# The ResTO-TerRiN Project: Contribution to the Systemic Modeling of Technical and Organizational Issues of a Territory Exposed to Natech Risk

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**Abstract**

This paper presents a brief summary of work being carried out under the Franco-Japanese research project ResTO TerRiN. The main goal of the project is to produce relevant knowledge and effective methods and tools to improve the resilience of a territory against Natech accidents (chemical accidents triggered by natural hazards) especially those due to flood / tsunami.

The work is based on a posteriori (in Japan and France) and a priori analysis of the industrial as well as the local governments' emergency management to the Natech accidents during the Great East Japan earthquake and tsunami (GEJET) and during severe flooding events in France. Survey questionnaires in Japan and France are being applied to chemical facilities, to government agencies, and to citizens in France and Japan The data collected are used to model the impact of the natural hazard events on the facilities and the safety barriers, as well as the community and overall social impacts. These results are then used to understand societal and territorial resilience to these complex disasters and propose a Natech resilience model. In this paper we present the preliminary results of the ongoing work in Japan.

## 1. INTRODUCTION

Chemical accidents triggered by natural hazards (known as Natechs) are relatively rare. In fact they represent between 2 – 7 % of all chemical accidents reported in databases in Europe and the United States, and show an increasing trend in the last 30 years (Sengul et al. 2012; Santella et al. 2011). Growing urban populations and industrialization in areas subject to natural hazards, coupled with environmental change due to climate change and other factors will contribute to an increase in the number of Natech accidents in the years to come (Cruz and Krausmann 2013).

Natural hazards are generally taken into account in the design of chemical plants by insuring that buildings and structures are built to codes. Nonetheless, they are mostly absent in process hazard assessment and chemical accident prevention programs. Thus, the safety and mitigation measures, and emergency response plans to prevent and respond to chemical accidents concurrent with natural disasters may not be effective under the natural disaster conditions. Furthermore, local government and civil protection authorities are often not aware of or not familiar with the dangers posed by certain industrial activities lacking knowledge and/ or training about chemicals and their potential health effects (Cruz et al. 2006).

Natech risk management is relatively complex. These technological accidents occur while the "system which should provide resilience" are already under "stress" due to the concurrent natural hazard event. In the case of a Natech the industrial plant is both impacted by the natural hazard event, and may become the source of additional “hazards” due to the release/ potential release of hazardous materials which may have direct and indirect impacts offsite to nearby residents and communities.

This project studies these aspects by considering two levels of analysis: the scale of the industrial site, called microscopic scale, and the scale of the territory or society, called macroscopic scale. These two spatial scales look at the problem from the perspective of "vulnerability" and via a comprehensive analysis of the notion of territorial or societal resilience to Natech accidents. With regard to the microscopic scale, we aim to improve the understanding of the physical and organizational vulnerability of industrial facilities exposed to natural hazards (particularly tsunamis and floods), to identify and define prevention and protection measures, to ensure that plant owners/operators and emergency organizations are able to cope with Natech events. The idea is to provide to industrial risk managers tools and guides for improved Natech risk management during both prevention and response. With regard to the macroscopic scale, the objective of this project is to build a Natech resilience model through the identification of Natech resilience criteria. In this paper we present the preliminary results of research work being carried out in Japan.

## 2. METHODOLOGY

The project consortium involves a multi-disciplinary team of researchers from Japan and France. In both countries data has been collected through interviews, field visits, survey questionnairesin case study areas: in the Tohoku area (Japan) and in several industrial areas in France, particularly the Presqu'île d'Ambès (Gironde). Furthermore, we review reports, documents and the scientific literature. This peninsula, in the north of Bordeaux, is located between two rivers (the Garonne and the Dordogne) not far from the Atlantic coast. Therefore, this territory can be inundated by both river floods and storm surges. There are several small and large facilities (11 SEVESO sites and ICPE plants) along the Garonne banks. The overall population of the peninsula, which is exposed to both technological and natural risks, is about 30.000. Thus, this territory is appropriate for the analysis of the flood natech events, although there have been no natech accidents to date (several SEVESO sites were inundated by the 1999 storm, and some technological accidents have taken place, but never a technological accident has been triggered by flood events).

In Japan, the main objective is to collect and analyze data and extract lessons learned from Natech events triggered by the Great East Japan earthquake and tsunami disaster of March 2011. Through field visits and person-to person interviews with industrial and government officials it has been possible to construct event trees and fault trees of the most important accidents triggered by the earthquake and tsunami. Furthermore, through mail surveys of industry and local residents we are assessing Natech disaster risk reduction practices, risk perception and disaster preparedness for these types of events. In this paper we present preliminary results of two mail surveys. One to industrial facilities in affected areas in Miyagi Prefecture, and the other to residents living near a refinery in Sendai that suffered fires after the tsunami.

An industrial mail survey was sent out through the Japan Industrial and Medical Gases Association (JIMGA) in Sendai to member companies. JIMGA had the contact information of these companies and was able to contact their managers directly even if the facilities were not in operation. We present here a summary of the responses of 21 companies. The industrial survey asked questions regarding damages and losses, performance of safety and mitigation measures, and the opertional readiness/ effectiveness of the emergency response. The resident/ household survey asked questions regarding risk perception of Natech hazards, disaster preparedness and the evacuation for the tsunami as well as the Natech accidents.

The household survey was led by research team members at Kobe University to residents living within an area of 2km in radius from the source of a Natech accident that occurred at the JX Refinery following the tsunami. The purpose of the survey was to understand residents' attitude and protective actions such as evacuation due to the Natech. The questionnaire also inquired about damages to homes or injuries to residents, and the evacuation order issuing process.

In France, a priori analysis of the industrials as well as the local governments' (e.g., city and prefecture governments, fire division/ departments, industrial emergency responders) involved in the management of the Natech disasters during severe flooding events or storm surges is led. By the way of field visits, survey questionnaires, and interviews, we identify and map all players/actors and their responsibility, mechanisms, public policies and tools which are used in planning for natural and technological emergencies. The aim is to represent the organizational and management frameworks to identify criteria which could characterize the global natech resilience of the territory. Moreover, we are capitalizing the knowledge of the industrials to improve our understanding of how they manage natural disasters, technological accidents and eventually natech events. These data are used to construct various models (systemic model, functional representation, statistical models and risk models). Subsequently, these models are used to elaborate the guidelines/tools, identify the resilience criteria. In this paper, we present the first elements of a model built to assess the flood-induced Natech vulnerability of an industrial site.

## 3. PRELIMINARY RESULTS

### 3.1 Survey of Industrial Facilities

The interviews, field visits and mail survey to industrial facilities have provided important information concerning damage and losses, chemical accidents and spills triggered by the earthquake and tsunami, the vulnerability of the facilities, the accident consequences, the performance of safety and mitigation measures, and the overall emergency response to contain them. The interviews and visits to affected companies have provided detailed information about the accident mechanisms and cascading events, and has allowed the construction of flow diagrams, event trees and fault trees. Figure 1 presents an event tree of the impact of the earthquake and tsunami at a refinery and other nearby facilities at an industrial park in Sendai. It is important to note that in Figure 1, the cascade of events, direct and indirect, that contributed to the triggering of releases and/ or spills, and escalation into a large fire. Some of the steps in the chain (e.g., oil spill spread by flood waters) of cascading events would not normally occur during day-to-day plant operation, and therefore may be overlooked if the potential for natural hazard loads are not considered in the risk assessment of chemical process plants. Detailed fault trees have been constructed to identify common cause failures and key line of events.

The mail surveys provided additional important information about impacted facilities. Table 1 presents a summary of the characteristics of the industrial facilities surveyed thus far. The majority of facilities are nationally owned, small and medium size, chemical companies with 50 or less employees. 40% of the companies were subject to strong ground shaking (Shindo scale: 6 plus), 30% were subject to ground shaking intensity of 5 or higher, and the other 30 % did not know. Six companies said their plants were subject to tsunami inundation heights of 3.0 meters or higher, with one of these reporting 9.5 m. See Table 2.

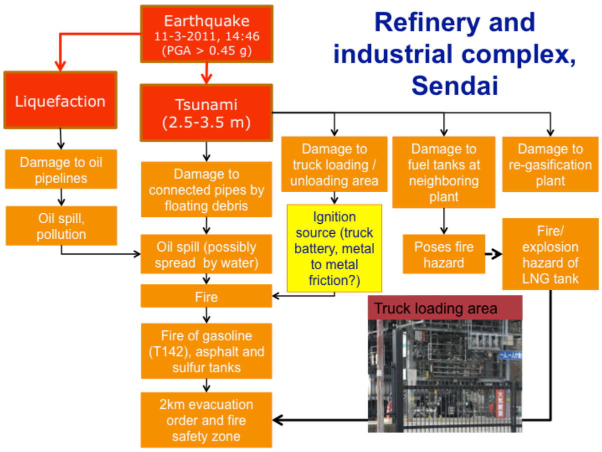


Fig. 1 Event tree showing the impact of the Great East Japan earthquake and tsunami at a refinery and an industrial park in Sendai.

All of the facilities reported some kind of damage. 76% of the facilities said they were directly damaged by the earthquake while 52% said the facilities were directly damaged (e.g., direct damage due to strong ground shaking; direct impact by tsunami wave and damage due to hydrodynamic and hydrostatic loads) by the tsunami. Indirect damages (e.g., collapse of nearby building on equipment; impact by floating debris) from the earthquake and the tsunami were also reported. Table 3 shows the statistics concerning overall damage at the facilities surveyed. It is important to note that the region experienced several large aftershocks causing additional direct and indirect damages at more than half of the facilities.

Furthermore, all of the facilities reported that they had to partially or completely shut down after the disaster. Complete shutdown of operations occurred at 18 facilities (86%) and 3 reported partial shutdown. Table 4 shows the causes of total or partial shutdown. 81% of facilities indicated 'loss of electricity' as one of the contributing factors for the total or partial shutdown, followed by 76% of facilities that indicated that direct / indirect damage contributed to the shutdown.

Table 1. Industrial facility characteristics

| | No. of facilities | Percent |
|---|---|---|
| Multinational | 1 | 5% |
| Plant size | | |
| Small | 13 | 62% |
| Medium | 5 | 24% |
| Large | 2 | 10% |
| No. of employees | | |
| (0-50) | 18 | 86% |
| (51-200) | 0 | 0% |
| (201+) | 3 | 14% |
| Type of industry | | |
| Chemical (High pressure gas ) | 18 | 86% |
| Oil refinery | 2 | 10% |
| Metallurgical | 1 | 5% |
| N | 21 | |

Despite the fact that 17 facilities suffered total or partial damage, only five reported the release of hazardous materials. Two of the releases occurred due to the earthquake, one due to the earthquake and tsunami, and two due to the tsunami. Two of the releases occurred sometime after the earthquake, while the tsunami-triggered releases occurred during the tsunami. Earthquake damage of storage tanks, pipelines and other equipment occurred due to structural failure of support structures, overturning of equipment and buckling, among other causes. Tsunami damage occurred due to inundation and water intrusion, debris impact and floating-off of equipment. Table 5 summarizes these findings.

Table 2. Reported tsunami inundation heights at the surveyed companies.

| Tsunami inundation height-h (m) | Number of facilities (N = 21) |
|---|---|
| Not flooded | 5 |
| Less than 1 m | 1 |
| $1 \leq h < 3.0$ | 2 |
| $\leq 3.0$ | 6 |
| Unknown | 7 |

Table 3. Overall damage

| Damages | No. of facilities | Percent |
|---|---|---|
| Earthquake | | |
| Direct damage | 16 | 76% |
| Indirect damage | 16 | 76% |
| Tsunami | | |
| Direct damage | 11 | 52% |
| Indirect damage | 8 | 38% |
| Aftershock | | |
| Direct damage | 11 | 52% |
| Indirect damage | 11 | 52% |
| Totally shut down | 18 | 86% |
| Partially shut down | 3 | 19% |
| N | 21 | |

Table 4. Causes of total and partial shutdown

| | No. of facilities | Percent |
|---|---|---|
| Direct/indirect damage | 16 | 76% |
| Blocked transportation routes | 3 | 14% |
| Loss of electricity | 17 | 81% |
| Lack of fuel supply | 1 | 5% |
| Supplier company was damaged | 2 | 10% |
| No/loss of backup power generation | 3 | 14% |
| Loss of water | 1 | 5% |
| N | 21 | |

Table 6 summarizes damages to emergency response systems (including buildings, equipment and resources) by the earthquake and the tsunami.

Table 5. Failure modes leading to chemical releases

| | No. of facilities | Percent |
|---|---|---|
| Earthquake damage (N=9) | | |
| Failure of welds | 3 | 33% |
| Failure of support structure | 2 | 22% |
| Pipe damage | 2 | 22% |
| Overturning of vessels/pump, etc. | 3 | 33% |
| Foundation buckling | 1 | 11% |
| Other damage (earthquake sensor) | 1 | 11% |
| Tsunami damages (N=10) | | |
| Inundation | 6 | 60% |
| Flotation | 2 | 20% |
| Impact by debris | 3 | 30% |
| Other (loss of electricity/ damage to warehouse) | 2 | 20% |

Damage to emergency response systems included direct damage to fire stations and fire trucks onsite, inundation of low lying emergency response equipment such as pumps and motors, floating off of emergency water pipelines, loss of utilities at emergency response/ services buildings, damage to IT equipment and damage to communication systems. Most facilities completely evacuated the plant sites before the arrival of the tsunami. Two facilities indicated that they had staff who stayed onsite. During the person-to-person interviews, several staff indicated that in the future, facilities in flood prone/ tsunami prone areas need to maintain emergency boats to move around once the danger has passed to rescue stranded workers or residents, or perform emergency response actions.

Table 6. Number of facilities reporting damage to emergency response systems

| Damages | No. of facilities | Percent |
|---|---|---|
| Earthquake | 5 | 24% |
| Tsunami | 7 | 33% |
| na | 9 | |
| N | 21 | |

### 3.2 Preliminary Findings of the Household Survey

The mail survey was sent to a random sample of 1,632 households, and 484 households responded, for a response rate of 29.4 %. Figure 2 presents the distribution of (a) sampled households and (b) returned questionnaires (Yu et al. 2015).

We used risk likelihood and severity to measure the risk perception levels by asking: how likely did you think a Natech would be a threat to your lives or property before the Tohoku earthquake, just after the earthquake shaking, and in the future 10 years. Furthermore, we asked to what extent residents felt that a Natech would affect their lives or property before the Tohoku earthquake, just after the earthquake shaking, when they perceived the danger of the Natech, when they received the Natech evacuation order, while staying at the evacuation shelters, and in the future 10 years.

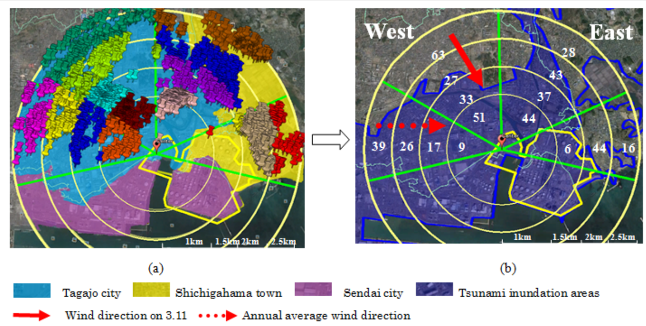


Fig. 2 Distribution of (a) sampled households and (b) number of households completing the questionnaire (Source : Yu et al. 2015).

One of the more interesting results of the survey is the fact that residents evacuated more than once. In fact 65% of respondents said they evacuated at least one time; over 30% evacuated the first time because of the Natech accident not the tsunami. Almost 50 % of the total that evacuated the first time, evacuated a second time, and over 66% of those that evacuated a second time, had to evacuate a third time. Some residents had to change shelter more than four times. Many residents evacuated on their own initiative without waiting for authorities to issue an evacuation order. During person-to-person interviews with residents, some indicated that there was a lack of clear information regarding where it was safe to evacuate to, or what they had to do in order to protect themselves and their families.

The survey asked about households' risk perception. The results show that people's risk perception in terms of the perceived likelihood that a Natech would cause harm to their lives or property increased (as expected) after experiencing the Natech during the Tohoku earthquake. However, as presented in Fig 3, no change was found for risk perception in terms of the perceived severity of the impacts of a Natech accident when compared with their responses before the Tohoku earthquake and in the next 10 years. This may be because no deaths, injuries or severe environmental damage due to the Natech was reported. We found that households felt that the Natech was very serious when: a. they perceived its occurrence, b. while they were staying at the first/second evacuation shelter, and c. when they received the Natech evacuation order.

Using logistic regression models, we also analyzed how risk perceptions together with geographic and demographic variables influenced people's evacuation decisions due to the Natech danger in order to comply with official orders.

Results showed that wind direction (B=2044, exp(B)=11.41, $p \leq 0.01$) and people's perception of the Natech severity when they perceived its occurrence motivated (B=1.77, exp(B)=5.89, $p \leq 0.05$) more people to evacuate. And we also found that being a female (B= 1.22, exp(B)=3.40, $p \leq 0.01$) made it more likely to comply with the Natech evacuation order.

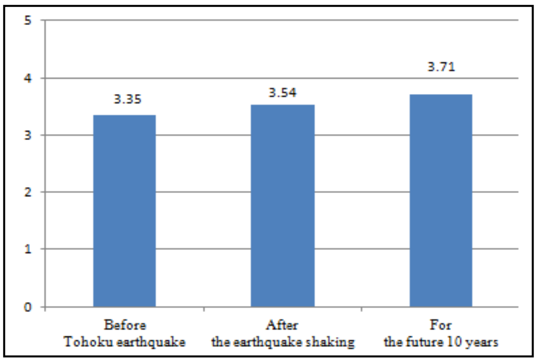


Fig. 3 Mean risk likelihood rating for natech (where 0 is not likely, and 5 is very likely) (Source: Yu et al. 2015).

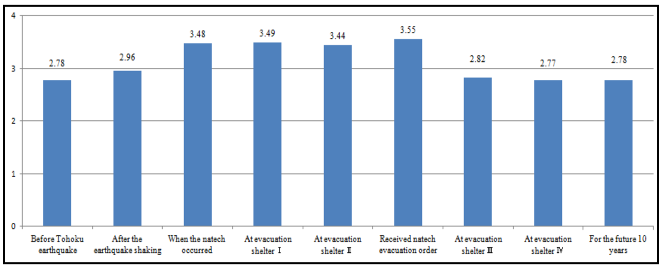


Fig. 4 Mean risk severity ratings for Natech throughout the evacuation process (where 0 is no severe impacts expected to 4 very severe impacts expected) (Source: Yu et al. 2015).

At last, to our surprise, results showed that people's perception about the Natech severity when they received the Natech evacuation orders played a negative role in evacuation motivation (B=-0.95, exp(B)=0.39, $p \leq 0.05$). This may due to the fact that many evacuees were reluctant to evacuate again for a Natech because they had already evacuated due to the earthquake/tsunami. Even those who have higher severity risk perception about the Natech when they received the Natech evacuation order were less likely to evacuate again. This finding may be important to emergency mangers or local officers to make a more effective plan to protect evacuees who may need to evacuate more than once.

### 3.3 First Elements of a Model to Assess Flood-Induced Natech Vulnerability of an Industrial Site (El Hajj et al., 2015)

The tools used to assess the vulnerability of industrial sites versus flood-induced Natech, will use final generic accidental scenarios (model) in the form of fault trees (Vesely et al., 1981).

This model is based, on the one hand, on all the data collected during the project, and on the other hand, on a systematic risk analysis methodology. The systematic approach uses the MADS model, which is the French acronym for "Analysis Method of Dysfunctional Systems" (Périlhon 2007), (Lesbats et al. 2014). These models are built in three steps :

a. Conceptual modeling of an industrial installation: This model is divided into several sub-systems responsible for triggering major accidents in case of flooding of an industrial site. The decomposition is an important step to facilitate the risk analysis: It is used to organize the information obtained through experience feedback and to conduct a rigorous analysis.
b. MADS analysis. By adopting the MADS MOSAR methodology and building on the analysis of past accidents, each sub-system of the industrial installation will be analyzed in order to understand how it would be responsible for major accidents in case of floods. Therefore, the identification of potential hazards and their process are established.
c. Accident scenarios development: In order to identify potential accidents triggered by flood events, a fault tree is associated to each sub-system.

Building on the analysis of data collected during the project, only parts of an industrial installation which are involved, directly or indirectly, in the generation of major accidents during floods were considered (sub systems). We have identified 6 sub systems (fig. 5):

- Critical equipment (hazardous materials containing equipment such as atmospheric storage tanks, atmospheric reactors and pipes…)
- Building structures,
- Intern utilities (heating, cooling systems…),
- Safety barriers
- Control and supervision systems,
- Intern hazardous materials release emergency organization.

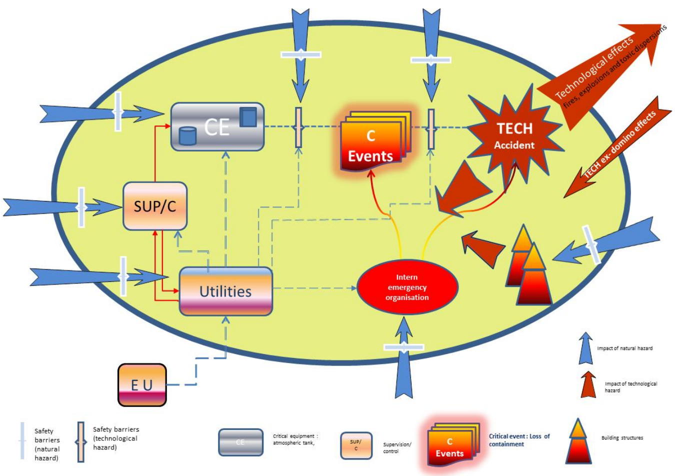


Fig. 5 Conceptual modeling of an industrial installation during a Natech event.

In a second step, an analysis of each sub-system of the industrial installation was done in order to find how it can be impacted by the natural hazard (target of hazard flow) and how it could be considered, after a flood event, as a system causing mechanical shocks (ch), overpressure (Pr), heat radiation (th), pollution (P), electrical hazards (el) and regulation and energetic hazards (En) (source of hazard). For instance, for the critical equipment atmospheric storage tank, the following questions are asked systematically: how the atmospheric storage tank can cause mechanical shocks, overpressure, heat radiation…following a direct contact with floodwaters or, indirectly after the inundation of the site. Therefore, the main hazard flows between all the sub-systems that can be observed after a flood episode of an industrial installation and all the potential hazards in an industrial site were identified. The results of this systematic analysis were presented in a table containing the different elements of the MADS hazard flow.

In a third step, based on the various tables containing the different elements of the MADS hazard flow, fault tree are built for each sub system. For example Fig. 6 presents the fault tree of the sub system Electricity utility.

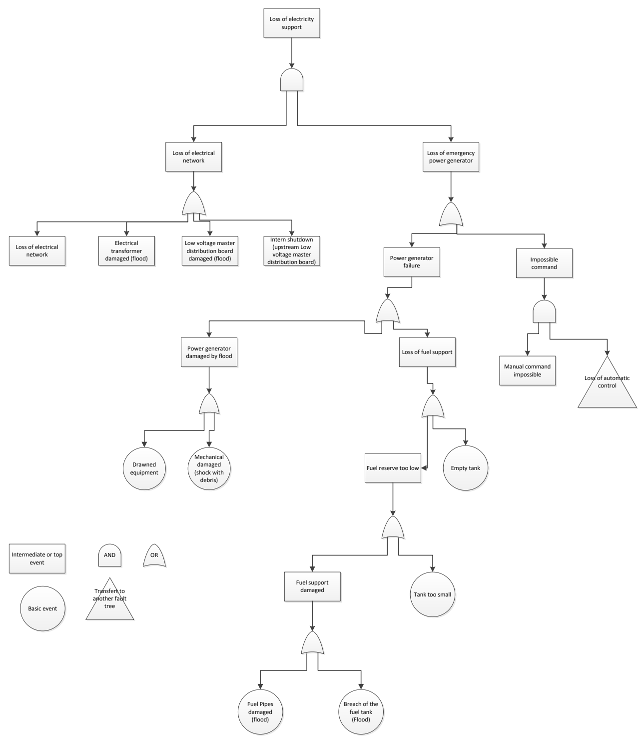


Fig.6 Fault tree of Electricity utility.

Consequently, the final results of our work will be the development of generic accident scenarios triggered by flood events. These scenarios will be built using all the fault trees of the various sub systems which can be impacted during a flood event. They can be used for flood Natech risk analysis, a diagnosis tool based on these scenarios to find the weak points regarding technological accidents triggered by floods and finally recommendations on how to mitigate these accidents in the form of a list of preventive and protective measures.

## 4. CONCLUSIONS

These preliminary results have highlighted that natural hazard events can directly and/ or indirectly impact industrial facilities that handle hazardous materials resulting in spills or smaller releases, which may escalate to major accidents through cascading events including due to the loss of lifeline systems and emergency response capabilities.

The survey facilities suffered damages and losses, but less than 20 % actually experienced releases. It is not clear at this point whether this is due to their location (located in a less vulnerable area), good risk management practices, or other causes. This needs to be further studied.

Further research is continuing with a focus on how to improve the effectiveness of the evacuation orders by identifying when, where, and how to issue and disseminate information about chemical accidents, and what emergency response actions residents can take (particularly in the absence of warnings or evacuation orders from local authorities). Another key point is to understand the dynamics of multiple evacuations such as identifying which groups are more likely willing to evacuate more than once and what factors are more effective in motivating them.

## ACKNOWLEDGEMENTS

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