Seismic risk of atmospheric storage tanks by probit analysis

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ABSTRACT: The risk assessment of industrial facilities is based on availability of integrated procedures to quantify human, environmental and economical losses related to relevant accidents, thus including earthquake actions. Accordingly, results of seismic risk analysis has to be integrated into quantitative risk analysis either for single establishment or for entire industrial areas. Moreover, it's worth noting that the evaluation of the "domino effect" leads risk analysts to take into account the escalation of industrial accident even starting from a relatively minor natural event such as low-intensity earthquakes. In this paper, some considerations are given regarding the intensity and probability of occurrence of earthquakes and the vulnerability of atmospheric storage tanks subjected to seismic actions. Eventually, structural vulnerability and seismic hazard have been compared aiming at defining a simple and useful statistic tool as the "probit analysis". Some indications on the industrial seismic-related accidental scenarios are also given.

1 INTRODUCTION

The risk assessment of industrial facilities is based on availability of integrated procedures to quantify human, environmental and economical losses related to relevant accidents, thus including earthquake actions. Accordingly, results of seismic risk analysis has to be integrated into quantitative risk analysis (QRA) either for single establishment or for entire industrial areas [Lees, 1996]. Moreover, it's worth noting that in the mainframe of the Seveso II directive [Council Directive 96/82/EC], the evaluation of the "domino effect" has forced risk analysts to keep into account the escalation of industrial accident even starting from minor natural events such as low-intensity earthquakes. Eventually, interdisciplinary efforts between seismic, structural and chemical engineers are required to obtain reliable QRAs.

Risk analysis deals with the occurrence of individual failure events and their possible consequences on the analysed system [Kirchsteiger, 1999]. With reference to an industrial installation, aiming at providing a quantitative methodology for risk analysis (quantitative risk analysis, QRA, or Probabilistic Risk Assessment, PSA, or Probabilistic Safety Assessment, PSA), a deterministic or a probabilistic approach can be used.

When specifically the seismic risk is of concern, a deterministic approach uses the maximum "credible" earthquake event and "worst case" scenarios are considered for the evaluation of consequences. If industrial installations are considered and people and/or equipment safety is of interest, this approach has to be coupled with another "deterministic" analysis, which keeps into account the evolution of the accidental scenario (the earthquake) starting from the material or the energy loss from the failed system of containment, i.e. the evaluation of consequences. Again, a worst case scenario should be considered. This approach leads to great overestimation of the total risk, often providing a risk grade which is both economically and politically not applicable, e.g. in the case of civil protection action. Moreover, the uncertainties on the initial conditions for either the seismic scenario or the evolution of the industrial accident scenario related to the earthquake itself, are often too large. This circumstance leads analysts to use a probabilistic approach, where uncertainties are explicitly taken into account and described through random variables, by their probability distribution.

Common measures for industrial quantitative risk include individual risk and societal risk [CCPS, 1989; Lees, 1996]. The individual risk for a point-location around a hazardous activity is defined as the probability that an average unprotected person permanently present at that point location, would get killed due to an accident at the hazardous activity.

The societal risk for a hazardous activity is defined as the probability that a group of more than N persons would get killed due to an accident at the hazardous activity [Bottelberghs, 2000]. The societal risk is often described as FN curve (frequency number curve), i.e. the exceedance curve of the annual probability of the event and the consequences of that event in terms of the number of deaths.

The practical evaluation of both individual and societal risk is a complex task which requires first the identification of all credible equipment failures, i.e. the “top event”. The latest has to be coupled with related probabilities of occurrence, based on historical analysis or process related analysis (e.g. fault tree analysis).

At this point, the physical phenomena which are able to produce damages to people, e.g. fire or explosion or dispersion of toxic substance, and equipment (aiming at domino effect evaluation) and the related probability (e.g. through event tree analysis), for each of the possible top events, has to be modelled, in order to produce the temporal and spatial distribution of overpressure, heat radiation and concentration. Moreover, the relationship of this variables with human being has to be assessed.

Eventually, it’s clear that QRA can only be considered as a rough evaluation of risk and that this instrument should only be used as a comparative tool, since arbitrary choices are often necessary, either on probability of occurrence of the top event or on the physical modelling of the entire accidental scenario or on the occurrence of damage. However, research efforts should be addressed to improve each of these aspects, in order to produce efficient “algorithms”.

In this work, some considerations either regarding the intensity and probability of occurrence of earthquakes, or the vulnerability of equipment - specifically atmospheric storage tanks - to seismic action are given. Structural vulnerability and seismic hazard quantitative results have been also compared aiming at defining the parameters of the simple statistic tool known as “probit analysis” [Finney, 1971; Vilchez, 2001].

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 summarize 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 peak values of variables experienced by the ground motion: the intensity of earthquakes is viewed as “ground shaking“, characterized by a peak ground acceleration (PGA), or a peak ground velocity (PGV), or a 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 (spectral acceleration).

Although experimental investigations have demonstrated 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 peak ground velocity is commonly used, while peak ground acceleration is more useful when steel storage tanks are under investigation. Hence, PGA is the global earthquake intensity measure used in the following.

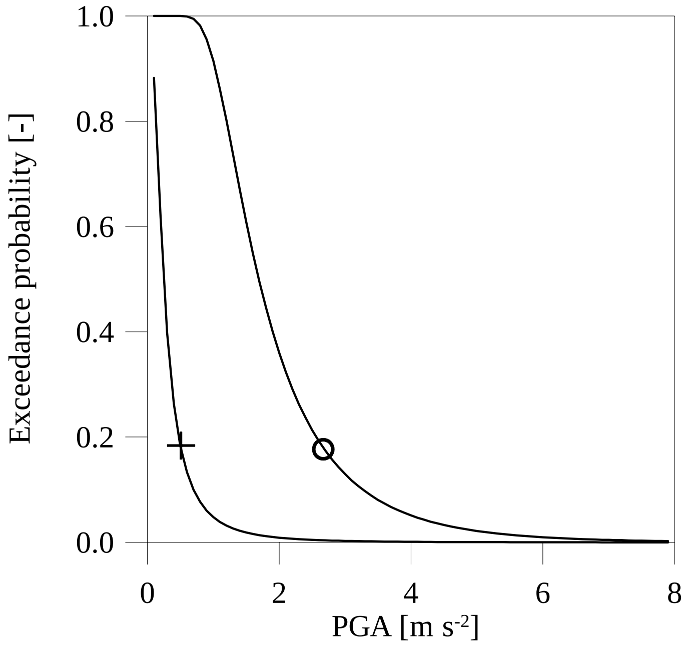

Figure 1. Hazard curves in terms of annual exceedance probability of Peak Ground Acceleration (PGA) for two equipment with service life of respectively: + : 50 year; O: 1 year

This assumption is necessary in the light of simplification that is needed when complex risk assessment of industrial plants is performed. Regardless intensity definition, seismic pre-accident risk assessment needs the definition of a probability of occurrence of earthquake, given its intensity. To this aim, seismic hazard (H) is related to the time interval T – i.e. the service life of the structure – and to the seismological seismic intensity parameter (PGA):

$$H(T) = P(PGA > a \mid T) \quad (3)$$

This relation gives the probability H that a given PGA exceeds the value of the constant *a* during T. Seismic hazard curves calculated for two equipment with a service life of respectively fifty and one year, evaluated at Benevento, located in south Italy, are reported in Figure 1.

Local authorities commonly produce the curves reporting the probability of occurrence of PGA both in Europe and US.

If different intensity parameters are used, all ground shaking parameters are related and can be found elsewhere [Claugh, 1982].

3 SEISMIC BEHAVIOUR OF ATMOSPHERIC STORAGE TANK

Starting from 1930 atmospheric storage steel tanks were fabricated as riveted, welded or bolted (especially for low values of height over radius ratio H/R); conversely in the last decades they were basically welded world-wide.

According to consolidated design and construction standards, these types of tanks exhibit strong structural similarities with water storage tanks. Nevertheless, the procedures [AWWA D100, 1996; AWWA D103, 1997; API Standard 620-650, 1998] provided by American Petroleum Institute and American Water Works Association do not prescribe any dynamic analysis, and the effects of earthquake actions are only evaluated in terms of overturning moment and total base shear.

Recently, Eurocode 8 (1998) has developed a more comprehensive and advanced guideline for the design of this type of facility from a structural standpoint.

The base plate of storage tanks is generally flat or conical shaped.

The tank shell consists of different steel courses approximately one meters and a half tall; their thickness decreases along the height and rarely exceeds two centimetres in the bottom course (large tanks reference value).

Shell thickness is calculated using empirical formulas (i.e. "one foot method") according to design guidelines and depends only on tank dimensions and content density. Shells include nozzles and openings and other piping connections. Roof can be shaped in many different ways as dome, conical or can be floating.

Roofs can be self-supported or columns supported in case of large diameters. International guidelines [API 620-650, 1998] provide minimum roof plate thickness and geometrical calculation (i.e. cone inclination, depending from diameter of tanks).

Tanks can be anchored or unanchored to the ground. Due to economical reasons; they are often simply ground or gravel bed rested; for large tanks and/or bad soil conditions concrete ring foundation can be effective.

Anchored tanks are more expensive and are generally recommended in seismic areas but their effectiveness is still under investigation.

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.

Assuming the same filling level and nominal dimensions, gravel rested tanks are subjected to uplifting and/or sliding motion, but the tearing of pipe connection can be activated in case of strong motions (Figure 2).

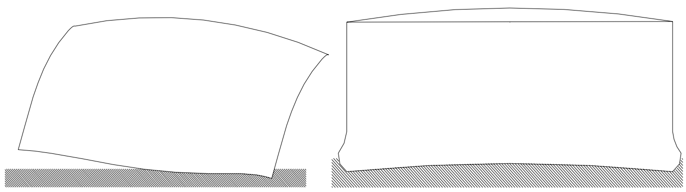

Figure 2. Unanchored atmospheric tank subjected to "uplifting" and "elephant foot" buckling.

The dynamic behaviour of atmospheric storage tanks subjected to a 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's sloshing (convective mass).

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.

Historical analysis and assessment of seismic damages of storage tanks has revealed 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.

4 THE PROBIT ANALYSIS

The usefulness of probit analysis relies on the relatively simple integration of the probit function with QRA algorithms (e.g. ARIPAL [Spadoni, 2000]) which have been produced in the past aiming at the definition of industrial individual and social risks, as they are commonly defined in literature [CCPS, 1994; Lees, 1996]. Moreover, comparison of seismic hazard of tanks with different geometry and filling level can be easily obtained by means of probit coefficients. This tool has been widely used in hazard assessment since the first Canvey Report [HSE, 1978] and the Rijnmond report (1982), although only referred to person injury.

The probit variable (usually represented as Y) is a dose-response relationship and gives a measure of having certain damage as a function of the intensity of the variable V (the "dose") through a linear correlation with the logarithm of V:

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

In this work, the dose has been considered as the seismic PGA whereas the effect is considered either as the structural damage of the tank or, more appropriately, the loss of containment of the tank subjected to a earthquake. The variable Y can be directly compared with the actual failure probability P by means of the integral [Vilchez, 2001]:

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

Comparison of value of k_1 e k_2 gives direct and useful information on the gravity of the accidental events.

5 RESULTS AND DISCUSSION

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.

For base constrained and rigid tanks (anchored), a complete seismic analysis requires solution of Laplace's equation for the motion of the contained liquid. Solution of the latter equation has to be carried to obtain the total pressure history on the tank shell during earthquakes.

When flexible tanks are considered, a structural deformation term must be also added to keep into account 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 (2000) and provide methods to take into account of geometrical parameters of the tank and the earthquake zone classification factors.

Actually, when QRA of industrial installations have to be performed, the number of tanks and the complexity of the assessment of risk indexes does not allow the detailed analysis of interaction of all possible intensity of earthquakes with equipment.

Hence, in the light of simplification, statistical and empirical tools derived from post-earthquake damage analyses are needed, in order to define simple and general vulnerability functions. Here, it's also worth noting that the similarity of seismic behaviour of water tanks and oil tanks, both operating at atmospheric condition, is certain, thus consistently enlarging the historical data set.

An extraction of data set used for the historical analysis of fragility of atmospheric storage tanks subjected to earthquakes is reported in Table 1. Here, and in the following, no separation between anchored and unanchored tanks has been taken into consideration.

Several studies [O'Rourke, 2000; Eidinger 2001] in the last decades have defined "damage states" (DS) in order to describe the seismic behaviour of steel tanks, starting from slight damage to the structures (DS2), to moderate damage (DS3), and finally to extensive damage (DS4) and total collapse of structure (DS5). The term DS1 refers to the absence of damage.

The DS values correspond to the classical limit states definition related to the economical loss to repair and restore the tank structure. Table 2 and 3 report the damage analysis obtained using limit states, starting from the historical data set reported in Table 1, for the total number of tanks and for the tank whose filling level is greater than 50%, following the assumption that only highly filled tanks feel the effect of earthquake.

Table 1. An extraction of data set used for the assessment of vulnerability of atmospheric storage tank subjected to earthquakes.

PGA [g**] Range	No. Damaged Tanks	Event*
0.17	49	*Long Beach (1933)*
0.19	24	*Kern County (1952)*
0.20÷0.30	39	*Alaska (1964)*
0.30 ÷ 1.20	20	*San Fernando (1971)*
0.24 ÷ 0.49	24	*Imperial Valley (1979)*
0.23÷0.62	41	*Coalinga (1983)*
0.25÷0.5	12	*Morgan Hill (1984)*
0.1÷0.54	141	*Loma Prieta (1989)*
0.35	38	*Costa Rica (1992)*
0.1÷0.56	33	*Landers (1992)*
0.3÷1	70	*Northridge (1994)*
0.17÷0.56	41	*Others*

*data from [Cooper, 1997; Wald, 1998; Haroun, 1983, Ballantyne and Crouse, 1997; Brown, 1995; Eidinger et al. 2001]
** g is gravity acceleration, ms^{-1}

Indeed, structural analysis and empirical observation

confirm that only filling level of 50% seems to be effective to vulnerability.
Moreover, the choice of a filling level results useful when QRA on large storage area is performed and no detailed information on the average tank fill level can be obtained. Actually, in the mainframe of industrial risk assessment, the loss of hazardous substances from their system of containment is the main issue.

In fact, unless very catastrophic earthquakes are considered (often very rare and producing a complete destruction of the industrial installation), the loss of containment is a main consequence of earthquake-equipment interaction, thus providing the triggering for the escalation of the accident scenario.

Moreover, it should be considered that typical accidental scenario involve vapour cloud explosion (VCE), flash fire, pool fire or toxic dispersion; they all strongly depend on the total amount of substance [CCPS, 1994].

Table 2. Analysis of damage states for all the atmospheric tanks subjected to earthquake 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 damage states 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**

Table 4. Analysis of damage states in terms of loss of containment for the atmospheric tanks subjected to earthquake as reported in the historical data set of Table 1.

PGA [g]	**Fill level [>50%]**		**Fill level [0-100%]**	
	RS≥2	RS=3	RS≥2	RS=3
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

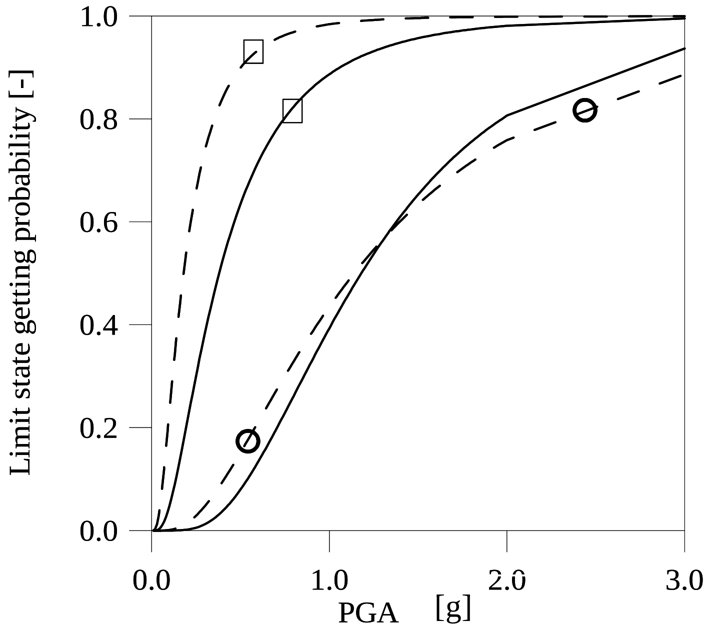

Figure 3. Experimental fragility curves for atmospheric steel tanks affected by earthquakes. Dotted line represents tank fill level > 50%. □: RS2; O: RS3.

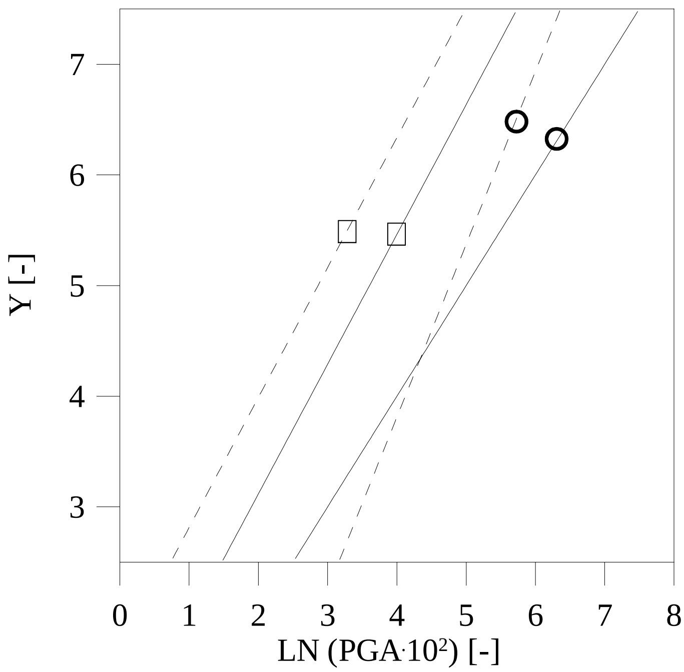

Figure 4. Probit analysis for steel tanks in seismic areas. Dotted line represents tank fill level >50%. □: RS2; O: RS3.

Table 5. Probit coefficient (Eq. 1) for atmospheric steel tank subjected to earthquake.

Risk State	**Fragility**		**Probit**	
	μ	**β**	$\mathbf{k_1}$	$\mathbf{k_2}$

RS ≥ 2	0.38	0.80	0.43	1.26
RS = 3	1.18	0.61	-2.83	1.64
RS ≥ 2 / fill level ≥ 50%	0.18	0.80	1.77	1.14
RS = 3 / fill level ≥ 50%	1.14	0.80	-0.92	1.25

Hence, in the following, the data set has been reorganized in terms of three classes of damage or "risk state" for the atmospheric tank considered as a whole, including tube connections for loading, valves and general equipment.

The first class corresponds to an earthquake which slightly affects the structure of the tank thus resulting in the total absence of loss of containment, although post-accident analysis should be performed.

This class has been identified as RS1. Next, a structural damage of the shell or of an auxiliary equipment which gives rise to a "slight loss of content" is defined as RS2. Finally, a consistent and rapid loss of content has been identified as RS3.

The latest class identifies the damage related to an earthquake which affects the tank integrity, giving rise to a catastrophic accident and total loss of containment. Table 4 reports the damage analysis in terms of loss of containment for the data set of atmospheric storage tanks subjected to the earthquake as reported in Table 1. Also, the same table reports the damage analysis when isolating tanks whose fill level is higher than 50%. Figure 3 reports the fragility curve (the probability of getting the considered limit state) as derived from Table 4.

The results are practically coincident with those obtained by former studies [Eidinger, 2001]. Again, the fragility curve for tanks with 50% fill level has been reported for convenience.

Through the relationship given in Eq.2 it's now possible to transform the fragility curve into a probit relationship with respect to PGA (Figure 4). Values of probit coefficient (see Eq. 1) as obtained from Figure 4 are reported in Table 5.

Here, it's clear the similarity of behaviour of tanks with fill level greater than at 50% with the complete probit function.

The obtained results should be used in conjunction with the evaluation of the accidental scenarios which can derive from the loss of containment itself. Of course, some assumptions are necessary in order to provide a risk assessment.

First, here only atmospheric storage tank are considered, thus flammable or toxic liquid flow into catch basins has to be analysed. Moreover, it is worth noting that ignition of fuel pool or flammable vapour cloud is very likely when seismic action is present.

In the case of low-intensity earthquakes, 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 to restore the plant normality within tens of minutes, at least for RS2 damages.

In this case, only toxic, flash fire (i.e. the fire of vapour cloud without the generation of destructive blast wave) and pool fire effects (in the close surrounding of tanks), should be considered, since vapour cloud explosions (a blast wave is produced in this case) need long term evaporation and fuel dispersion to give a potentially destructive homogenous flammable vapour cloud [CCPS, 1994].

Eventually, dispersion analysis has to be performed, either for the toxic dispersion or for the fuel air mixture within flammability limits (flash fire), and heat radiation effects on the structure and on the people has to be calculated, starting from the probability of occurrence of seism and from the probability of tank failure.

When RS3 damage occurs (and it's 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, vapour cloud explosion and toxic dispersion. To this regard, the probability of having flash fire or vapour cloud explosion is strongly dependent on the fuel reactivity and on the geometry either of the accidental vapour cloud or of the industrial installation (specifically on the geometrical confinement and degree of congestion).

Moreover, the effect of pool fire should be always added to the first two type of non-localised fires.

Description of the phenomena here reported are given elsewhere [Lees, 1996; Martin, 2000; Salzano, 2002].

Finally, the evaluation of domino effects should be always performed, particularly if pressurized tanks are in the nearby.

6 CONCLUSIONS

Risk assessment should always incorporate the probability of seismic occurrence, and its intensity, as a "top event", not only if industrial installation or areas lay on very seismic area but also when low intensity earthquakes are expected. Indeed, the loss of containment can trigger "domino effect" through several accidental scenarios which comprise explosion or fires.

In this work, a classification of damage state with respect to the peak ground acceleration (PGA), either in terms of structural effects, or in terms of simple loss of containment has been performed on the basis of a historical data set of atmospheric tanks.

Probit coefficient have been then statistically evaluated, in order to implement a seismic dose-effect relationship into algorithms, aiming at obtaining quantitative risk assessment.

Some indications on the risk assessment for different seismic-related scenario are given.

Further work should be addressed to the interaction of earthquake with other equipment, e.g. pressurized equipment, which often contain flammable or toxic substances and to the implementation of a fuzzy analysis starting from the results here reported.

7 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).

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