Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Loss Prevention in the Process Industries 16 (2003) 403–409
Journal of Loss Prevention in the process industries
www.elsevier.com/locate/jlp

Seismic risk of atmospheric storage tanks in the framework of quantitative risk analysis

E. Salzano [a,*], I. Iervolino [b], G. Fabbrocino [b]

[a] *Institute of Research on Combustion, CNR, Via Diocleziano 328, 80125 Napoli, Italy*
[b] *Department of Structural Analysis and Design, University of Naples "Federico II", P.le Tecchio 80, 80124 Napoli, Italy*

Abstract

The quantitative risk assessment of industrial facilities is based on integrated procedures to quantify human, environmental and economical losses related to relevant accidents. Accordingly, seismic risk analysis has to be integrated in order to obtain reliable results.

In this work, some considerations regarding the intensity and probability of occurrence of earthquakes and the vulnerability of atmospheric storage tanks subjected to seismic actions are given.

Structural vulnerability based on observational data has been processed in the form of "probit analysis", a simple and useful statistic tool. Suggestions concerning industrial seismic-related accidental scenarios are also given.

Keywords: Quantitative risk analysis; Earthquake; Storage tank; Domino effects; Probit analysis; Fragility

1. Introduction

Risk assessment is based on integrated procedures to quantify human, environmental and economical losses related to relevant accidents. More specifically, risk analysts deal with the prediction of occurrence of any individual failure event and the related possible consequences on the analysed system (Kirchsteiger, 1999). Accordingly, seismic hazard have to be integrated into quantitative risk analysis (QRA). Nevertheless, few methodologies has been developed to predict the behaviour of industrial equipment when subjected to earthquakes, unless time-consuming and equipment-specific structural analysis is considered.

In this work, some considerations concerning the intensity and probability of occurrence of earthquakes and the vulnerability of atmospheric storage tanks subjected to seismic actions are given.

When QRA of an industrial installation or more generally of an entire industrial area is performed, both a deterministic or a probabilistic approaches can be used.

If seismic risk is concerned, the deterministic approach is based on the maximum "credible" intensity of earthquake as the triggering event and a conservative estimate ("worst case" assumption) for the subsequent accidental scenario is made depending on the interaction of the earthquake shaking with equipment, which can result in a loss of material or energy. In the above form, the deterministic approach leads often to a significant overestimation of the risk, so that such a risk grade becomes both economically and politically not sustainable, e.g. in the case of civil protection action. Moreover, the uncertainties related to the initial conditions of the seismic scenario, to the failure of equipment, and to the uncertainties in the analysis of consequences of the possible destructive phenomena following the loss of hazardous substances are often too large. These circumstances lead analysts to use a probabilistic approach, where uncertainties are explicitly taken into account and described by probability distributions (Lees, 1996).

Common measures for probabilistic analysis of risks include the "individual risk" and the "societal risk" assessments. Details are reported elsewhere (CCPS, 1989; Lees, 1996; Bottelberghs, 2000). The practical evaluation of both risk indexes requires the identification of all the possible system failures with related probabilities of occurrence. Furthermore, evaluation of the

* Corresponding author. Tel.: +39-0817621922; fax: +39-0817622915.
E-mail address: salzano@irc.na.cnr.it (E. Salzano).

doi:10.1016/S0950-4230(03)00052-4

temporal and spatial distribution of variable of interest is needed to estimate the damage to equipment and communities surrounding the failed component (e.g. pressure for explosions, heat radiation for fire, concentration for toxic dispersion). As a consequence, simplified methodologies are clearly needed.

Here, the structural vulnerability of atmospheric storage tanks to seismic action is defined by means of the parameters of the simple statistic tool known as "probit analysis" (Finney, 1971; Vilchez, Montiel, Casal, & Arnaldos, 2001). This tool has been widely used in hazard assessment since the first Canvey report (HSE, 1978) and the Rijnmond report (1982), although referred to person injury.

The usefulness of this analysis relies on the relatively simple integration of the probit function with QRA algorithms (e.g. ARIPAL (Spadoni, Egidi, & Contini, 2000)). The probit variable Y is a dose–response relationship which gives a measure of having certain damage as a function of the intensity of the variable V (the "dose") (Finney, 1971):

$$Y = k_1 + k_2 \ln V \quad (1)$$

The variable Y can be directly compared with the actual probability P by means of the integral (Vilchez et al., 2001):

$$P(V) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} e^{-V^2/2} dV \quad (2)$$

In the mainframe of integration of QRA with seismic action, the dose V corresponds to the seismic peak ground acceleration (PGA), and the probability of occurrence of damage may refer alternatively to the loss of containment or to the structural damage of the tank, which may be followed by loss of containment depending on the level of failure.

2. The intensity and probability of occurrence of earthquakes

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" (Chopra, 1995). The choice of these intensity parameters is important since they summarise all the random features of earthquakes, including energy and frequency contents, which meaningfully affect the structural response of components (Eidinger, 2001).

Ground parameters refer to the intensity measures (IM) characterising 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 shown that different parameters are needed if the effects of earthquake on 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 (Eidinger, 2001). The latest will be used in the following. Of course, the probability of occurrence of the earthquake itself is needed, given its intensity. According to probabilistic seismic hazard analysis (PSHA) (Cornell, 1968), P should be always related to a time interval T—in the present case the service life of the structure. Eventually, a seismic hazard H (or "exceedance probability") is defined through the following equation:

$$H(T) = P[\mathrm{PGA} > a, T] \quad (3)$$

which represents the probability that a given seismic intensity exceeds the constant value a during the time interval T. Typical seismic hazard curves are reported in Fig. 1 for two different time intervals.

Local authorities commonly provide tools for PSHA

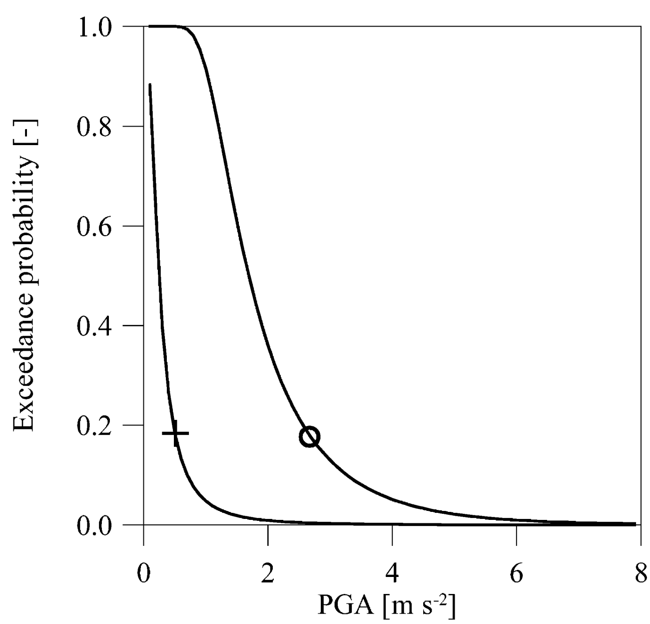

Fig. 1. Hazard curves in terms of annual exceedance probability of PGA for two equipment (with service life of respectively: +: 50 year; O: 1 year).

in terms of the IM of interest both in Europe and USA (e.g. available at http://www.usgs.gov). If different intensity parameters are used, all ground shaking parameters are related: details of correlations can be found elsewhere (Clough & Penzien, 1982).

3. Seismic behaviour of atmospheric storage tanks

Storage steel tanks are fabricated as riveted, welded or bolted (especially for low values of height over radius ratio H/R); in the last decades, they were basically welded world-wide (Fabbrocino, Iervolino, & Manfredi, 2002).

According to consolidated design and construction standards, these types of tanks exhibit strong structural similarities with water storage tanks. Nevertheless, several procedures (AWWA D100, 1996; AWWA D103, 1997; API Standard 620-650, 1998) do not prescribe any accurate dynamic analysis, and the effects of earthquake actions are only evaluated in terms of equivalent static action as overturning moment and total base shear; however, in the last years, a more comprehensive and advanced guideline for the design of this type of facility from a structural standpoint is reported in Eurocode 8 (1998).

Meaningful structural aspects of existing steel tanks can be summarised as follows: (i) the base plate is flat or conical shaped and the shell consists of different steel courses approximately 1 m and a half tall; their thickness decreases along the height and rarely exceeds 2 cm in the bottom course (large tanks reference value); (ii) shell thickness is calculated using simplified formulas (i.e. "one foot method") according to design guidelines and depends only on tank dimensions and content density; (iii) roofs are floating or shaped as dome or conical and can be self-supported or column-supported in case of large diameters; international guidelines provide minimum roof plate thickness and geometrical calculation (i.e. cone inclination, depending on diameter of tanks) (API 620-650, 1998).

Tanks are commonly classified as anchored and unanchored, depending on the type of restraint provided to the ground. Unanchored tanks are simply ground or gravel bed rested, while for large tanks and/or bad soil conditions, concrete ring foundation can be effective (API Standard 620-650, 1998). Anchored tanks are characterised by different mechanical devices limiting the relative displacements between base plant and foundation and are generally recommended in seismic areas but their effectiveness is still under investigations. Indeed, assuming the same filling level and nominal dimensions, gravel rested tanks are subjected to uplifting and/or sliding motion, and the tearing of pipe connection can be activated in case of strong motions (Fig. 2).

A key issue in steel tank design is welding; indeed, welds are sensitive to corrosion and can lead to wide cracks during earthquake events, particularly in the shell/roof and shell/base plate joint zones. Another critical aspect for the seismic behaviour of storage tanks is the foundation. The analysis of seismic damages pointed out the effects of foundation on collapse mechanisms and strength performances of the structure (Eidinger, 2001).

The dynamic behaviour of atmospheric storage tanks subjected to an earthquake is characterised by two predominant vibrating modes: the first is related to the mass that rigidly moves together with the tank structure (impulsive mass), the other corresponds to the liquid sloshing (convective mass) (Malhotra, Wenk, & Wieland, 2000).

Liquid sloshing during earthquake action produces several damages by fluid–structure interaction phenomena and can result as the main cause of collapse for full or nearly full tanks (Ballantyne and Crouse, 1997).

Historical analysis and assessment of seismic damages of storage tanks have shown that only full (or nearly full) tanks experienced catastrophic failures. Low H/R tanks only suffered cracks in conical roof connection, or damage by floating panel sinking.

The most common shell damage is the "elephant foot buckling" (EFB). For unanchored tanks and $H/R <$ 0.8, EFB is not experienced but the base plate or the shell connection can fail causing spillage (Ballantyne and Crouse, 1997).

A full stress analysis is certainly the more accurate way to design and to evaluate the risk of steel tanks under earthquake loads. This approach leads to the direct computation of the interaction between shell deformations and content motion during earthquakes (Haroun, 1999).

For base constrained and rigid tanks (anchored), a complete seismic analysis requires solution of Laplace's equation for the motion of the contained liquid, in order to obtain the total pressure history on the tank shell during earthquakes (Eurocode 8, 1998).

When flexible tanks are considered, a structural deformation term must be also added to take account of the "impulsive" and "convective" contributions.

Unanchored tanks are subjected to uplifting but also to sliding. Uplifting can crack base plate connection; besides it increases flexibility to the system isolating it. AWWA D-100 and API 650 focus their attention on base shear and overturning moment after Malhotra et al. (2000) and provide methods to take into account of geometrical parameters of the tank and the earthquake zone classification factors.

Actually, as stated above, the quantitative assessment of risk within a complex industrial installation needs the analysis of great number of components. Hence, in the light of simplification, statistical and empirical tools

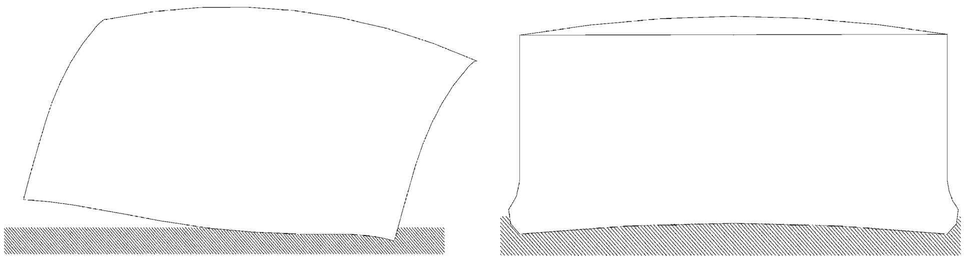

Fig. 2. Unanchored atmospheric tank subjected to “uplifting” and “EFB”.

derived from post-accident analysis are needed in order to define simple and general vulnerability functions.

4. Seismic fragility of tanks: results and discussion

Several studies in the last decades have defined “damage states” (DS) in order to describe the behaviour of atmospheric steel tanks subjected to earthquakes (O’Rourke, Eeri & So, 2000). According to HAZUS damage classification (1997), a slight damages to structures have been defined as DS2, a moderate damages as DS3, an extensive damages as DS4 and the total collapse of structure as DS5. The term DS1 refers to the absence of damage.

The DS values is an alternative formulation of the classical “limit state” definition, which has been extensively used to evaluate the economical effort needed to repair and restore the tank structures.

An observational approach to the development of seismic fragility relationships can be carried out based on the data set reported in Table 1; here, it is worth noting that similarity between seismic behaviour of atmospheric water and oil tanks enables a relevant increase of the number of available data to be used in the historical data set.

Based on this data set, Tables 2 and 3 report the damage analysis obtained by using limit states DS, for both the entire set number of tanks and for tanks whose filling level is greater than 50%. Indeed, structural analysis and empirical observation have confirmed that only those filling level seems to be vulnerable to earthquakes (Iervolino, Fabbrocino, & Manfredi, 2003). Moreover, the choice of a filling level results useful when QRA on large storage area is performed and detailed information on the average tank fill level are difficult to obtain.

Table 1
Data set used for the assessment of vulnerability of atmospheric storage tanks subjected to earthquakes. See references for details on the specific type and dimension of the tanks and related filling level

PGA (g[a])	Affected tanks	Damaged tanks	Event[b]
0.17	49	2	Long Beach (1933)
0.19	24	13	Kern County (1952)
0.20–0.30	39	35	Alaska (1964)
0.30–1.20	20	19	San Fernando (1971)
0.24–0.49	24	16	Imperial Valley (1979)
0.23–0.62	41	17	Coalinga (1983)
0.25–0.5	12	3	Morgan Hill (1984)
0.1–0.54	141	32	Loma Prieta (1989)
0.35	38	19	Costa Rica (1992)
0.1–0.56	33	13	Landers (1992)
0.3–1	70	28	Northridge (1994)
0.17–0.56	41	4	Others

[a] g is gravity acceleration.
[b] Data from Cooper (1997), Wald, Quitoriano, Heaton and Kanamori (1999), Haroun (1983), Ballantyne and Crouse (1997), Brown, Rugar, Davis, and Rulla (1995), Eidinger (2001).

Table 2
Analysis of DS for all the atmospheric tanks subjected to earthquake as reported in the historical data set of Table 1

PGA (g)	All	DS = 1	DS = 2	DS = 3	DS = 4	DS = 5
0.10	4	4	0	0	0	0
0.17	263	196	42	13	8	4
0.27	62	31	17	10	4	0
0.37	53	22	19	8	3	1
0.48	47	32	11	3	1	0
0.57	53	26	15	7	3	2
0.66	25	9	5	5	3	3
0.86	14	10	0	1	3	0
1.18	10	1	3	0	0	6
Total	532	331	112	40	25	16

Table 3
Analysis of DS for the atmospheric tanks subjected to earthquake with filling level greater then 50%

PGA (g)	All	DS = 1	DS = 2	DS = 3	DS = 4	DS = 5
0.10	1	1	0	0	0	0
0.17	77	22	32	12	8	3
0.27	43	16	12	10	4	0
0.37	22	3	11	4	3	1
0.48	25	12	9	3	1	0
0.57	48	22	14	7	3	2
0.66	15	4	2	3	3	3
0.86	10	7	0	0	3	0
1.18	10	1	3	0	0	5
Total	251	88	84	39	25	15

In the mainframe of QRA, the loss of hazardous substances from their system of containment is a key issue. Indeed, all the typical accidental scenarios in the process industry (vapour cloud explosions (VCE), flash fires, pool fires or toxic dispersions) strongly depend on the total amount of released dangerous substance (CCPS, 1994). Hence, in the following, the data set has been reorganised in terms of three classes defined as RS (risk state) with specific reference to the loss of containment (i.e. the damage). Further details on the accidental phenomena here cited are given elsewhere (Lees, 1996; Martin, Ali Reza, & Anderson, 2000; Salzano, Marra, Russo, & Lee, 2002).

The first class (RS1) corresponds to earthquakes slightly affecting the structure of the tank, thus a negligible loss of containment occur. A structural damage of the shell, or of auxiliary equipment, thus giving rise to "slight loss of content" is defined as RS2. Finally, a consistent and rapid loss of content has been identified as RS3. The latest class refers to the extended or catastrophic damage of tank resulting in the rapid total loss of containment.

Table 4 reports the damage analysis in terms of RS for the data set of atmospheric storage tanks reported in Table 1. For the sake of comparison, the "fragility curves" (defined as the probability of getting a specific limit state, in this case, a particular RS value), as derived from Table 4, are reported in Fig. 3, showing the statistic similarity of behaviour of atmospheric tank 50% filled with the behaviour obtained without taking into account the fill level.

Probit relationships which give the probability of damage in terms of loss of containment (RS) or in terms of DS with respect to PGA are then calculated (Fig. 4). Values of probit coefficients (see Eq. (1)) are reported in Table 5, together with fragility coefficients and related dispersion parameters.

The results reported in Fig. 3 and Table 5 can be

Table 4
Analysis of DS in terms of loss of containment for the atmospheric tanks subjected to earthquake as reported in the historical data set of Table 1. FL = fill level

PGA (g)	RS≥2	RS = 3	RS≥2	RS = 3
	FL (>50%)	FL(>50%)	FL (0–100%)	FL (0–100%)
0.10	0	0	0	0
0.17	55	11	67	12
0.27	26	4	31	4
0.37	19	4	31	4
0.48	13	1	15	1
0.57	26	5	27	5
0.66	11	6	16	6
0.86	3	3	4	3
1.18	8	5	9	6

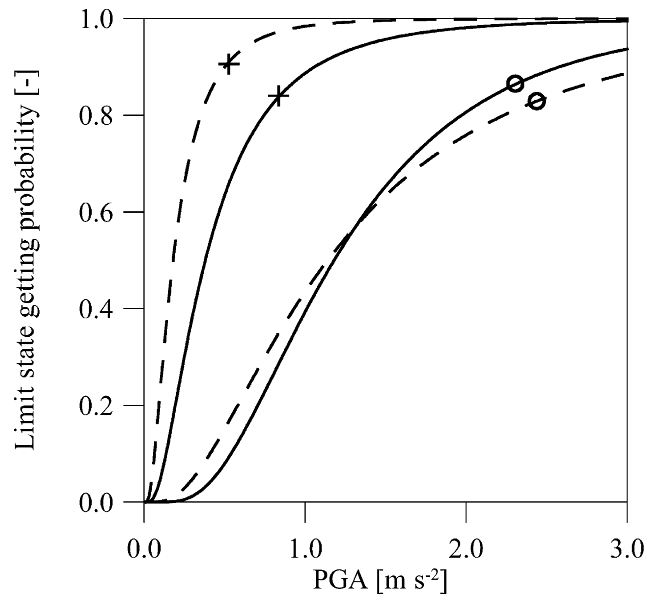

Fig. 3. Calculated fragility curves for atmospheric steel tanks affected by earthquakes. Dotted line: tank fill level > 50%. +: RS2; O: RS3.

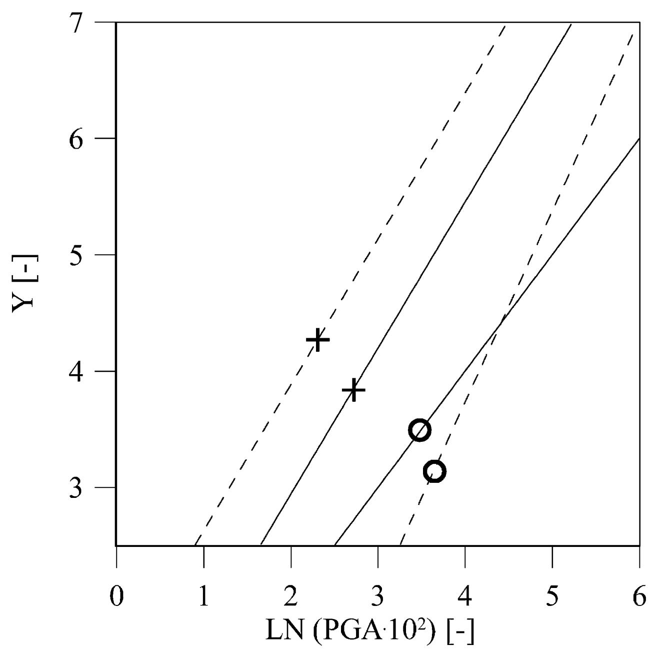

Fig. 4. Probit analysis for steel tanks in seismic areas. Dotted line: tank fill level > 50%. +: RS2; O: RS3.

easily analysed comparing the probit coefficients. Main conclusions are:

(a) for both anchored and unanchored tank, it is clear from the value of k_2 (the slope of the probit function), the similarity of behaviour of tanks whose fill level is greater than at 50% with the behaviour of tank evaluated for any fill level; the only exception occurs for the unanchored tank-RS2 value

Table 5
Fragility and probit coefficients ($Y = k_1 + k_2 \ln(10^2 \text{ PGA})$) for atmospheric steel tank subjected to earthquake. FL = fill level; μ and β are the median and the shape parameter of the log-normal distribution for fragility

Risk state	Tank	FL	Fragility		Probit	
			μ	β	k_1	k_2
RS≥2	All	All	0.38	0.80	0.43	1.26
RS = 3	All	All	1.18	0.61	−2.83	1.64
RS≥2	All	≥50%	0.18	0.80	1.77	1.14
RS = 3	All	≥50%	1.14	0.80	−0.92	1.25
RS≥2	Anchored	Near full	0.3	0.6	−0.06	1.49
RS = 3	Anchored	Near full	1.25	0.65	−2.43	1.54
RS≥2	Anchored	≥50%	1.71	0.8	−1.44	1.25
RS = 3	Anchored	≥50%	3.72	0.8	−2.42	1.25
RS≥2	Unanchored	Near full	0.15	0.7	2.28	1.08
RS = 3	Unanchored	Near full	1.06	0.8	−0.833	1.25
RS≥2	Unanchored	≥50%	0.15	0.12	5.69	0.39
RS = 3	Unanchored	≥50%	1.06	0.8	−0.83	1.25

(b) the minimum value of PGA needed to obtain a probit value different from 2.71 (which corresponds to the zero probability), which is easily assessed by the k_1 value (the intercept of the probit function) differs greatly from the anchored and unanchored and changes with fill level
(c) the absolute minimum of PGA is reached for the RS2 value of 50% filled unanchored storage tank, which can be considered as the reference tank for QRA on the safe side (worst case analysis or deterministic approach).

5. Conclusions

Risk assessment should always include the effects of earthquakes on equipments and the related probability of occurrence. Furthermore, in the mainframe of the Seveso II directive (Council Directive, 1996) evaluation of the “domino effect”, risk analysts have to take into account the escalation of industrial accidents even starting from minor natural events such as low-intensity earthquakes.

In this paper, classification of DS depending on the PGA, either in terms of structural effects, or in terms of loss of containment has been performed based on historical data set concerning atmospheric tanks in seismic areas.

Specific fragility curves in the form of probit functions have been defined in order to implement a seismic dose–effect relationship into QRA algorithms. To this aim, further evaluation of the accidental scenarios derived from the loss of containment itself has to be performed.

For low-intensity earthquakes, RS2 damage level, it is presumable that the response of operator and the safety procedures (e.g. sprinkler action) are able to prevent or at least to mitigate the risk of fire or explosion and restore the plant normality within tens of minutes. In this case, only toxic, flash fire and pool fire effects should be considered, whereas VCEs (and the related blast wave) need long term evaporation and fuel dispersion to give a potentially destructive homogenous flammable vapour cloud.

When RS3 damage occurs (and it is likely that several tanks are involved) or more generally structural damages induced by very catastrophic earthquakes are considered, the gravity of situation hardly allows the operator to take a full control even for the single equipment. All the scenarios should be then considered: pool fire, flash fire, VCE and toxic dispersion. To this regard, the probability of VCE, rather than flash fire, is strongly dependent on the fuel reactivity and on the geometrical scenario (specifically on confinement and degree of congestion). Moreover, the effect of pool fire has to be added to the effects of the first two non-localised fires.

6. Acknowledgments

The authors would like to acknowledge funding and support received from the Geophysics and Volcanology Italian National Institute (INGV) within the research project “Reduction of Infrastructures and Environment Seismic Vulnerability” (VIA) and Mr. V. Convertito, Department of Geophysics, University of Naples Federico II, for the collaboration in the development of sample hazard curves.

References

API 620—American Petroleum Institute (1998). *Design and construction of large, welded, low-pressure storage tanks*. Washington, DC, USA.
API 650—American Petroleum Institute (1998). *Welded steel tanks for oil storage*. Washington, DC, USA.

AWWA D100-96—American Water Works Association (1996). *Welded steel tanks for water storage*. Denver, CO, USA.

AWWA D103-97—American Water Works Association (1997). *Factory-coated bolted steel tanks for water storage*. USA.

Ballantyne, D., & Crouse, C. (1997). *Reliability and restoration of water supply systems for fire suppression and drinking following earthquakes*. National Institute of Standards and Technology, NIST GCR 97-720.

Bottelberghs, P. H. (2000). Risk analysis and safety policy developments in The Netherlands. *Journal of Hazardous Materials*, *71*, 59–84.

Brown, K., Rugar, P., Davis, C., & Rulla, T. (1995). Seismic performance of Los Angeles water tanks, lifeline earthquake engineering. In *Proceedings of the 4th US conference, ASCE, TCLEE monograph No. 6, San Francisco*.

CCPS—Center for Chemical Process Safety of the American Institute of Chemical Engineers (1989). *Guidelines for chemical process quantitative risk analysis*. New York: American Institute of Chemical Engineers.

CCPS—Center for Chemical Process Safety of the American Institute of Chemical Engineers (1994). *Guidelines for evaluating the characteristics of VCEs, flash fires and BLEVEs*. New York: Center for Chemical Process Safety of the American Institute of Chemical Engineers.

Chopra, A. K. (1995). *Dynamics of structures*. Prentice Hall.

Clough, R. W., & Penzien, J. (1982). *Dynamics of structures*. New York: McGraw-Hill.

Cooper, T. W. (1997). *A study of the performance of petroleum storage tanks during earthquakes, 1933–1995*. Gaithersburg, MD: National Institute of Standards and Technology.

Cornell, C. A. (1968). Engineering seismic risk analysis. *Bulletin of the Seismological Society of America*, *58*, 1503–1606.

Council Directive 96/82/EC of 9 December 1996 on the control of major-accident hazards involving dangerous substances. *Official Journal of the European Communities*, L 10/13, Brussels.

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

Eurocode 8 (1998). *Design of structures for earthquake resistance—Part 4: silos, tanks and pipelines*, UNI ENV 1998.

Fabbrocino, G., Iervolino, I., & Manfredi, G. (2002). *Structural issues in seismic risk assessment of existing oil storage tanks*. In Proceedings of 3rd international conference on computer simulation in risk analysis and hazard mitigation, 19–21 June 2002 Sintra, Portugal.

Finney, D. J. (1971). *Probit analysis*. Cambridge University Press.

Haroun, M. (1983). Behaviour of unanchored oil storage tanks: Imperial Valley Earthquake. *Journal of Technical Topics in Civil Engineering*, *ASCE*, *109*, 1.

Haroun, M. A. (1999). *Implications of recent nonlinear analyses on earthquakeic standards of liquid storage tanks*. In Proceedings of 5th US conference on lifeline earthquake engineering, TCLEE monograph No. 16, ASCE Seattle, USA.

HAZUS (1997). *Earthquake Loss Estimation Methodology*. National Institute of Building Sciences, prepared by Risk Management Solutions, Menlo Park, CA, USA.

HSE—Health Safety Executive (1978). *Canvey report: an investigation of potential hazards from operation in the Canvey Island/Turrock area*, London, UK, Stationery Office.

Iervolino, I., Fabbrocino, G., & Manfredi, G. (2003). *Contribution to integrated risk assessment of industrial facilities: the case of oil storage tanks in seismic regions*. In GNDT-MAE-SAFERR conference on seismic risk in urban areas, Erice, Italy.

Kirchsteiger, C. (1999). On the use of probabilistic and deterministic methods in risk analysis. *Journal of Loss Prevention in the Process Industries*, *12*(5), 399–419.

Lees, F. P. (1996). *Loss prevention in the process industries* (2nd ed.). Oxford, UK: Butterworth-Heinemann.

Malhotra, P. K., Wenk, T., & Wieland, M. (2000). Simple procedure for earthquakeic analysis of liquid-storage tanks. *Structural Engineering International*, *3*.

Martin, R. J., Ali Reza, A., & Anderson, L. W. (2000). What is an explosion? A case history of an investigation for the insurance. *Journal of Loss Prevention in the Process Industries*, *13*, 491–497.

O'Rourke, M.J., Eeri, M., & So, P. (2000). Seismic fragility curves for on-grade steel tanks. *Earthquake spectra*, vol. 16, NY, USA.

Rijnmond Public Authority (1982). *Risk analysis of six potentially hazardous industrial objects in the Rijnmond area, a pilot study*, Reidel Dordrecht, The Netherlands.

Salzano, E., Marra, F. S., Russo, G., & Lee, J. H. S. (2002). Numerical simulation of turbulent gas flames in tubes. *Journal of Hazardous Materials*, *95*(3), 233–247.

Spadoni, G., Egidi, D., & Contini, S. (2000). Through ARIPAR-GIS the quantified area risk analysis supports land-use planning activities. *Journal of Hazardous Materials*, *71*, 423–437.

Vilchez, J. A., Montiel, H., Casal, J., & Arnaldos, J. (2001). Analytical expression for the calculation of damage percentage using the probit methodology. *Journal of Loss Prevention in the Process Industries*, *14*, 193–197.

Wald, D. J., Quitoriano, V., Heaton, T. H., & Kanamori, H. (1999). Relationships between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California. *Earthquake Spectra*, *15*, 557.