

From Risk Management to Risk Governance: A Paradigm Shift for Natech Risk Reduction

Ana Maria Cruz⁽¹⁾

(1) Professor Emeritus, Kyoto University

Synopsis

Natural hazard-triggered technological accidents involving releases of hazardous materials are known as Natech. This article provides an overview concerning Natech incidence and trends, and carries out a spatial-temporal analysis to understand how Natech probabilities may change in the future. The results point to a potential increase in Natech probabilities in the future, which combined with growing population and industrialization in areas subject to natural hazards clearly point to the need to address Natech hazards and risk in a more holistic way. In order to promote societal resilience to these combined hazards, we propose an area-wide, comprehensive Natech risk management and rating system framework. The need to broaden the scope of analysis from individual installations, to the whole of communities is key to the framework, and necessarily calls for risk governance and risk communication efforts. Along this line of thought, efforts to develop and apply a serious game to improve risk awareness, raise risk perception, and promote risk communication are presented. Finally, some conclusions and recommendations for future research are discussed.

Keywords: Natechs, climate change, tropical storms, disaster management, United States

1. Introduction

Earthquakes, typhoons and other natural hazard events can impact industrial installations exposed to them. When this happens, hazardous materials can be released posing additional problems for nearby communities. The Great East Japan earthquake and tsunami disaster serves as an example. The earthquake and tsunami triggered several chemical accidents, mostly through cascading events, such as the oil spills from floating roofs due to liquid sloshing, and oil spills at a truck loading area and damaged pipelines due to floating debris impact due to the tsunami at a refinery in Sendai (Krausmann and Cruz 2013). Domino effects were also documented such as the fires and explosions at the Cosmo oil refinery in Ishihara city (Krausmann and

Cruz 2013). These natural hazard-triggered technological accidents are known as Natechs (Cruz 2003).

Natech events are relatively rare, but may have high consequences. For example, Girgin and Krausmann (2016) studied Natech related incidents involving hazardous liquid pipeline systems in the United States. Their results showed, that while the number of Natechs comprised 5.5 % of all pipeline incidents, their cost relative to the total was 18%. The authors noted that the Natech incidents resulted in more severe economic damage per incident than other incidents, although they occurred less frequently.

In addition to posing an economic risk to industry, Natech events add burden to emergency response efforts and can use up much needed

resources, complicating evacuation, and increasing uncertainties. This was the case following fires at an oil refinery in Korfez, Turkey, triggered by the Kocaeli earthquake of magnitude 7.4 on 17 August, 1999. The multiple fires posed an explosion risk of a nearby ammonia storage tank (which is both toxic and flammable) and ethylene storage tanks, prompting local responders to issue evacuation orders in an area several kilometers in radius. The evacuation orders resulted in withdrawal of search and rescue teams from the area as well leaving victims behind still trapped under debris (Cruz and Steinberg 2005, Steinberg and Cruz 2004).

Taking into account the above problems posed by Natech events, the overall goal of the Risk Management laboratory was twofold: a. to contribute to risk reduction from large-scale disasters (LSDs) impacts on industry and related infrastructures, and b. to promote societal resilience to LSDs and these secondary impacts through integrated disaster risk management. The main research topics included the study of Natech incidence and trends under climate change, the integration of natural hazards models into industrial risk assessment methodologies, area-wide Natech risk management and risk governance studies, understanding residents', industry, and government officials' risk perception and hazard adjustments, and promoting risk communication and participatory approaches for Natech risk reduction.

In the next section, I present a brief introduction of research carried out. First, Natech incidence in the United States is investigated, and the potential future effects of climate change on Natech probabilities in the future until 2100 are analyzed from a spatial-temporal point of view. Then, the need for a paradigm shift in Natech risk management is addressed through the development of an area-wide, comprehensive Natech risk management framework. The framework expands the scope of analysis of traditional industrial risk assessment from an individual establishment to the territory. That is it, includes the external environment, other businesses and industry, critical infrastructures, and communities in a territory potentially subjected to Natech risks. In order to manage risk in a territory, we need risk governance, supported by risk communication. We propose a methodology to

assess Natech risk in the territory, and then develop a serious game to raise risk awareness and risk perception, and promote risk communication among diverse stakeholders. Finally, we present some conclusions and challenges for future research.

2. Natech Incidence and Climate Change

Natech accidents account for 3-7 % of all reported hazardous materials releases in several databases around the world according to several studies (Young et al. 2005; Sengul et al. 2012; Necci et al. 2018).

Using data on chemical accident reports to the National Response Center in the United States between 1990 and 2017, a deep-learning-based framework to identify and retrieve Natechs was proposed (Luo et al. 2020). Over 32,000 Natech events (out of approximately 800,000 chemical release reports in that period) were identified and retrieved for further study. More than 97% of identified Natechs were hydrometeorological hazard related, with the highest number related to tropical storms (Luo et al. 2020). Indeed, one important question was whether climate change may be affecting overall Natech incidence due to its influence on tropical storm activity in the United States.

Climate change may pose challenges for tropical storm-related Natechs (TSNatech) risk management, as some studies have noted that it can influence tropical-storm intensity and duration, and the areas they affect. For example, as reported by Luo (2021), Mudd *et al.* (2014a, b) wrote that climate change may lead to more intense (maximum wind speed) and larger hurricanes (radius to maximum wind speed) in the future. According to Ting *et al.* (2019) more intense hurricanes may form along the US coast, due to the impacts of climate change on vertical wind shear. Luo (2021) also points out the results of other studies suggesting that climate change could result in more heavy rainfall caused by future tropical storms, and variations in moving speed of hurricanes. Furthermore, due to climate change, tropical-storm pathways may include larger latitudinal (Kossin *et al.* 2014) and longitudinal swathes (Collins *et al.* 2019). Thus, facilities and industrial installations across wider areas could be

affected by more intense or prolonged tropical storms due to climate change exposing them to potential Natech risk.

Therefore, it is important to understand whether and how climate change affects the frequency of TSNatechs in order to design mitigation and adaptation measures and improve industrial risk management.

results suggest an indirect link between climate change and the temporal-spatial variation of the incidence of related Natechs due to its effect on tropical storm activity.

In order to understand how TSNatech incidence will vary in the United States in the future, we conducted further work to predict TSNatech probabilities for the future 80 years using data sets

Table 1 Datasets, data sources and their use (Luo, 2021)

Name	Data Source	Usage	Reference
National Response Center (NRC)	United States Coast Guard	Natech identification	USCG, 2017
The Toxics Release Inventory Program basic data (TRI)	United States Environmental Protection Agency	Infrastructures identification TSNatech probability calculation	U.S. EPA, 2017
Oil and Natural Gas Platforms data (ONG)	Homeland Infrastructure Foundation-Level Data (HIFLD)	Infrastructures identification TSNatech probability calculation	HIFLD, 2018
Best Track Data (HURDAT2)	NOAA	Parameters extraction for historical tropical storms (duration, pathway, center location, etc.)	Landsea et al. 2015
The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)	Global Modeling and Assimilation Office (GMAO)	Wind energy calculation TS affected area identification	GMAO 2015
ScenarioMIP (SSP4-3.4, SSP4-6.0 and SSP5-8.5)	World Climate Research Programme (WCRP)	Wind energy calculation	Yukimoto et al. 2019a,b,c
Representative Concentration Pathways (RCP 2.6, RCP4.5, RCP6.0 and RCP 8.5)	World Climate Research Programme (WCRP)	Wind energy calculation	Yukimoto et al. 2015a,b,c

We analyzed the temporal-spatial variation of the incidence of tropical storm related Natechs (TSNatechs) and the relationship with the accumulated cyclone energy, the North Atlantic Oscillation (NAO) index and the Oceanic Nino Index (ONI) (Luo et al. 2021).

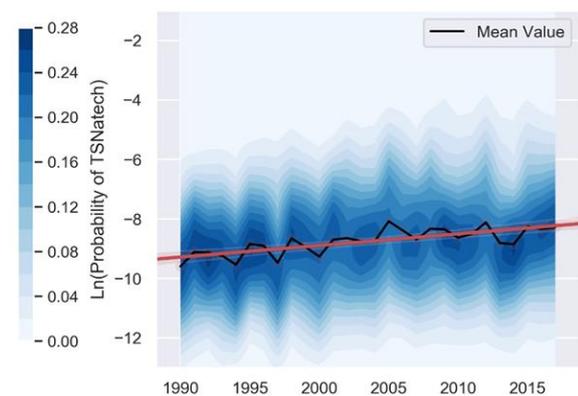


Fig. 1 Probability of TSNatech (Ln) in the period 1990-2017 in the United States.

The results of this work first, confirmed that the frequency and density of tropical storms-related Natechs are on the rise; and that the probability of TSNatech is increasing (see Fig. 1). Second, the

as shown in Table 1. We defined two study areas, A and B, to predict the TSNatech probability from a spatial and temporal point of view. See Fig. 2.

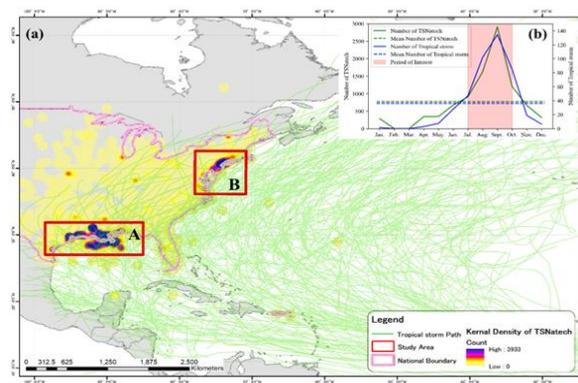


Fig. 2 Study areas A (along U.S. Gulf of Mexico) and B (along the East Coast of the U.S.) (Source: Luo, 2021)

A methodology applying a statistical model was developed to obtain empirical estimations for TSNatech probability. In the proposed methodology, wind energy was used as the variable to estimate TSNatech probability as it served as an evaluation metric for the potential energy which could be

released during the dissipation of tropical storm energy. This was done for the months with most tropical storms during the year and the corresponding TSNatech occurrences over the period 1990–2017 in each of the areas A and B. Based on this methodology, TSNatech probabilities were also estimated for 2021–2100, using Scenario MIP data.

Our study results showed a significant increase in TSNatech event occurrence probabilities in the future in both areas A and B, compared to TSNatech probabilities for the period 1990–2017. See Fig. 3.

Moreover, in a warming climate, our results indicate that the counts of extreme TSNatech probability may increase, and the clustered TSNatech event occurrences may also become more serious in the future. Furthermore, a changing climate may exacerbate existing vulnerabilities and other conditions leading to disasters. This was the case in Hokkaido, Japan, following an M6.6 earthquake that hit the island on 6 September 2018 triggering massive landslides. Patton et al. (2018) noted that the slopes were likely preconditioned for failure due to precipitation over the area from Typhoon Jebi on 4-5 Sept. 2018. While multi-hazard interactions were not considered in the present study, the above example shows that they may pose a real problem for exposed installations, and careful analysis is needed.

To conclude, in this study we found that the TSNatech occurrence probabilities may change with different pathways under different SSP climate scenarios. However, the mechanism of how the elements in the SSP scenarios affect the changes in TSNatech probability were unclear, making this a very important forward research direction.

Future work could address aspects such as equipment aging, land-use changes, changing or improving building standards, and whether facility managers / owners improve their approaches to risk management that were not addressed in this study.

Nevertheless, our results point to potential increases in TSNatech probabilities, and hence government officials, plant owners/ operators, first responders, and other related stakeholders in exposed areas should consider this risk when formulating risk reduction measures to protect facilities and communities from future events.

3. A change in paradigm in Natech risk assessment and management

The above results point to a potential increase in TSNatech probability in the United States due to climate change. Other areas around the world, including Japan, may experience an increase in the probability of Natechs in the future. However, limited data on Natech event occurrences in other parts of world limit the ability to carry out similar works.

Nonetheless, overall there have been significant advances in Natech research, particularly regarding the understanding of accident mechanisms (Sengul et al, 2012; Cruz and Steinberg 2005; Krausmann and Cruz, 2013; Misuri et al. 2022; Parra-Orduz and Cruz, 2024); development of quantitative risk assessment methodologies (e.g., Antonioni et al., 2007), the performance of safety barriers (Misuri et al., 2021) and understanding of risk drivers (Lam et al; 2019). There have been increased efforts to integrate models for a better understanding of event chains and consequences (Song et al. 2023), and there are increased efforts concerning risk management and risk governance (Saurez-Paba et al., 2025; Park and Cruz, 2022), and risk perception and risk communication studies (Borjigin et al., 2024; Tzioutzious et al., 2022; Yu et al., 2017). However, important challenges remain to ensure territorial resilience in the face of Natech risk.

Particularly, what does this mean for highly industrialized, urban areas that have high population living within or near installations that handle hazardous materials in the U.S., Japan and other parts of the world? In order to prevent or minimize damage and losses, we need a comprehensive, area-wide risk management framework. A comprehensive perspective of Natech risk management should advocate for territorial resilience enhancement. Resilience, as proposed by Aven (2011) is “the ability of a system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time, and composite costs, and risks”. In this sense, the concept of resilience assumes an important role for industrial installations, particularly the chemical and petrochemical industry.

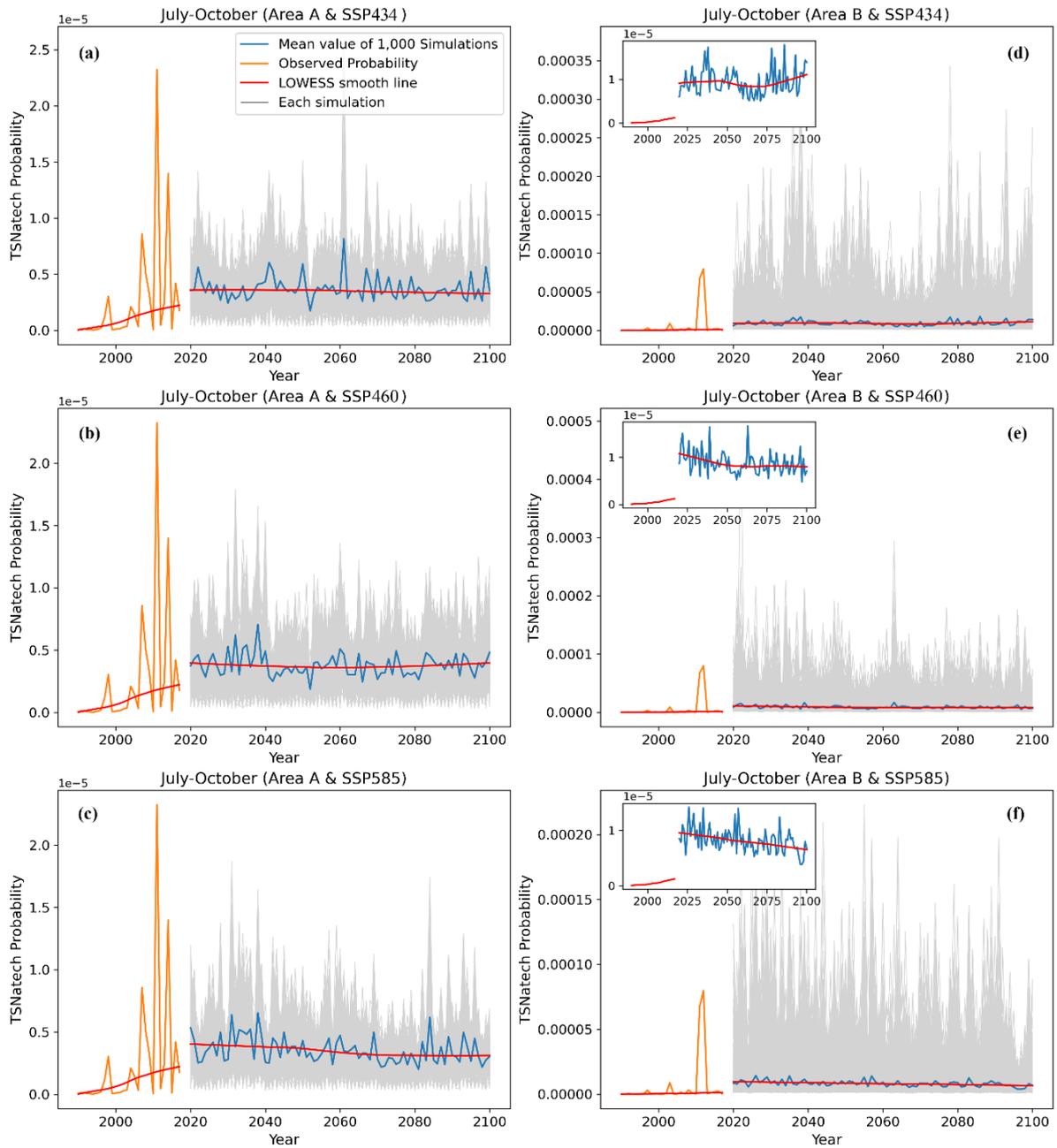


Fig. 3 Simulation results showing TSNatech probabilities, based on simulated climate data under different SSPs scenarios. Blue lines in each panel show the means for 1,000 simulated TSNatech probabilities; orange lines show estimated TSNatech event probabilities based on past TSNatech records; gray lines show each simulation result; red lines are smoothed lines, based on using the LOWESS method to track long-term trends in the simulated TSNatech probabilities (Source: Luo, 2021).

Several studies highlighted the need for resilient industries that can be prepared to face known and unknown hazards and mitigate their potential consequences (Jain et al. 2018a; Sahebjamnia et al. 2018; Niskanen 2018). In order to promote territorial resilience in areas exposed to Natech risks, we need to understand that the scope of analysis changes. That is the “system” is no longer only one industrial facility, but that the territory, including the facility, neighboring industries and business, interconnected infrastructure and surrounding residential areas, are in fact the system! Furthermore, the need for flexibility in order to adapt to rapidly changing dynamic situations is imperative.

Altogether, the crucial interconnections between industry and other organizations, infrastructure, the environmental and communities have not been extensively studied. These interconnections are particularly important in complex systems that form a network of linkages with a nonlinear interaction. Even with the existence of business continuity and recovery plans, organizations that fail to incorporate the overall interaction of such elements will remain uncertain in terms of the degree of resilience they can achieve. Consequently, taking into account that disruptions of different origin can pose both a potentially unpredictable and severe threat to the continuity of an organization’s operation, efforts need to be intensified in order to address resilience from a broader perspective (Bhamara et al., 2011); a perspective that contemplates a more holistic risk management viewpoint. Yet, although some studies have underscored the need for resilient industries, only recently researchers have called for an area-wide perspective, where a paradigm shift in Natech risk management fosters a holistic systems approach.

Building on the concepts of resilience engineering, but also performance rating systems, a comprehensive, area-wide Natech risk management framework and rating system, titled Natech RateME, was proposed (Suarez-Paba and Cruz, 2021).

The proposed framework is premised on a probabilistic risk assessment methodology, that can support industrial facilities’ management of onsite and offsite risk from complex events and that rates their performance in terms of minimum life losses. By evaluating their safety performance, their engagement to develop cooperation mechanisms

with local authorities and neighboring communities, and their commitment to disclose risk information, among other aspects, the framework, and the rating system, seek to contribute to overall territorial resilience.

Natech RateME considers the interaction between infrastructure systems present at industrial parks, the technical and organizational systems including safety culture and human factors, and governance, risk communication, and community participation. This framework constituting the first approach to support the strengthening of prevention and mitigation measures by enhancing facilities’ and governments’ abilities to manage Natech risk comprehensively (Suarez-Paba and Cruz, 2021).

4. Working with multi-stakeholders to promote area-wide Natech risk management and risk communication

Taking into consideration the need to move towards area-wide risk management, and given the opportunity to work directly with industry and other stakeholder in Colombia, some of the research efforts centered around the introduction of the comprehensive, area-wide risk management framework in the country. While new regulations introduced in 2012 in Colombia called for the analysis of natural hazard impacts on hazardous installations, there were no previous studies that investigated practices, risk awareness, knowledge regarding risk management. Thus, the work involved the development and application of both government and industrial surveys to gauge practices and challenges regarding Natech disaster risk management (DRM) in Colombia. The findings are indicate that from the perspective of government organizations, Natech risk management in Colombia is at its first stage. At the time of the survey there were no guidelines or technical references for its risk assessment. While the survey showed increased awareness regarding Natechs, most government officials felt that there was still limited understanding regarding this risk, and little information sharing and communication among government authorities, inspectors and so on at various levels of government. From the perspective of industry respondents, the results showed there

was increased awareness, in particular regarding the effects of heavy rainfall, floods and landslides and their potential to cause accidents at industrial installations and along oil and gas transmission pipelines. Despite the fact that the new regulation calls for risk information disclosure and the development of emergency management plans in the case of accidents, there was low perception of threat to local communities. Aging and maintenance of existing installations was considered a key issue when dealing with external natural hazard loads. Also, the surveys and interviews showed that accidents involving oil and gas transmission pipelines (one installation alone was handling over 8000 km of pipeline infrastructure across mountain areas) due to rain-induced landslides were a major problem.

The above findings showed that while increased awareness regarding the need to consider natural hazards in industrial risk management planning had increased, there were still many gaps. Lack of guidance on methodologies for Natech risk assessment were needed. Risk awareness, risk communication and information sharing, and the disclosure of risk information among stakeholders was still limited, resulting in distrust, lack of adequate disaster management plans, and so on. Furthermore, the respondents noted a high number of accidents along oil and gas transmission pipelines due to rain-induced landslides with impacts to communities.

The results of the surveys, and discussion with industry and government officials, showed the need to develop a methodology to determine potential failure of oil and gas transmission pipelines due to rain-induced debris flows which could serve to point out high risk areas, and serve as a tool for risk assessment. Furthermore, the survey results showed the need to raise awareness, improve hazard and risk knowledge, and promote risk communication among all stakeholders.

4.1 Simulation of rain-induced debris flow impact on and failure probability of transmission pipelines

In 2019, we proposed a study with the goal to contribute to the resilience of local communities exposed to Natechs related with accidents along

transmission pipelines damaged by rain-induced landslides. The study involved the modeling and simulation of oil and gas pipeline accidents, and the development, testing and application of a serious game for raising awareness and risk communication regarding these potential Natech events among all stakeholders.

We developed a novel methodology to simulate the cascade processes of debris flow propagation, the impact of debris flow on pipelines, and the estimation of pipeline failure probabilities considering pipeline arrangements and operating conditions (Song et al., 2023).

The proposed simulation model serves to inform pipeline operators in the prioritization of inspection and mitigation options, risk assessment and management, and to support government authorities to identify critical areas and develop emergency management plans.

For our study, the results of the simulation provided scenarios that could serve as a basis for discussion and learning among interested stakeholders.

4.2 Development and application of a serious game for Natech risk communication

Past studies have highlighted that stakeholder engagement in disaster risk management is essential for effective risk reduction (Samaddar et al., 2017; Pandey and Okazaki, 2005). This should also translate into open, risk-related decision-making processes with all stakeholders. Natech risk-related decision-making requires the disclosure of risk information and risk communication of these hazards in the territory, which is often a difficult task given the complexity of Natech events. Some researchers have noted that a shift away from top-down mechanisms to engaged, peer-to-peer relationships, and horizontal communication and cooperation are needed. The use of easy-to-understand language, and hands on, experiential learning can improve risk communication and knowledge transfer. In this context, participatory approaches, in particular serious games, can play an important role (Solinska-Nowak et al., 2018; Yamori, 2008).

Taking the above into consideration, a novel, educational game, entitled EGNARIA, with

emphasis on information disclosure for Natech preparedness was developed based on a comprehensive literature review (Tzioutzios, 2022). EGNARIA focuses on natural hazard scenarios (e.g., earthquake, tsunami, landslides, flooding) leading to potential chemical accidents. The game involves players who must take disaster preparedness actions in response to natural hazard events and chemical accidents. EGNARIA's aim is to increase stakeholder awareness of Natech accidents and to promote dialogues among stakeholders regarding risk reduction strategies, chemical information disclosure and risk-informed decision-making (Tzioutzios et al. 2024). Furthermore, a series of pre- and post-game questionnaires were developed and served to evaluate the game's impact on Natech awareness, perceptions and motivation to communicate regarding Natech risk through the prism of the Situational Theory of Problem Solving (STOPS) proposed by Kim and Grunig (2011).

A series of multistakeholder gaming workshops were carried out in Japan (1 gaming workshop in Japanese) and in Colombia (7 gaming workshops in Spanish) with excellent results showing significant increases in risk awareness, risk perception and risk communication regarding Natech hazards after playing the game. See Fig. 4 below.

Surveys and interviews were also carried out between 8-9 months after the gaming workshops to understand the mid-to long-term changes, and in particular, understand if participation in the workshops led to concrete risk reduction actions (Parra-Orduz, 2025). The study findings showed that the application of EGNARIA positively influenced Natech risk awareness, communication practices, and mitigation actions across multiple stakeholder groups in the short to mid-long term. The results also highlight the potential of serious games as valuable tools for stakeholder engagement with Natech risk management and promoting tangible risk reduction efforts (Parra-Orduz, 2025).



Fig. 4 Gaming workshops with multi-stakeholders: top left, top right and bottom right in Colombia; bottom left in Japan. (Photo credits: L.M. Parra-Orduz and A.M. Cruz, 2023).

The study also underscores the importance of longitudinal evaluation to understand the long-term effectiveness of such interventions. Further research could explore the contextual factors that may influence the workshop outcomes, as well as the longer-term effects.

5. Conclusion

Research regarding Natech hazards and risks has been increasing over the years with efforts focusing on past accident investigation, analysis of the incidence of Natechs, and the development of quantitative risk assessment methodologies. Recent research efforts have pointed to the need to better understand future Natech incidence and potential multi-hazards influenced by climate change, aging infrastructure, and other socio-economic factors. We have proposed an area-wide, comprehensive risk management framework and rating system that allows installations and the territory where they are located to rate their level of readiness and resilience against Natech risk. However, to apply such framework requires bringing diverse stakeholder together, which is not an easy task. Collaboration among scientists, public authorities, industries, and communities is needed to enhance risk awareness and societal resilience. For this to be effective, there needs to be trust, transparency regarding hazards and risk, and risk related decision making processes. We have proposed the use of serious games, as a way to break silos, and enhance risk awareness and risk perception and promote risk communication among

diverse stakeholders.

While theoretical and applied research continues to expand regarding Natech risk and risk management, efforts need to be made to close the implementation gap. Future efforts are needed to promote exchange of scientific knowledge in this field with scientists from other fields, practitioners, first responders, local, prefectural and national government authorities, civil society and community at large. This can be achieved through open dialogues or forum, and so on, in order to share experiences, good practices, innovative risk assessment methods, sustainable risk management strategies, and comprehensive risk reduction measures on Natech, as well as to understand the needs and concerns, and why not ensure participation of those potentially affected by future Natech events.

Acknowledgements

I would like to thank and acknowledge Kyoto University, the Ishizue Grant program, the Disaster Prevention Research Institute's Collaborative research funding programs, the JSPS Kakenhi Grants program, the JSPS Postdoctoral Research funding program, the Japan Foundation, and others for research funds received during the past 11 years.

References

- Antonioni G, Spadoni G, Cozzani V. (2007): A methodology for the quantitative risk assessment of major accidents triggered by seismic events. *J. Hazard Mater*, 147(1), pp. 48–59.
- Aven, T. (2011): On Some Recent Definitions and Analysis Frameworks for Risk, Vulnerability, and Resilience, *Risk Analysis*, 31(4), pp. 515-522.
- Borjigin, N.; A.M. Cruz, L.M. Parra-Orduz (2024). Understanding Managers' Motivation in Adopting Protective Measures: Preventing Supply Chain Disruptions from Flood-related Natechs. *Intern. J. Disaster Risk Reduction*, 114, pp. 104985.
- Collins, M., et al. (2019): Chapter 6: Extremes, Abrupt Changes and Managing Risks. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, pp. 589–655.
- Cruz, Ana Maria (2003): Joint natural and technological disasters: Assessment of natural disaster impact on industrial facilities in highly urbanized areas. Ph.D. Dissertation. *Dissertation Abstracts International*, Vol. 64-12, (202 p.), Section: B, page: 6261.
- Cruz, A. M., E. Krausmann (2013): Vulnerability of the oil and gas sector to climate change and extreme weather events, *Clim. Change*, 121, pp. 41–53.
- Cruz, A.M and L. J. Steinberg (2005): Industry Preparedness for Earthquakes and Earthquake-Triggered Hazmat Accidents during the Kocaeli Earthquake in 1999: A Survey. *Earthquake Spectra*, 21 (2), pp, 285-303.
- Girgin, S. and E. Krausmann (2016): Historical analysis of U.S. onshore hazardous liquid pipeline accidents triggered by natural hazards, *J. Loss Prevent. in the Proc. Ind*, Vol. 40, pp. 578-590. <https://doi.org/10.1016/j.jlp.2016.02.008>
- Jain, P., Mentzer, R. and Mannan, M. S. (2018): Resilience metrics for improved process-risk decision making: Survey, analysis and application, *Safety Science*, 108, pp. 13-28.
- Kim, J.-N. & Grunig, J. E. (2011): Problem Solving and Communicative Action: A Situational Theory of Problem Solving. *J. of Communication*, 61(1), pp. 120–149.
- Kossin, J.P., K.A. Emanuel, and G.A. Vecchi (2014): The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, 509, Nature Publishing Group, pp. 349–352.
- Krausmann, E. and Cruz, A.M. (2013): Impact of the 11 March, 2011, Great East Japan earthquake and tsunami on the chemical industry. *Natural Hazards*, 67 (2), pp. 811-828.
- Lam, C.Y., and A.M. Cruz (2019): Risk analysis for consumer-level utility gas and liquefied petroleum gas incidents using probabilistic network modeling: A case study of gas incidents in Japan. *Reliab. Eng. and System Safety*, 185 (May), pp. 198–212.
- Luo, X. (2021): Natechs and Climate Change: Wide-scale Spatial Modeling of the Occurrence Probability and Variability of Tropical Storm-Related Natech Events in the United States Under Various Climate Scenarios. Ph.D. Thesis, Graduate School of Engineering, Kyoto University, Japan.

- Luo, X., A.M. Cruz, D. Tzioutzios (2020): Extracting Natech Reports from Large Databases: Development of a Semi-Intelligent Natech Identification Framework, *Int. J. Disaster Risk Sci.*, 11, pp. 735–750. <https://doi.org/10.1007/s13753-020-00314-6>
- Misuri, A., A.M. Cruz, H. Park, E. Garnier, N. Ohtsu, A. Hokugo, I. Fujita, S. Aoki, V. Cozzani (2021): Technological accidents caused by floods: the case of the Saga prefecture oil spill, Japan 2019. *Intern. J. Disaster Risk Reduction*. 66, pp. 102634.
- Misuri, A.; G. Landucci, V. Cozzani (2021): Assessment of safety barrier performance in the mitigation of domino scenarios caused by Natech events, *Reliab. Eng. & System Safety*, 205, pp. 107278.
- Mudd, L., Y. Wang, C. Letchford, and D. Rosowsky (2014a): Hurricane wind hazard assessment for a rapidly warming climate scenario. *J. Wind Eng. and Industrial Aerodynamics*, 133. Elsevier, pp. 242–249.
- Mudd, L., Y. Wang, C. Letchford, and D. Rosowsky (2014b): Assessing climate change impact on the US east coast hurricane hazard: Wind and rain. *Structures Congress 2014 – Proc. of the 2014 Structures Congress*, pp. 1426–1436.
- Necci, A., S. Girgin, E. Krausmann (2018): Understanding Natech Risk Due to Storms - Analysis Lessons Learned and Recommendations, *EUR Report 29507*, <https://doi.org/10.2760/21366>
- Niskanen, T. (2018): A Resilience Engineering - related approach applying a taxonomy analysis to a survey examining the prevention of risks, *Safety Science*, 101, pp. 108-120.
- Pandey, B. & Okazaki, K. (2005): Community Based Disaster Management: Empowering Communities to Cope with Disaster Risks. *Reg. Develop. Dialogue*, 26(2), pp. 52–57.
- Parra-Orduz, L.M. (2025): *From Gameplay to Risk Reduction: A Mixed-Methods Evaluation of Serious Games to Improve Stakeholders' Awareness and Communication about Natech Risk*, Ph.D. Thesis, Graduate School of Engineering, Kyoto University, Japan.
- Patton, Jason R., Ross Stein, Shinji Toda, Volkan Sevilgen (2018): *Violent shaking triggers massive landslides in Sapporo Japan earthquake*, temblor.net <Accessed Feb. 1, 2025> <https://temblor.net/earthquake-insights/violent-shaking-triggers-massive-landslides-in-sapporo-japan-earthquake-7560/>
- Sahebjamnia, N., Torabi, S. A. and Mansouri, S. A. (2018): Building organizational resilience in the face of multiple disruptions, *International Journal of Production Economics*, 197, pp. 63-83.
- Samaddar, S., Okada, N., Choi, J. & Tatano, H. (2017): What Constitutes Successful Participatory Disaster Risk Management? Insights from Post-Earthquake Reconstruction Work in Rural Gujarat, India. *Natural Hazards*, 85(1), pp. 111–138.
- Sengul, H.; N. Santella, L.J. Steinberg, A.M. Cruz (2012): Analysis of hazardous material releases due to natural hazards in the United States, *Disasters*, 36, pp. 723–743. <https://doi.org/10.1111/j.1467-7717.2012.01272.x>
- Solinska-Nowak, A., et al. (2018): An Overview of Serious Games for Disaster Risk Management – Prospects and Limitations for Informing Actions to Arrest Increasing Risk. *Intern. J. Disaster Risk Reduction*, 31, pp. 1013–1029.
- Song, S.; W. Hua, X. Luo, A.M. Cruz (2023): Methodology for assessing pipeline failure probability due to a debris flow in the near field. *Heliyon*, 9(5), pp. E15956, <https://doi.org/10.1016/j.heliyon.2023.e15956>
- Steinberg, L. J., and Cruz, A.M. (2004): When natural and technological disasters collide: lessons from the Turkey earthquake of August 17, 1999. *Natural Hazards Review*, 5 (3), pp. 121-130.
- Suarez-Paba, M.C. and A.M. Cruz (2021). A paradigm shift in Natech risk management: Development of a rating system framework for evaluating the performance of industry. *Journal of Loss Prevention in the Process Industries*, 74, pp. 104615. <https://doi.org/10.1016/j.jlp.2021.104615>
- Suarez-Paba, M.C., A.M. Cruz, and F. Muñoz (2020): Emerging Natech risk management in Colombia: A survey of governmental organizations. *Safety Science*, 128, pp. 104777 <https://doi.org/10.1016/j.ssci.2020.104777>
- Suárez-Paba, M., Luo, X., Tzioutzios, D., & Cruz, A. M. (2025); Natech Risk Governance Initiatives and Way Forward. *Oxford Res Encycl. Natural Hazard Sci.* <https://oxfordre.com/naturalhazardscience/view/1.0.1093/acrefore/9780199389407.001.0001/acrefor>

[e-9780199389407-e-530](https://doi.org/10.1016/j.ijdrr.2024.105080)

- Ting, M., J.P. Kossin, S.J. Camargo, and C. Li (2019): Past and Future Hurricane Intensity Change along the U.S. East Coast. *Scientific Reports*, 9, pp. 1–8.
- Tzioutzios, D. (2022): Exploring Natech Risk Communication for Participatory Risk Management: Understanding citizens' communicative behaviour through a comparative study and a serious game, Ph.D. Thesis, Graduate School of Engineering, Kyoto University, Japan.
- Tzioutzios, D., Kim, JN. & Cruz, A.M.* (2022) Appetite for Natech Risk Information in Japan: Understanding Citizens' Communicative Behavior Towards Risk Information Disclosure Around Osaka Bay. *I. J. Disaster Risk Science*, **13**, 372–390.
- Tzioutzios, D.; S. Song, H. Bean, I. Chabay, and A.M. Cruz (2024): Serious gaming for Natech Risk Awareness: Introducing EGNARIA. *Intern.l J. Disaster Risk Reduction*, 115, pp. 105080.

<https://doi.org/10.1016/j.ijdrr.2024.105080>

- Yamori, K. (2008). Narrative Mode of Thought in Disaster Damage Reduction: A Crossroad for Narrative and Gaming Approaches, in: Sugiman, T. et al. (Eds.), *Meaning in Action: Constructions, Narratives, and Representations*, Tokyo: Springer Japan.
- Young, S; L. Balluz, J. Malilay (2004): Natural and technologic hazardous material releases during and after natural disasters: A review, *Sci. Total Environ.* 322, pp. 3–20. [https://doi.org/10.1016/S0048-9697\(03\)00446-7](https://doi.org/10.1016/S0048-9697(03)00446-7)
- Yu, J.; A.M. Cruz; and A. Hokugo (2017): Households' Risk Perception and Behavioral Responses to Natech accidents following the Great East Japan Earthquake and Tsunami. *Int J Disaster Risk Sci* (2017) 8 (1), pp. 1–15.

(Received October 14, 2025)