QUANTITATIVE PROBABILISTIC SEISMIC RISK ANALYSIS OF STORAGE FACILITIES

Antonio Di Carluccio, Iunio Iervolino, Gaetano Manfredi
Dip. di Analisi e Progettazione Sismica, Università di Napoli Federico II, Napoli (I)

Giovanni Fabbrocino
Dip. S.A.V.A., Università del Molise, Campobasso (I)

Ernesto Salzano
Istituto di Ricerche sulla Combustione, CNR, Via Diocleziano 328, Napoli (I).

Large part of European territory is affected by significant seismic hazard, which may possibly affect the integrity of industrial installation and give rise to consistent loss of energy or containment, either toxic or flammable. Although large scientific e regulatory efforts have been addressed to civil construction, industrial accidental scenarios triggered by earthquakes are poorly described. As a consequence, it is necessary to develop simplified tools for risk assessment and quantitative risk analysis which take into account explicitly the seismic vulnerability of industrial components. In this paper, fragility curves and probit functions for structural vulnerability in terms of mechanical damage and intensity of loss of containment have been crossed with outcomes of Probabilistic Seismic Hazard Analysis in order to assess the seismic risk. The analysis has been presented for atmospheric storage tank and pressurised equipment.

1. Introduction

The worldwide experience with probabilistic risk analysis (PRA) of industrial plants shows that the risk derived from external events, i.e. the events whose cause is external to all systems used in normal operation and emergency operation situations, can be a significant contributor to core damage frequency in some instance (NUREG/CR-2300, 1983). Typical example of these events are earthquakes, floods, high winds and nearby facility accidents. Among the external *natural* events, the most important is the earthquake. Indeed, large part of European territory is affected by significant seismic hazard. To this regard, recent regulatory on seismic hazard assessment, e.g. in Italy, has led to update and enlarge boundaries of seismic areas where constructions should be designed taking into account lateral forces generated by ground shaking. Nevertheless, with specific reference to industrial installation, the largest part of equipment are designed without the contribution of seismic action. As a consequence, the interaction between seismic excitation and industrial equipment may cause catastrophic accidents, as structural damage is possibly followed by loss of hazardous material, which in turns can trigger relevant accidents as fires or explosion, injuring people and increasing the overall damage to nearby area, either directly or through cascade effects (‘domino effects’). Besides, few simplified tools for natural-technological prediction have been presented in the literature in the recent years.
In this paper, aiming at Quantitative Risk Analysis of industrial facilities in seismic areas, fragility curves and probit functions for structural vulnerability in terms of mechanical damage and intensity of loss of containment are presented for either atmospheric storage tank and pressurised tank (above-ground). The functions can be easily crossed with outcomes of Probabilistic Seismic Hazard Analysis in order to evaluate industrial accidental scenarios likelihood and consequences.

2. Seismic risk assessment

The key elements of the quantitative probabilistic seismic risk analysis (QpsRA) are the hazard analysis-estimation, the evaluation of the fragility of components (building-like and no building-like structures) and the consequence analysis. On the structural point of view, the probability of seismic failure depends on the probability that the seismic demand D (i.e. the performance request) exceeds the structural seismic capacity C (i.e. the maximum performance of the structural component).

The probability of failure P_f, integrated over all the possible values of the ground motion intensity measure may be express as following:

$$P_f = \int_0^{\infty} d\left(Pr\left[D > C\right]\right) = \int_0^{\infty} \left[1 - F_D(u)\right] f_C(u) du \tag{1}$$

In Eq.(1), F_D is the cumulative probability distribution of the seismic performance demand for a given ground motion intensity, and f_C is the probabilistic density function of the seismic capacity of the structural component. In the other terms, by the total probability theorem, P_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 it is:

$$P_f = \sum_{All\, im^*} P\left[D > C \middle| IM = im^*\right] P\left[IM = im^*\right] \tag{2}$$

Finally, structural seismic risk is the convolution of P[D>C|IM=im*] (common referred as fragility curve, function of im) and P[IM=im*] which is the seismic hazard curve, the outcome of probabilistic seismic hazard analysis (C.A. Cornell, 1968; R.K. McGuire, 1995). These two contributions are analysed in the following.

2.1 Seismic hazard analysis

In hazard analysis, the frequencies of occurrence of different intensities of an earthquake are calculated and presented in form of hazard curve. These functions are often called “hazard intensities” and may be derived by developing a phenomenological model of the event starting from earthquake parameters estimated from historical data. Measured earthquakes signals refer to seismic waves radiating from the seism epicentre to the gauge location and can be related to global characteristics of the earthquakes: Magnitude, distance and soil type; these quantities are mainly reflected in the frequency content of the motion. Despite this simplification, earthquake signals carry several uncertainties and it is not even a trivial task to define a univocally determined intensity of earthquake, thus allowing comparison of records. However, geophysicists and structural engineers use to classify earthquakes on the basis of two classes of parameters such as “ground parameters” and “structural dynamic affecting factors” (A.K. Chopra, 1995). The choice of these intensity parameters is important since they summaries all the random features of earthquakes, including energy and frequency contents, which meaningfully affect the structural response of components (J.M. Eidinger, 2001). Ground parameters refer to the intensity measures (IM) characterizing the ground motion: PGA or alternatively peak ground velocity (PGV) and response spectra (RS) at the site location of the component. Structural affecting factors usually refer to the dynamic amplification induced on a single degree of freedom system with the same period of the analysed structure (first mode spectral acceleration), although experimental investigations have showed that different parameters are needed if the effects of the earthquake on the structures would be accurately reproduced by structural analysis. For instance, in seismic analysis of piping system PGV is commonly used, whereas PGA is more useful when steel storage tanks are under investigation (J.M. Eidinger, 2001).

Probabilistic seismic hazard analysis is represented by Eq. (3) where the integral, computed for each possible realization (pga*) of PGA gives a point of the hazard curve:

$$P\left[PGA > pga^*\right] = \iiint_{m,r,\varepsilon} P\left[PGA > pga^* \middle| M = m, R = r, E = \varepsilon\right] \times f_{M,R,E}(m,r,\varepsilon)\, dm\, dr\, d\varepsilon \tag{3}$$

In Eq.(3), according to PSHA, PGA exceedance probability is given by integration of probability contribution of magnitude (M), distance R and attenuation relationship “residual” (E). The term fM,R,E(m,r,ε) is their joint probability density function (PDF).

For the discussion presented herein PSHA has been carried out by a specifically developed code (V. Convertito, 2003), referring to the Sabetta and Pugliese (F. Sabetta, A. Pugliese, 1987) ground motion attenuation relationship, for the site of Sant’Angelo dei Lombardi (AV-southern Italy), Pomigliano d’Arco (NA-southern Italy) and Altavilla Irpinia (AV-southern Italy). Sant’Angelo dei Lombardi is classified by seismic Italian code as Zone 1 while the other two town are classified as Zone 2. In fact the seismic Italian code subdivide the national area in four different seismic zone, each one with different seismic hazard; the seismic condition of Zone 1 is more several than other Zones.

Figure 2 shows the hazard curves for the three towns; the time interval use for theis curves is one year.

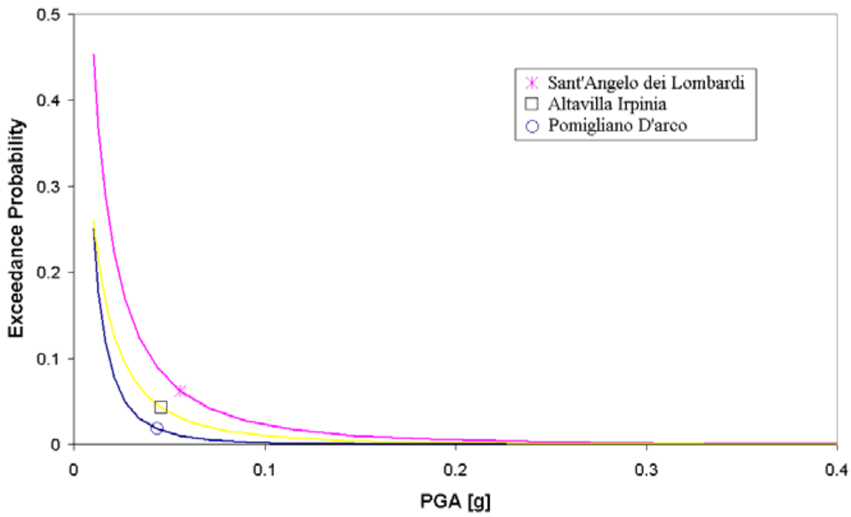

Figure 2: Seismic hazard curve for Sant’Angelo dei Lombardi, Altavilla Irpinia, Pomigliano D’Arco. Time interval: 1 year.

2.2 Fragility of components

The fragility or vulnerability of a component is defined as the conditional frequency of its failure. At this point, it is however essential to define the failure of interest. The HAZUS damage state list (HAZUS, 1997) reports a classification of the effects of seismic actions with respect to structural damage and its reparability (DS, damage state). When quantitative risk analysis of industrial areas or installations are of concern, these concepts are less significant because “loss of containment” of hazardous material, which however are related to DS, should be considered as different and specific limit states (RS). Hence, each risk state RS (identifying the intensity of loss), should be defined in terms of the probability of failure with respect to the intensity of earthquake.
As cited above, the probability of occurrence of any limit state DS and RS has been assessed by means of fragility curves, starting from a consistent historical data set describing the behaviour of equipment subjected to earthquake:

$$Fragility = Pr\left[RS \middle| PGA\right] = f\left(PGA\right) \tag{4}$$

In Eq. (4), PGA is the realization of the seismic intensity that is assumed to trigger the failure corresponding to the pre-assigned limit state. Experimental log-normal fragility curves can be easily converted into linear probit function Y, commonly used as input for QRA codes. The probit function allows simple recognition of hazard means of the following equation:

$$Y = k_1 + k_2 \, ln\left(PGA\right) \tag{5}$$

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 integral function. Numerical or graphical solution of this integral is reported in literature. Details of the entire statistical procedure are reported elsewhere (F.P. Lees, 1996; E. Salzano et al., 2003; J.A. Vilchez et al., 2001).
In the following the procedure is applied for atmospheric storage tanks and for pressurised tanks , as these equipment are common in industrialized countries and areas and because they typically contain large amount of flammable and toxic materials.

Atmospheric storage tank

For atmospheric tanks, detail of analysis is reported elsewhere (G. Fabbrocino et al., 2005). Here it’s only worth to report that five degrees of mechanical damage DS from null to catastrophic damage (J.M. Eidinger, 2001; M.J. O’Rourke, P. So, 2000; E. Salzano et al., 2003) 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 following tables report the fragility and the probit coefficients, either for DS and RS states, for both anchored (Table 1) and unanchored (Table 2) tanks and different fill levels.

Table 1: Seismic fragility and probit coefficients, anchored atmospheric steel tanks

DS	*RS*	*Fill level*	μ	β	k_1	k_2
≥ 2	≥ 2	Near full	0.30	0.60	-0.69	1.67
≥ 3	≥ 2	Near full	0.70	0.60	-2.08	1.67
≥ 4	3	Near full	1.25	0.65	-2.44	1.54
5	3	Near full	1.60	0.60	-3.49	1.67
≥ 2	≥ 2	≥ 50%	0.71	0.80	-0.33	1.25
≥ 3	≥ 2	≥ 50%	2.36	0.80	-1.86	1.25
≥ 4	3	≥ 50%	3.72	0.80	-2.43	1.25
= 5	= 3	≥ 50%	4.26	0.80	-2.61	1.26

Table 2: Seismic fragility and probit coefficients, unanchored atmospheric steel tanks

DS	*RS*	*Fill level*	μ	β	k_1	k_2
≥ 2	≥ 2	Near full	0.15	0.70	1.24	1.43
≥ 3	≥ 2	Near full	0.35	0.75	0.24	1.34
≥ 4	3	Near full	0.68	0.75	-0.64	1.34
5	3	Near full	0.95	0.70	-1.51	1.43
≥ 2	≥ 2	≥ 50%	0.15	0.12	-17.63	8.35
≥ 3	≥ 2	≥ 50%	0.62	0.80	-0.16	1.25
≥ 4	3	≥ 50%	1.06	0.80	-0.83	1.25
= 5	= 3	≥ 50%	1.13	0.10	-42.40	10.00

In order to include the data in Tables 1 and 2 in any pre-existing QRA tools, the results should be combined with probability of environmental condition (wind direction and intensity, atmospheric class) and probability of ignition if fire and explosion scenario are of concern. An example of application for an oil storage farm has been reported previously by the authors (G. Fabbrocino et al., 2005).

Pressurised equipment

Similar consideration as those reported above for atmospheric tanks can be applied for pressurised tanks contained toxic or flammable gases. Indeed, again, a damage state DS is possibly followed by a risk state RS whose intensity depends on many factors. The main difference is that even small structural damage to the shells or to the auxiliary system can give the catastrophic, often very rapid, loss of containment from the process or tank, due to pressure difference with atmosphere. Hence, structural damage and risk states DS and RS have to be organized in different way. To this aim, we propose only three DS: DS1: null damage; DS2: small cracks or failures; DS3: big cracks or failure of auxiliary system. Corresponding RS states are: RS1: no loss of containment; RS2: leakage; RS3: catastrophic loss of containment. The analysis should be then addressed by the consideration that RS2 is due to DS2 and RS3 is related to DS3.

A preliminary analysis has been conducted starting from the analysis reported in **, **
The transformation of Mercalli-modified intensity scale (MMI) to PGA has been performed by Ambraseys (1974) and Gutenberg Richter (1956) equation:

$$log\left(PGA\right) = a + b \cdot MMI \tag{6}$$

where a and b are constants. These procedure gives a minimum and maximum PGA which can be used for the definition of DS and RS. Results are reported in Table 3.

Table 3: Seismic fragility for pressurised equipment

DS	*RS*	μ	β	k_1	k_2
≥ 2	≥ 2	0.115	0.99	**	**
= 3	= 3	0.109	0.52	**	**

3. Conclusions

Results reported for atmospheric tanks and preliminary consideration reported for pressurised equipment can be useful for the risk assessment of industrial plants localized in urbanized areas.

4. Reference

NUREG/CR-2300, 1983, PRA Procedure Guide: A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants , U.S. Nuclear Regulatory Commission.

Cornell C.A., 1968, Engineering seismic risk analysis, B. Seismol. Soc. Am. 58, 1583-1606.

McGuire R.K., 1995, Probabilistic seismic hazard analysis and design earthquake: closing the loop, B. Seismol. Soc. Am. 85 (5), 1275-1284.

Chopra, A. K., 1995, Dynamics of structures. Prentice Hall.

Eidinger, J.M., 2001, Earthquakeic fragility formulation for water systems, ASCE-TCLEE.

V. Convertito, 2003,Extension of classical attenuation laws: influence and implications on the probabilistic seismic hazard analysis, Dipartimento di Analisi e Progettazione Strutturale, Università di Napoli “Federico II”, Ph.D. thesis.

F. Sabetta, A. Pugliese, 1987, Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records, B. Seismol. Soc. Am. 77, 1491–1513.

HAZUS, 1997, Earthquake Loss Estimation Methodology, National Institute of Building Science, Risk Management Solutions, Menlo Park, CA.

F.P. Lees, 1996, Loss Prevention in the Process Industries, second ed., Butterworth-Heinemann, Oxford.

E. Salzano, I. Iervolino, G. Fabbrocino, 2003, Seismic risk of atmospheric storage tanks in the framework of quantitative risk analysis, J. Loss Prevent. Proc. 16 403–409.

J.A. Vilchez, H. Montiel, J. Casal, J. Arnaldos, 2001, Analytical expression for the calculation of damage percentage using the probit methodology, J. Loss Prevent. Proc. 14 193–197.

Fabbrocino G., I. Iervolino, F. Orlando, E. Salzano, 2005, Quantitative risk analysis of oil storage facilities, in seismic areas, J. Hazardous Materials 12, 361-69.

J.M. Eidinger, 2001, Earthquakeic fragility formulation for water systems, ASCE-TCLEE.

M.J. O’Rourke, P. So, 2000, Seismic Fragility Curves for On-Grade Steel Tanks, Earthquake Spectra, 16, NY, USA.