequences since multiple simultaneous failures of chemical units may occur. Floods are the most frequent natural events triggering Natech events (Cozzani et al., 2010). Floods could impact a wide area in a short time, damaging chemical units and impeding mitigation actions. Moreover, the characteristic of flood events (e.g., frequency and intensity) is hard to predict, which poses a huge challenge to response measures. Therefore, developing an effective strategy to address flood Natech events is a complex and urgent work.

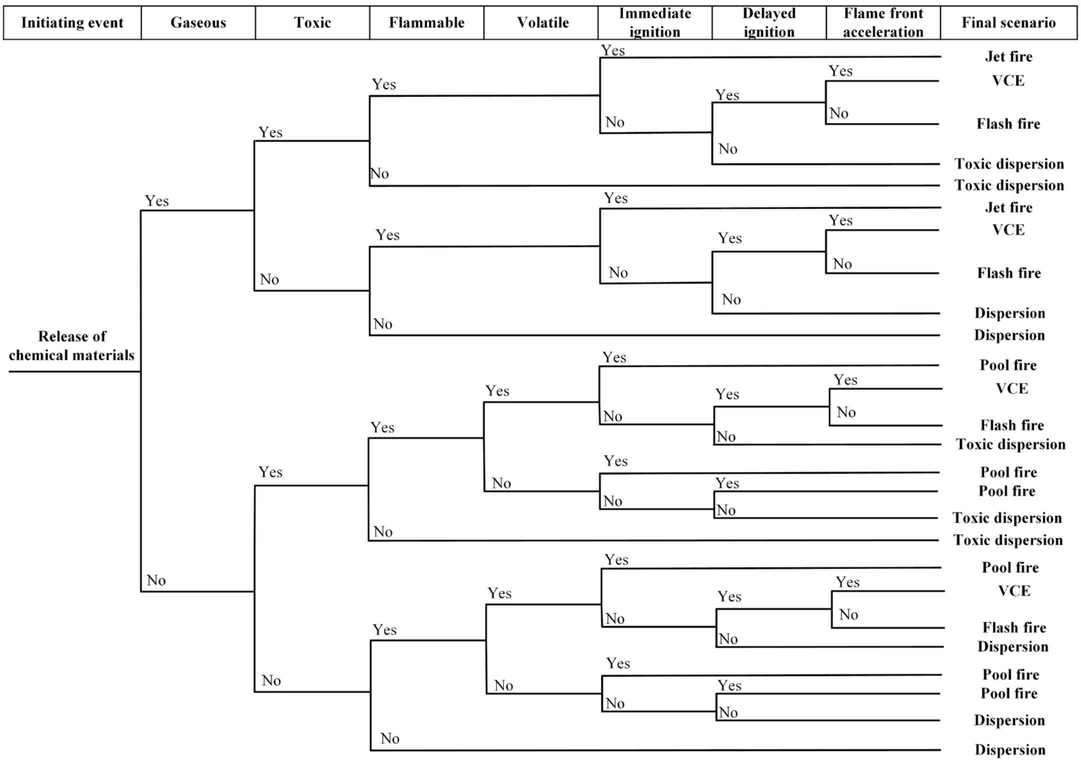
The Resilience concept, defined as the ability of a system to bounce back to the normal status when it has been impacted by unexpected events, provides a new insight to promote process safety. Dinh et al. (2012) clarified six principles and five factors that contribute to process resilience, which can guide the pro-active defense measures in chemical process or plants. Jain et al. (2018) developed the Process Resilience Analysis Framework to incorporate technical and social factors with the aim of improving risk management strategies in the design and operations of process system. Nevertheless, safety of a chemical cluster is a high-level complicated system engineering problem, involving the interaction of government, chemical cluster and chemical plants. Moreover, previous studies mainly focused on technological accidents and corresponding safety measures, however, systematic methodologies considering the whole chain to improve the safety level of a chemical cluster following Natech events are still lacking.

Paper Received: 10 December 2021; Revised: 18 March 2022; Accepted: 3 May 2022
Please cite this article as: Zeng T., Chen G., Reniers G., 2022, Coping with flood Natech events: A safety framework to make chemical clusters more resilient, Chemical Engineering Transactions, 90, 805-810 DOI:10.3303/CET2290135

In this paper, the characteristics of flood Natech events and Chinese standards for flood prevention in chemical clusters are summarized. Then, a comprehensive framework to build a long-term safety vision for chemical clusters coping with flood Natech events is developed, in which the role of government, chemical cluster, and chemical plant in different stages is discussed. The framework can enhance the resilience of chemical clusters to flood Natech events.

2. Characteristics of flood Natech events

A flood can cause the leakage of chemical materials in two ways: i) floodwater with a certain velocity and height can float and/or displace chemical installations through buoyancy and drag forces; ii) the debris carried by floodwater could impact chemical installations, leading to shell breach or rigid sliding. The release of chemical materials could cause water contamination that posing significant damage to environment, which is also the initial condition of subsequent technological accidents (e.g., fire, explosion, dispersion of toxic substances). Considering possible hazardous phenomena related to flood Natech events, three types of released materials can be classified, i.e., flammable materials, toxic materials and the ones that can violently react with water (Cozzani et al., 2010). For flammable materials, fire or explosion may occur in the presence of ignition sources. Toxic dispersion is a certain scenario after a continuous or instantaneous release of toxic materials. If the released substances have a violent reaction with water, which may generate: i) massive heat energy as an ignition source; ii) flammable or explosive vapor; or iii) toxic materials. Therefore, the third type of chemical substance reacting with floodwater can be considered as an intermediate process that generates necessary conditions for technical accidents. The post-release event tree shown in Figure 1 describes possible accident sequences and final scenarios in flood Natech events.



A flood usually affects a large-scale area and carries released chemical materials over a long distance. Multi-source leakages in flood Natech events are possible, significantly elevating the risk of domino effects (Antonioni et al., 2015). Toxic releases are not deemed to be the primary events initiating domino effects since they have no direct damage on secondary units. Cozzani et al. (2010) concluded that the final fire and explosion scenarios include pool fires, flash fires and vapor cloud explosion (VCE) based on the statistical analysis of past 272 flood Natech events. However, the escalation due to a flash fire is unlikely (Chen et al., 2020). Thus, pool fire or VCE can be considered as the primary accidental scenario in flood Natech events. Different escalation vectors (heat radiation, blast wave, and fragment) may exist and couple in the multi-

source primary accident scenarios, leading to a complex evolution and rapid escalation. Moreover, floods may render safety barriers even inoperable, which would obviously aggravate the propagation of accidents.
Flood Natech events have also thrown down many challenges for emergency response and recovery. The flood may damage the on-site available emergency resources and lifeline systems. Besides, the combination of initial damage due to a flood and secondary damage due to technological accidents could overwhelm the emergency response and evacuation, especially in the case of superposition of flood and technological accidents in different areas simultaneously. Recovery after flood Natech events is usually more complex and time-consuming than that following the conventional technological accidents, since the environmental, economic, production and social conditions of chemical plants and nearby areas may be severely damaged by the flood and cascading technological accidents. Careful planning, assessment, commissioning and preparation for the re-operation of a chemical cluster is essential, which is a long-time and complex process.

3. Chinese standards for flood prevention in chemical clusters

3.1 Background

The importance of avoiding or mitigating Natech events in chemical clusters has been recognized and emphasized by many countries and international organizations (Ricci et al., 2021). For instance, the Europe Union amended the Seveso III Directive for major chemical accident prevention in 2012, which explicitly advocated identification and risk analysis for industrial accidents triggered by natural events. In 2015, the United Nation published the Sendai Framework for Disaster Risk Reduction 2015-2030, in which the scope of disaster risk reduction has been broadened and natural disasters related technological hazards has been paid more attention to. There are more than 600 chemical clusters in China, and the 2020 revenue of petroleum and chemical industry has exceeded ¥11 trillion (€1.53 trillion). Chinese government made great contributions to the safety development of chemical clusters. Following the rapid industrial growth, a series of regulations and standards have been published to promote process safety, aiming to avoid and mitigate technological accidents. Although no specific safety regulation or standard for flood Natech events, some articles in several design standards mentioned flood prevention in chemical industrial areas. A review of those standards is beneficial for understanding the existing status and corresponding requirements in Chinese chemical clusters, which is of great significance for the prevention and mitigation strategy of flood Natech events.

3.2 Review of relevant standards

There are many standards for chemical industry in China, involving process and product, equipment and component, instrument and apparatus, marking and packaging, layout design, etc. The requirements of flood prevention usually have been integrated in design standards. Seven standards were selected, as follows:
1) GB 50201—2014 Standard for flood control;
2) GB 50475—2008 Code for design of general warehouse and lay down area of petrochemical industry;
3) GB 50489—2009 Code for design of general plot plan and transportation of chemical industrial enterprises;
4) GB 50737—2011 Code for design of petroleum storage depot;
5) GB 50187—2012 Code for design of general layout of industrial enterprises;
6) GB 50984—2014 Code for design of petrochemical plant layout;
7) GB 50074—2014 Code for design of oil depot.

Corresponding requirements in those standards are summarized in Table 1. From Table 1, it can be found that drainage system and site selection are the topic for flood prevention that were most frequently mentioned, the following ones are flood protection level and layout design, then the protection engineering in chemical industrial areas, and only one standard remarked how to improve plant design based on accident lessons. Avoiding flood events in the site selection is the most effective way for flood Natech events prevention. However, its application is limited in the planning stage and is also unrealistic for coastal or riparian areas. To fill this gap, some necessary factors (e.g., elevation planning and flood protection level) are emphasized in the design of chemical industrial areas that may be located in the coastal or riparian areas. Moreover, physical barriers are needed for major hazard installations, aiming to protect equipment from flood impacts. The drainage system has been mentioned by almost all selected standards. On the one hand, effective drainage can mitigate high water condition that may lead to the floatation of chemical installations, decreasing the probability of flood Natech events. On the other hand, the drainage system can prevent more extensive dispersion of leaked chemical materials, mitigating the consequence of flood Natech events. Finally, study from accident lessons would contribute to the improvement of safety strategy, preventing similar accidents from happening once again. However, the standards are the basic principles to guide the design of chemical industrial areas, development of a comprehensive safety framework for chemical clusters against flood Natech events still is a challenge and complex work involving multi-parties cooperation, accident evolution and safety measures in different stages.

Table 1: Summary of flood prevention requirements for chemical industrial areas in Chinese standards.

Aim	Standard	Requirement
Site selection	2, 3, 4, 5, 6, 7	i) Avoid being in the flood-prone area, otherwise, some reliable flood prevention measures need to be taken.
Layout design	2, 4, 5, 7	i) Designed elevation should add a safety height (at least 0.5m) on the calculated water level based on the flood return period.
Protection engineering	3, 5, 7	i) Flood control facilities should be considered in the layout design. The new protection engineering should be constructed in one stage. ii) Embankment for preventing flooding is a high cost-effectiveness engineering. For the oil depot, the wall height should exceed 2.5m.
Drainage system	2, 3, 4, 5, 6, 7	i) A complete and effective rainwater drainage system is needed, avoiding in-site water directly flowing to the outside area of plants. ii) Drainage facilities' location should be optimized according to the terrain. Underground pipes are recommended for chemical plants. iii) Open ditch is recommended for the rainwater drainage in tank farms.
Flood protection level	1, 3, 4, 5, 7	i) Four levels of flood protection are divided according to the scale of industrial enterprise. If an industrial enterprise, at any scale, in flooding may lead to explosions or large-scale leakage of hazardous materials, its protection level should be the highest level (Level I). ii) the requirement for different areas' design against floods is different, e.g., the petroleum storage depot should resist 100-year flood at least.
Improvement after accident	1	i) If an industrial enterprise experienced a flood, leading to severe consequences and/or long recovery time, its flood protection level should be raised.

4. Safety framework for chemical clusters

A chemical cluster is a group of chemical plants. The dependence of safety on a single stakeholder (government, chemical cluster, or chemical plant) or simple measures are undesirable, even ineffective. The prevention for floods and technological accidents have been considered in the ordinary safety measures of chemical industrial areas, but those measures are disorganized from the perspective of Natech prevention. Therefore, a systematic macro-design is needed to clarify the complex relationship between different stakeholders and to organize Natech-specific measures, Figure 2 shows the proposed safety framework. The objective and implementation of each stage of the framework are further discussed in detail.

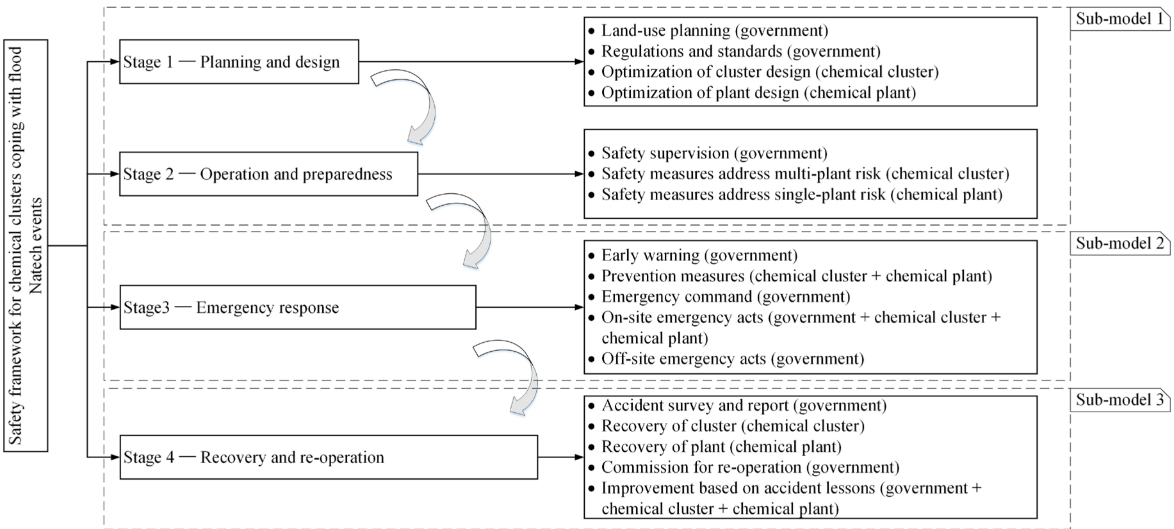


Figure 2: The safety framework for chemical clusters coping with flood Natech events.

i) Stage 1 - Planning and design

Government via land-use planning (LUP) theoretically could avoid flood Natech events. Based on the flood risk map, the site for hazardous industries can be kept away from the flood-prone areas. Besides, from a safety standpoint w.r.t. technological accidents, LUP can effectively protect people and key infrastructures (Reniers et al., 2018). However, complete dependency on LUP is impracticable, due to the dynamic characteristic of flood risk (especially considering the impact of climate change) and the limitation of land. Therefore, some regulations and standards are formulated by government agencies, as the basic rules to guide the design and construction of chemical clusters in flood zones. Cluster managers could further optimize the cluster design to reduce the likelihood of flood Natech events. For instance, critical plants can be placed outside the projected inundation area and external prevention barriers can be built through elevation planning and protection engineering. For chemical plants, similar to cluster design, its design could be further improved through optimization of installations arrangement and adding auxiliary safety facilities to hazardous installations. In particular, waterproofing for safety-critical systems to ensure its continued functions in flood condition (Krausmann et al., 2011) and a well-designed drainage system to segregate waste chemical substances and ground water should be considered in the stage of planning and design.

ii) Stage 2 - Operation and preparedness

In this stage, government usually plays a supervisory role for cluster safety through safety checks and interviews, the main responsibility lies with the chemical cluster and internal plants. For the chemical cluster, a cluster council could coordinate the internal chemical plants to achieve strategic cooperation about cluster safety in a macro view (Reniers, 2010). The unified safety planning involving safety budgets, safety resources, and emergency shelter through centralized decision-making is the best approach to satisfying the requirement of multi-plants. Moreover, the external danger and cross-broader accident effects could be effectively prevented and mitigated. The safety focus of plant could be concentrated on the internal risk. Innovative safety processes and techniques can be introduced to improve even update the origin ones. Additional safety barriers and measures can be further set for key units identified by vulnerability or risk assessment. Since floods may destroy external lifelines and emergency resources (Krausmann et al., 2011), the backup lifeline and resources should be prepared in a single chemical plant. Besides, the organizational risk reduction measures also should be highly regarded, including policies and laws, safety education and training, safety working procedures, emergency drills, emergency plans, etc. Addressing flood Natech risk needs multidisciplinary approaches (Reniers et al., 2018), setting up and carrying out specific organizational risk reduction measures should be expedited, both on the cluster level and plant level, guaranteeing staffs could take right measures under normal and abnormal situations.

iii) Stage 3 - Emergency response

Unlike other natural events, floods occurring usually have some prerequisites, like heavy rainfall, which provides extra time to mitigate flood Natech risk (Steinberg et al., 2008). Government authorities should timely publish flood warning, and the cluster council needs to quickly evaluate the warning information, then remind chemical plants to take some acts. Safety measures include the shutdown of complete processes, restraining critical units, transferring hazardous materials from possible flooding zones to a safe area, etc. However, flood Natech events still may occur, and effective and quick emergency response is needed to mitigate the enlargement of accidents. Unlike conventional technological accidents in a single plant, flood events may damage multiple units simultaneously and make the lifeline system unavailable (Antonioni et al., 2015), causing a rapid escalation of accidents through cross-broader effects and synergistic effects. Thus, the emergency response for flood Natech events is usually a large-scale and complicated work, and only relying on the emergency resources of plant and cluster is insufficient. Government should play the primary role in a large-scale emergency act. On the one hand, on-site emergency acts aim to guide the emergency evacuation of residents and aim to adequately control the accident evolution as much as possible in the context of limited emergency resources. On the other hand, off-site emergency acts include dispatching more emergency resources and rescuers from other places, even other cities, and carrying out search and rescue activities. In the case of large-scale emergency responses to cope with flood Natech events, how to avoid conflicts between emergency rescue and evacuation, how to guide panic persons evacuate to safety areas, how to take measures immediately to control accidents, and how to satisfy multi-positions emergency requirements are still challenging topics, and a scientistic emergency decision-making system is needed to support and optimize the emergency plan in real-time.

iv) Stage 4 - Recovery and re-operation

Many actions need to be carried out after a flood Natech event. At the government level, a detailed accident survey would be conducted. The major accidents may result in huge economic losses and serious social effects, which should be announced and reported by the official reliable sources to avoid adverse public opinions and to intensify the transparency of the accident. At the chemical cluster level, some macro recovery tasks need to be completed, involving site clean-up, rebuild of external barriers, risk re-assessment and cluster commissions. The recovery works on the chemical plant level mainly include damaged equipment repair or replace, installation of auxiliary components, function test and recovery of production line. After the assessment, consultation and approval of government authority, the chemical clusters could re-operation. It should be noted that accident lessons are very valuable for learning the evolution of flood Natech events, the effectiveness of mitigation and control measures, and the weakness of chemical cluster and plants. Corresponding laws and standards, risk assessment methods, and safety strategies of chemical clusters and plants can be targeted and improved to mitigate the impacts of flood Natech accidents.

As Figure 2 shows, the proposed framework can be further divided into three sub-models in the context of resilience against flood Natech events. For sub-model 1 adopted before the occurrence of accidents, i.e., the safety measures that preliminarily set in the planning and design stage or subsequently added in the operation and preparedness stage, aims to enhance the capacity of system to withstand the impact of flood Natech events and maintain its system performance in the origin level. The adaptability of chemical cluster can be defined as the ability to dynamically mitigate accident consequences and self-adjust according to the potential change of accidental scenarios. During the accidents, sub-model 2 can help chemical cluster to adapt the hazard scenarios, surviving more units and persons as possible through emergency actions. The recovery after flood Natech events is a time-consuming process. Sub-model 3 serves the recovery ability of a chemical cluster. The repair or reconstruction of damaged units through engineering measures only represents the recovery of technological performance. Full recovery should further consider the recovery of social and economic functions, which is finally completed until cluster re-operation.

5. Conclusions

In this paper, the flood Natech event phenomenon is explored using an event tree, and its potential impacts are further discussed. The flood prevention requirements for chemical industrial areas in Chinese standards are reviewed and summarized, in which the key aspects are site selection, layout design, protection engineering, drainage system and the flood protection level, etc. Finally, a comprehensive safety framework for chemical clusters coping with flood Natech events is developed, and the main work and the interaction between government, chemical cluster, and chemical plant in different stages is discussed. The framework is reinterpreted from the resilience view, and three sub-models are aligned with three fundamental capabilities of resilience, respectively. Insights gained from the proposed safety framework would be helpful to make chemical clusters more resilient, encompassing the whole process of planning and design, operation and preparedness, emergency response, and recovery and re-operation.

Acknowledgments

This study was supported by the Guangdong Key Research and Development Project (Number: 2019B111102001), the National Natural Science Foundation of China (22078109) and the China Scholarship Council (202006150080).

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