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Flooding of Industrial Facilities - Vulnerability Reduction in Practice

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International databases such as OFDA / CRED show that floods accounted for more than half of disasters registered for the 1990-2001 period. With consequences of climate change largely unpredictable at local level, future statistics are not likely to show any improvement. As human activities historically developed in river areas and floodplains, industrial facilities are structurally exposed to flooding. Past events witnessed industrial vulnerability to flooding, including direct impact on structure, loss of safety measures, loss of utilities, business interruption, etc.
In response of such natural-technological interaction, mitigation efforts have taken two main directions: land-use planning in flood-prone areas and vulnerability reduction in flood-prone facilities. This paper focuses on the former issue and presents a methodology for the mitigation of flood impacts on industrial facilities.

1. Introduction

Even if the accidents caused by flooding form a statistically marginal group in terms of events (see chemical accidents databases analysis made by Cozzani and al. (2010), and when compared to other more frequent major accidents (technical problems, human errors), it is clear that human, material and environmental consequences of these accidents can be significant and should not be neglected.
When flooded, industrial facilities present direct (damage to buildings, tanks, pipes, storage of raw materials and finished products, pumps, electrical, thermal and mechanical equipments) and indirect (business interruption, temporary unemployment, rising of insurance premium) consequences. As shown by the analysis of past accidents, the damages may cause major accidents within industrial plants. These include release of hazardous material, soil or water pollutions by hazardous substances for the environment, fires, explosions, dispersion of toxic clouds.
It is therefore necessary that industrial plants managers improve their understanding of potential impact of flooding on their facility, and analyse major accidents or release of hazardous materials that may be caused by such a natural event in order to prevent them.
Therefore INERIS (French Institute for Industrial Environment and Risks) proposes a methodology for the integration of flood hazard in industrial safety assessment, presented in the following paragraph. Then a suggestion of possible safety barriers against flood is made. However will be discuss the experience gained after implementation of this method to an industrial site.

2. Methodology for integration of flood hazard in industrial safety assessment

The methodology for the integration of flood hazard in risk-reduction process for industrial plants, proposed by INERIS, follows a sequence in 3 steps, as detailed below:

- Step 1: Characterization of flood hazard,
- Step 2: Preliminary risk analysis,
- Step 3: Detailed risk analysis.

2.1 Step 1 : Characterization of flood hazard

This first step aims at determining whether the studied plant is located in a floodable area or not. If it is the case, data are needed to better understand the flooding, such as type of flooding (direct overflow of rivers, overflow indirectly by rise of water table in aquifer, excess runoff, dike failure, tsunami), water height, flow velocity, speed of water level rising, flooding duration, return period of flood.
This work could rely, for example, on documents and/or flood hazard maps (see Figure 1 below), if any, produced or supervised by government and/or public administrations:

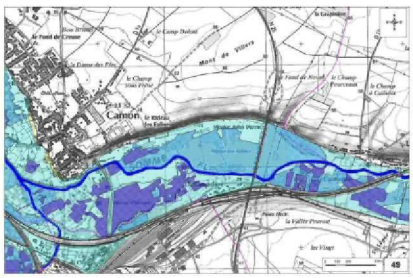


Figure 1: Example of flood hazard maps (Somme river - France)

It is underlined that the Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks requires Member States to identify (end of 2011) and map river basin districts and coastal areas at risk (end of 2013) for different flooding scenarios

2.2 Step 2 : Preliminary risk analysis

Based on information gathered in step 1, the topography of the industrial plant, and the location of buildings and facilities within plant perimeter, areas which could be affected by flooding are identified.
Maps of flooded areas in the plant, for different water heights, can be drawn (see Figure 2 below):

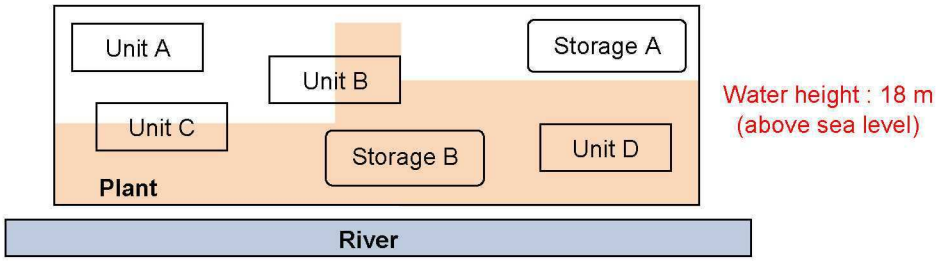


Figure 2: Potentially flooded areas on the industrial site

In the potentially flooded areas, we can identify facilities and equipments that could cause major technological accidents.
Selecting items vulnerable to flooding is based on analysis of:

- Lessons learned from floods that have already occurred on the studied plant or on similar industrial facilities,

- Hazardous properties of substances and preparations / mixtures contained in the facilities and equipments (use of Material Safety Data Sheets), with a particular attention drawn on the chemical products which emit flammable or toxic gases in contact with water,
- Consequences induced by the loss of utilities,
- The behaviour of structures under action of water (flotation, overturning, impact of a floating object).

For these selected equipments, the flood hazard should be considered as a common cause of failure for both the equipment and its associated safety devices.
A systematic risk analysis (Hazard Analysis, Hazard Identification - Hazid, for example) is performed for each equipment. The accidental sequences leading to dangerous phenomena (fire, explosion, toxic cloud dispersion, pollution) are detailed, and existing safety barriers are highlighted. See Table 1 below for an example of the type of accident sequence derived from the risk analysis process.

Table 1: Extract of Preliminary Risk Assessment - Storage tank containing flammable liquid

Initiating events	Critical event	Dangerous phenomena	Safety barriers
Ripple effect (for torrential floods) Collisions with floating objects	Significant breach in the tank	- Soil and water pollution - If ignition, fire and explosion	- Attach the bottom of the tank - Drain the tank in case of flood warning
...	...	...	...

Different dangerous phenomena, identified for each vulnerable equipment, are likely to occur simultaneously in case of flooding ("Initial event") which could be a common cause of "Critical events". The resulting accidental sequences are then represented graphically, as shown in Figure 3.

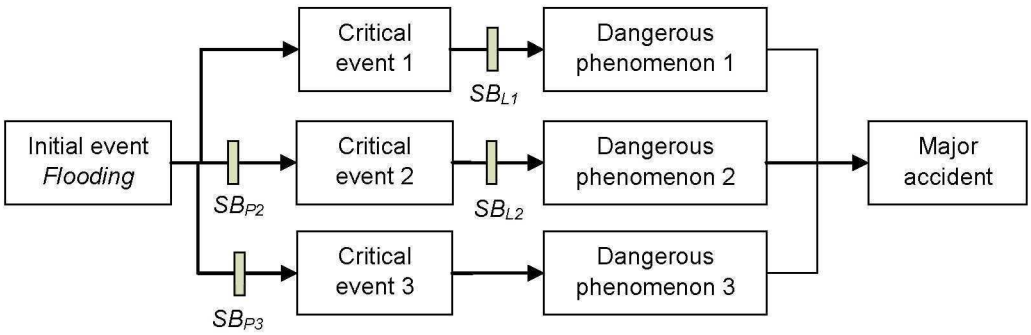


Figure 3: Representation of accidental sequences causing by flooding

2.3 Step 3 : Detailed risk analysis

The safety barriers are analysed more in details in terms of performance (efficiency, maintainability, testability). Each barrier shall be assessed also in terms of kinetics, depending on implementation time, availability of human resources, technical devices, etc. Depending of the available time before the arrival of water and resources in case of flooding, some safety barriers are also selected primarily for risk assessment and emergency plan (Figure 4).

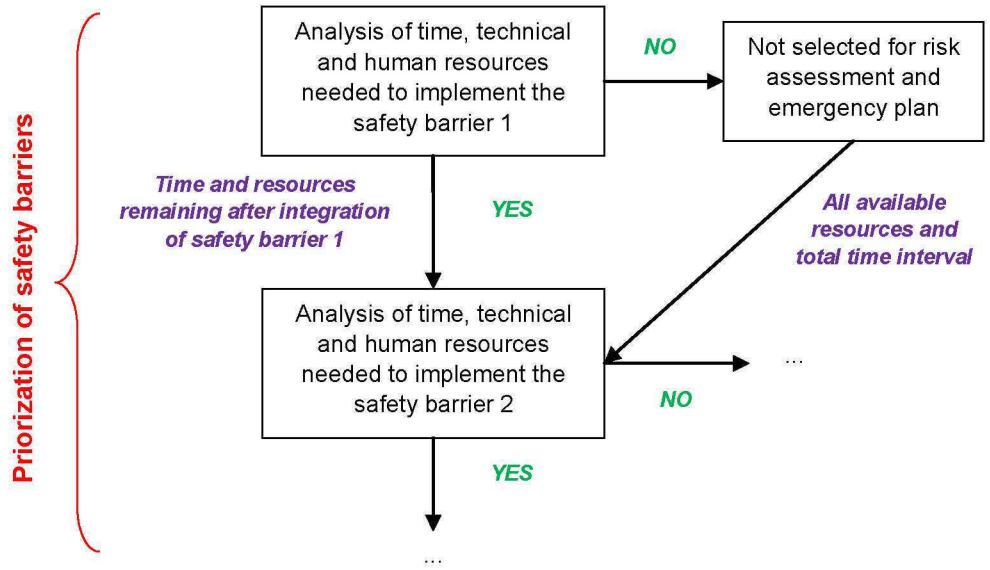


Figure 4: Selection of safety barriers for risk assessment and flooding emergency plan

For risk assessment, the first calculation is conservative because it does not take into account the existence of safety barriers (Figure 5). This leads then to a single major accident, characterized by a probability (Pf) equal to the probability of the flooding and a total severity (S) which is the union of severities of each accident caused by the different critical events CE1, 2 and 3. The dangerous phenomena DPh1m, 2m and 3m are phenomena of maximum intensity.

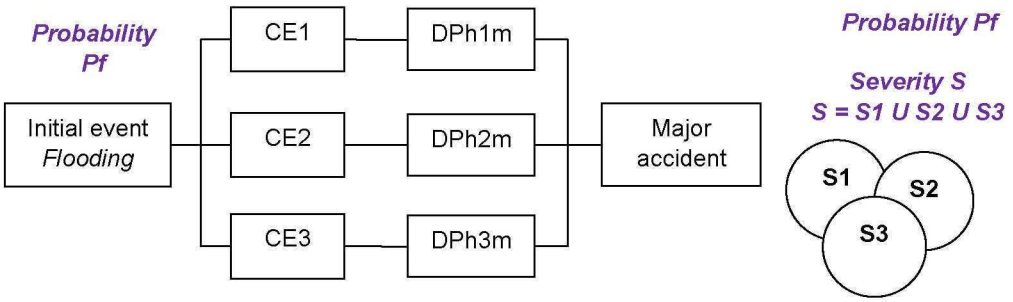


Figure 5: Probability and severity assessment - Conservative calculation

The second calculation takes into account the safety barriers, considering also their possible failure and consecutive major accidents that might occur.
We can consider for example the case where the barriers SB_{L1} and SB_{P2} are failing, while barriers SB_{L2} and SB_{P3} are working normally.
Therefore dangerous phenomenon DPh1 is characterised by a maximum intensity, DPh2 has limited intensity and DPh3 does not occur. The probability of occurrence of the major accident is determined by combining the probability of flooding (Pf) and the safety barriers failure probabilities (P_{L1}, P_{P2}, P_{L2}, P_{P3}) (see safety barriers performance evaluation approach developed in France and presented by Lenoble and Durand (2011): $P_{MA} = Pf \times P_{L1} \times P_{P2} \times (1 - P_{L2}) (1 - P_{P3})$
The severity of the major accident is the combination of the severity of DPh1 (maximum intensity) and the severity of DPh2 (limited intensity).

The same approach can be used to identify all other possible accidents.

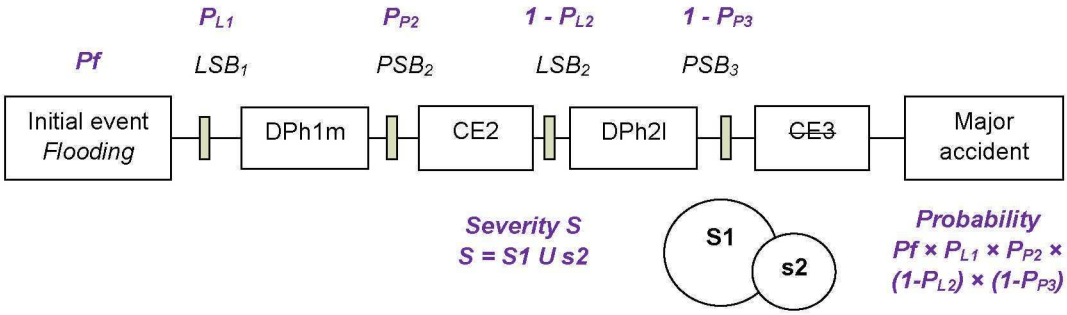


Figure 6: Probability and severity assessment - Example of calculation with safety barriers

2.4 Possible (and non exhaustive) measures to reduce vulnerability to flooding

An indicative list of possible measures to reduce the vulnerability of industrial facilities to flooding is proposed:

- Build walls around the critical equipments, those which are the most important for operation and safety,
- Close certain openings,
- Control, and if necessary, strengthen tanks attachment,
- Move storage to areas that are not likely to be flooded,
- Move equipments, sensors, networks (electricity, gas, water, telecommunications, computer system...) above the highest past flooding water height,
- Install system to cut automatically power and gas supplies,
- Provide pathways which cannot be flooded to make intervention easier, and refuge area outside water for staff...

The choice of measures may vary depending on the configuration of the plant.

Design arrangements are preferable to non-permanent measures that will be implemented just in case of flood warning.

The performance of safety barriers to protect against effects of flooding is highly dependent on the time available to secure industrial facilities and on the good operability of utilities (electricity, gas...), before the water arrival. However, in general, the industrialist does not have its own devices to monitor the river nearby, and must refer to information and alerts provided by authorities. The utilities networks can be cut at any time. It is hoped that the flood warning would be transmitted as soon as possible so that there is time to act.

3. Experience gained after implementation of the method to a French industrial site and perspectives

The INERIS method, presented in this paper, was tested in 2011 on an SEVESO low-tier industrial establishment in France. The first lessons learned are presented below.

The success of the step 1 depends on the data related to flood hazard. Luckily the information was available for the experimental field. But this is not the case currently for all areas potentially affected by flooding in France. In addition, data collected from various services (local authorities, flood forecasting service) may be contradictory. France and most countries in Europe have initiated the production of flooding maps, but this work will take a long time.

The choice of the flooding reference scenario can also cause problems: is the flood with a return period equivalent to 100 years (for design of buildings in France) acceptable for dangerous industrial facilities, or should we consider a more serious flooding (millennial flooding for example)? Do we have to assume that the chosen flooding reference scenario could be exceeded at any time, and rather to determine for which flood the plant will undergo major malfunctions?

If there are no measurements of the topography for the plant, the identification of areas prone to flooding could not be refined and the analysis will be considering large impacted areas.
Behavior under the action of water for usual industrial structures like atmospheric tank, pressure vessels, pipes can be determined, but it is more difficult for example for equipment such as reactors, columns, sensors, valves. The action of water in case of direct overflow of river must be distinguished from the action of water in case of failure of dike/dam or tsunami, because of the shock effect that this leads to structures. Calculation models or simple assessment criteria have to be established for industry so they can determine the vulnerability of their equipment.
We saw that dangerous phenomena such as fires, explosions, toxic clouds could be caused by flooding. The resulting human effects can be evaluated easily with commonly used tools. But, when hazardous substances are mixed with water, the impact on the environment (pollution of surface water, groundwater, soil) is difficult to assess. This aspect could be improved in the method.
The quantification of probability and severity is difficult and long to implement, especially when many critical events (with the associated dangerous phenomena) may occur and several safety barriers that must be considered. The major accidents identification would probably need to be computerized. Users of this methodology can however make the choice to implement qualitative approach only (step 1, step 2 and step 3 but only the priorization of the safety barriers and the establishment of a flood emergency plan).
INERIS guide explaining the different steps of this method (revised according to lessons learned into practice) is currently under preparation and will provide industry and legal authority with recommendations to prevent major accident in case of flooding.

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