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Natech Risk from Floods. Vulnerability of Critical Technical Systems Containing Hazardous Substances

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Natural hazards, such as earthquakes, floods, landslides, lightning, strong winds, etc. can cause release of toxic substances, fires and explosions when they affect critical technical systems of industrial plants that treat, store or transport dangerous substances (e.g.: pressure tanks, heat exchangers, columns, pipes, atmospheric tanks, etc.). This type of event is called Natech (Natural Hazard Triggering Technological Disasters). Among the natural events that can impact industrial plants are floods (river floods, high water, debris and mud flows, flash floods); they are a recurring but often overlooked characteristic also considering the climate changes we are experiencing. A lack of awareness of this type of natural hazard can significantly limit the effectiveness of management approaches against Natech incidents.
In this work, authors propose to analyze vulnerability of the critical technical systems listed above following flood events, introducing a vulnerability index "I_V". Flood vulnerability index "I_V" depends on:

- "I_{Ves}": Type of equipment, process storage conditions of the dangerous substances contained;
- "I_{Vdm}": Main Flood Damage to Critical Equipment Mode.

"I_V" is obtained as the average of "I_{Ves}" and "I_{Vdm}". This paper, after having determined the value of "I_V" for single technical system, lists the main prevention and mitigation actions inherent to flood events.
Keywords: Critical technical systems, hazardous substances, floods, natech risk, Seveso directive, vulnerability

1. Introduction

Statistics show with increasing evidence that Natech events are increasing in terms of frequency. The accident data extracted from the MARS database of the European Commission show that from 1985 to today in EU countries of the approximately 7000 accident events that occurred in industrial sites, approximately 3% of them are classified as Natech, having been induced by natural events such as floods (16%), earthquakes (8%), landslides (7%), strong winds (13%) and lightning strikes (56%). The increase in Natech events is partly due to the growth in the number of industrial structures and the exposed population. Modern societies are more vulnerable, especially in urban areas, due to the concomitant presence of high population densities and concentrations of dangerous industries and infrastructures. One of the aggravating factors of Natech events is connected to the location of these activities in urbanized areas or near which the releases of dangerous substances can endanger the health and lives of many people (UNI 10617:2019).
Natech risk is a combination of three fundamental factors:

- H (Hazard): probability of occurrence of natural event in a fixed time interval and in a certain area
- V (Vulnerability): Understood as the propensity of critical technical systems containing dangerous substances to suffer damage following a natural event, it can be expressed as expected damage; it is defined as expected because it refers to a phenomenon whose intensity and frequency are not certain, but linked to a probability curve
- E (Exposure): extent and severity of the damage to the receptors (people, goods, infrastructures, services) potentially involved by the effects caused by the natural event.

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Usually, expresses itself (Muratore et al., 2022):

Natech Risk = f (H, V, E) (1)

Expression (1) is not easy to calculate, because its three variables are characterized by other variables.
Authors propose a simplified index method regulated by equation (2). This method can be applied to the single pressure equipment present within the same establishment:

$I_{NR} = I_H * I_V * I_E$ (2)

Reducing the Natech Risk means intervening on the three factors highlighted above. This can be done on newly located establishments. In the presence of existing establishments, therefore already located in an area, little can be done on the "H" and "E" factors, while it is possible to intervene with physical and procedural measures on the "V" vulnerability factor by reducing it. Among the natural events that can impact industrial plants are floods which bring together various phenomena: river floods, high water, flash floods. In fact, art. 2 of Floods Directive, highlights that *'flood' means the temporary covering by water of land not normally covered by water. This shall include floods from rivers, mountain torrents, Mediterranean ephemeral water courses, and floods from the sea in coastal areas, and may exclude floods from sewerage systems* (European Union, Directive 2007/60/EC). These natural events of flood origin are recurring but often overlooked feature. A lack of awareness of this type of natural hazard can significantly limit the effectiveness of management approaches against Natech incidents.

This work aims to synthetically analyze the "V" vulnerability of the damage caused to the critical primary containment technical systems previously highlighted following natural flood events through the following steps:

- Identify the types of critical primary containment technical systems containing dangerous substances (e.g.: atmospheric tanks, pressure tanks, reactors, stirrers, distillation columns, heat exchangers, pressure pipes, etc.) by analyzing the storage and process conditions of the dangerous substances contained (e.g.: temperature, pressure, physical state, volume)
- Analyze all possible damage to the individual technical system (e.g.: buckling, rupture of pipes and connections, tearing, displacement, overturning, puncturing damage, ignition and sparking, overfilling, support leg failure, shell-to-button delachment, etc.)
- Identify the vulnerability (V) of each critical technical system which as we know is one of the essential factors for determining the natech risk (NR) together with the hazard (H) and exposure (E)
- Corrective prevention and mitigation actions for flood events

The aim of this work is to focus on identifying the vulnerability of the main critical systems that are involved in a flood.

2. Actions and effects of floods and flash floods on structures, systems, and equipment

Operator of an establishment, based on information on dangers of flooding in the area where establishment is located, must integrate risks assessment that can be induced by these natural events.

The actions of floods and flash floods on establishments are:

a) those induced by the presence of water (floods with water speed < 1.5 m/s):

a1) horizontal hydrostatic thrust (in Newton, N), proportional to the square of the hydrometric height "h" (in meters, m) of the flood: $F_h = ½ γ b h^2$; $γ= ρ*g$ being the specific weight of the water (approximately 10000 in N/m^3), while "b" is the width in meters of the stream

a2) the buoyancy force, vertical force from bottom to top in Newton equal to $F_v = γ A h$, where "A" is the area of the horizontal surface in contact with water in m^2, while γ and h are defined above

a3) chemical and biological contamination

b) those determined by speed of the current (floods or flash floods with water speed > 1.5 m/s):

b1) hydrodynamic thrust exerted by the current (in Newton), proportional to the square of the speed "v" of the flood in m/s, F_d = thrust + momentum = $P A + ρ A v^2 = ½ γ b h^2 + ρ A v^2$ where "P" is the barycentric pressure of area A, while "ρ" is the density of water (approximately 1000 Kg/m^3), in case of water speed v < 1.5 m/s the value of F_d is slightly higher than F_h (point a1)

b2) impact of debris brought by the flood, the impact force expressed in Newton is equal to $F_i = mv/t$, where "m" is the mass of the impacting object in Kg, "v" is the speed of the object and "t" is the duration in seconds of the impact

b3) washout

b4) undermining of the foundations

Consequences of actions described above [points a) and b)] may consist in damage to buildings and storage and process equipment which may induce: 1) dispersion and transport of substances through air, water and soil dangerous for humans and environment; 2) development of violent reactions due to contact between water and chemical compounds that can generate toxic gases; 3) triggering of fires and explosions, with the probability of involving other equipment containing dangerous substances (domino effect).

In addition, among consequences, we can have interruption of electricity supply, damage to fire prevention systems, damage to IT systems, etc.

3. Flood vulnerability of critical equipment

In this article, critical equipment refers to technical systems for the primary containment of dangerous substances that may be involved in accidents sequences due to natural causes of flood origin.
Establishments where these technical primary containment systems are present are: chemical plants, petrochemical plants, refineries, petroleum product depots (liquids), liquefied gas depots (LPG, LNG), regasification plants, energy production systems, etc.
In order to determine the "I_V" flood vulnerability index of the aforementioned technical systems of primary containment of dangerous substances for the primary containment of dangerous substances, authors believe that it depends on: 1) type of equipment (e.g. atmospheric tank or under pressure tank); 2) type of dangerous substance; 3) storage operating conditions (pressure, temperatures, physical state, volume); 4) the different ways of damage depending on each type of equipment. In reference to this, the following are considered separately:

- I_{Ves}, equipment and substances vulnerability index
- I_{Vdm}, damage mode vulnerability index

In reference to this, the value "I_V" is taken as average of "I_{Ves}" and "I_{Vdm}":

$$I_V = (I_{Ves} + I_{Vdm}) / 2 \quad (3)$$

3.1 Type of equipment, process storage conditions of the dangerous substances contained. "I_{Ves}" determination

To determine value of flood vulnerability linked to technical systems for primary containment of dangerous substances "I_{Ves}", it is necessary to analyze dangerous substance, type of equipment and type of hypothesized rupture.

A) Hazardous substances and storage operating conditions

It is important to register dangerous substances present in establishment through analysis of the safety data sheets through, for example, the danger indications (H phrases or additional information on the EUH 0xx dangers reported in CLP European Regulation n. 1272/2008). We can have substances sensitive to heat (H251, H252, H240, H241, H242, H230, H231), substances reacting with water (H260, H261, EUH 014, EUH 029, EUH 031 and EUH032), substances reacting with air (H250, EUH 019).
Furthermore, it is necessary to take into consideration process and storage conditions of dangerous substances and how these influence possible accident scenarios; for example, here are some qualitative considerations that usually help the risk analyst (Landucci et al., 2014):

- Higher storage and process temperature of the dangerous substances present, greater damage occurs following release scenarios
- High pressure produces a driving force that results in a high rate of release of hazardous material in the event of rupture or leakage of a primary container of hazardous substance. Furthermore, a pressurized gas means more substance present in the storage. Furthermore, in the event of structural failure of the pressure storage, the projection of fragments in all directions must be taken into consideration
- State of matter influences quantity of dangerous substance present. Liquids contain a greater quantity of hazardous substances per unit volume than gases. However, gases have other properties that make them dangerous, they are usually stored and processed at high pressure
- Gases liquefied under pressure (e.g. LPG, LNG) have dangerous properties of both liquids and gases. They have a high density, comparable to those of liquids, are stored under pressure and evaporate immediately after release
- A further important aspect is the volume of hazardous chemicals. Higher volumes lead to larger accident scenarios, leading them to affect the outside of establishment

B) Types of primary containers of dangerous substances

Atmospheric tanks (anchored and unanchored) containing liquid substances

Anchored ones require solid foundations and a fixing mechanism to resist horizontal forces (earthquake, floods, etc.). Unanchored atmospheric tanks are particularly subject to horizontal forces, nevertheless, their use is more widespread because they are less expensive from the construction point of view.
In reference to this we can, with expert judgment, identify I_{Ves}, based on values ranging from 1 to 4:

Atmospheric tanks anchored with double bottoms and containment basins, which contain combustible liquids and with maximum filling: $I_{Ves} = 3$; if the filling is 50%: $I_{Ves} = 2$.
Atmospheric tanks not anchored and with maximum filling: $I_{Ves} = 4$; if the filling is 50%: $I_{Ves} = 3$.

Pressure tanks, reactors, agitators, columns, heat exchangers, pressure pipes
For this type of equipment, built in Europe according to 2014/68/EU Directive (PED – Pressure Equipment Directive), it is possible to determine the PED risk category: I, II, III, IV (going from I to IV, the risk increases). PED Directive contains specific tables from which the PED risk category can be obtained based on pressure energy contained (Pressure, Volume or DN for pipes) and the dangerousness or non-dangerousness of the fluid contained. Authors propose, with expert judgment, to identify I_{Ves} as reported in table 1, below (Muratore et al., 2023).

Table 1: Vulnerability index "I_{Ves}" for different types of pressure equipment

	Pipeline	Pipeline	Pipeline	Tall and lean pressure equipment (*)	Tall and lean pressure equipment (*)	Tall and lean pressure equipment (*)	Stubby pressure equipment (**)	Stubby pressure equipment (**)	Stubby pressure equipment (**)
	R1	R2	R3	R1	R2	R3	R1	R2	R3
Cat. PED: IV	Not Applicable	Not Applicable	Not Applicable	4	4	4	3	3	2
Cat. PED: III	3	3	2	3	3	3	2	2	2
Cat. PED: II	3	2	2	3	2	2	2	1	1
Cat. PED: I	1	1	1	2	2	2	1	1	1

(*) Equipment in which height (h)/radius (r) is greater than 4 (h/r>4). (**) Equipment in which height (h)/radius (r) is less than 4 (h/r<4).

To determine the type of failure of a flood equipment we can distinguish: slow submergence or low speed wave with release category R1 and R2; high speed submersion (Flash Flood) with release category R1, R2 and R3. For R1 we define a break that results in the instantaneous release of the entire contents (in less than 2 minutes). For R2 we define a break that causes the continuous release of the entire contents (in more than 10 minutes). For R3 we define a failure that involves the continuous release from a hole with an equivalent diameter of 10 mm.

3.2 Main flood damage to critical equipment. "I_{Vdm}" determination

The main flood damage to critical primary containment equipment is reported below (Necci, Krausmann, 2022):
Buckling damage: Deformation of metal enclosures is typical for many types of natural hazards when a sudden load affects the structure.
Rupture of pipes and fittings: Damage to piping typically results in loss of containment. Earthquakes and floods have been responsible for deformation and rupture of pipe networks especially at flanges and other types of connections by displacement of units connected to the network.
Tearing of metal shell: When the deformation is sufficiently large, the metal sheets that compose the shell of a vessel may fall apart and cause a loss of containment (LOC).
Detachment of the shell-to-bottom connection: In most atmospheric storage tanks the shell walls and bottom can be composed of two separate metal sheets. When buckling affects the lower part of a vessel, the annular connection between the wall and the bottom is heavily stressed.
Support leg failure: Many equipment units have support legs to sustain their weight. These legs are typically designed to sustain the equipment's own weight including its content and some horizontal excitation. In the case of earthquakes, lateral loads can exceed the design specification of support legs and cause their failure, resulting in the entire equipment to collapse on the ground.
Displacement and overturning: Flood (as well as earthquake) can exert strong forces on equipment, creating translation and rotation phenomena which can lead to a loss of contents.
Puncturing damage: Sharp objects pushed by floods, earthquakes, winds, etc. against equipment and pipes can cause deformations and holes with loss of containment.
Ignition and sparking: In addition to lightning, another cause of ignition are earthquakes and floods. They can induce violent movements of metal parts which can collide or brush against each other generating sparks.
Overfilling: Water can pour into important units containing hazardous materials during flooding and heavy rain events. In this case, the unit is not technically damaged, but its function and containment are compromised. This is a frequent LOC event for process plant parts.

Below is table 2, where the various modes of damage due to flooding are related to the main primary critical technical systems that contain dangerous substances (Necci, Krausmann, 2022).

Table 2: Damage modes vs Critical Technical Systems

Damage Mode	Flood (1)	Flash Flood (2)	Atmospheric Tanks	Pressurized tanks	Heat exchangers	Pipes under pressure
Buckling	X	X	X			
Rupture of pipes and fittings	X	X	X	X	X	X
Tearing	X	X	X			
Detachment of the shell-to-bottom connection		X	X			
Support leg failure		X	X	X	X	X
Displacement and overturning	X	X	X	X	X	X
Puncturing damage	X	X	X			
Ignition and sparking:	X	X	X			
Overfilling	X	X	X			

(1) Slow onset floods such as coastal floods and riverine floods. (2) Rapid onset flooding, including dam failures and tsunamis.

Using the data above, can be determined "I_{Vdm}" (value of vulnerability index) of each critical equipment linked to the different damage modes. This value considers number of different possible failure modes associated with each equipment. More numerous the possible failure mechanisms of an equipment, higher the value will be, always in a range from 1 to 4. Authors propose for each type of equipment:

- I_{Vdm} = 2, for a number of damage modes up to 4
- I_{Vdm} = 3, for a number of damage modes greater than 4 and up to 6
- I_{Vdm} = 4, for a number of damage modes greater than 6

Once the values of I_{Ves} (paragraph 3.1) and I_{Vdm} (paragraph 3.2) have been determined, we are able to determine I_V, overall flood vulnerability index, for each critical equipment with equation (3).

4. Corrective prevention and mitigation actions for flood events

Finally, authors report the main corrective actions for the prevention and mitigation of flood events. Among the interventions aimed at this purpose we can distinguish two classes: permanent interventions and temporary interventions (Muratore et al., 2023).

(i) Permanent interventions, aimed at increasing the resistance of industrial infrastructures with appropriate choices of materials and design solutions:

(a) anchoring at the level of foundations of the equipment under pressure so that they do not float or suffer overturning phenomena
(b) construction and / or strengthening of containment barriers or protection banks of waterways
(c) development and construction of an effective drainage system that contrasts the rise in the hydrometric level
(d) positioning of pressurized and / or cryogenic storage systems above the maximum expected hydrometric level
(e) construction of protective fences for equipment and machinery
(f) movement of electrical machinery, fire extinguishing systems, IT systems and energy distribution above the maximum expected hydrometric level
(g) preparation of signaling of evacuation routes in the presence of floods
(h) reinforcement pipes and connections
(i) provide flexible connections for pipes where possible
(j) strategic storage and placement of hazardous substances to avoid chemical incompatibility

(ii) Temporary interventions, strictly linked to the times with which the Authorities are able to disseminate the phase of a possible flood with warnings (public early warnings). The early warning consists of the set of actions, that can be implemented between the moment in which there is a reasonable certainty of the occurrence of a flood event in a given location and, the moment in which the event occurs (in the case of meteorological events, this interval can reach 24/48 hours as opposed to the earthquake which can last only a few seconds). These actions consist of measures to be taken in the event of imminent danger, including:

(k) interruption and safety of dangerous industrial processes; deactivating parts or subsystems of the system (automatic block or shut-off valves) to prevent the release of dangerous substances
(l) anchoring of the structures most at risk and structurally more fragile with steel cables or similar

(m) verification of the tightness of the storage tanks, through the hermetic sealing of the silos and underground storage tanks
(n) de-location and storage of reactive chemicals and hazardous materials in areas at higher and safer altitudes
(o) activate autonomous production of electricity or energy saving, so that the control systems are also available during the event
(p) evacuation of personnel not essential for emergency operations
(q) internal emergency plans (IEP), in order to consider any preventive alert systems that may be present in the plant or in the area where it is located and to ensure that the actions to be implemented in response to early adoptions have been identified and clearly indicated in said documentation warnings issued by such systems.

(iii) Resilience interventions, in addition to the two classes of interventions (permanent and temporary) identified above in points (i) and (ii), it is now essential to add a further point (iii):
(r) develop organizational resilience in establishment (including those containing pressure equipment) involving all safety actors (primarily workers who interface with the plants).

5. Conclusions

Reducing the Natech Risk means intervening on the three factors H (Hazard), V (Vulnerability) and E (Exposure). This can be done on newly located establishments. In the presence of existing establishments, therefore already located in an area, little can be done on the "H" and "E" factors, while it is possible to intervene with physical and procedural measures on the "V" vulnerability factor by reducing it.
Purpose of this article is to identify a method for determination of the vulnerability inherent in flood events involving critical technical systems for primary containment of hazardous substances.
Once the "I_V" vulnerability has been determined, the main corrective actions for the prevention and mitigation of flood events are reported. The implementation of these actions determines the reduction of the vulnerability index and consequently of the overall natech risk.
Finally, although the work focuses on establishments covered by the European Seveso directive (2012/18/EU), the principles of damage caused by natural flood events on the various technical systems that contain dangerous substances can also be adopted in other industrial sectors excluded by Seveso directive.

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