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Na-Tech accidents induced by floods: an approach to hazard and risk assessment

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Several accidental events that occurred in chemical and process plants in the last decades evidenced that floods may cause severe damages to process plants and storage sites, resulting in multiple and extended releases of hazardous substances. Moreover, besides conventional release scenarios (fires, explosions and toxic clouds), floods may cause two further critical events: significant environmental contamination due to water pollution, and release of toxic gases and flammable vapours generated by reactions of chemicals with water. In the present study a qualitative assessment procedure was defined to identify the possible modes of structural damage of equipment items, also considering different categories of floods. The procedure also allows the identification of the credible scenarios that may be associated to the different modes of structural damage and then the identification of critical equipment items. The methodology was applied to the analysis of some case-studies.

1. Introduction

Major accidents in industrial plants and storage sites where relevant inventories of hazardous substances are present may be triggered by natural events as floods, due to the damage of process equipment resulting in a loss of containment (LOC). Severe accidents are reported in the literature and in the databases (MHIDAS 2001, Reinders 2003) but limited data are available about the impact of floods in process and chemical plants. Moreover scarce attention was devoted to the assessment of the risk related to these events and to the analysis of the consequences of possible accidental scenarios. The industrial accidents triggered by flood events may be a relevant cause not only of direct damages to the population in nearby residential areas due to the effects of the event (blast waves, toxic releases, etc.), but also of indirect damages due to the delay of emergency rescue operations following the event.
The present study was dedicated to the analysis of the hazard deriving from the impact of floods on sites where a relevant inventory of hazardous substances are present. The starting point of the study was the analysis of the past accidents in order to identify the category of equipment more frequently involved in these events, the more recurrent damage modalities and the consequent scenarios associated. A procedure for the industrial risk qualitative assessment of accidents triggered by flood events in industrial facilities was developed. The final aim of the study was the assessment of the contribution of natural events to the risk indexes of conventional QRA, in the perspective of a “robust” and effective emergency planning in residential areas near to industrial sites.

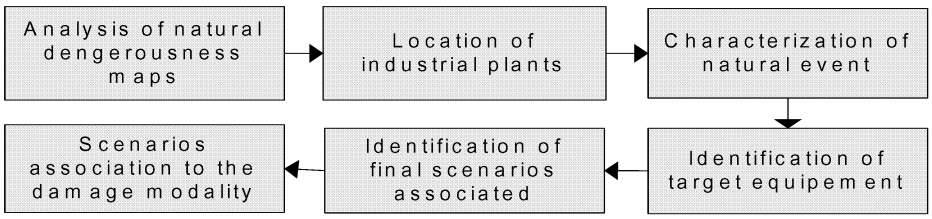

Figure 1. Flowchart of the procedure developed for the assessment of accidental scenarios triggered by floods involving industrial plants

2. Procedure for the assessment of industrial risk caused by floods

2.1 Introduction to the procedure

The available past accident data about the industrial accidents caused by floods are too scarce to carry out a detailed analysis. The information about past accidents, recorded in the databases, are not sufficient to define correctly the possible failure modality of equipment items. Furthermore, the characterization of the flood events is mostly based only on the return time, since severity parameters are usually not available unless specific analyses were performed on the site. In particular, the expected water depth and the flood energy or flood speed are usually not reported in general flood hazard assessment studies. Thus, it is still not possible to obtain simplified models to assess the vulnerability or the fragility of the different equipment items. Therefore, at the state, in the case of floods, only a qualitative assessment procedure was defined to identify the possible modes of structural damage of equipment items, also considering different categories of floods. The procedure allows the identification of the credible scenarios that may be associated to the different modes of structural damage. The identification of critical equipment items and the qualitative ranking of hazards were also allowed by the procedure. At the present stage of development, the assessment methodology is based on the application of the six main steps of the procedure shown in figure 1.

2.2 Identification of critical equipment items and assessment of the incidental scenarios associated

The starting point for the evaluation of the incidental scenarios which may follow flood events is the analysis of the hazard condition causing the final scenario. The parameters involved in this analysis are: i) the hazardous properties of the substances; ii) the hold-up of the equipment, that influences the quantity of substance released; iii) the expected type of structural damage. The substances of concern in the case of floods should be selected. Besides toxic and flammable substances usually considered in conventional QRA approaches, in the case of floods the analysis should be extended to substances reacting with water developing toxic gases and/or flammable vapours. Indeed, the behaviour of these substances may lead to further incidental scenarios that may require a revision of the event trees used in the assessment, as discussed in the following. In order to identify the critical equipment items, the four following categories of equipment were defined, having a progressively increasing hold-up: 1) reactors and heat exchangers; 2) columns; 3) piping; 4) vessels (process and storage). Only the scenarios credible in the case of flood impact were retained and associated to the different storage or operating conditions. The credible scenarios identified as a possible consequence of flood impact were thus associated to the different storage or operating conditions. This analysis was carried out for three main substance categories: i) substances toxic for

human health; ii) substances hazardous for the environment; and iii) flammable substances. Furthermore, the substances that may present a specific hazard in the case of flood events (i.e. substances that react with water) should be considered. Indeed, it must be remarked that besides conventional release scenarios (fires, explosions and toxic clouds), floods may cause two further critical events: significant environmental contamination due to water pollution, and release of toxic gases and flammable vapours generated by reactions of chemicals with water. Thus, severe environmental contamination as well as toxic cloud dispersion may be triggered by floods. However the scenario severity depends both on the substance quantity, on its reactivity, solubility and toxicity. Therefore, on the basis of the characteristics and of the expected severity of the scenarios associated to the each equipment category, it was possible to identify the more critical categories of process equipment, and to rank the hazard associated to each critical category assigning a degree of severity increasing from 1 to 4, as shown in table 1.

Table 1. Matrix for the identification of the more critical equipment items in different storage conditions.

Equipment category	***Liquefied Gas***	***Liquid (cryogenic, evaporating, stable)***	***Gas***
Vessels	4	4	3
Piping	4	3	2
Columns	4	2	1
Reactors and heat exchangers	3	2	1

2.3 Structural damage modality definition and association to possible final scenarios

The procedure developed in this study also allows the identification of credible scenarios, defined in the previous step, to the different modes of structural damage. To this aim, the equipment items were classified on the basis of structural characterisics. Indeed, it is expected that the structural analogy should lead to similar damage states. The scarce data available on past accidents and having a sufficient detail confirmed this assumption. The equipment categories defined for this purpose are the following: i) cylindrical vertical vessels having diameter to height (D/H) ratio higher than 1 (atmospheric); ii) cylindrical vertical vessels having D/H<1 (atmospheric and pressurized); iii) cylindrical horizontal vessels (atmospheric and pressurized). Three possible modalities of water impact were assumed and were associated to credible typologies and extents of structural damage. Also on the basis of the release categories suggested in the “Purple book” (Uijt de Haag et al. 1999), three classes of releases were considered for storage and process equipment, as well as for piping: R1, the instantaneous release of the complete inventory (in less than two minutes) following severe structural damage; R2, the continuous release of the complete inventory (in more than ten minutes); R3 the continuous release from a rupture having an equivalent diameter of 10 mm. Table 2 shows an example of the release categories associated to different modalities of impact of floods involving cylindrical vertical vessels.

Table 2. Modes of structural damage for pressurized vessels: cylindrical verical vessels, D/H<1, and cylindrical horizontal vessels.

Modality of water impact	*Type of structural damage*	*Release category*
Slow submersion	Failure of flanges and connections	R3
Modearate speed wave	Failure of flanges and connections	R3
High speed speed	Shell fracture	R2
	Impact with/of adjacent vessels	R1
	Failure of flanges and connections	R3

The accidental scenarios that are expected to follow the releases were identified by the event tree technique. Besides the event trees usually applied in conventional QRA, others were introduced in order to consider the scenarios triggered by substances reacting with water. The figure 2 shows an example of a specific event tree developed for the substances identified by risk phrases R14, R15, R14/15 and R15/21 under Directive 67/548/EEC and following amendments. Table 3 reports some examples of the final accidental scenarios associated to atmospheric vessels involved in floods. As shown in the table, the scenarios are mostly dependent on the release category and on the type of hazard posed by the substance. The table also evidences that the particular features of flood events are also likely to result in accidental scenarios in which water contamination takes place.

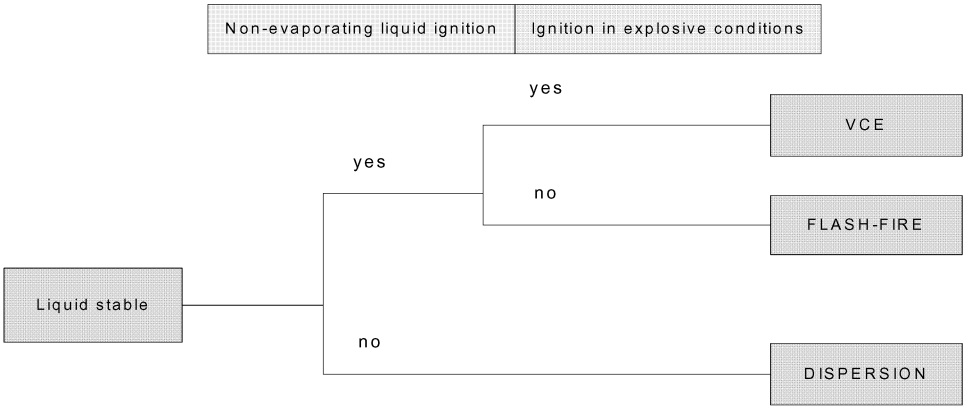

Figure 2. Event tree modified for istantaneous release of liquid substances generating inflammable vapours by reaction with water (substances classified with risk phrases R14, R15, R14/15, R15/21)

Table 3. Summary of the association between structural damage and final scenarios for atmospheric vessels containing inflammable or toxic substances.

Damage typology	*Release categoty*	*Final scenarios*	
		flammable	*toxic*
Catastrophic failure	R1	Pool-fire Fireball VCE	Water contamination, dispersion
Failure of roof or shell fracture	R2	Pool-fire VCE	Water contamination, dispersion
Impact of/with adjacent vessels or with trailed objects	R1	Pool-fire Fireball VCE	Water contamination, dispersion
Failure of flanges and connections	R3	Minor poolfire, VCE	Water contamination

2.4 Case-studies

The above discussed procedure was applied to understand the criticality of these events for the sites falling under the obligations of the "Seveso" Directive in an Italian region.

Table 4. Example of the critical release scenarios triggered by flood events identified for "Seveso" sites in an Italian region

Critical Sites	*Substances/activity classification*	*Quantity (t)*	*Frequency (years^{-1})*	*Scenarios associated*
1 (A)	Gas liquefied extremely inflammable and natural gas	170	0.002	Fireball-VCE-flash fire-jet fire
2 (A)	Chromic acid-toxic R23-25, dangerous for the environment R50, R51/53	5.4	0.002	Toxic vapour dispersion-water contamination
3 (A)	Ammonia-toxic R23-25, inflammable R10, other category R14	2	0.002	Toxic vapour dispersion-pool fire-violent reaction with water
4 (B)	Phytopharmacological/ Phytosanitary products	-	0.005	Water contamination

3. Conclusions

In this study a procedure for the qualitative assessment of industrial risk caused by floods was developed. The methodology allows the identification of the possible modes of structural damage of equipment items and the definition of the associated scenarios. The analysis of past accidents highlighted the possible hazards due to flood-induced releases and showed the criticality of such accidents in the presence of relevant flood events. The application of the procedure to some case-studies confirmed the actual possibility of interactions between industrial risk and flood risk, thus calling for the need of a specific assessment of the problem in land-use planning.

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