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Quantitative Risk Assessment of accidents induced by seismic events in industrial sites

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Several accidents occurred in the last decades evidenced that the impact of seismic events in industrial plants may trigger accidental scenarios involving the release of relevant quantities of hazardous substances. Severe scenarios typical of the process industry, as fires, explosions, toxic releases, water pollution were reported as the consequence of seismic events in industrial areas. Although the severity of this kind of accidents, scarce attention was devoted to the assessment of risk due to major accidents triggered by seismic events and a comprehensive approach to risk assessment and emergency planning in industrial sites extended to include the possible external hazard factors is still needed. In the present study, a specific approach was developed for the assessment of local and societal risk indexes caused by accidental scenarios triggered by earthquakes. The approach allows the identification and the consequence assessment of all the possible scenarios that may follow the seismic events. The starting point of the procedure was the use of available historical data to assess the expected frequencies and the severity of seismic events. Simplified empirical vulnerability models (fragility curves) were used to assess the damage probability of equipment items due to a seismic event. The data on the frequency of the natural events have to be combined with the data of the equipment vulnerability, in order to calculate a release probability, indispensable to obtain the final risk value. The procedure was implemented in a GIS-based software tool in order to manage the high number of event sequences that are likely to be generated in large industrial facilities. The developed methodology requires a limited amount of additional data with respect to those used in a conventional QRA.
The application of the procedure to a storage plant sited in the Emilia-Romagna region evidenced that the scenarios initiated by seismic events may be important in the comprehensive assessment of industrial risk.

1. Introduction

Figure 1 shows the flowchart of the procedure developed for the assessment of the risk caused by natural events in industrial plants. The procedure was derived from the well known scheme used for conventional risk assessment. As shown in the flowchart, the starting point of the methodology is the analysis of natural hazards in the site where the facility of concern is located (steps 1-2). The characterization of the frequency and the severity of natural event (step 3) by a sufficiently simple approach, suitable for the use in a risk assessment, is of utmost importance in order to obtain damage probabilities from simplified vulnerability or fragility models, based on single parameters suitable to characterize the severity of the event (step 6). Reference scenarios should be associated to each critical equipment item (step 4) identified in step 3. Critical equipment items are those that have the potentiality to cause a severe scenario due to an escalation triggered by the natural event. The severity of the scenario triggered by the natural event depends both on the hold-up and on the properties of hazardous substances in the equipment of concern. It should be considered that more than one reference scenario may take place simultaneously due to the damage of more than one unit (steps 7-8). Thus, also the consequence assessment of the resulting scenarios should be carried out combining the consequences of each of the reference accidental events identified (step 9). Finally, the conventional risk recomposition procedure may be applied for the calculation of the additional contribution to individual and societal risk of the accidental scenarios induced by natural events and identified by the above procedure

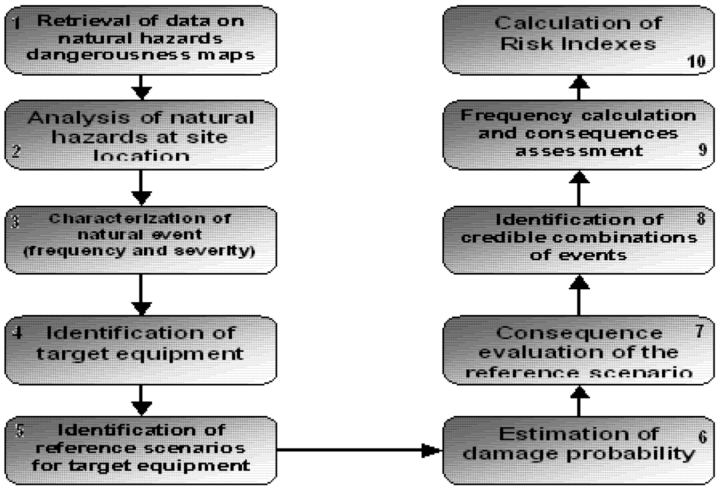

Figure 1. Flowchart of the procedure developed for the risk assessment of accidental scenarios triggered by natural events involving industrial plants

2. Earthquake and damage characterization

2.1. Characterization of the local seismicity

The first issue in the application of the approach shown in figure 1 is the characterization of the initiating event. The specific features of QRA call for simplified representations of the complex nature of the events that may cause the LOC scenarios. Thus, in the present approach, the characterization of a natural event was performed by the identification of one or more than one reference events, the estimation of the occurrence of the reference events, and a simplified representation of the severity of the event by a few specific parameters. In the case of earthquakes, Peak Ground Acceleration (PGA) is particularly useful to characterize the severity of the event (Cornell, 1968). This choice is due to its simplicity of measurement, obtained by a direct reading of the accelerogram at any given location. Furthermore, almost all historical database are expressed according to this variable and the direct conversion from magnitude to earthquake intensity by means of attenuation relations is also possible.

The probability of occurrence of an earthquake having a given severity may be estimated by the widely used Probabilistic Seismic Hazard Analysis (PSHA) (Cornell, 1968; Bommer, 2002; Field, 2003). The PSHA methodology gives, for any location, the seismic hazard curves in terms of Poissonian probability of exceedance (EP), i.e. the probability that PGA exceeds a specific reference value α of the same variable, calculated on the basis of a given recurrence time. Generally, EP curves are given with respect to 1 year or 50 years as reference time. For the specific case of industrial risk assessment, the latter value is a useful value because it represents the average lifetime of equipment, at least from a structural point of view.

Both in Europe and in the USA, seismic hazard curves and data are widely available. In the present framework, for the aim of implementing a quantitative risk analysis, these hazard curves have been simplified by considering only a 50-years time basis, through the following correlation:

$$EP\left[PGA > \alpha\right] = a \cdot e^{-b \cdot PGA} \tag{1}$$

where a and b are two constants which depend on the local seismicity and which may be calculated by a best fit procedure from the original PSHA hazard curves.

2.2. Critical equipment and failure probability models

Large atmospheric vessels, mainly used for the storage of liquid hydrocarbons, are the category of equipment more frequently damaged by seismic events. On the basis of data reported on past accidents, the damage of this category of tanks following an earthquake often resulted in tank or pool fires. Contamination of surface water as a result of the LOC was also reported. Pressurized storage vessels and long pipelines were also involved in several LOC events following earthquakes, triggering fires or environmental contamination. Thus, atmospheric and pressurized vessels having a large inventory of flammable or toxic substances, as well as large diameter pipelines, should be considered as the more critical equipment items in the assessment of risk due to seismic events in process plants.

The accidental scenarios that may follow the damage of industrial equipment caused by an earthquake are influenced by two main factors: i) the characteristics of the substance released, and ii) the LOC intensity. The framework of risk assessment suggests to adopt a simplified approach to the assessment of damage extension of equipment, based on a definite number of discrete damage states (DS). In the present study, two damage states were defined to classify the damage experienced by equipment items in a seismic event:

- Damage State 1 (DS1): limited structural damage, as the rupture of connections or the buckling of equipment, resulting in a low intensity of LOC, causing a partial loss of vessel inventory or the entire loss in a time interval higher than 10min;
- Damage State 2 (DS2): extended structural damage, causing the complete loss of containment of vessel inventory in a time interval lower than 10 minutes.

The expected severity of the accidental event following the structural damage is mainly dependent on the loss intensity and on the properties of the released substance.

In the present framework, simplified models are required to estimate the expected probability of a given damage state following an earthquake having a given PGA. A correlation linking the conditional probability of the i-th damage state, P(DSi), to the PGA of the earthquake is required for each equipment item. The fragility curves (Iervolino et al., 2004) are used to assess the resistance of a structure to a given PGA These curves are based on the assumption of a log-normal distribution of damage probability data with respect to PGA values. Fragility curves based on the analysis of historical data were proposed for anchored and unanchored atmospheric tanks, and, more recently, for pressurized equipment (Campedel et al, in press).
However, in conventional QRA, probit functions are more widely used than fragility curves (Finney, 1971). A linear correlation is present between the probit variable and the dose (the independent variable of the log-normal distribution), that is the PGA value in the case of concern:

$$\mathrm{Pr}_s = a + b \cdot \ln(dose) \tag{2}$$

Table 1 reports the probit coefficients used for the different categories of industrial equipment considered in the case-studies.

Table 1: probit coefficients for the assessment of DS_2 probit value by eq.(2) (Cozzani et al, 2007, Salzano et al, 2006).

Target	Probit equation	Dose, D	Dose units
Atmospheric storage, unanchored.	Y = -0.833 + 1.25·ln(D)	PGA	g%
Atmospheric storage, anchored	Y = -2.43 + 1.54·ln(D)	PGA	g%
Pressurized storage, any	Y = 5.146 + 0.884·ln(D)	PGA	g

2.3. Definition of reference events

The characterization of industrial risk by the above procedure requires the selection of reference events of given severity and known return time that may be used as the starting point for consequence evaluation. However, a methodology for the proper selection of reference events is needed, in order to assure that the risk assessment based on reference events gives a correct representation of industrial risk, since a relevant uncertainty in the final results may derive from an arbitrary selection of the reference events. A procedure is needed to decide how many and which reference events should be selected in the analysis. On one hand, a higher the number of reference events considered should results in more representative results of the analysis. On the other hand, the number of reference events considered highly influences the computational time required for the analysis. In the present study, two different approaches to the comparison of reference events were compared: in a first approach, a high number of reference events, *n*, was considered (up to 5) in order to approximate by a discrete representation the hazard curve of the site. By this approach, the overall release probability from each equipment item is calculated as follows:

$$P_{NC} = \sum_{1}^{n} f_i P_{DS2,i}(PGA) \tag{3}$$

A second approach was based on the convolution of the hazard and the fragility curves:

$$P_{NC} = \int_{0}^{+\infty} \frac{dH(PGA)_t}{dPGA} P_{DS2}(PGA)\, dPGA \tag{4}$$

The expected frequencies of the release may be obtained from eqs.(3) and (4) simply dividing the calculated probability by the return time used for the calculation of the hazard curve (50 years in the case).

Even if the frequency values of the release from each equipment item obtained by the two approaches may be similar (as far as the discrete events in the first approach represent a proper discretization of the hazard curve), the application of the two approaches may, at least in principle, lead to very different results. As a matter of fact, the application of steps 7 to 10 of the procedure (see figure 1) needs to be repeated for each reference events. Thus, considering several reference events having a different severity may lead to different accidental scenarios and to different consequences of the reference events. This aspect will be further discussed in the following.

2.4. Consequence assessment of the accidental scenarios

In order to assess the consequences of the scenarios, it is necessary to consider that the accidental events may take place simultaneously or subsequently, and their effects may be synergetic, simply additive or mutually exclusive, depending on the type of scenarios and on the distance of the damaged units. Moreover, the physical effects may be different (e.g. thermal radiation from a fire and a toxic release). The approach based on probit models is the standard method used in QRA in order to calculate the expected magnitude of an accident in risk recomposition procedures. Several widely used models are available to evaluate the dose-effect relation for human responses to toxic substances, thermal radiation and blast waves (Van Den Bosh, 1997). The development of a software tool was a necessary step in order to apply the methodology discussed above. A specific software package was added to the Aripar-GIS software. The Aripar-GIS software was developed in the framework of the ARIPAR project, and allows the assessment of individual and societal risk due both to fixed risk sources and to risk sources associated to transport systems in an extended area. The seismic package was developed in order to apply the above procedure to the analysis of large industrial plants or of extended industrial areas. The user should input to the software the PGA vector, the reference scenarios, the position and the vulnerability model associated to each critical item identified by the above procedure. The software procedure automatically generates all the possible overall scenarios (for each earthquake magnitude considered).and performs the quantitative evaluation of the risk in the area of interest by the above procedure on the basis of a simplified lay-out that should be implemented in a GIS environment. Further details are reported elsewhere (Antonioni et al, 2007).

3. Case-studies

3.1. Case-study 1

The first case study was aimed at the comparison of the risk assessment using two different approaches for the calculation of the overall release probability P_{NC}. A complete risk assessment has been performed for a section of a distillery where a large inventory of ethanol is stored in six atmospheric tanks having a nominal capacity of 2500 m³ each. The tanks meet API Standard 650 requirements thus their other structural and working features are those reported in table 2.

The Damage State 2 and the release of the total inventory in about 10 minutes was assumed as the LOC caused by an earthquake. This resulted in a pool fire with the same area of the whole catch basin. Thus, using DS_2 conditional probability coefficients reported in table 1 for unanachored atmospheric tanks, the hazard and fragilty curves convolution of the plant site for a return period of 50 years can be calculated using equation 4 (P_{NC} = 0.143). The same value can be obtained assuming a single "reference earthquake" with a PGA of 0.2g and a frequency of 4.1×10^{-3} yr^{-1}, being 70% the conditional probability of Damage State 2, given the refernce earthquake.

Table 2

Diameter (m)	Height (m)	Bottom thickness (mm)	Minimum shell thickness (mm)	Catch basin area (m²)	Filling degree	Anchoring
16	12.5	9	7÷8	400 (20×20)	90%	None

Following the other approach, four discrete events have been used in order to represent the hazard curve. Their frequencies and PGAs are reported in table 3 where also the conditional probability P_{DS2} is calculated.

Table 3

Seismic Event	F (1/yr)	PGA (g)	P_{DS2} (%)
Ev. 1	1.16×10^{-2}	0.042	4.5
Ev. 2	4.78×10^{-3}	0.109	36.6
Ev. 3	2.90×10^{-4}	0.175	63.2
Ev. 4	1.36×10^{-4}	0.215	73.4

Societal risk (FN curves in figure 2) for both approaches were calculated using Aripar-GIS software with a uniform population distribution of 100 inhabitants per hectare, only for the sake of comparison. A straightforward comparison of the expected number of fatalities per year (ENF) is also reported in the figure in order to clarify how the average risk index, does not vary very much, while, looking at the curves, there are some minor differences for low and high number of fatalities. A single reference earthquake will slightly underestimate low N frequencies, on the other and this approach will overestimate the high N frequencies.

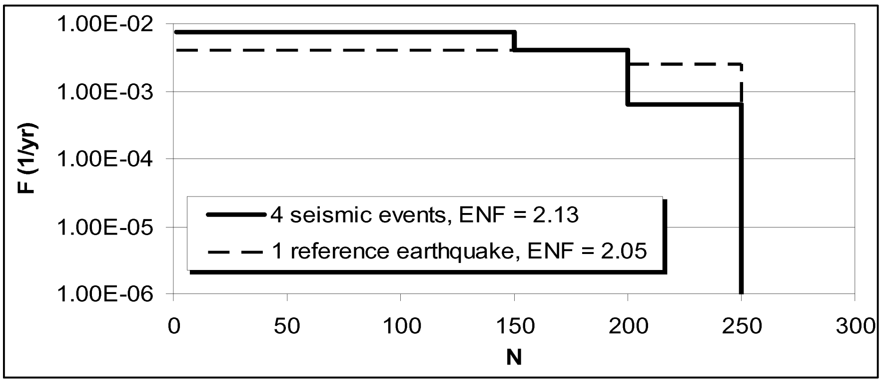

Figure 2. Societal risk results for case study 1

3.2. Case-study 2

In the second case-study, a small ethanol storage facility was examined, aiming to the comparison of the conventional QARA with an extended QARA, which includes seismic events. Figure 3 shows the lay-out considered for this case-study.

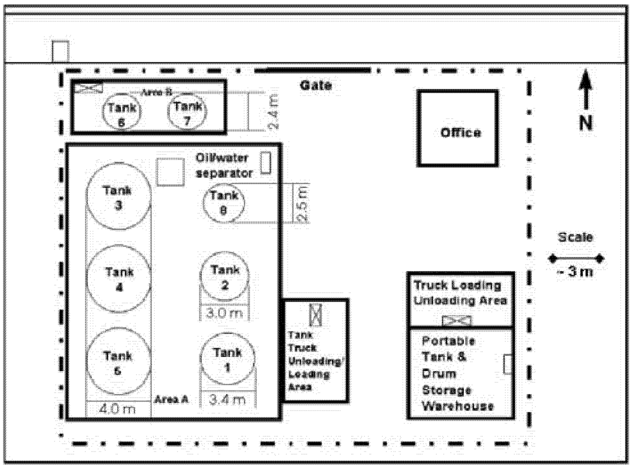

Figure 3. Lay-out considered for the second case-study analyzed

A single scenario (see table 4) was associated to each equipment item, and was considered as the only possible primary (conventional) and/or secondary (triggered by earthquake) event.

Table 4. Reference scenario considered. The frequencies include ignition probability where appropriate

Unit	Type of release	Released mass	Frequency (events/year)	Reference-scenario
Tank1-5 and Tank8	catastrophic	All inventory (ethanol)	$3.25 \cdot 10^{-7}$	Pool fire 230m² (Area A)
Tank6-7	catastrophic	All inventory (ethanol)	$3.25 \cdot 10^{-7}$	Pool fire 30m² (Area B)

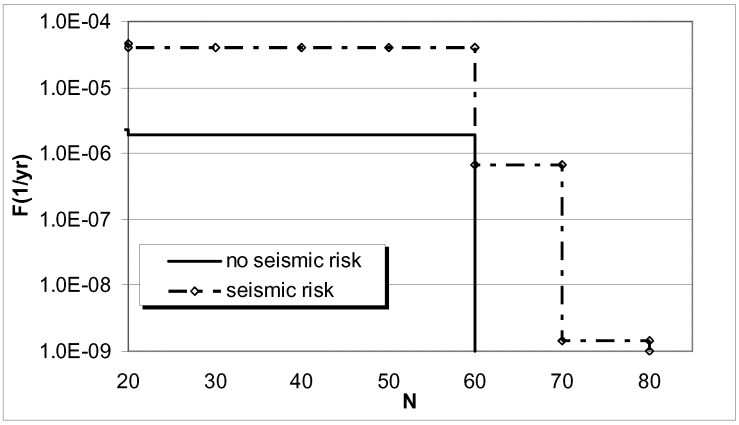

Figure 4. Case-study 2: results obtained for societal risk

The calculations were performed again using the Aripar-GIS software, the same high and unrealistic value of the population density (100 persons per hectare) was assumed in order to better evidence the influence of seismic scenarios on the societal risk curve. As shown in the figure 4, two effects should be expected including earthquake-triggered scenarios in societal risk curves: i) an increase in the values of frequency, F, corresponding to the reference scenarios chosen for each unit: this is caused by the increase in the overall frequency of the reference scenarios due to the possibility that the equipment may fail also due to a seismic event; and ii) an increase in the maximum value of expected fatalities, N, caused by the assumption that seismic events may trigger scenarios simultaneously involving more than one unit (Cozzani et al., 2006).

4. Conclusions

A general procedure for the assessment of the industrial risk caused by Na-Tech events was applied to assess the effects of earthquakes in chemical plants. The methodology was implemented in GIS-based risk recomposition software allowing the calculation of individual risk maps and of societal risk deriving from industrial accidents. The developed methodology requires a limited amount of additional data with respect to those used in a conventional QRA, and allows with a limited effort the quantitative assessment of the contribution to the individual and societal risk indexes of accidental scenarios triggered by natural events. Since the results were sensitive to the reference scenarios assumed in the analysis, alternative criteria were analyzed for their definition. The use of a convolution of the derivative of the seismic hazard curve with the equipment fragility curve resulted in the definition of a single representative reference event that was shown to effectively represent the actual seismic hazard of the site.
The application of the methodology to case-studies confirmed that accidental scenarios initiated by natural events may have a relevant influence on industrial risk, both raising the expected frequency of single scenarios and causing specific severe scenarios simultaneously involving several plant units. The results of the present study evidence the importance of considering the possible interactions between natural and technological hazards in land-use planning.

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