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Flood risk assessment for pressure equipment

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Floods are natural phenomena that cannot be prevented, but increasing human settlements and economic assets in floodplains and the reduction of the natural water retention by land use together with climate change contribute to increase the likelihood of adverse impacts of flood events. In light of the recent hydrogeological instability phenomena throughout Europe, we conduct an in-depth study on the aspects related to the management of flood risk in workplaces with pressure equipment. In the presence of pressure equipment, the flood risk can lead to the release of dangerous substances, concomitant events such as explosions, toxic dispersions, surface pollution of water bodies and aquifers. For a correct assessment of flood risk, we considered three factors: H (Hazard): probability of occurrence of a flood event in a fixed time interval and in a certain area; V (Vulnerability): probability of equipment damage related to maximum water velocity (v) and maximum water height (h); E (Exposure): extent and severity of the damage to the receptors (people, goods, infrastructures, services) potentially involved by the effects caused by the flood event.
The purpose of this work is to propose an index method for a preliminary flood risk assessment for pressure equipment (Steam Generators, Reactors, Pressure Vessels, Piping, etc.) present in industrial plants. After defining the level of risk, if it is not acceptable, the main corrective actions are proposed.

Keywords: flood risk, occupational safety, risk assessment, risk treatment, pressure equipment and assemblies.

1. Introduction

In Europe, economic losses due to floods have steadily increased in recent years. Many manufacturing activities in all sectors are vulnerable to adverse weather conditions. The danger of flooding can never be eliminated and therefore every employer using pressure equipment (Steam Generators, Reactors, Pressure Vessels, Piping, etc.) must prepare in advance to limit the impact that a flood can have on its activities through a series of prevention and / or protection actions. Pressure equipment, present in the process industry establishment, are normally sources of risk due to operational causes (breakdowns and malfunctions inside the establishment). Climatic changes have highlighted the presence and potential importance of external factors such as floods that can negatively affect pressure equipment. The purpose of this work is to propose an index method for a preliminary flood risk assessment for pressure equipment (Steam Generators, Reactors, Pressure Vessels, Piping, etc.) present in industrial plants. After defining the level of risk, if it is not acceptable, the main corrective actions are proposed. This work is developed based on a previous article (Muratore A., et al.) presented at ESREL 2022 international conference entitled "Flood risk identification and analysis for pressure equipment". The authors, being pressure equipment safety experts, chose to analyze the impacts of flooding on pressure equipment and not on other types of equipment, including for example atmospheric storage tanks. We want to highlight that the present study has the pressure equipment as its objective, since the latter, in the event of breakage, lead to losses of both product and energy. In fact, containing fluids under pressure, for example: an outflow of gas leads to the formation of a cloud, which will be subject to a transport and diffusion phenomenon depending on the local meteorological characteristics. Toxic substances can be transported very far from the source of release, just as the cloud can catch fire and possibly explode at a distance from the source of release, with damage to people and environment even outside the boundary of the industrial plant.

Furthermore, some of the activities that contain pressure equipment fall within the scope of Directive 2012/18/EU. In relation to the latter aspect, the operator of a plant with major accident hazards must also provide for the adaptation of its Safety Management System – Major Accident Prevention Policy (SMS-MAPP), to prevent or limit the consequences for human health and the environment. According to ISO 31000: 2018 *"risk"* is *"effect of uncertainty on objectives"*. *"Risk assessment is the overall process of risk identification, risk analysis and risk evaluation"*. For "*risk level*", we consider *"the size (measurement) of a risk in terms of the combination of consequences and probability*". The level of flood risk is a combination of three fundamental factors:

- H (Hazard): probability of occurrence of a flood event in a fixed time interval and in a certain area;
- V (Vulnerability): probability of equipment damage related to maximum water velocity (v) and maximum water height (h);
- E (Exposure): extent and severity of the damage to the receptors (people, goods, infrastructures, services) potentially involved by the effects caused by the flood event.

Usually, expresses itself:

$$Flood\ Risk = f\ (H, V, E)\ (1)$$

Expression (1) is not easy to calculate, because its three variables are characterized by other variables.

Authors propose a simplified index method regulated by the expression (2). This method can be applied to the single pressure equipment present within the same establishment:

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

Where I_{RF} is the Flood Risk index that depends on I_H: Hazard index of the place where pressure equipment is located, I_V: Vulnerability index of the pressure equipment and I_E: Exposure index. In the following paragraphs, it will be described how to determine I_H, I_V, I_E. From a graphical point of view, everything can be represented by a three-dimensional matrix with orthogonal axes I_H, I_V, I_E, giving each of the three indices numerical values ranging from 1 to 4.

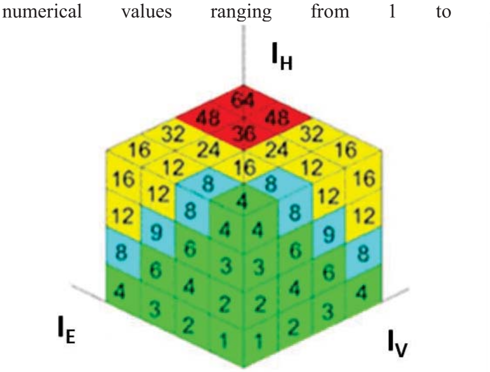

Fig. 1. Three-dimensional flood risk matrix for pressure equipment

2. Actions and effects of floods on pressure equipment and industrial plants

The employer of an industrial plant based on the information acquired on the dangers of floods and landslides in the area where the plant is located must integrate the risk assessment with particular reference to pressure equipment present. The actions of floods on pressure equipment can be hydrodynamic, hydrostatic, erosion, flotation, etc. These actions can be divided into two categories (Muratore A., et al.):

- Induced by water (horizontal hydrostatic thrust, buoyancy thrust, etc.);
- Determined by the speed of the current (hydrodynamic thrust, impact of debris brought by the flood, washout and undermining of foundations / anchors, etc.).

The employer must be aware that flood events can cause serious damage to industrial plants and trigger the accidental release of hazardous substances into the surrounding environment. The direct consequences can consist of:

(i) damage to buildings and storage and process equipment (where pressure equipment is often present), due to the thrust of water and the impact with the structures of debris, even large ones, dragged by the force of the water, which can induce containment losses of dangerous substances capable of determining:
   (a) dispersion and transport in the air (in case of formation of a toxic cloud), in the water and in the soil of substances that are dangerous for man and for environment;
   (b) development of violent reactions due to contact between water and chemical compounds that can generate toxic gases;
   (c) ignition of fires and explosions, with the possibility of involving other equipment and tanks containing dangerous substances (domino effect).

(ii) in the interruption of vital services such as the electricity supply;

(iii) in the saturation of the effluent recovery network;

(iv) in the impossibility of accessing the establishment or parts of it.

3. Hazard index of the place where pressure equipment is located (I_H)

Directive 2007/60/EC (Floods Directive) relating to the assessment and management of flood risk with the aim of reducing risks of negative consequences deriving from floods, provides for a preliminary assessment of the risk of floods, the development of hazard maps and flood risk and the preparation and implementation of flood risk management plans. In Italy, the Italian Institute for Environmental Protection and Research, (Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA)), published in 2021 Mosaicking (ref. year 2020) (Trigila A. et al.) which defines extension of the floodable areas throughout the Italian territory for each of the probability scenarios provided by art. 6 of Floods Directive:

- High Probability Hazard (HPH): high probability of floods;
- Medium Probability Hazard (MPH): medium probability of floods;

- Low Probability Hazard (LPH): low probability of floods.

These scenarios correspond to the floodable areas following flood events with return times. The mapping of the hydraulic hazard areas on the national territory correspond three hazard scenarios:

- HPH with a return time between 20 and 50 years (high probability of floods);
- MPH with return time between 100 and 200 years (medium probability of floods);
- LPH with a return time of more 200 years (low probability of floods or extreme event scenarios).

In addition to the extension of flood, the flood hazard maps should indicate, for each of the three scenarios highlighted above, the height (height with respect to the mean sea level) or the depth of the flood (height with respect to the ground) (h) and the velocity of the flow (v). Table 1 shows the values of I_H (hazard index) divided into three levels linked to the return period of the flood.

Table 1. Hazard index (I_H)

I_H	Levels related to return period of flood
1	Location of the plant containing the target units (pressure equipment) in a flood hazard area (Low Probability Hazard LPH - low probability of floods)
3	Location of the plant containing the target units (pressure equipment) in a flood hazard area (Medium Probability Hazard MPH - medium probability of floods)
4	Location of the plant containing the target units (pressure equipment) in an area of hydraulic danger (High Probability Hazard HPH - high probability of floods)

From what has been highlighted above, in Italy it is possible to establish (I_H) flood hazard index according to the location of the plant that contains pressure equipment; in addition to this we can have information on the height (h) of the flood defined above and possibly the velocity of the flow (v). If velocity of the flow is not shown in the maps, can be made to the Manning formula (3):

$$v = \frac{1}{n}\left(\frac{A}{p}\right)^{\frac{2}{3}} s^{\frac{1}{2}} \quad (3)$$

where:

v is the cross-sectional average velocity (L/T; m/s);
n is the Manning coefficient. Units of n are often omitted, however n is not dimensionless, having units of: ($T/[L^{1/3}]$; $s/[m^{1/3}]$).
A is the cross sectional area of flow (L^2; m^2);
p is the wetted perimeter (L; m);
s is the stream slope or hydraulic gradient, the linear hydraulic head loss (L/L); it is the same as the channel bed slope when the water depth is constant. ($s = h_f/L$).
Figure 2 is a representation of Italy with the floodable areas by flood hazard scenario: high (High Probability Hazard - HPH) and medium (Medium Probability Hazard - MPH), Mosaicking ISPRA, 2020 (Trigila A. et al.).

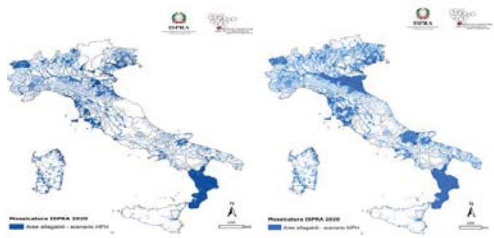

Fig. 2. Mosaicking ISPRA 2020 for high (HPH) (on the left) and medium (MPH) (on the right) hazard scenarios

4. Vulnerability index of individual pressure equipment (I_V)

The vulnerability index (I_V) that authors propose in this work depends on:

- type of failure that involves a given release (R1, R2, R3);
- PED risk category of pressure equipment (Risk category I, II, III, IV).

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.

4.1. *Determination of type of breakage*

In the previous paragraph, we saw that the hazard maps also contain the height values (h) and the velocity of the alluvial flow (v). These values will be used to determine the damage estimate of equipment. In the case of floods, simplified and consolidated models for estimating damage to equipment are not available in the literature. Therefore, starting from the analysis of few available data, a simplified damage model was developed, which links the maximum water velocity (v) and the maximum water height (h) to the probability of damage to equipment (Antonioni G., et al.):

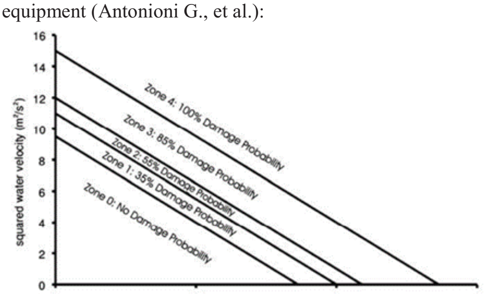

Fig. 3. Flood event probability of damage, function of the water level and the square of the water velocity

Figure 3 shows the regions associated with different damage probability values. Once these damage probabilities have been estimated (see Fig. 3: Zone 0, Zone 1, Zone 2, Zone 3, Zone 4), authors associate these damage probabilities with: Impact mode, Structural damage and Risk categories (R1, R2, R3) as shown in Table 2.

Table 2. Correlation between flood impact mode, structural damage of equipment and risk category R1, R2, R3

Damage Probability	Impact mode	Structural damage	Risk categories
Zone 0, Zone 1	Slow submersion	Failure of flanges and connections	R3
Zone 2	Low velocity wave	Mantle fracture Failure of flanges and connections	R2 R3
Zone 3, Zone 4	High velocity wave	Impact with adjacent structures Mantle fracture Failure of flanges and connections	R1 R2 R3

4.2. *Determination of PED risk category for each pressure equipment*

Using the product directive 2014/68/EU (PED – Pressure Equipment Directive), relating to pressure equipment and/or assemblies, it is possible to determine PED risk category: I, II, III, IV (going from I to IV the risk increases). The Directive contains specific tables from which PED risk category can be obtained according to the pressure energy contained and the dangerousness of the fluid

4.3. *Determination of vulnerability index (I_V)*

Table 3 shows vulnerability index values for each type of pressure equipment. The values depend on the type of release, which in turn depends on damage probability (Fig. 3) as well as on PED risk category (see par. 4.2).

Table 3. Vulnerability index for different type of pressure equipment (I_V)

	Pipeline	Pipeline	Pipeline
	R1	R2	R3
PED cat.: IV	Not Applicable	Not Applicable	Not Applicable
PED cat.: III	3	3	2
PED cat.: II	3	2	2
PED cat.: I	1	1	1
	Tall and lean pressure equipment (i.e. equipment where height (h) / radius (r) is greater than 4, h/r>4)	Tall and lean pressure equipment (i.e. equipment where height (h) / radius (r) is greater than 4, h/r>4)	Tall and lean pressure equipment (i.e. equipment where height (h) / radius (r) is greater than 4, h/r>4)
	R1	R2	R3
PED cat.: IV	4	4	4
PED cat.: III	3	3	3
PED cat.: II	3	2	2
PED cat.: I	2	2	2
	Stubby pressure equipment (i.e. equipment where height (h) / radius (r) is less than 4, h/r<4)	Stubby pressure equipment (i.e. equipment where height (h) / radius (r) is less than 4, h/r<4)	Stubby pressure equipment (i.e. equipment where height (h) / radius (r) is less than 4, h/r<4)
	R1	R2	R3
PED cat.: IV	3	3	2
PED cat.: III	2	2	2
PED cat.: II	2	1	1
PED cat.: I	1	1	1

5. Exposure index (I_E)

Exposure takes into account human lives, environmental damage, economic damage, etc. To determine exposure deriving from floods involving pressure equipment, one must start from the type of dangerous substances that are present, their physical state, the type of processing (process, storage, etc.), the type of expected event (explosion, toxic release, fire, dispersion of toxic fumes following a fire), the amount of dangerous substances. For estimation of exposure in this article, a qualitative method based on expert judgment is proposed, attributing an increasing weight from 1 to 4 according to the importance of the surrounding land use class. Greater weights have been assigned to residential classes which involve a constant anthropic presence and decreasing weights to different types of productive activities, favoring the more concentrated activities (industrial activities), compared to extensive activities (agricultural activities). Table 4 shows a correlation between exposure index (I_E) and land use classes surrounding the establishment containing pressure equipment.

Table 4. Relationship between Exposure index (I_E) and land use classes

I_E	Land use classes surrounding the establishment
1	Credible scenarios following impact of a flood event on pressure equipment, which has repercussions both inside establishment and outside establishment on areas with uncultivated ground
2	Credible scenarios following impact of a flood event on pressure equipment, which has repercussions outside establishment on extensive agricultural areas (agricultural activities)
3	Credible scenarios following impact of a flood event on pressure equipment, which has repercussions outside establishment on industrial areas
4	Credible scenarios following impact of a flood event on pressure equipment, which has repercussions outside establishment on areas affected by production and commercial activities involving a constant human presence
4	Credible scenarios following impact of a flood event on pressure equipment, which has repercussions outside establishment on areas with residential homes and areas of certain impact (strategic buildings)

In the last scenario, strategic buildings mean control rooms, emergency management offices, first aid, fire sheds, etc. of establishment where pressure equipment is located.

6. Flood risk index (I_{RF}) for pressure equipment and risk treatment

By applying what is indicated in the previous paragraphs, it is possible to obtain the numerical values (from 1 to 4) for I_H, I_V and I_E. Therefore using expression (2) we can obtain a numerical value for Flood Risk Index (I_{RF}), which varies for each critical target unit (pressure equipment) within the same industrial site. Table 5, based on the numerical value of I_{RF} for various target equipment, show different risk acceptability, intervention priorities and corrective actions for prevention and mitigation. Paragraph 7 detail corrective actions of prevention and mitigation.

Table 5. I_{RF}, Risk acceptability

I_{RF}	Risk acceptability	Intervention priority of corrective actions	Corrective actions for prevention and mitigation
$I_{RF} > 32$	Not tolerable	Intervention priority 1 Corrective Actions cannot be postponed	Permanent interventions: (a), (b), (c), (d), (e), (f), (g), (h), (i), (j). Temporary interventions: (k), (l), (m), (n), (o), (p), (q) Organizational resilience: (r)
$12 \leq I_{RF} \leq 32$	Improvable	Intervention priority 2 Corrective actions in the short/medium term to be planned	Permanent interventions: (a), (b), (c), (d), (e), (f), (g), (h), (i), (j). Temporary interventions: (k), (l), (m), (n), (o), (p), (q) Organizational resilience: (r)
$I_{RF} < 12$	Tolerable	Intervention priority 3 Corrective actions to be included in a continuous improvement cycle	Temporary interventions: (k), (l), (m), (n), (o), (p), (q) Organizational resilience: (r)

7. Corrective actions of prevention and mitigation for floods on pressure equipment

As corrective actions to prevent and / or protect against potential events induced by flood phenomena, emergency planning is required that includes the improvement of mitigation measures in order to reduce damage to pressure equipment. Among the interventions aimed at this purpose we can distinguish two classes: permanent interventions and temporary interventions (Muratore A. et al.).

(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 take into account 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) 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).

Providing for specific and further training which aims to create a resilient organization capable of responding to events, monitoring what happens, knowing how to anticipate risks and ultimately learn from past experience (Poljanšek K., et al.).

8. Conclusion

The purpose of this work is to develop a preliminary flood risk assessment, according ISO 31000:2018 standard "Risk Management - Principles and guidelines", based on an index method for individual pressure equipment (steam generators, reactors, vessels, exchangers, pipes, etc.) present in industrial plants.
Once the level of risk has been defined, if it is not acceptable, authors propose some of the main corrective actions, in order to facilitate the employer's decision-making processes regarding the prevention and/or protection measures to be implemented with the related intervention priorities (Risk Treatment). Furthermore, some of the activities that contain pressure equipment fall within the scope of Directive 2012/18/EU. In relation to the latter aspect, the operator of a plant with major accident hazards must also provide for the adaptation of its Safety Management System – Major Accident Prevention Policy (SMS-MAPP), to prevent or limit the consequences for human health and the environment.
Finally, we want to highlight that the present study has the pressure equipment as its objective, since the latter, in the event of breakage, lead to losses of both product and energy. In fact, containing fluids under pressure, for example: an outflow of gas leads to the formation of a cloud, which will be subject to a transport and diffusion phenomenon depending on the local meteorological characteristics.
In reference to this, toxic substances can be transported very far from the source of release, just as the cloud can catch fire and possibly explode at a distance from the source of release, with damage to people and the environment even outside the boundary of establishment.

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