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A methodology for the quantitative risk assessment of major accidents triggered by seismic events

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Abstract

A procedure for the quantitative risk assessment of accidents triggered by seismic events in industrial facilities was developed. The starting point of the procedure was the use of available historical data to assess the expected frequencies and the severity of seismic events. Available equipment-dependant failure probability models (vulnerability or fragility curves) were used to assess the damage probability of equipment items due to a seismic event. An analytic procedure was subsequently developed to identify, evaluate the credibility and finally assess the expected consequences of all the possible scenarios that may follow the seismic events. 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, and yields with a limited effort a preliminary quantitative assessment of the contribution of the scenarios triggered by earthquakes to the individual and societal risk indexes. The application of the methodology to several case-studies evidenced that the scenarios initiated by seismic events may have a relevant influence on industrial risk, both raising the overall expected frequency of single scenarios and causing specific severe scenarios simultaneously involving several plant units.

Keywords: Major accident hazard; Quantitative risk analysis; Industrial risk; Natural events; NaTech risk analysis

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1. Introduction

Major accidents in industrial plants and storage sites where relevant inventories of hazardous substances are present may be triggered by seismic events, due to the damage of process equipment resulting in a loss of containment (LOC). Many severe accidents were reported as a consequence of seismic events in process plants [1–4]. Table 1 summarizes the results of the analysis of the available literature concerning the effect of severe seismic events in chemical plants and storage sites. As confirmed by the data reported in the table, industrial accidents triggered by seismic events may be a relevant cause of direct and indirect damage to the population, due both to the direct effects of the event (blast waves, toxic releases, fire radiation) and/or to the delay that may be caused to emergency rescue operations following the seismic event in nearby residential areas. Thus, a correct assessment of the seismic component of industrial risk is a fundamental issue to be addressed in the analysis of major accident hazards. Moreover, in seismic zones, the assessment of the possible interaction among seismic events and industrial accidents is of utmost importance for a "robust" and effective emergency planning in residential areas near to industrial sites.

Structural analysis based on the use of finite element calculations is the more common method used to assess the resistance of buildings to seismic events [5]. However, this approach is time consuming and may hardly be extended to the assessment of a large number of structures, e.g. as in the case of a tank park of an oil refinery. Quantitative risk assessment (QRA) techniques may be applied at least for a preliminary analysis of the risk due to seismic events and to identify critical process equipment where the application of more detailed assessment methods may be required [6–8]. As a matter of fact, an earthquake may be considered as a particular initiating event leading to equipment damage followed by a loss of containment (LOC) from one or multiple units.

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Table 1
Summary of the available literature data on the reported consequences of seismic events involving industrial plants having relevant inventories of hazardous substances

Number of events described in the literature	14
Number of damaged equipment items	182
Number of losses of containment following damage	126
Number of fires or explosions	105

The present study focused on the development of an analytic procedure for the quantitative assessment of the industrial risk due to accidents triggered by seismic events in a QRA framework. The starting point of the procedure was the use of available historical data to assess the expected frequencies and magnitude of seismic events. Available equipment-dependant failure probability models (vulnerability or fragility curves) were used to assess the damage probability of equipment items. A specific procedure was developed to: (i) identify the accidental scenarios that may follow a seismic event; (ii) evaluate the credibility of the accidental events; and (iii) assess the expected consequences of the possible scenarios. The procedure was implemented in a software tool based on a Geographical Information System (GIS), to ease the assessment of the large number of event sequences that are likely to be generated by the damage of a large industrial facility in a seismic event. The software also allows the calculation and the representation of the individual and societal risk curves due to industrial accidents triggered by seismic events. The procedure and the software tool were applied to several case-studies in order to establish the potential of the approach.

2. Procedure for the quantitative assessment of industrial risk caused by seismic events

Fig. 1 shows the flowchart of the procedure developed for the quantitative assessment of the risk caused by seismic 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 identification of the credible seismic events (step 1) and of critical equipment items, that are likely to cause major accidents as a consequence of damage caused by earthquakes (step 2). Reference scenarios should be associated to each critical equipment item (step 3). On the basis of the reference scenarios identified for each equipment item, a specific procedure should be applied for the identification of the overall expected scenarios, in order to take into account that more than one reference scenario may take place simultaneously due to the damage of more than one unit (steps 4–7). 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 8). 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 seismic events and identified by the above procedure. In the following, each step of the procedure will be discussed in detail.

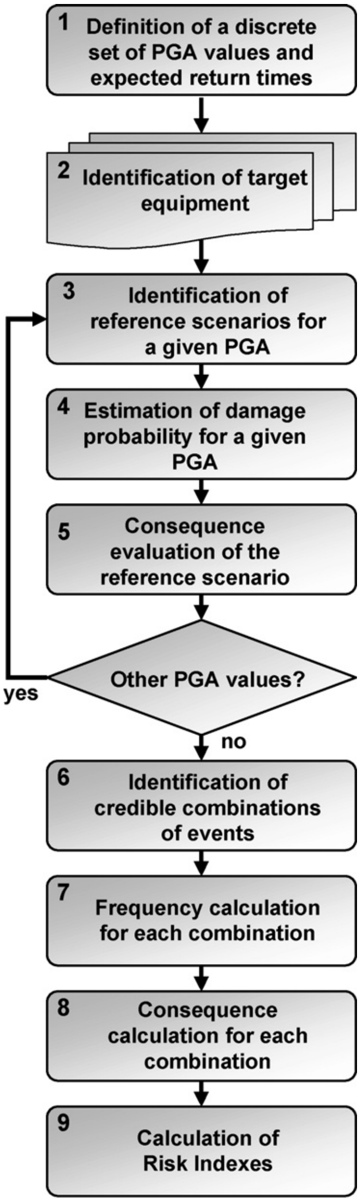


Fig. 1. Flowchart of the procedure developed for the quantitative risk assessment of accidental scenarios triggered by seismic events involving industrial plants.

3. Criteria for the identification of target equipment and of reference scenarios

3.1. Identification of critical target equipment

The analysis of past accidents evidenced that seismic events may cause relevant damage to equipment, that may result in an extended loss of containment (LOC). Large atmospheric vessels, mainly used for the storage of liquid hydrocarbons, are the category of equipment more frequently involved in these accidents. Several events are reported in which the damage of this category of tanks following an earthquake 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.

3.2. Identification of the reference scenarios

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. Quite obviously, the hazardous properties of the substance released influence the scenarios that may follow the release, and thus the event tree that should be considered in the analysis. On the other hand, the LOC intensity is mainly affected by the intensity of the structural damage, by the operating conditions of the damaged vessel (in particular, operating pressure and temperature at the release), and by the physical state of the released substance. Thus, a schematic identification of the reference scenario for the equipment item of concern may be based on three main factors: (i) the extension of the damage reported by the vessel, (ii) the operating conditions, and (iii) the hazard posed by the released substance.

Several reports concerning the detailed analysis of the damage occurred to storage vessels in seismic events are available in the literature [9–13]. Specific methods were developed in the field of structural engineering for the assessment of the resistance of buildings to earthquakes. However, these methods are far too complex and time consuming to be applied in the risk assessment of a chemical or process plant, were the possible damage of a large number of structures should be considered. The framework of risk assessment suggests the introduction of simplified methodologies for the description of the damage intensity that may follow an earthquake. An approach based on a definite number of discrete damage states was used in the literature to evaluate the economical damage of equipment following an explosion [14] as well as that due to natural events [15]. More recently, this approach was applied to the description of damage due to blast waves in the assessment of domino accidents [16,17].

The damage of a structure or of an equipment item may be roughly evaluated defining a limited number of damage states (DS). In the present approach, two damage states were defined to classify the damage experienced by equipment items in a seismic event:

- *Damage state 1 (DS_1):* Limited structural damage, as the rupture of connections or the buckling of equipment, resulting in a low intensity of the loss of containment, causing a partial loss of vessel inventory or the entire loss in a time interval higher than 10 min.
- *Damage state 2 (DS_2):* Extended structural damage, causing the complete loss of containment of vessel inventory in a time interval lower than 10 min.

In the framework of the risk assessment of accidental events induced by earthquakes in process plants, the link between the extension of structural damage and the intensity of the loss of containment is of fundamental importance. As a matter of fact, 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 particular, the loss intensity from pressurized or from atmospheric vessels may show strong differences in the final consequences even in the presence of similar structural damages. Moreover, if the same loss intensity is considered, toxic substances may cause in general more severe scenarios than flammable substances in the case of volatile releases. On the other hand, in the case of non-volatile releases, flammable substances may cause in general more severe hazards than substances having an acute toxicity for humans.

The identification of the reference scenarios to be considered in the assessment of the consequences of seismic events in process plants should be based on the above discussion. Table 2 summarizes the expected scenarios following the above defined damage states of equipment items. For the sake of simplicity, only two categories of equipment items were considered: atmospheric and pressurized equipment. As a working hypothesis, a limited volatility was assumed for atmospheric releases, a high volatility was assumed in the case of pressurized releases. The scenarios listed in the table are those usually considered in conventional event trees applied in the QRA of industrial plants [18], on the basis of the substance hazard and of the assumed release conditions. The reference scenarios considered in the present approach may be derived from those listed in Table 2. The framework of the present approach suggests to consider the worst credible scenario among those listed in the table for each damage state and substance hazard. As a matter of fact, it must be considered that the seismic event is likely to damage as well the active and passive plant mitigation systems, as the pipes of fire curtains or fire deluges and the catch basin systems. Thus, a conservative approach requires to take into account the possible unavailability of the safety systems for the mitigation of accidental scenarios that may be triggered by seismic events. On the basis of this approach, the suggested reference scenarios are summarized in Table 2(b). The reference scenarios listed in the table were the starting point of the case-studies discussed in the followings.

4. Expected frequencies of reference scenarios

4.1. Expected frequency and severity of the seismic event

The first step in the assessment of the expected frequencies of the reference scenarios is the evaluation of the expected frequencies of the seismic events. The return time of an earthquake is often obtained on the basis of historical data. In several geographical locations data are available over a wide range of time, so it is possible to estimate the expected frequency of a generic earthquake. However, the evaluation of the expected damage due to a seismic event is not possible without the estimation of the severity of the event. This magnitude may be expressed by qualitative approaches (e.g. by the well known Mercalli–Cancani–Sieberg, or MCS scale) or using quantitative

Table 2
Expected scenarios (a) and reference scenarios assumed for consequence assessment (b) of LOC events following the damage of atmospheric and pressurized vessels in seismic events

Damage state	Substance hazard	Atmospheric vessels	Pressurized vessels
(a) Expected scenarios			
DS1	Flammable	Minor pool fire	Minor jet fire
	Toxic	Minor evaporating pool	Boiling pool Toxic dispersion
DS2	Flammable	Pool fire Flash fire VCE	BLEVE/fireball Flash fire VCE
	Toxic	Evaporating pool Toxic dispersion	Boiling pool Toxic dispersion
(b) Reference scenarios			
DS1	Flammable	Pool fire	Jet fire
	Toxic	Toxic dispersion from evaporating pool	Toxic dispersion from jet release
DS2	Flammable	Pool fire	VCE
	Toxic	Toxic dispersion from evaporating pool	Toxic dispersion from boiling pool

indexes (e.g. the Richter scale). A quantitative scale based on clear physical assumptions must be used when the purpose is to assess the seismic risk. However, assigning a frequency to a seismic event with a given magnitude is more difficult, due to the lack of historical data, in particular for severe events.

Two categories of parameters may be used to describe earthquakes: (1) “ground parameters” and (2) “structural dynamic affecting factors” [5]. Experimental investigations have shown that a complete set of these parameters is needed to reproduce the effects of an earthquake in the framework of structural analysis. Nevertheless, it has also been pointed out that a single parameter, the peak ground acceleration (PGA), may be sufficient when the behaviour of steel equipment is under investigation in the framework of a QRA, due to the uncertainties that the analysts have to face [9,12]. Even if it is well known that PGA is a poor damage indicator, this parameter was assumed in several approaches as a representative parameter of the local severity of a seismic event. Hence, a PGA vector having an arbitrary number of elements, n, may be defined in order to represent the discretization of all the possible earthquake severities, expressed in terms of peak ground acceleration, in the area where the facility of interest is located. In this approach, the frequency of exceedance of a given PGA value is expressed by Eq. (1), developed from data of available seismic studies:

$$f_i = f(\mathrm{PGA}_i) \qquad (1)$$

where PGA_i is the ith element of the PGA vector, representing a PGA value. Usually, the above function is not directly available from seismic studies, but may be easily derived from conventional exceedance probability curves, which report the expected probability of an earthquake with a PGA higher than a given value over a time interval T [9]:

$$P = P(\mathrm{PGA} > a, T) \qquad (2)$$

The conventional exceedance probability curves are easily available from governmental agencies as well as from scientific institutions. If data from existing seismic studies are used, the analyst has to ensure that non-damaging effects of low energy near-site earthquakes characterised by short strong motion durations are removed from the hazard curves to avoid overly conservative results.

4.2. Damage probability of critical equipment items

In order to estimate the expected damage of equipment items following an earthquake, several approaches are possible. As discussed above, in the framework of the QRA of industrial plants undergoing an earthquake, 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 ith damage state, $P(\mathrm{DS}_i)$, to the PGA of the earthquake is required for each equipment item. In the conventional approach to the probabilistic analysis of damage caused by seismic events, fragility curves are used to assess the resistance of a structure to a given PGA [12,13,19–21]. Fragility curves are based on the assumption of a log-normal distribution of damage probability data with respect to PGA values. In this approach, the mean, μ, and the standard deviation, σ, of the data are usually provided:

$$P_s = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{x} \exp\left(-\frac{(z-\mu)^2}{2\sigma^2}\right) \mathrm{d}z \qquad (3)$$

where P_s is the probability of the damage state to which the parameters of the fragility curve are referred. Fragility curves based on the analysis of historical data were proposed for anchored and unanchored atmospheric tanks [5,9], and, more recently, for pressurized equipment [22].

However, in conventional QRA, the so called “probit” functions [1,23,24] are more widely used than fragility curves to correlate data that are expected to follow a log-normal distribution. The following expression defines the relation between the "probit" variable and probability [24]:

$$P_s = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Pr(x)-5} \exp\left(-\frac{(z-\mu)^2}{2\sigma^2}\right) \mathrm{d}z \tag{4}$$

A linear correlation is thus obtained between the "probit" variable and the independent variable, x, of the log-normal distribution, that is the PGA value in the case of concern [24]:

$$Pr_s = a + b \cdot \ln(x) \tag{5}$$

Eq. (5) is usually referred to as a "probit" function in the QRA practice [1,23]. Approaches based on fragility curves (Eq. (3)) and on "probit" functions (Eqs. (4) and (5)) are equivalent. The following relation is present between the parameters of the fragility curve in Eq. (3) and the constants of the "probit" function given by Eq. (5):

$$a - \mu = 5 \quad \text{and} \quad b \cdot \sigma = 1 \tag{6}$$

Thus, the above relations were used to calculate the "probit" functions equivalent to the fragility curves proposed in the literature to assess the damage of equipment due to seismic events. Table 3 reports the "probit" coefficients used for the different categories of industrial equipment considered in the case-studies. Damage probabilities were obtained from "probit" functions using Eq. (4). The use of the observational "probit" functions reported in Table 3 may also ensure that the effect of non-damaging effects of low energy near-site earthquakes characterised by short strong motion durations is correctly accounted for in the model for the calculation of damage probability. Nevertheless, it must be remarked that the general approach proposed in the present study may be used with any other model for the calculation of the probability of a given damage state of an equipment item following an earthquake having a known PGA.

4.3. Frequencies of accidental scenarios following seismic events

If the expected frequency of a seismic event having a given PGA is known, the expected frequency of a reference scenario involving a single equipment item may be calculated as follows:

$$f(R)_k^i = f_i \cdot P(\mathrm{DS}_j)_k^i \tag{7}$$

where $f(R)_i^k$ is the expected frequency of the reference scenario involving the kth equipment item following a seismic event having a PGA value equal to PGA$_i$; f_i is the expected frequency of the ith PGA value; and $P(\mathrm{DS}_j)_k^i$ is the expected probability of the jth damage state of unit k following a seismic event having a PGA equal to PGA$_i$. Since different earthquakes may be considered as mutually exclusive, the overall expected frequency of the reference scenario R involving equipment k may be calculated as follows:

$$f(R)_k = \sum_{i=1}^{n} f_i \cdot P(\mathrm{DS}_j)_i^k \tag{8}$$

where n is the total number of elements of the PGA vector defined above.

However, the damage of more than one unit may follow the seismic event. Thus, the overall scenarios that may follow the seismic event are given by a single reference scenario (if a single equipment item is damaged) or by a combination of reference scenarios (if several units are simultaneously damaged). Thus, the actual overall scenarios that may follow a seismic event in a process plant are all the possible combinations of the reference scenarios associated to each of the critical equipment items identified in step 2 of the procedure. If m critical items were identified and an index r is arbitrarily associated to each different reference scenario considered in the procedure, each overall scenario that may follow the seismic event may be identified by a vector S having s elements ($1 \leq s \leq m$):

$$S_{s,t} = [r_{1,t}, \ldots, r_{s,t}] \tag{9}$$

where the elements of the vector are the indexes of the reference scenarios that take place in the t-th combination of s scenarios considered, $S_{s,t}$. The probability of the scenario $S_{s,t}$ may thus be calculated from the probabilities of each of the reference scenarios considered in the combination:

$$P_{s,t}^i = \prod_{j=1}^{m} [1 - P_j^i + \delta(j, S_{s,t})(2 \cdot P_j^i - 1)] \tag{10}$$

where P_j^i is the probability of each reference scenario considered, obtained from the above discussed probabilistic damage models (Eqs. (4) and (5)), and the function $\delta(j, S_{s,t})$ equals 1 if the jth event belongs to the t-th combination, 0 if not. The overall expected frequency of the $S_{s,t}$ combination may thus be obtained combining Eq. (10) with Eq. (8):

$$f_{s,t} = \sum_{i=1}^{n} f_i \cdot P_{s,t}^i \tag{11}$$

Table 3
"Probit" functions for equipment seismic fragility [20,22] and for human vulnerability [1,23] used in the case-studies (Y: "probit" value; PGA: peak ground acceleration; I: radiation intensity; p_s: peak static overpressure; C: toxic concentration; t_e: exposure time)

Scenario	Target	Probit equation	Dose, D	Dose units
Seismic event	Atmosph. storage, unanch.	$Y = -0.833 + 1.25 \ln(D)$	PGA	g%
Seismic event	Atmosph. storage, anchored	$Y = -2.43 + 1.54 \ln(D)$	PGA	g%
Seismic event	Pressurized storage, any	$Y = 5.146 + 0.884 \ln(D)$	PGA	g
Radiation	Human	$Y = -14.9 + 2.56 \ln(D)$	$I^{1.33}\, t_e$	I: kW/m^2; t_e: s
Overpressure	Human	$Y = 1.47 + 1.37 \ln(D)$	p_s	p_s: psig
Toxic release: NH_3	Human	$Y = -9.82 + 0.71 \ln(D)$	$C^2\, t_e$	C: ppm; t_e min

It is easy to verify that Eqs. (10) and (11) may be reduced to Eq. (8) if a single reference scenario is considered (m equal to 1). On the other hand, if m is higher than 1, the total number of different scenarios that may be generated by a seismic event with a given PGA is:

$$\nu_i = 2^m - 1 \tag{12}$$

The total number of scenarios that need to be assessed in the quantitative analysis of the risk caused by seismic events, ν, is given by the sum of all the scenarios considered for each element of the PGA vector:

$$\nu = \sum_{i=1}^{n} \nu_i = n(2^m - 1) \tag{13}$$

Obviously, this may be reduced by the application of cut-off criteria based on the calculated frequency and/or the conditional probability (Eq. (10)) of the scenario.

5. Consequence assessment and risk recomposition

5.1. Consequence assessment

As shown in Fig. 1, after frequency calculation, the consequences of each seismic scenario must be assessed (steps 5 and 8). If more than one reference scenario is expected to take place (due to the damage of more than one equipment item) there are several issues that should be addressed in this step: 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 of the different events that may take place may be different (e.g. thermal radiation from a fire and a toxic release). A complete analysis of the effects of interacting scenarios is still an open problem in consequence analysis, even considering the use of approaches based on advanced tools as computational fluidodynamic codes. In the framework of risk analysis, due to the uncertainties present in the assessment of the single scenarios that are likely to take place, a simplified approach to the problem is acceptable to obtain at least a rough estimate of the magnitude of the expected consequences. A previous study, mainly addressed to the analysis of domino effect [25,26] evidenced that the consequence assessment of complex scenarios may be approached by a simple sum of the "vulnerability maps" generated by the single events. Vulnerability maps [27] (a matrix yielding the death probability due to the accidental event as a function of the position with respect to the source of the event) may be obtained from the damage maps of the single events by the application of standard "probit" models for human vulnerability [23]. 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, and several well known and widely used models are available to evaluate the dose–effect relation for human responses to toxic substances, thermal radiation and blast waves [1,23].

5.2. Software procedure for risk recomposition

It is quite evident from Eq. (3) that the above procedure for the quantitative assessment of the contribution to individual and societal risk of seismic accidents results in the assessment of a very high number of scenarios even in rather simple lay-outs. Therefore, 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 [28], 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 software and the procedures used for individual and societal risk calculations are extensively described elsewhere [29,30]. 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 (see Table 3). The software allows the identification of all the possible accidental events for each earthquake magnitude considered. The software procedure automatically generates all the possible overall scenarios 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. Possible domino effects induced by primary accidents may be as well taken into account by a specific procedure [26].

6. Case-studies

6.1. Description of the case-studies

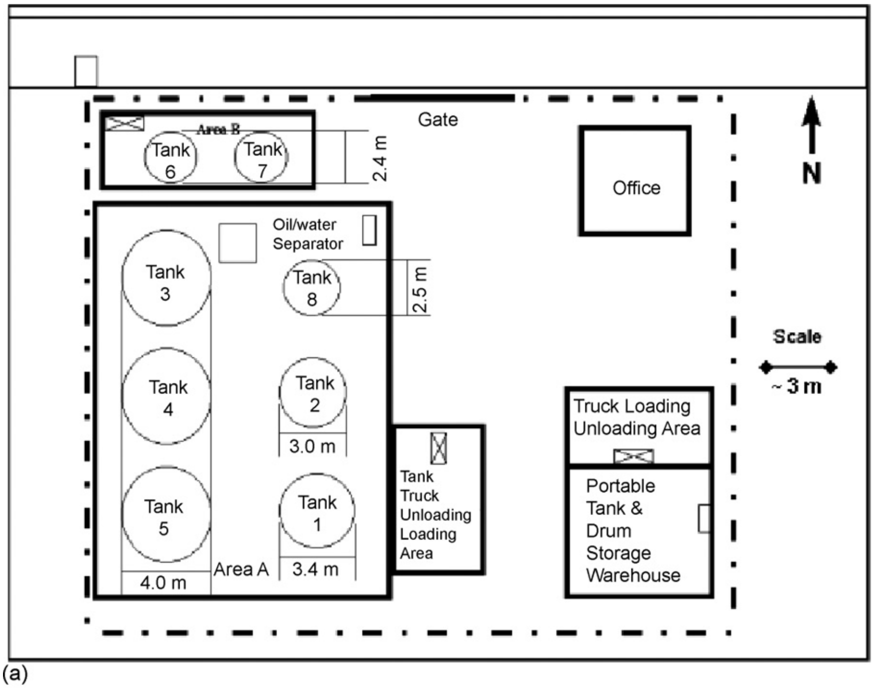
The procedure developed was tested analysing several case-studies. Three different sets of case-studies were defined in order to understand different aspects of the industrial risk associated to seismic events. The first set consisted of two simplified cases in which a single equipment item and a single PGA value were considered. The analysis of this set of case-studies was aimed to better understand the procedure and to evaluate the individual risk associated to the reference scenarios. In the second set (case-studies 3 and 4) a small storage facility was studied, aiming to the assessment of the expected number of damaged units and of the release scenarios following seismic events having a different severity, expressed by the PGA value. Finally, in the third set of case-studies (case-studies 5–7) a complete risk recomposition was performed.

All the case-studies were based on plant lay-outs and process equipment derived from those of existing chemical plants and oil refineries. Several common assumptions, discussed in the following, were introduced in the analysis. Table 4 summarizes the relevant characteristics of the equipment considered in the case-studies. The tanks were considered unanchored unless specified. Fig. 2 reports the lay-outs considered for case-studies 3, 4, 6 and 7. For the sake of simplicity, a single scenario was associated to each equipment item, and was considered as the

Table 4
Relevant characteristics of the equipment items considered in the case-studies

Unit	Type	Substance	Content (*t*)	Reference lay-out (figure)	Case-studies
D1	Atmospheric	Gasoline	24	Fig. 2a	3, 4
D2	Atmospheric	Gasoline	16	Fig. 2a	3, 4
D3	Atmospheric	Gasoline	38	Fig. 2a	3, 4
D6–7	Atmospheric	Gasoline	8	Fig. 2a	3, 4
D8	Atmospheric	Gasoline	9	Fig. 2a	3, 4
TK1–8	Atmospheric	Ethanol	2000	Figs. 2b and 5a	1, 2, 5, 6, 7
TK 9	Pressurized (sphere)	LPG	1400	Fig. 2b	7
TK 10	Pressurized (horizontal cylinder)	Ammonia	150	Fig. 2b	7

only possible primary and/or secondary event. The scenarios were defined on the basis of credible accidental events involving the equipment items described in Table 4, also following the suggestions given by the “purple book” [18]. Table 5 reports the details of the events considered for each equipment item. The study was mainly aimed to the assessment of events triggered by earthquakes, thus only severe scenarios were considered: pool fires involving the complete tank inventory and vapour cloud explosions (VCEs) following the catastrophic rupture of equipment items. The conventional literature models described in the



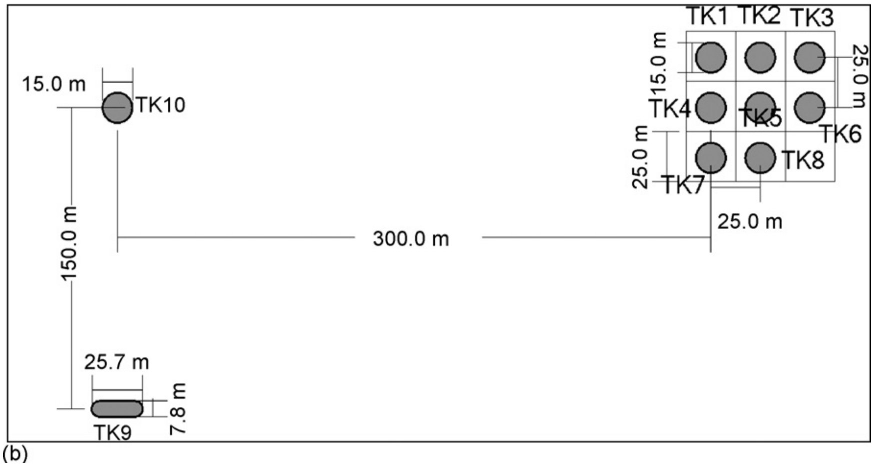


Fig. 2. Lay-outs considered for the case-studies analyzed. (a) Lay-out considered for case-studies 3 and 4; (b) lay-out considered for case-studies 6 and 7.

Table 5
Reference scenarios considered for each equipment item

Unit	Type of release	Released mass	Frequency (events/year)	Reference scenario
D1–D5 and D8	Catastrophic	All inventory	3.1×10^{-7}	Pool fire 230 m^2 (area A catch basin)
D6–D7	Catastrophic	All inventory	3.1×10^{-7}	Pool fire 30 m^2 (area B catch basin)
TK1–8	Catastrophic	All inventory	3.1×10^{-7}	Pool fire, 25 m diameter
TK 9	10 min release	All inventory	5.0×10^{-7}	Toxic dispersion (neutral gas continuous release)
TK 10	10 min release	All inventory	4.5×10^{-7}	VCE

Conventional frequencies include ignition probability where appropriate.

“yellow book” [31] were used for consequence assessment. The results of the consequence assessment models were used to generate the vulnerability maps of the reference scenarios triggered by seismic events, using the “probit” models listed in Table 3 [1,23].

6.2. Risk due to the reference scenarios in single process units

Case-studies 1 and 2 only consider a single equipment item. In the present analysis, it was assumed that the reference scenario defined in Table 5 may be triggered either by an earthquake or by faults and/or operational errors involving the unit. In case-study 1, a single seismic event was considered. As shown in Table 6, a PGA value of 0.8 g and a return period of 1 year were assumed. These very high and unrealistic values were used only in order to check the validity of the procedure, enhancing the possible effect of the seismic event on the calculated risk indexes. A single unanchored atmospheric tank (indicated as TK1 in Tables 4 and 5) was considered. Using the “probit” functions in Table 3, the DS_2 damage probability resulted equal to 0.361. Since the frequency of the seismic event was arbitrarily assumed equal to 1 event/year, Eq. (7) yields an expected frequency of tank damage equal to 0.361 events/year. Thus, the individual risk due to the seismic event may be easily calculated. The results are reported in Fig. 3. As shown in the figure, a maximum individual risk value of 0.361 events/year was calculated for this case-study. Since the wind dependency of pool fire radiation was neglected (as reasonable for low wind velocities), circular contours were obtained for the isorisk curves. Assuming a uniform population density typical of an industrial area (5 persons/ha), the potential life loss (PLL) was calculated, yielding a value of 1.3 fatalities/year. Once again it must be recalled that this very high value of PLL is due to the unrealistic frequency assumed for the seismic event considered in the case-study.

In case-study 2, more realistic data were assumed for the expected severity and frequency of the seismic event, as shown in Table 6. The same tank used in case-study 1 was considered. Assuming a PGA value of 0.224 g, a significantly lower value of the DS_2 probability was obtained, equal to 0.026. The corresponding value of the PLL resulted of 2.94×10^{-4} fatalities/year. These more realistic values of damage probability and of PLL were compared to those obtained from a simplified conventional safety assessment of the tank, based on the reference scenario and on the primary frequency reported in Table 5. The PLL value resulted of 1.8×10^{-6} fatalities/year. As expected, the ratio among the PLL values resulted equal to the ratio among the overall frequencies of the events (5.4×10^{-5} events/year for the seismic event versus 3.1×10^{-7} events/year for the “conventional” accidental event). The case-study evidences that the procedure developed is suitable to evaluate the contribution to industrial risk of seismic events in the framework of a conventional QRA.

6.3. Assessment of the expected number of damaged units following a seismic event

The second set of case-studies (case-studies 3 and 4) was aimed to assess the number of damaged units and the frequencies of the different overall accidental scenarios that may be expected as a consequence of a seismic event. The case-studies were based on the lay-out shown in Fig. 2a. In case-study 3 the probability and the expected frequency of all the possible scenarios that may be triggered by a single seismic event were assessed. The first column of Table 7(a) reports the overall probabilities of scenarios involving a given number of damaged units. For the

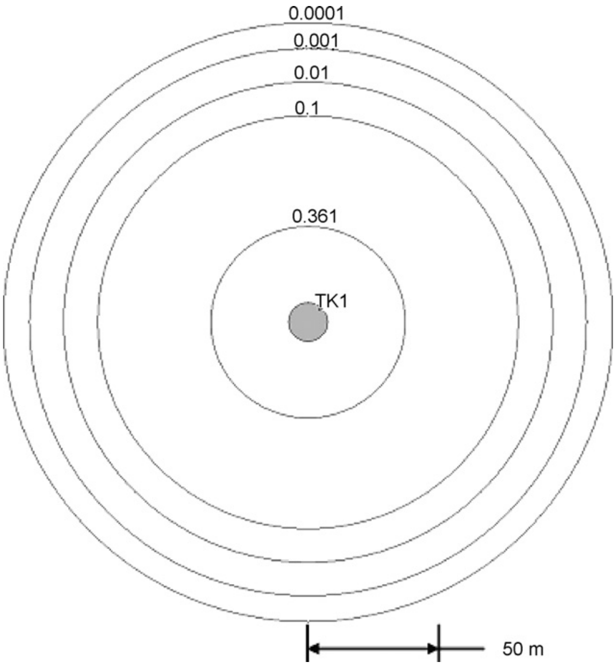


Fig. 3. Case-study 1: individual risk due to the reference scenario triggered by the seismic event considered in the analysis.

Table 6
Summary of the case-studies defined in the present study

n	Lay-out (figure)	Seismic primary events		Equipment items	Population density (persons/ha)
		PGA (g)	Return period (year)		
1	Fig. 3	0.8	1	TK1	5
2	Fig. 3	0.224	475 (10% PE in 50 year)	TK1	5
3	Fig. 2a	0.817	100,000	D1–8	n.d.
4	Fig. 2a	0.05; 0.15; 0.25; 0.35	475 (10% PE in 50 year)	D1–8	n.d.
5	Fig. 5	0.817	100,000	TK1–2	100
6	Fig. 2b	0.224	475 (10% PE in 50 year)	TK1–8	5
7	Fig. 2b	0.224	475 (10% PE in 50 year)	TK1–10	5

All tanks were considered unanchored, unless specified in the text. PE: probability of exceedance of the PGA over the given reference period, n.d.: not defined.

sake of comparison, the probabilities were estimated considering both unanchored and anchored atmospheric tanks. As shown in Table 3, the "probit" models for equipment damage yield the same damage probability for a given PGA value if the equipment items are of the same category, as in the case (see Table 4). Thus, the overall probability of scenarios having the same number of damaged units follows a binomial distribution with a probability of success equal to the damage probability of that equipment category, P_s. Fig. 4 shows the probability values obtained by this distribution for case-study 3. The expected number of damaged tanks may be calculated as the mean of the distribution, $m \cdot P_s$, where m is the total number of tanks in the lay-out. As expected, the mean number of collapsed tanks decreases from 3 to 1.8 considering respectively unanchored and anchored tanks, since the collapse probability of each tank is 0.371 for unanchored tanks and 0.224 for anchored tanks.

In case-study 4, several PGA values were considered for the same lay-out. Table 7(a) reports the overall probabilities of

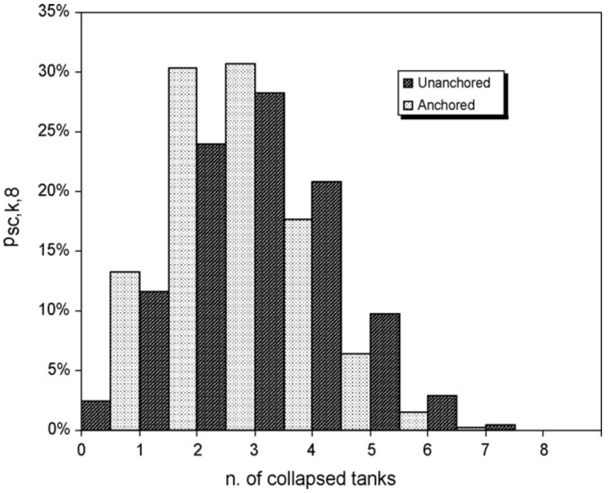


Fig. 4. Case-study 3: probability of having a given number of damaged tanks due to a seismic event.

Table 7
Probabilities (a) and expected frequencies (b) of an accidental event triggered by an earthquake and resulting in given a number of damaged items as a function of PGA and tank type

n: damaged items	PGA: 0.05; RP: 475		PGA: 0.15; RP: 475		PGA: 0.25; RP: 475		PGA: 0.03; RP: 475	
	U	*A*	*U*	*A*	*U*	*A*	*U*	*A*
(a) Probabilities								
0	9.99×10^{-1}	1.00	9.44×10^{-1}	9.97×10^{-1}	7.52×10^{-1}	9.61×10^{-1}	5.04×10^{-1}	8.58×10^{-1}
1	5.31×10^{-4}	1.66×10^{-6}	5.46×10^{-2}	3.00×10^{-3}	2.18×10^{-1}	3.79×10^{-2}	3.60×10^{-1}	1.33×10^{-1}
2	1.23×10^{-7}	$<10^{-8}$	1.38×10^{-3}	3.96×10^{-6}	2.77×10^{-2}	6.52×10^{-4}	1.13×10^{-1}	9.01×10^{-3}
3	$<10^{-8}$	$<10^{-8}$	2.00×10^{-5}	$<10^{-8}$	2.01×10^{-3}	6.42×10^{-6}	2.01×10^{-2}	3.49×10^{-4}
4	$<10^{-8}$	$<10^{-8}$	1.81×10^{-7}	$<10^{-8}$	9.11×10^{-5}	$<10^{-8}$	2.25×10^{-3}	8.45×10^{-6}
5	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	2.64×10^{-6}	$<10^{-8}$	1.61×10^{-4}	1.31×10^{-7}
6	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	7.17×10^{-6}	$<10^{-8}$
7	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	1.83×10^{-7}	$<10^{-8}$
8	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$
(b) Frequencies								
1	1.12×10^{-6}	3.51×10^{-9}	1.16×10^{-4}	6.34×10^{-6}	4.62×10^{-4}	8.02×10^{-5}	7.62×10^{-4}	2.87×10^{-4}
2	2.60×10^{-10}	$<10^{-10}$	2.92×10^{-6}	8.35×10^{-9}	5.91×10^{-5}	1.38×10^{-6}	2.41×10^{-4}	1.99×10^{-5}
3	$<10^{-10}$	$<10^{-10}$	4.23×10^{-8}	$<10^{-10}$	4.31×10^{-6}	1.36×10^{-8}	4.22×10^{-5}	7.91×10^{-7}
4	$<10^{-10}$	$<10^{-10}$	3.82×10^{-10}	$<10^{-10}$	1.96×10^{-7}	$<10^{-10}$	4.84×10^{-6}	1.96×10^{-8}
5	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	5.73×10^{-9}	$<10^{-10}$	3.48×10^{-7}	3.12×10^{-10}
6	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	1.05×10^{-10}	$<10^{-10}$	1.56×10^{-8}	$<10^{-10}$
7	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	4.01×10^{-10}	$<10^{-10}$
8	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$
Max. individual risk	1.12×10^{-6}	3.51×10^{-9}	1.19×10^{-4}	6.34×10^{-6}	5.26×10^{-4}	8.16×10^{-5}	1.05×10^{-3}	3.08×10^{-4}

Cut-off values used in calculations: 10^{-8} for probabilities, 10^{-10} events/year for frequency. (*U*) unanchored tanks; (*A*) anchored tanks, (RP) return period (years).

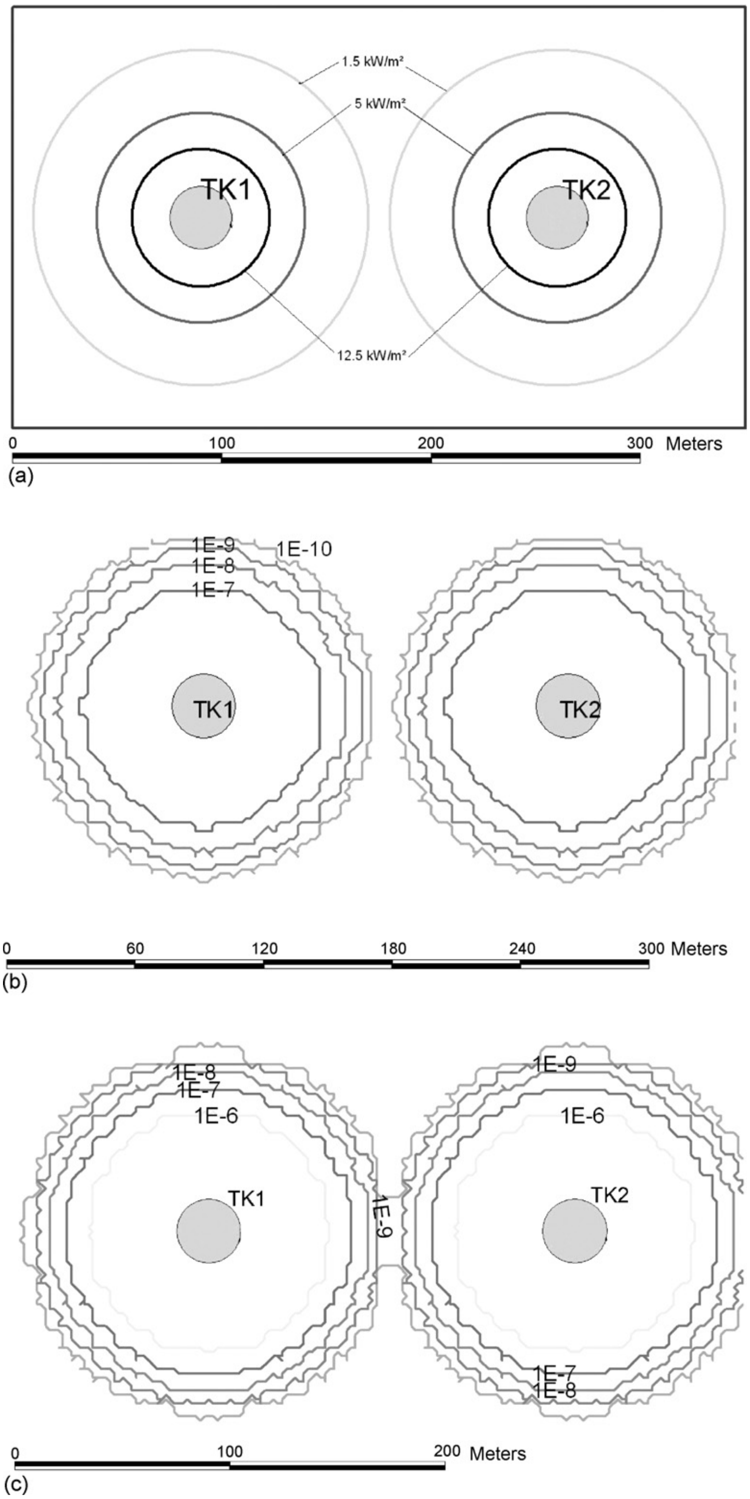


Fig. 5. Case-study 5: (a) impact area of the reference scenarios; (b) individual risk not considering seismic events; (c) individual risk considering seismic events.

scenarios involving a given number of units, while Table 7(b) reports the corresponding expected frequencies of the scenarios, calculated by Eq. (7). Table 7(b) also reports the maximum value calculated for the individual risk for each PGA value. The results evidence both the influence of the PGA values and of the equipment category on the overall values of individual risk.

6.4. *Individual and societal risk caused by seismic events in industrial facilities*

The third set of case-studies (5–7) shows the results of complete risk assessments aimed to the calculation of the contribution of seismic events to individual and societal risk. The calculations were performed using the Aripar-GIS software.

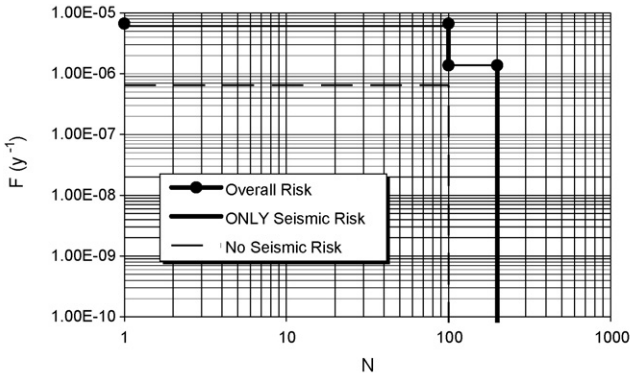


Fig. 6. Case-study 5: results obtained for societal risk.

Case-study 5 is actually a simplified case, aiming to understand the effects of the scenarios triggered by seismic events on individual and societal risk curves. A high and unrealistic value of the population density was assumed in order to better evidence the influence of seismic scenarios on the societal risk curve. Two atmospheric tanks at a distance of 150 m were considered. The distance among the tanks was chosen so that separate impact areas were obtained for the reference scenarios considered in the case-study (see Table 5), as shown in Fig. 5a. The comparison of Fig. 5b and c evidences the expected increase in the individual risk values caused by the seismic scenarios. Fig. 6 shows the influence of the seismic scenarios on the societal risk. As shown in the figure, two effects should be expected including earthquake-triggered scenarios in societal risk curves:

(1) 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 (in this case-study, the value of *F* increases from 6.5×10^{-7}, in the absence of seismic events, to 6.7×10^{-6}, that is the sum of the original value with two times that obtained from Eqs. (9) and (10), considering *s* equal to 1).

(2) 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. This assumption is never introduced in conventional QRA, unless domino events are considered [26,32]. Quite obviously, assuming that several reference scenarios may take place at the same time results in overall events having a higher overall value of expected fatalities than that of the single reference scenarios.

Case-studies 6 and 7 show the results of risk recomposition in more complex and more realistic lay-outs. Fig. 7 shows the changes in individual and societal risk due to the seismic

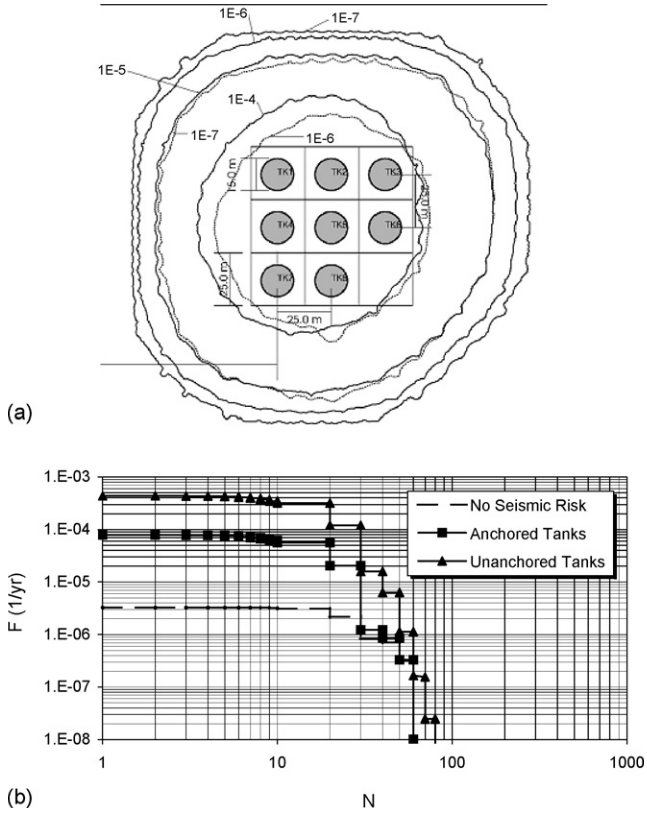


Fig. 7. Case-study 6: (a) individual risk (events/year); (b) societal risk. Dashed lines: results not including seismic scenarios; solid lines: results including seismic scenarios.

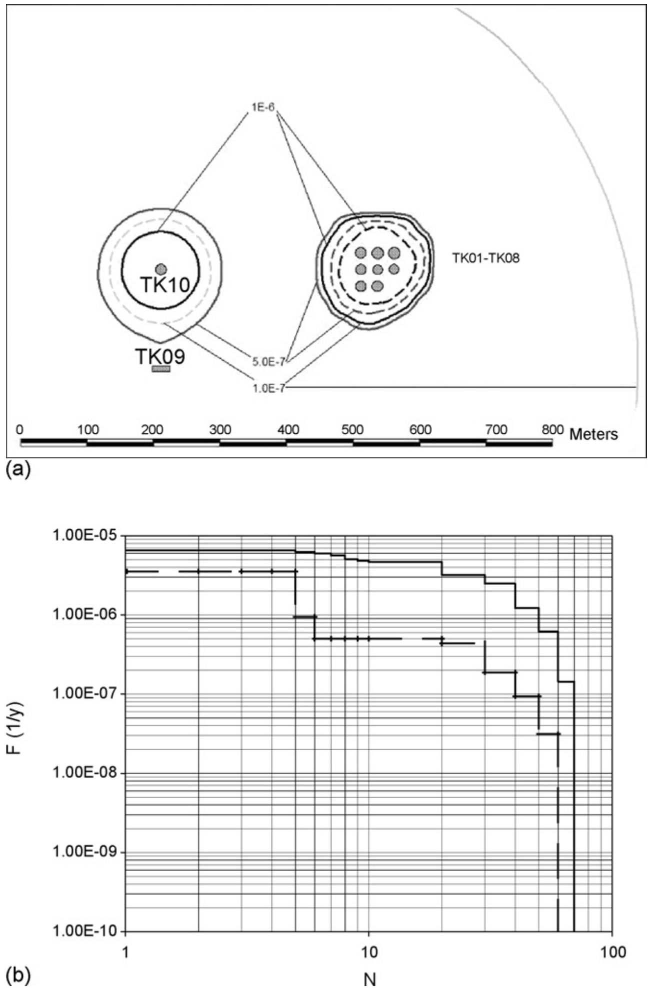


Fig. 8. Case-study 7: (a) individual risk (events/year); (b) societal risk. Dashed lines: results not including seismic scenarios; solid lines: results including seismic scenarios.

contribution for case-study 6, where only atmospheric tanks were considered. Fig. 8 shows the results for case-study 7, where also pressurized storage tanks having a relevant inventory of toxic substances were considered. As shown in the figures, the seismic scenarios result in important modifications of the individual and societal risk. The effect is particularly evident in the case of pressurized tanks, since the expected failure frequencies due to seismic events may result significantly higher than conventional failure frequencies usually assumed in QRA, reported in Table 6. As a matter of fact, important contributions to the overall values of these risk indexes seem to derive from the assessment of the accidental scenarios triggered by seismic events. These results are confirmed by the analysis of past data on accidental events in industrial plants, that evidenced the possibility of severe events due to extended damage to several units and to the disruption of active safety systems caused by the loss of water and energy supplies.

7. Conclusions

A procedure for the quantitative risk assessment of accidental scenarios triggered by seismic events in industrial facilities was developed. The methodology was implemented in a 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 proved to allow with a limited effort a preliminary quantitative assessment of the contribution of the earthquake-triggered scenarios to the individual and societal risk indexes. Although the developed procedure will by no means substitute the more detailed approaches based on structural analysis, the results provided are useful at least to identify the critical equipment or plant units were such an assessment is needed. The possibility to estimate by the present approach the probability of severe scenarios involving multiple plant units is of fundamental importance to assess the criticality of seismic events for the integrity of the plant and for the safety of the nearby area, also considering the delay in emergency response that may be caused by the seismic event. As a matter of fact, the application of the methodology to several case-studies confirmed that accidental scenarios initiated by seismic 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.

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