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Assessment of safety barrier performance in Natech scenarios

REVISED VERSION

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ABSTRACT

The impact of natural hazards on chemical and process facilities may lead to catastrophic technological accidents defined as Natech events. In the present study, a performance assessment of safety barriers during extreme natural events as floods and earthquakes was carried out. Assessing the performance of safety barriers during such complex scenarios is a key issue to identify the final consequences and the evolution of Natech events. Due to the scarcity of available data, an anonymous survey was carried out, involving more than 40 experts of different nationalities and background. Categories of safety barriers highly vulnerable to the impact of natural events were identified. Baseline values for performance modification factors describing how barrier performance may be affected by floods and earthquakes were obtained from the expert elicitation procedure. The results may support the probabilistic analysis of Natech scenarios, in order to achieve a more accurate assessment of final consequences and of possible escalation.

Keywords:

Natech; Safety barriers; Natural hazards; Performance Assessment; Expert elicitation

1. Introduction

In recent years, a growing concern is caused by the threats generated by the interaction between natural hazards and technological installations, the so called Natech (Natural-hazard triggered Technological) scenarios [1]. In a number of disastrous natural calamities that stroke heavily industrialized regions in different parts of the world, severe technological accidents followed the natural events, directly affecting the population and causing huge damages to industrial assets [2-4]. The World Health Organization in a recent document remarked that, also as a consequence of climate change, both the frequency and the magnitude of natural calamities are growing [5]. This trend rises serious concern that the likelihood and magnitude of Natech events will consequently increase as well [6].

Chemical and process installations are among the most critical infrastructures which could be targeted by natural hazards. Indeed, as a consequence of structural damage to facilities, loss of containment of hazardous substances is likely to take place. The incidence of Natech events was estimated to be as high as 5% out of the total of records reported in industrial accident database up to about 20 years ago [3]. However, such figures are presumably even higher nowadays, due to the increasing frequency of natural hazards linked to climate change [7-9]. For instance, Hurricane Harvey had an unprecedented intensity which has been directly linked to climate change [10], and triggered a multitude of Natech events and massive hazmat releases from shutdown procedures [11].

The main criticalities characterizing Natech scenarios are related to the broad impact area that natural events generally have. For instance, floods and earthquakes have the potential to cause the simultaneous failure of different equipment items in a process installation, leading to multiple loss of containment events and to complex accident scenarios [12-14]. Previous studies demonstrated how accidents developing from natural hazards have to potential to cause severe fires, explosions, toxic dispersion and environmental contamination [15-18]. Furthermore, Natech accidents are likely to escalate generating cascading events involving surrounding equipment, or domino effect [19], further exacerbating the already catastrophic consequences of the initial scenario.

In order to prevent technological accidents or to mitigate their consequences, safety procedures and specific technical solutions are usually adopted, usually referred to as safety barriers in the technical literature [20-41]. Examples of safety barriers are water deluge systems to protect vulnerable equipment from fire, catch basins to prevent liquid spread in case of a spill, foam systems, etc. However, a number of case histories demonstrated the possible ineffectiveness of conventional safety technological measures in case of Natech events, due to the specific conditions caused by the impact of the natural event [42-44, 4, 11].

Despite the growing interest in the analysis of Natech scenarios and the recognized criticalities related to the performance of safety barriers, systematic approaches for the analysis of the performance of safety barriers in Natech scenarios are lacking. Thus, in the present study, a specific analysis was carried out to understand the behaviour of safety barriers during Natech events, in order to derive quantitative criteria for their expected performance. Due to the scarcity of data, available information was analysed with the support of an expert elicitation procedure. The reasons why an expert elicitation procedure was selected for the purpose are manifold. First of all, given the novelty of the problem addressed and the unavailability of quantitative information on safety systems failure during Natech events, expert judgment constitutes a solid starting point to face the issue [45]. Moreover, an analogous methodology has been successfully employed for determination of indicators estimating performances of protection systems in the context of physical security of process installation [46]. Finally, expert elicitation has been recognized in the literature to be particularly suitable for issues which are not practically measurable despite a theoretical basis is present [47]. Thus, a reference set of safety barriers was defined and their expected performance under the impact of a natural event was analysed both qualitatively and quantitatively. The qualitative analysis was carried out to evidence criticalities and to highlight the most vulnerable items. The quantitative assessment was based on a method developed in previous studies, dedicated to accident escalation quantitative risk assessment (QRA) [30-32]. The method incorporates the concepts of availability and effectiveness to express the level of confidence of the barriers [22-24], and adopts a LOPA (layer of protection analysis) approach [20].

In the following, the basic concepts of safety barriers and the methodology adopted for performance quantification are introduced (Section 2). The expert elicitation procedure and the proposed methodology to tailor barrier performance data accounting for the impact of natural hazards are discussed in Section 3. The main results of the study, together with a discussion on their applicability and limitations are provided in Section 4. Conclusions are given in Section 5.

2. Schematization and assessment of safety barriers

The concept of safety barrier is used within the process industry referring to measures to protect vulnerable assets (e.g., people, environment, reputation, etc.) against hazards posed by failures or deviations of systems [25].

There is a considerable amount of scientific and technical literature dedicated to barriers and barrier management [20-41]. Safety barriers may be generically defined as physical and non-physical means planned to prevent, mitigate or control undesired events or accidents [40]. Within the Norwegian oil & gas sector, according to [33], safety barriers are defined as: *"systems of technical, operational and* *organizational elements, which are intended individually or collectively to reduce the possibility for a specific error, hazard or accident to occur, or which limit its harm/disadvantages".*

This definition is quite similar to the one developed within the ARAMIS framework, where safety barriers are defined as technical and organizational solutions provided to directly serve safety functions, which, in turn, are technical or organizational actions intended to prevent, avoid or control the occurrence of hazardous events, or to mitigate their consequences [22-24]. The concept of barrier function, that is, barrier design purposes, is shared by multiple literature sources [22-34, 40], and is necessary to distinguish without ambiguity between functions and how they are practically accomplished through the implementation of barrier systems. More specifically, Svenson [34] defines "barrier function" each task implemented by barrier systems to arrest accident evolution. Sklet [40] defines barrier functions as functions planned to prevent, control, or mitigate undesired events, recalling the definition proposed within the ARAMIS framework [22-24]. A comprehensive review of terminology commonly used in the field of barrier management can be found elsewhere [40].

Given the quite broad definitions reported above and the multiplicity of sectors in which barrier conceptualization is applied (for instance, in [41] it is applied for identification of emerging hazards linked to new technologies such as biogas production), it clearly appears that several criteria may be adopted to categorize safety barriers. A possibility is to classify barriers based on whether their safety function is aimed at reducing the frequency of a hazardous event, namely proactive barriers; or to lessen its outcomes, namely reactive barriers [25]. Reason [35, 36] proposed a universal classification based on defense-in-depth concepts and on the type of functions implemented by barriers, which is deemed generally valid for all organizations, regardless of their operating hazards. Another possibility is provided by Hollnagel [28, 29], who categorizes barriers in:

- physical and material barrier systems, whose function is expressed by physical means;
- functional barrier systems, which are based on creation of preconditions impeding actions;
- symbolic barrier systems, which require interpretation by someone to express their function;
- incorporeal barriers, which are in fact organizational barriers in the industrial context.

The categorization adopted in the following is based on barrier working principle, and has been widely adopted in previous literature [20-24, 30-32]. Hence, safety barriers are categorized in passive, active and emergency/procedural barriers.

All the systems that do not require activation to perform their functions are defined passive barriers (e.g., pressure relief devices, fireproofing materials, catch basins). On the other hand, active barriers need activation to perform their functions and are generally more complex systems linked to subsystems for detection and for signal processing. Fire protection systems such as sprinklers and water deluge systems (WDS) are common examples of active barriers [48-50]. Lastly, emergency/procedural barriers include procedures and contingency plans developed for responding to the occurrence of major accident scenarios (e.g., intervention of fire brigades, internal or external emergency teams) [51].

Barriers may be characterized by a number of properties determining their performances. For instance, according to Hollnagel [28, 29], barrier quality should be evaluated considering a set of conditions, among which are efficiency, robustness, resource need, and availability. Norwegian Petroleum Safety Authority highlights that performance requirements must be verifiable and related to barrier element properties, including aspects as reliability, effectiveness, integrity, functionality, and robustness among others [33].

In order to assess the expected performance of safety barriers during Natech events, a concise approach to performance quantification is required. A number of methodologies for the assessment of safety barrier performance through a limited number of parameters have been proposed in the literature. For instance, among simplified methods it is worth mentioning LOPA, a well-established framework for barrier performance assessment based on the concept of Independent Protection Layers (IPLs) [20, 39]. The method proposed in the IEC 61508 [52] for safety instrumented systems is based on the evaluation of the required safety integrity level (SIL) through a simplified risk-based approach, which is then specifically tailored for the process sector in the IEC 61511 [53]. A further approach sharing some common traits with LOPA and IEC 61508 standard is the MIRAS method proposed within the ARAMIS project [22-24]. More recently, a two-parameter approach was proposed for the specific framework of domino effect prevention, based on the probability of failure on demand (PFD) and effectiveness of the barrier [31]. The PFD expresses the probability that the system is unavailable when it is required to express its safety function, and the effectiveness is the probability that the barrier successfully performs its escalation prevention function once successfully activated. Since one of the most critical features of the impact of natural hazards on process facilities is the possibility that severe cascading scenarios are triggered, this approach was adopted in the present study.

PFD values for simple components can be found in technical literature, while in the case of complex systems (such as active safety barriers) the PFD has to be evaluated through fault tree analysis (FTA) considering system architecture [54], or, in the absence of data, through simplified risk-based approaches such as the Risk Graph [52,53]. A comprehensive set of baseline reliability data sources are reported by Necci et al. [54].

The effectiveness parameter, accounting for the quality of the performed barrier function, is not assessed in standard LOPA studies [20, 39], and needs to be estimated considering performance data dependent of the type of system, as well as on operational management, system installation and maintenance [30, 32].

3. Methodology

In order to investigate the performance of safety barriers in Natech scenarios, a specifically developed approach was applied. The steps of the study carried out are summarized in Fig. 1. Each step of the approach is discussed in the following.

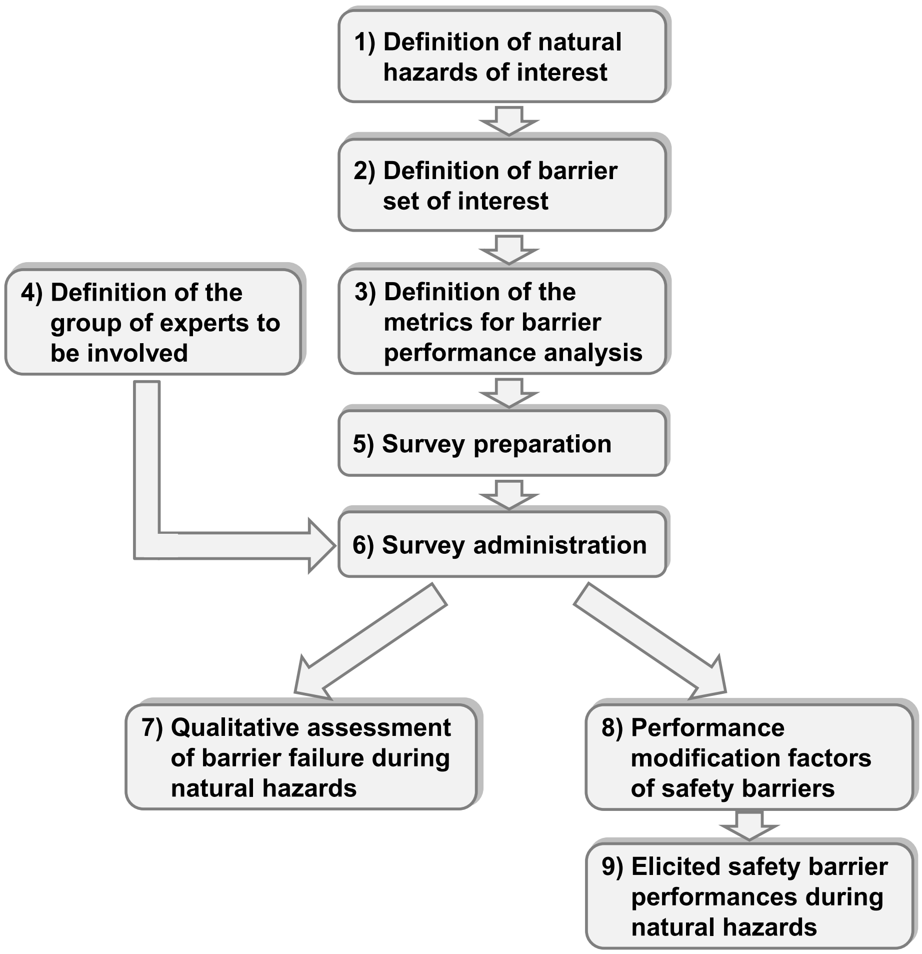

Figure 1: Flowchart of the approach adopted in this study for barrier performance estimation in Natech events.

3.1 Natural events considered in the study

In step 1, the boundaries of the study were set to define the detail of the activity and to make affordable the elicitation process. In particular, it was decided to limit the study to the impact of earthquakes and floods. These were selected since they are the natural events that more frequently triggered severe Natech accidents [1]. In perspective, the approach developed may be applied to assess barrier performance in case of other types of natural events (e.g. tsunamis, lightning, tornados, etc.).

However, in order to focus the elicited group of experts and to limit the complexity of the survey, the decision was taken to limit this study to the analysis of these two significant categories of events.

3.2 Definition of a set of reference safety barriers

The second starting point of the study was the definition of a set of safety barriers to be analysed (step 2 in Fig. 1). This is needed both to limit the extension of the study and to allow the preparation of a reference scheme and a description of the function of each safety barrier considered, to support the expert elicitation. In the present study, only technical active and passive safety barriers were considered. The choice to exclude organizational and procedural barriers is motivated by need to limit the complexity of the study and to the high site specificity of their performances (e.g., presence of internal emergency teams, distance of the plant from closest firefighter station, presence of specific plans for natural disaster), that undermines the general validity of the performance parameters obtained. On the contrary, baseline values for active and passive technical barriers are mostly related to system architecture, thus are linked to the inherent structure of the safety system. Indeed, according to lessons learnt from previous accidents, some specific failure patterns can be identified [55].

The definition of the set of barriers to consider was based on a preliminary evaluation of equipment items and substances most frequently involved in earthquake and flood triggered accidents based on past accident events. Indeed, it has been highlighted that atmospheric tanks storing an elevated inventory of flammable liquids (e.g., petroleum products) are particularly vulnerable during earthquakes and floods [16, 56], and escalation due to fire may be critical during such Natech incidents, as confirmed by relevant case histories (see Section 1). These findings constituted the drivers for the selection of the set of safety barrier considered. Indeed, since one of the main criticalities of Natech events triggered by flood and earthquakes is the high possibility of accident escalation through domino effect, the investigated barrier set is mainly composed of escalation prevention systems. Moreover, fire protection systems constitute a significant part of the set also because these systems are required in accepted standards on fire protection of petroleum storages (e.g., see [57]).

It is worth specifying that the analyzed set of barriers is not aimed at providing an exhaustive and complete list of possible technological solutions for escalation prevention, rather it is composed of barriers which, based on past accident analysis, may be prone to fail following the impact of natural events. For example, PSVs, despite being the most common passive safety barrier to prevent vessel overpressure, have not been included in the analysis since, due to their features, their failure was never reported in available data on Natech scenarios.

The final set of selected safety barriers considered in the analysis is composed of the 16 items listed in Table 1, which also reports a short description and an identification code (SB.k, with k=1,…,16). Items SB.1-SB.9 are active barriers, while SB.10-SB.16 are passive barriers. It is worth noting that the Emergency Blow-Down (EBD) line was considered passive since it is constituted of pipework (and possibly a KO drum) which are always in place, not needing an activation.

Table 1: Safety barriers considered in the survey prepared for expert elicitation

Safety barrier	**Barrier ID**	**Classification [20]**	**Short description**
Inert-gas blanketing system	SB.1	Active	System for inert gas delivery to storage tanks to prevent the possible formation of flammable atmospheres.
Automatic rim-seal fire extinguishers	SB.2	Active	Automatic foam delivery system for prompt extinguishment of rim-seal fires developing in the roof area of atmospheric storage tanks.
Fixed / Semi-fixed foam systems	SB.3	Active	Systems for tank fire extinguishment by means of foam/water delivery.
WDS / Water Curtains / Sprinklers	SB.4	Active	Systems for water delivery during fire, either for flame extinguishment or critical asset protection (e.g., LPG vessels).
Hydrants	SB.5	Active	Water sources for fire brigades located in multiple areas of the plant.
Fire activated valves	SB.6	Active	Valves activating in case of fire nearby.
Fire and gas detectors	SB.7	Active	Field sensors for detection of flames and gases.
SDVs	SB.8	Active	Isolation valves activating during emergency situations.
BDVs	SB.9	Active	Depressurization valves activating during emergency situations.
Fire walls	SB.10	Passive	Physical barriers for fire protection.
Blast walls	SB.11	Passive	Physical barriers for blast protection.
Fireproofing	SB.12	Passive	Coating materials for fire protection.
Bunds / Catch basins	SB.13	Passive	Physical systems for liquid retaining in case of spill.
Emergency Blowdown line to flare stack	SB.14	Passive	Line for flaring employed during emergency situations.
Mounding tanks	SB.15	Passive	Locating vessels into gravel/ground mounds for fire protection.
Burying tanks	SB.16	Passive	Locating vessels underground for fire protection.

3.3 Metrics for performance analysis of safety barriers

Failure modes, which have been highlighted by past accident analysis, constitute the basis of the definition of the metric for performance parameter adjustment (step 3 in Fig. 1).

A performance modification factor $\phi_{j,i}$ was defined, expressing the plausibility that, during j-th natural hazard, the *i*-th safety barrier will not be available, due to direct impact of the natural event on the facility.

Based on the analysis of past accident and of failure modes, natural hazards are supposed to affect the availability of active barriers (and in turn their PFD), but to have a negligible effect on the effectiveness of such category of barriers. On the contrary, in case of passive barriers the effectiveness is the only parameter which is supposedly modified (e.g., the effective capability of catch basins to retain liquid spills), since barriers belonging to this category do not need to be activated and the concept of PFD is not applicable.

Thus, in case of active barriers, the modification factor $\phi_{j,i}$ is used to determine a tailored value of $PFD_{j,i}$ starting from a baseline $PFD_{0,i}$ reported by literature sources [52, 58, 59]:

$$\boldsymbol{PFD_{j,i} = 1 + (\phi_{j,i} - 1)(1 - PFD_{0,i})} \quad (1)$$

with $\phi_{j,i} \in [0,1]$. The effectiveness for this category of barriers is assumed to be unmodified:

$$\boldsymbol{\eta_{j,i} = \eta_{0,i}} \quad (2)$$

where $\eta_{0,i}$ is the baseline value for barrier effectiveness, independent of the natural event considered. It is worth noting that according to Eq. (1), $PFD_{j,i}$ is a linear function of the factor $\phi_{j,i}$.

In case of passive technical safety barriers, the performance characterization of *i*-th passive barrier during *j*-th natural hazard may be calculated as follows:

$$\boldsymbol{\eta_{j,i} = (1 - \phi_{j,i})\, \eta_{0,i}} \quad (3)$$

with $\phi_{j,i} \in [0,1]$. According to Eq. (3), the effectiveness $\eta_{j,i}$ is a linear decreasing function of $\phi_{j,i}$. In case the natural hazard does not affect the integrity of the barrier (i.e., $\phi_{j,i} = 0$) the performance parameter of the barrier corresponds to its original baseline value, $\eta_{0,i}$.

A reference set for the baseline values of the safety barriers considered is proposed in previous studies (see [31, 54] and references cited therein). However, the selected baseline data sources do not affect the conceptual framework developed in the present study.

3.4 Expert elicitation

An extended group of experts of different nationalities (from Europe, US, Canada, and Asia) was invited to participate in a specific on-line survey in order to obtain information on the expected performance of the reference set of safety barriers defined in the two categories of Natech events selected for the study. Experts of different nature were involved in the survey, involving both academics, i.e. scholars in the field of process safety and industrial design; and practitioners, such as targeting consultancy directors, members of control authorities, facility managers (step 4 in Fig. 1). Involving experts with heterogeneous background is useful to cover all relevant aspects of the subject matter, thus enhancing the completeness of results [45].

The actual number and background of experts answering the survey are reported in Section 4. An ad-hoc survey has been prepared (step 5 in Fig. 1) and administered to the group of experts (step 6 in

Fig. 1) through the Google Form web-app. The transcription of the survey form can be found in Appendix A.

Together with the survey, a brief description of each considered barrier was provided to the experts. Given the heterogeneous background of the expert pool, a preliminary section to investigate the background of respondents has been included in the survey. The number of years of experience, together with the belonging institution have been asked. It should be noted that information on status/background of experts is asked in favor of thorough documentation, and it is deemed a suitable trade-off between anonymity and objectivity in this kind of studies [45].

For both the natural events considered, two questions regarding each safety barrier were asked. Experts were requested to express their opinion on the possibility that the safety barrier could be affected by the specified natural event. A short qualitative answer was required: “YES”, “NO”, “NOT SURE” (e.g., “Do you think in case of floods impacting process facilities, the automatic rim-seal fire extinguisher could be damaged and could be unavailable in case of demand?”). Experts were also given the possibility to leave the question unanswered.

The second question concerned the expert’s opinion on the likelihood of the safety barrier failure as an immediate consequence of the natural event considered. Experts were asked to provide an answer through the verbal scale presented in Fig. 2. The verbal scale was later translated in numerical values according to the association shown in Fig. 2. The choice of adopting a verbal scale with a background translation to numerical values was preferred to directly requiring to experts a numerical answer since this approach, since it was successfully applied in several previous studies, and generally helps respondents providing answers more intuitively [60].

Figure 2: Verbal scale adopted in the survey and corresponding quantitative translation adopted in the analysis of the answers.

3.5 Assessment of performance modification factors

Answers to the qualitative part of the survey were firstly analysed in order to perform a preliminary qualitative assessment of barrier failure (step 7 in Fig. 1). Since categorical answers were posed to respondents in this part (see Section 3.4), a simple statistical analysis was sufficient to obtain the percentage of experts agreeing on whether each barrier would fail or not (or being not sure). Results are then compared with those obtained from the quantitative questions in terms of performance modification parameters to check their coherence.

Modification factors to be used in Eqs. (1) and (3) in order to update the baseline figures for safety barrier performance in case of Natech accidents caused from flood and earthquakes were obtained from the elaboration of quantitative expert answers (step 8 in Fig. 1). After the quantitative translation using the verbal scale in Fig. 2, expert judgments for each barrier were combined to obtain a distribution of values for the modification factor by a linear weighting procedure, associating the same weight to each expert. Even if possibly oversimplified, that applied is the most common and the simplest approach for averaging results obtained from multiple sources. More refined methods, for instance supra Bayesian combination, have not been applied since they would have required an elevated computational effort [61], without providing any added value to results due to the elevated degree of uncertainty of the study.

The results were analyzed comparing distributions obtained for different barriers. However, performance parameters need to be expressed concisely to be suitable for risk analysis. Thus, to summarize the information obtained for each barrier, the median value of each distribution has been chosen as a statistical indicator representing performance modification factor (step 8 in Fig. 1). In Section 4.3 this choice was further discussed.

Elicited modification factors are then implemented in the proposed metric to assess active and passive safety barrier expected performances during the reference natural hazards (step 9 in Fig. 1).

4. Results and Discussion

4.1 Results of the survey

The survey was answered by 41 experts. The final number of answers considered is of 38, since 3 respondents declared not to have specific experience within the context of safety barriers and their answers were not further considered. The final number of involved experts was considered satisfactory, in agreement with some literature studies (e.g., see [62]). Fig. 3 summarizes the professional background (panel a) and the years of experience of the pool of respondents (panel b).

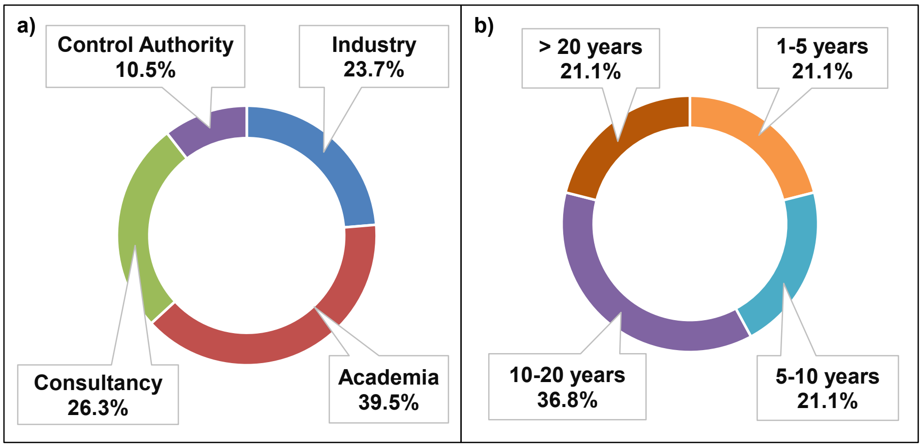

Figure 3: Summary of professional background (a) and year of experience (b) of the pool of experts.

Qualitative results obtained from the analysis of the answers to the first type of question for each barrier (concerning if the barrier would likely be affected by the impact of the natural event) are reported in Fig. 4. Missing answers were associated to the "Not sure" category in Fig. 4, since it was assumed that a missing answer could be interpreted as an uncertainty of the expert in determining an answer.

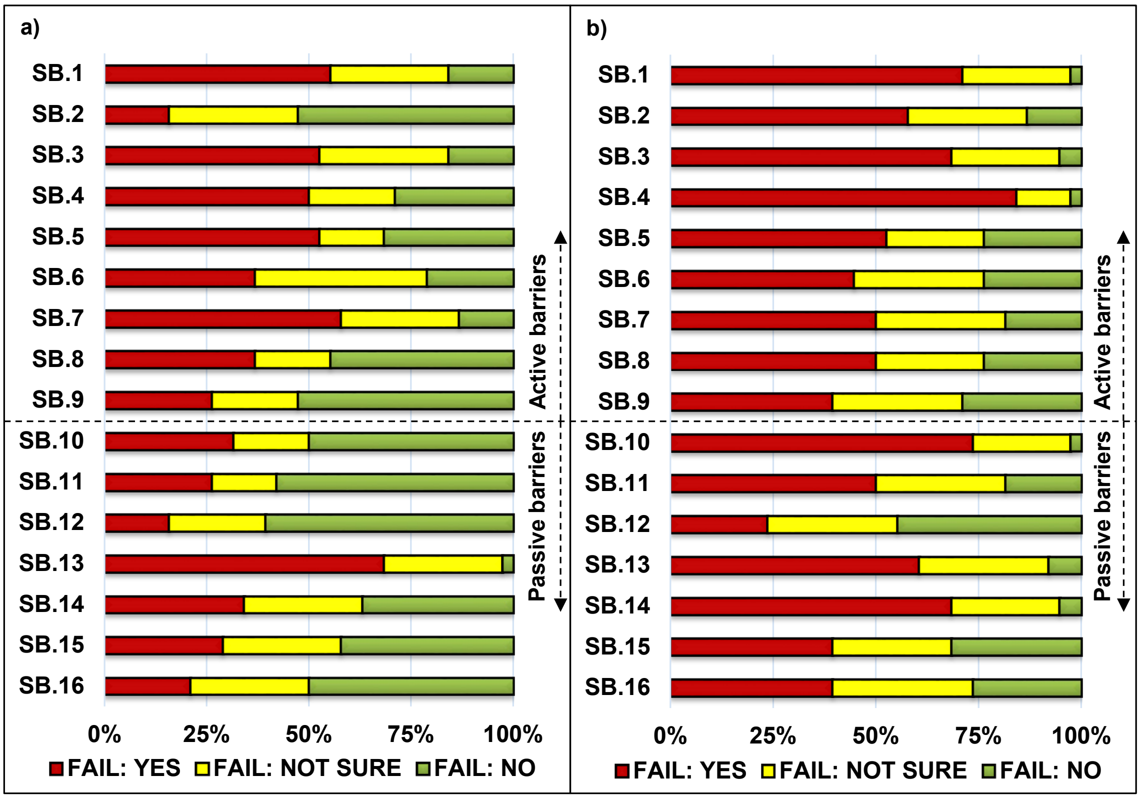

Figure 4: **Results obtained from the survey concerning the likelihood of barrier failure or unavailability in the case of the impact of (a) flood or (b) earthquake. The key to barrier ID is reported in Table 1.**

Qualitative results on failure of safety barriers in case of floods are presented in Fig. 4a. As it can be noted from the figure, active safety barriers (SB.1 to SB.9) are in general perceived by experts to be more vulnerable to floods with respect to passive safety barriers (SB.10 to SB.16). Indeed, more than half of the experts indicated that 5 active barriers out of 9, and 1 passive barrier out of 7 would be damaged and unavailable during flooding scenarios. The active barriers recognized as likely to be unavailable in the case of a flood by most of experts are mainly complex systems for fire prevention and mitigation, that is, inert gas blanketing systems (SB.1), foam systems (SB.3), sprinklers and water deluge systems (SB.4), hydrants for fire brigades (SB.5), and detection devices as fire & gas detectors (SB.7). Automatic rim-seal fire extinguishers (SB.2) have been considered unlikely to be affected by most experts, presumably due to their position, above floating roofs of atmospheric storage tanks. An elevated uncertainty is present concerning the impact of floods on fire activated valves (SB.6), probably due to the high specificity of such safety systems. Both SDVs and BDVs (SB.7 and SB.8, respectively) have been considered to be unaffected by most of experts, reflecting the fact that these systems are usually designed fail-safe.

For what concerns passive barriers, it is clear that the most critical items perceived by experts are bunds and catch basins (SB.13). Interviewed experts seem to have clear in mind the possibility that these systems may be overtopped by floodwaters, annealing the possibility to express their safety function of retaining possible liquid spills, as it was also highlighted by past accident analysis [16]. The other passive barriers seem not to be significantly affected by floodwaters according to experts' opinion.

Finally, it is worth remarking that if uncertainty is conservatively associated to likelihood of failure (i.e., considering the sum of "fail" and "not sure" answers) the failure of 12 out of 16 items is deemed plausible by more than 50% of experts.

Qualitative results on the failure of safety barriers in the case of earthquakes are presented in Fig. 4b. It is clear from the figure that in most cases the failure of the barriers due to seismic events is expected by the majority of experts.

Among active barriers, the only items which in experts' opinion are unlikely to fail (Fail % lower than 50) are fire activated valves (SB.6) and BDVs (SB.9). The criticality of active fire protection systems has been strongly highlighted. Indeed, these systems are those considered more vulnerable among the investigated set of active barriers. For instance, WDS and sprinklers (SB.4) are expected to be damaged in an earthquake by about 85% of respondents, while the failure of both foam systems (SB.3) and inert gas blanketing systems (SB.1) is expected by about 70% of experts. These systems are composed of a pipework distribution network (i.e., for delivering firefighting water, foam, or inert

gas, respectively), which may be vulnerable during seismic events, as evidenced by past Natech accident analysis [56].
Among passive barriers, a total of 4 out of the 7 systems present in the selected set of safety barriers were considered likely to fail by more than half of the experts in the pool. The most critical events resulted firewalls (SB.10), emergency blowdown lines (EBD line) (SB.14) and bunds and catch basins (SB.13) whose failure in case of earthquake is expected respectively by 74%, 68% and 60% of the experts participating in the survey. The criticality of the EBD line evidenced by the survey is probably due to the importance given by experts to the elevated vulnerability of piping during seismic events, emerging from accident analysis [56]. As expected, firewalls, bunds and catch basins may be particularly prone to structural failures due to seismic loads. The extensive damages to concrete dikes during Koaceli Earthquake (1999) (see Section 1) is an example confirming the vulnerability to earthquakes of these safety barriers [42].
When the results obtained for earthquakes (Fig. 4b) are compared to those obtained in the case of floods (Fig. 4a), it clearly emerges that the consulted experts consider the failure of the set of technical safety barriers considered more likely in the case of an earthquake than in the case of a flood. Indeed, if only 6 items are considered likely to fail by more than 50% of experts in the case of a flood, when earthquake is considered this number rises to 11. On average, active barriers have been assessed likely to fail by about 43% of experts during floods, and by about 58% of experts during earthquakes. A similar trend is found for passive barriers, with an average of 33% of experts considering failure likely in case of floods, and 51% in case of earthquakes.
Nevertheless, both in the case of floods and of earthquakes, experts agree that passive barriers are generally more robust than active barriers, despite few specific cases (e.g., catch basins are likely to be submerged by floodwaters).

4.2 Barrier performance modification factors

The analysis of the answers obtained to the second set of questions, requiring the experts to express a verbal graduation of the likelihood of barrier failure during natural hazards, allowed gathering a distribution of the modification factors $\phi_{j,i}$ by the procedure described in Section 3.5. The distributions of the elicited performance modification parameter are reported in Fig. 5 in the concise form of boxplots. Further details on the results, and a detailed description of the distributions obtained for each barrier are presented in Appendix B.
In coherence with previous studies (see [46]), assuming the median value of each distribution as the value for the performance modification factor is suggested. The adoption of the mean value as a statistical indicator in this case is not considered the best choice, since it is not fully representative of

the distribution in case of disperse judgments: the influence of outliers on the variation of the mean value is rather elevated in the set of data obtained, while the median of the distribution is less affected by outliers, thus better representing the central tendency of data [63, 64].

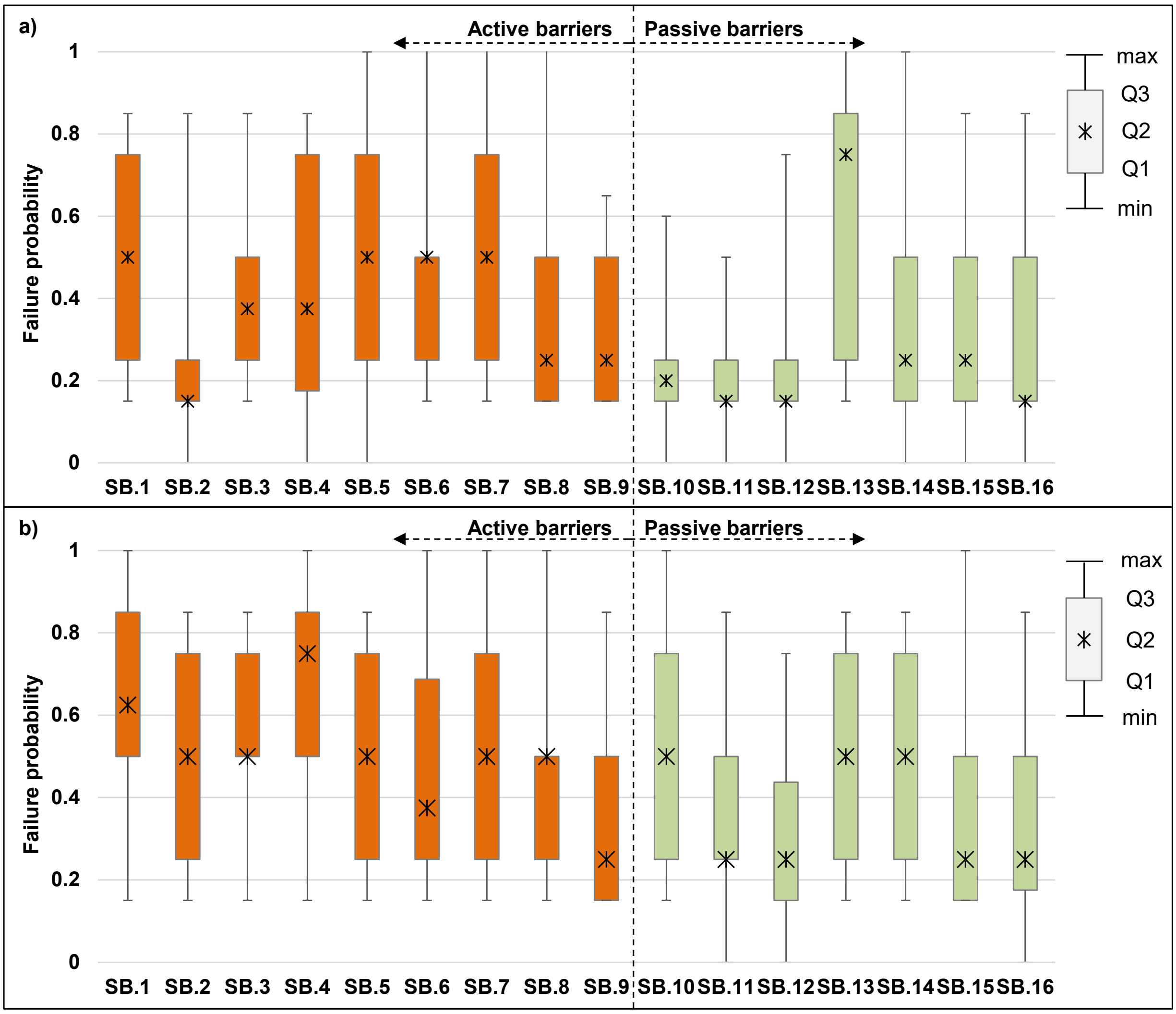

Figure 5: Results obtained from the elicitation of performance parameter φ for (a) floods and (b) earthquakes (Q1= higher value for the 1st quartile, Q2= highest value for the 2nd quartile (median value of the dataset), Q3= highest value for the 3rd quartile. Orange = Active barrier, Green = passive barrier. 0: failure impossible; 1: failure certain; see Fig. 2 for quantitative translation criteria of verbal scales). The key to safety barrier ID is reported in Table 1.

Distributions of the performance parameters during floods are presented in Fig. 5a. The most vulnerable active systems identified by the experts are the inert gas blanketing system (SB.1), hydrants (SB.5), fire activated valves (SB.6), and fire and gas detectors (SB.7), with median values of the elicited performance parameter of about 0.5. As evident from Fig. 4a, some of these items were recognized as critical by the majority of experts also in the qualitative answers.

It should be remarked that the distributions of answers have a high dispersion for some items. For instance, figures for WDS and sprinkler systems (SB.4) show a large disagreement among respondents (i.e., median of 0.375, Q1 and Q3 of 0.175 and 0.75 respectively), despite they had been deemed likely to fail by the majority of experts in the qualitative part of the survey. The same issue affects the set of the most vulnerable items (SB.1, SB.5 and SB.7). The possible reasons of such distributions are probably due to differences considered by the experts in the layout of complex systems as active barriers.

Automatic rim-seal fire extinguishers (SB.2), SDVs (SB.8) and BDVs (SB.9) show low values of the modification parameter (respectively of 0.15, 0.25 and 0.25), highlighting their expected resilience to floods. It should also be noted that the distribution elicited for SB.2 is peculiarly narrow, indicating that the majority of experts agree on the scarce vulnerability of this barrier.

Among passive barriers, the catch basins and bunds (SB.13) are by far the items showing the highest value of modification factor (0.8). This result was expected, since the large majority of experts had already identified the vulnerability of such retaining systems during floods. The other passive barriers investigated have been assessed to be only slightly affected by floodwaters, showing low values of the performance modification parameter (apart from SB.13, the average median value is of about 0.2).

The distributions of the performance parameter for each barrier considering earthquake are shown in Fig. 5b. In this case the most vulnerable items are by far the gas blanketing system (SB.1) and WDS and sprinklers (SB.4), with median values of 0.625 and 0.75, respectively. These results are in line with the qualitative answers (see Fig. 4b), highlighting that experts are clearly oriented concerning the vulnerability of these systems in the case of earthquakes. Most of the other active barriers are considered as well likely to be affected by earthquakes, showing median values of 0.5 in 5 out of 7 cases. Surprisingly, different figures result for SVDs (SB.8) with respect to BDVs (SB.9), in spite of the similarity of such safety systems.

Passive barriers are deemed to be significantly affected by seismic loads in 3 out of 7 cases, with the most critical items being firewalls (SB.10), bunds and catch basins (SB.13), and emergency blowdown line (SB.14): median value is of 0.5 for each of the three distributions. For this subset of barriers, the effectiveness is halved with respect to their expected performance during standard operating conditions. Again, the results are in line with those obtained from qualitative answers. The category of passive barriers is associated to an average performance modification parameter equal to 0.36, lower than that corresponding to the set of active systems considered (equal to 0.5), confirming that such category of barriers is considered more resilient to earthquakes.

In order to compare the quantitative performance results obtained for floods and earthquakes, the average distribution of position parameters was calculated for the entire set of barriers investigated.

More specifically, the following parameters were calculated for floods and earthquake: the average over the entire set of barriers of the minimum and maximum value (Min and Max) and of the highest figure in the 1st, 2nd, and 3rd quartiles ($\overline{Q}_1$, $\overline{Q}_2$, and $\overline{Q}_3$ respectively) of the distributions.

The results are reported in Fig. 6. From the figure it clearly emerges that the investigated barriers are deemed in general more vulnerable to earthquakes than to floods. Indeed, considering earthquakes, $\overline{Q}_2$ is of 0.5 for active barriers and 0.375 for passive ones, while the corresponding values for floods are of 0.378 and 0.271 respectively. Fig. 6 further confirms that the investigated active barriers are considered to be more vulnerable to both natural hazards than passive barriers. It should also be noted that the difference among the impact of floods and earthquakes is slightly higher for active barriers than for passive barriers, in general. Indeed, the average difference in performances among $\overline{Q}_1$, $\overline{Q}_2$ and $\overline{Q}_3$ parameters, is of 0.12 for active barriers and 0.1 for passive barriers.

The differences between the average position of outliers (i.e., Min and Max position parameters) have not been assessed in the comparison since they express the extreme points of each distribution, which in some cases are determined by the judgment of a limited group of experts in disagreement with the majority. For instance, the distribution elicited for automatic rim-seal fire extinguisher (SB.2) in case of floods, shows a maximum value of 0.85, which has been expressed only by 2 experts out of 38 analysed, while the really narrow distribution confirms general agreement among respondents.

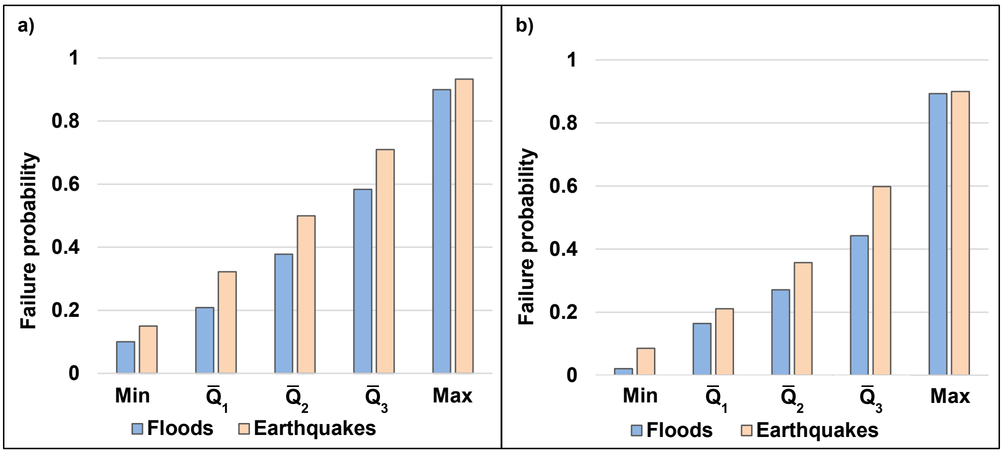

Figure 6: **Average parameters of the distributions calculated for (a) active barriers and (b) passive barriers. Min = average minimum value, $\overline{Q}_1$= average higher value in the 1st quartile, $\overline{Q}_2$ = average median value, $\overline{Q}_3$ = average highest value in the 3rd quartile, Max= average maximum value.**

4.3 Discussion

The modification parameters elicited from the survey in perspective may be considered as a first step to assess safety barrier performance in probabilistic QRAs of Natech events [14]. However, due to the scarcity of data, this study only represents a first exploration of the topic and important limitations, in particular when quantitative data are of interest, should be considered. Actually, in order to maintain a general validity of the assessment, it was decided to ask experts to consider a “plausible” intensity of natural hazards. Indeed, defining the characteristics and the intensity of natural hazards would have restricted the applicability domain of the study. On the one hand, the absence of intensity specification is thus in favor of a more general validity of the study. Onn the other hand, it also limits the direct applicability of results in the quantitative assessment of specific scenarios. The modification parameters obtained should be thus considered as generic baseline values. Site-specific values for quantitative assessment studies need to be derived from tailoring procedures, based on more detailed data both on the intensity of the natural event and on the specific features of the safety barrier considered.

An additional limitation of the present study is the inherent uncertainty affecting expert elicitation procedures. Experts may be unable to properly express their knowledge within the framework of the prepared survey, or they may be not confident with the verbal scale they were provided of. It is also possible that experts would have preferred to express their opinions on the likelihood of barrier failures through numerical distributions. For instance, some authors suggest to employ the Classical Model to better characterize judgment features, thus requiring experts to provide their subjective parameter distributions for each surveyed item in terms of 5^{th}, 50^{th} and 95^{th} percentiles [65]. However, this procedure would have made the survey harder to be completed by experts, and was considered inappropriate considering the scarcity of data and the explorative nature of the present study. Furthermore, the combination of the distributions obtained would have required a proper assessment of the relative weights of expert knowledge, which was not practically feasible.

Some analyzed safety systems show a wide dispersion of the answer distributions, indicating a limited agreement among experts. One of the possible causes may be the technical complexity of some systems analyzed. In particular, for active barriers, a more refined analysis can be required to obtain reliable results. A possibility may be to study these systems through more sophisticated approaches considering the impact of natural hazards in each relevant subsystem. For instance, a failure mode and effect analysis (FMEA) could be used to assess which subsystems are critical during natural hazards, and what is the effect of damages to parts of system architecture [55].

The present study was limited to the analysis of technical barriers. However, this limitation derived only from the need to limit the number of barriers considered in the survey to limit the time required to the experts to complete it, and also from the background of selected experts. Procedural barriers and emergency measures may be assessed as well within the proposed framework. Indeed, during natural hazards the actions of plant operators and emergency teams, may be heavily hindered due to the high stressing environment and the complexity of scenarios [4].

5. Conclusions

In the present study, the performances of common safety barriers adopted in chemical and process plants during natural hazards have been investigated by expert elicitation. Some safety barriers were identified as having a critical vulnerability to natural hazards. Baseline values to describe how the performance of safety barriers is modified during floods and earthquakes were obtained from the expert elicitation procedure. These parameters may support the probabilistic analysis of Natech scenarios, in order to achieve a better estimate of final consequences and possible domino effects. The results lay the basis for an improved risk-informed decision making on proactive strategies enhancing the safety of chemical and process plants against natural disasters.

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Appendix A

The present appendix reports the transcription of the form adopted to carry out the expert elicitation.

The form is reported in Table A.1

Table A.1 Transcription of the survey form

The scope of the present questionnaire is to gather experts' opinions on the possibility that several common safety barriers used in chemical and process plants could fail if impacted by natural events. The safety barriers considered are described in the file that you received attached to the e-mail including the link to the survey.
The survey is limited to the impact of generic FLOOD and SEISMIC events (i.e., EARTHQUAKES) affecting the site where the barrier is present. The term "generic" in this context means that the opinion has to be expressed independently of the intensity of the event: in answering the questions you should evaluate how plausible is the failure of a protection measure in case of such events. It must be remarked that the present elicitation is to gather performance estimates: you should assess the plausibility of barrier failure and/or inefficient response considering its architecture (e.g., subsystems, dependence on power-grid connection, position of pumps, pipework, fail-safe design, etc.).
In case you do not know (or you are not familiar with) a specific system mentioned in the survey, you can skip the question. In case you know the system, but you are not sure about the answer you can skip the question as well.
In line with EU research standards, this survey is strictly anonymous. This research is purely of an academic nature, it is only intended to further and improve knowledge on the performance of protection measures adopted in industrial facilities.

Personal information
You are kindly asked to answer to a couple of questions for understanding your background.
1. Which kind of institution do you belong to?
Answers: [Academia/Industry/Consultancy/Other: (specify)…………]
2. How many years of experience do you have in the context of safety barrier management?
Answers: [No experience/ From 1 to 5/From 5 to 10/From 10 to 20/More than 20]

SB1. Inert Gas Blanketing System
With inert gas blanketing system we refer to the whole system for padding tanks containing flammable liquids, comprising the inert supply tank, and the relative distribution piping.
3. Do you think in case of flood event impacting process facilities, the inert gas blanketing system could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
4. Based on your experience and judgement, how likely do you think it is that the inert gas blanketing system is unavailable in case of demand, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
5. Do you think in case of seismic event impacting process facilities, the inert gas blanketing system could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]

6. Based on your experience and judgement, how likely do you think it is that the inert gas blanketing system is unavailable in case of demand, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

<u>SB.2 Automatically Actuated Rim-Seal Fire Extinguishers</u>
With automatically actuated rim-seal fire extinguishers we refer to a safety system against rim-seal fires located on the roof of flammable liquid storage tanks.
7. Do you think in case of flood event impacting process facilities automatically actuated rim-seal fire extinguishers could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
8. Based on your experience and judgement, how likely do you think it is that automatically actuated rim-seal fire extinguishers are unavailable in case of demand, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
9. Do you think in case of seismic event impacting process facilities automatically actuated rim-seal fire extinguishers could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
10. Based on your experience and judgement, how likely do you think it is that automatically actuated rim-seal fire extinguishers are unavailable in case of demand, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

<u>SB.3 Fixed/Semi-Fixed Foam Systems</u>
With fixed/semi-fixed foam systems we refer to systems for tank fire extinction by providing water-based foam to the fire area.
11. Do you think in case of flood event impacting process facilities fixed/semi-fixed foam systems could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
12. Based on your experience and judgement, how likely do you think it is that fixed/semi-fixed foam systems are unavailable in case of demand, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
13. Do you think in case of seismic event impacting process facilities fixed/semi-fixed foam systems could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
14. Based on your experience and judgement, how likely do you think it is that fixed/semi-fixed foam systems are unavailable in case of demand, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

<u>SB.4 Water Deluge System / Water Curtains & Sprinklers</u>
With water deluge system, water curtains we refer to safety systems to mitigate the risk posed by external fire to critical areas where the fire shall not spread. With sprinklers we refer to the system providing water to burning area.
15. Do you think in case of flood event impacting process facilities water deluge system, water curtains & sprinklers could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
16. Based on your experience and judgement, how likely do you think it is that water deluge system, water curtains & sprinklers are unavailable in case of demand, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
17. Do you think in case of seismic event impacting process facilities water deluge system, water curtains & sprinklers could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
18. Based on your experience and judgement, how likely do you think it is that water deluge system, water curtains & sprinklers are unavailable in case of demand, as immediate consequence of SEISMIC event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

<u>SB.5 Hydrants</u>
With hydrants we refer to sources where fire brigades can connect firehoses to deliver water to burning areas. The system of firefighting water distribution to hydrants can be supposed the same to provide water to WDS and sprinklers.

19. Do you think in case of flood event impacting process facilities hydrants could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
20. Based on your experience and judgement, how likely do you think it is that hydrants are unavailable in case of demand, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
21. Do you think in case of seismic event impacting process facilities hydrants could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
22. Based on your experience and judgement, how likely do you think it is that Hydrants are unavailable in case of demand, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

SB.6 Fire Walls
With fire walls we refer to physical barriers to protect assets from fire.
23. Do you think in case of flood event impacting process facilities fire walls could be damaged and could be unavailable?
Answers: [YES/NO/NOT SURE]
24. Based on your experience and judgement, how likely do you think it is that fire walls are unavailable, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
25. Do you think in case of seismic event impacting process facilities fire walls could be damaged and could be unavailable?
Answers: [YES/NO/NOT SURE]
26. Based on your experience and judgement, how likely do you think it is that fire walls are unavailable, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
SB.7 Blast Walls
With blast walls we refer to physical barriers resistant to blast waves.
27. Do you think in case of flood event impacting process facilities blast walls could be damaged and could be unavailable?
Answers: [YES/NO/NOT SURE]
28. Based on your experience and judgement, how likely do you think it is that blast walls are unavailable, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
29. Do you think in case of seismic event impacting process facilities blast walls could be damaged and could be unavailable?
Answers: [YES/NO/NOT SURE]
30. Based on your experience and judgement, how likely do you think it is that blast walls are unavailable, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
SB.8 Fireproofing
With fireproofing we refer to specific coating material intended to protect equipment from fire.
31. Do you think in case of flood event impacting process facilities fireproofing could be damaged and could be ineffective?
Answers: [YES/NO/NOT SURE]
32. Based on your experience and judgement, how likely do you think it is that fireproofing is ineffective, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
33. Do you think in case of seismic event impacting process facilities fireproofing could be damaged and could be ineffective?
Answers: [YES/NO/NOT SURE]
34. Based on your experience and judgement, how likely do you think it is that fireproofing is ineffective, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
SB.9 Bunds / Catch Basins
With bunds / catch basins we refer to physical barriers around tanks storing hazardous liquids, sized to retain the whole content of the tank preventing liquid spread. Concrete, earth, or steel are used to build these structures.

35. Do you think in case of flood event impacting process facilities bunds / catch basins could be damaged and could be ineffective?
Answers: [YES/NO/NOT SURE]
36. Based on your experience and judgement, how likely do you think it is that bunds / catch basins are ineffective, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
37. Do you think in case of seismic event impacting process facilities bunds / catch basins could be damaged and could be ineffective?
Answers: [YES/NO/NOT SURE]
38. Based on your experience and judgement, how likely do you think it is that bunds / catch basins are ineffective, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
SB.10 Fire Activated Valves
With fire activated valves we refer to valves activated through melting elements or by heat detectors. The valves instrument air to operate correctly.
39. Do you think in case of flood event impacting process facilities fire activated valves could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
40. Based on your experience and judgement, how likely do you think it is that fire activated valves are unavailable in case of demand, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
41. Do you think in case of seismic event impacting process facilities fire activated valves could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
42. Based on your experience and judgement, how likely do you think it is that fire activated valves are unavailable in case of demand, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
SB.11 Fire and Gas Detectors
With fire and gas detectors we refer to sensors located in the field to detect fire, heat, smoke, or gas leaks, cabled to an alarm in control room.
43. Do you think in case of flood event impacting process facilities fire and gas detectors could be damaged and could be unavailable?
Answers: [YES/NO/NOT SURE]
44. Based on your experience and judgement, how likely do you think it is that fire and gas detectors are unavailable, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
45. Do you think in case of seismic event impacting process facilities fire and gas detectors could be damaged and could be unavailable?
Answers: [YES/NO/NOT SURE]
46. Based on your experience and judgement, how likely do you think it is that fire and gas detectors are unavailable, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
SB.12 Shut Down Valves (SDVs)
With shut down valves (SDVs) we refer to fail-close valves aimed at the isolation of the equipment when activated. SDVs may be activated manually or by process/local/emergency shut-down logic.
47. Do you think in case of flood event impacting process facilities shut down valves (SDVs) could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
48. Based on your experience and judgement, how likely do you think it is that shut down valves (SDVs) are unavailable in case of demand, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
49. Do you think in case of seismic event impacting process facilities shut down valves (SDVs) could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
50. Based on your experience and judgement, how likely do you think it is that shut down valves (SDVs) are unavailable in case of demand, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
SB.13 Blow Down Valves (BDVs)

With blow down valves (BDVs) we refer to fail-open valves venting process fluid to flare, aimed at providing a fast depressurization of the equipment. BVDs may be activated manually or by emergency shut-down logic.
51. Do you think in case of flood event impacting process facilities blow down valves (BDVs) could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
52. Based on your experience and judgement, how likely do you think it is that blow down valves (BDVs) are unavailable in case of demand, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
53. Do you think in case of seismic event impacting process facilities blow down valves (BDVs) could be damaged and could be unavailable in case of demand?
Answers: [YES/NO/NOT SURE]
54. Based on your experience and judgement, how likely do you think it is that blow down valves (BDVs) are unavailable in case of demand, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
SB.14 Emergency Blow Down (EBD) line to flare stack
The BDV is activated to depressurize equipment through opening a line to flare stack. The EBD line connecting the equipment to the flare is likely to have a flash KO drum for liquid separation.
55. Do you think in case of flood event impacting process facilities the emergency blow down (EBD) line to flare stack could be damaged and could be unavailable?
Answers: [YES/NO/NOT SURE]
56. Based on your experience and judgement, how likely do you think it is that the emergency blow down (EBD) line to flare stack is unavailable in case of demand, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
57. Do you think in case of seismic event impacting process facilities the emergency blow down (EBD) line to flare stack could be damaged and could be unavailable?
Answers: [YES/NO/NOT SURE]
58. Based on your experience and judgement, how likely do you think it is that the emergency blow down (EBD) line to flare stack is unavailable, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
SB.15 Mounding storage
With mounding storage we refer to locating tanks into above-ground piles of gravel/earth (i.e., mounds) for protection from external fire.
59. Do you think in case of flood event impacting process facilities mounds protecting the tanks could be damaged and could become ineffective in protecting tanks in case of fire?
Answers: [YES/NO/NOT SURE]
60. Based on your experience and judgement, how likely do you think it is that the protection given by mounds becomes ineffective, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
61. Do you think in case of seismic event impacting process facilities mounds protecting the tanks could be damaged and could become ineffective in protecting tanks in case of fire?
Answers: [YES/NO/NOT SURE]
62. Based on your experience and judgement, how likely do you think it is that the protection given by mounds becomes ineffective, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
SB.16 Burying storage
With burying storage (underground) we refer to positioning storage tanks below ground level.
63. Do you think in case of flood event impacting process facilities the protection given by earth covering buried tanks could be compromised?
Answers: [YES/NO/NOT SURE]
64. Based on your experience and judgement, how likely do you think it is that the protection given by earth covering buried tanks becomes ineffective, as immediate consequence of flood event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]
65. Do you think in case of seismic event impacting process facilities the protection given by earth covering buried tanks could be compromised?
Answers: [YES/NO/NOT SURE]
66. Based on your experience and judgement, how likely do you think it is that the protection given by earth covering buried tanks becomes ineffective, as immediate consequence of seismic event?
Answers: [Certain/Probable/Expected/Fifty-Fifty/Uncertain/Improbable/Impossible]

Appendix B

The detail of the distributions obtained from experts' answers are reported in Table B.1 for floods and in Table B.2 for earthquakes.

Table B.1: Description of performance parameter distribution for each safety barrier for floods. The reader can refer to Table 1 for concise barrier descriptions and classification.

Safety barrier	Barrier ID	Performance estimate factor	Distribution description
Inert-gas blanketing system	SB.1	0.5	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.5 3rd quartile = 0.75 Maximum = 0.85 Average = 0.441 Sample Std.Dev. = 0.259
Automatic rim-seal fire extinguishers	SB.2	0.15	Minimum=0 1st quartile = 0.15 2nd quartile = 0.15 3rd quartile = 0.25 Maximum = 0.85 Average = 0.284 Sample Std.Dev. = 0.217
Fixed / Semi-fixed foam systems	SB.3	0.375	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.375 3rd quartile = 0.5 Maximum = 0.85 Average = 0.434 Sample Std.Dev. = 0.236
WDS / Water Curtains / Sprinklers	SB.4	0.375	Minimum=0 1st quartile = 0.175 2nd quartile = 0.375 3rd quartile = 0.75 Maximum = 0.85 Average = 0.439 Sample Std.Dev. = 0.279
Hydrants	SB.5	0.5	Minimum=0 1st quartile = 0.25 2nd quartile = 0. 5 3rd quartile = 0.75 Maximum = 1 Average = 0.493 Sample Std.Dev. = 0.308
Fire activated valves	SB.6	0.5	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.5 3rd quartile = 0.5 Maximum = 0.85 Average = 0.418 Sample Std.Dev. = 0.238
Fire and gas detectors	SB.7	0.5	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.5 3rd quartile = 0.75

			Maximum = 1 Average = 0.537 Sample Std.Dev. = 0.281
SDVs	SB.8	0.25	Minimum=0.15 1st quartile = 0.15 2nd quartile = 0.25 3rd quartile = 0.5 Maximum = 1 Average = 0.343 Sample Std.Dev. = 0.238
BDVs	SB.9	0.25	Minimum=0.15 1st quartile = 0.15 2nd quartile = 0.25 3rd quartile = 0.5 Maximum = 0.85 Average = 0.318 Sample Std.Dev. = 0.222
Fire walls	SB.10	0.2	Minimum=0 1st quartile = 0.15 2nd quartile = 0.2 3rd quartile = 0.25 Maximum = 0.85 Average = 0.282 Sample Std.Dev. = 0.245
Blast walls	SB.11	0.15	Minimum=0 1st quartile = 0.15 2nd quartile = 0.15 3rd quartile = 0.75 Maximum = 0.85 Average = 0.274 Sample Std.Dev. = 0.240
Fireproofing	SB.12	0.15	Minimum=0 1st quartile = 0.15 2nd quartile = 0.15 3rd quartile = 0.25 Maximum = 0.85 Average = 0.261 Sample Std.Dev. = 0.252
Bunds / Catch basins	SB.13	0.75	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.75 3rd quartile = 0.85 Maximum = 1 Average = 0.597 Sample Std.Dev. = 0.275
Emergency Blowdown line to flare stack	SB.14	0.25	Minimum=0 1st quartile = 0.15 2nd quartile = 0.25 3rd quartile = 0.5 Maximum = 1 Average = 0.334 Sample Std.Dev. = 0.236
Mounding tanks	SB.15	0.25	Minimum=0 1st quartile = 0.15 2nd quartile = 0.25 3rd quartile = 0.5 Maximum = 0.85 Average = 0.357 Sample Std.Dev. = 0.275
Burying tanks	SB.16	0.15	Minimum=0 1st quartile = 0.15

			2nd quartile = 0.15 3rd quartile = 0.5 Maximum = 0.85 Average = 0.289 Sample Std.Dev. = 0.230

Table B.2 Description of performance parameter distribution for each safety barrier for earthquakes. The reader can refer to Table 1 for concise barrier descriptions and classification.

Safety barrier	**Barrier ID**	**Performance estimate factor**	**Distribution description**
Inert-gas blanketing system	SB.1	0.625	Minimum=0.15 1st quartile = 0.5 2nd quartile = 0.625 3rd quartile = 0.85 Maximum = 1 Average = 0.607 Sample Std.Dev. = 0.238
Automatic rim-seal fire extinguishers	SB.2	0.5	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.5 3rd quartile = 0.75 Maximum = 0.85 Average = 0.489 Sample Std.Dev. = 0.255
Fixed / Semi-fixed foam systems	SB.3	0.5	Minimum=0.15 1st quartile = 0.5 2nd quartile = 0.5 3rd quartile = 0.75 Maximum = 0.85 Average = 0.571 Sample Std.Dev. = 0.238
WDS / Water Curtains / Sprinklers	SB.4	0.75	Minimum=0.15 1st quartile = 0.5 2nd quartile = 0.75 3rd quartile = 0.85 Maximum = 1 Average = 0.620 Sample Std.Dev. = 0.246
Hydrants	SB.5	0.5	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.5 3rd quartile = 0.75 Maximum = 0.85 Average = 0.482 Sample Std.Dev. = 0.282
Fire activated valves	SB.6	0.375	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.375 3rd quartile = 0.6875 Maximum = 0.85 Average = 0.445 Sample Std.Dev. = 0.262
Fire and gas detectors	SB.7	0.5	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.5 3rd quartile = 0.75 Maximum = 1 Average = 0.480 Sample Std.Dev. = 0.264
SDVs	SB.8	0.5	Minimum=0.15 1st quartile = 0.25

			2nd quartile = 0.5 3rd quartile = 0.5 Maximum = 1 Average = 0.433 Sample Std.Dev. = 0.246
BDVs	SB.9	0.25	Minimum=0.15 1st quartile = 0.15 2nd quartile = 0.25 3rd quartile = 0.5 Maximum = 0.85 Average = 0.368 Sample Std.Dev. = 0.236
Fire walls	SB.10	0.5	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.5 3rd quartile = 0.75 Maximum = 1 Average = 0.514 Sample Std.Dev. = 0.271
Blast walls	SB.11	0.25	Minimum=0 1st quartile = 0.25 2nd quartile = 0.25 3rd quartile = 0.5 Maximum = 0.85 Average = 0.405 Sample Std.Dev. = 0.257
Fireproofing	SB.12	0.25	Minimum=0 1st quartile = 0.15 2nd quartile = 0.25 3rd quartile = 0.4375 Maximum = 0.75 Average = 0.314 Sample Std.Dev. = 0.234
Bunds / Catch basins	SB.13	0.5	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.5 3rd quartile = 0.75 Maximum = 0.85 Average = 0.464 Sample Std.Dev. = 0.249
Emergency Blowdown line to flare stack	SB.14	0.5	Minimum=0.15 1st quartile = 0.25 2nd quartile = 0.5 3rd quartile = 0.75 Maximum = 1 Average = 0.530 Sample Std.Dev. = 0.234
Mounding tanks	SB.15	0.25	Minimum=0.15 1st quartile = 0.15 2nd quartile = 0.25 3rd quartile = 0.5 Maximum = 1 Average = 0.411 Sample Std.Dev. = 0.259
Burying tanks	SB.16	0.25	Minimum=0 1st quartile = 0.175 2nd quartile = 0.25 3rd quartile = 0.5 Maximum = 0.85 Average = 0.391 Sample Std.Dev. = 0.251

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