Journal of Hazardous Materials A123 (2005) 61–69

Journal of Hazardous Materials

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Quantitative risk analysis of oil storage facilities in seismic areas

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Received 22 October 2004; received in revised form 23 April 2005; accepted 25 April 2005
Available online 23 May 2005

Abstract

Quantitative risk analysis (QRA) of industrial facilities has to take into account multiple hazards threatening critical equipment. Nevertheless, engineering procedures able to evaluate quantitatively the effect of seismic action are not well established. Indeed, relevant industrial accidents may be triggered by loss of containment following ground shaking or other relevant natural hazards, either directly or through cascade effects ('domino effects').

The issue of integrating structural seismic risk into quantitative probabilistic seismic risk analysis (QpsRA) is addressed in this paper by a representative study case regarding an oil storage plant with a number of atmospheric steel tanks containing flammable substances. Empirical seismic fragility curves and probit functions, properly defined both for building-like and non building-like industrial components, have been crossed with outcomes of probabilistic seismic hazard analysis (PSHA) for a test site located in south Italy. Once the seismic failure probabilities have been quantified, consequence analysis has been performed for those events which may be triggered by the loss of containment following seismic action. Results are combined by means of a specific developed code in terms of local risk contour plots, i.e. the contour line for the probability of fatal injures at any point (x, y) in the analysed area. Finally, a comparison with QRA obtained by considering only process-related top events is reported for reference.

Keywords: Earthquake; Seismic risk; Industrial risk; Quantitative risk analysis; Multi-hazard

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1. Introduction

Large part of European territory is affected by significant seismic hazard. On the other hand, industrial installations require mandatory risk assessment and development of preventive and protective actions [1]. Nevertheless, when industrial facilities and in particular chemical, petrochemical and oil processing industries are concerned, interaction of the earthquake with equipment may trigger relevant accidents resulting in release of hazardous materials (fires, explosions), injuring people and increasing the overall damage to nearby area, either directly or through cascade effects ('domino effects').

As a consequence, quantitative risk analysis (QRA) of industrial facilities has to take properly account of multiple hazards threatening critical equipments, which can possibly lead to catastrophic accidents.

Despite these considerations, engineering procedures to evaluate quantitatively the effects of seismic action on equipment are not well established, even if a large research effort has been undertaken to develop effective and sustainable, at least from a computational viewpoint, seismic reliability procedures [2] and qualitative aspects of the relationship between natural and technological disaster have been recently analysed by joint activities by European Commission DG Joint Research Centre, Institute for the Protection and Security of the Citizen (DG JRC) and United Nations International Strategy for Disaster Reduction (ISDR) [3].

In this paper, empirical seismic fragility curves and probit functions defined for both building-like and non building-like industrial equipment, have been crossed with outcomes of probabilistic seismic hazard analysis for a test site located

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doi:10.1016/j.jhazmat.2005.04.015

in south Italy. Once the seismic failure probabilities have been quantified, consequence analysis has been performed for those events which may be triggered by the loss of containment following seismic action. Results have been then combined by means of a specific developed code in terms of local risk contour plots, i.e. the probability of fatal injures at any point (x, y) in the analysed area. In order to better point out the role of seismic hazard in industrial risk, the sole earthquake is then first assumed as triggering event. Hence, purely process-related “top events” are first excluded. A comparison with classical process-related quantitative risk analysis outcomes is then reported for reference, in order to show the relevance of seismic effects on risk indexes.

2. Seismic risk analysis of industrial components

Quantitative probabilistic seismic risk analysis (QpsRA) requires the evaluation of collapse probability of critical components and, subsequently, the analysis of phenomena triggered by loss of hazardous materials.

On the structural side, convolution of site’s seismic hazard and vulnerability of each component leads to the collapse probability $P_{\rm f}$ (*failure probability*), which is the probability of the seismic capacity C being exceeded by the seismic demand D, integrated over all the possible values of the ground motion intensity measure (IM) (i.e. peak ground acceleration or PGA) [4].

$$P_{\rm f} = \int_0^\infty {\rm d}\,({\rm Pr}[D > C]) = \int_0^\infty [1 - F_{\rm D}(u)]\, f_{\rm C}(u)\,{\rm d}u \qquad (1)$$

In Eq. (1), $F_{\rm D}$ is the cumulative probability distribution of the seismic performance *demand* for a given ground motion intensity, and $f_{\rm C}$ is the probabilistic density function of the seismic *capacity* of the structure/component. More explicitly, by probability algebra: the event of collapsing due to seismic action may be represented as the union of mutually exclusive events each of those representing component’s collapse when a given level of seismic intensity occurs.

$$\text{Collapse} = \bigcup_{i=1}^{\infty} \{\text{Collapse} \cap \text{IM}_i\} \qquad (2)$$

Events in Eq. (2) are mutually exclusive since collapse cannot take place for a given $\text{IM} = \text{IM}_i$ if another value already has led the system to failure, therefore failure probability is given by the sum of the probabilities of the elementary events defined. In other terms, by total probability theorem, $P_{\rm f}$ is given by the probability of the system failing for all possible values of seismic intensity (IM) combined with the probability of the latter occurring, therefore one can write:

$$P_{\rm f} = \sum_{\text{All im}^*} P\left\lfloor D > C|\text{IM} = \text{im}^*\right\rfloor P\left\lfloor \text{IM} = \text{im}^*\right\rfloor \qquad (3)$$

Finally, structural seismic risk is the convolution of $P[D > C|\text{IM} = \text{im}^*]$ (commonly referred as *fragility curve*, function of im*) and $P[\text{IM} = \text{im}^*]$ which is the *seismic hazard curve*, the outcome of probabilistic seismic hazard analysis [5,6].

Here it is worth noticing that the structural failure $P[C > D|\text{IM}]$ in Eq. (3) does not depend on other earthquake characteristic such as magnitude or source-to-site distance, as this happens when IM is “sufficient”, e.g. has a exhaustive explanatory power on the structural response. The topic of sufficient intensity measures for seismic risk assessment of structures is wide and is detailed elsewhere. For reviews, see [7,8].

According to this procedure, seismic risk has been carried out for all structures in the plant, therefore seismic hazard analysis has been required to get the occurrence probability $P[\text{IM} = \text{im}^*]$ in terms of the same intensity measure used to describe the seismic vulnerability of the component in question. Peak ground acceleration (PGA) has been considered as the ground motion intensity measure (IM) due to the nature of the damage database used. Further details may be found elsewhere [9]. In the following sub-sections, probabilistic seismic hazard analysis and vulnerability review are presented.

2.1. Seismic hazard

Measured ground motions refer to seismic waves radiating from the earthquake focus to the site and can be related to three types of mechanisms that interact to generate the actual signal: *source*, *path* and *site*. Efficient ground motion intensity measures for engineering applications should be strongly correlated with structural seismic response. These parameters summarize all the random features of earthquakes, including energy, frequency contents, phases and others which may affect the structural response of structures. Currently, the problem of definition of good predictors for inelastic seismic behaviour of structures is one of the main topics of earthquake engineering. However, empirical vulnerability analyses are often carried out in terms of peak ground acceleration, mainly because it is relatively easy to infer (i.e. by earthquake intensity conversion) while others intensity measures (as first-mode spectral acceleration) may not be available at the site for post-earthquake damage observation.

Probabilistic seismic hazard analysis is represented by Eq. (4) where the integral, computed for each possible realization (pga*) of PGA gives a point of the hazard curve. For the study case discussed herein PSHA has been then carried out by a specifically developed code [10], referring to the Sabetta and Pugliese [11] ground motion attenuation relationship, for the site of Altavilla Irpinia (AV—southern Italy) where the plant is assumed to be located (Fig. 2).

$$\begin{aligned} &P[\text{PGA} > \text{pga}^*] \\ &\quad = \iiint_{m,r,\varepsilon} P\,[\text{PGA} > \text{pga}^*|M = m,\ R = r,\ E = \varepsilon] \\ &\qquad \times f_{M,R,E}(m, r, \varepsilon)\,{\rm d}m\,{\rm d}r\,{\rm d}\varepsilon \end{aligned} \qquad (4)$$

In Eq. (4), according to PSHA, IM (e.g. PGA) exceedance probability is given by integration of probability contribution of magnitude (M), distance (R) and attenuation relationship "residuals" (E). The term $f_{M,R,\mathrm{E}}(m, r, \varepsilon)$ is their joint probability density function (PDF).

In Fig. 2, two time intervals are reported: 1 year, which has been utilized in the present study because the resulting risk indexes are calculated over 1 year, and 50 years basis, which is the reference curve for structural design purposes (Technical Service Life, TSL).

On this subject, it is worth noting that from a structural standpoint, many industrial and tertiary installations are characterized by specific design requirements and can become suddenly obsolete. Thus in many cases, the design reference period is called functional service life (FSL), which is generally lower than TSL [12].

Quite obviously, any other application should proceed in the same way by changing only the probabilistic characterization of the seismicity of the site of interest.

2.2. *Vulnerability: statistical inference of earthquake damage*

All typical accidental scenarios in the process industry (vapour cloud explosions, flash fires, tank and pool fires or toxic dispersions) depend on the total amount of released dangerous substance [13–15]. Accordingly, a quantitative probabilistic seismic risk analysis should define seismic vulnerability in terms of structural limit states of interest for content release. Therefore, existing data concerning post-earthquake damage observations for steel tanks have been reviewed in order to optimize the limit state classifications of equipment response [16]. In fact, according to HAZUS damage state list [17], the effects of seismic actions have been related to structural damage and its reparability (DS, damage state). When QpsRA (or QRA) are concerned, this concept is less significant than "loss of containment"; the latter is related to DS, but can be actually considered as a different and specific limit state. More in detail, five degrees of mechanical damage DS [18,19] have been reviewed to set three levels of intensity of loss of containment, defined as RS (risk state): no loss—RS1; moderate loss—RS2; extensive loss of containment—RS3.

The RS states have been defined in order to describe the seismic behaviour of storage tank with reference to the accidental scenarios which can possibly follow the seismic structural damage of the tank. Because of incomplete descriptions of the actual damage to some tanks into empirical database considered, the definition of damage state DS and/or RS is somehow left to judgment.

The probability of occurrence of any limit state has been then assessed by means of fragility curves, starting from a consistent historical data set describing the behaviour of tank subjected to earthquakes:

$$\begin{aligned}\text{Fragility} &= \Pr[\text{material release}|\text{PGA}]\\ &= \Pr[\text{RS}|\text{PGA}] = f(\text{PGA})\end{aligned} \tag{5}$$

Table 1
Seismic fragility and probit coefficients for anchored atmospheric steel tanks

Limit state (RS)	Fill level	μ (g)	β (g)	k_1	k_2
≥2	Near full	0.30	0.60	7.00	1.67
3	Near full	1.25	0.65	4.65	1.54
≥2	≥50%	0.71	0.80	5.43	1.25
3	≥50%	3.72	0.80	3.33	1.25

In Eq. (5), PGA is the realization of the seismic intensity (IM) that is assumed to trigger the failure corresponding to the pre-assigned limit state.

Experimental log-normal fragility curves for steel storage tanks can be easily converted in the linear probit function Y, commonly used as input for the QRA consequence analysis and codes. The probit function allows simple recognition of hazard by means of the following equation

$$Y = k_1 + k_2 \ln(\text{PGA}) \tag{6}$$

where PGA is expressed in terms of g, the gravity acceleration. The function Y is correlated to the classical probability of occurrence by means of the following integral function [20]:

$$P_{\text{RS,DS}} = \int_{-\infty}^{Y_{\text{RS}}} [\exp(-0.5u^2)]\,\mathrm{d}u \tag{7}$$

Numerical or graphical solution of this integral is reported in the literature. Details of the entire statistical procedure are reported elsewhere [13,16,21]. Tables 1 and 2 report the coefficient for fragility and probit for every RS level, for different tank levels, for either unanchored atmospheric storage tank or anchored storage tank, as resulted from a specific statistical analysis based on consistent number of data reported in the literature (see [16] for more details and for the definition of probit function for DS limit states). The minimum threshold value of PGA for loss of containment differs greatly from the anchored and unanchored and changes with fill level. The absolute minimum is reached for 50% filled unanchored storage tank, which can be considered as the safe side option for QpsRA when few information on the type of foundation of tank or on the fill level, which possibly varies with time, are available. Probit coefficients have been used for the quantitative risk analysis of fuel storage plant reported in Fig. 1. Specifically, likelihood of RS2 and RS3 occurring have been obtained calculating, for any PGA of the hazard curve reported in Fig. 2, the

Table 2
Seismic fragility and probit coefficients for unanchored atmospheric steel tanks

Limit state (RS)	Fill level	μ (g)	β (g)	k_1	k_2
≥2	Near full	0.15	0.70	7.83	1.43
3	Near full	0.68	0.75	5.53	1.34
≥2	≥50%	0.15	0.12	20.82	8.35
3	≥50%	1.06	0.80	4.93	1.25

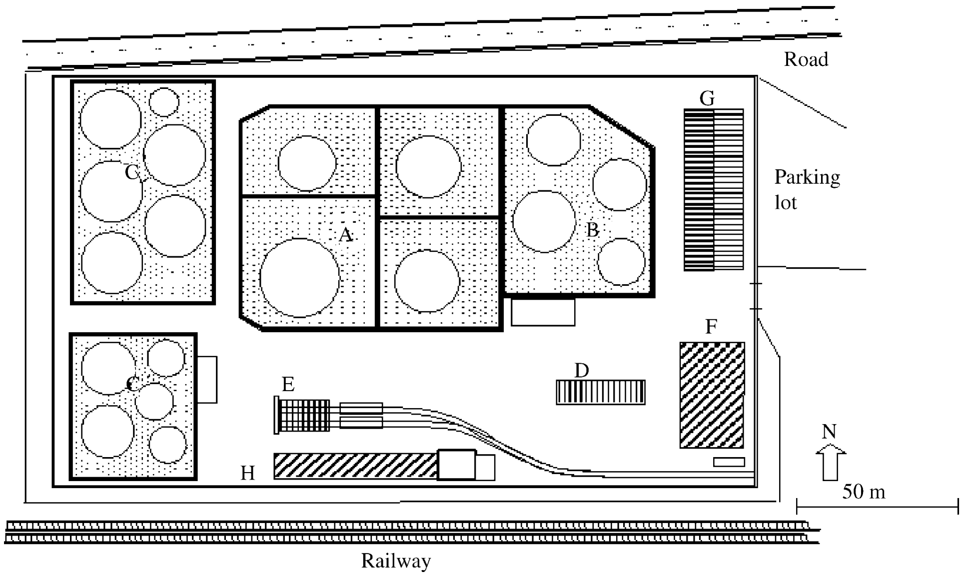

Fig. 1. The analysed storage tank. Total surface: 30,000 m^2. Total fuel capacity 60,000 m^3.

corresponding probability of loss of containment (by means of data reported in Tables 1 and 2). Results for the combination of fragility curves and RS probability, are reported in Fig. 3.

Furthermore, as mentioned in previous sections, other than non building-like structures (tanks), the buildings in the storage area have been considered in the analysis because their collapse may lead to catastrophic consequences as well if there is occupancy at the time of the earthquake. Consistently to what is done for tanks, fragility and probit functions for buildings have been obtained on empirical basis. In Table 4 probit coefficients derived from Rossetto and Elnashai [22] vulnerability data are reported, as expressed in terms of PGA, the latest expressed in *g*.

It is worth noting that seismic vulnerability of building in QpsRA should also considered whether automatic safety systems are sheltered in ordinary structure, since their collapse affects the response of the system to the industrial accident.

3. The storage installation

The risk analysis reported in this work refers to a storage facility composed by a number of atmospheric steel tanks containing flammable substances (Fig. 1). The plant is assumed to be located in the Irpinia area, southern Italy, which is characterized by considerable seismic hazard according to the national classification issued by Italian Seismic Survey [23].

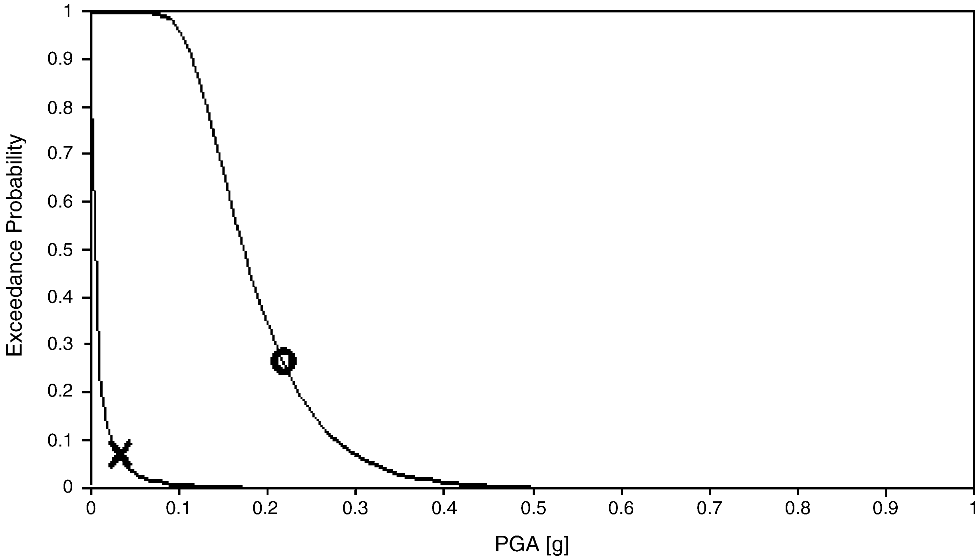

Fig. 2. Hazard curves at the test site. Time interval: (○) 50 years; (×) 1 year.

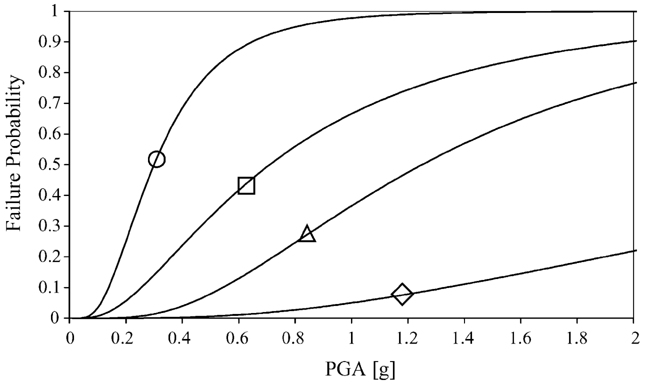

Fig. 3. Fragility curves used in this study for anchored storage tanks. (◯) RS ≥ 2, near full; (□) RS = 3, near full; (△) RS ≥ 2, fill ≥ 50%; (◇) RS = 3, fill level ≥50%. Failure probability is expressed in terms of annual probability.

Table 3
Legend and description of the main buildings and fuels stored in the oil plant

Legend	Item	Roof	Total tank capacity (m^3)
A	Gasoline, light gasoline, $T_{fp} < 21\,°C$	Floating	20,000
B	Kerosene, fuel oil, $21\,°C < T_{fp} < 65\,°C$	Fixed	30,000
C	Diesel oil, fuel oil, $T_{fp} > 65\,°C$	Fixed	13,000
D	Loading point, tank truck	–	
E	Loading point, rail tank	–	
F	Office building	–	
G	Office building	–	
H	Building	–	

T_{fp} is the flash point.

The layout, the separation distances and the classification of storage tanks are designed in agreement with main Italian and International guidelines [24–28]. Control room is installed in the basement of building identified by letter “F” in Fig. 1A national road and a railway track are close to the border of the installations. The surroundings are basically unpopulated, since the plant is located in a rural area.

All storage tanks are assumed as anchored, since it is the most common solution adopted for this kind of structures located in seismic areas [19]. Seismic design of tanks was based on international construction standards adopted both for water and oil storage on-grade steel tanks [29,30]. Table 3 reports further details on the stored fuel and constructions.

Building-like structures in the plant are reinforced concrete, low-rise constructions. Their seismic vulnerabilities have also been taken into account, since collapse may be not negligible in computing risk of death or injuries.

4. Quantitative probabilistic seismic risk analysis

Quantitative risk analysis supports risk management and decision-making by identifying accidental scenarios and by ranking these scenarios according to their probability of occurrence [31]. Specifically, QRA analyses the system as an integrated socio-technical system: hundreds of sequences are analysed in contrast with the relatively small number of design-basis accident in conventional analysis. As a consequence, several simplifying assumptions are often necessary, and comparisons with levels of risk acceptability are only possible if consolidated choices for evaluation of scenarios and consequence analyses are used.

Typical measures for probabilistic analysis of industrial risks include “local risk” assessment and “societal risk” assessment, i.e. the relationship between the number of fatalities N and the cumulative frequency F at which the number N or more fatalities are predicted to occur [32–34]. Here, local risk is intended as the annual probability of fatal injuries at any point (x, y) within the analysed area, without taking into account the probability of presence of human in the same area. For the aims of the paper we have shown local risk in terms of *iso*-contour. Details about consequence analysis carried out in the proposed test case are reported in the following sections.

4.1. *Consequence analysis*

For the aims of quantitative risk analysis, the evaluation of scenarios are carried out depending on assumptions made in compliance with well-established methodologies and/or guidelines [13–15,35–37].

Dispersion analysis has been carried out starting from extensive loss (RS3) or moderate leak (RS2) from any of the storage tanks. Typical atmospheric conditions, keeping into account the climate of south Italy, have been considered ($T_{amb} = 20\,°C$). Gasoline, kerosene, diesel oil and fuel oil also have typical chemical composition [38]. Gasoline gives the main contribution to flash fire and vapour cloud explosion (VCE) risks, for the relatively higher volatility, even if VCE is unlikely, also for the geometric characteristic of industrial area which is relatively un-congested. The unified dispersion model (UDM) implemented in the PHAST [39] package has been adopted. The package includes the prediction of the time-varying releases from tanks, to be used as source term for dispersion analysis, i.e. the temporal evolution of the leak from the damaged tanks, the subsequent formation of pool (for the RS2 case a leak surface with a diameter of 0.1 m has been assumed) and the evaporation rate from the surface of pool which is formed in the catch basin. The dispersion analysis has been performed for two atmospheric stability classes (F2 and D5), assumed to be representative. Also, a four-sector wind rose assuming equal probability either for sectors or for the two atmospheric classes has been used.

For the aims of this analysis, only loss of life has been evaluated and reported, for any scenario, but the risk of any kind of damage (to the human being, e.g. irreversible damage) can be easily assessed by introducing specific vulnerability functions.

The evaluation of consequences of flash fire, vapour cloud explosion and fires has been performed assuming the maximum predicted amount of vapour within the flammability limits, for the entire history of dispersion. To this regard, it is assumed that QRA has to be always as conservative as possible, whatever the finality of the assessment: "worst case" should always be considered when uncertainties are faced, aiming at deterministic assessment even in the framework of probabilistic safety assessment. This approach is particularly effective when late or early ignition assumption has to be considered. Indeed, it strongly affects the results of QRA because the amount of flammable vapour can possibly increase as the time before ignition is longer, at least for continuous release of vapour from pools. Moreover, intensity of loss (the RS2 and RS3 limit states) certainly influences the pool formation and the subsequent vapour dispersion. Eventually, it has been assumed that late ignition occurs in any case, i.e. the maximum amount of flammable vapour is considered, thus working on the "safe side". Conversely, ignition probabilities for flash fire or vapour cloud explosion has been set, respectively, to 0.03 and 0.08 of the total probability of RS2 or RS3 occurrences, after Cox et al. [40]. However, a very low probability of ignition (1×10^{-6} per loss) has been used for the ignition probability of diesel oil and heavy fuel oil (class C fuels), considering their high flash point and the presence of emergency interventions.

The mass of flammable vapour between the lower and upper flammability limits (LFL, UFL) has been used for evaluating the field of overpressure due to vapour cloud explosion by means of the multi-energy method (MEM) [41,42], through the total combustion energy. An "average" strength factor ($F = 5$) has been used even if low congestion environment characterizes the storage plant (with typical strength factor between 2 and 5), again aiming at retaining the safe side.

Finally, the PHAST code has been used for the prediction of evolution of smoky pool fires, which relates on the well-assessed model of Thomas [43], Burgess and Hertzberg [44], Mudan and Croce [45] and Cook et al. [46], for the pool fire burn rate, for the flame shape from pool and for the evaluation of radiation from pool flames, respectively.

For the evaluation of consequences of flash fire, the typical cut-off criterion of lower flammability limit (LFL) has been used: any person within the cloud identified by the LFL border is in fact dead. In the other cases, the vulnerability of individuals exposed to explosion or pool fire, has been evaluated by probit functions, respectively, for the peak overpressure and heat exposure, as given in Lees [13] and Crowl and Louvar [47]. For what concerns the time of exposure to heat t_h, a total duration of 60 s is considered. For the sake of simplicity, for each source (i.e. failure of tank in catch basin), the effects of explosions, flash fires or pool fires on human being have been considered mutually exclusive at any point: the maximum effect addresses also the probability of occurrence of the accidental scenario. This assumption is valid for the effects of flash fire, which are certainly superimposed to other effects over the LFL threshold distance; on the other hand, beyond LFL distance, i.e. in the far field, it is likely that blast wave is the only effect. Finally, if flash fire or vapour cloud are not possible for the low volatility of components, the only possible scenario is the pool fire, which is then preponderant in the near field. The assumption of exclusivity should be obviously to be re-considered in the case of toxic dispersion, which is not the case of this study. Domino effects have been considered only for tanks located in the same catch basin.

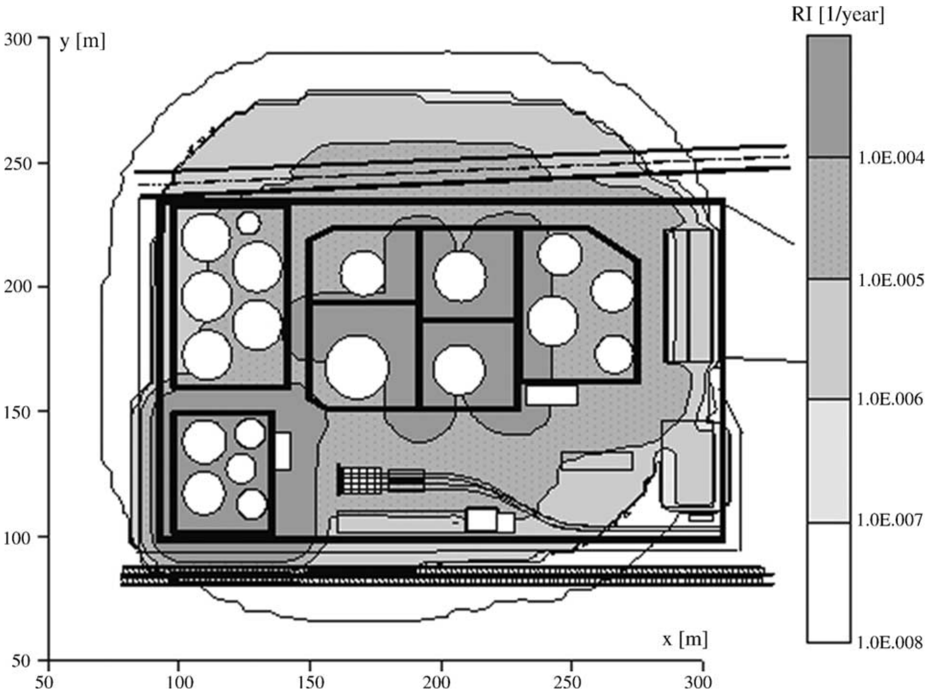

Fig. 4. Local risk RI (year^{-1}) for the fuel storage plant as obtained by QpsRA.

Table 4
Seismic fragility and probit coefficients for buildings located in the plant area

Limit state	Collapse
Building	F, G, H
k_1	35.20
k_2	3.98

The collapse of buildings due to earthquake has also been assessed in this analysis, by using probit models reported in Table 4. In the case of individuals located in the interior of buildings, the effects of flash fire, pool fire or explosion are null unless the blast overpressure is able to damage the building itself (peak overpressure greater than 0.3 bar).

4.2. Results: seismic risk indexes

For the purpose of the quantitative seismic risk analysis, a specific ANSI C code has been developed, starting from the statistic functions and plant information given above. The numerical layout covers 400 m × 400 m and it has been discretized by 1 m^2 cells.

The local risk has been calculated by using the classical relation:

$$\mathrm{RI}(x, y) = \sum_i \left\{ \sum_{\mathrm{RS}} \left[P_{\mathrm{f|RS},i}\, p(e|i)\, p(c|e)\, p_i \right] \right\} \tag{8}$$

In Eq. (8), index i refers to the accidental scenarios derived for the interaction of any earthquake with its related probability with the storage tank resulting in any intensity of loss of containment defined by $\mathrm{RS}(P_{\mathrm{f|RS}})$, $p(e|i)$ is the probability that the ith scenario propagates from the catch basin to the location x, y in terms of physical effect (e), i.e. overpressure (vapour cloud explosion) or heat radiation (pool fire, flash fire), for the toxic dispersion being excluded in the case of fuel storage areas here analysed. The same term $p(e|i)$ contains also all the information on the environmental condition (wind sector probability, atmospheric stability class), and on the ignition probability. The term $p(c|e)$ refers to the probability that the physical effect (e) produces the effect (c), mortality in the case of this analysis, assuming the constant presence of the individuals in the x, y location. Finally, the term p_i refers to the mitigation provided by the mitigation effects provided by indoor location of individuals.

Results of the calculation obtained by the entire set of assumption are reported in Fig. 4 in terms of map of local risk RI as previously defined, but only related to the accidental scenarios following earthquakes. Fig. 4 shows that local risk is relatively high only at the upper border wall of the storage plant, even if the analysis has been performed according to conservative assumptions for consequence analysis, with limited use of "event tree". To this regard, the main contribution to the high level of risk is due to flash fire, which is mainly related to the conservative assumption of late ignition.

Results of Fig. 4 have to be compared with acceptance criteria. To this aim, several thresholds values have been identified in many countries but, quite obviously, no one represents a universal rule. Here, we only report the reference given by HSE in UK [48,49], which reports a threshold value of 10^{-3}/year for workers and 10^{-4}/year for public (see also ALARP, As Low As Reasonable Practical, limits). These values are essentially not overtaken in the industrial area if pool basin (which are very rarely travelled by workers)) are excluded. It is also worth mentioning the very high seismicity of the industrial location.

4.3. Results: process-related risk indexes

The effectiveness of seismic action can be pointed out if above results are compared with QRA performed by considering typical top events related to plant operation, thus excluding earthquakes. Quite obviously, the accidental phenomena are related to loss of containment also in the case of process-related top events. Hence, the consequence analysis and the related choices (e.g. ignition probabilities), and modelling of accidental scenarios are analogous and not reported here for the sake of brevity. The main differences are on the typology of top event and related annual probability of occurrence. To this regard, the set of industrial accidents and failure rate as listed or reported in Control of Major Accident Hazards Regulations (COMAH, HSE, UK) [50], the well known Yellow and Purple Books [36,37], Rijnmond Public Authority [48], Lees [13], have been used for the process-related QRA. Table 5 reports the most important events considered in the QRA for storage tanks. Rare events ($<10^{-7}$) or events which are very unlikely to develop relevant accidental scenarios (e.g. leakage in small diameter or buried pipelines), have been discarded.

Here, it is worth mentioning that Rijnmond Report considers an earthquake annual occurrence of 10^{-8} events/year. Recombination of results is reported in Fig. 5 in terms of local risk, to be compared with Fig. 4.

Comparison of QpsRA with standard QRA shows that, at least for relatively low risk fuel storage tanks containing mainly with low flammable substances such as oil, and in high seismicity areas, the seismic risks can prevail over the risk derived from simple process and well controlled operations. To

Table 5
Some process and operational events considered for QRA in the storage plant

Item	Event	Annual probability of occurrence
Atmospheric storage tank	Serious leakage	1.0×10^{-4}
	Catastrophic rupture	6.0×10^{-6}
	Overfilling	2.7×10^{-6}
Pump	Catastrophic rupture	1.0×10^{-4}
Loading arm	Serious leakage	3.0×10^{-6}
	Catastrophic rupture	3.0×10^{-8}
Pipework > 150 mm	Serious leakage	3.0×10^{-9}/sector
	Catastrophic rupture	1.0×10^{-10}/sector

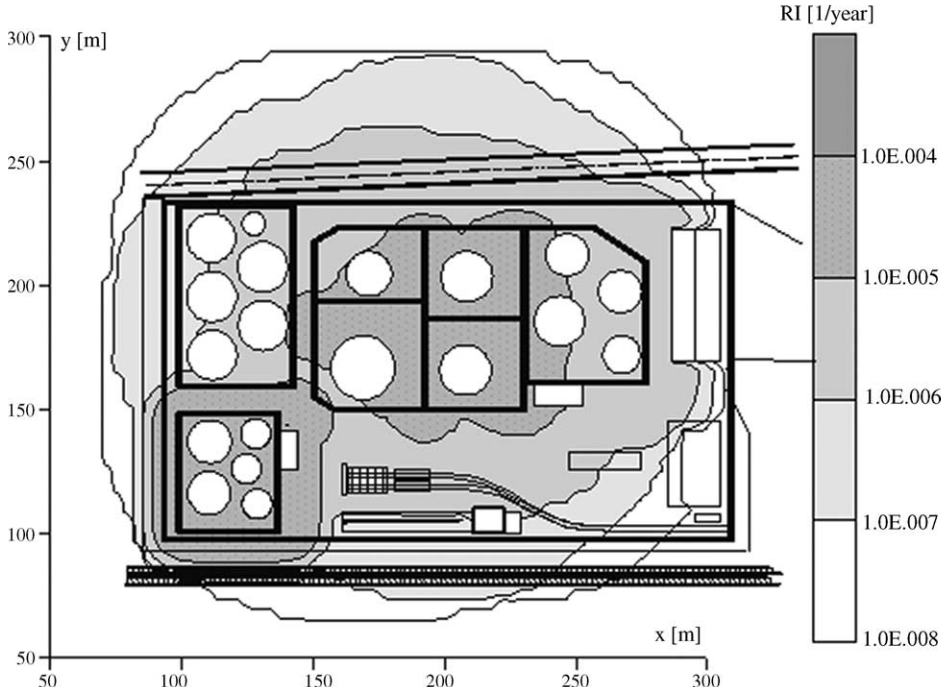

Fig. 5. Local risk RI (year^{-1}) for the fuel storage plant as obtained by process-related QRA.

this regard it should be noted that seismic action can strongly affect building integrity, with the related high probability of collapse. On the other hand, accidental scenarios produced by loss of containment of low flammable fuels from atmospheric equipment can be destructive on building if vapour cloud explosions, rather unlikely, occur. This assumption fails when pressurised equipment or highly reactive fuels are considered.

5. Conclusions

The case study presented shows how integration of seismic risk assessment into quantitative risk analysis can be effectively based on easy to manage statistical tools like fragilities and probit functions. More specifically, QpsRA may be successfully carried out if seismic fragility analyses of critical components are developed in terms of limit states that may trigger industrial accidents (i.e. hazardous materials release).

Use of empirical vulnerability functions does not represent a limitation of the study; in fact, available numerical procedures able to set reliable fragility functions (and probit coefficients) for industrial components need further development to cover all the relevant failure modes of equipment.

Acknowledgements

Authors gratefully acknowledge the support received from the National Group for the Defence against Earthquakes (GNDT) within the research project “*Reduction of Infrastructures and Environment Seismic Vulnerability*” (VIA). Project Coordinator: Prof. G.M. Calvi, Università di Pavia. Task Coordinator: Prof. G. Manfredi, Università di Napoli “Federico II”.

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