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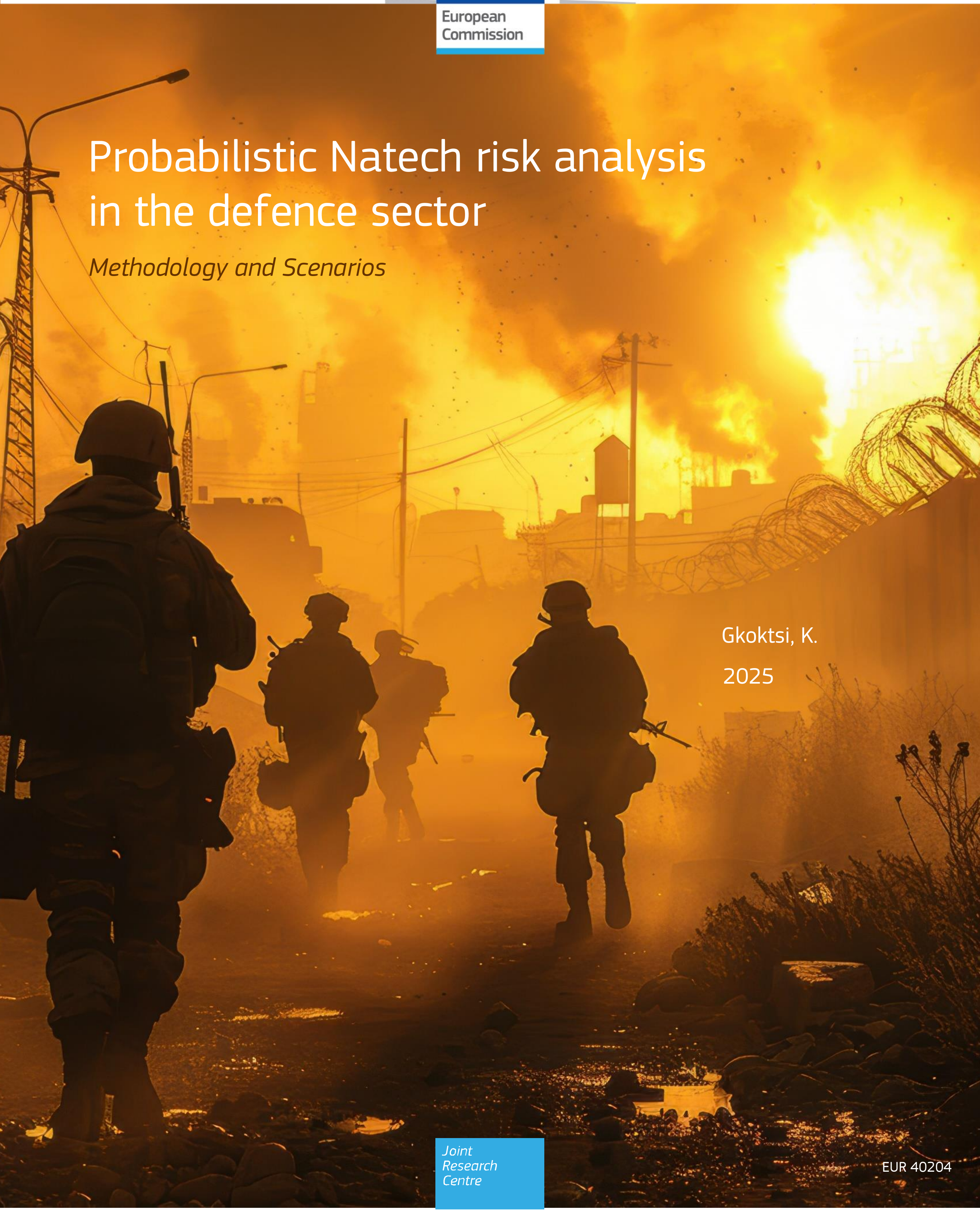

Probabilistic Natech risk analysis in the defence sector

Methodology and Scenarios

Gkoktsi, K.

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Contents

Abstract

Natural hazard-triggered technological (Natech) accidents refer to releases of hazardous substances due to natural hazard impacts to technological systems, leading to toxic emission, fire, or explosion events. While relevant EU policy and legislation (e.g., SEVESO III Directive 2012/18/EU) exist for industrial facilities, military installations are usually excluded from their scope. Nonetheless, Natech accidents could also occur in military facilities that store, process, or transport hazardous substances (e.g., explosives), potentially leading to severe consequences, which can be of vital importance for the national security, the safety of citizens, the environment, and the economy. Recent EU military policy acts address the issue of the resilience of defence infrastructure or defence-related critical energy infrastructure under climate-related impacts, but Natech risks are not explicitly covered therein.

This technical report aims to complement existing EU policies and increase the awareness on Natech risks in military facilities by providing scientific evidence. In this respect, a detailed methodology is presented for quantitative (probabilistic) Natech risk analysis for the defence infrastructure, offering a template methodology for similar risk analyses due to natural hazard impacts. Site-specific case studies are carried out, considering three Natech scenarios of increasing complexity. Earthquakes and cascading tsunamis are selected as triggering natural hazards that impact a fictitious military facility, which comprises a diesel oil tank farm and a magazine with explosives. Two Natech accident mechanism are analysed, which involve the direct mechanism due to immediate physical damage to defence assets, and the propagation mechanisms due to domino effects. Natech risk analyses are conducted for a reference period of one year, considering the risk metric of human health impacts. Thus, the annual individual risk of death or severe injuries is computed due to the physical effects of heat radiation in the event of fire, or blast overpressure in case of explosions. For the examined scenarios, the derived individual risks are mapped in contour plots, showing the risk occurrence rate and the associated impact zones. Recommendations are also provided for all examined scenarios towards Natech risk reduction measures and mitigation of adverse consequences.

The developed case-studies could also support the scenario-building initiative of the Union Civil Protection Mechanism (UCPM) for disaster management planning at Union level.

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1 Introduction

Natural hazards of any type (i.e., geophysical[1], hydrological[2], meteorological[3], climatological[4]) can impact civilian and military facilities and lead to the release of hazardous substances, which can be developed further into toxic emission, fire, or explosion events, or a combination of them. Such events are termed *Natech accidents* (natural hazard triggered technological accidents) and they can cause adverse consequences to human health and the environment.

Although Natech accidents represent a small percentage of chemical accidents in relevant databases (Krausmann et al., 2016; Ricci et al., 2021), they should be properly considered and carefully analysed given their inherent complexity due to the multiple hazards involved (i.e., both natural and technological), leading to potentially high impact consequences. The complexity of Natech accidents is reflected into the following aspects (Krausmann et al., 2019; Necci and Krausmann, 2022a):

- Multiple Natech accidents can be triggered simultaneously by a natural hazard, which can impact large geographical areas.
- A Natech accident can propagate and lead to the development of domino/cascading events due to secondary effects (i.e., structural damage and substance releases due to heat radiation in case of fire or blast overpressure in case of explosion).
- Safety barries or critical utility networks can lose their functionality or get damaged due to natural hazard impacts. This can lead to unmitigated and uncontrolled Natect accidents, which can act as a vector of escallation of the disaster.
- Response operations may be rendered quite difficult in the aftermath of a Natech accident. This can be attributed to the following threefold: (i) hampered access to affected sites in case of severe damage or obstruction of transport infrastructure, (ii) issuing of evacuation orders around affected areas, and (iii) competition of scarce emergency response resources (personnel and equipment) that are required to deal with the emergencies created by both natural and technological hazards.

Specifically for the case of Natech accidents triggered by climatological natural hazards, the above challenges can be exacerbated by climate change, which leads to more extreme events as it increases both the frequency and intensity of the associated natural phenomena.

At EU level, the SEVESO III Directive (DIRECTIVE 2012/18/EU) explicitly requires the development of safety reports that include Natech risk analyses for industrial establishments that store, process or handle hazardous substances. To facilitate the compliance with the requirements of the SEVESO III Directive, the *European Commission's Joint Research Centre* (EC-JRC) has developed a technical guidance on Natech risk management for operators of hazardous sites and competent national authorities (Necci and Krausmann, 2022a). This technical guidance covers the elements required for the efficient implementation of the risk management process, in line with the ISO Risk Management Guidelines (ISO 31000:2018(E)). Further, it discusses the main challenges along this process, drawing

[1] e.g., earthquakes, volcanic eruptions, tsunamis, landslides

[2] e.g., floods, flash floods, storm surges

[3] e.g., tornados, hurricanes/cyclones/typhoons, thunderstorms

[4] e.g., droughts, wildfires, heat waves, cold waves, thawing permafrost

also from the conclusions of a previous study, such as lack of relevant guidance, incomplete or inadequate measures for Natech risk reduction (Krausmann and Baranzini, 2012). The technical Natech risk management guidance is complemented by the guiding principles for industry (management and labour), public authorities, communities and other stakeholders prepared by the *Organisation for Economic Co-operation and Development* (OECD, 2023), and the recently published guidance for senior leaders in industry and public authorities (OECD/European Union, 2024). The latter focuses on the leadership level and it covers aspects associated with Natech risk governance, Natech risk analysis, emergency preparedness and response, communication, and cross-border effects. This topic has also attracted great attention from the scientific community and important research findings can be found in recent review papers and the references therein (He et al., 2022; Mesa-Gómez et al., 2020; Suarez-Paba et al., 2019; Valente et al., 2025).

While a lot of progress has been achieved towards Natech risk assessment in industrial facilities, limited information is publically available for relevant initiatives in military installations. In a recent review paper on the assessment of critical infrastructure resillience, no relevant scientific publication was retrieved for the defence sector, which was one of the 21 sectors covered in the state-of-the-art review (Yang et al., 2023). This can be attributed to the sensitive nature of this sector, which is of national security importance, as well as to the fact that EU policy acts usually exclude military installations from their scope. Relevant regulations and standards may exist at national or military organisational level. Although not explicitly covering Natech risks in military facilities, EU military policy and legislation have been recently developed to address the resilience of defence infrastructure or defence-related critical energy infrastructure under climate-related impacts (*Climate Change and Defence Roadmap* (EEAS(2020) 1251), *Strategic Compass for Security and Defence* (Council of the European Union 7371/22), *Joint Communication on a new outlook on the climate change and security nexus* (JOIN(2023) 19 final). More details on EU policy and legislation framework for *Climate Change, Security and Defence* can be found in the report prepared by EC-JRC and the *European Defence Agency* (EDA) (Tavares da Costa et al., 2023).

This technical report aims to complement the above EU initiatives and increase awareness on Natech risks in military facilities based on scientific evidence. This is driven by the vital importance of such risks due to their potentially severe consequences for the national security, the safety of citizens, the environment, and the economy, even in case of minor damage to defence infrastructure or impaired operations in other critical sectors that military facilities depend upon (e.g., power network).

In this respect, Chapter 2 presents the most important factors in military facilities that are associated with Natech risks. It gives an overview of the composition of military infrastructure, including operational dependences on critical utility networks (e.g., power, water, communication) and the typically considered protections systems used as accident prevention or mitigation measures. The most commonly hazardous substances encountered in military facilities are also reported. The definition of Natech accidents or near misses is provided, and the associated accident mechanisms are identified. To better explain the above definitions and accident mechanisms, three past Natech events in military facilities are analysed.

Chapter 3 presents the regulatory framework and compliance standards that are directly or indirectly associated with Natech risks in military facilities in the EU. The EU military policy and legislation relevant to climate change and defence is first presented. EU civilian policies and legislations are also reported, which do not apply but are indirectly linked to areas of security and defence (e.g., due to civilian-military operational dependencies). International standards are also presented at the end of this chapter.

A methodology for probabilistic (quantitative) Natech risk analysis in military facilities is presented in Chapter 4. The associated mathematical framework is detailed, offering a template methodology for similar risk analyses due to natural hazard impacts. The presented methodology covers the following three main models: (i) the exposure model, i.e., people, structures, elements, and contents exposed to Natech accidents; (ii) the natural hazard model; and (iii) the consequence/loss model. The latter comprises a three-level approach for the estimation of structural/non-structural damage (level 1), the release of hazardous substances (level 2), and the computation of the adverse consequence to exposed assets due to the physical effects of fire, explosion or toxic dispersion (level 3). The presented methodology is in line with the risk management process as per the ISO Risk Management Guidelines (ISO 31000:2018(E)), covering the risk identification and risk analysis steps of the risk assessment process. A complete Natech risk assessment would include the risk evaluation step, i.e., the decision-making process based on the establishment of risk acceptance criteria, which is not covered herein as it falls within the remit of Member States or other stakeholders.

To demonstrate the implementation of the above methodology, Chapter 5 carries out site-specific case studies considering three scenarios associated with two Natech accident mechanisms. Scenario 1 is a simplified case of an earthquake-triggered Natech accident that causes direct damage to a diesel oil tank farm, resulting into the release of flammable substances that are developed into a fire event (primary Natech accident). This scenario is further extended in scenario 2, which simulates a multi-hazard Natech risk analysis in the same tank farm due to tsunami events triggered by earthquakes. The last scenario (scenario 3) builds on scenario 1 and examines the propagation of the primary Natech accident to a magazine that stores explosives. The physical effects of fire (i.e., heat radiation) create a domino event that adversely affects the magazine and leads to explosions. The scenarios presented in this report could support the scenario-building initiative for disaster management planning at Union level, in line with the UCPM as per Regulation (EU) 2021/836 and Decision No 1313/2013/EU.

Concluding remarks and areas for future developments are summarised in Chapter 6.

2 Natech risks in military infrastructure

This chapter presents the most important factors in military facilities that are associated with Natech risks. Section 2.1 gives an overview of the composition of military infrastructure. This refers to the different systems and processes a military facility comprises for its normal functionality, as well as the typically considered protections systems and measures for the prevention or mitigation of abnormal conditions, disruptions, or damage. Section 2.2 lists hazardous materials that are the most commonly encountered in such facilities. Section 2.3 gives the definition of Natech events (i.e., accidents or near misses) and introduces the three typical mechanisms due to which a Natech accident can develop. Finally, section 2.4 presents examples from two past Natech accidents and one Natech near miss that occurred in military facilities.

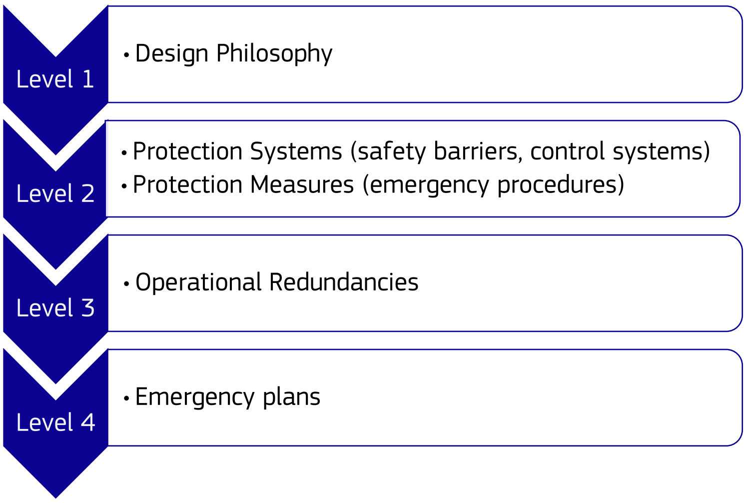
2.1 Military infrastructure composition and functionality

Military infrastructure (e.g., military bases, command and control centres, weapon storage facilities, communication networks, and critical logistics hubs) is a complex network of interconnected systems and processes that function collaboratively to provide essential services of national security importance. Examples of essential services include mission-critical functions, such as the training, deployment, maintenance, and operations of military forces and equipment.

The military infrastructure is connected with and depends upon other critical sectors for its normal operation. This is defined herein as the **operational dependencies** in military infrastructure, which include the dependence on the energy infrastructure for the power supply of specialised equipment and processes, the water network for cooling or emission control operations, and the telecommunication sector for the functionality of monitoring and control systems.

As presented in Figure 1, a multi-level prevention and mitigation strategy is typically developed to protect people (military personnel and the population), the environment, and property exposed to risks due to potential accidents in military facilities that handle, store, process, or transport hazardous substances.

Figure 1. Multi-level prevention and mitigation strategy for the military infrastructure.



At the first level lies the **design philosophy** for the construction of new hazardous sites or the retrofit of existing ones. The aim of the design philosophy is to provide robust structural systems that withstand external actions from natural and man-made hazards. In this respect, the developed design codes, standards, and guidelines set the structural performance criteria to control structural damage, prevent accidents and limit their consequences (design standards for explosive facilities and industrial systems are detailed in sub-sections 3.1.3 and 3.2.3, respectively). To satisfy these criteria, high-resistant load bearing structural systems (primary systems) are designed with high-strength construction materials, ancillary elements (i.e., non-structural components attached to primary structures), and the associated connections are appropriately designed to resist actions and tolerate strains. Depending on the type of natural hazard, primary structures could also be equipped with smart systems to reduce external actions or mitigate their adverse effects. For example, seismic energy dissipating devices and control systems are typically used for the protection of structures against earthquake hazards (Hosseini and Beskhyroun, 2023).

The second level entails the consideration of **protections systems and measures**, which are used to minimise the impact of disruptive events or damage, mitigate their consequences, and ensure continuity of military operations. Disruptive events or damage could threaten the integrity of defence infrastructure and its assets, or impair military readiness and operational capabilities. This can lead to severe consequences for the national security, the safety of citizens, the economy, and the environment. The protection systems and measures are physical safety barriers (i.e., secondary structural systems or non-structural elements), digital control systems (i.e., non-structural elements such as instruments and sensors for gas, leak, fire detection), or emergency procedures (e.g., automatic process shut-down). These systems can be categorised as either passive or active measures. Organisational protection measures include, for example, emergency planning and training.

Passive measures are inherent safety features in equipment and structures, which are built-in by design and provide permanent protection (static intervention systems). The following passive systems can be adopted to prevent **explosions** and mitigate their consequences:

- Suppressive shielding, such as blast walls, blast curtains, blast-resistant enclosures, sacrificial panels, reinforced doors and windows (i.e., physical barriers used to absorb and dissipate the energy produced during explosions, contain explosion fragments and debris, and provide thermal protection to personnel and sensitive equipment).
- Blast traps, explosion trap, flame arrestor (i.e., safety devices that withstand the pressure of an explosion and prevent the spread of damage or flames; they are typically installed in distribution pipelines and ducts that transport flammable substances, and placed at locations prone to explosions, such as vents or storage tanks).
- Sandbags (i.e., used as protective military fortification walls to withstand blast waves and other threats).
- Earth cover (i.e., used for the protection of infrastructure and personnel by absorbing and mitigating the energy from explosions, minimising the consequences of accidental explosions, including the reduction of debris impact risks).

To contain or control the release of **chemical substances** (e.g., fuels) handled in military facilities, the following passive systems can be used:

- Secondary containment systems (i.e., containment dikes or bunds typically constructed around above ground storage tanks to prevent environmental contamination in case of accidental chemical/fuel spills and leaks).
- Sandbags used to absorb spills and prevent their spread.

— Flare stacks (i.e., combustion device used as an emergency blowdown line to burn off excess gasses and vapours that cannot be processed or stored, thus preventing their immediate release into the air).

Active measures are typically mechanical or electronic non-structural elements, which are automatically or manually activated in the event of a disaster upon detection of abnormal operations and/or conditions (dynamic intervention systems). Examples of active mitigation systems include:

— Emergency shut-down systems (i.e., automatic shut-down process when a hazard is detected).

— Remote control and isolation system (i.e., systems to remotely isolate exposed equipment to hazardous conditions and prevent the spread of spills, leaks, explosions).

— Fire suppression systems (e.g., fire-fighting equipment/extinguishers, deluge systems, sprinklers, foam dispenser, gas suppression systems to control/extinguish fires).

— Explosion suppression systems (e.g., release of water mist, inert gases, chemical suppressants to prevent ignition and quench an explosion at its early stage).

— Automatic pressure relief systems (i.e., mechanical systems such as valves or rupture disks that are activated to prevent explosions by venting gases and releasing overpressure from equipment).

— Ventilation systems (i.e., mechanical systems activated to disperse vapour and gases and prevent their accumulation).

— Cooling systems (i.e., mechanical systems activated to cool equipment and prevent overheating or runaway reactions).

— Early warning systems, instruments and sensors that detect abnormal operations and conditions (gas, leak, fire, pressure increase, temperature increase) and trigger the activation of other safety systems (e.g., emergency shut-down, ventilation or cooling systems, alarm systems to alert personnel).

The above active and passive protection measures and systems are summarised in Table 1.

Table 1. Active and passive measures and systems to prevent explosions and chemical releases or mitigate their consequences

Active protection measures	**Explosions**	**Chemical Releases**
Emergency shut-down systems	√	√
Remote control and isolation system	√	√
Fire suppression systems	√	√
Explosion suppression systems	√	
Automatic pressure relief systems	√	√
Ventilation systems	√	√
Cooling systems	√	√
Early warning systems	√	√
Passive protection measures		
Suppressive shielding	√	
Blast traps, explosion trap, flame arrestor	√	
Sandbags	√	√
Earth cover	√	
Secondary containment systems		√
Flare stacks		√

Another level of the prevention and mitigation strategy in hazardous sites entails the consideration of **operational redundancies**, i.e., the dispersion and duplication of critical services. For example, back-up power systems should be in place and ready for use in case of failure in the critical power network, ensuring safe and uninterrupted operations of energy-dependent systems. Other examples entail redundant communication networks and alternate command centres. It is important to ensure that the employed redundant systems do not have the same vulnerabilities or failure mechanisms under the same impact vectors (e.g., natural hazard impacts).

If accident prevention fails, preparedness is needed to mitigate the consequences of a Natech accident. This enables the reduction of damage and loss at a military site, as well as effective emergency response, including the containment of Natech accidents, evacuation, and warning of the potentially affected population, if necessary. **Emergency plans** are usually based on worst-case scenarios, and would assume that protection systems are unavailable in the case of Natech accidents, as they might also be affected by the natural hazard impact that caused the Natech accident (Krausmann et al., 2016).

2.2 Hazardous materials in military facilities

Depending on the military activities and defence operations, military facilities store or handle various types of hazardous substances, i.e.:

- **Ammunition and explosives**, including bombs, land mines, fuses, detonators, pyrotechnics, missiles, rockets, propellants and other associated items. Residues from munitions and explosives manufacturing, testing, and disposal activities may contain also hazardous substances such as heavy metals, propellants, and explosives residues.
- **Chemicals substances** are used for defensive or offensive purposes (e.g., nerve agents, blister agents, and riot control agents). Large quantities of fuel (gasoline, diesel, jet fuel, other petroleum products) are stored in military facilities for multiple uses, including (i) lubricants for vehicles (tactical, non-tactical, vessels, aircrafts) and equipment, (ii) for maintenance, cleaning, laboratory use, or other purposes.
- **Toxic waste** can be generated as a by-product of various activities, including vehicle maintenance, cleaning operations, and manufacturing processes.
- **Radioactive materials** (i.e., uranium, plutonium, and radioactive waste), may be stored in military installations involved in nuclear operations or research.

In accordance with the Regulation (EC) No 1272/2008 and its consolidated version as of 01/12/2023, and the SEVESO III Directive (DIRECTIVE 2012/18/EU), hazardous substances are classified in the following four sections based on their impact, i.e.:

- Health hazards (Section H)
- Physical hazards (Section P)
- Environmental hazards (Section E)
- Other hazards (Section O)

The above sections are divided into several hazard categories based on the type and characteristics of the involved substances, e.g., toxic, explosive, flammable gas/aerosol/liquid, self-reactive substances.

It is noted that the United Nations Organisation (UNO) has developed an international system of classification for transport of dangerous goods, which includes nine Hazard Classes and a “Not Regulated” category. The UNO classification systems has been adopted by the U.S. Department of Defense (DoD) for the classification of ammunition and explosives, and their storage based on compatibility groups (U.S. Army Defense Ammunition Centre, 2012 - Yellow Book).

2.3 Definitions and mechanisms of Natech events

A Natech event in civilian or military infrastructure can be characterised as an *accident* or a *near miss* according to the following definitions:

- A **Natech accident** is a natural hazard-triggered technological accident, which involves emission, fire, or explosion events due to the release of hazardous material and uncontrolled operations, leading to adverse consequences for human health or the natural and built environment.
- A **Natech near miss** is a natural hazard-triggered technological event that disrupts, or has the potential to disrupt an essential service. Release of hazardous material could occur under controlled conditions, preventing the development of an accident (emission, fire, or explosion) and not causing any danger to human health or the natural environment.

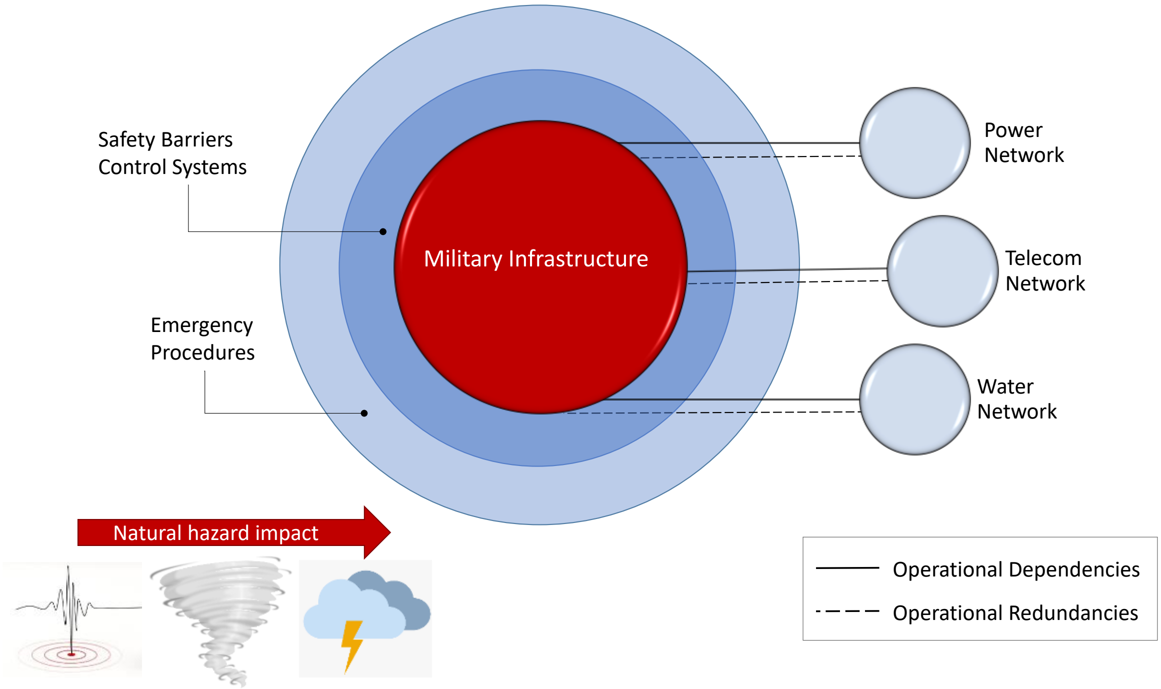
The trigger of a Natech event includes all natural hazards*, i.e., geophysical* (e.g., earthquakes, volcanic eruptions, tsunamis, landslides), *hydrological* (e.g., floods, flash floods, storm surges), *meteorological* (e.g., tornados, hurricanes/cyclones/typhoons, thunderstorms), and *climatological* (e.g., droughts, wildfires, heat waves, cold waves, thawing permafrost). These triggers can be fast- or slow-onset events.

A Natech accident can develop through one of the following three mechanisms (Misuri and Cozzani, 2024):

1. **Direct accident mechanism** (Figure 2). Release of hazardous material due to immediate damage to civilian or military infrastructure and assets, directly induced from natural hazard impacts. This mechanism is typically referred as a “primary Natech scenario”.
2. **Propagation accident mechanism** (Figure 3). Release of hazardous material due to escalation of a Natech accident causing domino effects and cascading events. Damage to civilian or military infrastructure and assets is induced from the physical consequences of a fire and/or an explosion accident following a primary Natech scenario (e.g., damage due to heat radiation from fire or blast waves).
3. **Indirect accident mechanism** (Figure 4). Release of hazardous material due to damage or disruption in critical utility networks, such as power blackout or loss of cooling water (i.e., impaired operational dependencies), leading to process upsets and/or loss of functionality in protection systems and measures. Civilian or military infrastructure is indirectly impacted due to unmitigated and uncontrolled events in the aftermath of a natural hazard.

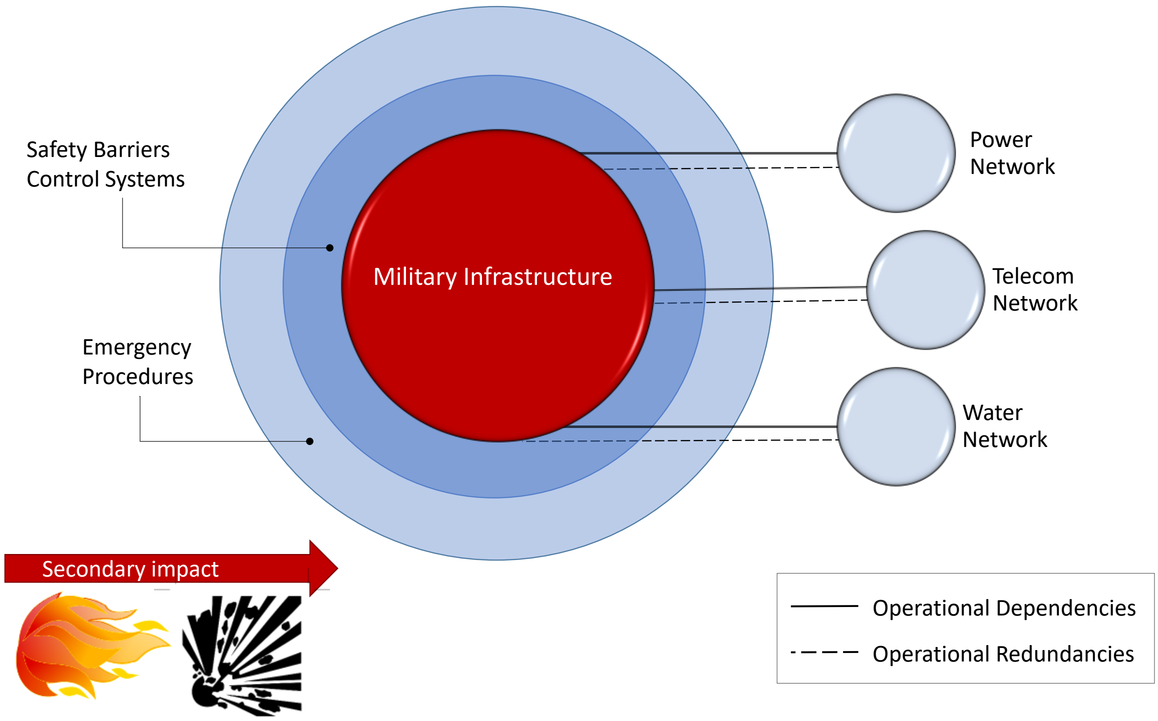
It is noted that the two first accident mechanisms (i.e., direct and propagation) have been extensively studied and relevant quantitative risk analysis (QRA) approaches have been developed. Although the indirect accident mechanism (i.e., third mechanism) has been discussed in the literature, it has only been introduced very recently within a comprehensive QRA approach for Natech accidents (Misuri and Cozzani, 2024). The *Fukushima Daiichi NPP nuclear disaster in 2011* and the *Arkema accident in 2017* are two examples of major Natech accidents developed through the indirect mechanism (Misuri and Cozzani, 2024).

Figure 2. Direct Natech accident mechanism: immediate damage to military infrastructure due to natural hazard impacts (damage is indicated with solid red hatch).



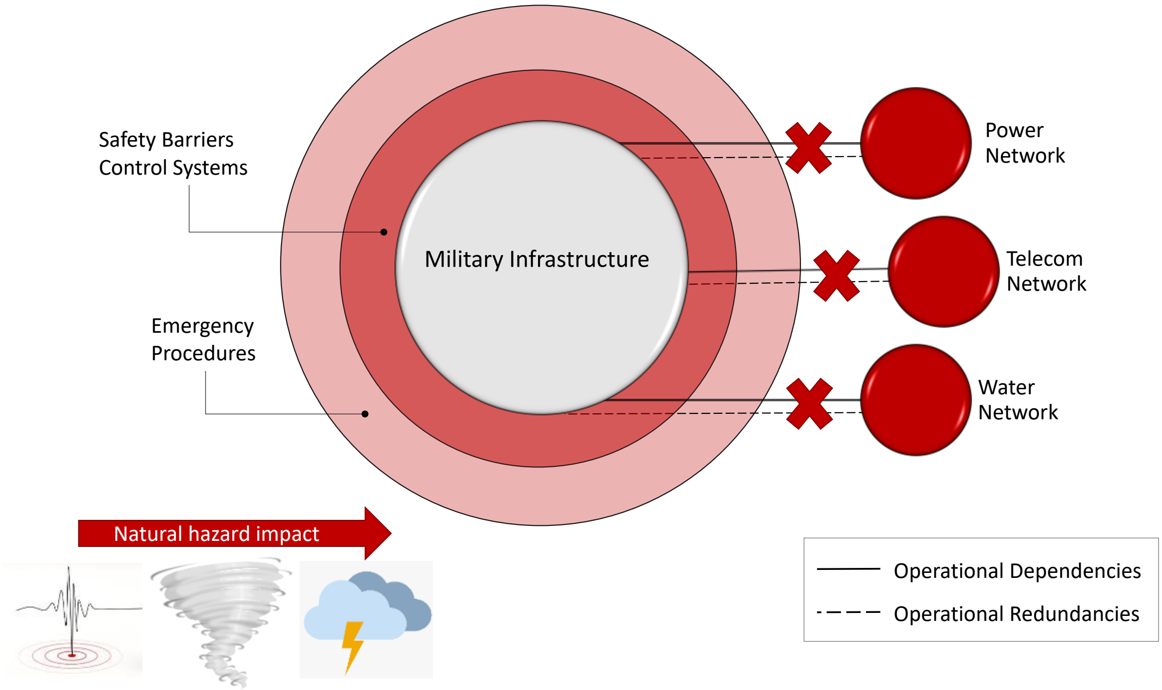
Source: earthquake image @ Tumisu/Pixabay @; tornado image @ OpenClipart-Vectors/Pixabay; lightning image @inspire-studio/Pixabay.

Figure 3. Propagation Natech accident mechanism: damage to military infrastructure due to the physical effects of fire heat radiation or blast overpressure from a primary Natech accident (damage is indicated with solid red hatch).



Source: flame image @ Clker-Free-Vector_Images/Pixabay; explosion image @ OpenIcons/Pixabay.

Figure 4. Indirect Natech accident mechanism: disruption or damage to critical utility networks due to natural hazard impacts, leading to process upsets and loss of protection systems and measures (damage/disruption is indicated with solid red hatch and red crosses).



Source: earthquake image @ Tumisu/Pixabay @; tornado image @ OpenClipart-Vectors/Pixabay; lightning image @inspire-studio/Pixabay.

2.4 Examples of past Natech accidents and near misses in military facilities

The analysis of past events enables the identification of failure patterns or good practices at operational or organisational level, providing significant insights that can be used as lessons learned to prevent accidents in the future or to better mitigate their consequences. Such analyses aim also to raise awareness and improve risk management practices which can be particularly beneficial for policy-making.

To understand better the causes and contributing factors in Natech events, two past Natech accidents and one near miss are analysed herein. These past Natech events can also be found in the eNatech database (https://enatech.jrc.ec.europa.eu/) developed by the EC-JRC.

2.4.1 Nea Anchialos Airbase, Greece – Wildfires, 2023

The *Nea Anchialos Airbase* (111 Combat Wing) is an air force military facility in Greece, which is located in a coastal rural area near the Almyros town of the Magnesia regional unit in the region of Thessaly. It comprises an air force ammunition depot six kilometres north of the plane runaways. Earth dikes were constructed at the perimeter of the depot in line with the *North Atlantic Treaty Organisation* (NATO) provisions for storing, exclusively, bombs of general use. Apart from F-16 missiles and NATO-type buried ammunition, the depot stored also bombs of general use (1000 kg, 500 kg, and 250 kg) that were placed at a location above ground, covered by earth and sheltered with sheds (i.e., simple steel constructions).

On 26 July 2023 and amid a prolonged heatwave in Greece, two major wildfires broke out in the area of Magnesia, Greece, in Almyros town and near the town of Velestino, respectively. Under strong winds[5], the wildfires spread and reached the *Nea Anchialos Airbase* and its ammunition depot. This was further enabled by the presence of flammable materials at the northern side of the Air Base, which forms a slope of limited access. The affected area inside the military facility was roughly 800-900 meters long and 100-150 meters deep, which had not been cleaned (deforested) appropriately by the competent authorities. Further, the width of the existing fire protection zones was very narrow, rendering inadequate the protection against a wildfire spread.

Under these conditions at the ammunition depot, the thermal load significantly increased. In the absence of appropriate fire safety measures, such as water sprays for cooling or use of retarding liquids/agents, the stored munitions exploded. This Natech accident is reported in the eNatech database[6] based on national[7,8,9] and international[10] news articles. According to a national newspaper[11], it was estimated that the explosion occurred due to the overheating of the munitions rather than their direct contact with the flames of the fire. Thus, several explosions were triggered, and blast shock waves were felt up to the city of Volos in Magnesia, which is found several kilometres away from the ammunition depot (Figure 5). No severe injuries or casualties were reported. Material damage occurred due to the shattering of windows in nearby houses.

Figure 5. Location of Nea Anchialos Airbase 111 Combat Wing with respect to the city of Volos. The location is indicated with the arrow-pointed red rectangular at the top left map of Greece.

Source: Google Maps.

[5] The combined action of high ambient temperature, low humidity, and strong winds is termed as "fire weather" conditions

[6] https://enatech.jrc.ec.europa.eu/view/natech/102

[7] https://doureios.com/poy-epashan-ta-metra-pyrasfaleias-stin-apothiki-pyromahikon-tis-111-pterigas-mahis/

[8] https://www.ot.gr/2023/08/02/epikairothta/stoixeia-sok-gia-tis-ekrikseis-sto-stratopedo-sti-nea-agxialo-ti-deixnei-to-porisma/

[9] https://www.thepresident.gr/2023/08/04/paradothike-to-porisma-tis-ede-gia-ti-fotia-stin-apothiki-pyromachikon-sti-nea-agchialo/

[10] https://www.bbc.com/news/world-europe-66334787

[11] https://www.kathimerini.gr/society/562541887/agchialo-neo-vinteo-apo-ti-stigmi-tis-ekrixis-stin-apothiki-pyromachikon/

In response to the **Natech accident**, the following actions were taken:

— An evacuation order for the area was given as a protection measure towards the Air Base's personnel, several nearby towns were evacuated and 133 residents of the nearby town of Nea Anchialos were sea-transferred to a safer location.

— On-site and national firefighting trucks arrived at the site and sprayed coolant agents to extinguish the fire. Dozens of firefighters worked in the area, which were assisted by 15 fire engines.

— A security zone was set up around the Greek Air Force Base.

— F-16 fighter jets were moved from a nearby air base, as a precautionary measure.

Personnel at the air force base had been trained for this kind of emergency, which enabled the fast evacuation of the Air Force Base and the transfer of the F-16 planes to nearby airports. The situation, though, remained critical due to the potential scattering of active projectiles and ammunitions over large distances.

According to the official conclusions of the *Sworn Administrative Examination Board*, this Natech accident was primarily attributed to omissions and negligence by Air Force officials, i.e.:

- inadequate design of the fire protection system in case of unburied ammunitions stored outdoors; and

- inappropriate removal/cleaning of flammable materials from the surrounding area with dense vegetation.

The above conclusions brought into light the need for more efficient fire safety measures to deal with asymmetric threats against military installations, as well as the requirement for a wider consensus at the level of *General Staffs* and the ratification of relevant fire design standards. It further showed that demanding cleaning operations at sites of limited accessibility would require the use of expert teams and specialised equipment. This lesson learned should pave the way towards relevant mandates to be issued for other military bases under similar conditions. Especially for the development of protective fire zones, they should comply with the minimum required dimensions to allow access to firefighting trucks and prevent the transfer of thermal loads from adjacent sources (e.g. wildfires).

The appropriately designed earth dikes were proved to be a good practice in restraining the spread of the shock waves and preventing additional adverse consequences. Further, NATO-type buried ammunitions were not affected by the wildfires, which verified the effectiveness of safely storing ammunitions underground.

2.4.2 Evangelos Florakis Naval Base, Cyprus – Heat and humidity, 2011

Evangelos Florakis Naval Base (previously known as *Mari Naval Base*) is a Navy base in the Vassilikou area in Cyprus, which is found at the southern coastal area of the island between Limassol and Larnaca (approximately 28 km east from Limassol). At approximately 0.4 km and 0.5 km north-west from the Naval Base lies the old and the new A1 highway, respectively, which connect Nicosia and Limassol. In the vicinity of the Naval Base are the towns: Mari (ca. 1.5 km north-east), Zygi (ca. 4.5 km east), Kalavasos (ca. 5.0 km north), and Pentakomo (ca. 4.5 km north-west). The *Vassilikos Power Plant,* the largest power facility in Cyprus, is located at the east site boundaries of the Naval Base (Figure 6). Until the Natech accident in 2011, the *Evangelos Florakis Naval Base* was the main location of the Command of the Navy Base and one of the five primary commands (also called sub-commands) of the Navy.

Figure 6. Location of Evangelos Florakis Naval Base and Vassilikos Power Station.

Source: Google Maps.

On 13 February 2009, the cargo of a freighter ship[12] was confiscated and stored in a dedicated area within the *Evangelos Florakis Naval Base*, based on the decision taken by the Cyprus government on the previous day. The cargo comprised 98 containers with a large quantity of explosive material (e.g., 120 mm, 122 mm, 125 mm, and 160 mm high explosive artillery shells, 7.62 mm shell casings, compressed gunpowder, silver dollar-sized slugs, primers, and magnesium primers). From the 98 containers, 81 stored roughly 481 tonnes of various types of gunpowder. The containers were stacked closely together and placed at an outdoor area without environmental protection from the weather conditions and the direct sunlight.

The inappropriate storage method of the explosives combined with their exposure to high temperature and humidity over a period of more than two years led to a catastrophic Natech accident on 11 July 2011. According to the official investigation (Poliviou, 2011), a fire

[12] On 19-20 January 2009, the course of a freighter ship (a Cypriot-flagged Russian-owned vessel named *Monchegorsk*), travelling from Iran to Syria, was intercepted at the Red Sea following the inspection by the USA Navy and the conclusion that the cargo violated the Council Resolutions Security Protocol of the United Nations Organisation, which imposed sanctions against Iran. Official diplomatic discussions took place among Cyprus, Egypt, Iran, Syria and the USA, and it was decided that the ship should sail to a Cypriot port.

broke out on 11/07/2011 at 04:30 (local time) at the area of the stored containers, which was attributed to the self-ignition of the contained substances that were subject to chemical reactions inside the containers[13,14]. The prolonged storage of explosive substances under high ambient temperature and humidity resulted in the modification of the contained substances' (propellants) chemical state, their destabilisation and decay. This created extremely unstable and dangerous storage conditions within the containers that triggered a feedback loop of increased internal temperature and pressure, resulting in the production of more gas vapours, thus causing the wall buckling of a top container in the stack. The container's deformation was first witnessed by an officer seven days before the accident on 4 July 2011, but his concerns were ignored. The adverse internal storage conditions allowed the self-ignition of the vapours. This resulted in the **propagation** of the hazardous situation, as the radiant heat from the substance deflagration adversely affected the other containers in the stack, which spontaneously combusted and detonated, resulting in a massive explosion at 05:50 (local time) on 11/07/2011.

Figure 7. Damage at the Vassilikos Power Station due to the domino event.

Source: Deutsches Zentrum für Luft- und Raumfahrt, CC BY 3.0, via Wikimedia Commons.

As a result of the massive explosion, 13 people died (i.e., six firefighters and seven naval officers) and 62 were injured. The explosion created a crater on the ground (approximately 40 m in diameter and 10 m in depth), triggering further a series of **domino events**, as the accident hazard propagated

[13] During the period 08 - 11/07/2011, the average air temperature was approximately 30 °C. On the date and time of the Natech accident, the ambient temperature was between 21.5 °C and 23.2 °C, and the air humidity was ranging from 91% to 97%. The maximum air humidity at 97% was recorded at 05:00 (Poliviou, 2011).

[14] A sabotage action was excluded and there was no evidence that the fire and explosion were triggered from an external source of heat, such as scrub fires at the vicinity of the storage area. The fact that the accident occurred at the coolest temperature of the day strengthens the argument that the substance ignition was triggered by chemical reactions, which could have started at any time (Poliviou, 2011).

to the nearby *Vassilikos Power Station.* Several buildings of the Power Station were severely damaged or completely destroyed from the blast[15] (Figure 7). Thus, operations at the Power Station were halted, which caused widespread power cuts to approximately half of Cyprus. Due to the power station shutdown, the power supply to seawater desalination plants was interrupted which, in turn, adversely affected the supply of drinking water. Extensive damage was also caused in the surrounding area as five vehicles were destroyed (i.e., two fire trucks, two National Guard vehicles, one vehicle of the electricity authority in Cyprus) and several others found in the Naval Base, and the A1 highway were severely damaged. Several buildings in the Naval Base suffered extensive damage and temporary structures were completely destroyed. In the wider area and within a radial distance of two kilometres from the location of the explosion, residential and other buildings suffered light damage.

According to the official investigation, the main drivers of this Natech accident were organisational malpractices as well as omissions and negligence from competent authorities, i.e.:

- The explosives storage area did not conform to Ammunition Storage Regulations[16]. The 98 containers were stacked all together, which violated the requirement for safe separation distance of explosives and their storage in smaller quantities.

- The inappropriate stacking method (i.e., the stack height and the close proximity of containers) limited the accessibility for inspection and impeded the proper ventilation of the containers. If appropriate control measures had been applied, such as ventilation or shading of the containers, it may have eliminated the de-stabilisation of the explosives or, at least, it would have slowed down the degradation effect on the explosives.

- The storage of a large quantity of explosives in the vicinity to the *Vassilikos Power Station* and the *A1 highway* indicates that the safe distance criteria[17], based on the quantity of stored explosives, were not taken into consideration for the protection of the nearby critical infrastructure in the event of an explosion within the site.

- The incident on 04/07/2011 regarding the deformed container and the concerns expressed by a Naval Base officer were ignored. The magnitude of the explosion and its consequences would have been potentially reduced if the deformed container was safely disposed, the stack was separated, and the containers were cooled. The above operations, though, may have posed a life risk to the personnel executing this task.

[15] The EU Civil Protection Mechanism estimated that the minimum cost for the re-operation of the Vassilikos Power Station would amount to 330 - 700 million EUR (Poliviou, 2011).

[16] No reference is provided in the official investigation (Poliviou, 2011). It is speculated that this refers to NAVSEA OP 5 (2001).

[17] No reference is provided in the official investigation (Poliviou, 2011). It is speculated that this refers to Chapter 7 in NAVSEA OP 5 (2001).

- The Safety Considerations rules (NAVSEA OP 5 (2001), section 4.5.1)[18] had not been followed for the safe evacuation of personnel in the event of fire in ammunition and explosives sites. Non-essential personnel at both the naval base and the power station should have been evacuated and operations should have been halted since the incident on 04/07/2011, when the deformed container was noticed.

- The naval officers were not adequately informed about the content of the 98 containers and the associated hazards, nor did they have the required knowledge on handling such material, which was different from the ones typically stored at the naval base. There was also lack of knowledge on the required emergency response operations on-site in case of fire or explosion of this specific hazardous material.

- The fire brigade also showed lack of relevant knowledge (i.e., stored hazardous material in the naval base) and it was not properly informed in a timely manner about the hazardous situation. The emergency response operations by the fire brigade were rather inadequate, as no specialised emergency response plan was followed for the special case of fire and explosion associated with explosives containers.

2.4.3 Naval air weapon station China lake, California – Earthquake, 2019

The *U.S. Naval Air Weapon Station China Lake* (NAWS) is a military installation established in 1943, which was constructed in 1935 for civilian use. The NAWS is the U.S. Navy's largest single landholding with its main site and its two ranges covering an area of more than 4500 km^2 (95% of this land is undeveloped as of 2010)[19]. It is located in the Western Mojave Desert region of California, next to the Ridgecrest town (240 km north of Los Angeles), and it is a seismically active region. The NAWS primary mission is to support the research, development, acquisition, testing, and evaluation (RDAT&E) of various weapons systems and technologies for the United States Navy. This includes air-to-air and air-to-ground weapons, missiles, rockets, and other ordnance.

On the 4th of July 2019, the *2019 Ridgecrest earthquake sequence* was triggered southwest of Searles Valley in eastern California, approximately 150 km northeast of the San Andreas Fault (i.e., the major plate boundary in the region). This was a sequence of earthquake events that was marked by two major ground shakings and hundreds of aftershocks along two orthogonal seismic faults. The first strong seismic event occurred on 04/07/2019 (at 10:34 local time) with a 6.4 M_w moment magnitude, which was followed by the 7.1 M_w powerful shaking after about 34 hours (on 05/07/2019 at 20:19 local time). The intensity of those seismic events was estimated to be VIII (i.e., severe shaking, moderate/heavy damage)[20] and IX (i.e., violent shaking, heavy damage)[21] , respectively, in the Modified Mercalli Intensity scale. Both epicentres were located within the NAWS area (Figure 8). In the aftermath of the 7.1 M_w event – which was the largest earthquake in the state since 1999 – the Naval base was declared as mission incapable and non-essential personnel were evacuated.

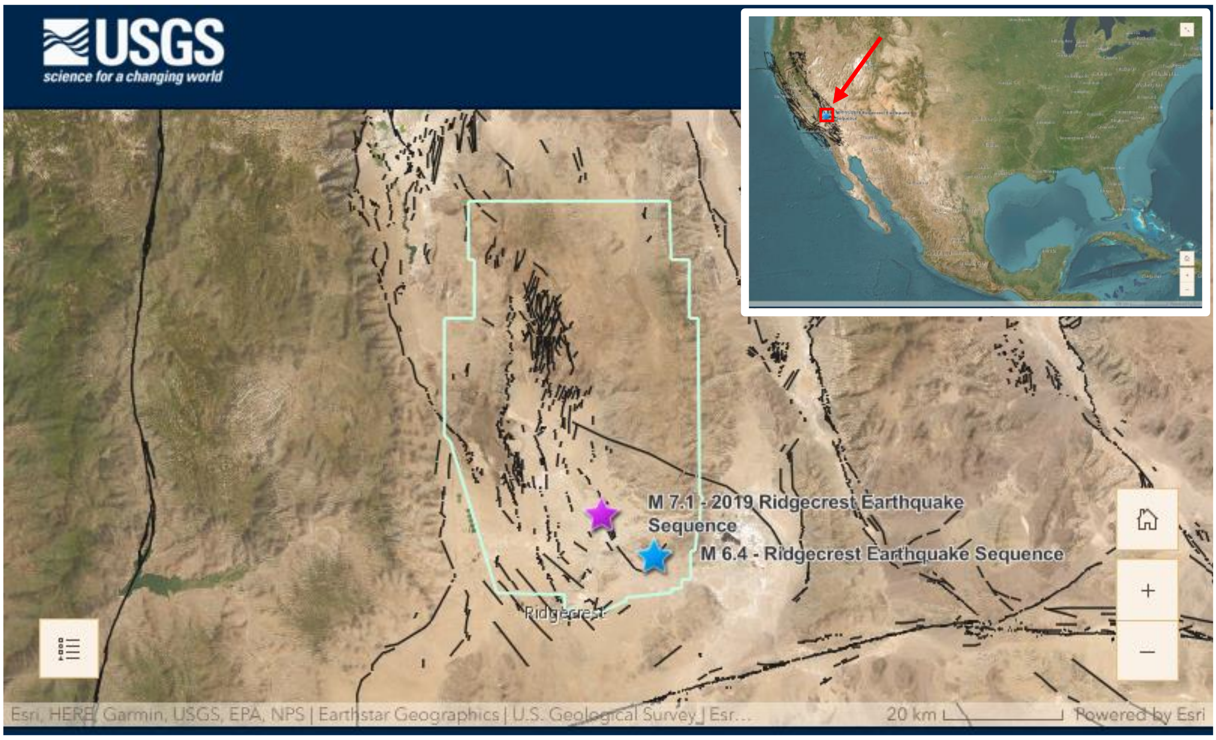
[18] No reference is provided in the official investigation (Poliviou, 2011). It is speculated that this refers to section 4.5.1 in NAVSEA OP 5 (2001).

[19] https://en.wikipedia.org/wiki/Naval_Air_Weapons_Station_China_Lake

[20] https://earthquake.usgs.gov/earthquakes/eventpage/ci38443183/executive

[21] https://earthquake.usgs.gov/earthquakes/eventpage/ci38457511/executive

Figure 8. Epicentre of 7.1 Mw (purple star) and 6.4 Mw (blue star) earthquake events of the 2019 Ridgecrest sequence with respect to the NAWS site boundaries (light green curve) and seismic faults (black curves). The site location is indicated with the arrow-pointed red rectangular in the top left map.



Source: https://earthquake.usgs.gov/storymap/index-ridgecrest.html.

Due to operational security considerations associated with the Navy policy, officials could not disclose detailed information on the earthquake-induced damage to the U.S. Naval military installation (Brandenberg et al., 2019; EERI, 2020; Tavares da Costa and Krausmann, 2021). Based on an online presentation given by the *Navy Facilities Engineering System Command* (NAVFAC) on 01/08/2019, it was revealed during a radio interview[22] that the U.S. Naval facilities and infrastructure near the epicentres sustained extensive damage. The total replacement cost was estimated to be 5.2 billion USD, which included the actual economic losses due to damage and additional costs required for the seismic upgrade and retrofitting of existing facilities in the NAWS that did not comply with modern seismic codes.

In fact, several buildings in the naval base were constructed after the *Loma Prieta* earthquake in 1989, and, since then, there were several revisions in the U.S. building codes for the seismic design of structures. However, at the time of the *2019 Ridgecrest earthquakes*, there was no requirement to seismically retrofit existing structures when building codes were modified, unless specifically requested by law. The above suggests that a large building stock in the naval base was nearly 30 years old and, potentially, not retrofitted according to the latest seismic design requirements as of 2019. Among these structures, at least 800 old buildings were damaged, including 69 buildings that each required a minimum amount of five million dollars for repair or replacement operations. Further,

[22] audio material available in https://www.kvpr.org/environment/2019-08-23/why-it-could-take-5-billion-to-clean-up-quake-damage-at-china-lake

it was required to either fully demolish or fully replace a great number of large-size buildings, such as two hangars that were constructed in the 1940s, an air traffic control tower, laboratory facilities, and a fire bay. Repair operations were also scheduled for the damaged road infrastructure near the epicentres[23]. Precautionary measures were taken to mitigate the risks posed by the damaged infrastructure.

In the absence of any other information relevant to the release of hazardous substances with adverse consequences to human health and the environment, the above incident could be categorised as a **near miss Natech event** that disrupted the essential functions of the U.S. Naval base and resulted in considerable economic consequences due to damage to infrastructure and specialised equipment.

[23]https://militarycouncil.ca.gov/2019/10/24/earthquakes-or-no-navy-expands-china-lake-with-more-land-for-future-weapons-drones/

3 Regulatory frameworks and compliance standards

This section presents the regulatory framework and compliance standards that are directly or indirectly associated with Natech risks in military facilities in the EU. Section 3.1 focuses on EU military policy and legislation, primarily around the climate change and defence angle. It briefly presents the EU-NATO cooperation and the associated engagement towards the resilience and protection of critical infrastructure in the Euro-Atlantic area. The broadly related "Army in Europe" is also presented herein, which primarily serves the purpose of presenting relevant design standards developed for the construction of explosive facilities.

Given the operational dependence of military facilities on civilian infrastructure (e.g., critical utility networks), Section 3.2 presents relevant EU civilian policies and legislations, which are implicitly or explicitly associated with Natech risks, but they do not apply to areas of security and defence. The presented legal frameworks and practices concern the resilience of critical entities, which incorporates the protection of critical infrastructure, the prevention of major accidents in industrial facilities with hazardous substances, design standards for industrial facilities, and the EU crisis management mechanisms. International standards and instruments are also presented herein, which include the Sendai Framework for disaster risk reduction in 2015-2030 and the ISO Standards for risk management.

3.1 Military policy and legislation for handling dangerous substances

EU policy acts usually exclude military installations from their scope. Military organisations in EU Member States may develop their own standards according to national security requirements. National regulations might also exist for the construction of defence facilities and safety procedures for handling dangerous substances, which can be based on international guidelines. While a thorough review of relevant national policies or safety standards for military facilities is beyond the scope of this study, Natech risk management measures and practices at civilian hazardous installations would be equally applicable to military sites.

3.1.1 EU policies on climate change and defence

At EU level, it was recently recognised that the EU's external policy should better integrate the climate, peace and security nexus (Council of the European Union 7248/23). In this respect, the recent EU policies shown in Figure 9 highlight the need for climate-related actions in military and defence operations and logistics.

Figure 9. EU policies on climate change and defence.

The **Climate Change and Defence Roadmap** (EEAS(2020) 1251) is a working document of the *European External Action Service* (EEAS) that sets concrete EU actions, in line with the *European Green*

Deal COM/2019/640 final), to address emerging climate change-related challenges in the defence sector. Focusing on defence research and development, industry and technology or infrastructure, as well as the *EU Civilian and Military Common Security and Defence Policy* (CSDP), EU actions are set for the short-term (2020-2021), medium-term (2022-2024), and long-term (2025-onwards) within the following three areas: (i) operational dimension (i.e., military and civilian missions and operations, capabilities, and infrastructure), (ii) capability development, and (iii) multilateralism and partnership. Specifically for the climate change risks in the defence infrastructure, the following actions are determined, i.e.:

- Improve scenario-building and strategic planning assumptions by integrating risks due to climate change (capability development, short-term action);
- Fund research and development activities for applications on defence operations under extreme conditions (capability development, mid-term action);
- Identify new collaborative projects by Member States (MSs), defence industry and *Research and Technology Organisations* to address, among others[24], the safe use of chemicals through design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling (capability development, mid-term action);
- Conduct studies on climate change impact on the European defence infrastructure and on the resilience of defence-related critical energy infrastructure against hybrid and asymmetrical threats (capability development, mid-term action);
- Include relevant defence and CSDP-related aspects to promote climate security from the perspective of adaptation and mitigation (multilateralism and partnership, medium-term action)
- Increase the understanding of climate change and environmental degradation on the defence sector and EU crisis management (multilateralism and partnership, mid-term action).

Other broadly related actions associated with the prevention of, preparedness for, and response to climate change risks and natural disasters in the defence sector include:

- Foster humanitarian civil-military cooperation, including preparedness and response to natural and humanitarian disasters (operational dimension, short-term action);
- Explore possibility to support African partner countries in strengthening the response capacity of the security services to man-made and natural disasters, and enhancing civil protection services (multilateralism and partnership, short-term action);
- Include climate change and environmental aspects in the revised priorities to reinforce the UN-EU strategic partnership on peace operations and crisis management (multilateralism and partnership, mid-term action).

The **Strategic Compass for Security and Defence** (Council of the European Union 7371/22) sets the objective to protect critical infrastructure and increase EU resilience against climate-related risks

[24] e.g., waste management, component tracing, environmental protection, water management, resources input

and natural disasters, among others[25]. It acknowledges that climate change and environmental degradation have the potential to adversely affect the energy infrastructure and act as risk multipliers with direct implications on security and defence. The EU is committed to invest in the resilience, competitiveness, and innovation of the *European Defence Technological and Industrial Base*. Funds will be also given for defence technological innovations to reduce technological and industrial dependencies[26]. It further aims to develop common benchmarks and standards for the resilience of defence-related critical infrastructure. The Strategic Compass calls for full implementation of the *Climate Change and Defence Roadmap* and invites MSs to prepare national climate and defence strategies. More details on EU policy and legislation framework for *Climate Change, Security and Defence* can be found in a joint publication by the EC-JRC and EDA (Tavares da Costa et al., 2023).

Along these lines, the **Joint Communication on a new outlook on the climate change and security nexus** (JOIN(2023) 19 final) establishes an enhanced framework and puts forward concrete measures, in line with the EU's *Integrated Approach to External Conflicts and Crises* to support MSs in adapting their armed forces to climate change, and mitigating their climate footprint. Further, it stresses out the need for the evaluation of climate change impacts and associated risks in defence planning and investments to ensure the resilience of military infrastructure and uninterrupted military operations[27] under challenging climate conditions. To support this goal, relevant Commission services and the EDA will conduct further comprehensive studies and continue to organise tabletop exercises to examine relevant potential future risks due to dependences associated with the defence-related critical energy infrastructure.

The recently published **report by Sauli Niinistö (2024)**, the Special Adviser to the President of the European Commission (2019-2024) and Former President of the Republic of Finland, builds on and complements the above EU strategies, initiatives, and policies. The report focuses on the enhancement of the civilian and defence preparedness and readiness in Europe and proposes relevant recommendations to inform future actions, in line with the mandate of the High Representative and the Commission for the period 2024-2029. It is recognised that the resilience and preparedness of defence organisations should be enhanced, considering climate change impacts among others. Further, a comprehensive EU risk assessment framework needs to be developed to address both man-made and natural hazard threats in a holistic manner (i.e., threats and hazards ranging from extreme weather events to armed conflicts). For the EU crisis response to threats, risks, and challenges, the use of scenario-based risk assessments is recommended, which could also feed into the development of a wider EU policy on external shocks and crises.

3.1.2 EU-NATO cooperation and U.S. Army in Europe

In the Euro-Atlantic area, NATO is the foundation of collective defence for its members, and includes 23 EU Member States[28]. NATO primarily focuses on security and defence aspects, while the EU

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[25] e.g., hybrid threats, cyberattacks, man-made disasters

[26] Examples of critical dependences include semiconductors, cloud and edge technologies, quantum computing, and artificial intelligence

[27] E.g., use of military equipment, deployment of military capabilities across land, air, and sea, military assistance to civilian authorities in response to natural disasters

[28] Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden. https://www.consilium.europa.eu/en/policies/eu-nato-cooperation/#0

coordinates EU crisis management, peace-keeping and conflict prevention, drawing on civilian and military assets, providing resources for civilian aid, economic stabilisation, and governance initiatives in line with the CSDP[29]. The EU-NATO cooperation keeps expanding and it builds on the EU Strategic Compass (Council of the European Union 7371/22), the NATO Strategic Concept (2022), and three joint declarations (2023, 2018, and 2016)[30]. The most recent joint declaration was adopted in January 2023[31], which calls for a closer EU-NATO cooperation to address common security threats and challenges. It aims to strengthen the EU-NATO Strategic Partnership in existing areas while deepening the cooperation in other areas, including resilience issues and the protection of critical infrastructures.

Critical support to NATO is provided by the "Army in Europe", i.e., the operational structure and presence of the United States Army in Europe that primarily operates under the command of U.S. Army Europe and Africa (USAREUR-AF)[32]. This command oversees U.S. Army operations, training, and collaboration efforts across Europe and parts of Africa, ensuring U.S. forces are prepared to support NATO allies, respond to crises, and promote stability in the region. The **Army in Europe Regulation** (AE Reg 385-64) is a policy document that establishes safety standards for handling and storing ammunition and explosives (A&E) in the Army in Europe. These U.S. Army provisions apply only if they are allowed by EU MSs based on national laws or status of forces agreements. The regulation must be used in conjunction with:

- Defence Explosives Safety Regulation (DESR 6055.09);
- The Army Safety and Occupational Health Program (AR 385-10); and
- Ammunition and Explosives Safety Standards (DA Pamphlet 385-64).

The established A&E safety programme is based on risk assessment to support the decision-making process for the safe management of A&E items. This entails the implementation of risk management practices at all levels to identify potential hazards, control or eliminate potential consequences, and protect people, mission resources, and the environment. The competent authority for the review and approval of this policy is the *Army in Europe Explosives-Policy Action Committee* (EPAC), which provides policy recommendations to NATO as well as to the *Department of the Army Explosives Safety Council* (DAESC) and the *Department of Defence Explosives Safety Board* (DDESB).

3.1.3 Design Standards for explosive facilities for the Army in Europe

Design codes, standards, and guidelines are developed for the construction of structures to withstand external actions from natural or other hazards, prevent accidents, and limit their consequences. For military-specific structures, additional criteria and sets of standards may apply at national scale, or even at military organisation level, depending on the special safety and security requirements, and operational needs in defence facilities. Design procedures and construction techniques in explosive facilities are detailed in DA Pamphlet 385-64 (Chapter 15) by setting the following two objectives:

— Protection of personnel, the environment, and valuable material (primary objective).

[29] https://www.eeas.europa.eu/eeas/common-security-and-defence-policy_en

[30] https://www.consilium.europa.eu/en/policies/eu-nato-cooperation/#partnership

[31] https://www.nato.int/cps/en/natohq/official_texts_210549.htm

[32] https://www.europeafrica.army.mil/

— Maximum cost-effectiveness in both planning and facility utilisation (secondary objective).

Specialised experience is required for the design of explosive facilities and the construction of passive protection systems to eliminate the effects of weapons and increase the resilience of the facilities (i.e., protective construction, Department of Defence (1961)). Specifically for the design of buildings in facilities exposed to the damaging effects of potential explosions, two important safety considerations are regarded:

— **Appropriate construction features** to be implemented to reduce the quantity of stored explosives, dissipate the physical effects of blast overpressure or thermal radiation, and minimise the amount and range of fragments and debris produced during an explosion.

— **Planning of explosive facilities and proper location** with respect to potentially exposed sites to prevent damage and injuries in case of accidents.

The design of buildings, such as magazines that typically store ammunitions and explosives, shall ensure that no collapse would occur in case of accidental explosions and blast overpressure. The magazines resistance to blast and shock waves is ensured through the consideration of special construction features (i.e., headwalls and blast doors), which are appropriately designed to withstand overpressure. Magazines are allowed to deform, but the deformations should be limited and the stored substances should remain intact. Unless specific design requirements are met (e.g., presence of firewalls, substantially dividing walls, protection from external overpressure, specified magazine facilities), the construction and support of buildings should ensure the venting of an internal explosion with the minimum number of large fragments. Special considerations should be taken for the design of windows and skylights, which are secondary elements sensitive to explosions that can result in serious injuries to personnel due to glass breakage. The design should limit such elements to the minimum required number, opting for blast resistant windows when possible. Magazines should also be equipped with lightning protection systems, and appropriate means for air circulation or dehumidification. Other considerations specified in DA Pamphlet 385-64 for the design and protective construction of explosive facilities include:

— **Fire protection systems** (e.g., firewalls, fire doors, automatic sprinkler systems, interior finishes and floors);

— **Safe exit routes** (e.g., means of egress, safety chutes, emergency exits and fire escapes, fixed industrial stairways and fixed ladders, platforms, runways, railings, passageways, roads, walks, and gates);

— **Powerhouse equipment** (e.g., boiler, engines, pressurised vessels), hardware (e.g., piping, ducts), refrigeration equipment (e.g., air conditioning), process steam equipment, ventilation systems, and electrical equipment;

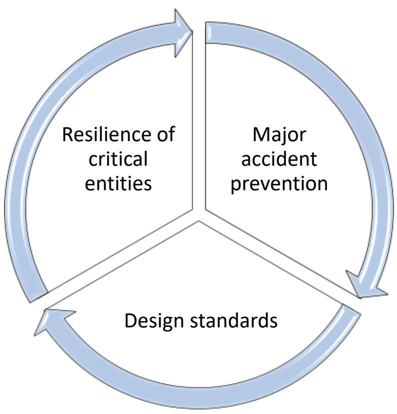
— **Drain lines and sumps** for waste treatment of explosives.

Regarding the location of explosive storage facilities, a site and general construction plan should be in place before the construction or modification of the facility, as specified in the AE Reg 385-64. This master plan should map all explosives facilities and surrounding structures, providing accurate distances for explosives operations and facilities on all installations. Thus, explosive safety separation distances between (potential) explosive sites should be provided, indicating the areas to be avoided for the construction of other structures that could be adversely affected by fragment projectiles or blast waves due to explosions. These areas are determined by the so-called *explosives safety quantity-distance* (ESQD) *arcs*, which define the risk impact zones based on the type and quantity of the explosives involved. When ESQD arcs are extended beyond Army in Europe units (e.g., ammunition sites in Germany), restricted areas should be defined for public traffic routes (blue zone III), inhabited building distance (red zone IV) and special protected objects (green zone V). These restricted areas should also be indicated in the master planning maps. Further, separation distances between structures and (potential) explosive sites should also be determined for fire prevention purposes (i.e., 30 m inert storage separation for structures with combustible material, or 15 m otherwise).

3.2 Civilian policy and legislation for handling dangerous substances

This section presents the policy and legislation framework associated with civilian installations as they may incorporate civilian infrastructure and equipment. As detailed in section 2.1, military installations are operationally dependent on critical infrastructure (e.g., critical power, water, telecommunication networks) that are owned and operated by national or foreign civilian entities. Therefore, EU Ministry of Defences (MoDs) may have no control to limit disruptions or damage to civilian critical infrastructure due to natural hazards, including climate change impacts (Tavares da Costa et al., 2023). This, in turn, can compromise the normal operational conditions in military installations, making them prone to Natech risks due to impaired operational dependencies that could cascade to Natech accidents or near misses (i.e., indirect Natech accident mechanism). The following sub-sections present (i) EU policies and legislation on resilience of critical entities, major accident prevention, and structural design (Figure 10), which primarily address the accident prevention angle; (ii) the EU crisis management mechanisms; and (iii) relevant international standards and instruments.

Figure 10. Accident prevention through EU legislation on resilience of critical entities, major accident prevention, and structural design.



3.2.1 Resilience of critical entities – protection of critical infrastructure

The **EU Directive on the resilience of critical entities** (DIRECTIVE (EU) 2022/2557) repealed Council Directive (EU) 2008/114/EC[33] and entered into force in 2023, establishing a common

[33] The DIRECTIVE (EU) 2008/114/EC focused on the protection of critical infrastructure across the energy and transport sector. With its repeal by DIRECTIVE (EU) 2022/2557, the scope was broadened to eleven sectors and it was shifted towards the concept of the resilience of critical entities.

framework across EU for enhancing the resilience of critical entities[34] that provide essential services. The latter is defined as a service that is crucial for the maintenance of vital societal functions, economic activities, public health and safety, or the environment. The Directive applies to public and private entities across eleven sectors (i.e., energy, transport, banking, financial market infrastructure, health, drinking water, waste water, digital infrastructure, public administration, space, and production, processing and distribution of food). It does not apply to critical entities with activities in the areas of national and public security, defence or law enforcement, unless the provided services are marginally related to those areas[35]. The Directive sets the objective of enhancing the resilience of critical entities to prevent disruptions in essential services. It mandates MSs to carry out comprehensive risk assessments of critical entities, considering natural and man-made hazards, as well as hybrid threats (e.g., terrorism, sabotage, public health emergencies, and cyber incidents). Cross-sectoral and cross-border risks should also be included, accounting for disruptions due to (inter)dependencies among different sectors and potential cascading effects. The Directive sets harmonised rules and support measures to ensure that critical entities can prevent, respond to, mitigate consequences, and recover from disruptions.

3.2.2 Major Accident Prevention

In July 2012, the European Parliament and the Council of the European Union adopted the **SEVESO III Directive** (DIRECTIVE 2012/18/EU), which applies to industrial establishments that involve dangerous substances and could potentially lead to major accidents. However, this Directive does not apply to military facilities. It replaces the Council Directive 96/82/EC and it lays down rules for the prevention of major accidents and limitation of their consequences for human health and the environment across the EU. To meet these objectives, operators are obliged to take all necessary measures for accident prevention and consequence mitigation, including for emergency response planning operations. This information should be provided to competent authorities in the form of a safety report, which should include details on risk analyses for possible major-accident scenarios and the probability or the conditions under which they occur. Internal or external triggering events should be considered, in particular operational causes, domino effects, and natural hazard impacts. Thus, the **SEVESO III Directive explicitly requires the consideration of Natech risk analysis for industrial establishments in the EU**.

3.2.3 Design standards for industrial facilities in Europe

Industrial structures and equipment could be found in military facilities for production, storage, transportation or handling of chemicals and fuels required in various military operations. The design of industrial units, such as silos, tanks, pipelines, towers, masts and chimneys, is covered in Part 4 of the European Standards (EN) Eurocodes[36]. The list below provides the relevant EN provisions for the second generation of Eurocode (prEN Standards), unless noted otherwise:

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[34] e.g. operators of oil pipelines, power networks

[35] The Green paper on a European programme for critical infrastructure protection (COM(2005)576 final) provided a list of indicative critical infrastructure sectors, which included a sector on public and legal order and safety (sector VII), as well as a sector on civil administration that covered the armed forces products or services (sector VIII - 25).

[36] The EN Eurocodes are a set of 10 European Standards (EN 1990 – EN 1999) for the design of civil engineering structures. The EN Standards EN 1991 – EN 1999 are divided in several Parts to cover the structural design of special structures and other specific matters.

- **Eurocode 0**: Basis of structural and geotechnical design (prEN 1990:2023, superseding EN 1990:2002 and EN 1997-1:2004).
- **Eurocode 1**: Actions on structures – **Part 4:** Silos and tanks (prEN 1991–4:2024, superseding EN 1991–4:2006).
- **Eurocode 2**: Design of concrete structures - **Part 3**: Liquid retaining and containment structures (the current EN Standard EN 1992-3:2006 is not replaced in the second generation of Eurocodes)[37].
- **Eurocode 3**: Design of steel structures – **Part 3**: Towers, masts and chimneys (prEN 1993-3:2024, superseding EN 1993-3-1:2006 and EN 1993-3-2:2006).
- **Eurocode 3**: Design of steel structures – **Part 4-1**: Silos (prEN 1993-4-1:2024, superseding EN 1993-4-1:2007).
- **Eurocode 3**: Design of steel structures – **Part 4-2**: Tanks (prEN 1993-4-2:2024, superseding EN 1993-4-2:2007).

Specifically for the **seismic design of industrial facilities**, the following EN Standards also apply:

- **Eurocode 8**: Design of structures for earthquake resistance – **Part 1-1**: General rules and seismic actions (prEN 1998-1-1:2024, superseding EN 1998–1:2004).
- **Eurocode 8**: Design of structures for earthquake resistance – **Part 4**: Silos, tanks, pipelines, towers, masts and chimneys (prEN 1998-4:2023, superseding EN 1998–4:2006 and EN 1998–6:2005).

According to the EN Standards, industrial facilities are designed to withstand seismic forces by ensuring that all the following **performance requirements** are fulfilled[38]:

- Protection of human life and prevention of personal injuries.
- Protection of the environment.
- Preservation of full or limited industrial functionality based on damage limitation principles.
- Important lifeline systems should remain functional for civil protection operations (e.g., critical utility networks – energy, water, and telecommunication –, hospitals, fire stations, emergency routes, safety systems).
- Cascading effects should be avoided by preventing damage to connected structural components, adjacent facilities, and nearby buildings.
- Economic and social consequences should be minimised.

To determine the impact of systems failure to human life, economic, social and environmental aspects, a consequence classification scheme is defined in EN Eurocodes. Industrial facilities and

[37] https://www.concretecentre.com/News/2023/2nd-Generation-Eurocode-2.aspx

[38] The information herein is based on the “Webinar 4: Silos, tanks, pipelines, towers masts and chimneys”, which is part of the “Eurocode 8 – Second generation webinar series” accessible from the link: https://ec8webinars.org/

buildings that contain or handle hazardous substances are classified under the Consequence Class 3, which is associated with high consequences to the exposed people and environment due to systems failure. The EN1998-4 splits the Consequence Class 3 into two categories: CC3a and CC3b. The selection of the target consequence class depends on the adopted structural performance requirements, i.e.:

- **The Consequence Class CC3a** is selected when the integrity of structures and ancillary elements[39] is of vital importance for public safety and the environment, or when there is a risk of cascading effects due to systems failure (i.e., damage to connected components, adjacent facilities and nearby buildings).
- **The Consequence Class CC3b** is selected for all structures and systems whose failure could adversely affect the functionality of important lifeline systems for civil protection operations.

For the selected consequence class, the following **Limit States** should be verified i.e.:

- **Significant Damage (SD) Limit State**: Industrial structures and ancillary elements can be significantly damaged but without losing their structural integrity. Any potential leakage/loss of content should be controlled.
- **Damage Limitation (DL) Limit State**: The severity and extent of damage should be limited, ensuring that restoration operations could recover the system's capacity up to a predefined level. Liquid-filled systems should remain leak-proof.
- **Operational (OP) Limit State**: The industrial system and all ancillary elements should remain fully functional. Liquid-filled systems should remain leak-proof.

It is noted that EN1998 – Part 4 **does not cover** the limit state of **Near Collapse (NC)**.

For the seismic design of industrial structures, a limit state verification should be performed for certain target seismic intensity levels, which are defined through the return period of an earthquake event at a given location, as reported in Table 2. For example, in the case of the higher consequence class CC3b, the SD limit state should be verified for a rare earthquake event with a return period of 2500 years, which pertains to an annual rate/probability of exceedance at 0.04%. The more stringent DL limit state should be verified for a more frequent earthquake event of lower seismic intensity, which pertains to a return period of 250 years and the annual rate/probability of exceedance at 0.4%.

Table 2. EN 1998-4: Earthquake return periods for limit states and consequence classes

Limit State	**Return Period**	
	Consequence Class CC3a	**Consequence Class CC3b**
Significant Damage (SD)	1300	2500
Damage Limitation (DL)	150	250

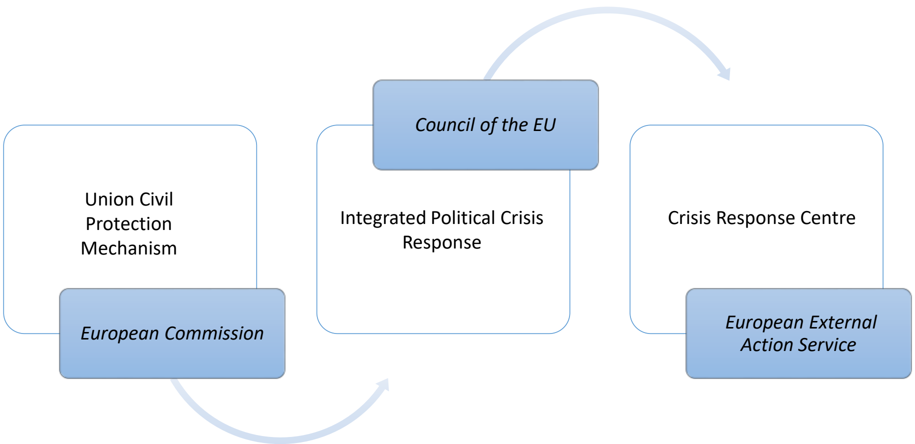
Source: excerpt from Table 4.2 in prEN 1998-4:2023

[39] Ancillary elements are defined as non-structural components attached to structures in industrial facilities

3.2.4 Crisis Management

When a crisis occurs inside or outside the EU, the European Commission, the Council of the EU, and the EEAS undertake key roles with distinct responsibilities for crisis management operations, ensuring collaboration and coordination of activities where appropriate (Figure 11). The different roles of the EU institutions and body are analysed in the following sections.

Figure 11. Crisis management at EU level.



3.2.4.1 *Crisis Management - European Commission, DG ECHO*

In May 2021, the Regulation (EU) 2021/836 amended the Decision No. 1313/2013/EU on the **UCPM**. This Regulation aims to improve the Union's response to natural and man-made hazards, by strengthening cooperation between the Union and the MSs and facilitating coordination in the field of civil protection, primarily the protection of people, but also the environment and property. The cooperation may also include civil-military cooperation when appropriate, by using military capacities in support of civil protection operations. The Regulation introduces Union disaster resilience goals in the following areas (Commission Recommendation C(2023) 400 final):

- *Anticipate*, i.e., improve risk assessment, anticipate, manage, and plan disaster risk.
- *Prepare*, i.e., increase risk awareness and preparedness of the population.
- *Alert*, i.e., enhance early warning.
- *Respond*, i.e., enhance the UCPM response capacity.
- *Secure*, i.e., ensure a robust civil protection system.

The above disaster resilience goals are non-binding objectives, serving as a baseline for the prevention of, preparedness for, and response to all kinds of natural and man-made hazards, including consequences of acts of terrorism, technological, radiological or environmental disasters occurring inside and outside the Union. The considered disasters include also risks associated with potential cross-border impacts or disaster risks that can cause multi-country transboundary effects. In view of the ever increasing climate change impact, climate-related risks are also considered, while low probability risks with high impact consequences are regarded where appropriate. The Regulation calls for comprehensive disaster risk management and planning based on regular risk assessments and analyses of disaster scenarios. The UCPM structure consists of:

- the *Emergency Response Coordination Centre* (ERCC), i.e., the coordination hub between all EU MSs and UCPM Participating States[40] that ensures the rapid deployment of emergency support to disaster-stricken countries;

- the *European Emergency Response Capacity* (EERC), i.e., a voluntary pool of pre-committed capacities from Member States and trained experts; and

- the *Common Emergency Communication and Information System* (CECIS), i.e., a web-based alert and notification application that enables communication and information sharing between the ERCC and the contact points of the countries participating in the UCPM.

3.2.4.2 Crisis Management - Council of the European Union

In 2006, the Council adopted the *Emergency and Crisis Coordination Arrangements* (CCA) as a platform for information exchange and coordination of actions between MSs in the event of a major crisis. In 2013 the Council adopted the **EU Integrated Political Crisis Response (IPCR)** arrangements as an extension of CCA that represent a more flexible and scalable mechanism, making better use of existing resources, structures and capabilities. With the Council Implementing Decision (EU) 2018/1993 dated in December 2018, the Council adopted an implementing decision enacting the IPCR into a legal act. The IPCR arrangements set up a framework for **coordinated response at Union political level** (i.e., at the highest political level) for crises inside or outside the Union, which have wide-range impact or political significance. The IPCR crisis mechanism supports the Presidency of the Council of the EU to deal with major natural disasters, cross-sectorial man-made disasters, cyber-attacks, hybrid threats, acts of terrorism, and armed conflicts. The IPCR mechanism can be activated by either the Presidency of the Council, or a MS invoking the Solidarity Clause (i.e., Article 222(2) of the Treaty on the Functioning of the EU). The Presidency of the Council coordinates the political response to major cross-sectorial crises by bringing together the European Commission, the EEAS, EU agencies, affected MSs, and other key stakeholders. Decisions on possible EU actions are taken by the *Committee of the Permanent Representatives of the Governments of the MSs to the EU* (Coreper), the *Council of the EU* or the *European Council*. Depending on the type of crisis and the associated political needs of the response, structures with intelligence or military expertise may be deployed by the *High Representative of the Union for Foreign Affairs and Security Policy* and the EEAS, as well as other structures and Union Agencies in the field of the *Common Foreign and Security Policy* (CFSP) or the CSDP, where appropriate. EU Delegations may also contribute to response to crises with external dimension. The IPCR mechanism aim to share information, collaborate, and coordinate the crisis response using the following tools:

- *Informal high-level roundtables*, convened by the Presidency with the support and advice of the General Secretariat of the Council (GSC).

- *Integrated Situational Awareness and Analysis* (ISAA) *reports*, developed by Commission services and the EEAS, based on their respective roles and responsibilities to share information about the current situation, analysis conducted by the Union and MSs, and the decisions and measures taken by relevant stakeholders.

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[40] Albania, Bosnia-Erzegovina, Iceland, Montenegro, North Macedonia, Norway, Serbia, Türkiye, Ukraine, Moldova

- A Council-owned, dedicated and protected *web platform* that facilitates a timely exchange of information.

- A central *24/7 contact point* at Union level with MSs competent authorities and other stakeholders, provided by the ERCC.

The IPCR mechanism can be in monitoring level for sharing of information on a voluntary basis, or it can be activated in two possible modes, i.e., information sharing mode and full activation mode.

In January 2018, the Council of the EU adopted a framework for an **Integrated Approach to external conflicts and crises** (Council Conclusions 5413/18), as part of its broader *Global Strategy for the EU's Foreign and Security Policy* (European Union Global Strategy (2016)), completed by the *Implementation Plan on Security and Defence* (Council of the European Union 14392/16). Using a wide range of EU policies and instruments across various fields[41], the Integrated Approach establishes a more coherent and holistic EU engagement to address conflicts and crises outside its borders, while ensuring the safety and security of people in those areas. The concept of the Integrated Approach was further consolidated through the **Strategic Compass for Security and Defence** Council of the European Union 7371/22, an action plan for strengthening the EU's *Security and Defence policy* by 2030 (see also sub-section 3.1.1). Among the objectives of the **Strategic Compass** is the reinforcement of the EU's *Civilian and Military CSDP*, by enhancing the capacity to undertake full range of civilian and military crisis management tasks. The coordination of civilian-military aspects is ensured by the *High Representative of Union for Foreign Affairs and Security Policy*, who is also a *Vice President of the European Commission* (HR/VC). The Civilian CSDP Compact (2023) contributes to the further development and strengthening of civilian missions responding to threats and challenges, which undermine the executive, judicial or legislative system in crisis areas. Climate change is also recognised as a security challenge due to its effect on conflicts and crises across the globe, challenging the EU's ability to defend its interests and those of its partners[42].

3.2.4.3 Crisis Management - EEAS

The **EEAS**, the Diplomatic Service of the EU, is responsible for **monitoring and assessing crises outside the EU that affect EU security interests**. It focuses on the protection of EU Delegations (including EU staff, premises, assets, and information) and EU citizens in non-EU countries against crises and threats, ranging from natural hazards to deliberate attacks (e.g., armed conflicts), which pose a threat to human life, health, or security. In July 2022, the EEAS *Crisis Response Centre* (CRC) was created to serve as a single-entry point for all crisis-related issues in the EEAS for emergencies threatening EU Delegations and EU citizens around the world[43]. The CRC comprises the *EU Situation Room*, which is a 24/7 information hub that provides global, comprehensive, and timely early warning, situational awareness and horizon scanning to all actors involved in crisis preparedness and response. To coordinate crisis response operations, the CRC brings together EU institutions and services that work on security, consular, military, political, administrative, intelligence or communication matters.

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[41] diplomatic, security, defence, financial, trade, development cooperation, and humanitarian aid fields

[42] Examples are given in the Strategic Compass for Security and Defence, such as scarcity of and competition for natural resources (farm land, water), exploitation of energy resources for political purposes, access to critical raw material, value chain management and sustainability, economic and political shifts caused by the transition away from fossil fuels, impact on key energy infrastructure causing direct implications on security and defence.

[43] https://www.eeas.europa.eu/eeas/crisis-response_en

CRC closely cooperates with the European Commission's ERCC, the Council of the EU (including IPCR framework), crisis centres in EU MSs, and international partners (i.e., like-minded countries and organisations).

3.2.5 International Standards and Instruments

3.2.5.1 International design standards for industrial facilities

Further to the EN Eurocodes described in section 3.2.3, several international Standards can be also consulted for the design of industrial facilities in Europe, such as:

- American Petroleum Institute Standards (API STD 620, API STD 650, API STD 653, API STD 2510).
- American Society of Mechanical Engineers Standards (ASME B31E (2008), ASME B31.4 (2022), ASME B31.8 (2022)).

3.2.5.2 Sendai Framework for disaster risk reduction in 2015-2030

In 2016, the European Commission issued the staff working document SWD(2016) 205 final/2, which is an action plan on the implementation of the Sendai Framework for disaster risk reduction within the period 2015-2030 based on a disaster risk-informed approach for all EU policies. The Sendai Framework, adopted in 2015 by UN MSs, provides an international approach for disaster risk management policy and operations, excluding the defence sector and incorporating all-hazards risks (i.e., natural, environmental, man-made, technological, and biological hazards and risks. It invites stakeholders[44] to implement, on a voluntarily basis, the following four priorities:

- **Priority 1**: Understand disaster risk.
- **Priority 2**: Strengthen disaster risk governance to manage disaster risks.
- **Priority 3**: Invest in disaster risk reduction for resilience.
- **Priority 4**: Enhance disaster preparedness for effective response and "Build Back Better".

The Sendai framework is linked with existing EU policies and programmes for disaster risk management, mostly along the civil protection and humanitarian aid operations (Decision No. 1313/2013/EU). It is also associated with other EU policies, which include, among others:

- the Directive on the resilience of critical entities (DIRECTIVE (EU) 2022/2557);
- the SEVESO III Directive on the control of major-accident hazards involving dangerous substances (DIRECTIVE 2012/18/EU);
- the Directive on safe offshore oil and gas operations (DIRECTIVE (EU) 2013/30/EU) with provisions on risk management and assessment for consequences limitation in case of an accident;
- the Regulation on the trans-European energy infrastructure (Regulation (EU) No 347/2013) with guidelines on climate- and disaster-resilient energy projects;

[44] UN States, national and local authorities, regional and international organisations, other stakeholders

— the Flood Directive (DIRECTIVE 2007/60/EC) on the assessment and management of flood risks.

While existing EU policies contribute to the implementation of the Sendai framework, this occurs in a rather fragmented way, suggesting that a systematic risk-informed approach for all EU policies is missing. In this respect, the Commission has defined the following key areas, in line with the four Sendai priorities, which serve as a set of measures towards an EU risk-informed policy arena, i.e.:

— **Key area 1**: Build risk knowledge in EU policies.

— **Key area 2**: An all-of-society approach in disaster risk management.

— **Key area 3**: Promote EU risk informed investments.

— **Key area 4**: Support the development of a holistic risk management approach.

In 2023, the *United Nations Office for Disaster Risk Reduction* (UNDRR) published the midterm review report on the implementation of the Sendai Framework (UNDRR, 2023).

3.2.5.3 Risk Management ISO Standards

The **ISO 31000:2018(E) - Risk Management Guidelines** is an international standard that provides guidance on managing any type of risk organisations may face. These international guidelines provide a common risk management approach that organisations can apply to their activities and support the decision-making at all levels. According to this approach, the risk management comprises the following three main components:

— The **principles**, which refers to the elements required for the creation and protection of value, setting up the foundation of an effective risk management.

— The **framework**, which refers to the leadership and associated commitments for efficient risk management governance.

— The **process**, which refers to the implementation of policies, procedures, and practices for managing risks at strategic, operational, programme, or project level within an organisation.

Specifically for the **risk management process**, this is an iterative procedure among the following key elements:

— communication and consultation;

— establishment of the scope, context and criteria, risk assessment and risk treatment;

— monitoring and reviewing; and

— recording and reporting.

Focusing on the second key element, establishing the scope, context and criteria of a risk management process is crucial for setting specific objectives (including the reference time and location) in line with the decisions that are sought, understanding the internal and external environment of the activity to be risk-assessed, and defining criteria for accepting or rejecting a risk. The **risk assessment** is an overall process that is divided in three sub-areas, i.e.:

— The **risk identification**, which entails the description of risks (e.g., sources of risk, threats and opportunities, causes and events, vulnerabilities and capabilities, etc.).

— The **risk analysis**, which refers to qualitative or quantitative analysis techniques used to understand the nature, characteristics, and level of risk (e.g., likelihood of events and consequences, nature and magnitude of consequences, etc.).

— The **risk evaluation**, which is used for the decision-making process through the comparison of the risk analysis results with the established risk criteria.

The selection of a decision and its implementation are reflected into the **risk treatment**.

In support of the ISO 31000:2018(E), the **ISO IEC 31010:2019 – Risk management/Risk assessment techniques** is a guidance document for selecting and applying risk assessment techniques in various situations, facilitating the decision-making process for managing uncertainties, risks, and opportunities in practice.

4 Methodology: Probabilistic Natech risk analysis in military facilities

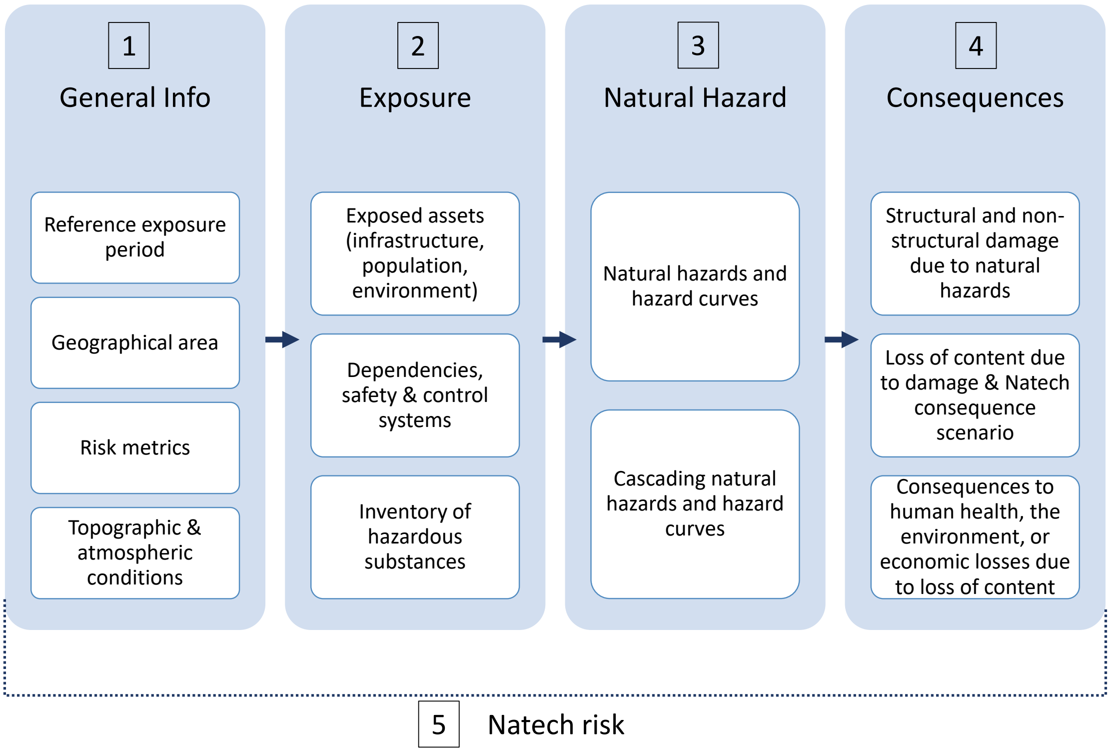
4.1 Methodology overview

Probabilistic Natech risk analysis is used to evaluate the adverse consequences to assets (people, structures, elements, contents) exposed to Natech accidents, and their likelihood of occurrence in a given exposure period. The Natech risk is evaluated from the convolution of the natural hazard that triggers a technological accident, the exposure of assets to natural-technological hazards, and the adverse consequences to the exposed assets, which is expressed as (Baker et al., 2021; Porter, 2001):

[Natech Risk] = [Exposure] x [Natural Hazard] x [Consequences] (4.1)

In the above, the term "consequence" can also be found in the literature as "vulnerability" or "loss" depending on the application; these terms can be used interchangeably (Baker et al., 2021). To evaluate the Natech risk based on Eq. (4.1), the minimum required information is shown in Figure 12 and described below.

Figure 12. Probabilistic Natech risk methodology.



1. **General Information: Scope, context and criteria**
    - Define the reference exposure period for the risk analysis (e.g., one year).
    - Define the geographical area for the risk analysis.

- Define the risk metric or risk metrics for the Natech risk evaluation. Examples of risk metrics include: casualties/fatalities, environment consequences, economic losses (i.e., material loss, direct costs due to damage and repair costs, business downtime), impaired military operations and readiness.

- Determine the topographic and atmospheric conditions for the dispersion pathways of the hazardous substance.

2. Exposure Model[45]

- Identify the exposed facilities and their equipment, the operational dependences to critical utility networks (e.g., power, water), the existence of protective measures, safety and control systems within the selected geographical area.

- Make an inventory of the hazardous substances involved in the exposed facilities. The inventory should include the properties of hazardous substance (e.g., flammable, explosive, toxic) and their chemical reactivity with air and water.

3. Natural Hazard Model[46]

- Identify the natural hazards affecting the selected geographical area.

- Identify possible cascading natural hazards (e.g., earthquake-triggered tsunamis, landslides, soil liquefaction).

- Select site-specific natural hazard curves for the reference exposure period.

4. Consequence Analysis Model[47]

- For the considered natural hazard(s), use of fragility curves to evaluate the potential physical damage to structural systems (facilities and equipment), and non-structural elements (e.g., critical utility services, safety barriers and control systems) at various damage severity levels, termed as *Damage States* (DS).

- Given the damage in structural systems and non-structural elements, evaluate the *Loss of Content* (LOC) in each DS. This is commonly termed as *risk state* and it entails the estimation of the quantity of the released hazardous substances, the exposure pathways (air, soil, water), and the substances dispersion due to atmospheric conditions, terrain, wind speed and direction.

- For the given LOC, determine the potential physical consequence scenario associated with fire, explosion, or toxic dispersion. Assess whether the identified consequence scenario can develop into a domino event due to secondary effects and cascading hazards.

[45] In line with the risk identification step of the risk assessment process as per the ISO 31000:2018(E) standards

[46] In line with the risk identification step of the risk assessment process as per the ISO 31000:2018(E) standards

[47] In line with the risk analysis step of the risk assessment process as per the ISO 31000:2018(E) standards

- Estimate the consequences due to the physical effects of heat radiation (fire), blast overpressure (explosion), and toxic exposure (toxic dispersion) for the selected risk metric(s).

5. **Natech risk calculation**[48]

   - Combine the results of the steps above to calculate the Natech risk. This is the aggregated consequences (or losses) for the exposed area to Natech hazards in the selected reference period.

Details on the steps 2 – 5 and the associated mathematical framework are analysed separately in the following sub-sections.

4.2 Exposure model

The exposure model incorporates the spatially distributed assets that are exposed to and adversely affected by natural and technological hazards (Natech accidents). Depending on the scope of the Natech risk analysis and the selected consequence risk metric(s), simplified or more complex exposure models can be defined to assess:

- health and safety implications;
- environmental impacts;
- economic losses;
- impaired military operations and readiness.

The next sub-section describes the assets that can be included in the exposure model for Natech risk analyses in military installations.

4.2.1 Infrastructure

An exposure model would comprise military infrastructure assets (structural systems, equipment), which contain or handle hazardous substances and are prone to Natech accidents through the development of the following mechanisms, i.e.:

- Immediate structural damage due to direct natural hazard impacts.
- Structural damage from secondary effects due to hazard propagation and domino events.
- Indirect impacts to infrastructure due to failures in operational dependences.

The above mechanisms are associated with exposure models of increasing complexity, as more infrastructure assets and services should be taken into consideration to sufficiently capture the complex dynamics in interconnected and operationally dependent systems. Thus, the last Natech accident mechanism pertains to an exposure model with the highest sophistication level. In addition to structural systems and equipment, it comprises spatially distributed critical utility networks (energy,

[48] In line with the risk analysis step of the risk assessment process as per the ISO 31000:2018(E) standards

water, and telecommunications networks), transport infrastructure, auxiliary pipework, as well as non-structural elements, such as safety and control systems.

The next sub-sections describe two of the most commonly used military equipment for storing explosives, and chemicals and fuels.

4.2.1.1 Military facilities for storing explosives

Military and defence facilities typically store various types of explosives (e.g., ammunition, missiles, grenades). For safety and security purposes, explosives are stored under controlled environmental conditions within **magazines**, which are buildings specifically designed to withstand explosions and prevent the propagation of blast waves to nearby entities (see also section 3.1.3).

To sufficiently describe the structural performance of magazines and determine their vulnerability under natural-hazard or other impacts, the following attributes should be specified:

— Design considerations at construction or retrofit phase (e.g., load resisting system and ductility requirements). This information can be found in the applied design codes, which can be inferred by the date and place of construction or retrofit;

— Construction material (e.g., reinforced concrete);

— Geometrical characteristics (i.e., shape and size of walls, floors, roof);

— Support conditions (i.e., above ground, earth covered).

The above attributes are the salient features of a structural system, which are taken into consideration when fragility curves are derived. As detailed in section 4.4, the use of fragility curves (i.e., probability of structural damage exceedance of a certain damage state/severity level for a given natural hazard intensity measure) are used within the consequence analysis (level 1), which is an integral part of the Natech risk analysis.

The list of attributes also includes risk reduction measures, which could be considered in the Natech risk calculations:

— Active or passive mitigation measures (e.g., segregation compartments);

— Safety and control systems (e.g., temperature, humidity, and ventilation monitor systems).

Bunkers and vaults are secure underground or partially buried structures, designed to withstand external threats, such as explosions and attacks. These structures are typically used for military, civilian and industrial purposes.

4.2.1.2 Military facilities using, handling, storing or transporting chemicals and fuels

Military facilities use, handle, store or transport chemicals and fuels. Such facilities typically store large quantities of fuel (e.g., gasoline, diesel, jet fuel, other petroleum products), which are required for the use of military equipment and the fuel supply of vehicles (e.g., tactical, non-tactical, vessels, aircrafts). Fuel could be transported to military sites via pipelines[49] and trucks, or even ships in the case of coastal military bases. Military facilities could also store flammable or combustible liquid substances (e.g., solvents, paints), which are primarily used for equipment maintenance, cleaning purposes, or manufacturing processes. Other chemical agents used for defensive or offensive purposes (e.g., nerve agents, blister agents, and riot control agents) can also be found in military and defence facilities.

Fuels and chemicals are stored in **storage tanks**, which are commonly grouped together in dedicated areas known as **fuel farms**, enabling the efficient storage, distribution, and management of fuel supply. In case of space limitations or needs for fuel transport, smaller quantities can be stored in **drums or barrels**, which are placed on pallets or racks and sheltered in protected areas.

The following attributes should be specified in the exposure model, which are used to derive or select fragility curves for storage tank, i.e.:

- Design considerations at construction or retrofit phase as per the applied design codes, which can be inferred by the date and place of construction or retrofit;
- Construction material (i.e., reinforced concrete, steel, fiberglass);
- Intended use and storage conditions (e.g., atmospheric tanks, pressurised vessels, substance filling level);
- Geometrical characteristics (i.e., shape and size);
- Support conditions (i.e., above ground/elevated and supported by substructures, on-ground, underground/embedded);
- Foundation system (i.e., anchored, unanchored);
- Roof type and shape (open, floating, fixed, dome, single or double).

The following risk reduction measures could also be included in list of attributes, i.e.:

- Active or passive mitigation measures (e.g., containment dikes, fire protection);
- Safety and control systems (e.g., leak detection and monitor systems).

4.2.2 Population

Regulations on major chemical accidents require the evaluation of lethal effects to people due to the release and dispersion of hazardous substances. The population is typically considered in the exposure model to determine the individual risk and the societal risk (number of people, fraction of the population) exposed to fatal Natech accidents (Purple Book, 1999).

For the evaluation of the individual risk, each individual is assumed to be unprotected in an outdoor area. For the computation of the societal risk, the exposed population is split in two categories, i.e., (i) the unprotected population outdoors, and (ii) the protected population indoors that wear protective

[49] According to the Seveso III Directive (DIRECTIVE 2012/18/EU) that applies to industrial facilities and excludes military sites, the risk analysis should take into consideration the transport of hazardous materials via pipelines within the perimeter of the facility. No requirement exists for pipelines outside the site perimeter.

clothes. Depending on the type of the indoors area (i.e., residential, industrial, recreational, commercial, offices, hospitals, schools), the fraction of the exposed population varies with time due to the differences in the occupancy of buildings during daytime and night-time (i.e., people are moving from residential to other areas for several reasons, including work purposes) (Purple Book, 1999).

To incorporate the above attributes in the exposure model, detailed population data are required together with the type and spatial distribution of indoors areas. Depending on the scope on the risk analysis, this information should be collected at local, regional, or national level, including also future projections on the population density and land cover. Collecting such data in high resolution may be a rather difficult task, but useful sources of information could be found in public census data, land-use plans and spatial development strategies, as well as Geographical Information Systems. Relevant exposure models in terms of population and buildings (residential, commercial, and industrial) can be found in the EFEHR database for Europe, and the GEM database for the globe[50].

4.2.3 Environment

The release and dispersion of hazardous substances due to Natech accidents commonly result in contamination of land and water bodies, leading to environmental degradation and potentially reducing the quality of drinking water and agricultural products, which could become unfit for consumption and use. Further, chemical and/or toxic spills to groundwater, surface water, and surface soil could endanger the flora and fauna of the affected areas.

To evaluate environmental impacts from Natech accidents and prioritise clean-up operations in soil and water bodies due to hazardous material releases, the spatial distribution of the following environmental and ecological attributes should be considered in the exposure model:

- location of water bodies, land, and agricultural areas;
- wildlife population and vegetation covering.

4.2.4 Economy

Monetary attributes are included in the exposure model when the risk analysis objective is the evaluation of incurred economic losses due to:

- repair/replacement costs subject to material damage (structural, non-structural) and/or content loss (hazardous substances);
- operational downtime.

The latter is associated with the cost of losing operational capacity when critical military operations are impaired and halted. Examples include economic losses due to relocation of operations to other facilities, disrupted maintenance of military assets that risk to become unfit for deployment, continued daily operational costs (e.g., utilities, logistics, personnel salaries) while the military facility remains mission incapable. The operational downtime can also adversely affect the military readiness

[50] The EFEHR and GEM databases also include data associated with the buildings replacement cost, which is part of the economic attributes of the exposure model.

to respond to national security threats, which can be aggravated in case of delayed recovery operations in the aftermath of a Natech accident.

The associated economic cost, expressed in terms of current currency value and future projections, could be retrieved from the National Statistical Office of each country, such as construction costs (Crowley et al., 2021).

4.3 Natural hazard analysis

The natural hazard analysis is case-specific and it depends on the type of the natural hazard (e.g., earthquakes, floods, hurricanes) due to the different physical phenomena developed. In this section, the probabilistic seismic hazard analysis (PSHA) will be presented, considering the physical phenomena due to earthquakes that occur across seismic faults. The same principles can be followed for the probabilistic hazard analysis of other natural hazards, which, however, is not covered herein for the sake of brevity.

Earthquakes generate seismic waves, whose immediate impact is reflected into ground shaking and permanent ground deformation due to fault rupture, uplift, subsidence, or folding. Earthquakes can also trigger cascading natural hazards, such as tsunamis, landslides, and soil liquefaction. Focusing on the primary seismic hazard, this is commonly quantified through a site-specific seismic hazard curve, which is defined as the probability (or rate) of exceeding a certain level of ground shaking at a given site and in a specified period, for a range of intensity levels. Based on the total probability theorem, the seismic hazard curve was first introduced in 1968 to account for the uncertainties involved in the seismic ground motion (Cornell C. Allin, 1968). First, the total number of seismic faults, *N*, that can adversely affect a given site should be determined. The associated seismicity of each seismic source is given by the mean rate of an earthquake occurrence at the i^{th} seismic source, v_i, and the probability density function, $f(M_w)$, which expresses the number of earthquakes that can be generated at a specific seismic source with a moment magnitude greater than or equal to M_w (Gutenberg and Richter, 1949). To account for the attenuation of the considered ground motion with respect to the epicentral distance, *R* (i.e., the distance between the seismic source and the site location), appropriate ground motion equation functions are used, and the associated uncertainties are given by the probability density function *f(R).* The simplest form of a seismic hazard curve is expressed as (Baker et al., 2021):

$$F(h) = \lambda(H > h) = \sum_{i=1}^{N} v_i \int_M \int_R P(H > h|M_w, R)\, f(M_w) f(R) dM_w dR \tag{4.2}$$

where $P(H > h|M, R)$ is the probability of a given seismic intensity measure, *H*, exceeding a specific seismic intensity level, *h*, when an earthquake with moment magnitude M_w occurs at an epicentral distance *R* from the site. The double integral in Eq. (4.2) is used to account for all pairs of (M_w, *R*) values at the examined site location. For more complex seismic hazard models, the interested reader is referred to Baker et al. (2021). It is noted that different seismic intensity measures can be used depending on the application. The maximum ground motion amplitudes, i.e., the peak ground acceleration (PGA), the peak ground velocity (PGV), and the peak ground displacement (PGD), are among the most commonly used intensity measures.

4.4 Consequence analysis

To measure the adverse effects of a Natech accident to the exposed assets, a consequence metric should be specified in one of the following terms: casualties, environmental degradation, economic losses, or downtime/impaired military operations and readiness. This assessment entails a consequence analysis model, which comprises the following three levels:

- **Level 1**: Estimation of the physical damage induced to exposed structural systems and non-structural elements due to natural hazard impacts (i.e., fragility curves).
- **Level 2**: Estimation of the release of hazardous substances (i.e., LOC) due to physical damage in exposed systems/elements. Determination of the developed accident scenario due to LOC (e.g., fire, explosion, or toxic dispersion) and evaluation of the accident physical effects (heat radiation, blast wave overpressure, toxic dose).
- **Level 3**: Estimation of the consequences to the exposed assets (people, structures, environment) through the transformation of the accident physical effects to the selected consequence risk metric, *C*.

The general form of a consequence function is expressed as the probability of exceedance of a given consequence metric value, *c*, conditioned on the hazard intensity value, *h*, i.e.:

$$P(C \geq c|H = h) = 1 - F(c|h) \tag{4.3}$$

Where $F(c|h)$ is the cumulative distribution function of *c* conditioned on *h*. It is noted that the term "consequence function" can also be found in the literature as "vulnerability function", "damage function", or "loss function"; these terms can be used interchangeably.

The methodology described below is compatible with the default "consequence analysis" calculations in the RAPID-N tool (Necci and Krausmann, 2022b), which is based on the guidance by the U.S. *Environmental Protection Agency* (EPA) for offsite consequence analysis in case of accidental chemical releases and the associated adverse effects to the exposed population. In this respect, a simplified consequence analysis can be performed based on the computation of the so-called *endpoint distance*, i.e., the maximum distance of adverse consequences in human health (i.e., serious injuries for short-time exposure) due to the physical effects of fire, explosion, or toxic dispersion. Beyond this distance, it is expected that any health risk would be eliminated due to the dissipation of physical effects. It is noted that the presented methodology can be easily extended to account for other consequence risk metrics given the availability of appropriate exposure models and consequence functions.

4.4.1 Level 1: Physical damage to structural systems and non-structural elements

To evaluate the vulnerability of physical systems, a fragility function is defined as the probability of exceedance of a give damage state DS_i conditioned on a natural hazard intensity value *h.* This is mathematically expressed as (Porter, 2001):

$$F_{DS_i}(h) = P(DS \geq DS_i|H = h) = \Phi\left(\frac{\ln(h/\theta_{DS_i})}{\beta_{DS_i}}\right) \tag{4.4}$$

where Φ is the standard log-normal cumulative distribution function (or Gaussian function), θ_{DS_i} and β_{DS_i} are the median and logarithmic standard deviation, respectively, at the i^{th} damage state.

The probability for observing exactly DS_i is given from the discrete fragility curves (Porter, 2001)

$$P(DS = DS_i|H = h) = \begin{cases} 1 - P(DS \geq DS_0|H = h) & DS_0 = 0 \\ P(DS \geq DS_i|H = h) - P(DS \geq DS_{i+1}|H = h) & 1 \leq DS_i \leq n_D \\ P(DS \geq DS_i|H = h) & DS_i = n_D \end{cases} \quad (4.5)$$

Where, DS_0 is the undamaged structural state, and n_D is the considered damaged state at the highest severity level. Eq. (4.5) is valid for sequential damage states, occurring when a structural component is damaged at DS_i if and only if it was previously damaged at DS_{i-1}.

For the case of a cascading natural hazard H_2 triggered by hazard H_1, Eq. (4.4) takes the form:

$$F_{DS_i}(h_1, h_2) = P(DS \geq DS_i|H_1 = h_1, H_2 = h_2) = \Phi\left(\frac{\ln(h_1/\theta_{c,DSi})}{\beta_{c,DSi}}\right) \quad (4.6)$$

For i^{th} damage state, θ_{c,DS_i}, and β_{c,DS_i} are the median and logarithmic standard deviation, respectively, under the combined effect of H_1, and H_2.

4.4.2 Level 2: Loss of containment, accident scenario, and physical effects

The second level of the Natech consequence analysis is split in two steps, i.e.:

Step 1: Estimation of LOC.

Step 2: Determination of the Natech accident scenario (e.g., fire, explosion, toxic dispersion), the associated physical effects (e.g., heat radiation, blast wave overpressure, toxic dose), and endpoint distances.

4.4.2.1 Loss of containment

The LOC event refers to the release of a hazardous substance due to physical damage in structural systems and non-structural elements. Hazardous substances can be classified as flammable, explosive, or toxic in liquid or gas physical state.

The quantity of the released substance depends on the structural damage severity level (damage state), the amount and type of substance involved, the physical and storage conditions, and the release time. The substance release flow rate (i.e., instantaneous or continuous) is determined by the substance thermodynamics (e.g., pressure and temperature), fluid mechanics (e.g., mass density, viscosity, Reynolds number), and transport properties (e.g., viscosity, heat conductivity, diffusivity). The dispersion of a released substance depends further on the environmental conditions (i.e., atmospheric and meteorological data) and the site topography (urban or rural landscape, obstructed or flat terrain).

The default calculations in the RAPID-N tool build on two substance release scenarios, in line with the U.S. EPA guidance, i.e., the *Risk Management Program* (RMP) guidance for offsite consequence analysis (U.S. EPA, 2009), to define the so-called “risk states”, i.e., the set of parameters used for the evaluation of the *source-term* parameters (e.g., substance release rate and duration, equivalent hole diameter, pool area, evaporation rate), the *LOC analysis* parameters (e.g., type of accident scenario, conditional release probability), and the *consequence analysis* parameters (i.e., endpoint distances due to human exposure to the physical effects of thermal radiation, blast wave overpressure, or toxic dose) (Necci and Krausmann, 2022b).

Within the probabilistic Natech risk analysis framework, the *LOC* event conditioned on a *DS* should be expressed as a random variable, requiring detailed structural modelling and analysis, as well as the determination of specific criteria for each damage state, i.e., threshold values of damage limit states that would lead to a *LOC* event (Alessandri et al., 2018). In the absence of this information, the *DS*/*LOC* relationships can be deterministically defined based on expert engineering judgement. The RAPID-N tool uses a deterministic approach using the *DS*/*LOC* matrix presented in Table 3. Except from the catastrophic structural failure, each structural damage state is approximated with an equivalent hole in a vessel or pipe of increasing diameter at higher damage severity levels. This concept originates from the alternative RMP release method (U.S. EPA, 2009) and the guidelines for quantitative risk analysis in stationary atmospheric tanks and vessels (Purple Book, 1999). A continuous flow rate is adopted for the released substance, which corresponds to the release duration reported in Table 3. Based on expert judgement, each LOC event is associated with a single probability of release conditioned on a damage state, *P*(*LOC*/*DS*). For the catastrophic structural failure, the RAPID-N calculations consider the instantaneous release of the entire inventory at $t_{rel} = 1\ s$, which pertains to the conditional release probability P(*LOC*/*DS*)= 100% (i.e., certain release event in case of catastrophic structural damage).

Table 3. Conditional probability of loss of containment per damage state

LOC	**Damage State (DS)**	**Release type**	**Release duration**	**P(LOC/DS)**
LOC0	No damage	No release	-	0%
LOC1	Damage equivalent to hole of 10 mm diameter	Continuous	10 min	30%
LOC2	Damage equivalent to hole of 25 mm diameter	Continuous	10 min	50%
LOC3	Damage equivalent to hole of 100 mm diameter full (or bore rupture, hole equal to maximum diameter of the connected pipes)	Continuous	30 min	80%
LOC4	Catastrophic damage	Instantaneous	1 sec	100%

Source: Necci and Krausmann (2022b)

The substance release rate from a hole is given from the expression (U.S. EPA, 2009):

$$q_{rel} = A_h c_d \sqrt{\rho(2\rho g h_{fh} + 2(P_s - P_a)} \qquad (4.7)$$

where, A_h is the hole area (in m^2) associated with the hole diameter reported in Table 3, c_d is the discharge coefficient, ρ is the substance mass density (in kg/m^3), g=9.81m/s^2 is the acceleration of gravity, h_{fh} is the substance filling level above the hole (in m), P_s is the pressure inside a storage tank or vessel (in Pa), and P_a is the atmospheric pressure (in Pa). The released quantity, Q_{rel} (in kg) is obtained from the following expression

$$Q_{rel} = min\begin{cases} q_{rel}\ t_{rel} \\ Q_{fh} \end{cases} \tag{4.8}$$

where Q_{fh} is the stored substance above the hole.

For the instantaneous release of the entire inventory at $t_{rel} = 1\ s$ due to catastrophic damage, the release rate is computed as

$$q_{rel} = \frac{Q_{rel}}{t_{rel}} \tag{4.9}$$

The released volume (in m^3) is obtained from

$$V_{rel} = \frac{Q_{rel}}{\rho} \tag{4.10}$$

For Natech accidents triggered by earthquake hazards, a deterministic *DS*/*LOC* correlation matrix could be used, as the ones proposed by Alessandri et al. (2018) for anchored and unanchored storage tanks, which were derived from empirical structural damage evidence during past earthquake events together with expert judgement. Alternatively, the fragility curves proposed by Salzano et al. (2009) can be used for anchored and unanchored storage tanks, pressurised horizontal storage tanks, pressurised reactors and pumps. These fragility curves have been defined as cumulative log-normal distributions and probit functions to express the probability of *LOC* with respect to a seismic hazard intensity parameter, considering also a threshold value for the latter (Salzano et al., 2009).

4.4.2.2 Accident scenarios and physical effects

Based on the substance hazard class, its physical state in storage conditions, and the site conditions at the time of the release, the following accident scenario can be defined (Necci and Krausmann, 2022b):

1. **Pool fire**: Release of flammable liquid or liquefied gas by refrigeration, evaporation and ignition of the top liquid layer.
2. **Vapour Cloud Explosion (VCE)**: Massive and rapid release of flammable liquid, gas, vapour, mist. Released substance is mixed with the air under turbulent conditions, creates a cloud of highly reactive flammable vapours that is exploded upon ignition.
3. **Vapour Cloud Fire (VCF) or flash fire**: Release and rapid ignition of flammable liquid, gas, vapour, mist without resulting in explosion.
4. **Boiling Liquid Expanding Vapour Explosion (BLEVE)**: Release of flammable liquid that is stored above its atmospheric boiling point temperature. Upon release, the liquid is rapidly depressurised and instantaneously transitioned to vapour, creating a vapour cloud that expands and rise in a fireball.
5. **Toxic dispersion**: Release and dispersion of toxic liquids or gases.

For the above accident scenarios, the associated conditional probabilities and endpoint distances are presented in the following sub-sections.

4.4.2.2.1 Pool fire

For flammable liquids, the conditional ignition probability depends on the release rate, q_{rel}, and expressed as (Cox et al., 1990):

$$P(S_{ign}|LOC) = \begin{cases} 1\%, & q_{rel}(kg/s) < 1 \\ 3\%, & 1 \leq q_{rel}(kg/s) \leq 50 \\ 8\%, & q_{rel}(kg/s) > 50 \end{cases} \tag{4.11}$$

For regulated substances with a specified Pool Fire Factor, *PFF*, the endpoint distances due to thermal radiation are given from the following expression:

$$d_e = PFF\sqrt{A_p} \tag{4.12}$$

where A_p is pool fire area (in m^2) computed as (U.S. EPA, 2009):

$$A_p = \begin{cases} A_{p,min}, & V_{rel} \leq V_{dike} \ \ and\ A_{p,min} \leq A_{dike} \\ A_{dike}, & V_{rel} < V_{dike} \ \ and\ A_{p,min} > A_{dike} \\ A_{dike} + A_{p,min}, & V_{rel} > V_{dike} \end{cases} \tag{4.13}$$

The above expression takes into consideration the presence of a containment dike as a passive risk mitigation measure to contain liquid spills; V_{dike} and A_{dike} are the volume (in m^3) and bund area (in m^2) of the containment dike, respectively. The quantity $A_{p,min}$ is computed as

$$A_{p,min} = \begin{cases} V_{rel}/h_{p,min}, & V_{rel} \leq V_{dike} \\ (V_{rel} - V_{dike})/h_{p,min}, & V_{rel} > V_{dike} \end{cases} \tag{4.14}$$

where $h_{p,min}$ is the minimum pool fire depth (in m).

For substances without a specified *PFF* (e.g., gasoline, diesel fuel no.2), the endpoint distances , d_e (in m), due to thermal radiation are computed from the simplified equations as per the TNO point model (U.S. EPA, 2009):

$$d_e = \sqrt{\frac{RH_c\, q_c\, H_c\, \tau_a}{4\pi Q_H}} \tag{4.15}$$

Where RH_c is the radiative fraction of heat of combustion, q_c is the combustion rate for pool fire (in kg/s), H_c is the specific heat combustion of diesel fuel (in J/kg), τ_a is the atmospheric transmissivity, and Q_H is the thermal radiation per unit area (in W/m^2). The latter is computed from the equation below (U.S. EPA, 2009):

$$q_c = \begin{cases} \dfrac{0.001\, H_c A_p}{H_v + c_p(T_b - T_a)}, & T_b > T_a \\ \dfrac{0.001\, H_c A_p}{H_v}, & T_b < T_a \end{cases} \tag{4.16}$$

Where T_a is the ambient temperature (in K), T_b is the boiling point (in K), H_v is the specific heat of vaporisation (in J/kg), and c_p is the specific heat capacity of the hazardous substance (in J/kg K), and A_p is the fire pool area (in m^2) as per Eq. (4.13).

4.4.2.2.2 Vapour cloud explosion

For flammable gases/vapors, the conditional probability of vapor cloud explosion is given as (Cox et al., 1990):

$$P(S_{VCE}|LOC) = P(S_{VCE}|S_{ign})\, P(S_{ign}|LOC) \tag{4.17}$$

where

$$P\left(S_{VCE}\middle|S_{ign}\right)=\begin{cases}4\%, & q_{rel}(kg/s)<1\\ 12\%, & 1\le q_{rel}(kg/s)\le 50\\ 30\%, & q_{rel}(kg/s)>50\end{cases} \tag{4.18}$$

and

$$P\left(S_{ign}\middle|LOC\right)=\begin{cases}1\%, & q_{rel}(kg/s)<1\\ 7\%, & 1\le q_{rel}(kg/s)\le 50\\ 30\%, & q_{rel}(kg/s)>50\end{cases} \tag{4.19}$$

The endpoint distance, d_e (in m), due to vapour cloud explosion is computed as a function of the peak overpressure value, P_o (in kPa), from the following expression (Necci and Krausmann, 2022b):

$$d_e=\left(1.347+\frac{9.122\cdot 10^7}{1+\left(\frac{P_o}{2.607\cdot 10^{-8}}\right)^{0.8}}\right)\sqrt[3]{\gamma\, m\frac{H_c}{H_{cTNT}}} \tag{4.20}$$

Where γ is the yield factor (i.e., the portion of the cloud that contributes to the explosion), m is the mass of the flammable substance in the cloud (in kg), H_c and H_{cTNT} is the specific heat combustion of the flammable substance and of trinitrotoluene (TNT)-equivalent mass, respectively (in J/kg).

4.4.2.2.3 Vapour cloud fire

The conditional probability of vapor cloud fire is obtained from

$$\begin{aligned}P(S_{VCF}|LOC)&=P\left(\overline{S_{VCE}}\middle|S_{ign}\right)P\left(S_{ign}\middle|LOC\right)\\&=\left(1-P\left(S_{VCE}\middle|S_{ign}\right)\right)\ P\left(S_{ign}\middle|LOC\right)\end{aligned} \tag{4.21}$$

where $P\left(\overline{S_{VCE}}\middle|S_{ign}\right)$ is the complementary probability to $P\left(S_{VCE}\middle|S_{ign}\right)$.

The U.S. EPA guidelines (U.S. EPA, 2009) provide reference tables for endpoint distances due to the dispersion of flammable clouds in the air, which have been developed for the alternative RMP release scenario.

4.4.2.2.4 BLEVE

In case of BLEVE accident, the conditional probability of ignition of the released flammable liquid is obtained from Eq. (4.11). The resulting physical effect of thermal radiation due to BLEVE is extended to an endpoint distance, d_e (in m), which is computed from the simplified equations as per the TNO point model (U.S. EPA, 2009), i.e.:

$$d_e=\sqrt{\frac{2.2\ RH_c\ H_c\,\tau_a\,m_f^{0.67}}{4\pi\ Q_H}} \tag{4.22}$$

Where RH_c is the radiative fraction of heat of combustion, H_c is the specific heat combustion of diesel fuel (in J/kg), τ_a is the atmospheric transmissivity; m_f is the mass of the fuel in the fireball (in kg), and Q_H is the thermal radiation per unit area (in W/m^2).

4.4.2.2.5 Toxic dispersion

For toxic substances, the conditional probability of toxic dispersion is

$$P(S_{tox}|LOC) = 100\% \tag{4.23}$$

The endpoint distances due to dispersion of toxic vapours in the air are obtained from the reference tables in the U.S. EPA guidelines (U.S. EPA, 2009), which have been developed for the worst-case RMP release scenario.

4.4.3 Level 3: Consequences due to physical effects of Natech accidents

For the selected risk metric (e.g., casualties, environmental degradation, economic losses, or downtime/impaired military operations and readiness), the adverse Natech consequences are computed due to the exposure of assets (people, structures, environment) to the physical effects of fire, explosion, or toxic dispersion. The associated probability of exceedance of the consequence metric value *c* for a given hazard intensity value *h* is conditioned on the physical consequence scenario *S* for each *LOC* scenario and each physical damage *DS*, i.e.:

$$P(C \geq c|H = h) = P(C \geq c|S, LOC, DS, H) \tag{4.24a}$$

Based on the total probability theorem, the consequence curve with respect to *h* is obtained from

$$P(C \geq c|H) = \int_{S} \int_{LOC} \int_{DS} P(C \geq c|S)\, f(S|LOC)\, f(LOC|DS)\, f(DS|H)\, dS\, dLOC\, dDS \tag{4.24b}$$

Where $P(C \geq c|S)$ is the exceedance probability of the consequence metric value *c* conditioned on the physical consequence scenario *S*, $f(S|LOC)$ is the probability density function of *S* conditioned on LOC, $f(LOC|DS)$ is the probability density function of *LOC* conditioned on *DS*, and $f(DS|H)$ is the probability density function of *DS* conditioned on *H*.

For the non-parametric consequence model with *N* discrete damage state values, DS_i *(for i=1,...,N)*, *M* discrete loss of containment values, LOC_j *(for j=1,...,M)*, and *K* discrete physical consequence scenarios, S_k *(for k=1,...,K)*, the triple integral of Eq. (4.24b) becomes:

$$P(C \geq c|H) = \sum_{k=1}^{K} \sum_{j=1}^{M} \sum_{i=1}^{N} P(C \geq c|S_k)\, P(S_k|LOC_j)\, P(LOC_j|DS_i)\, P(DS_i|H) \tag{4.24c}$$

The above expressions can be easily extended to the case of a cascading natural hazard H_2 triggered by hazard H_1, i.e.:

$$\begin{aligned} &P(C \geq c|H_1, H_2) \\ &= \int_{S} \int_{LOC} \int_{DS} P(C \geq c|S)\, f(S|LOC)\, f(LOC|DS)\; f_c(DS|H_1, H_2)\, dS\, dLOC\, dDS \end{aligned} \tag{4.25}$$

where $f_c(DS|H_1, H_2)$ is the probability density function of *DS* conditioned on H_1, and H_2.

The above expressions can be further extended to account for more complex Natech risk analyses, considering physical damage in multiple hazardous facilities, *HF,* and domino effects, *DE*. For the single natural hazard case, this is expressed as:

$$P(C \geq c|H) = \int_{DE}\int_{HF}\int_{S}\int_{LOC}\int_{DS} P(C \geq c|DE) f(DE|S)\, f(S|LOC)\, f(LOC|DS)\, f(DS|HF,H)\; dS\; dLOC\; dDS\; dHF\; dDE \tag{4.26}$$

Eq. (4.26) was adapted from the expression defined by Alessandri et al. (2018). Natech risk regulations and guidelines rely on the consequence metric of human health impact due to Natech accidents (U.S. EPA (2009), Purple Book (1999)). This refers to the lethal effects from the exposure of population to the thermal radiation from fires, blast overpressure from explosions, or inhalation of toxic vapours. The lethal effects are expressed through the following two parameters:

— **Individual risk**: This expresses the probability of death of an individual, P_E, due to exposure to physical effects. It is illustrated with individual risk contour plots on a topographic map.

— **Societal risk**: This refers to the fraction of the population at death risk at a certain location due to exposure to physical effects. It is presented with *FN* curves to express the cumulative frequency, *F*, of Natech accidents with *N* or more deaths.

4.4.3.1 Human health consequences due to pool fire and BLEVE

For the consequence scenario of pool fire, *S*, due to the release and ignition of flammable substances, the individual risk, $P(C|S)$, is computed from the probability of death, P_E as per the following expression (Purple Book, 1999):

$$P(C|S) = P_E = \begin{cases} \frac{1}{2}\left[1 + erf\left(\dfrac{-41.38 + 2.56\ln\left(Q_H^{\frac{4}{3}}t\right)}{\sqrt{2}}\right)\right] & Q_H < 35\ kW/m^2 \\ 1 & Q_H \geq 35\ kW/m^2 \end{cases} \tag{4.27}$$

The above expression is related to the lethal effects of human exposure to heat radiation, Q_H, for a maximum duration of 20 s. It is noted that a certain probability of death (P_E=100%) occurs for $Q_H \geq 35\ kW/m^2$, given that this threshold value corresponds to ignition of buildings for an exposure time of 20 s. For $Q_H < 35\ kW/m^2$, the error function erf that appears in Eq. (4.27) is given as

$$erf = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2} dt \tag{4.28}$$

Regarding the societal risk, the fatal probability for the population inside, $F_{E,in}$, and outside, $F_{E,out}$, a protected space is given as:

$$F_E = \begin{cases} [F_{E,in} = 0,\ F_{E,out} = 0.14P_E], & Q_H < 35\ kW/m^2 \\ [F_{E,in} = 1,\ F_{E,out} = 1], & Q_H \geq 35\ kW/m^2 \end{cases} \tag{4.29}$$

4.4.3.2 Human health consequences due to vapour cloud explosion

For the consequence scenario of vapour cloud explosion, *S*, the individual risk, $P(C|S)$, is computed from the probability of death, P_E as per the following expression (Purple Book, 1999):

$$P(C|S) = P_E = \begin{cases} 1, & P_o > 0.3\ barg \\ 0, & P_o < 0.3\ barg \end{cases} \tag{4.30}$$

Where P_o is the peak overpressure.

Regarding the societal risk, the fatal probability for the population inside, $F_{E,in}$, and outside, $F_{E,out}$, a protected space is given as:

$$F_E = \begin{cases} [F_{E,in} = 1, \;\; F_{E,out} = 1], & P_o > 0.3\, barg \\ [F_{E,in} = 0.025, \;\; F_{E,out} = 0], & 0.1 < P_o < 0.3\, barg \\ [F_{E,in} = 0, \;\; F_{E,out} = 0], & P_o < 0.1\, barg \end{cases} \quad (4.31)$$

It is noted that the above expressions are not valid for detonation of explosives, in which case the duration of the blast is different.

4.4.3.3 Human health consequences due to toxic dispersion

For the consequence scenario of explosion, *S*, the individual risk, $P(C|S)$, is computed from the probability of death, P_E as per the following expression (Purple Book, 1999):

$$P(C|S) = P_E = \frac{1}{2}\left[1 + erf\left(\frac{a + b\ln(C_t^n t) - 5}{\sqrt{2}}\right)\right] \quad (4.32)$$

Where, the coefficients *a, b, n* are constant values associated with toxicity of the hazardous substance (e.g., Table 5.2 in Purple Book (1999)), C_t is the toxic concentration, *t* is the exposure time that is limited to 30 min, and *erf* is the error function in Eq. (4.28).

Regarding the societal risk, the fatal probability for the population inside, $F_{E,in}$, and outside, $F_{E,out}$, a protected space is given as:

$$F_E = [F_{E,in} = 0.1P_E, \;\; F_{E,out} = P_E] \quad (4.33)$$

4.4.4 Natech risk calculation

For the selected risk metric and the reference exposure period, the expected (aggregated) Natech risk is obtained from the convolution integral below

$$\lambda = R(C \geq c) = \int_h P(C \geq c|H)\, f(h) dh \quad (4.34)$$

In the above expression, the Natech consequence curve $P(C \geq c|H)$, obtained from Eqs. (4.24a) - Eq. (4.26) for all hazard intensity values, *h*, is convolved with the derivative of the natural hazard curve, $f(h) = \frac{dF(h)}{dh}$. For the special case of individual Natech risk analysis in the reference exposure period of one year, the above equation gives the expected annual probability of death, λ_E, due to a Natech accident.

The above equation is rarely solved in closed form. Typically, hazard curves and consequence curves are expressed at *N* discrete values of *h,* and *c*, respectively. Therefore, Eq. (4.34) takes the form (Porter, 2001):

$$\begin{aligned} \lambda = R(C \geq c) = \sum_{i=1}^{N} \Big(& p_{i-1}(c)\, F_{i-1}\left(1 - e^{m_i \Delta h_i}\right) \\ & - \frac{\Delta p_i(c)}{\Delta h_i}\, F_{i-1}\left(e^{m_i \Delta h_i}\left(\Delta h_i - \frac{1}{m_i}\right) + \frac{1}{m_i}\right) \Big) \end{aligned} \quad (4.35)$$

where

$p_i(c) = P(C \geq c|H = h_i)$;

$\Delta p_i(c) = p_i(c) - p_{i-1}(c)$;

$F_i = F(h_i)$;

$\Delta F_i = F_i - F_{i-1}$;

$\Delta h_i = h_i - h_{i-1}$; and

$m_i = \frac{\ln(F_i/F_{i-1})}{\Delta h_i}$.

For the case of a cascading natural hazard H_2 triggered by hazard H_1, the Natech risk is computed from the following expression:

$$\lambda = R(C \geq c) = \int_{h_1} \int_{h_2} P(C \geq c|H_1, H_2)\, f_c(H_1, H_2)\, dh_1\, dh_2 \tag{4.36}$$

Where, $P(C \geq c|H_1, H_2)$ is given in Eq. (4.25) and $f_c(H_1, H_2)$ is the conditional probability density function for H_1 and H_2.

4.5 Natech risk analysis with the RAPID-N tool

The *Rapid Natech Risk Assessment Tool*, RAPID-N[51], was developed in 2010-2012 by the European Commission Joint Research Centre with initial support by the Scientific and *Technological Research Council of Turkey* (TUBITAK). RAPID-N performs Natech risk analyses and mapping at local (i.e., single facility) and/or regional (i.e., multiple facilities) scale. It can be used by competent authorities for emergency and land-use planning through the identification of hazardous civil and military installations that are prone to Natech accidents.

The current version of RAPID-N supports the direct impact Natech mechanism (i.e., immediate structural damage) for historic or scenario-based earthquake hazards, considering a single hazard intensity value at each site. For historic earthquakes, data, such as shakemaps, moment magnitudes, and focal depths, are retrieved from the *U.S Geological Survey* (USGS) database[52] and the *European-Mediterranean Seismological Centre* (EMSC)[53] for moderate and strong earthquakes with moment magnitude equal and above 5.5. Other natural hazard triggers (e.g., floods) are currently under development. A database is integrated into RAPID-N comprising:

— A historic earthquake data catalogue;

— Ground Motion Prediction Equations (GMPE);

— Seismic fragility curves;

— A list of hazardous substances and the associated properties;

[51] https://rapidn.jrc.ec.europa.eu/

[52] https://www.usgs.gov/programs/earthquake-hazards

[53] https://www.emsc-csem.org/

— Relationships between damage states and risk states (i.e., *DS*/*LOC* matrices);

— Parameters and functions used in the consequence scenario analysis (i.e., release of hazardous substances, endpoint distances).

The RAPID-N calculation framework is shown in Figure 13 and it entails the following steps:

Step 1 – Exposed assets. Single or multiple hazardous sites (termed "industrial plants") are defined in RAPID-N based on the preferred scale of analysis (i.e., local or regional scale). The regional Natech risk analysis is the default option in RAPID-N. It relies on multiple hazardous sites located within a radial area from the earthquake epicentre. The default cut-off radius is 200 km, which can be adjusted according to the preferred geographical area for the risk analysis. A local Natech risk analysis can be performed when a single industrial plant is selected. Regardless of the analysis scale (local or regional), RAPID-N provides disaggregated Natech risk analysis results for each equipment (termed "plant unit") of the considered industrial plant(s) at all considered damage states.

Step 2 - Calculation of hazard intensity parameters. The PGA and the epicentral distance (i.e., distance of the plant unit location from the earthquake epicentre) are either retrieved from the available shakemaps (historic earthquakes), or evaluated from GMPEs that exist in the RAPID-N database or defined by the user.

Step 3 – Consequence analysis: estimation of structural damage (methodology Level 1). Based on the typology and properties of the plant unit, the most suitable fragility curve is selected from the RAPID-N database. For the given hazard intensity value (e.g., PGA) calculated in Step 2, the associated damage probability is extracted from the selected fragility curve for all considered DSs.

Step 4 – Consequence analysis: LOC and physical effects of Natech accident (methodology Level 2). In this step, the structural damage is related with a LOC event. Based on the type of the released hazardous substances from each plant unit, the most probable consequence scenario of a technological accident is identified (i.e., fire, explosion, or toxic dispersion). The resulting physical effects of thermal radiation or blast overpressure are evaluated using the functions in the RAPID-N database. Results are provided for (1) the released hazardous substances; (2) the probability of occurrence of this scenario conditioned on the damage state of each plant unit in the hazardous site(s); and (3) the endpoint distances of the physical effects for a given heat intensity value (fire consequence scenario) and/or a given overpressure value (explosion consequence scenario). By default, RAPID-N builds on the U.S. EPA guidance for offsite consequence analysis (U.S. EPA, 2009), considering two substance release scenarios, i.e.:

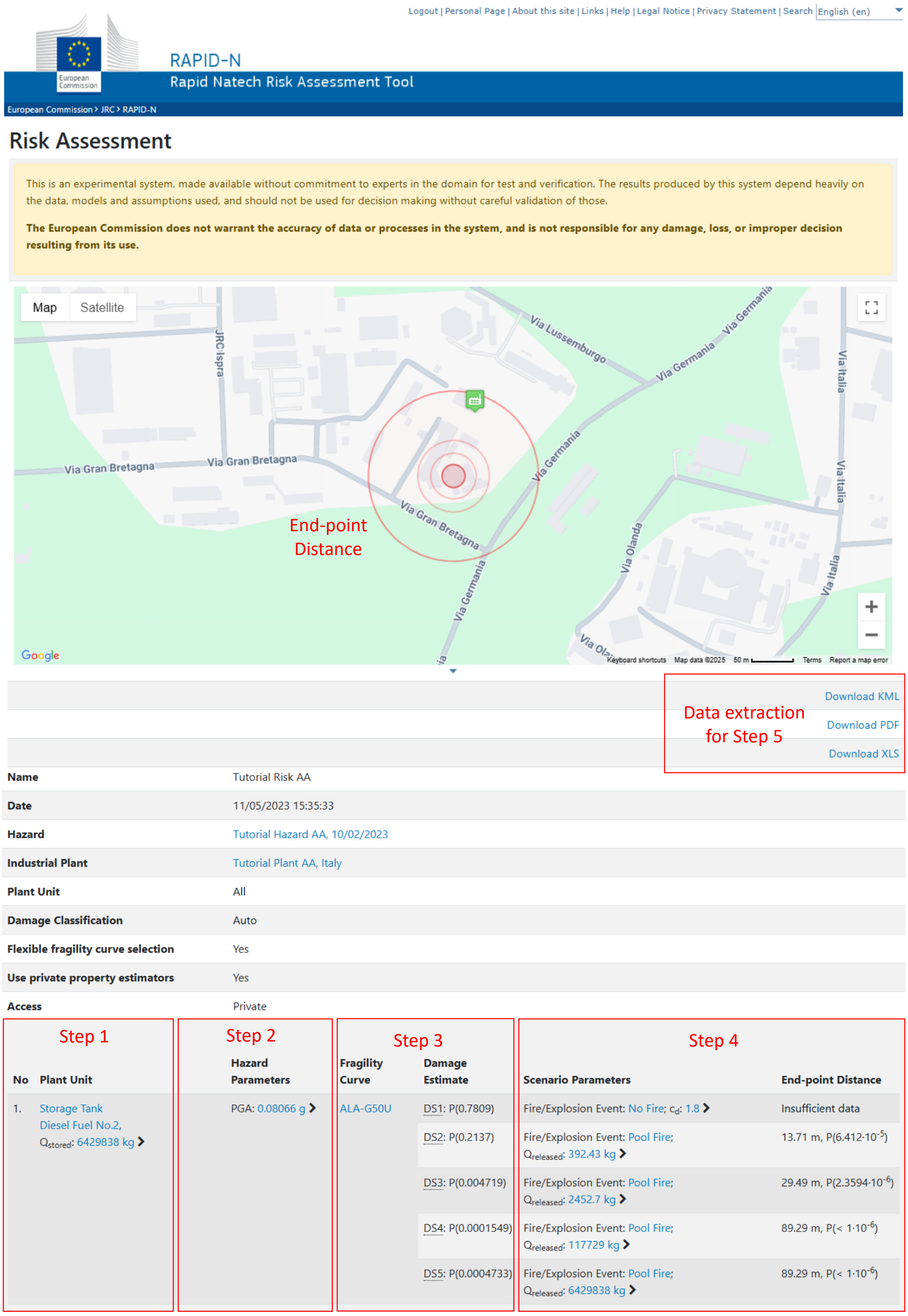
— **Worst-case release scenario**. This approach is associated with the release of the entire quantity of the stored substance in a relatively short time (i.e., 10 min release duration). This is a conservative approach for modelling the physical effects of toxic dispersion and vapour cloud explosion.

— **Alternative release scenario**. This approach entails the modelling of a substance release from a hole in a vessel or pipe. This is a less conservative approach for modelling the physical effects of pool fire, vapour cloud fire, and boiling liquid expanding vapour explosion.

For more advanced analyses, RAPID-N offers the option to assess the physical effects of Natech accidents using the ADAM consequence analysis tool (Fabbri et al. (2017), Necci and Carbunescu (2020)). The derived endpoint distances per damage state of each plant unit are mapped in interactive scenario-based risk impact zones.

Step 5 – Multiple analyses and data processing. Multiple analyses can be executed in RAPID-N to take into consideration: (1) the entire range of hazard intensity values in line with a site-specific hazard curve, and (2) a wide range of the risk analysis values associated with the determined physical effects (i.e., various heat intensity values or overpressure values for the case of fire or explosion consequence scenario, respectively). From the above analyses, the derived disaggregated data can be further processed by the user to complete the evaluation of the Natech risk for the given consequence scenario.

Figure 13. Natech risk analysis in RAPID-N.



Name	Tutorial Risk AA
Date	11/05/2023 15:35:33
Hazard	Tutorial Hazard AA, 10/02/2023
Industrial Plant	Tutorial Plant AA, Italy
Plant Unit	All
Damage Classification	Auto
Flexible fragility curve selection	Yes
Use private property estimators	Yes
Access	Private

No	Plant Unit	Hazard Parameters	Fragility Curve	Damage Estimate	Scenario Parameters	End-point Distance
1.	Storage Tank Diesel Fuel No.2, Q_{stored}: 6429838 kg	PGA: 0.08066 g	ALA-G50U	DS1: P(0.7809)	Fire/Explosion Event: No Fire; c_d: 1.8	Insufficient data
				DS2: P(0.2137)	Fire/Explosion Event: Pool Fire; $Q_{released}$: 392.43 kg	13.71 m, P($6.412 \cdot 10^{-5}$)
				DS3: P(0.004719)	Fire/Explosion Event: Pool Fire; $Q_{released}$: 2452.7 kg	29.49 m, P($2.3594 \cdot 10^{-6}$)
				DS4: P(0.0001549)	Fire/Explosion Event: Pool Fire; $Q_{released}$: 117729 kg	89.29 m, P($< 1 \cdot 10^{-6}$)
				DS5: P(0.0004733)	Fire/Explosion Event: Pool Fire; $Q_{released}$: 6429838 kg	89.29 m, P($< 1 \cdot 10^{-6}$)

Source: Excerpt from RAPID-N.

5 Case Studies: earthquake-triggered Natech accident in a non-civilian facility

The scope of this chapter is to demonstrate the implementation of the methodology detailed in the previous chapter and potentially support the UCPM scenario-building exercises for disaster management planning at Union level. Thus, site-specific case studies are carried out herein, considering the following three Natech scenarios.

— **Scenario 1**: This is a simplified case of an earthquake-triggered Natech accident in line with the direct Natech accident mechanism. According to this scenario, earthquake hazard cause direct damage to a diesel oil tank farm within a fictitious military facility. Due to structural damage, flammable materials are released, which are ignited under an ignition source, resulting into a pool fire event. This simplified scenario forms the basis, which is extended in subsequent scenarios for the simulation of the more complex Natech events.

— **Scenario 2**: Building on scenario 1, a multi-hazard Natech risk analysis is conducted due to cascading tsunami events triggered by earthquakes. Similarly as before, this scenario is associated with the direct Natech accident mechanism, as the diesel oil tank farm of the fictitious military facility is directly damaged by the cascading natural hazards. Two consequence scenarios are examined herein, i.e., the pool fire event and the substance dispersion event subject to the failure of a containment dike.

— **Scenario 3**: This is an extension of scenario 1 to qualitatively simulate the propagation Natech accident mechanism. At the vicinity of the seismically damaged tank farm, a magazine with explosives is assumed to exist. Following the fire event as per scenario 1, the magazine is assumed to be adversely affected by heat radiation, the physical effects of fire, which in turn triggers a domino event that results into massive explosions.

It is noted that the above scenarios are purely imaginary, and they serve no other purpose rather than the ones expressed herein.

5.1 Scenario 1: Earthquake-triggered Natech accident – direct impact mechanism

In this scenario, the methodology detailed in chapter 4 is used to perform a simplified Natech risk analysis in MATLAB. It is noted that RAPID-N tool was not used in this study, as it partially supports the probabilistic Natech risk analysis methodology detailed in chapter 4. As presented in section 4.5, a RAPID-N risk analysis is conducted for a single natural hazard intensity value (i.e., one PGA value for earthquake hazard trigger) and a single value for heat radiation intensity (in case of fire consequence scenario) and/or a single blast overpressure value (in case of explosion consequence scenario). However, a probabilistic Natech risk analysis requires the consideration of the entire range of natural hazard intensity values, as well as the entire range of for heat radiation intensity and/or blast overpressure values. This means that RAPID-N provides disaggregated Natech risk analysis data[54], which requires the execution of multiple RAPID-N risk analyses to sufficiently capture the

[54] The RAPID-N risk analysis terminates at the 2nd level of the consequences analysis as per the methodology described in chapter 4.

range of values of interest, followed by manual post-processing operations, by the user, on the RAPID-N output data. These computational limitations highlight areas for further improvement of the RAPID-N tool towards a comprehensive probabilistic Natech risk analysis framework for civilian and military facilities. To eliminate these limitations, the MATLAB software is used herein to mathematically simulate the probabilistic Natech risk analysis methodology of chapter 4, and obtain the required aggregated Natech risk analysis results in an automated way.

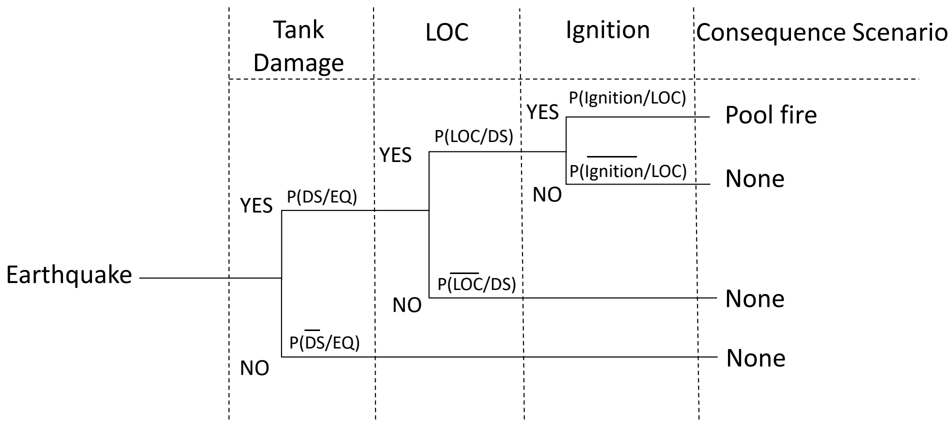
In this simplified scenario, a Natech accident is assumed to be triggered by seismic events, inducing direct structural damage to a fuel tank farm in a fictitious military facility (the direct Natech accident mechanism). A containment dike and leak collection tanks are also considered herein, which are used for the calculation of the pool fire area as per Eq. (4.13) under the pertinent consequence scenario. For the sake of simplicity, the potential failure of these safety systems is not considered in this case study. Similarly, no other safety and control system is considered, neither the potential impact to critical utility networks. The effect of the weather class and the wind direction are also ignored.

Figure 14 shows the event tree used for the Natech risk analysis, which comprises:

- The conditional probability of the simultaneous structural damage to the four storage tanks due to an earthquake event with a given intensity and probability of occurrence;
- The conditional probability of release of flammable diesel oil liquid (i.e., LOC) given the damage of the tanks;
- The conditional probability of ignition given the LOC;
- The most probable consequence scenario of pool fire given the ignition of the released substance.

In the event tree below, the conditional probability of a complementary event is denoted with an overbar. For example, the conditional probability $P(\overline{DS}/EQ)$ represents the probability of an intact/undamaged storage tank (i.e., damage state *DS*0) for a given earthquake event, which is mathematically expressed as $P(\overline{DS}/EQ) = 1 - P(DS/EQ)$.

Figure 14. Event tree for earthquake-triggered Natech risk analysis in a diesel oil tank farm.



5.1.1 Geographical area of site, exposed facility and equipment

Figure 15 shows the considered fictitious military base, which is assumed to be located on an island which is subject to high seismicity. The assumed topography, soil type, and atmospheric conditions are given in Table 4.

Table 4. Site conditions

Topography	Soil type	Ambient Temperature	Ambient Pressure	Relative Humidity	Wind Speed
Rural	Soft soil (type D, EC8)	25 °C	1 atm	50 %	5 m/s

Figure 15. Fictitious military facility (green shape) and four storage tanks in the fuel tank (red circles).

Source: Background map @ Google maps; excerpt from RAPID-N.

It is assumed that the fictitious military installation comprises a fuel tank farm with four identical steel atmospheric Storage Tanks (ST1, ST2, ST3, ST4) as shown in Figure 16. The in-between separation distance from the tank shell walls is 3.4 m (the centroid distance is 12.5 m). Each tank is a slender vertical cylinder with diameter D_t= 9.1 m (i.e., tank radius R_t=4.55 m), above ground height H_t= 15.2 m, and anchored at its base.

A concrete dike is assumed to exist, which acts as a passive risk mitigation measure, designed to contain oil spills and prevent their spread into the environment. Each storage tank is equipped with a leak collection tank of 25 m^3 capacity, while a secondary containment is assumed to be built around the entire tank farm with a capacity of V_{dike}=1,389.3 m^3. The external walls of the secondary containment are assumed to be H_{dike}= 1.2 m tall and placed at a distance of 5.5 m from the shell walls of the two external storage tanks in each direction, which is roughly 0.6 times the diameter of the tank; thus, the net bund area is A_{dike}= 1,157.8 m^2. It is noted that no design requirements have been taken into consideration for the assumed containment dike (i.e., its capacity and dimensions are heuristically defined herein). The plan view of the tank farm with the dike is presented in Figure 16 and the capacity of the containment system (i.e., leak collection tank and secondary containment) is reported in Table 5.

Figure 16. Fuel farm in fictitious military facility.

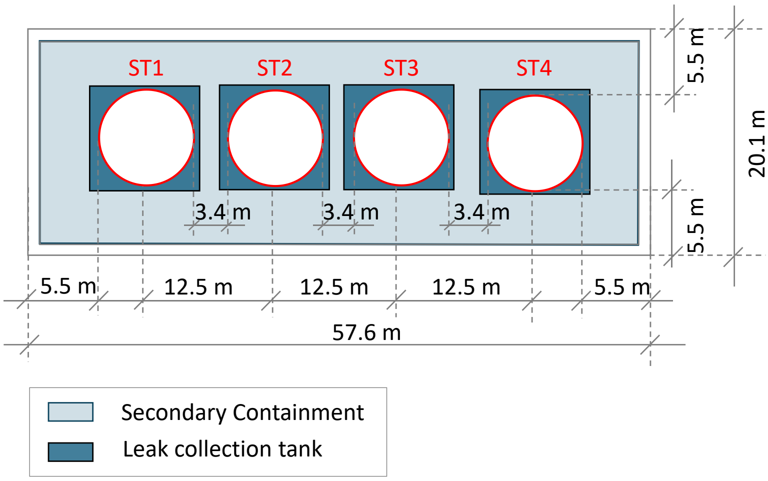


Table 5. Dike specifications

Containment	Capacity (m^3)
Leak collection tank	25
Secondary Containment	1,389.3

5.1.2 Inventory of hazardous substances

It is assumed that all storage tanks contain diesel fuel oil with a liquid filling height at h_f= 12.92 m, associated with a substance fill percentage at φ=85%. This assumption pertains to highly vulnerable storage tanks under seismic actions due to high tank-liquid mass that increases the inertial forces (i.e., worst case scenario). The slenderness ratio is $\frac{h_f}{R_t} = 2.84$ and the stored quantity in the tank farm is Q_{tot}=3,058,696 kg (i.e., Q=764,674.0 kg per storage tank). The fuel is stored at atmospheric conditions. The type and properties of the contained hazardous substance are reported in Table 6 and Table 7, respectively.

Table 6. Inventory of hazardous substances – scenario 1

Substance Name	CAS Number	EC Number	Substance State	Quantity (kg)
Diesel Fuel No.2	68476-34-6	270-676-1	Flammable liquid and vapour	3,058,696

Table 7. Properties of diesel fuel No.2

Mass density, ρ	Specific Heat of Vaporisation, H_v	Specific Heat of Combustion, H_c	Specific Heat capacity, c_p	Flash Point	Boiling Point, T_b	Melting Point
g/cm³	**kJ/kg**	**MJ/kg**	**kJ/kgK**	**°C**	**°C**	**°C**
[0.87, 0.95]	250	45	2.05	52	[282, 338]	[-30, -18]

5.1.3 Reference period and risk metric

The risk analysis is conducted for a reference period of one year.

The human health impact is selected as a risk metric, in line with regulations and guidelines on the exposure and effects after the release and dispersion of hazardous substances (U.S. EPA (2009), Purple Book (1999)).

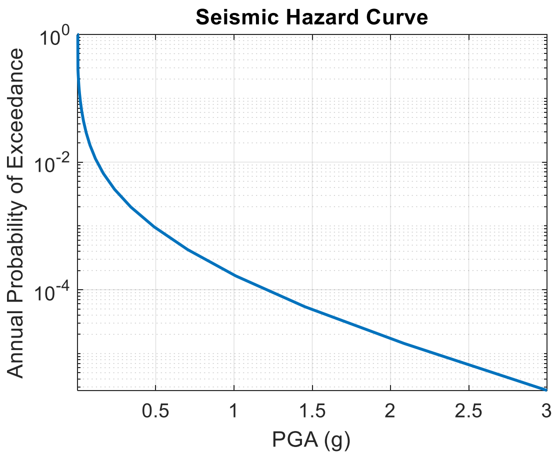
5.1.4 Seismic hazard

For the considered area, the site-specific seismic hazard curve is obtained from the EFEHR platform (http://hazard.efehr.org), using the recently developed European Seismic Hazard Model 2020 (ESHM20). Using the arithmetic mean, the retrieved seismic hazard curve pertains to rock site conditions and expresses the probability of exceedance of any given PGA value in 50 years ($P_{H,50y}$). For the selected reference period of one year, the following expression is used to compute the seismic hazard curve in terms of the annual probability of exceedance ($P_{H,1y}$), i.e.:

$$P_{H,1y} = 1 - e^{\left(\frac{\ln(1-P_{H,50y})}{50}\right)} \tag{5.1}$$

The derived seismic hazard curve is presented in Figure 17, where the x-axis comprises 25 discrete PGA values in the range [0.5 mg, 3.0 g] while y-axis presents the associated annual probability of exceedance in logarithmic scale.

Figure 17. Site-specific seismic hazard curve for the annual probability of exceedance



Source: EFEHR platform (http://hazard.efehr.org).

Indicatively, Table 8 reports the PGA values and the associated annual probability of exceedance for three seismic hazard return periods at 475 years, 2475 years and 4975 years.

Table 8. PGA and annually probability of exceedance for three seismic hazard return periods

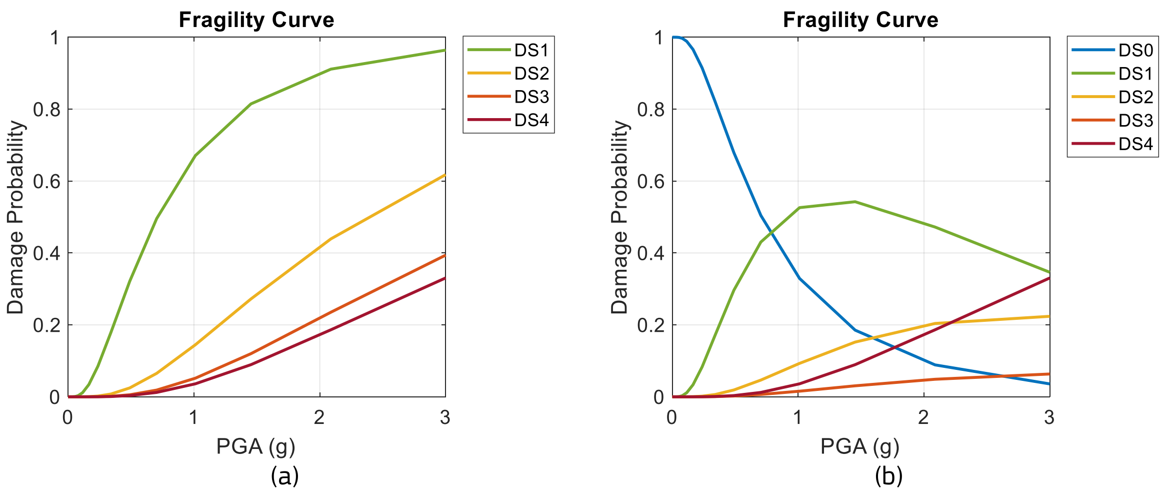
Return Period (y)	PGA (g)	$P_{H,1y}$
475	0.328	0.21 %
2475	0.721	0.04 %
4975	0.938	0.02 %

5.1.5 Consequence Analysis

5.1.5.1 Seismic fragility curves

A damage classification for storage tanks is adopted (FEMA, 2010), which entails four damage severity levels at damage states DS1 - DS4. These damage states correspond to sequential structural damage (i.e., a storage tank has been damaged at DS1 before reaching DS2, and so on for the other severity levels at DS3 and DS4). The considered damage states are reported in Table 9 together with a description of the associated loss of containment, which is based on engineering judgement. The "undamaged" state of the storage tanks is denoted as DS0. For the four considered damage states DS1 - DS4, Figure 18(a) presents the adopted fragility curves for anchored storage tanks with fill percentage at $\varphi \geq 50\%$ (American Lifelines Alliance, 2001). The fragility curves in Figure 18(a) express the probability of exceedance of a given damage state, *DSi*, conditioned on a given PGA value, $P(DS \geq DS_i|PGA)$, computed from Eq. (4.4) using the median and logarithmic standard deviation reported in Table 10. Using the expressions in Eq. (4.5), the associated discrete fragility curves, $P(DS = DS_i|PGA)$, are computed and plotted in Figure 18(b) for DS0 – DS4.

Figure 18. Seismic fragility curves: (a) cumulative and (b) discrete probability density functions.



Source: American Lifelines Alliance (2001).

Table 9. Sequential damage states for storage tanks (FEMA, 2010)

Damage State	Structural Damage	Loss of containment
DS0	No damage	no loss of containment
DS1	Minor damage, no loss of functionality	no loss of containment
DS2	Considerable damage	minor loss of containment
DS3	Severe damage	major loss of containment
DS4	Collapse	complete loss of containment

Table 10. Fragility curve for anchored storage tanks -median and logarithmic standard deviation (American Lifelines Alliance, 2001)

Damage State	**Median, θ_{DSi}**	**Standard deviation, β_{DSi}**
DS1	0.71	0.8
DS2	2.36	0.8
DS3	3.72	0.8
DS4	4.26	0.8

5.1.5.2 Loss of containment and consequence scenario

For each of the five considered structural damage states, DS0 – DS4, LOC scenarios are assumed, in line with the procedure outlined in the manual of the RAPID-N tool (Necci and Krausmann, 2022b). Table 11 gives the description of the considered *LOC* scenarios together with the conditional release probability for the associated *DS*.

Table 11. Loss of containment per damage state under earthquake hazard

Damage State	**LOC**	**Description**	**P_{EQ}(LOC/DS)**
DS0	LOC0	No release	0
DS1	LOC1	Leak, hole of equivalent 10 mm diameter, 10 min release duration	30%
DS2	LOC2	Minor release, hole of equivalent 25 mm diameter, 10 min release duration	50%
DS3	LOC3	Major release, hole equivalent to maximum diameter of connected pipes (assumed 100 mm), 30 min release duration	80%
DS4	LOC4	Instantaneous release of entire inventory (release duration 1 s)	100%

Source: Necci and Krausmann (2022b)

The substance release rate from a hole is computed from Eq. (4.7) where:

- A_h is the hole area associated with the hole diameter given in Table 11;
- $c_d = 0.61$ is the discharge coefficient for $A_h > 0.1\, mm^2$;
- *ρ= 0.91 g/*cm^3 is the average mass density of fuel oil;
- $g=9.81\ m/s^2$ is the acceleration of gravity;
- $h_{fh} = 12.92\, m (= h_f)$ is the substance filling level above the hole, which is taken equal to the substance filling level, h_f, under the assumption of the hole location at the bottom of the tank;

- P_s is the pressure inside the storage tank; and
- P_a is the atmospheric pressure (for atmospheric storage tanks $P_s = P_a = 1\ atm$).

The released quantity is computed from Eq. (4.8) for t_{rel} as per Table 11 and Q_{fl}= Q= 764,674.0 kg per storage tank (the hole is assumed to be located at the bottom of the tank). The released volume is next computed from Eq. (4.10) using the released quantity and the fuel oil mass density. For the catastrophic damage case and instantaneous release of the entire inventory, the released quantity is $Q_{rel} = Q$, which coincides with the release rate, computed from Eq. (4.8) by substituting the released duration of $t_{rel} = 1\ s$.

For the five considered pairs of *DS-LOC*, Table 12 gives the release rate, the release quantity, the released volume, and the annual probability of release per each storage tank. The total released quantity in the tank farm and the associated annual probability of release are further reported in Table 13.

Table 12. Release rate, released quantity and volume, and annual probability of release per storage tank for each DS/LOC –Scenario 1 earthquake hazard

Single storage tank					
Damage State	**LOC**	**Release rate**	**Released Quantity**	**Released Volume**	**Annual probability of release**
		q_{rel} (kg/s)	**Q_{rel} (kg)**	**V_{rel} (m^3)**	**λ_{rel}**
DS0	LOC0	0	0	0	0
DS1	LOC1	0.70	416.41	0.46	3.55E-04
DS2	LOC2	4.34	2,602.5	2.86	3.97E-05
DS3	LOC3	69.40	124,922	137.30	9.34E-06
DS4	LOC4	7.65 E+05	764,674	840.30	2.71E-05

Table 13. Released quantity and annual probability of release in the tank farm for each DS/LOC –Scenario 1 earthquake hazard

Tank Farm			
Damage State	**LOC**	**Released Quantity**	**Annual probability of release**
		Q_{rel} (kg)	**λ_{rel}**
DS0	LOC0	0	0
DS1	LOC1	1,665.64	1.42E-03
DS2	LOC2	10,410	1.59E-04
DS3	LOC3	499,688	3.74E-05
DS4	LOC4	3,058,696	1.08E-04

It is assumed that the fuel tank in the fictitious military facility stores Q_{tot}=3,058,696 kg of flammable diesel fuel in liquid state. In the event of a Natech accident, the release of the hazardous substance could potentially lead to pool fire under an ignition source. Based on the release rate, q_{rel}, in Table 12, the conditional ignition probability is obtained from Eq. (4.11) and reported further in Table 14.

Table 14. Conditional ignition probability per release rate

Damage State	**Loss of containment**	**Conditional probability of ignition**
DS$_i$	**LOC$_i$**	$P(S_{ign}\|LOC)$
DS0	LOC0	0
DS1	LOC1	1%
DS2	LOC2	3%
DS3	LOC3	8%
DS4	LOC4	8%

5.1.5.3 Physical effects and endpoint distances

Considering the above calculations on the release and ignition of flammable substances, the human health impact due to heat radiation (i.e., the physical effect of fire) is next computed. In this study, the heat radiation intensity takes values within the range $5 \leq Q_H(kW/m^2) \leq 35$. The lower limit of $Q_H = 5\ kW/m^2$ is the threshold value for irreversible injuries to people, e.g., second degree burns (Green Book, 1992). The upper limit of $Q_H = 35\ kW/m^2$ is the threshold value for ignition of buildings for an exposure time of 20 s, associated with a certain probability of death (P_E=100%) (Purple Book, 1999). For the considered range of heat radiation intensities, the associated endpoint distances are computed from Eq. (4.15) for:

- a radiative fraction of heat of combustion $RH_c = 0.4$;
- the specific heat combustion of diesel fuel $H_c = 45\ MJ/kg$;
- atmospheric transmissivity $\tau_a = 1$;
- the combustion rate for pool fire, q_c , which is computed from Eq. (4.16) for $T_b = 583\ K$ (the boiling point of diesel fuel, the average value from the range reported in Table 7), $H_v = 250\ kJ/kg$ (specific heat of vaporisation for diesel fuel), and $c_p = 2.05\frac{kJ}{kg\ K}$ (specific heat capacity for diesel fuel), and the pertinent values mentioned above.

Using Eq. (4.13) and Eq. (4.14), the pool fire area, A_p , is computed for $h_{p,min}$=1 cm, and substituted in Eq. (4.16). The obtained results are reported in Table 15.

Table 15. Pool fire area per damage state

Damage State	**Pool Fire Area**
	A_p (m^2)
DS0	0
DS1	45.76
DS2	285.99
DS3	1,157.8
DS4	1,157.8

Having defined the above quantities, the endpoint distances, d_e, are then computed for seven heat intensity values, Q_H, in range of $[5, 35]\ kW/m^2$ for all damage states of each storage tank. For the two limiting values, the computed endpoint distances are presented in Table 16. For the each storage tank, Figure 19 shows the maximum endpoint distance per damage state, which is associated with irreversible injuries to people for heat radiation at $Q_H = 5\ kW/m^2$ (lower threshold value). It is noted that the endpoint distance in DS4 (red dashed curve) coincides with the pertinent distance in DS3 (orange solid curve), in line with the values reported in Table 16. For the tank farm, the envelope of the pertinent endpoint distances is illustrated in Figure 20, which shows that the maximum endpoint distance for irreversible injuries occurs at $dx_{e,max}$= 152.51 m along the longitudinal direction (x-axis) and $dy_{e,max}$= 133.76 m along the lateral direction (y-axis).

Table 16. Endpoint distances per damage state for the lower and upper limits of the heat radiation- single storage tank

	Heat Radiation Q_H = 5 kW/m²	**Heat Radiation Q_H = 35 kW/m²**
Damage State	**Endpoint distance (m)**	**Endpoint distance (m)**
DS0	0	0
DS1	26.59	10.05
DS2	66.48	25.13
DS3	133.76	50.56
DS4	133.76	50.56

Figure 19. Endpoint distance per DS for irreversible damage at Q_H=5kW/m²; (a) ST1; (b) ST2; (c) ST3; (d) ST4.

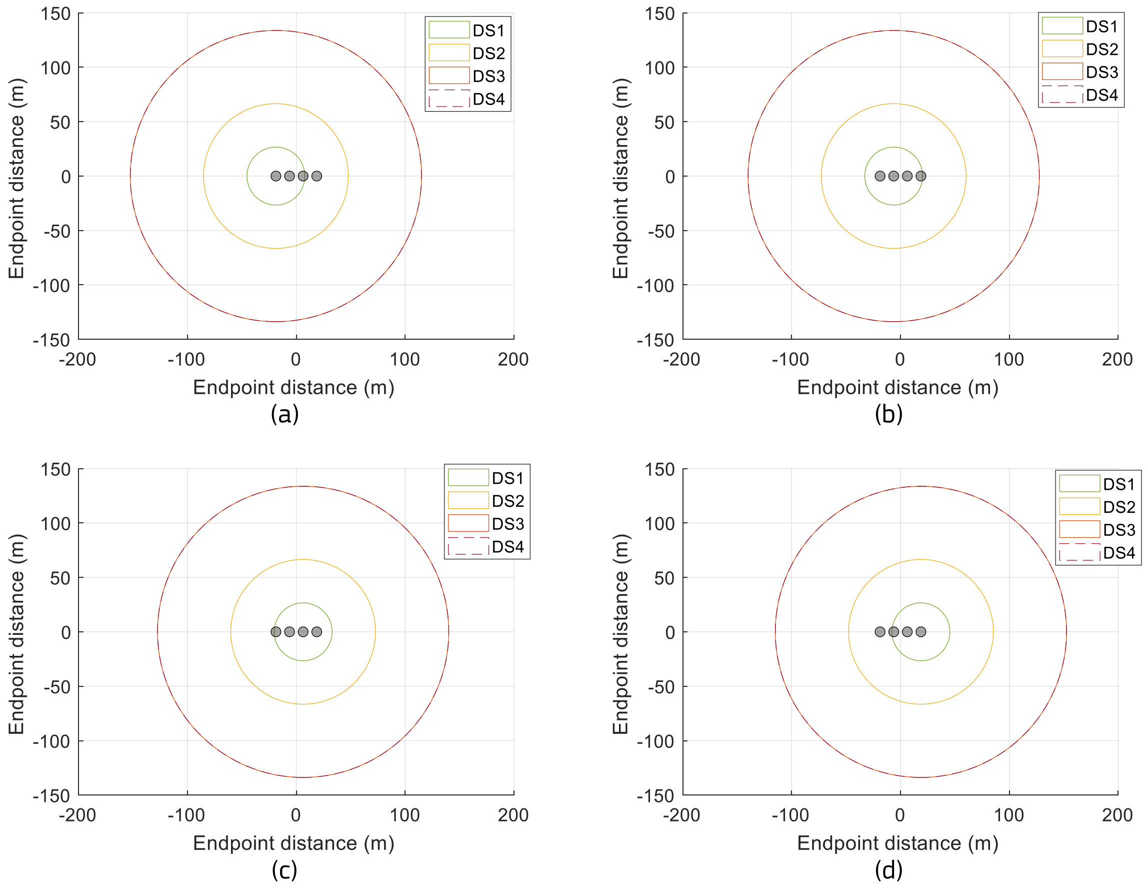
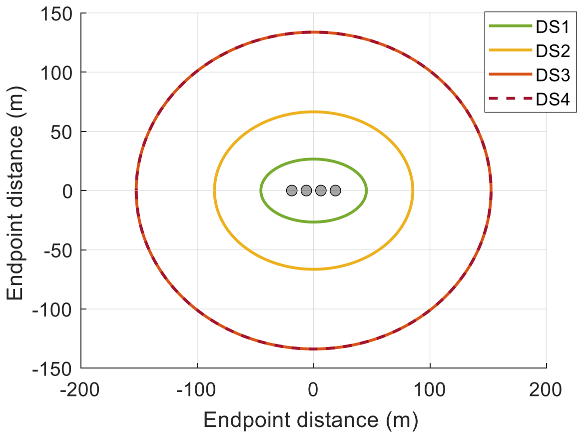


Figure 20. Envelope of endpoint distance in storage tank per DS for irreversible damage (Q_H=5kW/m^2)



5.1.6 Natech risk calculation

For the Natech risk analysis, each storage tank will be first analysed separately. For each structural damage state, DS0-DS4, the pertinent (discrete) fragility curve in Figure 18(b) is convolved with the seismic hazard curve in Figure 17 and multiplied with the conditional probabilities $P(LOC|DS)$ and $P(S_{ign}|LOC)$ in Table 11 and Table 14, respectively. To compute the annual probability of a Natech accident for each storage tank per each damage state, Eq. (4.24c) is replaced by Eq. (5.2) below, and substituted further in Eq. (4.34). The obtained results are presented in Table 17, where λ_{EQ}(Natech/ST/DS) denotes the annual probability of a Natech accident per each *ST* in each *DS*, triggered by earthquake (EQ) hazard.

$$P(C \geq c|DS_i, H) = \sum_{k=1}^{K} \sum_{j=1}^{M} P(S_k|LOC_j)\, P(LOC_j|DS_i, H) \qquad (5.2)$$

Table 17. Probability of Natech accident per damage state - single storage tank

Damage State	Annual Probability of Natech accident per ST in each DS λ_{EQ}(Natech/ST/DS) (y^{-1})
DS0	0
DS1	3.55 E-06
DS2	1.19 E-06
DS3	7.47 E-07
DS4	2.17 E-06

To account for all damage states per storage tank, the associated annual probability of a Natech accident is computed as

$$\lambda_{EQ}(Natech/ST) = \sum_{i=0}^{4} \lambda_{EQ}(Natech/ST/DS_i) = 7.66\ E - 06\ \ y^{-1}$$

For the tank farm, the above annual probability is easily extended to the following expression considering the simultaneous release of diesel fuel from the four storage tanks, i.e.:

$$\lambda_{EQ}(Natech) = \sum_{i=1}^{4} \lambda_{EQ}(Natech/ST_i) = 3.06\,E-05\;\;y^{-1}$$

To evaluate the loss in terms of human health impact (i.e., the lethal effects due to the human exposure to heat radiation for a maximum duration of 20 s), the probability of death, P_E, is computed from Eq. (4.27) for seven heat radiation values in the range of interest, i.e., $Q_H \in [5, 35]\; kW/m^2$, and $t = 20\; s$ (i.e., individual risk). The obtained results are presented in the fifth column of Table 18. These values are multiplied with the annual probability of a Natech accident in the tank farm (i.e., $\lambda_{EQ}(Natech) = 3.06\,E-05\;\;y^{-1}$), to derive the individual risk, which is reported in the last column of Table 18. It is noted that these aggregated Natech risk analysis results would have been obtained from the post-processing of data derived from 175 risk analyses in the RAPID-N tool (i.e., seven analyses for the considered range of heat intensity values, each performed 25 times for all PGA values of the site-specific seismic hazard curve in Figure 17). However, the use of the RAPID-N tool was excluded due to the limitations explained at the beginning of this section.

The individual risk contour plots are presented in Figure 21, considering the maximum endpoint distances along the longitudinal and lateral direction reported in the third and fourth column of Table 18.

Table 18. Maximum endpoint distances and individual risk for various heat radiation levels

	Heat Radiation	**Maximum horizontal endpoint distance**	**Maximum vertical endpoint distance**	**Individual Risk due to Heat Radiation**	**Individual Risk due to Natech**
	Q_H (kW/m²)	**dx_e (m)**	**dy_e (m)**	**Death Probability P_E**	**Annual Probability of death λ_E (Natech) (y^{-1})**
Irreversible injuries	5	152.51	133.76	1.75E-06	5.36E-11
Death	10	113.33	94.58	0.01	3.53E-07
	15	95.98	77.23	0.19	5.73E-06
	20	85.63	66.88	0.54	1.64E-05
	25	78.57	59.82	0.80	2.46E-05
	30	73.36	54.61	0.93	2.85E-05
	35	69.31	50.56	1.00	3.06E-05

Table 18 and Figure 21 show that a pool fire event due to an earthquake-triggered Natech accident in the military tank farm is associated with an annual individual risk of death in the range of [3.06 E-05, 3.53 E-07] for Q_H=[10, 35] kW/m². As denoted with the red areas in Figure 21, the highest individual risk (λ_E(Natech)=3.06 E-05 y^{-1}) occurs at the highest heat radiation value (Q_H=35 kW/m²), which is found at a radial distance up to roughly 70 m away from the military tank farm (i.e., the source of fire). At higher distances, the annual individual risk of death is gradually decreasing, reaching the lowest rate of λ_E=3.53 E-07 y^{-1} for Q_H=10 kW/m² at a radial distance of roughly 115 m from the tank farm. At greater distances and up to 153 m, approximately, there is no further danger of individual risk of death for heat radiation intensity at around Q_H=5 kW/m². Nonetheless, people can suffer from irreversible injuries due to second degree burns, which is associated with an annual probability of λ_E(Natech)=5.36 E-11 y^{-1}. As readily observed in Figure 21, the risk of death is mostly limited within the site boundaries of the military base, while irreversible injuries to people could also be incurred at a relatively small coastal area outside the site.

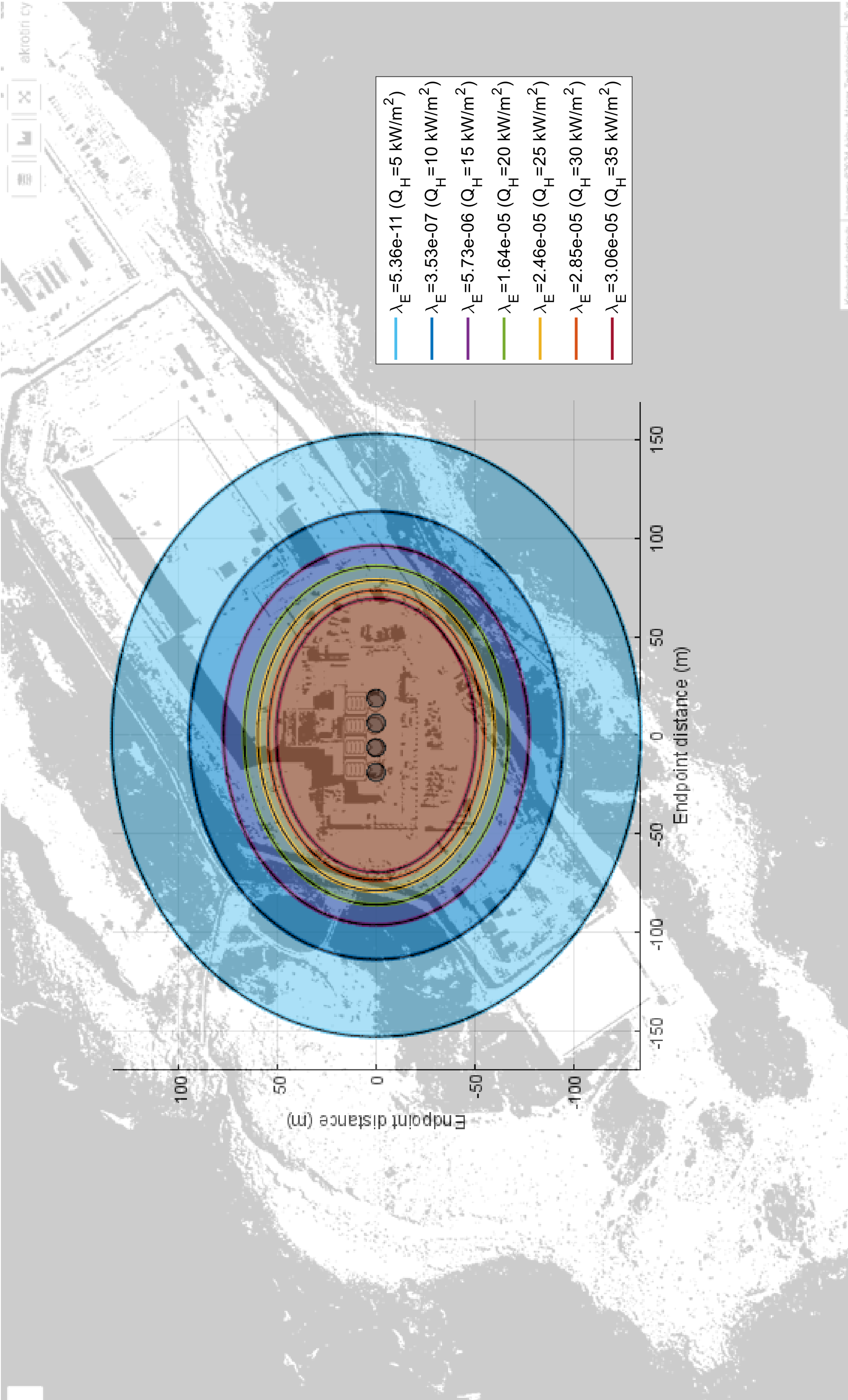
According to the ISO Standards ISO 31000:2018(E), a complete Natech risk assessment would further include the risk evaluation step, i.e., the decision-making process based on established risk acceptance criteria, a task that falls in the remit of Member States or other stakeholders. In this case study, risk acceptance criteria are not established but recommendations are provided for the mitigation of the consequences and the reduction of the annual risk of death and irreversible injuries. To achieve this goal, the storage tanks liquid filling level should be reduced, which is beneficial for two reasons:

(i) it would improve the seismic performance of the storage tanks as the reduced liquid mass would result in smaller inertial forces exerted on them; and

(ii) the quantity of the potentially released substances would reduce, limiting the extend of pool fire consequences and reducing further the associated risks.

Another recommendation is the seismic retrofit of the storage tanks to increase their robustness, thus reducing their seismic vulnerability. Both these measures (lower filling level and seismic retrofit) would improve the fragility curves of Figure 18, leading to lower damage probabilities under the same seismic intensity values, ultimately reducing the adverse consequences to human health. It is also recommended the use of appropriate safety measures, such as fire suppression systems to extinguish the fire as promptly as possible, and the use of sandbags to absorb spills and prevent their spread. In case the above options are not possible, the re-location of the military facility would be recommended. This would be based on land-use planning by taking into consideration locations that pertain to lower seismic intensity and are found away from residential areas.

Figure 21. Individual risk contour plot for Natech accident in the tank farm



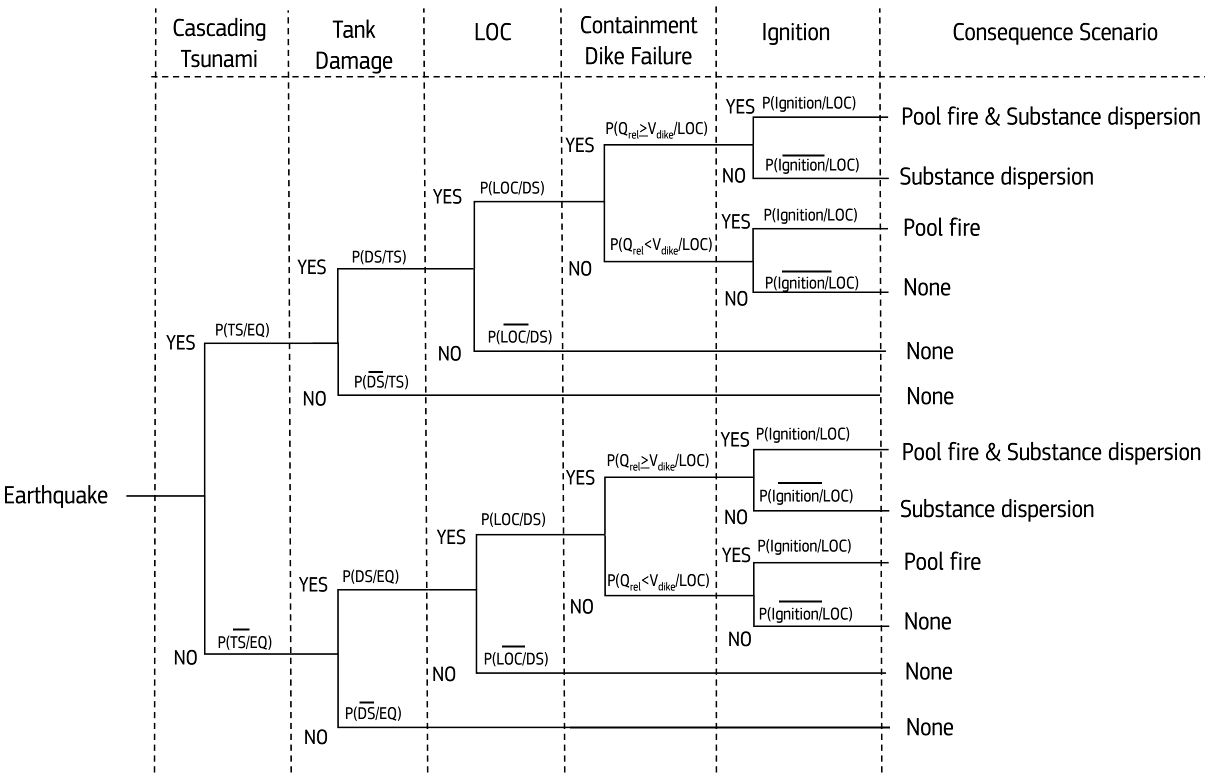
Source: Background map @ Google maps.

5.2 Scenario 2: Multi-hazard Natech risk analysis under earthquake and tsunami

In this case study, a multi-hazard Natech risk analysis scenario is developed to account for the direct Natech accident mechanism subject to cascading natural hazards. This case study builds upon the scenario 1 (section 5.1) and takes into consideration two additional elements in the Natech risk analysis:

1. Cascading tsunami events triggered by earthquakes.
2. The potential failure of the containment dike[55] (the passive risk mitigation measure).

Figure 22. Event tree for cascading multi-hazard Natech risk in a diesel oil tank farm.



By integrating the above considerations into the event tree of Figure 14, this is expanded to the one shown in Figure 22, which comprises the following events:

- The conditional probability of a cascading tsunami triggered by an earthquake event of a given intensity and probability of occurrence.
- The conditional probability of structural damage to the four storage tanks due to the occurrence of the multi-hazard event.

[55] A containment dike is designed to prevent spills of hazardous materials into the environment. When it fails to perform its intended purpose due to overfill or structural damage, this is regarded as "failure" of a containment dike. A "catastrophic failure" would imply the complete structural damage (e.g., collapse) of the dike.

— The conditional probability of release of flammable liquid diesel oil (i.e., LOC) given the damage of the tanks.

— The conditional failure probability of the containment dike in case of exceedance of its capacity to contain the released substances.

— The conditional probability of ignition given the release of flammable liquids (diesel oil).

— The consequence scenario of substance dispersion conditioned on the failure of the containment dike, or the consequence scenario of pool fire conditioned on the ignition of the released substance, or the combination of both consequence scenarios.

In this case study, the effect of the weather class and the wind direction are ignored. Further, the potential impact of the cascading natural hazards to critical utility networks is not taken into consideration.

5.2.1 Geographical area of site, exposed facility and equipment

The considered fictitious military facility (Figure 15) is located at a coastal area, which is also prone to cascading tsunami hazards triggered by undersea earthquakes (below or near the ocean floor) that induce the sudden displacement of large volumes of water.

Similarly to scenario 1, it is assumed that a fuel tank farm exists in the military installation, which comprises the four storage tanks (ST1, ST2, ST3, ST4) in Figure 16, which are filled with diesel oil. As detailed in section 5.1.1, the same geometrical characteristics of the tanks are assumed herein (i.e., slender vertical cylinders anchored at the base, D_t= 9.1 m diameter, H_t= 15.2 m above ground height).

It is estimated that the minimum distance of the tank farm from shore is approximately 90 m. This distance is important to determine the attenuation of the tsunami wave height and the associated inundation depth at the site location. However, the wave height attenuation is neglected in this study due to the absence of more detailed information on the terrain landscape and the propagation of the tsunami waves. Despite this limitation, this consideration can be regarded as a worst-case scenario associated with more conservative tsunami risk analysis results, which is towards the safety side.

5.2.2 Inventory of hazardous substances

A substance filling level at φ=50% is assumed per storage tank, which was selected as an intermediate percentage value to simulate vulnerable storage tanks under both considered natural hazards (earthquakes and tsunamis). It is noted that the storage tank vulnerability strongly depends on the substance filling level, observing a trade-off under seismic and tsunami hazards. Under seismic ground motions, the higher liquid filling level leads to more vulnerable storage tanks due to increased inertial forces, resulting from the higher tank-liquid mass. On the contrary, under tsunami waves, storage tanks become less vulnerable as the liquid filling level is increasing. This is attributed to higher weight of the tanks, which is primarily driven by the weight of the contained substance, leading to increased friction forces that contribute to higher resistance against buoyance and drag tsunami forces.

The considered substance filling level at φ=50% pertains to a liquid filling height at h_f=7.60 m, and slenderness ratio $\frac{h_f}{R_t} = 1.67$. The stored quantity in the tank farm is Q_{tot}=1,799,232 kg (i.e., Q=449,808.0 kg per storage tank). The inventory of the contained fuel is reported in Table 19 while the associated properties of the substance are given in Table 7.

Table 19. Inventory of hazardous substances – scenario 2

Substance Name	CAS Number	EC Number	Substance State	Quantity (kg)
Diesel Fuel No.2	68476-34-6	270-676-1	Flammable liquid and vapours	1,799,232

5.2.3 Reference period and risk metric

Similarly to scenario 1, a reference period of one year is selected for the multi-hazard Natech risk analysis. Further, a quantitative probabilistic risk analysis is conducted for the individual risk due to the physical effect of heat radiation under the consequence scenario of pool fire. For the substance dispersion consequence scenario, the associated annual probability of occurrence is computed while a qualitative description is provided for the environmental contamination risk due to the release of diesel oil into water body and land.

5.2.4 Seismic and tsunami hazard

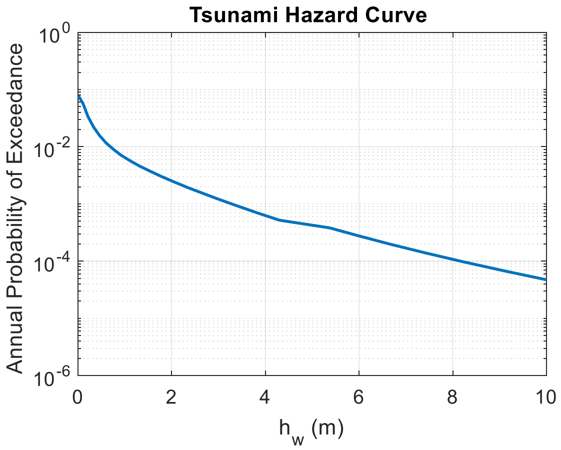
Similarly to scenario 1, the considered site-specific seismic hazard curve is shown in Figure 17, which expresses the annual probability of exceedance, $P_{H1,\mathrm{1y}}$, of any given PGA value. As detailed in section 5.1.4, this seismic hazard curve is retrieved from the EFEHR platform (http://hazard.efehr.org), using the ESHM20 model, and treated with Eq. (5.1) to account for the selected reference exposure period of one year. For more information, the interested reader is referred to section 5.1.4.

For onshore/inland critical infrastructure, **tsunami hazard intensity** can be characterised by the following quantities, i.e.: (i) inundation depth, (ii) flow velocity, and (iii) momentum flux, i.e., a measure of the energy flux per unit area. These quantities are associated with hydrostatic and hydrodynamic forces that are exerted onto structures (e.g., ASCE7-22).

In this case study, the site-specific tsunami hazard curve is obtained from the TSUMAPS-NEAM platform (https://tsumaps-neam.eu/neamthm18/), using the recently developed probabilistic tsunami hazard model NEAMTHM18. From the interactive map in the considered platform, the tsunami hazard is retrieved from the point of interest nearest to the coordinates of the examined military base (Figure 15). The retrieved mean tsunami hazard curve is expressed as the probability of exceedance of any given inundation depth, h_w, for the exposure time of 50 years, $P_{H2,\mathrm{50y}}$. The NEAMTHM18 model provides tsunami hazard curves with respect to inundation depths, while the flow velocity and momentum flux intensity measures are not take into consideration, which are further ignored in this study. The tsunami hazard curves in the TSUMAPS-NEAM platform are available for inundation depths up to 100 m. However, an upper limit value of h_w = 10 m is selected herein, which is based on the assumption that the tank is submerged for a maximum tsunami height level at around the substance filling height, i.e., at h_f = 7.60 m. Eq. (5.1) is further used to compute the tsunami hazard curve $P_{H2,\mathrm{1y}}$ in terms of the annual probability of exceedance versus h_w in the range [0, 10] m. The derived curve is shown in Figure 23. Indicatively, Table 20 gives the h_w values and their associated annual probability of exceedance for three return periods at 475 years, 2475 years and 4975 years.

It is noted that the same tsunami hazard curve is considered for the four storage tanks in the tank farm of the military facility. A more refined analysis would require the consideration of different tsunami waves landing on each storage tank, based on the associated distance from the shore and the wave attenuation due to their propagation. However, this is not taken into consideration in this case study due to the absence of relevant information, as explained in section 5.2.1.

Figure 23. Site-specific tsunami hazard curve for annual probability of exceedance and inundation depth in the range [0, 10] m.



Source: NEAM Tsunami Hazard Model 2018 (https://tsumaps-neam.eu/neamthm18/).

Table 20. Inundation height, h_w, and the annually probability of exceedance for three tsunami hazard return periods

Return Period (y)	**h_w (m)**	$P_{H2,1y}$
475	2.23	0.21 %
2475	5.21	0.04 %
4975	12.40	0.02 %

5.2.5 Consequence Analysis

5.2.5.1 Seismic and tsunami fragility curves

Under the earthquake hazard, the seismic fragility curves detailed in sub-section 5.1.5.1 are also adopted herein. Seismic fragility curves are considered for anchored storage tanks with fill percentage at $\varphi \geq 50\%$ (American Lifelines Alliance, 2001). Figure 18(a) and Figure 18(b) show, respectively, the cumulative and discrete probability density functions of the considered seismic fragility curves at four damage states, DS1-DS4. The description of the four DS and the associated loss of containment are given in Table 9.

Under the tsunami hazard, storage tanks can be structurally damaged due to either tsunami forces (buoyance and drag forces) or impact forces originating from floating debris. Tsunami hazard can also adversely affect the soil stability, leading to soil erosion and scouring of the tanks foundation support. In this case study, the following tsunami-induced failure mechanisms of storage tanks are considered, i.e.:

— **Tank failure due to shell wall buckling (DS1).** This tank failure occurs when net pressure on the tank shell wall reaches a critical value, which is an inherent property of the vessel and depends on the construction material (i.e., steel), and the geometrical properties (diameter, wall thickness) of the tank (Timoshenko and Gere, 1961). The net pressure is determined by the equilibrium of horizontal forces acting on the tank shell, i.e., external hydrostatic and hydrodynamic tsunami forces, and internal hydrostatic forces from the contained substance in the tank.

— **Tank uplift (DS2)**. This failure mechanism occurs when anchors fail in tension due to tsunami buoyancy forces that overcome the vertical resistance of anchors and the weight of the tank (i.e., tank self-weight and weight of the stored substance).

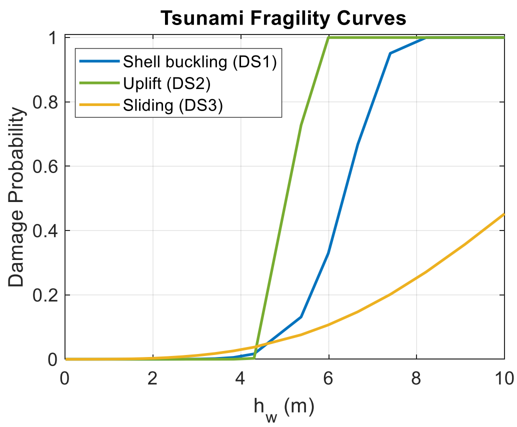
— **Tank sliding (DS3)**. This occurs under the shear failure of anchors due to tsunami drag forces that overcome the horizontal tank resistance coming from the anchors and the frictional forces.

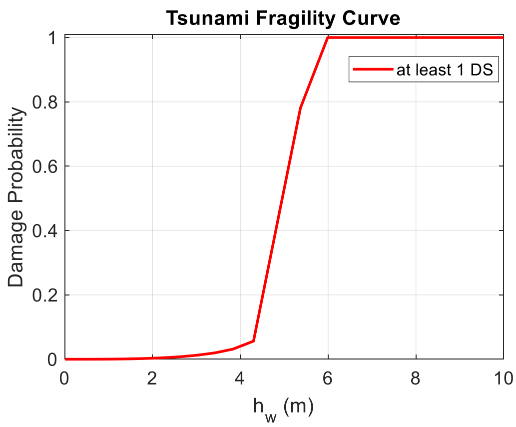
Tsunami fragility curves for slender tanks are used, which have been analytically derived from the Weibull distribution considering the above three damage states conditioned on the substance filling level, φ, and the tank submersion, expressed by the ratio h_w/h_f (Vitale, 2024). For the fixed substance filling level at φ=50%, Figure 24(a) shows the derived tsunami fragility curves, which are expressed as the probability of exceedance of a given damage state, *DSi*, i.e., $P(DS \geq DS_i|H = h_w)$, for any given tsunami inundation depth, h_w, in the range [0, 10] m. The Figure 24(b) illustrates the fragility curve for the probability of at least one tank failure mechanism occurring due to tsunami hazard, which is given from the following expression

$$P(DS|H = h_w) = 1 - \prod_{i=1}^{3}\left(1 - P(DS_i|H = h_w)\right) \tag{5.3}$$

In the above equation, *i*=[1, 2, 3], which is associated with the tsunami damage states at DS1, DS2, and DS3, respectively. The tsunamic fragility curve in Figure 24(b) is used hereafter, assuming that it corresponds to considerable tank damage.

Figure 24. Tsunami fragility curves for inundation depth in the range [0, 10] m.





Source: Vitale (2024)

5.2.5.2 Loss of containment and consequence scenarios

Under the earthquake hazard, the same procedure is followed as detailed in section 5.1.5, considering Table 11 and the conditional release probability for each DS_i, i.e., $P_{EQ}(LOC/DS_i)$.

Under the tsunami hazard, it is assumed that a major loss of containment would occur under any of the three failure mechanisms, DS1 – DS3, due to rupture of tanks connections with the piping systems, which is equivalent to LOC3 in Table 11 (i.e., major release associated with a hole equivalent to maximum diameter of connected pipes and 30 min release duration). Table 21 gives the conditional release probability for the tank failure when at least one structural damage is induced from tsunami (TS) water forces.

Table 21. Loss of containment per damage state under tsunami hazard

Damage State	**LOC**	**Description**	**P_{TS}(LOC/DS)**
DS	LOC3	Major release, hole equivalent to maximum diameter of connected pipes, 30 min release duration	80%

Source: Necci and Krausmann, (2022b) for earthquake hazard

For the two natural hazards, Table 22 gives the release rate, the released quantity and volume, and the annual probability of release for a single storage tank in the considered DSs. Similarly, Table 23 reports the released quantity, volume, and annual probability of release for the tank farm.

Table 22. Release rate, released quantity and volume, and annual probability of release per storage in each DS/LOC –Scenario 2

Single storage tank						
Natural Hazard	**Damage State**	**LOC**	**Release rate**	**Released Quantity**	**Released Volume**	**Annual probability of release**
			q_{rel} (kg/s)	**Q_{rel} (kg)**	**V_{rel} (m^3)**	**λ_{rel} (y^{-1})**
Earthquake	DS0	LOC0	0	0	0	0
	DS1	LOC1	0.53	319	0.35	3.55E-04
	DS2	LOC2	3.33	1,996	2.19	3.97E-05
	DS3	LOC3	53.23	95,811	105.29	9.34E-06
	DS4	LOC4	4.50 E+05	449,808	494.30	2.71E-05
Tsunami	DS	LOC3	53.23	95,811	105.29	3.66 E-04

Table 23. Released quantity and volume, and annual probability of release in the tank farm per DS/LOC – Scenario 2

Tank Farm					
Natural Hazard	**Damage State**	**LOC**	**Released Quantity**	**Released Volume**	**Annual probability of release**
			Q_{rel} (kg)	**V_{rel} (m^3)**	**λ_{rel} (y^{-1})**
Earthquake	DS0	LOC0	0	0	0
	DS1	LOC1	1,277	1.40	1.42E-03
	DS2	LOC2	7,984	8.77	1.59E-04
	DS3	LOC3	383,244	421.16	3.74E-05
	DS4	LOC4	1,799,233	1977.2	1.08E-04
Tsunami	DS	LOC3	383,244	421.16	1.46 E-03

5.2.5.2.1 Consequence scenario: substance dispersion

Focusing on the tank farm under earthquake hazard, it is readily observed that the released volume due to the damage of the storage tanks in damage states DS1 and DS2 is below 25 m^3, which indicates that the oil spill is contained at the leak collection tank. When the storage tanks are damaged at DS3, the released volume exceeds the capacity of the leak collection tank but it remains below the capacity of the dike, V_{dike}=1,389.3 m^3, suggesting that the oil spill would remain within the secondary containment. However, under the catastrophic tanks failure in DS4, it is expected that diesel oil will spill over the dike as the released volume would exceed the capacity of the secondary containment by 587.9 m^3. Thus, in case of catastrophic tank failure, the substance would disperse in water bodies and land, which is associated with a certain event with a conditional probability of dispersion $P_{EQ}(S_{disp}|LOC4)$=100%. For all other DSs (i.e., DS1, DS2, DS3), the dispersion of the released substance is an unlike event due to the presence of the containment dike, which pertains to a conditional probability of dispersion $P_{EQ}(S_{disp}|LOCi) = 0$, where i=[0, 1, 2, 3].

Under the tsunami hazard, it is assumed that the tanks are severely damaged, leading to major substance releases. The released volume exceeds the capacity of the leak collection tank but it remains below the capacity of the dike (equivalent to the case DS3-LOC3 under earthquake hazard). It is likely, though, that the containment dike would fail when the tsunami inundation height is greater than the height of the dike wall (i.e., H_{dike}= 1.2 m), in which case the tsunami waters would act as a dispersion vector of the released oil, contaminating a larger area of water bodies and land. In this respect, a conditional probability of dispersion is obtained from the following expression

$$P_{TS}(S_{disp}|LOC3) = \begin{cases} 0\%, & h_w < 1.2\,m \\ 100\%, & h_w \geq 1.2\,m \end{cases} \tag{5.4}$$

The above information is summarised in Table 24.

Table 24. Conditional probability of substance dispersion– Scenario 2

Natural Hazard	**Damage State**	**LOC**	**Conditional probability of oil dispersion**
			$P(S_{disp}\|LOC)$
Earthquake	DS0, DS1, DS2, DS3	LOC0, LOC1, LOC2, LOC3	0 %
	DS4	LOC4	100 %
Tsunami	DS	LOC3	0 % or 100 %

5.2.5.2.2 Consequence scenario: pool fire

Regarding the consequence scenario of pool fire, this depends on the probability of ignition of the released flammable substance (diesel oil) for all considered DSs under earthquake and tsunami hazards. This conditional probability is a function of the release rate, q_{rel}, as expressed in Eq. (4.11). For the examined case, the release rate, q_{rel}, and the associated conditional probability of ignition are reported in Table 25 for each structural damage state/loss of containment.

Table 25. Conditional probability of ignition – Scenario 2

Natural Hazard	Damage State	LOC	Release rate	Conditional probability of ignition
			$q_{,rel}$ (kg/s)	$P(S_{ign} \vert LOC)$
Earthquake	DS0	LOC0	0	0%
	DS1	LOC1	0.53	1%
	DS2	LOC2	3.33	3%
	DS3	LOC3	53.23	8%
	DS4	LOC4	4.50 E+05	8%
Tsunami	DS	LOC3	53.23	8%

5.2.5.3 Physical effects and endpoint distances

5.2.5.3.1 Consequence scenario of substance dispersion

To evaluate the endpoint distances for the consequences scenario of substance dispersion, a dispersion model is required to simulate the spread of oil spills with tsunami water. In the absence of such model herein, the environmental risks due to contamination of land and waters are qualitatively assessed and endpoint distances are not computed.

5.2.5.3.2 Consequence scenario of pool fire

For the consequence scenario of pool fire, the procedure described in section 5.1.5.3 is considered to evaluate the human health impact due to the release and ignition of diesel oil. For the two considered natural hazards, Table 26 reports the pool fire area, A_p, per damage state, which is computed from Eqs. (4.13), (4.14) for $h_{p,min}$=1 cm. These values are substituted in Eq. (4.16) together with the diesel oil properties in Table 7, and Eq. (4.15) is further used to compute the endpoint distances for heat radiation intensity values in the range of $[5,\ 35]\ kW/m^2$.

Table 26. Pool fire area per damage state

Natural Hazard	Damage State	Pool Fire Area
		A_p (m^2)
Earthquake	DS0	0
	DS1	35.10
	DS2	219.35
	DS3	1,157.8
	DS4	1,157.8
Tsunami	DS	1,157.8

The obtained results are reported in Table 27. Similarly to Scenario 1, the considered Natech accident in the tank farm pertains to the maximum endpoint distance obtained from the envelope curve as per Figure 20, which corresponds to $dx_{e,max}$= 152.51 m, $dy_{e,max}$= 133.76 m along the the longitudinal and transerse direction, respectively, for irreversible injuries to people due to second degree burns (i.e., $Q_H = 5\ kW/m^2$). It is noted that the computed endpoint distances do not take into consideration any potential consequences due the substance dispersion in water bodies and land. This less conservative approach also ignores the potential stratification of flammables on tsumani waters and their ignition, which can act as a vector of dispersion of fires with tsunami waters, creating a major secondary hazard for military personnel and assets (infrastructure, equipment, hazardous content), as well as emergency responders and operations.

Table 27. Endpoint distances per damage state for the lower and upper limits of the heat radiation- single storage tank

		Heat Radiation Q_H = 5 kW/m^2	Heat Radiation Q_H = 35 kW/m^2
Natural Hazard	**Damage State**	**Endpoint distance (m)**	**Endpoint distance (m)**
Earthquake	DS0	0	0
	DS1	23.29	8.80
	DS2	58.22	22.05
	DS3	133.76	50.56
	DS4	133.76	50.56
Tsunami	DS	133.76	50.56

5.2.6 Single-hazard Natech risk calculation

In this section, Natech risk analysis is conducted for a single natural hazard triggering event. Thus, Natech risk analysis results are obtained separately for earthquake and tsunami hazards. The obtained results will be combined in section 5.2.7 to evaluate the multi-hazard Natech risk. This is a simplified approach that is typically considered in the literature to approximate Eq. (4.36) when the conditional probability density function of two natural hazards (i.e., $f_c(H_1, H_2)$ for hazards H_1 and H_2) is unknown.

5.2.6.1.1 Consequence scenario of substance dispersion

This section presents results in terms of the probability of occurrence of a Natech accident with the physical consequences of oil dispersion into water and land. These results are computed separately for the seismic and tsunami hazard. It is assumed that the cascading tsunami event occurs almost at the same time as the seismic event, which is a simplification of the interaction phenomenon between the two events.

For the earthquake hazard, the same procedure is followed as per section 5.1.6 (scenario 1). Given that this consequence scenario occurs due to the catastrophic tank failure, only the (discrete) fragility curve in DS4 is considered as per Figure 18(b), which is convolved with the seismic hazard curve in Figure 17 and multiplied with the conditional probabilities $P_{EQ}(LOC|DS)$ and $P_{EQ}\left(S_{disp}\middle|LOC\right)$ in Table 11 and Table 24, respectively. Using Eq. (4.34) and Eq. (5.2) for DS_i = DS4, the annual probability of an earthquake-triggered Natech is derived for a single storage tank as $\lambda_{EQ}(Natech, disp/ST) = 2.71\ E-05\ \ y^{-1}$. For the storage farm, the pertinent annual probability is given as

$$\lambda_{EQ}(Natech, disp) = \sum_{i=1}^{4} \lambda_{EQ}(Natech/ST_i) = 1.08\ E-04\ \ y^{-1}$$

Similarly for the tsunami hazard, Eq. (4.34) and Eq. (5.2) are used to compute the annual probability of a Natech accident for each storage tank, considering the tsunami hazard curve in Figure 23, the fragility curve in Figure 24(b), the conditional probability $P_{TS}(LOC3|DS) = 80\%$ and $P_{TS}\left(S_{disp}\middle|LOC3\right)$ taken from Eq. (5.4). Thus, the annual tsunami-triggered Natech probability of is obtained for a single storage tank as $\lambda_{TS}(Natech/ST) = 3.65\ E-04\ \ y^{-1}$. For the storage farm, the annual tsunami-triggered Natech probability is computed as

$$\lambda_{TS}(Natech, disp) = \sum_{i=1}^{4} \lambda_{TS}(Natech/ST_i) = 1.46\,E-03\ \ y^{-1}$$

The above results are summarised in Table 28.

Table 28. Probability of Natech accident per natural hazard for the consequence scenario of substance dispersion

	Earthquake-triggered Natech	**Tsunami-triggered Natech**
	λ_{EQ}(Natech/ST) (y-1)	**λ_{TS}(Natech) (y-1)**
Single Tank	2.71 E-05	3.65 E-04
Tank Farm	1.08 E-04	1.46 E-03

By comparing the single-hazard Natech risk analysis results in Table 28, it is readily observed that the occurrence rate of a tsunami-triggered Natech accident is roughly an order of magnitude higher compared to the earthquake-triggered Natech event.

5.2.6.1.2 Consequence scenario of pool fire

For the cascading natural hazards, Table 29 reports the annual probability of a Natech accident due to pool fire conditioned on each damage state of a single storage tank. These values have been computed from Eq. (4.34) and Eq. (5.2) by substituting:

— the natural hazard curves (Figure 17 and Figure 23 for the earthquake and tsunami, respectively)

— the discrete fragility curve (Figure 18(b) and Figure 24(b) for the earthquake and tsunami, respectively)

— the conditional release probabilities (Table 11, Table 21 for the earthquake and tsunami, respectively); and

— the condition ignition probability (Table 14, Table 24 for the earthquake and tsunami, respectively).

Table 29. Probability of Natech accident per damage state - single storage tank

		Probability of Natech accident per DS
Natural Hazard	**Damage State**	**λ_{EQ}(Natech/ST/DS), λ_{TS}(Natech/ST/DS) (y^{-1})**
Earthquake	DS0	0
	DS1	3.55 E-06
	DS2	1.19 E-06
	DS3	7.47 E-07
	DS4	2.17 E-06
Tsunami	DS	2.93 E-05

For the above, the annual probabilities of a Natech accident leading to a pool fire consequence scenario due to damage to a single storage tank are computed from the following expressions, i.e.:

$$\lambda_{EQ}(Natech/ST) = \sum_{i=0}^{N=4} \lambda_{EQ}(Natech/ST/DS_i) = 7.66\,E-06\ \ y^{-1}$$

$$\lambda_{TS}(Natech/ST) = \lambda_{EQ}(Natech/ST) = 2.93\,E-05\,y^{-1}$$

For the tank farm, the associated annual probabilities are:

$$\lambda_{EQ}(Natech, fire) = \sum_{i=1}^{4} \lambda_{EQ}(Natech/ST_i) = 3.06\,E-05\ \ y^{-1}$$

$$\lambda_{TS}(Natech, fire) = \sum_{i=1}^{4} \lambda_{TS}(Natech/ST_i) = 1.17\,E-04\ \ y^{-1}$$

The above results are summarised in Table 30.

Table 30. Probability of Natech accident per natural hazard for the consequence scenario of pool fire

	Earthquake-triggered Natech	**Tsunami-triggered Natech**
	λ_{EQ}(Natech/ST) (y-1)	**λ_{TS}(Natech)**
Single Tank	7.66 E-06	2.93 E-05
Tank Farm	3.06 E-05	1.17 E-04

The comparison of the single-hazard Natech risk analysis results in Table 30 reveals that a tsunami-triggered Natech accident is roughly an order of magnitude higher compared to the earthquake-triggered Natech event. By comparing Table 28 and Table 30 for two examined consequence scenarios per natural hazard, it is readily observed that the substance dispersion occurs at a more frequent rate compared to the pool fire scenario.

5.2.7 Multi-hazard Natech risk calculation

For the multi-hazard Natech risk analysis, the combined annual probability of a Natech accident due to earthquake and tsunami is expressed as:

$$\lambda_{EQ,TS}(Natech) = P(TS/EQ)\,\lambda_{TS}(Natech) + P(\overline{TS}/EQ)\,\lambda_{\overline{TS}}(Natech) \qquad (5.5)$$

Where $P(TS/EQ)$ is the conditional probability of an earthquake-triggered tsunami event, $P(\overline{TS}/EQ) = 1 - P(TS/EQ)$ is the conditional probability of the complementary event, i.e., the occurrence of an earthquake event without triggering a tsunami event, and $\lambda_{\overline{TS}}(Natech)$ is the annual probability of a Natech accident that it is not caused by tsunamis.

For the special case of cascading tsunami events due to earthquakes, it is easily inferred that $\lambda_{\overline{TS}}(Natech)$=$\lambda_{EQ}(Natech)$, i.e., the annual probability of a Natech accident in the absence of cascading natural hazards coincides with the single earthquake-hazard event. For completeness, it is assumed herein that the conditional probability of an earthquake-triggered tsunami event is $P(TS/EQ)$=10%, and the complementary conditional probability is $P(\overline{TS}/EQ) = 90\%$.

5.2.7.1.1 Consequence scenario of substance dispersion

For the tank farm, Eq. (5.5) is used to compute the annual probability of occurrence of a Natech accident associated with the dispersion of diesel oil on ground and in water due to earthquake and cascading tsunami events. By substituting in Eq. (5.5) the probabilities given in Table 28, the following probability of occurrence is obtained:

$$\lambda_{EQ,TS}(Natech, disp) = 2.43\ \mathrm{E}-04\ y^{-1}$$

5.2.7.1.2 Consequence scenario of pool fire

Similarly for this consequence scenario of pool fire in the tank farm due to cascading tsunamis triggered by earthquakes, Eq. (5.5) is used to compute the annual probability of occurrence of a Natech accident due to the ignition of the released diesel oil. By substituting in Eq. (5.5) the probabilities given in Table 30, the following probability of occurrence is obtained:

$$\lambda_{EQ,TS}(Natech, fire) = 3.93\ \mathrm{E}-05\ y^{-1}$$

For completeness, the above results are summarised in Table 31. From this table, it is easily deduced that the substance dispersion event occurs at a more frequent rate compared to the pool fire scenario under the multi-hazard Natech accident trigger. This remark is in line with previous observations made in section 5.2.6 for the single-hazard Natech accidents.

Table 31. Probability of Natech accident for cascading natural hazards

Natech consequence scenario	**$\lambda_{EQ,TS}$(Natech) (y-1)**
Substance dispersion	2.43 E-04
Pool fire	3.93 E-05

To evaluate the loss in terms of human health impact, the TNO methodology (Purple book, 1999) is adopted. Following the procedure described in section 5.1.6, the individual risk due to heat radiation is computed for seven heat radiation values, Q_H, in the range $[5, 35]\ kW/m^2$ and reported in Table 32. These values are multiplied with the annual probability of a Natech accident in the tank farm to derive the annual probability of death, which is given in the last column of Table 32. The individual risk contour plots are presented in Figure 25 considering the maximum endpoint distances along the longitudinal and lateral direction reported in the third and fourth column of Table 32.

Table 32. Maximum endpoint distances and individual risk for various heat radiation levels for the multi-hazard Natech risk analysis

	Heat Radiation	**Maximum horizontal endpoint distance**	**Maximum vertical endpoint distance**	**Individual Risk due to Heat Radiation**	**Individual Risk due to Natech**
	Q_H (kW/m^2)	**dx_e (m)**	**dy_e (m)**	**Death Probability P_E**	**Annual Probability of death $\lambda_{E,}$(Natech) (y^{-1})**
Irreversible injuries	5	152.51	133.76	1.75E-06	6.88E-11
Death	10	113.33	94.58	0.01	4.53E-07
	15	95.98	77.23	0.19	7.35E-06
	20	85.63	66.88	0.54	2.11E-05
	25	78.57	59.82	0.80	3.16E-05
	30	73.36	54.61	0.93	3.66E-05
	35	69.31	50.56	1.00	3.93E-05

Table 32 and Figure 25 show that a pool fire event due to Natech accident in the military tank farm triggered by the multi-hazard earthquake and cascading tsunami event is associated with an annual individual risk of death in the range of [3.93 E-05, 4.53 E-07]. The highest individual risk, λ_E(Natech)=3. 93 E-05 y^{-1}, occurs for a heat radiation value at Q_H=35 kW/m^2, which corresponds to the red area shown in Figure 25, extended up to an approximate 70-meter radial distance away from the military tank farm (i.e., the source of fire). At higher distances, the annual individual risk of death is gradually decreasing, reaching the lowest rate of λ_E(Natech)=4.52 E-07 y^{-1} for Q_H=10 kW/m^2 at a radial distance of roughly 115 m from the tank farm. At greater distances, there is no further danger of individual risk of death. However, people can suffer from irreversible injuries due to second degree burns subject to a heat radiation intensity at Q_H=5 kW/m^2. This threat is associated with an annual probability of λ_E(Natech)=6.88 E-11 y^{-1} and it could affect people in areas up to roughly 153 m from the tank farm, as shown with the light blue areas in Figure 25.

By comparing Figure 25 and Figure 21 for the case of the pool fire consequence scenario, it is easily seen that the multi-hazard Natech risk analysis results are similar to the ones obtained under scenario 1 (i.e., earthquake hazard-triggered Natech accident). This is the expected outcome for the multi-hazard case examined herein, given the assumption that the cascading tsunami hazard occurs at a much lower probability (i.e., $P(TS/EQ)$=10%) compared to an earthquake hazard (i.e., $P(\overline{TS}/EQ) =$ 90%) at the given site. The slightly higher individual risks due to the multi-hazard Natech accident are attributed to the contribution of the tsunami-triggered Natech accident and its relatively higher occurrence rate as opposed to the earthquake-trigger Natech accident (see also the single-hazard Natech risk analysis results presented Table 30).

Similarly to scenario 1, Figure 25 shows that the risk of death is limited within the site boundaries of the military base, while irreversible injuries to people could also be incurred at a relatively small coastal area outside the site. It is reminded that the obtained results are based on a simplified interaction phenomenon between the two natural hazards (earthquake and tsunami events) and conservative assumptions. A more realistic scenario would require the following:

— Use of attenuation models for the tsunami wave height and the associated inundation depth at the site location.

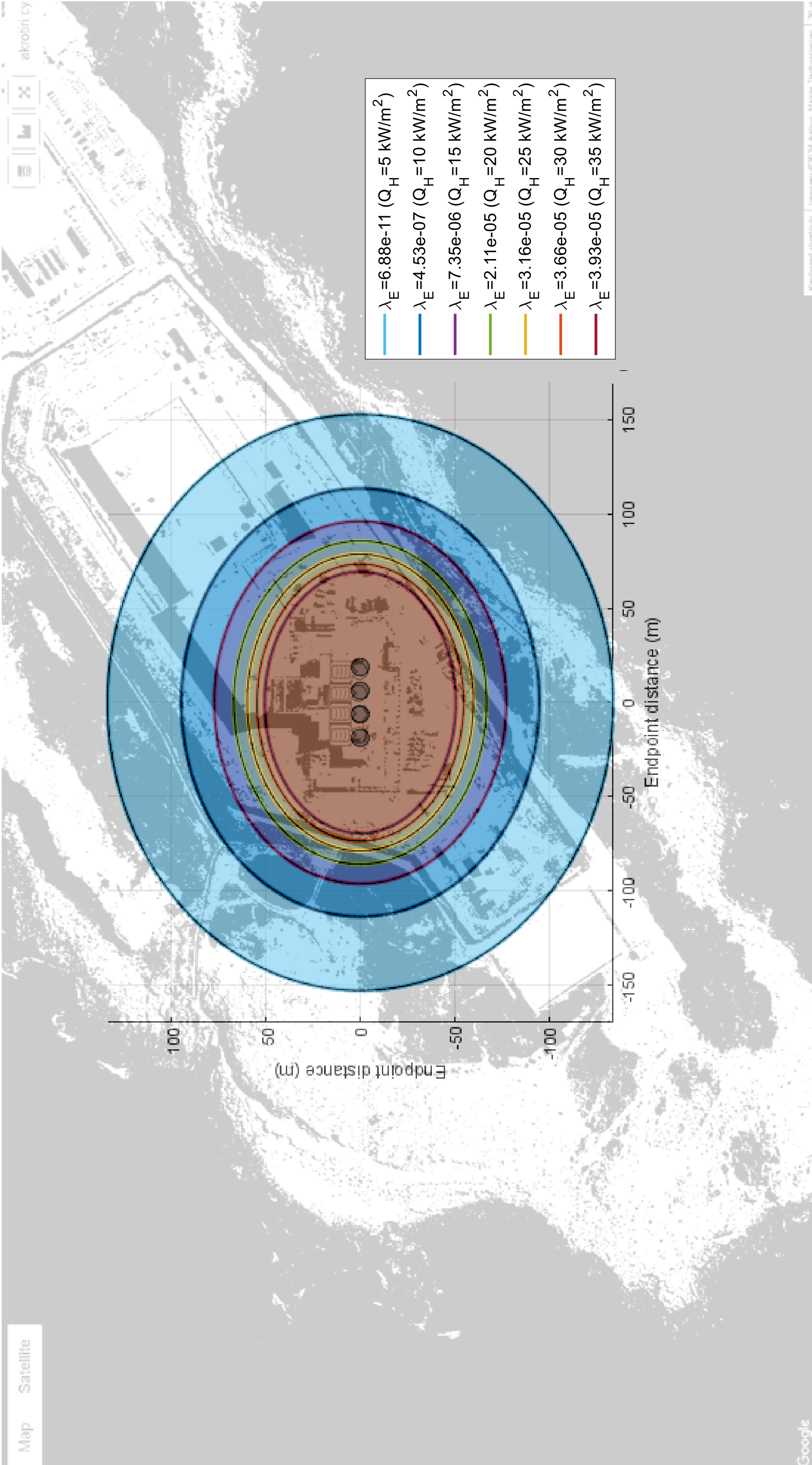
— The evaluation of the tsunami hazard intensity with respect to inundation depth, flow velocity, and momentum flux.

— Use of dispersion models for the simulation of substance dispersion in water bodies and land.

— The consideration of the stratification of flammables on tsumani waters and their ignition.

To reduce the multi-hazard impact to the tank farm, land-use planning would be recommended, considering the re-location of the military facility at locations of lower seismicity and away from coastal and residential areas. In case this is not possible, it would be recommended the adoption of appropriate protection systems and measures, which are not vulnerable to both earthquake and tsunami hazards.

Figure 25. Individual risk contour plot for multi-hazard Natech risk analysis in the tank farm – consequence scenario of pool fire



Source: Background map @ Google maps.

5.3 Scenario 3: Natech accident through propagation mechanism

In this scenario, a qualitative Natech risk analysis is developed to address the Natech accident mechanism developed through domino effects and the propagation of hazard. This scenario builds upon the previously developed scenario 1 (described in section 5.1).

5.3.1 Geographical area of site, exposed facility, equipment, and inventory of hazardous substances

Similarly to scenario 1, a fictitious military base is assumed herein, which is presented in Figure 26 and comprises the same fuel farm as per scenario 1 that stores Q_{tot}=3,058,696 kg of diesel oil (i.e., storage tanks filled at φ=85% of their capacity). A magazine is located at 80 meters from at the east side of the tank farm, and it is assumed to store Q_{exp}=5,000 kg ammunitions of general use. The inventory of the hazardous substances is given in Table 33.

Table 33. Inventory of hazardous substances – scenario 3

Substance Name	CAS Number	EC Number	Substance State	Quantity (kg)
Diesel Fuel No.2	68476-34-6	270-676-1	Flammable liquid and vapour	3,058,696
Ammunition of general use	-	-	Explosive	5,000

Figure 26. Fictitious military facility (green shape) comprising a fuel farm with four storage tanks (red circles) and a magazine (red rectangular).

Source: Background map @ Google maps; excerpt from RAPID-N.

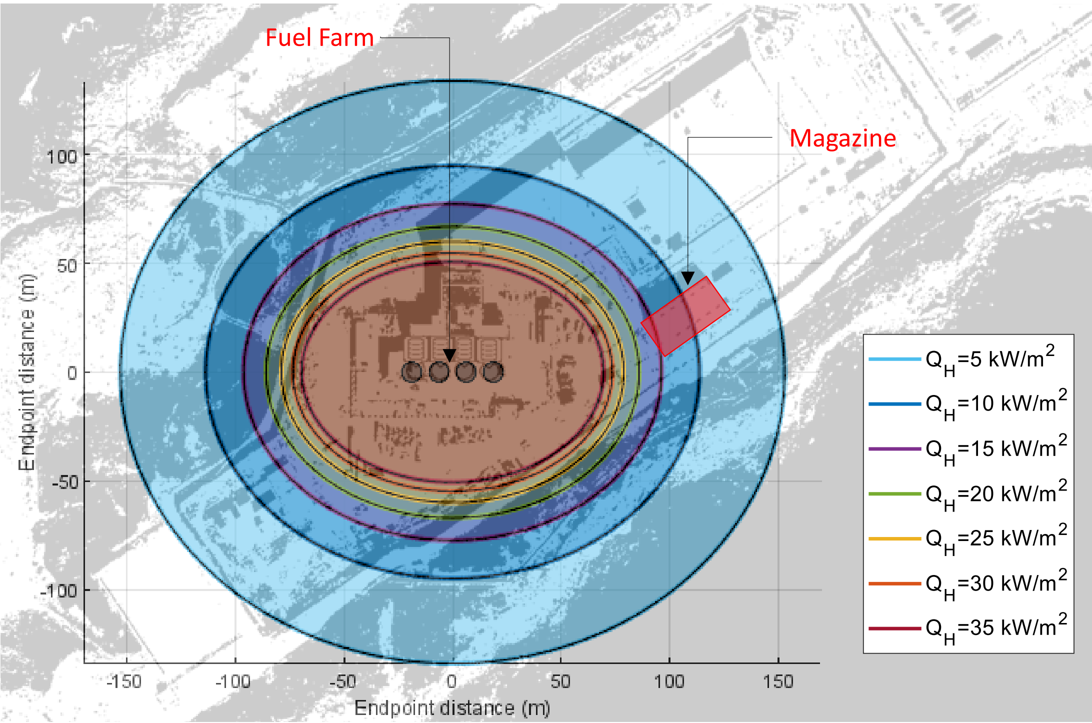
5.3.2 Reference period and risk metrics

A reference period of one year is selected for the Natech risk analysis. A qualitative risk analysis is conducted considering as risk metrics the impact to human health, buildings, vehicles and aircrafts due to blast and fragmentation from detonation of explosives. The latter reflects the secondary effects of the considered domino event, which is triggered by heat exposure of the ammunitions stored in the magazine.

5.3.3 Consequence Analysis – consequence scenario, physical effects, and endpoint distances

Under scenario 1, it was evaluated that an earthquake-triggered Natech accident at the fuel tank would lead to a pool fire consequence scenario due to the release and ignition of flammable liquids (i.e., diesel fuel). Figure 27 illustrates the heat radiation of the pool fire for various intensity levels, showing that the magazine falls within three heat radiation zones with heat intensity between $Q_H = 5\ kW/m^2$ and $Q_H = 15\ kW/m^2$. Thus, it is assumed that a domino Natech event occurs due to the overheating and detonation of the ammunitions stored in the magazine, leading to a massive explosion. This assumption serves the purpose of the development of a domino scenario event, but further investigation is required on the exact heat intensity level that would lead to overheating and detonation of explosives.

Figure 27. Pool fire heat radiation with respect to the magazine location.



Source: Background map @ Google maps.

According to the Army in Europe Regulation (AE Reg 385-64), five severity zones are defined as per Table 34 to qualitatively describe the explosion effects on personnel, and material damage in terms of buildings, combat vehicles, and aircrafts.

For the five severity zones of Table 34, the blast and fragmentation endpoint distance due to explosion is calculated from the following expression:

$$d_e = \begin{cases} 2.4\, Q_{exp}^{1/3} & ZONE\ I \\ 4.4\, Q_{exp}^{1/3} & ZONE\ II \\ 7.2\, Q_{exp}^{1/3} & ZONE\ III \\ 9.6\, Q_{exp}^{1/3} & ZONE\ IV \\ 20\, Q_{exp}^{1/3} & ZONE\ V \end{cases} \quad (5.6)$$

Where Q_{exp} is the net explosive quantity in kilograms and the endpoint distance, d_e, is given in meters.

Table 34. Severity zones and qualitative description of consequences due to explosion, blast and fragmentation

		Consequences/Impact			
Severity Zones	**Explosion effects**	**Personnel**	**Building**	**Vehicles**	**Aircrafts**
ZONE I	Catastrophic due to blast	Deaths	Destroyed	Destroyed	Destroyed
ZONE II	Catastrophic due to blast and fragments	Serious injuries and deaths	Near total destruction	Severe damage	Severe damage
ZONE III	Critical due to fragments	Serious injuries	Extensive damage – 50% of replacement cost	Extensive body damage	Considerable damage
ZONE IV	Marginal due to fragments and debris	Moderate Injuries	Major damage – 20% of replacement cost	Minor damage	Minor damage, operational
ZONE V	Negligible due to debris	Minor injuries	Minor damage – 5% of replacement cost	No damage	Operational

5.3.4 Natech risk calculation due to domino event

Under scenario 1, it was evaluated that an earthquake-triggered Natech accident at the fuel tank would occur with an annual probability $\lambda(Natech) = 3.06\,E-05\ \ y^{-1}$. Considering the likelihood of a domino event being triggered from the overheating and detonation of explosives, Eq. (5.6) is used to compute the endpoint distances at the five severity zones for Q_{exp}=5,000 kg.

Table 35. Severity zones and endpoint distances

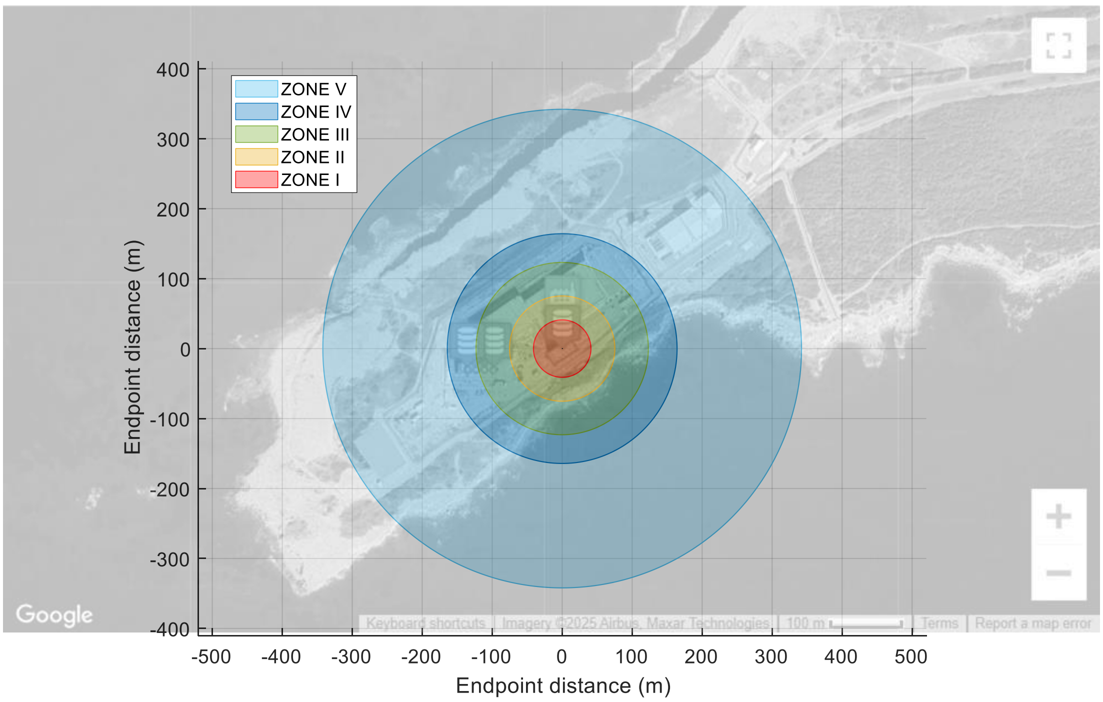
Severity Zones	Endpoint distance, d_e (m)
ZONE I	41
ZONE II	75
ZONE III	123
ZONE IV	164
ZONE V	342

The computed values of the endpoint distance are reported in Table 35 and the associated contour map is illustrated in Figure 28. It is readily observed that the explosion due to the domino event can lead to catastrophic consequences associated with fatalities, severe casualties, and complete destruction of buildings, vehicles and aircrafts within a radial area up to 75 m (zone I and II). Serious injuries and extensive material damage could occur up to a distance of 123 m (zone III) from the location of the magazine. Fragments and debris from the blast can reach regions located up to 164 m (zone IV) away from the military base, causing moderate injuries to people, significant building damage, and light damage to vehicles. This domino event could adversely affect people and buildings even in areas up to 342 m (zone V) away from the source of the explosion, leading to minor injuries and structural damage due to debris from the blast.

By comparing the contour maps in Figure 21 and Figure 28 under scenario 1 and 3, respectively, it is shown that the Natech consequences are more critical for the secondary explosion event rather than the primary event of pool fire due to direct earthquake impact to the fuel farm. In fact, minor injuries due to explosion can occur within a radial area up to 342 m, which is roughly two times higher compared to the endpoint distance of the pool fire event (i.e., 152.51 m for irreversible injuries).

The above results are based on an assumed heat intensity level that would lead to overheating and detonation of explosives. It is acknowledged that this assumption may not be realistic and further investigation is required. In the absence of more information herein, it is recommended the relocation of the magazine to a distance much greater than 155 m from the tank farm, where negligible heat radiation intensity values are expected under a Natech accident as per scenario 1. If the above is not possible, the quantity of stored explosives should be reduced to limit the extent of adverse consequences while ensuring that appropriate construction features have been implemented as detailed in section 3.1.3.

Figure 28. Explosion severity map – blast and fragmentation endpoint distances



Source: Background map @ Google maps.

6 Conclusions

This technical report focuses on natural hazard-triggered technological (Natech) accidents in military facilities. This is an issue of vital importance for the national security, the safety of citizens, the environment, and the economy. Nonetheless, limited information is publically available for relevant initiatives in military installations despite the severe consequences of even minor damage in defence infrastructure or impaired operations in critical utility networks that military facilities depend upon.

Relevant EU policy acts, such as the SEVESO III Directive (DIRECTIVE 2012/18/EU), have been developed for civilian facilities, which, however, usually exclude military installations from their scope. Recent developments in EU military policy and legislation address the resilience of defence infrastructure or defence-related critical energy infrastructure under climate-related impacts. However, there is no comprehensive EU legislation for Natech risk management in military facilities. It is acknowledged that relevant regulations and standards may exist at national or military organisational level, but a relevant review is beyond the scope of this report.

This technical report sets the objective to complement the above EU initiatives and increase the awareness on Natech risks in military facilities, based on scientific evidence. To meet this objective, the Natech risk drivers in the defence sector are first analysed in Chapter 2, and definitions are given for the three typical Natech accident mechanisms, i.e.:

— The **direct accident mechanism** associated with immediate damage to military infrastructure due to natural hazard impacts;

— The **propagation accident mechanism** associated with domino effects due to secondary events; and

— The **indirect accident mechanism** associated with damage or disruption in critical utility networks and/or protection systems and measures.

Examples of past Natech accidents and near misses are also provided to increase clarity. The EU regulatory framework is next presented in Chapter 3, covering relevant military and civilian EU policies as well as international standards.

A detailed methodology for quantitative probabilistic Natech risk analysis in military facilities is presented in Chapter 4, offering a template methodology for similar risk analyses due to natural hazard impacts. The associated mathematical framework is presented, which entails the following three models:

(i) the exposure model, i.e., people, structures, elements, and contents exposed to Natech accidents;

(ii) the natural hazard model; and

(iii) the loss/consequence model.

The latter can be viewed as a three-level approach, i.e.:

— **Level 1**: estimation of structural/non-structural damage due to natural hazard impacts.

— **Level 2**: estimation of the release of hazardous substances due to structural/non-structural damage.

— **Level 3**: estimation of the adverse consequence to exposed assets due to the physical effects of fire, explosion or toxic dispersion.

To demonstrate the implementation of the above methodology, three scenarios are developed in Chapter 5, which are associated with the direct and the propagation Natech accident mechanisms. In **scenario 1**, the direct Natech accident mechanism is assessed for a fictitious military facility, which is assumed to be located on an island subject to high seismicity. Thus, an earthquake-triggered Natech risk analysis is conducted, considering the direct natural hazard impact to a diesel oil tank farm. Due to earthquake-induced structural damage, flammable substances are released, which are further ignited and developed into a pool fire consequence scenario event. Considering the individual risk for the reference period of one year, the Natech risk analysis results are obtained in terms of the annual probability of death and irreversible injuries due to human exposure to heat radiation, i.e., the physical effect of fire. For the considered heat radiation range between 5 kW/m^2 and 35 kW/m^2, it is shown that the individual risk ranges between 3.06E-05 and 5.36E-11 on an annual basis. The obtained results are mapped with contour plots, showing that the individual risk is mostly limited within the site boundaries of the military base. Recommendations are also provided for the mitigation of the consequences and the reduction of the Natech risks. Such recommendations include the improvement of the seismic resilience of storage tanks through the reduction of the stored quantity or via seismic retrofit solutions, the appropriate use of safety measures, as well as the re-location of the military facility considering land-use planning.

Scenario 2 builds on scenario 1 to evaluate a direct Natech accident mechanism under cascading natural hazards that impact the same fictitious military facility. A multi-hazard Natech risk analysis is conducted for cascading tsunami events triggered by earthquakes. This scenario examines further the potential failure of a containment dike in case of exceedance of its capacity to contain the released substances. Two Natech consequence scenarios are analysed, i.e., the pool fire event as in scenario 1, and the substance dispersion event. The latter consequence scenario is qualitatively assessed due to the absence, in this study, of an appropriate dispersion model to simulate the spread of the released substances with tsunami water. Further, the potential stratification of flammables on tsumani waters is not covered herein. A simplified approach is adopted to evaluate the multi-hazard Natech risk. Thus, Natech risk analysis is performed for each natural hazard separately, and the obtained results are further combined using a standard expression from the literature and assuming a conditional probability of an earthquake-triggered tsunami event, $P(TS/EQ)$=10%, and its complementary conditional probability $P(\overline{TS}/EQ) = 90\%$. For the pool fire consequence scenario, Natech risk is computed in terms of the individual risk (i.e., probability of death and irreversible injuries) in line with scenario 1. As expected, the obtained Natech risk analysis results are of the same order of magnitude and slightly higher than the ones obtained in scenario 1 (i.e., individual risk in the range of [3.93 E-05, 6.88E-11]). To reduce the Natech risks, it is recommended the re-location of the military facility at regions of lower seismicity and away from coastal and residential areas, as well as the use of appropriate protection systems and measures.

The final **scenario 3** is an extension of scenario 1 that simulates the propagation Natech accident mechanism. A magazine, storing ammunitions and explosives of general use, is assumed to be located at the vicinity of tank farm within the fictitious military facility. Following the pool fire consequence event under scenario 1, a domino Natech event is assumed to occur due to overheating and detonation of the ammunitions stored in the magazine, leading to a massive explosion. The Army in Europe Regulation (AE Reg 385-64) is used to perform a qualitative Natech risk assessment based on five severity zones and the associated explosion effects on personnel and material damage in terms of buildings, combat vehicles, and aircrafts. Blast and fragmentation endpoint distances due to explosion are computed. It is shown that the domino explosion event could lead to more severe consequences to the population, given that minor injuries due to explosion could occur up to an endpoint distance which is two times higher than the one under the primary pool fire event. It is recommended the re-location of the magazine at a distance much greater than 155 m from the tank farm to reduce the heat radiation impact to the magazine and the stored explosives. Other recommendations include the reduction of the stored explosives and the implementation of appropriate construction features.

For the above scenarios, Natech risk analysis calculations have been performed in MATLAB, based on the default "consequence analysis" calculations in the RAPID-N tool (Necci and Krausmann, 2022b), which rely on U.S. EPA guidance for offsite consequence analysis in case of accidental chemical releases and the associated adverse effects to the exposed population. The EC-JRC developed RAPID-N tool has not been used herein as it partially supports the probabilistic Natech risk analysis methodology presented in this report. Thus, areas for further improvement of the RAPID-N tool are identified towards a comprehensive probabilistic Natech risk analysis in civilian and military facilities.

Finally, it is noted that the above scenarios could be used to support the scenario-building initiative for disaster management planning at Union level, in line with the Union Civil Protection Mechanism as per Regulation (EU) 2021/836.

References

Alessandri, S., Caputo, A.C., Corritore, D., Giannini, R., Paolacci, F., Phan, H.N., 'Probabilistic risk analysis of process plants under seismic loading based on Monte Carlo simulations', *Journal of Loss Prevention in the Process Industries*, Vol. 53, 2018, pp. 136–148.

American Lifelines Alliance, *Seismic fragility formulation for water systems, Part 1 - Guidelines*, 2001

API STD 2510, *Design and Construction of LPG Installations*, American Petroleum Institute, Edition 9, August 2020.

API STD 620, *Design and Construction of Large, Welded, Low-Pressure Storage Tanks*, American Petroleum Institute, Edition 12, October 2013, Addendum 3, September 2021.

API STD 650, *Welded Tanks for Oil Storage,* American Petroleum Institute, Edition 13, March 2020, Errata 1 January 2021.

API STD 653, *Tank Inspection, Repair, Alteration, and Reconstruction*, American Petroleum Institute, Edition 5, November 2014, Addendum 3, November 2023.

Army in Europe Regulation (AE Reg) 385-64, *Safety – Explosives Safety. United States Army Europe*, 20 July 2020. https://media.defense.gov/2020/Jul/20/2002459495/-1/-1/0/AER385-64.PDF

Army Regulation (AR) 385-10, *Safety – The Army Safety and Occupational Health Program*, Department of the Army, Washington, DC, 24 July 2023. https://armypubs.army.mil/epubs/DR_pubs/DR_a/ARN34981-AR_385-10-000-WEB-1.pdf

ASCE7-22, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures,* American Society of Civil Engineers, 2022.

ASME B31.4, *Pipeline Transportation Systems for Liquids and Slurries*, American Society of Mechanical Engineers, 2022.

ASME B31.8, *Gas Transmission and Distribution Piping Systems*, American Society of Mechanical Engineers, 2022.

ASME B31E, *Standard for the Seismic Design and Retrofit of Above-Ground Piping Systems,* American Society of Mechanical Engineers, 2008.

Baker, J. W., Bradley, B. A., Stafford, P. J., *Seismic Hazard and Risk Analysis*, Cambridge University Press, University of Cambridge, 2021. doi:10.1017/9781108425056

Brandenberg, S. J., Wang, P., Nweke, C. C., Hudson, K., Mazzoni, S., Bozorgnia, Y., Hudnut, K. W., Davis, C. A., Ahdi, S. K., Zareian, F., Fayaz, J., Koehler, R. D., Chupik, C., Pierce, I., Williams, A., Akciz, S., Hudson, M. B., Kishida, T., Brooks, B. A, E., *Preliminary Report on Engineering and Geological Effects of the July 2019 Ridgecrest Earthquake Sequence*, Geotechnical Extreme Event Reconnaissance Association, 2019.

C(2023) 400 final. *Commission Recommendation of 8.2.2023 on Union disaster resilience goals*, 08 February 2023. https://data.consilium.europa.eu/doc/document/ST-6281-2023-INIT/en/pdf

Civilian CSDP Compact. European Union Common Security and Defence Policy, *Civilian CCSDP Compact: Towards more effective civilian missions,* 2023. https://www.eeas.europa.eu/sites/default/files/documents/2023/Civilian%20CSDP%20Compact%20Report_22.05.2023.pdf

COM(2005) 576 final. *Green Paper on a European programme for critical infrastructure protection*, 17 November 2005. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52005DC0576

COM/2019/640 final. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions – The European Green Deal*, 2019. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640%20

Consolidated text: Regulation (EC) No 1272/2008. *The European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 (Text with EEA relevance)*, 01 December 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008R1272-20231201

Cornell C. A., 'Engineering Seismic Risk Analysis', *Bulletin of the Seismological Society of America,* Vol. 58, No 5, 1968, pp. 1583–1606.

Council Conclusions 5413/18. *The Integrated Approach to External Conflicts and Crises*, 22 January 2018. https://data.consilium.europa.eu/doc/document/ST-5413-2018-INIT/en/pdf

Council Directive 2008/114/EC of 8 December 2008. *Identification and designation of European critical infrastructures and the assessment of the need to improve their protection (Text with EEA relevance)*, 23 December 2008. https://eur-lex.europa.eu/eli/dir/2008/114/oj

Council Directive 96/82/EC of 9 December 1996. *Control of major-accident hazards involving dangerous substances*, 14 January 1997. https://eur-lex.europa.eu/eli/dir/1996/82/oj

Council Implementing Decision (EU) 2018/1993 of 11 December 2018. *The EU Integrated Political Crisis Response Arrangements*, 17 December 2018. https://eur-lex.europa.eu/eli/dec_impl/2018/1993/oj

Council of the European Union 14392/16. *Implementation Plan on Security and Defence*, 14 November 2016. https://www.consilium.europa.eu/media/22460/eugs-implementation-plan-st14392en16.pdf

Council of the European Union 7248/23. *Council conclusions on Climate and Energy Diplomacy - Bolstering EU climate and energy diplomacy in a critical decade*, 09 March 2023. https://www.consilium.europa.eu/media/62942/st07248-en23.pdf

Council of the European Union 7371/22. *A Strategic Compass for Security and Defence – For a European Union that protects its citizens, values and interests and contributes to international peace and security*, 21 March 2022. https://data.consilium.europa.eu/doc/document/ST-7371-2022-INIT/en/pdf%20

Cox, A.W., Lees, F.P., Ang, M.L., *Classification of hazardous locations*, Institution of Chemical Engineers, Institution of Chemical Engineers, Great Britain, 1990.

Crowley, H., Dabbeek, J., Despotaki, V., Rodrigues, D., Martins, L., Silva, V., Romão, X., Pereira, N., Weatherill, G., Danciu, L., *European Seismic Risk Model (ESRM20)*, EFEHR Technical Report 002, V1.0.1, 2021, pp. 1–84. doi:10.7414/EUC-EFEHR-TR002-ESRM20.

Decision No 1313/2013/EU of the European Parliament and the Council of 17 December 2013. *A Union Civil Protection Mechanism*, 20 December 2013. https://eur-lex.europa.eu/eli/dec/2013/1313/oj

Defence Explosives Safety Regulation (DESR) 6055.09. *DoD Explosives Safety Standards*, Edition 1, Change 1, Department of Defence Explosives Safety Board, Department of Defence Directive, United

States of America, 23 February 2024. https://www.denix.osd.mil/ddes/denix-files/sites/32/2024/03/DESR-6055.09-Edition1-Change-1-240227-Final.pdf

Department of Defence, *Protective construction review guide (hardening,* Vol. I, office of the assistant secretary of defense (installations and logistics), office of the deputy secretary (properties and installations), United States of America, 1961. https://apps.dtic.mil/sti/pdfs/AD0422993.pdf

Department of the Army (DA) Pamphlet 385-64. *Safety – Ammunition and Explosives Safety Standards*. Department of the Army, United States of America, 24 July 2023. https://armypubs.army.mil/epubs/DR_pubs/DR_a/ARN31050-PAM_385-64-000-WEB-1.pdf

Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022. *Resilience of critical entities*, *repealing Council Directive 2008/114/EC*, 27 December 2022. https://eur-lex.europa.eu/eli/dir/2022/2557/oj

Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007. *Assessment and management of flood risks*, 06 November 2007. https://eur-lex.europa.eu/eli/dir/2007/60/oj

Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012. *Control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC,* 24 July 2012. https://eur-lex.europa.eu/legal-content/GA/TXT/?uri=CELEX:32012L0018

Directive 2013/30/EU of the European Parliament and of the Council of 12 June 2013. *Safety of offshore oil and gas operations and amending Directive 2004/35/EC*, 28 June 2013. https://eur-lex.europa.eu/eli/dir/2013/30/oj

Earthquake Engineering Research Institute (EERI), *EERI Earthquake Reconnaissance Report: 2019 Ridgecrest Earthquake Sequence*, 2020. http://learningfromearthquakes.org/2019-07-04-searles-valley/images/2019_07_04_Searles_Valley/PDFs/EERI-LFE-Ridgecrest-Earthquake-Sequence-Report-v1.1.pdf

EEAS (2020) 1251. *Climate Change and Defence Roadmap*. European External Action Service, Brussels, 9 November 2020. https://data.consilium.europa.eu/doc/document/ST-12741-2020-INIT/en/pdf

EN 1990:2002. *Eurocode 0: Basis of Structural Design*, European Committee for Standardization, Brussels, Belgium, 2002

EN 1991–4:2006. *Eurocode 1: Actions on structures – Part 4: Silos and tanks*, European Committee for Standardization, Brussels, Belgium, 2006

EN 1992-3:2006. *Eurocode 2: Design of concrete structures - Part 3: Liquid retaining and containment structures*, European Committee for Standardization, Brussels, Belgium, 2006

EN 1993-3-1:2006. *Eurocode 3: Design of steel structures - Part 3-1: Towers, masts and chimneys – Towers and masts*, European Committee for Standardization, Brussels, Belgium, 2006

EN 1993-3-2:2006. *Eurocode 3: Design of steel structures - Part 3-2: Towers, masts and chimneys – Chimneys*. European Committee for Standardization, Brussels, Belgium, 2006

EN 1993-4-1:2007. *Eurocode 3: Design of steel structures - Part 4-1: Silos*, European Committee for Standardization, Brussels, Belgium, 2007

EN 1993-4-2:2007. *Eurocode 3: Design of steel structures - Part 4-2: Tanks*. European Committee for Standardization, Brussels, Belgium, 2007

EN 1997-1:2004. *Eurocode 7: Geotechnical design - Part 1: General rules*. European Committee for Standardization, Brussels, Belgium, 2004

EN 1998–1:2004. *Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings*. European Committee for Standardization, Brussels, Belgium, 2004

EN 1998–4:2006. *Eurocode 8: Design of structures for earthquake resistance – Part 4: Silos, tanks and pipelines*. European Committee for Standardization, Brussels, Belgium, 2006

EN 1998–6:2005. *Eurocode 8: Design of structures for earthquake resistance – Part 6: Towers, masts and chimneys*. European Committee for Standardization, Brussels, Belgium, 2005

European Union Global Strategy (EUGS). *Shared Vision, Common Action: A Stronger Europe – A Global Strategy for the European Union's Foreign and Security Policy*, June 2016. https://www.eeas.europa.eu/sites/default/files/eugs_review_web_0.pdf

Fabbri, L., Binda, M., Bruinen de Bruin, Y., *Accident Damage Analysis Module (ADAM) – Technical Guidance*, EUR 28732 EN, Publications Office of the European Union, Luxembourg, 2017, doi 10.2760/719457.

FEMA, *Hazus-MH MR5 - Advanced Engineering Building Module (AEBM) - Technical and user's manuals*, Building Sciences and Technology Acting Branch Chief, 2010.

Green Book. Directorate-General for Social Affairs and Employment (Pays-Bas), *Methods for the determination of possible damage to people and objects resulting from the release of hazardous materials- CPR 16E*, edited by Committee for the prevention of the disasters, Sdu Uitgevers, Den Haag, 1992.

Gutenberg, B., Richter, C.F., *Seismicity of the earth and associated phenomena*, Princeton University Press, Princeton, 1949.

He, Z., Chen, C., Weng, W., 'Multi-hazard risk assessment in process industries: State-of-the-Art', *Journal of Loss Prevention in the Process Industries*, Vol. 76, 2022.

Hosseini, S.E.A., Beskhyroun, S., 'Fluid storage tanks: A review on dynamic behaviour modelling, seismic energy-dissipating devices, structural control, and structural health monitoring techniques', *Structures*, Vol. 49, 2023, pp. 537–556.

ISO 31000: 2018 (E). *Risk management – Guidelines*, 2nd ed, International Organization for Standardization, Switzerland, 2018.

ISO 31000:2009(E). *Risk management - Principles and guidelines*, 1st ed, International Organization for Standardization, Switzerland, 2009.

JOIN(2023) 19 final. Joint Communication to the European Parliament and the Council, *A new outlook on the climate and security nexus: Addressing the impact of climate change and environmental degradation on peace, security and defence*, 28 June 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023JC0019

Krausmann, E., Baranzini, D., 'Natech risk reduction in the European Union', *Journal of Risk Research*, Vol. 15, No. 8, 2012, pp. 1027–1047.

Krausmann, E., Cruz, A.M., Salzano, E., *Natech Risk Assessment and Management: Reducing the Risk of Natural-Hazard Impact on Hazardous Installations*, ed. 1, Elsevier, 2016.

Krausmann, E., Girgin, S., Necci, A., 'Natural hazard impacts on industry and critical infrastructure: Natech risk drivers and risk management performance indicators', *International Journal of Disaster Risk Reduction*, Vol. 40, 2019.

Mesa-Gómez, A., Casal, J., Muñoz, F., 'Risk analysis in Natech events: State of the art', *Journal of Loss Prevention in the Process Industries*, Vol. 64, 2020.

Misuri, A., Cozzani, V., *A Roadmap for the Comprehensive Assessment of Natech Risk: Management and Control of Technological Accidents Triggered by Natural Hazards in the Framework of Climate Change*, Elsevier, 2024.

NATO Strategic Concept. *Adopted by Heads of State and Government at the NATO Summit in Madrid*, 29 June 2022. https://www.nato.int/nato_static_fl2014/assets/pdf/2022/6/pdf/290622-strategic-concept.pdf

NAVSEA OP 5. Naval Sea System Command, Department of the Navy, *Ammunition and explosives ashore: Safety Regulations for handling, storage, production, renovation and shipping,* Vol. 1, Rev. 7, 2001.

Necci, A., Carbunescu, D., *Integration of risk analysis tools: RAPID-N and ADAM*, JRC122481, European Commission, 2020.

Necci, A., Krausmann, E., *How to Use RAPID-N – Methodology, Models, Technical Information and Tutorials*, EUR 31170 EN, Publications Office of the European Union, Luxembourg, 2022b, doi:10.2760/231493, JRC130323

Necci, A., Krausmann, E., *Natech risk management – Guidance for operators of hazardous industrial sites and for national authorities*, EUR 31122 EN, Publications Office of the European Union, Luxembourg, 2022a, ISBN 978-92-76-53493-8, doi:10.2760/666413, JRC129450.

OECD and the European Union, *Managing Risks from Natural Hazards to Hazardous Installations (Natech): A Guide for Senior Leaders in Industry and Public Authorities*, Series on Chemical Accidents, OECD Publishing, Paris, 2024. https://doi.org/10.1787/9bb63229-en.

OECD, *OECD Guiding Principles for Chemical Accident Prevention, Preparedness and Response,* Edition *3*, Series on Chemical Accidents, OECD Publishing, Paris, 2023. https://doi.org/10.1787/162756bf-en

Polis Poliviou, *Πόρισμα μονομελούς ερευνητικής επιτροπής για τη διεξαγωγή έρευνας σχετικά με την έκρηξη που επισυνέβη την 11η Ιουλίου 2011 στη Ναυτική Βάση "Ευάγγελος Φλωράκης" στο Μαρί*, 2011. https://web.archive.org/web/20111005090635/http://media.cna.org.cy/pdf/PORISMA.pdf

Porter, K., *A Beginner's Guide to Fragility, Vulnerability, and Risk*, University of Colorado Boulder, 2001, pp. 1 -139. https://www.sparisk.com/pubs/Porter-beginners-guide.pdf

prEN 1990:2023. *Eurocode 0: Basis of structural and geotechnical design.* European Committee for Standardization, Brussels, Belgium, 2023

prEN 1991–4:2024. *Eurocode 1 - Actions on structures – Part 4: Silos and tanks*. Draft. European Committee for Standardization, Brussels, Belgium, 2024

prEN 1993-3:2024. *Eurocode 3: Design of steel structures - Part 3: Towers, masts and chimneys*. Draft. European Committee for Standardization, Brussels, Belgium, 2024 prEN 1993-4-1:2024. *Eurocode 3: Design of steel structures - Part 4-1: Silos*. Draft. European Committee for Standardization, Brussels, Belgium, 2024

prEN 1993-4-2:2024. *Eurocode 3: Design of steel structures - Part 4-2: Tanks*. Draft. European Committee for Standardization, Brussels, Belgium, 2024

prEN 1998-1-1:2024. *Eurocode 8: Earthquake resistance design of structures—Part 1: General rules and seismic action*, Draft, European Committee for Standardization, Brussels, Belgium, 2024

prEN 1998-4:2023. *Eurocode 8: Earthquake resistance design of structures—Part 4: Silos, tanks, pipelines, towers, masts and chimneys*, Draft, European Committee for Standardization, Brussels, Belgium, 2023

Purple Book. Directorate-General for Social Affairs and Employment (Pays-Bas), *Guidelines for Quantitative Risk Assessment - CPR 18E*, Committee for the prevention of the disasters (Editor), Sdu Uitgevers, Den Haag, 1999.

Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008. *Classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006*, 31 December 2008. http://publications.europa.eu/resource/cellar/6bf54b59-7673-461b-b8e1-f24c545cbd3c.0006.05/DOC_1

Regulation (EU) 2021/836 of the European Parliament and of the Council of 20 May 2021. *Amending Decision No 1313/2013/EU on a Union Civil Protection Mechanism*, 26 May 2021. https://eur-lex.europa.eu/eli/reg/2021/836/oj/eng

Regulation (EU) No 347/2013 of the European Parliament and of the Council of 17 April 2013. *Guidelines for trans-European energy infrastructure and repealing Decision No 1364/2006/EC and amending Regulations (EC) No 713/2009, (EC) No 714/2009 and (EC) No 715/2009*, 25 April 2013. https://eur-lex.europa.eu/eli/reg/2013/347/oj

Ricci, F., Casson Moreno, V., Cozzani, V., 'A comprehensive analysis of the occurrence of Natech events in the process industry', *Process Safety and Environmental Protection,* Vol. 147, 2021, pp. 703–713.

Salzano, E., Garcia Agreda, A., Di Carluccio, A., Fabbrocino, G., Risk assessment and early warning systems for industrial facilities in seismic zones, *Reliability Engineering and System Safety, Vol.* 94, 2009, pp. 1577–1584.

Sauli Niinistö, *Safer Together – Strengthening Europe's civilian and military preparedness and readiness,* 2024. https://commission.europa.eu/document/5bb2881f-9e29-42f2-8b77-8739b19d047c_en

Suarez-Paba, M.C., Perreur, M., Munoz, F., Cruz, A.M., Systematic literature review and qualitative meta-analysis of Natech research in the past four decades. *Safety Science,* Vol. 116, 2019, pp. 58–77.

SWD(2016) 205 final/2. Commission Staff Working Document, *Action Plan on the Sendai Framework for Disaster Risk Reduction 2015-2030 - A disaster risk-informed approach for all EU policies*, 17 June 2016. https://civil-protection-humanitarian-aid.ec.europa.eu/system/files/2016-06/1_en_document_travail_service_part1_v2.pdf

Tavares da Costa, R. and Krausmann, E., *Impacts of Natural Hazards and Climate Change on EU Security and Defence*, EUR 30839 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-41947-1, doi:10.2760/244397, JRC126315

Tavares da Costa, R., Krausmann, E., Hadjisavvas, C., *Impacts of climate change on defence-related critical energy infrastructure*, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/03454, JRC130884

Timoshenko, S., Gere, J., *Theory of Elastic Stability*, Ed. 2, McGraw Hill, New York, 1961.

U.S. EPA. *Risk Management Program Guidance for Offsite Consequence Analysis,* United States Environmental Protection Agency, Office of Solid Waste and Emergency Response, Chemical Emergency Preparedness and Prevention Office, 2009.

UNDRR, *The Report of the Midterm Review of the Implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030*, Geneva, Switzerland, 2023

U.S. Army Defense Ammunition Centre. *Hazard Classification of United States Military Explosives and Munitions. Logistics review and technical assistance office,* Rev 15, 2012. https://www.fuji.marines.mil/Portals/111/Documents/range%20control/YellowBook.pdf

Valente, M., Ricci, F., Cozzani, V., 'A systematic review of Resilience Engineering applications to Natech accidents in the chemical and process industry', Reliability Engineering and System Safety, Vol. 255, 2025.

Vitale, A., *PhD thesis: Earthquake and Tsunami multi-hazard risk analysis of a petrochemical plant*, Università degli Studi di Napoli Federico II, 2024.

Yang, Z., Barroca, B., Weppe, A., Bony-Dandrieux, A., Laffréchine, K., Daclin, N., November, V., Omrane, K., Kamissoko, D., Benaben, Frederick, Dolidon, H., Tixier, J., Chapurlat, V., 'Indicator-based resilience assessment for critical infrastructures – A review', Safety Science, Vol. 160, 2023.

List of abbreviations and definitions

Abbreviations	Definitions
A&E	Ammunition and Explosives
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BLEVE	Boiling Liquid Expanding Vapour Explosion
CAS Number	Chemical Abstracts Service Number
CC	Consequence Class
CCA	Emergency and Crisis Coordination Arrangements
CECIS	Common Emergency Communication and Information System
CFSP	Common Foreign and Security Policy
Coreper	Committee of the Permanent Representatives of the Governments of the MSs to the EU
CRC	Crisis Response Centre
CSDP	Common Security and Defence Policy
DAESC	Department of the Army Explosives Safety Council
DDESB	Department of Defence Explosives Safety Board
DE	Domino Effect
DG	Directorate-General
DL	Damage Limitation (Limit State)
DoD	Department of Defense
DS	Damage State
EC Number	European Community Number

Abbreviations	Definitions
EC8	Eurocode 8
ECHO	European Civil Protection and Humanitarian Aid Operations
EC-JRC	European Commission's Joint Research Centre
EDA	European Defence Agency
EEAS	European External Action Service
EERC	European Emergency Response Capacity
EFEHR	European Facilities for Earthquake Hazard and Risk
EMSC	European-Mediterranean Seismological Centre
EN	European Standard
EPA	Environmental Protection Agency
EPAC	Army in Europe Explosives-Policy Action Committee
EQ	Earthquake
ERCC	Emergency Response Coordination Centre
erf	Error function
ESHM20	European Seismic Hazard Model 2020
ESQD	Explosives Safety Quantity-Distance
EU	European Union
GMPE	Ground Motion Prediction Equation
GSC	General Secretariat of the Council
HF	Hazardous facilities
HR/VC	High Representative of Union for Foreign Affairs and Security Policy/Vice President of the European Commission

Abbreviations	Definitions
IPCR	Integrated Political Crisis Response
ISAA	Integrated Situational Awareness and Analysis
LOC	Loss of Containment or Loss of Content
MoD	Ministry of Defence
MS, MSs	Member State, Member States
Natech	Natural hazard triggered technological accident
NATO	North Atlantic Treaty Organisation
NAVFAC	Navy Facilities Engineering System Command
NAWS	U.S. Naval Air Weapon Station China Lake
NC	Near Collapse (Limit State)
NEAMTHM18	Tsunami Hazard Model 2018 for North East Atlantic and Mediterranean (NEAM) region
OECD	Organisation for Economic Co-operation and Development
OP	Operational (Limit State)
PFF	Pool Fire Factor
PGA	Peak Ground Acceleration
PGD	Peak Ground Displacement
PGV	Peak Ground Velocity
PSHA	Probabilistic Seismic Hazard Analysis
QRA	Quantitative Risk Analysis
RAPID-N	Rapid Natech Risk Assessment Tool
RDAT&E	Research, Development, Acquisition, Testing, and Evaluation

Abbreviations	Definitions
RMP	Risk Management Program
SD	Significant Damage (Limit State)
ST	Storage Tank
TNO	Netherlands Organisation for Applied Scientific Research (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek)
TNT	Trinitrotoluene
TS	Tsunami
TUBITAK	Technological Research Council of Turkey
U.S.	United States
UCPM	Union Civil Protection Mechanism
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction
UNO	United Nations Organisation
USAREUR-AF	U.S. Army Europe and Africa
USGS	U.S Geological Survey
VCE	Vapour Cloud Explosion
VCF	Vapour Cloud Fire

List of symbols and operations

Symbols	Definitions
a	Coefficient associated with toxicity of the hazardous substance
A_{dike}	Net bund area of containment dike
A_h	Hole area
A_p	Pool fire area
b	Coefficient associated with toxicity of the hazardous substance
C	Consequence risk metric
c_d	Discharge coefficient
C_{DS}	Physical damage consequences to structural systems and non-structural elements
C_{NATECH}	Consequences due to Natech accident (e.g., casualties, environmental consequences, economic losses, or impaired military operations)
c_{p}	Specific heat capacity of substance
C_t	Toxic concentration
d_e	Endpoint distance
DE	Domino effects (in risk analysis)
DS_i	i^{th} Damage State
D_{t}	Diameter of vertical cylinder storage tank
dx_e	Endpoint distance along the x-axis (longitudinal direction)
dy_e	Endpoint distance along the y-axis (transversal direction)
erf	The error function

Symbols	Definitions
$f(X)$	Probability density function of X
$F(X)$	Cumulative distribution function of X
$F_{E,in}$	Fatal probability for population inside a protected space
$F_{E,out}$	Fatal probability for population outside a protected space
g	Acceleration of gravity
H, H_1, H_2	Hazard intensity measure
h, h_1, h_2	Value of hazard intensity level
H_c	Specific heat combustion
H_{cTNT}	Specific heat combustion of TNT-equivalent mass
H_{dike}	Height of containment dike walls
HF	Number of hazardous facilities (in risk analysis)
h_f	liquid filling level
h_f/R_{t}	slenderness ratio
h_{fh}	Liquid filling level above a hole in a tank
$h_{p,min}$	Minimum pool fire depth
H_{t}	Above ground height of vertical cylinder storage tank
H_{v}	Specific heat of vaporisation of substance
h_w	Tsunami inundation depth
i, j, k	Dummy variables
m	Substance mass
m_f	Mass of the fuel in fireball
M_w	Seismic moment magnitude

Symbols	Definitions
n	Coefficient associated with toxicity of the hazardous substance
n_D	highest damage severity level
$P(\bar{X})$	Complement probability of $P(X)$
$P(X\|Y)$	Conditional probability of X given conditioned on Y
P_a	Atmospheric pressure
P_E	Probability of death
PFF	Pool Fire Factor
$P_{H,1y}$	Annual probability of hazard exceedance
$P_{H,50y}$	Probability of hazard exceedance in 50 years
P_o	Peak overpressure
P_s	Pressure inside a storage tank
Q	Quantity of stored hazardous substance in storage tank
q_c	Combustion rate for pool fire
Q_{exp}	Quantity of explosives
Q_{fh}	Liquid quantity above a hole in a tank
Q_H	Heat radiation intensity per unit area
Q_{rel}	Released liquid quantity
q_{rel}	Liquid release rate
Q_{tot}	Total quantity of hazardous substance stored in a tank farm
R	Epicentral distance
RH_c	Radiative fraction of heat combustion

Symbols	Definitions
R_t	Radius of vertical cylinder storage tank
S	Physical consequence scenario (substance dispersion, fire, explosion, toxic exposure)
S_{ign}	Ignition consequence scenario
S_{tox}	Toxic dispersion consequence scenario
S_{VCE}	Vapor cloud explosion consequence scenario
t	Time
T_a	Atmospheric temperature
T_b	Boiling point of substance
t_{rel}	Duration of liquid release
V_{dike}	Capacity/volume of containment dike
v_i	Mean rate of an earthquake occurrence at the i^{th} seismic source
V_{rel}	Released liquid volume
$\beta_{c,DSi}$	logarithmic standard deviation at the i^{th} damage state for combined effect of natural hazards H_1 and H_2
β_{DSi}	logarithmic standard deviation at the i^{th} damage state
γ	Yield factor in VCE, i.e., the portion of the cloud that contributes to the explosion
Δ	Difference operation
$\theta_{c,DSi}$	median at the i^{th} damage state for combined effect of natural hazards H_1 and H_2
θ_{DSi}	median at the i^{th} damage state

Symbols	Definitions
$\lambda(H>h)$	Natural hazard curve, i.e., probability (or rate) of exceeding a certain hazard intensity level at a given site and in a specified period, for a range of intensity levels
λ_E *(Natech)*	probability (or rate) of individual risk due to a Natech accident in a specified period for a range of seismic intensity levels
λ_{EQ} *(Natech)*	probability (or rate) of an earthquake-triggered Natech event in a specified period for a range of seismic intensity levels
$\lambda_{EQ,TS}$ *(Natech)*	probability (or rate) of a Natech event due to earthquake and cascading tsunami hazards in a specified period for a range of hazards intensity levels
λ_{rel}	probability (or rate) of substance release in a specified period for a range of seismic intensity levels
λ_{TS} *(Natech)*	probability (or rate) of a tsunami-triggered Natech event in a specified period for a range of tsunami intensity levels
ρ	Mass density
σ	Standard deviation
τ_a	Atmospheric transmissivity
Φ	standard log-normal cumulative distribution function (Gaussian function)
φ	substance fill percentage

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