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Analysis of Major Industrial Accidents Triggered by Natural Events Reported In the Principal Available Chemical Accident Databases

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1. Introduction

1.1 Natech events

The term "Natech" refers to natural disasters triggering technological accidents. In fact, because of the interaction between the natural and the industrial risk it is possible that several effects take place in industrial plants and in the storage sites, causing for example damage to pipelines, to process equipment, to storage tanks and consequently the release of hazardous materials.

There are different kinds of natural events or, in general terms, of natural causes of industrial accidents (landslides, hurricanes, high winds, tsunamis, lightning, cold/hot temperature, floods, heavy rains etc.), nevertheless in the present study the attention is focused only on seismic and flood events. In fact, several accidents occurred in the last decades in industrial sites evidenced that typology of natural phenomena may cause severe damages to equipment items, resulting in losses of containment, thus in multiple and extended releases of hazardous substances. Because of these multiple and simultaneous failures with release, cascading events are more likely to occur during a natural disaster than during normal plant operation. Some examples of Natech events like the flood in the Samir refinery in Mohammedia, Morocco, in 2002 (Krausmann et al. 2007) or the Kocaeli earthquake in Turkey in 1999 are available in the scientific literature or in the accident databases (Figures 1-3). In both cases the natural event occurred in a refinery and involved several storage equipment items and generated fires and explosions. These reports allow to better understand the particular severity of the industrial accidents triggered by flood and seismic events (ARIA 2006, DFC 2003, MARS 2006, MHIDAS 2001, NRC 2007, Reinders et al. 2003, TAD 2004).

The reference for the prevention of chemical accident in the European Commission is the *Seveso Directive II* (96/82/EC). The aim of the Seveso Directive is "*Prevent Major accidents which involve dangerous substances and to limit their consequences for man and environment with a view to ensuring high levels of protection throughout Community in a consistent and effective manner"* (Council Directive 1996).

The Seveso Directive is addressed indirectly to Natech risk management; in fact it calls for the analysis of the external events in "The identification and accidental risk analysis and prevention methods". The analysis of external events which can lead to chemical accident implies the consideration of the potential threat of natural hazards in the hazard analysis, and carrying out mitigation measures in case an accident occurs (Cruz et al. 2004). Nevertheless the methodologies and the actions that can be taken to achieve these requirements are not specified and limited work has been devoted to the development of quantitative assessment procedures for Natech risk.

Figure 1.Fire in the refinery due to earthquakes.(Turkey, 1999)

Figure 2.Flood impact in a refinery

Figure 3.Hydrocarbons spread by floodwaters

1.2 Aim of the work

Since there are different kinds of natural events and the consequences of their impact on the industrial sites can vary depending on the natural phenomena, it could be useful to develop a general and unified framework for the assessment of the risk due to Natech events in order to have an only approach of effect/impact analysis for every case of natural cause. The aim is to implement a procedure for the assessment of the contribution of Natech events to standard industrial risk indices beside the QRA (quantitative risk analysis). Figure 4 shows an example of the general procedure to assess Natech risk (Antonioni et.al 2007, Cozzani et al. 2007).

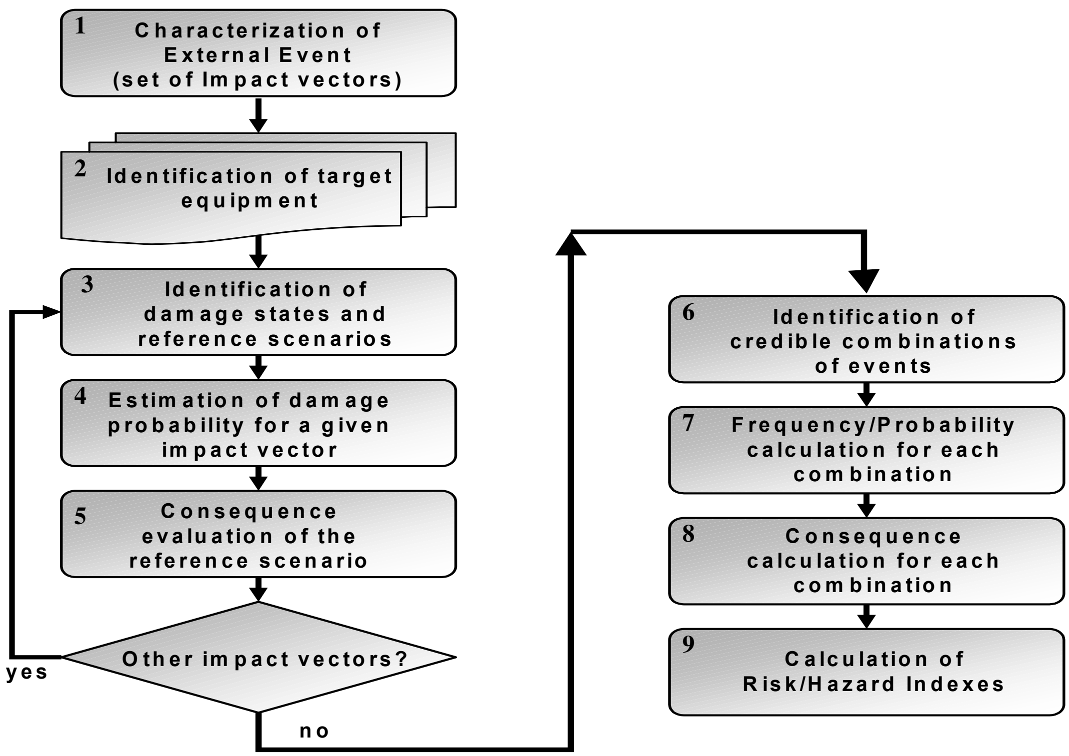


Figure 4.Procedure for the assessment of the industrial risk caused by natural events.

As we can see in this figure the framework is general but in two steps (the first and the fourth) some parameters specific for the considered natural event need to be inserted. The aim is to arrive at the quantification of the value of the industrial risk indices, but this requires applying in the fourth step specific sub-models in order to describe the vulnerability of every equipment item target of the natural event.

In Figure 5 an example of fragility curves is shown.

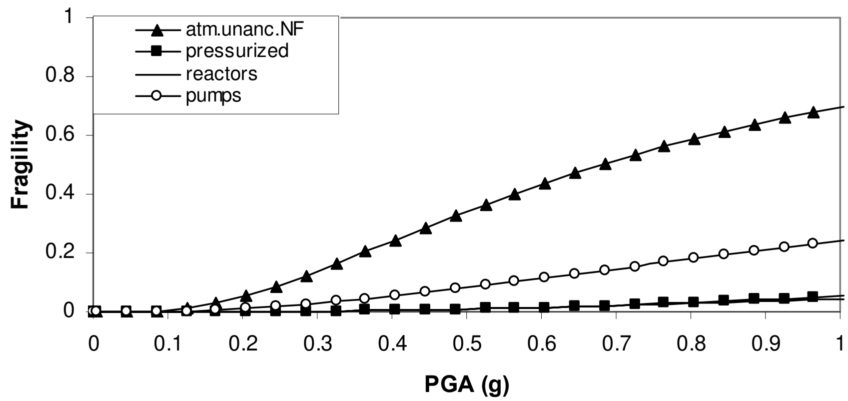


Figure 5. Seismic fragility curves for some equipment items

Those simplified empirical equipment vulnerability models are based on observational data and allow in the case of seismic events to evaluate the damage probability for different kind of equipment items (Campedel et al. 2007). Therefore, in the case of earthquake it is already possible to obtain the values of the industrial risk indices, although these models need to be improved in order to increase their reliability.

At present, in the case of a flood event, it is only possible to arrive at a preliminary identification of possible damage to equipment and of the consequences of the release of hazardous materials, but it is not possible yet to obtain a precise quantification of the hazard and risk associated to these events. In fact there are not sufficient data to define exactly the damage states and their probability of occurring, so simplified vulnerability models are not available yet. Furthermore it is difficult to obtain data about the characterization of the flood event, and, as we saw in Figure 4, this represents the first step of the developed procedure.

In order to characterize the flood impact vector it is sufficient to refer to two parameters: frequency and severity of the flood. The standard parameter for the frequency is the return period (T_r) measured in years and given by hydrological studies. Since there are different kinds of flood events, for example floodplain inundation with high water level or flash flood with high water velocity, we need to distinguish the possible modalities of flood impact (slow submersion, moderate speed wave, high speed wave). The flood severity can be quantified by two parameters: water depth and water speed. Figure 6 shows an example of maps with water speed and water depths obtained after a simulation of flood scenarios using a two dimensional hydraulic model.

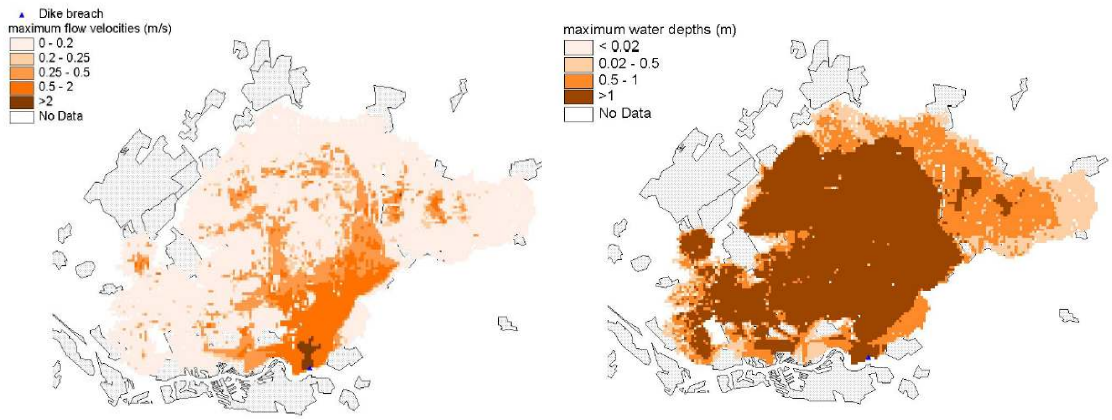


Figure 6.Maps with water velocities and water depths obtained with specific software tools.

It is very useful to know the value of the severity parameter because thus it is possible to calculate the overall pressure acting on the process/storage equipments items on the basis of the hydrostatic and hydrodynamic pressure.

Knowledge of the overall pressure value allows to identify different failure modalities for the process/storage vessels. For example, for atmospheric storage tanks it is possible that the external pressure leads to collapse of the shell for instability due to reaching the critical pressure. Instead, for pressurized horizontal vessels the yielding of support structures like the anchorage saddles is possible. Thus the overall pressure value can be correlated to different damage modalities. In order to do this the exact damage states need to be known and these damage classes need to be correlated to the intensity of the severity parameters. Only in this way simplified equipment vulnerability models can be developed. Also it is very useful to obtain the threshold limit values for structural damage with loss of containment and with consequent release of hazardous materials. In the scientific literature some examples are available (DCP 2003):

- *h* : *High water level* condition (*h* > **1** m and minimum velocity required *v* = **0.25** m/s)
- *v : High flow condition* (v > **2** m/s and water level h = **0.5** m): support structures may start to collapse
- high risk :h = **1**m and v = **1**m/s

But these values are not sufficient to carry out a detailed vulnerability analysis in order to develop the “fragility” functions as in the case of seismic events.

A starting point in order to obtain these data and to get a possible correlation between data of natural event severity and effects on the equipment items can be the historical analysis of past accidents. In fact, the aim would be the review of records on industrial accidents triggered by natural events to identify:

- the categories of equipment more frequently involved in these events
- the more recurrent damage modalities
- the associated scenarios
- a possible correlation between the severity parameter of the natural event and the vulnerability of the equipment items in order to develop simplified models.

It was possible to identify different credible ways of structural damage depending on the water impact modalities for some storage equipment categories; in Table 1 an example is shown for pressurized vessels: cylindrical vertical vessels, D/H<1 (D is the diameter and H the height) and cylindrical horizontal vessels. The results of the historical analysis can be useful to confirm these defined correspondences between the damage classes and the severity of the flood event.

Table 1.Structural damage modality for pressurized vessels: cylindrical vertical vessels, D/H<1 and cylindrical horizontal vessels.

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

In general terms the accidents involving hazardous materials can have severe consequences on the population, on the environment and on property. Therefore it is very important to reduce their incidence. The information obtained through the historical analysis allows to avoid the recurrence of accidents and to improve the emergency response in future accidents.

1.3 Contents of the report

This report contains the results obtained through a statistical analysis of past industrial accidents triggered by flood and seismic events. On the basis of the records reported in the principal accident databases and in other sources it was possible to organize the data in pie and histogram charts and in some tables.

The results allowed to confirm some results obtained previously, to highlight new aspects and to compare the different effects caused by the two natural events. Unfortunately it was not possible to find the specific data that would have allowed the quantification of the damage equipment probability. However, the analysis clarified which aspects still need to be studied in detail and which way to follow in order to develop simplified vulnerability models for the principal equipment items.

2. Retrieval and organization of past accidents data

2.1 Available data sources

The historical analysis was carried out through the consultation of the principal available European chemical accident databases (ARIA, FACTS, MHIDAS, MARS, ICHEME database) and of one from the United States (NRC). Different keywords and approaches were used because each database presents distinctive characteristics in recording and organizing the data. Finally, before to begin the statistical analysis it has been useful to make homogeneous the extracted data preparing the Excel files in order to organize the records on the basis of the same category of information (date, location, involved substance etc.) Only the records related to the Natechs in fixed installations and pipelines have been extracted for the analysis.

In Figure 7 the distribution of the identified records among all the analyzed databases reported.

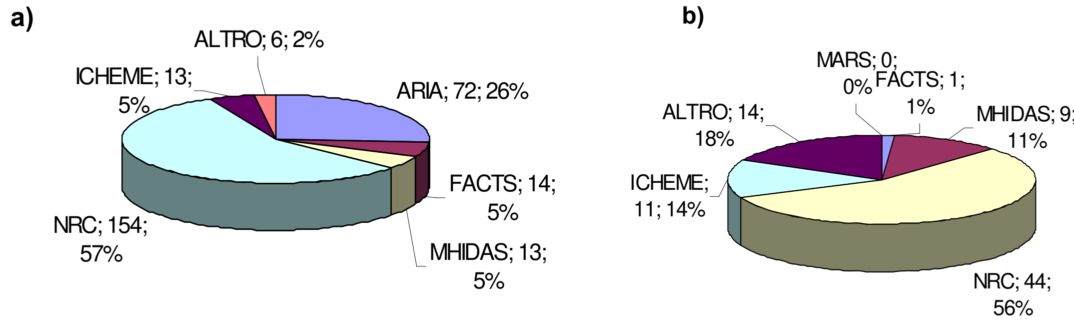


Figure 7.Distribution of the Natech accident events identified in the analysis of the available chemical accident databases: (a) flood events (272 records, 1960-2007), (b) seismic events (78 records, 1930-2007).

As it is possible to see the most records are from NRC database, instead in some cases there are not data from ARIA or MARS database because their recorded data were already extracted previously in other databases.

ARIA

The ARIA database (Analyse, Recherche et Information sur les Accidents) is managed by the French Ministry of Ecology and Sustainable Development (ARIA 2006). In this database it is possible to find the records about actual accidents but also near misses which could compromise the health, the public safety, the agriculture, the nature and the environment. The information recorded in this database is mainly from the Department of Civil Protection and from the French Ministry of the Environment. The recorded accidents involve the industrial plants and the farms of the France and of other countries. In total, the recorded events are 30859 and only 25361 occurred in France in the period from 1900 to 2005. Considering only 2005 the most significant accidents are 1978 for the French territory and 105 for the other foreign countries. On the basis of a detailed analysis previously carried out, the accidents with natural causes represent 5% of the records related to 2005 (1978) and 7% of those related to the period from 1992-2005. Table 2 shows the distribution of the causes for the accidents of which the cause is known: 808 records which represent 41% of the events occurred in 2005, and 8538, or 39% of the accidents occurred between 1992 and 2005.

Table 2. Distribution of the causes of the accidents in the ARIA database.

Principal causes of the accidents	**2005 (%)**	**1992-2005 (%)**
Anomalies in the organization	19	14
Human error	19	23
Loss of the process control	8.9	9.7
Incorrect use of the hazardous materials	3.5	1.7
Insufficient and inadequate intervention	0.7	1.7
Dangerous equipments	2.5	3.1
Lack of feeding	3.8	44
Lack of utilities	0.7	0.6
Natural causes	5	7
External events	1.6	2.2

Principal causes of the accidents	2005 (%)	1992-2005 (%)
Chronic pollution	0.6	3.1
Attempts/criminal external attacks	8.3	7.1
Other causes	2.5	6.7

The historical analysis of the ARIA database was carried out considering the period from 1900 to 2006 (31 December) and using the following keywords:

- Seismic event: *seisme, movement du terrain, troumblement de terre*
- Flood events: *precipitations, inundation, crue, debordement*

The total number related to accidents caused by natural events is 846 and it covers the period form 1948 to 2006. Only 72 records were selected, neglecting events not really correlated to a natural event or involving rail/road/ship transport of hazardous materials or not actually correlated to industrial installations.

When the records are detailed enough their severity is quantified through the European scale shown in the Figure 8.

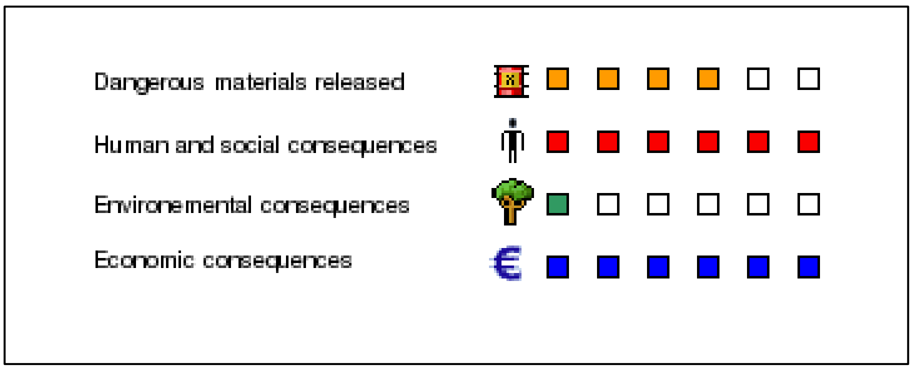


Figure 8. European scale of the accidents

For every accident a reference level is assigned to four different parameters: dangerous materials released human and social consequences, environmental consequences and economic consequences.

FACTS

The FACTS database (Failure and Accidents Technical information System) is a product of TNO industrial and external safety and it contains information on the accidents which caused or could cause (near misses) severe consequences. The information stored in FACTS is often obtained from professional sources, such as accident reports made by companies, government agencies or from publications in technical periodicals and other literature. Of course, information from a number of sources is confidential. FACTS contains more than 21,600 descriptions of accidents involving hazardous materials. All accidents recorded in FACTS are coded in abstracts so as to make the data available for the purposes of risk and safety management, risk analyses, damage prevention, training and emergency response (FACTS online (website), Reinders et al. 2003).

The accidents retrieved from FACTS are presented on three different informational levels. The first level is the 'accident table' containing an overview of the main features of the selected accidents. The second level is the 'accident abstract', containing coded identification and a description of the accident. The third and last level is the 'extended abstract' which, if available, contains the complete textual information about the accident.

In the case of this database it was not possible to consult directly the records because FACTS was not available directly, but 30 accidents caused by seismic and flood events were found through a publication from Delft University (Reinders et al. 2003). After a selection of the available records only 15 events were used in the statistical analysis. These records are related to previous FACTS version (2001) in which there are 17000 recorded accidental events and only an 1.76% with natural causes.

TAD by IChemE

The IChemE database is a product of the Institution of the Chemical Engineers, an international professional membership organization for people who have an interest in and relevant experience in chemical engineering. In order to carry out the historical analysis only data about the industrial accidents triggered by flood and seismic events were extracted. The following Figure 9 shows an example of a record from the IChemE database for the seismic impact on a refinery with accompanying damage to a storage tank. This report represents the structure followed in this database to organize and to present the recorded data. The information is often very concise as in this case. In fact, there are no details about the type of structural damage and about the presence or release of stored substances and the release mechanism and path.

2163 24 February 1981
Source : ICHEME **Location :** , GREECE **Injured :** 0 **Dead :** 0
Abstract An earthquake damaged a tank at a refinery storage. [refining, damage to equipment]
Lessons [None Reported]

Figure 9. Example of a record from the IChemE database for an earthquake impact on an industrial plant.

The IChemE database contains data obtained through different sources such as for example “Loss prevention bulletin”, or “Institute of Insurers” and the research of the stored records can be undertaken choosing specific keywords (which in the present work was only “flood” and “earthquake”).

MARS

The MARS (Major Accident Reporting System) is a database set up and maintained by the European Commission’s Joint Research Centre in Ispra (MAHB) that allows to carry out a complex text retrieval and pattern analysis. This database is used by EU and OECD (Organization for Economic co-operation and development) member countries to report industrial accidents in the MARS standard format and to exchange accident information on this basis.

For every record there are three sections: Report Profile, Short Report and Full Report. The Report Profile contains information to identify the event: date and place of the event, establishment (name and address plant, type of industry and Seveso status). All data contained in the Report Profile are confidential.

In the other two sections it is possible to find more details about the causes of the accidents, the circumstances, the evolution and the consequences, and the responses to major accidents. The Short Report is public information and contains free text fields which allow the quick notification of available information about the accident within a few months, and contains fields such as immediate effects, substances directly involved, immediate sources of accidents, emergency measures taken, lessons learned and suspected causes.

The Full Report is also confidential and contains far more detailed information about the accident and has both free text and predefined selection lists to control the input. It is prepared by the Competent Authorities after the event has been completely investigated (which could be several months or even years) and the causes, the evolution and the consequences of the accident are fully understood.

The historical research of this database was carried out selecting among the suspected causes of the Short Report only the environmental causes. Only 32 accidental events were found of the 602 total records (Status September 2007) and of these only one event was related to floods.

<u>MHIDAS</u>

MHIDAS (the Major Hazard Incident Data Service) is a database managed by AEA Technologies Ltd. (Warrington,UK) by commission of the British Health and Safety Executive. This database contains information on 7000 accidents that occurred in transports, during process activity, or the storage of hazardous materials and with potential off-site impact. The impact generated by an accident comprises: number of fatalities, damage to the plants, to property and the environment. The stored files are based mainly on the information from dailies and then they are very schematic, concise and organized through keywords and often the reconstruction of the events is not immediate.

Every record stored in MHIDAS is coded on the basis of a standard form including details like the involved hazardous substances, number of fatalities, number of injured, number of evacuation and a short description of the accident. In MHIDAS it is possible to find records from 95 countries, mainly from USA, UK, Canada, France, Germany and India. The historical research was carried out using the following keywords:

- Seismic event: *earthquake*,
- Flood event: *flood, flooding*

We decided to analyse only 13 records related to flood events and 9 related to seismic events on the basis of the considerations done in the previous paragraphs.

<u>NRC</u>

The NRC (National response center) is the sole federal point of reference for reporting oil and the chemical spills in the USA. In fact, every day the National Response Center receives reports about the release of hazardous substances such as chemical, radiological, biological and etiological discharges into the environment anywhere in the United States and its territories. The NRC contains all the received records in the national database where each file represents a particular calendar year and contains the data related to incidents which occurred during that year. Every record contains the following information frame:

- Time and date of the accident
- Location of the accident (City and State)
- Incident type
- Source and cause of the release
- Type and quantity of the involved material
- Number and type of injuries
- Weather conditions
- Medium affected
- Emergency personnel respond

In the NRC database it is possible to find some summaries (an example is shown in Figure 10) on the most significant industrial accidents. In fact, it publishes the summary reports periodically upon receipt of documentary information from the Federal On-Scene Coordinator.

Occurrence Date:	13 July
Location:	Austell, GA
NRC Report Number:	765364
Source:	Storage Tank
Material:	Gasoline
Severity:	Major
Quantity Discharged:	13,000 Gallons
Quantity in Water:	Unknown
Body of Water Affected:	Unknown
Federal On-Scene Coordinator:	EPA Region IV
Description: On July 13, 2005 at 1321 (EDT) the National Response Center received a report from British Petroleum of a 13,000 gallon discharge of gasoline from three underground storage tanks due to flooding. The incident occurred on July 13, 2005 at 1130 (Local Time) at 141 Maxham Road in Austell, GA. The caller did not know if any of the gasoline reached a waterway. Five employees evacuated the immediate area due to the spill. There were no reports of any fires, injuries, or fatalities. An emergency response team is on-site. EPA IV is the FOSC. **Case Closed.**	

Figure 10. Example of a record with the summary of a severe accident.

The data can be accessed with Excel but the record do not always contain detailed information about the accident and the related scenarios. In fact, very frequently is only the presence of the release without specification of the source or the damage modality which led to the loss of containment is reported.

In order to carry out the research in this database is not possible to refer to keywords but instead word filters were used. For example for this analysis we selected “natural phenomena" and "flood", "earthquake" in the available natural causes, and "storage tanks" and "pipelines" in the type of accident. It was not possible to quantify exactly the total number of accidents caused by floods because for every file related to one year the total number of records is around 30000 results.

2.2 Data of interest

The aim of this analysis was to research detailed information about industrial accidents triggered by seismic and flood events, in order to obtain enough data to improve the developed procedure for the assessment of the Natech risk. The data of interest can be different depending on the considered natural event. In the case of earthquakes some simplified vulnerability models are available in order to describe and to analyze the behavior of the equipment items during a seismic event. In fact, on the basis of the observational data some empirical functions have been developed, called "Probit" and they can be converted into fragility curves to quantify the probability of an equipment item to reach a given damage state. Nevertheless, these models are not available for every type of equipment item and the same degree of detail is not present in all models. Therefore, they need to be continuously improved to increase the reliability of the results. For seismic events the following data is required:

- Data on the modalities of structural damage with and without release
- Information about possible ignition which followed the release
- Data on the typology of accidental scenario
- Data on the typologies of equipments more involved

In the case of a flood event, as was explained in the previous paragraphs, a correlation between the parameters of the characterization of the natural event and the impact on the equipment items still needs to be found. Therefore simplified vulnerability models are not available yet, consequently it is not possible to quantify the final value of the industrial risk indices. In the case of this natural event, besides the data listed above for the earthquake case, the following data needs to be collected:

- Characterization of the typology of the flood event (flashflood or plain flood)
- Data on the values of the water level and water velocity
- Data on the correspondence between the parameters of the characterization of the flood event and the effects on the equipment items, in order to develop preliminary vulnerability models.
- Examples of the link between the severity of flood event and to take place of accidental scenarios typical of the process industry.
- All data useful to confirm the supposed damage modalities and consequent accident scenarios because of the flood impact on the industrial site (see Table 2 a-b).

Table 2 (a) Structural damage modalities for atmospheric tanks: cylindrical vertical vessels, D/H>1 (b) Schematization summarizing structural damage-final scenarios for the atmospheric vessels.

a)

Modality water impact	***Type of Structural damage***	***Release category***
Slow submersion	Complete failure of connected pipings	R6
	Failure flanges and connections	R3
	Detachment/opening vent valves	R6

Modality water impact	***Type of Structural damage***	***Release category***
	Collapse for instability (catastrophic failure)	R1
moderate speed wave	Failure flanges and connections	R3
	Detachment/opening vent valves	R6
High speed wave	Roof failure and Shell fracture	R2
	Impact with/of adjacent vessels	R1
	Complete failure of connected pipings	R6
	Failure of flanges and connections	R3

b)

Damage typology	***Release category***	***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 pool-fire, VCE	Water contamination

3. Accident analysis

3.1 Criteria for the selection of accidents

During the historical analysis of the data, we decided to define some selection criteria in order to identify only the most significant records for achieving our objectives. Therefore only accidents involving industrial activities and/or hazardous substances which have the potential to generate an accident event with off-site consequences (major accident), as for example refineries, storage site with high capacity, toxic gas production etc., were considered. These categories include not only industrial plants that fall under the Seveso Directive but also all the sites which could generate severe accidents because of stored or handled hazardous materials. Only the following equipment items were considered:

- **Loading and unloading transport:** pipeworks, pumps and compressors
- **Storage:** atmospheric/pressurized storage tanks, warehouses
- **Process:** process vessels reactors, heat exchangers, pipeworks, pumps, compressors.

The numerous accidents involving transformers were not considered, neither those related to small storage items like drums. Only in few cases connected to the flood impact it is possible to consider warehouses if the stored substances can react violently with water generating flammable and toxic gas. In this case a severe accident is possible only if a large amount is stored.

3.2 Limitations in the quality of the data

During the historical analysis some limitations in the quality and availability of the data did not allow us to satisfy all the expectations relative to the developments of simplified models to apply in the procedure for the quantitative assessment of the Natech risk. As it is possible to see in Table 3, for every database the number of records related to the natural events is always very low. The real number of the Natech accidents could be higher because not all the events are correctly recorded. In fact, often the information sources are the journals where the events are published only if they have caused a strong social impact (for example a high number of fatalities). Also, when the natural events have only increased the severity of the accident, without representing the cause, they are often neglected; consequently not many data are available in order to carry out a complete and exhaustive analysis.

Table 3. Natech events in the principal analyzed chemical accident databases.

databases	Total number of records	% Natech events
ARIA (BARPI)	30859	2-3
FACTS (TNO)	22214	2-3
ICHEME	n.a.	n.a.
MARS (MHABS)	602	4-5
MHIDAS (HSE)	7000	2
NRC	n.a.	n.a.

Other obstacles encountered in the present work were some limitations in the quality of the data; in fact, the available information is often fragmented and not very detailed. In most cases the reference to the damage of equipment items is only expressed in general terms, without specifying which modalities led to the loss of containment. In many records only the presence of the release is reported without indicating if the leakage came from a hole in the pipelines or from shell failure in a storage tank. Consequently, it is very difficult to reconstruct the dynamics of the accidents and to define what the most probable damage classes are that led to the final scenarios like fires, explosions, toxic clouds dispersion and water pollution.

In the case of flood events very frequently the information about the type of flood and the water impact modalities is missing. Only in a limited number of records it was possible to find the values of the water levels and, in the rare cases, of the water velocity. In some cases it was possible to find the same information available in more databases and a comparison indicated how every database can report and highlight different details or information. In Figure 11 two examples of the same accident record from IChemE and from FACTS are shown. The record is related to the flood impact on a storage plant. In every database it is possible to find the information about:

- The number of damaged equipment items: 50
- The substance involved: propane
- The kind of accident scenario: flash fire
- The number of evacuated people: 11500
- The effects on the equipments: storage tanks torn from the foundations and leakage of vapors from the pipe connections.

In both cases the information is consistent, but the record from FACTS is more detailed and contains information less concise about the dynamics of accident and about the capacity of damaged equipments. Then during a work of historical analysis the accidents repeated more than once in more databases have to be identified, the available information have to be compared and made homogeneous for the analysis.

a)

6176 02 August 1993

Source : HAZARDOUS CARGO BULLETIN INCIDENT LOG, 1993, SEP.
Location : St Louis; Missouri, USA

Injured : 0 **Dead :** 0

Abstract

Floods loosened 50 propane storage tank foundations at tank farm, causing vapours to leak from the pipe connections. Flash fire led to the evacuation of 11 500 people.
[gas / vapour release]

Lessons

[None Reported]

b)

SEQ.NR. 12
ACC NR (FACTS) 13646
ACC DATE 1993 0802
COUNTRY USA
LOCATION TANKYARD
ACTIVITY STORAGE
CHEMICALS PROPANE
FATALITIES
INJURIES
SCENE RIVER FLOODED OVER AN EARTHEN LEVEE AND 50-51 TANKS FLOATED FROM THEIR SUPPORTS CAUSING FIRE AND EVACUATION
CONFIDENT
ACC DESC
CLASS * * *
EXT ABSTR At a tank farm, 50-51 tanks, each containing 114/m3 of propane, floated from their support/foundations as river flooded over an earthen levee. Leaking propane vapours at pipe connections ignited with flash fires. 8000-11500 residents evacuated due to explosion fire risk from leaking tanks. Tanks were strapped down and attached to concrete base.

Figure 11. Records about the same accident obtained from (a) IChemE database and (b) FACTS database.

4. Results of statistical analysis of accidents triggered by floods

4.1 Characterization of the flood event

As mentioned in the previous paragraphs it is important to find data about the natural event characterization to evaluate the different effects suffered by the equipment items depending on the severity of the flood event. In most records the natural event is described only in general terms, without specifying the exact value of the water level and speed, but giving a qualitative evaluation of the event.

Analyzing the 272 records selected through the chosen criteria, only 70 more detailed accidents were identified and the information shown in Figure 12 was obtained.

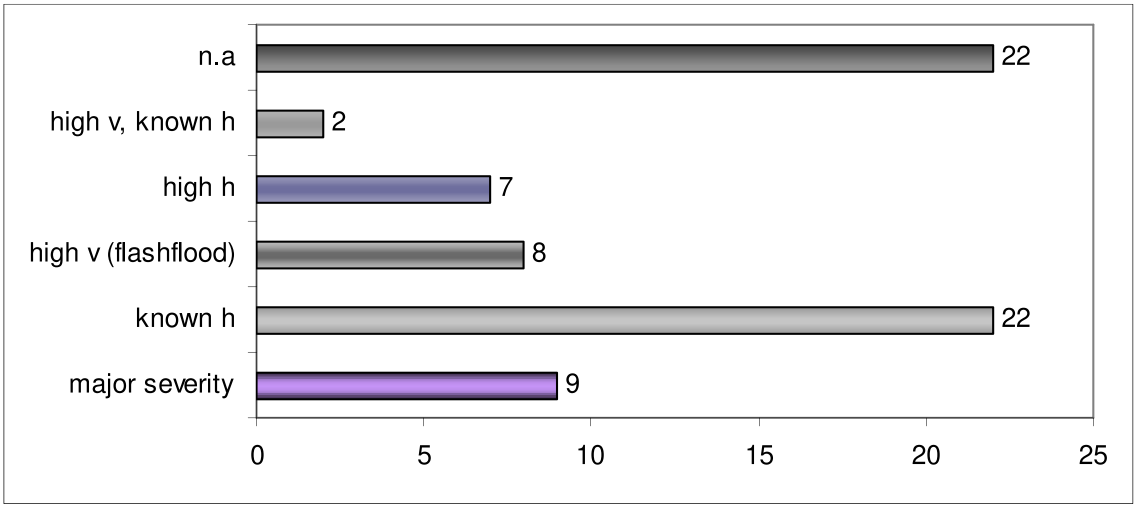


Figure 12. Diagram with available information on the characterization of the flood event in 70 more detailed records.

Figure 12 shows that more data on the water level than the water speed is available, but in many cases (22 records) this information is missing altogether. Only 24 records gave information on the water depth. In the pie chart in Figure 13 the results obtained for 18 records (from the 22 records excluding the cases with warehouses) are shown.

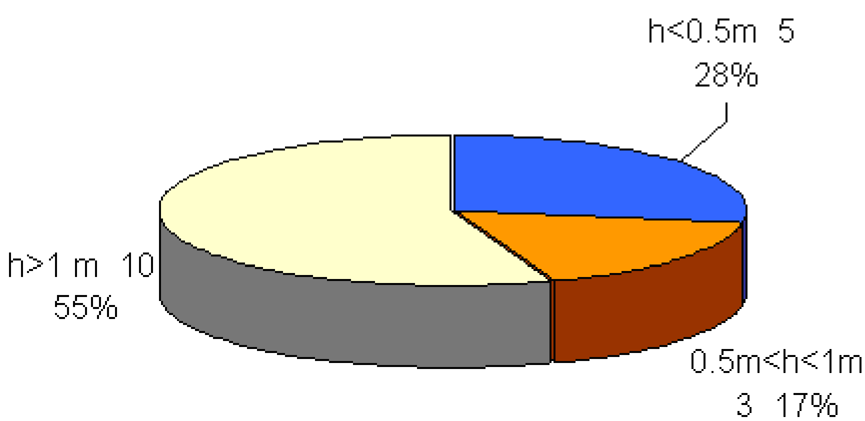


Figure 13. Distribution (number and per cent) of 18 records with the quantified value of the water depth.

Only in 34 cases there was sufficient data to identify the link between natural event severity and the final scenario or effects on the equipments items, as shown in the following table.

Table4. Some examples of records with the link between severity of the event and effects (release or scenarios) on the equipment items.

Accident record	***Characterization natural event***	***Equipment involved***	***Accident scenario***
(NRC) 19/07/2006 Byghamton, NI	Major flood event	Storage tank (chemical facility)	Fire, dispersion
(NRC) 20/06/2006 Sulfur, IA	Major severity flood	2 underground storage tanks	Release of 226556 m^3 crude oil
(NRC) 29/03/2005 Bloosmburg, PA	High water level		Release and water contamination
(NRC) 13/07/2005 Austell, GA	Major severity	3 underground storage tanks	Released 49 $m^{3,}$ gasoline
(NRC) 13/07/2004 Sheffield TWP, PA	Heavy flood	pipelines	Release and water contamination
(NRC) 14/08/2004 Victorville, CA	Flash flood	chemical tanks and storage tanks	Sulfuric acid, sodium hypochlorite and diesel release, water contamination
(NRC) 28/07/2003 Canton OH	Heavy flood	storage tank, piping	Xylene released 0.056 m^3, water contamination
(NRC) 30/07/2003	Flash flood	2 underground storage tanks	Fuel oil, 3.4 m^3 ground contamination
(NRC) 12/11/2003 Guajanilla PR	Very heavy flood	2 oil/water separators	Water contamination
(NRC) 13/11/2003 Ponce PR	Heavy flood	Storage tanks	Water contamination
(NRC) 18/11/2003 League City TX	High water level	pipelines	Water contamination
(NRC) 25/04/2000 Jellico TN	High water level	pipelines	Water contamination
(NRC) 24/06/2002 South Willamsport	High water level	Storage tanks	Water contamination
(NRC) 19/12/2002 Jonesboro AR	Excessive water	underground storage tank, piping	Ground contamination
(MHIDAS) 13/10/81 Justin, Texas	Heavy flood	Storage tanks	Gasoline and diesel fuel release Pool and vapour dispersion
(ARIA) France	1 m water level	Pressurized storage tanks	Release LPG
(other source) 2002 Spolana, Czech republic	1.5 m, critical flow	storage tank	Release chlorine and water contamination
(FACTS)	high water level	Storage tank	Fire and water contamination
(FACTS) 2000 USA	high flow	2 Storage tanks	Diesel oil propane, release water contamination
(MHIDAS) 30/01/2000 Calacoto, Bolivie	Flash flood	Pipelines	Water contamination
(FACTS) 2005 Australia	high flow	Storage tank	Water contamination
(FACTS) 2004 USA	.6-1.5 m, water level	Storage tanks	Ethylene, polyethylene, olefins, aromatics, acetylene release
(ARIA) 1994 USA	high flow, 0.38-0.508 m,	37 Pipelines	Fire and water contamination
(FACTS)	high flow	Storage tanks	Diesel, released 14000m^3 water contamination
(ARIA) USA	high flow	Storage tanks	Gasoline release, water

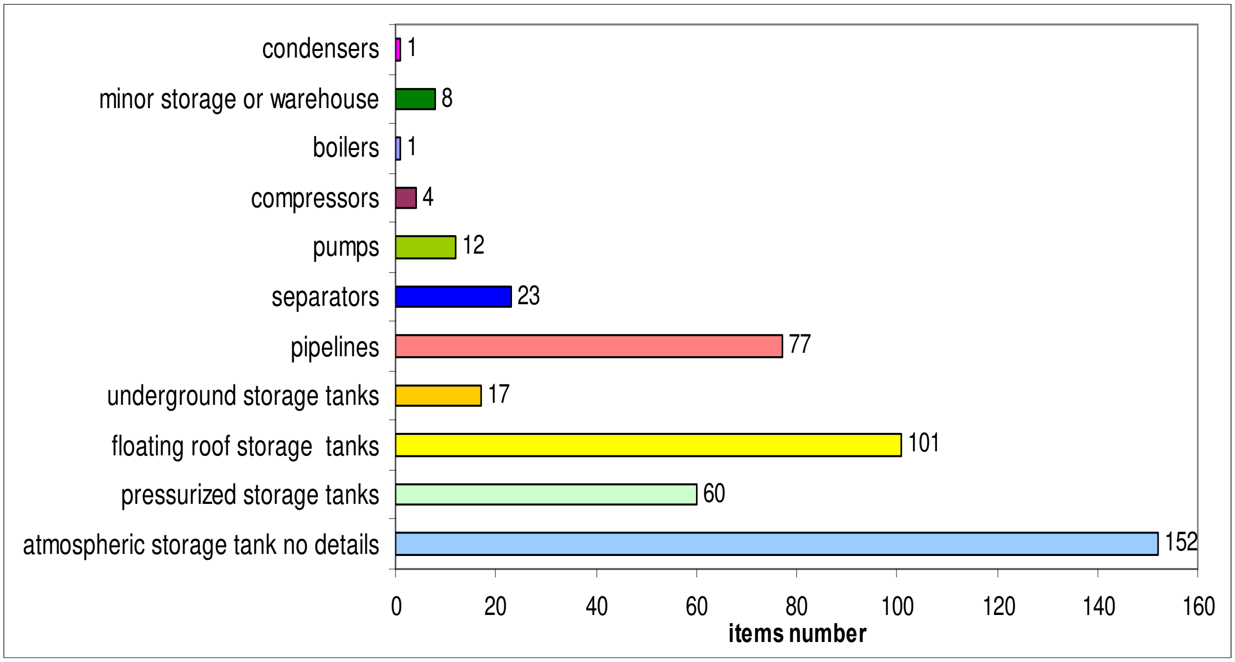
Accident record	Characterization natural event	Equipment involved	Accident scenario
			contamination
(FACTS) 25/11/2000 Mohammedia, Maroc	high flow, 1 m	Storage tanks refinery	Hydrocarbons release fire, water contamination, explosion
(FACTS) 1990 USA	high water level	Pipelines	Water contamination
(ARIA) 31/07/2002 Manesti, Romania	high flow	Pipelines	Water contamination
(MHIDAS) 11/06/2001 Ecuador	high flow	Pipelines	Natural gas release
(ARIA) 4/12/2003 Arles, France	1.43 m	Warehouse	Phytosanitary products water contamination
(ARIA) France	0.8 m	Warehouse	Phytosanitary products water contamination
(ARIA) 4/12/2003 Saint Gilles, France	0.9 m	Warehouse	Phytosanitary products water contamination
(ARIA) 27/12/1999 France	1 m	Inorganic chemical industry	Chemicals, released 2000 t
(ARIA) 23/09/1999 France	0.4 m		Hydrocarbons release

4.2 Equipment items involved and flood effects

The historical analysis allowed the identification of the equipment item categories that are mainly involved in this type of accident. Figure 14 shows the obtained results through the statistical analysis of 272 records. Pipelines and storage tanks (atmospheric and pressurized) are the equipment items that are most susceptible to damage because of the flood impact. This conclusion does not surprise because these two categories of storage and transport equipment have a high substance hold-up and in the case of failure with loss of containment they can initiate accident scenarios with significant severity. It is also evident that atmospheric tanks are more vulnerable than pressurized tanks. In fact, a certain water level is sufficient to cause the collapse of the tank shell or to induce tank floating, while a high water speed is required to loosen the foundations (anchorage saddles) of pressurized vessels.

Figure 15 shows the main impact of a flood event on the equipment items. These results were obtained analyzing only 66 records that had the required level of detail for this type of analysis. It is difficult to find information about the dynamics of the accident or about the suffered structural damages. In the selected records it was not possible to find many details about the flood effects on the equipments. The two cases of the roof failure have been considered even if they are not direct effects of the flood event; in fact also the floods due to heavy rains can cause frequently this typology of damage.

a)



b)

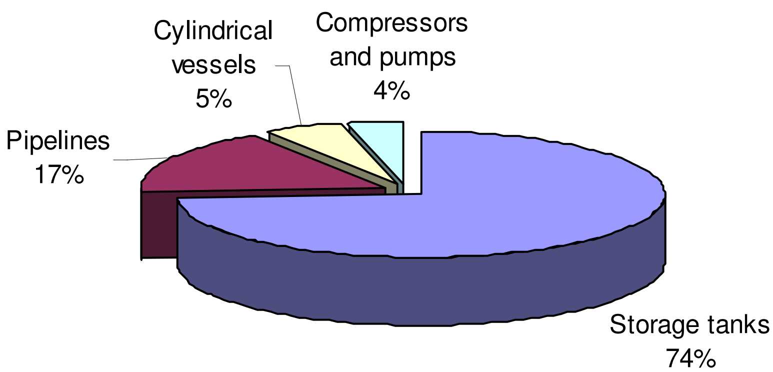


Figure 14. Specific categories (a) of the equipment items mainly involved in accidents triggered by flood events and more general categories (b).

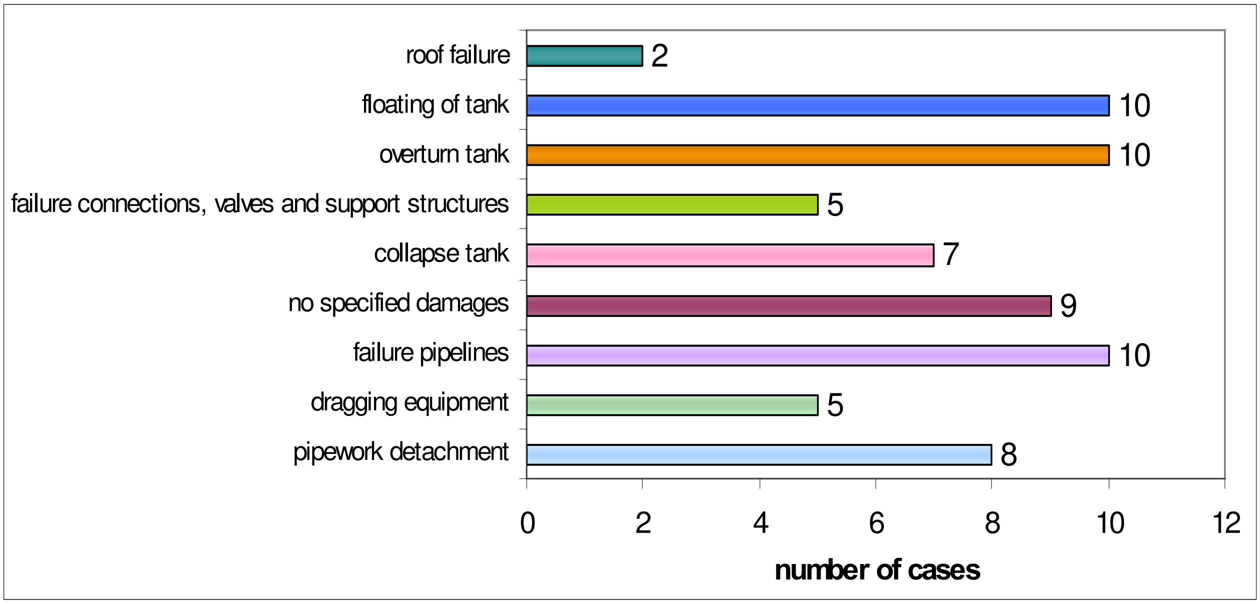


Figure 15. Effects suffered by the equipment items because of the flood impact. The results were obtained through the analysis of 66 accidents.

4.3 Activities and substances involved in the accidents and consequences

The analysis we performed allowed us as well to obtain useful information about the substances involved in the accidents. These results, shown in Figure 16, are coherent with the previous conclusions on the impact of floods on equipments categories. In fact, since the atmospheric storage tanks are the most vulnerable items, the most involved substances are gasoline, oil and diesel, usually stored in this kind of vessels.

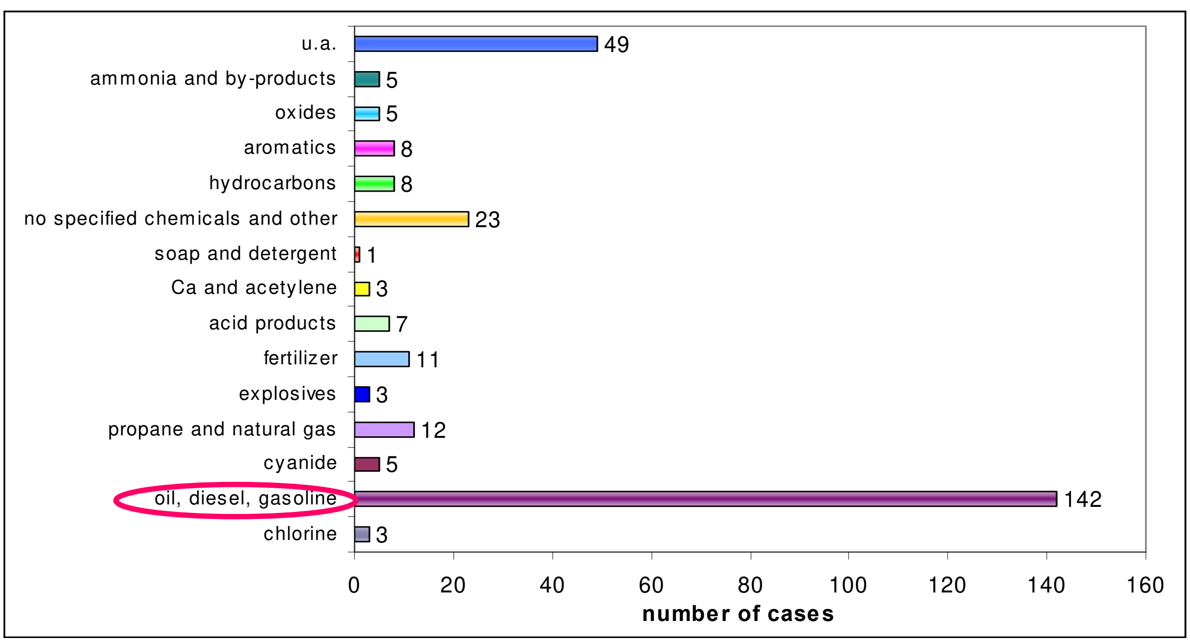
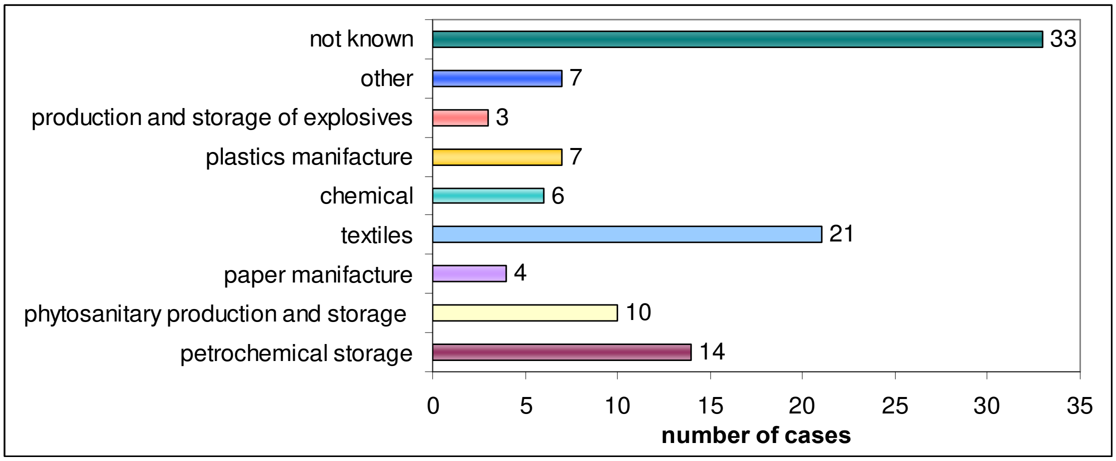


Figure 16. Substances involved in flood-triggered Natech accidents.

Since not all databases contain the same kind of information or details, some results on the industrial activities involved in Natech accidents and their consequences were obtained using the records only from MHIDAS, FACTS and ARIA. As we can see in Figure 17 this information is very general and in many records these data are not known.

a)



b)

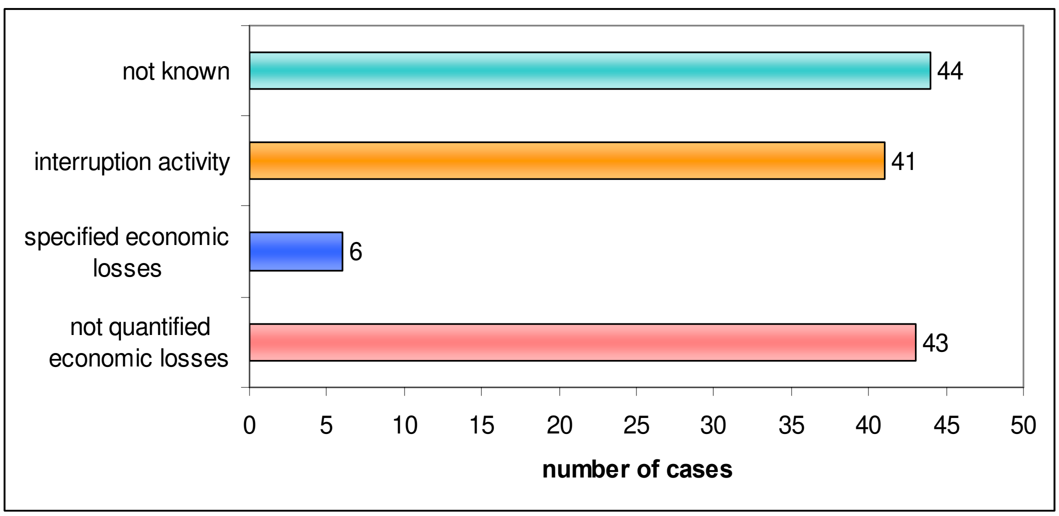


Figure 17. Histograms with the industrial activities involved in flood-triggered Natechs (a) and diagram with the consequences of the accidents on the basis of the records from ARIA, FACTS and MHIDAS.

4.4 Accident scenarios caused by floods

Another result obtained concerns the accident scenarios triggered by flood events, as reported in Figure 18.

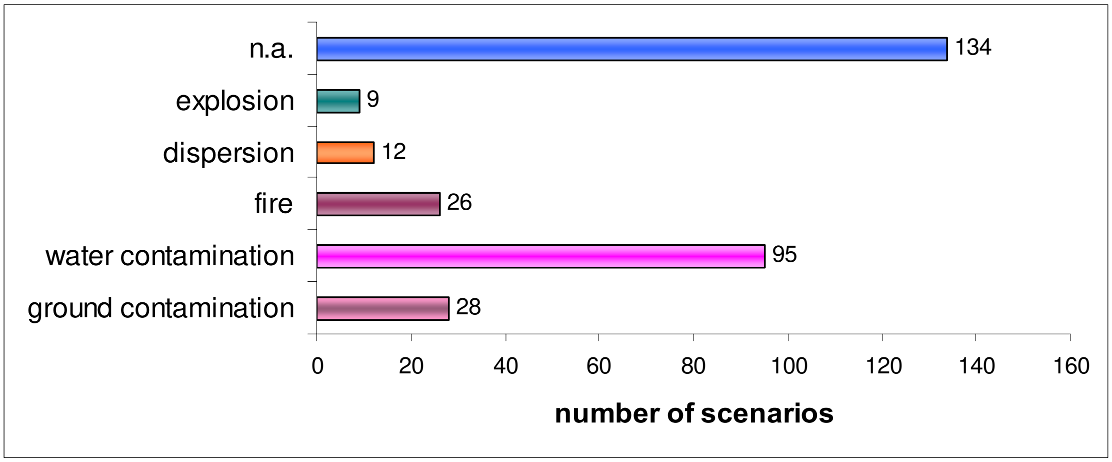


Figure 18: Accident scenarios initiated by flood events.

The most recurrent final scenario is water contamination. In fact, the released substances stratify and are spread by the floodwaters contaminating wide areas. Consequently, it is possible to have as secondary scenarios ground and underground waters contamination.

In the case of a flood event two scenarios typical of the process industry - fire and toxic dispersion - can assume a different significance. In fact, if substances reacting with water are involved in the accident (see Table 5) and in a significant amount, it is possible that flammable or toxic gases are developed, generating fire or dispersion scenarios.
In Table 6 the supposed scenarios are defined for the case of accident caused by flood.

Table 5. Risk phrases of particularly hazardous substances in the case of a flood event

Risk phrases	***explanation***
R15	After contact with water it releases gas highly flammable
R14	It reacts violently with water
R14/15	It reacts violently with water developing extremely flammable gases
R15/21	After contact with water it releases extremely flammable gases
R29	After contact with water it releases toxic gases
R31	After contact with acids it releases toxic gases
R32	After contact with acids it releases highly toxic
R51	Toxic for aquatic organisms
R52	Noxious for the aquatic organisms
R53	It can cause long-term damages to aquatic organisms
R50/53	Highly toxic for aquatic organisms, it can cause long-term effects to the aquatic environment
R51/53	Toxic for aquatic organisms, it can cause long-term effects to the aquatic environment
R52/53	Noxious for aquatic organisms, it can cause long-term effects to the aquatic environment

Table 6. Probable scenarios caused by the impact of a flood event on an industrial site.

Possible scenarios generated by floods	
Water contamination with significant damages to environment	Primary scenario: contamination of rivers and lakes. The severity is depending on the quantity and solubility
	Secondary scenario: contamination of the ground and of the underground water
Fires and explosions	Pool-fires usually due to ignition of flammable substances spread by floodwaters Flash-fires o VCE generated by developed vapors
Toxic clouds dispersion	Clouds vapours/gas due to continuous release of collapse of the tank
Violent reactions with water and secondary scenarios	Flash-fires e VCE: developed in quantity enough to generate a cloud in the LEL and UEL limits
	The severity is depending on the quantity and CL_{50}

Our analysis confirmed the hypothesis about scenarios initiated by substances reacting with water. In fact, six examples were found with flood impact on warehouses and storage tanks with accompanying violent reactions with water, as shown in Table 7. The severity of these accidents is immediately evident because in three cases three different scenarios occurred.

Table 7. Examples of records with violent reactions of chemicals with water.

N°	***Date***	***Flood target***	***substances***	***Final scenarios***
1	1998	Warehouse	Ca and H_2 (after water contact)	fire
2	04/01/1987	Atmospheric storage tanks	Nitric and sulphuric acids	Toxic gas cloud dispersion
3	25/11/1967	Warehouse	Phosphorus	Fire explosion Toxic gas cloud dispersion
4	27/06/1982	Warehouse	Sulphuric trioxide and oleum	explosion Toxic gas cloud dispersion
5	08/1984	Warehouse	Ca and acetylene (after water contact)	fire explosion
6	28/08/1983	Warehouse	cyanide	Toxic gas cloud dispersion

5. Results of the statistical analysis of accidents triggered by seismic events

5.1 Equipment items involved, structural damage categories and scenarios triggered by /earthquakes

The same analysis as for flood-triggered Natech accidents was performed for earthquakes that triggered accidents in industrial sites. In contrast to floods, it is not difficult to find data about the severity and the return period of the seismic events because these data are available depending on the geographical coordinates. Simplified empirical vulnerability models are available for some equipment categories, thus it is possible to calculate the final values of the industrial risk indices. Nevertheless the historical data are useful in order to support and improve the methodologies and the existent models.

The results obtained through an analysis of 78 records, allowed to better clarify which process and storage equipment suffers damage during a seismic event (see Figure 19), which are the more frequent structural damages (figures 20-21) and which accident scenarios are more common (Figure 22). It was also possible to compare the different effects due to seismic and flood events. As for flood-triggered Natechs also in the case of earthquakes the most vulnerable equipment is the storage and transport items, however, the pressurized vessels have a higher resistance than atmospheric tanks. This conclusion does not surprise considering their different structure and the bigger thickness of the shell and also this result confirms the behavior of the owned vulnerability functions. In fact the available models for this category of equipments give very low values of damage probability.

The pie chart in Figure 20 shows the distribution of the inflicted damage to transport and storage equipment. This result is interesting because it underlines the greater danger of this kind of accidents, since the probability of damage with loss of containment is higher than the probability of only structural damage and consequently they can more easily initiate accident scenarios. The details reported in the records allowed to define the five categories of possible structural damage with and without release available in Table 8.

Figure 21 provides some examples of typical damage suffered by storage tanks during accidents triggered by earthquakes.

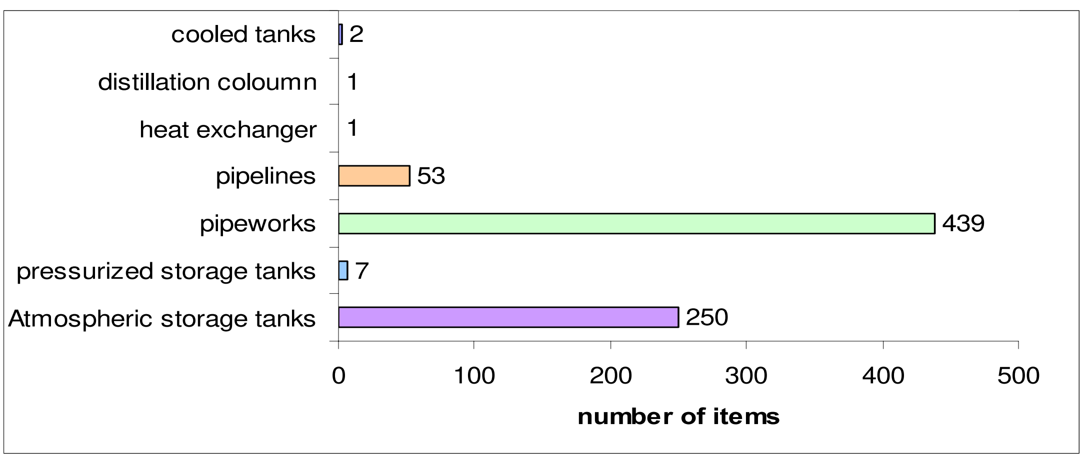


Figure 19. Categories of equipment items involved in accidents triggered by seismic events.

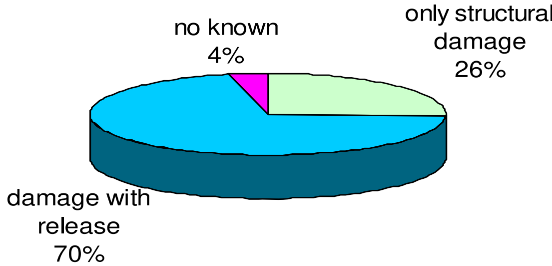


Figure 20. Per cent distribution of the different damage typologies.

Table 8. Damage classes based on the analyzed historical data.

Structural damage without release	
Minor	Elephant foot buckling, deformation of support structures, stretching of the bolts.etc
Moderate	Detachment of the bolts, failure of the connections/weldings, roof top failure, failure of columns and support structures
Structural damage with release	
Minor	Leak from flanges and connections
Severe	Failure with loss from roof top or shell
Catastrophic	Collapse or overturn tank with loss of complete inventory

a)

b)

Figure 21a-b. (a) Sloshing damage to upper shell of tank (left), Elephant-foot buckling of the tank wall. (b)yielding of the support structures (left), collapse of the tank (right).

Other information was obtained about the typologies of initiated accident scenarios (Figure 22). In many records (27 cases) these data were not available and the same number of scenarios was found for the case of fires and the pool without ignition, but considering both the pipelines and the storage tanks.

The analysis was repeated selecting only the 29 records involving storage tanks and considering only flammable substances. This analysis allowed to deduce some interesting conclusions for example about the average number of the damaged equipment per event and the maximum number of involved equipments per event. The data about the number of structural damage with release and of those with ignition permitted to evaluate a preliminary ignition probability as shown in Table 9.

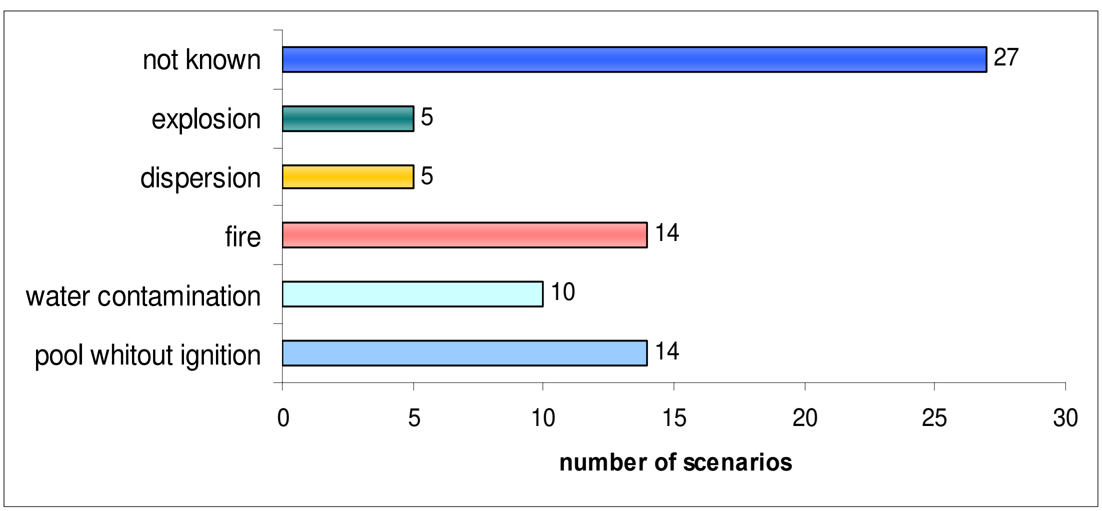


Figure 22. Accident scenarios initiated by earthquakes.

Table 9. Results obtained from the analysis of 29 records related only to flammable substances.

Number of seismic events	**29**
Number of damaged equipment	**≥254**
Max number of damaged equipments in one event	**97**
Medium number of damaged equipments in one event	**9**
Number of damaged equipments with release	**≥180**
Number of cases of release with ignition	**≥137**
Ignition probability	**0.761**

6. Discussion

Our study highlights the necessity to obtain a sufficient amount of detailed data in order to make an in-depth analysis or to develop modeling. It was also possible to assess how the databases report the same event underlining different aspects or neglecting others. Consequently the information, if available, is often fragmented and that makes the reconstruction of the dynamics of a Natech accident difficult.

An aim would be to find a way to collect all the available information and to organize it systematically in one database only. The Institute for the Protection and the Security of the Citizen of the European Commission's Joint Research Centre in Ispra (VA) in collaboration with the Department of DICMA of the University of Bologna is laying the basis to prepare a specific database for only Natech events. At present a possible functional framework of the database has been outlined. The essential data to be included in the database comprise:

- Accident code, location and date of the accident
- Industrial activity
- Type of the equipment (target): for example in the case of storage tanks it is important to specify the size and the capacity
- Involved substance
- Final scenario
- Consequences: (number of injured, of dead, economic losses)
- Cause of accident: (characterization of the natural event with severity and frequency parameter)
- Abstract: short description with details about the number of the involved items, their condition at the time of the accident, and modalities of the damage which led to the loss of containment
- Lessons learned

The search of the records has to be possible through the use of specific keywords about the kind of natural event, the category of equipment involved or the accident scenario etc.

7. Conclusions

The present work allowed to identify a significant number of technological accidents triggered by floods and earthquakes in industrial plants. Even though the real number of accidents could be higher because not all the events are reported or correctly recorded, it was possible to highlight some aspects which demonstrate that natural causes of accidents must not be neglected in the conventional quantified risk analysis. In fact, the obtained results indicate that:

- The severity of the Natech accident scenarios is often higher because many items are damaged at the same time so **multiple** and **simultaneous** sources of release are generated;
- The number of the possible scenarios can be higher for example in the case of a flood event because of additional scenarios (fire and dispersion due to flammable/toxic gases generated by contact with water);
- Some categories of equipment may be more vulnerable or dangerous because of the impact of the natural events for example the pressurized vessels and the warehouses (for the storage of phytosanitary products or substances reacting with water).

Furthermore the effects of the natural events on the equipment items can be summarized in the following points:

- The items with the highest vulnerability during a natural event are storage tanks with the related connections;
- The different vulnerability of the atmospheric and pressurized tanks depends on the type of the natural event;
- The systems of pipelines and of pipeworks are very vulnerable to the natural event and represent a not negligible source of risk with high probability of release and environmental impact.
- The storage of flammable substances generates very frequently scenarios of explosions and fires;
- The water contamination scenario is very recurrent in the accidents triggered by floods.

Consequently, the behavior of storage tanks and of all the equipment with high hold-up needs to be studied in detail to develop vulnerability models or to improve those available (for seismic events), in order to quantify the industrial risk generated by Natech events. As was discussed in previous sections, the carried out historical analysis does not allow to use directly the found data in order to take at this aim, nevertheless it is possible to follow a further approach for the vulnerability analysis. In fact, in the case of a flood event some simplified structural models can be used to correlate the resistance of equipment to the severity of flood event. The severity of the flood event can be quantified through the overall pressure acting on the equipment, which consists of the hydrostatic and hydrodynamic pressure.

Therefore, for atmospheric storage tanks it is possible to calculate the critical pressure value which leads to the tank collapse, obtaining in this way a threshold limit value for the water level. For pressurized vessels it is useful to calculate the resistance of the support structures to the hydrodynamic pressure, through the analysis of the forces on the bolts of the anchorage saddle. In this way it is also possible to obtain the threshold limit value for the water speed.

At present this modeling is under development and represents a possible starting point for further developments and improvements of the procedure for the assessment of the risk to chemical installations due to by natural events.

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European Commission

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Abstract

The term Natech refers to natural disasters triggering technological accidents. In fact, because of the interaction between the natural and the industrial risk it is possible that several effects take place in industrial plants and in the storage sites, causing for example damage to pipelines, to process equipment, to storage tanks and consequently the release of hazardous materials.

There are different kinds of natural events or, in general terms, of natural causes of industrial accidents (landslides, hurricanes, high winds, tsunamis, lightning, cold/hot temperature, floods, heavy rains etc.), nevertheless in the present study the attention is focused only on seismic and flood events. In fact, several accidents occurred in the last decades in industrial sites evidenced that typology of natural phenomena may cause severe damages to equipment items, resulting in losses of containment, thus in multiple and extended releases of hazardous substances. Because of these multiple and simultaneous failures with release, cascading events are more likely to occur during a natural disaster than during normal plant operation. Some examples of natech events like the flood in the Samir refinery in Mohammedia, Morocco, in 2002 or the Kocaeli earthquake in Turkey in 1999 are available in the scientific literature or in the accident databases . In both cases the natural event occurred in a refinery and involved several storage equipment items and generated fires and explosions. These reports allow to better understand the particular severity of the industrial accidents triggered by flood and seismic events.

The reference for the prevention of chemical accident in the European Commission is the Seveso Directive II (96/82/EC). The aim of the Seveso Directive is Prevent Major accidents which involve dangerous substances and to limit their consequences for man and environment with a view to ensuring high levels of protection throughout Community in a consistent and effective manner. (Council Directive 1996)

The Seveso Directive is addressed indirectly to Natech risk management; in fact it calls for the analysis of the external events in The identification and accidental risk analysis and prevention methods. The analysis of external events which can lead to chemical accident implies the consideration of the potential threat of natural hazards in the hazard analysis, and carrying out mitigation measures in case an accident occurs.

Nevertheless the methodologies and the actions that can be taken to achieve these requirements are not specified and limited work has been devoted to the development of quantitative assessment procedures for Natech risk.

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