Seismic Risk Formulation of Atmospheric Steel Tanks in Oil Storage Systems

Giovanni Fabbrocino, Iunio Iervolino, Gaetano Manfredi

***Abstract* — Combustion of fossil fuels is one of three ways to produce electric power (steam; electrochemical; hydroelectric). Several environmental exposures, as hazardous waste, air pollution, flammable and combustible fluids are related to power facilities. Fuel storage areas are particularly vulnerable sub-systems of power and industrial plants determining *relevant industrial risk*. Recent catastrophic seismic events occurred in last years increased attention about risk related to seismic hazard. Due to recent Italian rules (follow up of European Community guidelines) oil storage systems have been classified as risk or relevant risk facilities. National industrial risk classification data analysis pointed out that many exposures are located in seismic areas that are, in addition, very populated. In the present paper some issues related to probabilistic approach to vulnerability assessment of atmospheric steel tank for oil storage are discussed. Procedures for risk assessment starting from concise vulnerability formulation and seismic hazard quantitative parameters are analyzed. Review of experimental and field data is reported and research needs are finally summarised.** [*]

***Index Terms* — Risk Analysis, Safety, Seismic factors.**

I. INTRODUCTION

Oil storage facilities are a very common system in power, industrial and transportation facilities (i.e. airports or seaports). Risk related to seismic hazard has been undersized for long time in many countries, and also in Italy, basically due to lack of sufficient knowledge.

Furthermore, areas exposed to earthquakes, even if represent a large part of Italian country, have been properly classified only recently. Catastrophic seismic events occurred in last years increased attention about risk related to seismic hazard. Industrial risk assessment requires development of reliable procedures, according to recent national codes.

The importance of the topic is also confirmed by the analysis of available data concerning site seismicity and location of critical industrial plants. In fact, latest territorial seismic classification by the National Seismic Survey [33] has been crossed with recent investigation concerning risk plants data by Italian Environmental Department [34]. It has been recognised that several facilities containing toxic or flammable substances are located in areas formerly considered as not exposed to earthquake action hazard, and therefore they have been designed without any consideration of lateral loads, or according to obsolete seismic codes.

Risk classification of facilities depends on the kind hazardous materials and their quantities stored or circulating. Therefore large flat-bottomed steel tanks for oil storage are an interesting component if environmental/seismic risk reduction is concerned. Recent structural engineering research studies aim to develop concise tools based on a probabilistic approach that express performance levels (in terms of limit state getting probability) against a macro-seismic intensity parameter as Peak Ground Acceleration or Spectral Acceleration [1]-[2]. This "fragility" formulation is suitable for several risk analysis purposes. From a structural point of view, convolution of vulnerability curves and a hazard curve provide a simple quantitative assessment of failure risk due to seismic actions and is also a key stepping in industrial risk assessment processes.

Fig. 1. Tupras refinery (Turkey) after 1999 Koaceli Earthquake. The refinery suffered over $100 million damages [36].

The full probabilistic risk evaluation approach requires definition of concise parameters able to identify a structural type and describe the typical structure or equipment.

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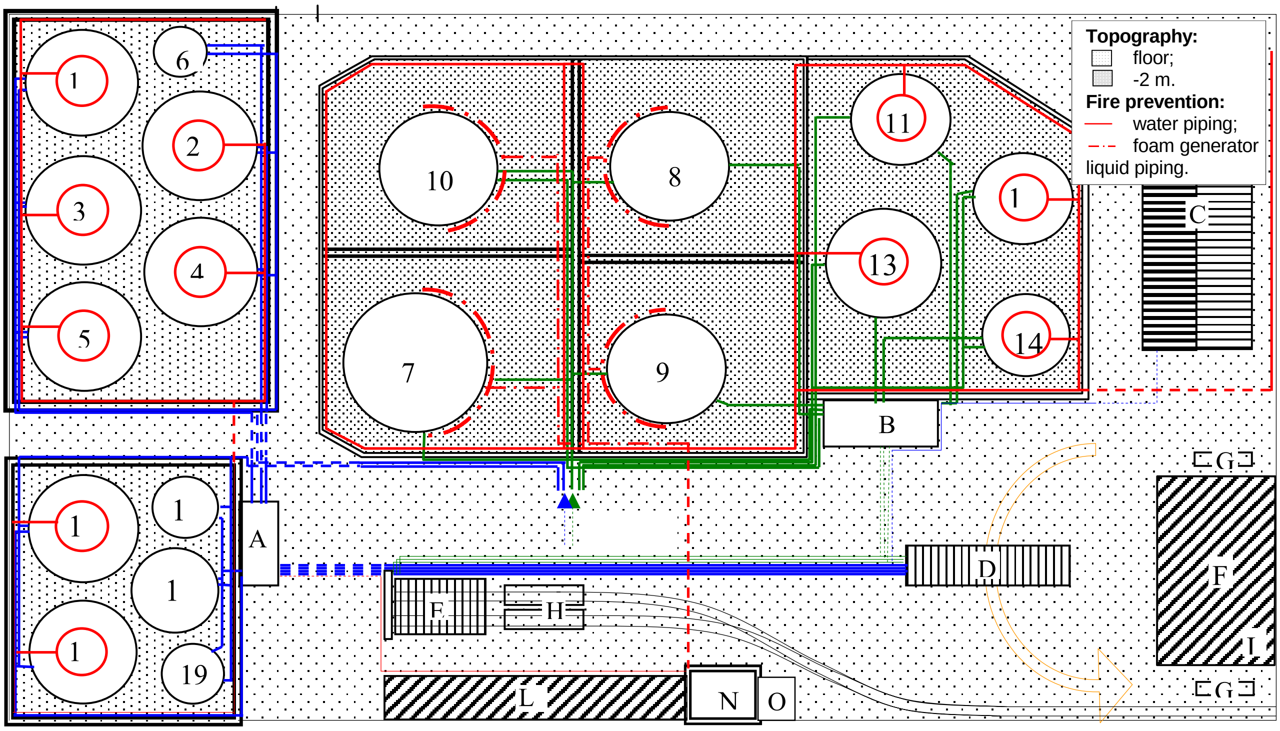
To optimize deterministic model, limit state functions related to seismic damage action have to be formulated [9]. Safe domain boundary expressions take account of structural uncertainties therefore can be statistically treated to get the failure probability. The analytical approach is quite new in structural vulnerability assessment and may not be trivial to perform. Alternative way is represented by traditional methods based on fitting experimental data about performance of components with the same construction features. Effectiveness of observational fragility formulation requires a large number of data that may be unavailable for all the component of the whole plant. Anyway existing curves [12] may be an effective reference to optimize and check the numerical analyses. Fragility of single element is the first step in system risk evaluation if interactions and correlation are already known [6].



Main Components
A Black liquids pumping system
B White liquids pumping system
C Drums warehouse
D Trucks filling
E Trucks filling
F Offices building
G Trucks weighting
H Trucks weighting

		Tanks		
N°	**Capacity (m^3)**	**Diameter (m)**	**Height (m)**	**Type**
1,2,3,4,5	4000	20	13	Fixed Roof
6	724	9.6	10	Fixed Roof
7	6785	24	15	Floating roof
8,9	4700	20	15	Floating roof
10	3817	18	15	Floating roof
11,12	2720	17	12	Fixed Roof
13	3770	20	12	Fixed Roof
14	2100	15.6	11	Fixed Roof
15,16	3053	18	12	Fixed Roof
17,18,19	1130	12	10	Fixed Roof

Fig. 2. Layout of a typical oil storage subsystem storing sufficient quantity of liquid to be considered as risk plant (courtesy by Dr. Salzano, CNR-IRC).

II. RISK OF OIL STORAGE SYSTEMS

One of main environmental hazards in all developed countries comes from industrial plants and the related risk of relevant accidents. Due to 1999 deregulation, U.S. electricity utility industry [19] environmental insurance has become grater then ever.

European situation is similar; in fact, European community has recently developed new safety guidelines. In Italy, many risk facilities are located in seismic areas often near to urban zones due to former policies of industrial development and unplanned extension of residential areas [18]. Accident induced by seismic action is shown in Fig.2. Recently Italian Environmental Department released guidelines for assessment of risks related to industrial plants. In 1999 decree 334 [32] provide the definitions of risk and relevant risk exposed plants considering quantities and type of treated materials and investigations to assess industrial risk on the national territory have been promoted.

Until October 2001 one thousand *industrial risk* plants and power systems have been registered in Italy, about 50% of them are considered as *relevant industrial risk plants* (see Fig. 3). It has been estimated that risk can involve the health of five millions of citizens and five thousand hundred can be direct victims [35].

Emergency level related to this situation is pointed out by further data concerning location of public buildings respect to industrial facilities; in fact on a total amount of seven thousand school buildings, 5% (233) are located within one kilometer far from a industrial facility and 1% (70) are far less then two hundred meters.

It is worth noting that all criteria to estimate risk level of an industrial facility are based on two critical parameters: the type of treated and/or stored material (inflammable, explosive, toxic) and the stored quantity within the area.

TABLE I
ITALIAN RISK PLANTS LOCATED IN SEISMIC AREAS

	#	%
Relevant Risk Plants	406	39
Risk Plants	688	61
Chemical/Petrochemical Risk Plants	280	27
TOTAL	**1024**	
Risk in Seismic Areas	198	62
Relevant Risk in Seismic Areas	119	38
TOTAL (SEISMIC)	**317**	
Plants in Seismic Cat. III	41	13
Plants in Seismic Cat. II	261	83
Plants in Seismic Cat. I	15	4

Risk assessment guidelines do not provide any provision to take account explicitly of structural performances, probably due to lack of information about real plants layout and structural detailing of components and systems [24]-[31], but require a quantitative analysis of total risk, giving only principles without addressing reliable and effective tools.

If large storage tanks are concerned, concurrent fire and pollution effects due to oil release in water or soil can induce damages, and even explosions can be generated. The review of seismic hazard data provided by Italian Seismic Survey and industrial risk plant catalogue by Italian Environmental Department points out that thirty percent of total number of dangerous facilities and eleven percent of relevant risk plants are located in seismic areas (see. Table 1). Oil storage facilities have to contain five thousands tons of liquid to be considered as "at risk" and 50.000 for "relevant risk".

Twenty seven percent on the total amount industrial risk plants are chemical or petrochemical facilities and the eighteen percent of them is located in seismic area.

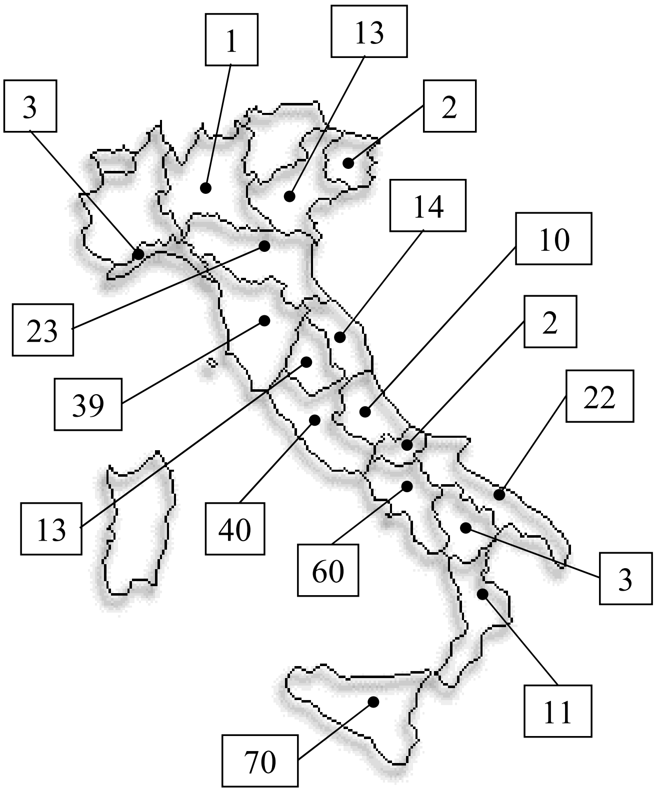


Fig. 3. Location of risk and relevant industrial risk plants in the Italian territory that is exposed to seismic hazard.

III. RISK ASSESSMENT

Due to classical definition probabilistic definition for a certain system

$$Risk = Hazard \bullet Vulnerability \tag{1}$$

The dot product represents the convolution of functions. Result, in statistical terms, is one minus system reliability. It is probability of structural survival during the reference time interval (the same as hazard).

$$Rel(T) = 1 - Risk(T) = 1 - P_f(T) \tag{2}$$

Traditional structural reliability methods define hazard and vulnerability in terms of *demand* and *capacity* respectively, that are the same performance index. In events *algebra* approach the failure can be expressed by the following

$$Risk = P_f(T) = P[\,failure \mid h\,]P[\,Hazard = h,T\,] \tag{3}$$

All terms are related to a macro-seismic parameter that is the most common way to represent hazard for a certain site and fragility curves for a structural kind. Therefore is possible to explore the relation between seismic hazard and fragility using a non-structural parameter (seismological).

A. Seismic hazard and structural vulnerability tools

The goal of probabilistic seismic hazard analysis is to quantify the probability of exceeding various ground-motion levels at a site given all possible earthquakes. Seismic hazard is a random seismic parameter; traditionally, peak ground acceleration (PGA) has been used to quantify ground motion in PSHA (it's used to define lateral forces and shear stresses in the equivalent-static-force procedures of some building codes, and in liquefaction analyses). Today the preferred parameter is Response Spectral Acceleration (SA), which gives the maximum acceleration experienced by a damped, single-degree-of-freedom oscillator (the simplest representation of building response).

$$Hazard(T) = P[PGA \geq a \mid T] \tag{4}$$

Therefore, a *hazard curve* can be plotted for each site. It gives the probability that a given PGA is exceeded during a reference time interval; the latter is generally related to the service life of the structure.

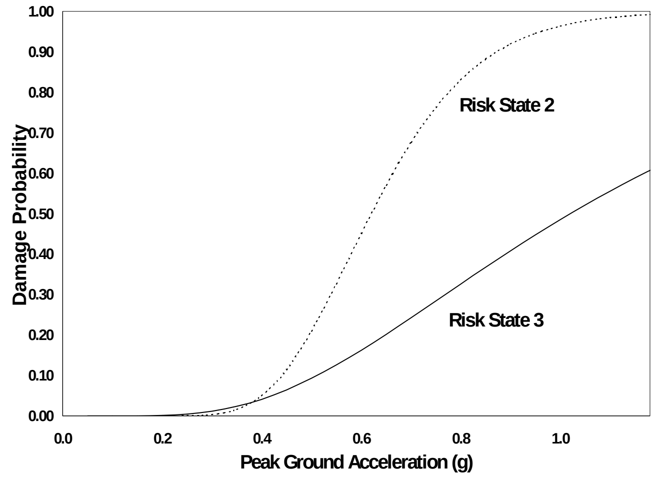


Fig. 4. Experimental fragility curves for moderate end large content loss.

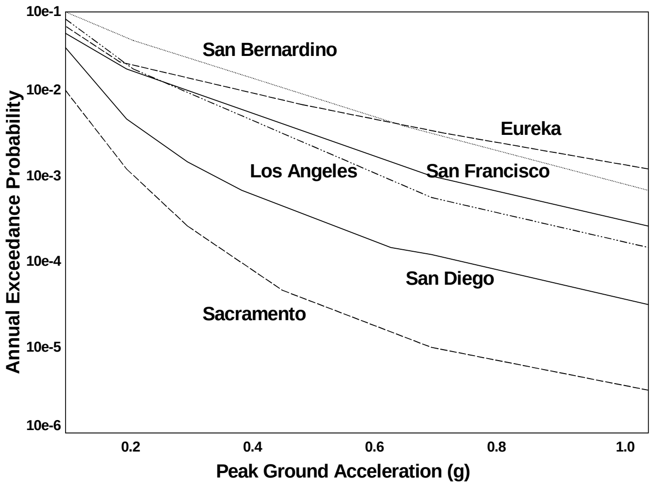


Fig. 5. Example of hazard curves in terms of annual exceedance probability of Peak Ground Acceleration.

Hazard (see Fig. 5) is provided by geophysics; it depends on distance to the expected source of ground motion. It can be considered as hexogen data in risk analysis.

Seismic vulnerability for each component of a structural, industrial or power system is the failure probability against the same seismic parameter as the hazard. In probabilistic terms

$$Vulnerability(a) = P[Failure \mid PGA = a] \tag{5}$$

Obviously "failure" is a conventional definition of a certain limit state reaching. Many methods have been developed to get seismic vulnerability both in analytical and experimental ways. A general purposes tool is fragility curve that provide the failure probability if the system experience a given earthquake intensity (see. Fig. 4). Each curve is related to one failure mode.

B. Risk evaluation procedure

Since the vulnerability is the probability that a given structural performance parameter is exceeded hazard and fragility curves are related to Cumulative Mass Functions of two random variables that are load (S) and resistance (R). Probability that the system remains in the safe domain during its life is the probability that the S never exceed R as discussed before.

$$Risk = P[S \geq R] = 1 - P[S < R] = \tag{6}$$

$$= \int_0^\infty \left[\int_0^s f_R(r)dr \right] f_S(s)ds = \tag{7}$$

Due to their randomness S and R are completely described by Probability Density Functions. This approach is well known by structural engineers as full probabilistic approach to design of structures.

Failure probability at first member of (6) is related to economical and social factors by politics. Since the S PDF is known as hexogen data, a particular R distribution is design process target.

From reliability point of view (typical of industrial engineering) the failure probability within the service life of the system is the target of de S and R process analysis. It's worth noting that the event corresponding to the structural failure is the intersection of the happening of the earthquake (S) and the contemporary failure of the structure (R). Therefore deriving hazard and fragility probability mass functions and convoluting (7) provide a simple risk evaluation procedure.

The discussed procedure has to be developed to get the risk about a single structural system or component. Industrial facilities can be affected by *domino effect* witch is the accident of a component induced by the failure of another element.

For instance a failure of an oil tank due to seismic action can start a fire; the flame can overheat the shell of a near tank (*jet fire*) that can explode also if sustained no damage from earthquake if safety distances between tanks is not properly designed.

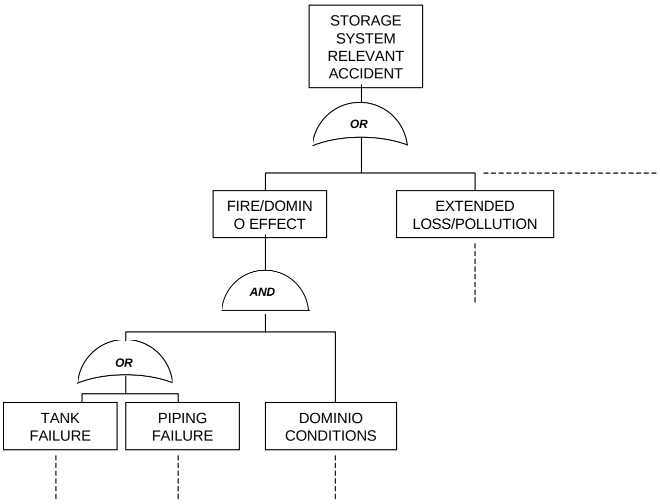


Fig. 6. Fault Tree possible scheme for oil storage systems analysis.

Domino effect and interaction of elements have to be taken into account in industrial risk analyses, as guidelines suggest. This task requires complex system reliability analyses as FMECA/FMEA or Fault Tree Analysis (Fig. 6) that are based on the *logic relations* [6] between single elements and their failure modes.

IV. Steel Tanks for Oil Storage

An oil storage facility is considered at risk if it contains more than fifty thousands liters of fuel. In Fig. 3, a typical storage system is described; it's clear that the most important components on a risk point of view are tanks.

In post seismic losses analysis, industrial engineers are interested about type and extension of damage, its impact on the serviceability and the loss in terms of system stop time or amount of money to repair [12], [14], [15], [16].

Field experiences show that "relevant accidents" are related to content spillage or loosing. Thus, any curve has to account of a different limit state, and in particular:

- Uplifting if there are dragging pipes attached to the bottom plate;
- Sliding of unanchored tanks that can provoke inlet/outlet pipes breakage if attached to the shell;
- Elephant foot buckling with or without contemporary welding failure on the opposite side.

Due to the similarity of water and oil storage tanks, designed with same standards, many seimic damage data have been collected in the past century for this type of structure. Many different *Damage States* have been defined by former studies about seismic behavior of steel tanks (Fig. 6). They correspond to classical limit states definition related to the economical loss to repair and restore

- No damage
- Slight damage
- Moderate damage
- Extensive damage
- Collapse

Economic loss to repair the tank is a proper parameters for water system tanks (that are the same in design and fabrication standards) but does not apply to risk facilities [14]-[18].

Following the previous discussion, damage states should be defined in terms of accident inducing capability than the proposal is of three damage states for experimental performance report database reclassification:

- No damage
- Slight content loss
- Consistent content loss

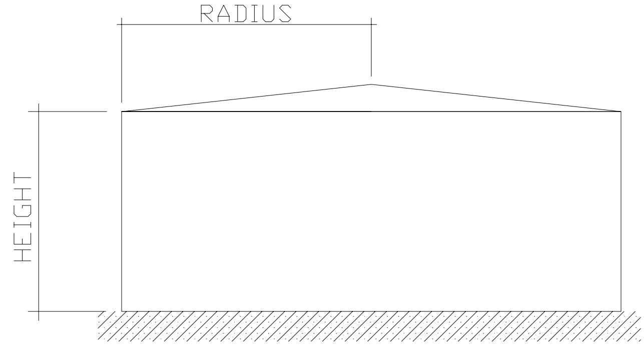


Fig. 7. Scheme of typical large on-grade flat bottomed steel tank for oil storage.

Several formulation of seismic damage different fragility curves can be obtained from the same data set [13]. In the following table the Cooper 1997 database has been revised. Only tanks that have the fragility meaningful parameters (exciting PGA, H/D ratio, filling percentage) have been considered.

Although damage description for each considered tank has been revised, result of Damage State re-classification is a combination of the former. DS2 and DS3 data (see Table II) became RS2 and DS3 and DS4 became RS3 where RS stay for "Risk State" according to the definition that a damage state is meaningful due its correlation to relevant incident risk. Results of reclassification are summarised in Table III.

TABLE II
Fragility Data Set from [13].

PGA (g) intervals	*ALL*	*DS≥1*	*DS≥2*	*DS≥3*	*DS≥4*	*DS=5*
ALL	528	327	41	47	25	16
]0,1-0,17]	263	196	42	13	8	4
]0,17-0,27]	62	31	17	10	4	2
]0,27-0,37]	53	22	19	8	3	1
]0,37-0,48]	47	32	11	3	1	2
]0,48-0,57]	53	26	15	7	3	2
]0,57-0,66]	25	3	5	5	3	3
]0,66-0,86]	14	10	1	1	3	0
]0,86-1,18]	10	1	0	0	0	6

TABLE III
Data set re-organized for risk analysis pourposes.

PGA (g) intervals	*ALL*	*RS≥2*	*RS=3*
ALL	240	183	57
]0,1-0,17]	65	55	10
]0,17-0,27]	57	42	15
]0,27-0,37]	29	24	5
]0,37-0,48]	11	9	2
]0,48-0,57]	24	19	5
]0,57-0,66]	26	18	8
]0,66-0,86]	10	5	5
]0,86-1,18]	5	3	2
>1,18	13	8	5

The most common random model assumed to define a demand/capacity quantity in structural problems is the lognormal that are a transformation of the Gaussian model to eliminate negative mean less values. This is probably due to the general applicability of the Gaussian model to describe many natural phenomena and the ignorance of engineers about the probabilistic modelling of the structure in the subject. It is worth noting that the normal (or lognormal) distribution is applicable by definitions to phenomena ruled to a very large number of random effects each with a negligible influence. In tanks random relevant parameters are limited in number as already discussed. This is why a stronger probabilistic characterization of failure probability has to be investigated.

To fit fragility curves in these data a PDF of the PGA to reach a certain Risk state have been defined. Starting from data in table III observational failure probabilities have been estimated, then median and dispersion values have been calculated for each of two limit states listed above. Therefore fragility can be resumed in the following table

TABLE IV
OBSERVATIONAL RISK ANALYSIS FRAGILITY.

Risk State	*Median (μ)*	*Dispersion (β)*
RS≥2	0.62	0.27
RS=3	1.02	0.52

$$P(RS \mid PGA) = \Phi\left[\frac{1}{\beta}\ln\left(\frac{PGA}{\mu}\right)\right]$$

Re-building of experimental fragility provide the positive effects that is the reduction of the betas of observed probabilities against the fitting curve. This is due to the aggregation of a more homogenous damage data into a smaller number of limit states.

V. ANALYTICAL FRAGILITY FORMULATION

Experimental fragility is suitable in loss and repair costs expenditure estimation of wide areas affected by damage of large number facilities. Their availability is strongly limited by requirement of a large number of homogeneous data; otherwise large scatter results. Simplest analytical fragility formulation consists in code-based stress/displacements calculations carrying in statistical safety factors.

Sufficient code formulations is not available for all failure modes described before due the light calculation way adopted by industrial facilities design guidelines [7], [10], [27]-[29]. Alternative way is a full probabilistic analysis of structural *demand* (hazard) and *capacity* (vulnerability). This approach requires several optimized model for each damage state considered. A probabilistic treatment of results of deterministic analyses has to be performed followed by uncertainties analyses.

Analytic fragility formulation must be able to include a different deterministic simulation engine for each focused mechanism. To better investigate influence of factors on structural response, separation of materials randomness is needed, then a response surface may be useful after capacity simulation method.

Considering tanks, for instance, uplifting failure and elephant foot buckling conditions are both related to the overturning moment by the compressive stress in the shell [3]-[5], [7]. A simple deterministic model may be useful to investigate dynamic behavior [5]. Obtain the same failure expression for others damage mechanisms may be more complex. Circumferential welding strength and coupling limit displacement function have to be modeled to get a complete seismic fragility analysis.

VI. FINAL REMARKS

Risk of industrial plants has been undersized for long time. Risk assessment methods by structural engineering treat system component experimental vulnerability data in terms of serviceability and bare elements repair costs. This is why oil storage system are similar (in a structural point of view) to water systems that are not exposed to relevant accident risk.

Damage States taken from ACI and HAZUS seems to be not useful for relevant risk analyses. Failure modes and effects based damage states have to be defined.

Risk analyses, by *probit methods* have to predict health and environmental effects of failure of storage and productive system of toxic and polluting substances (*Area Risk*) [8]. To this purposes general and reliable structural fragility tools are needed. Available number if experimental data about seismic performance of industrial facilities (i.e. for tanks) is not sufficient to build-up fragility curves for each component type. Analytical way in vulnerability is the only remaining option. Many methods have been developed to analyze seismic structural *demand* and *capacity* for structures. Assuming as hazard description the probability exceedance of seismic parameter vulnerability has been defined as the probability of failure given the same parameter.

Vulnerability of structures can be obtained by a probabilistic treatment of data from deterministic dynamic modeling of the system. This procedure requires a strong mathematical formulation of failure modes in terms of limit state functions. Code-basing fragility curves can be helpful for this purposes but code formulas have to be cleaned by default safety factors they already and they are not available for all observed failure mechanisms.

This is why each failure mode has to be investigated and modeled in terms of structural quantities [20]-[22]. Experimental data fragility curves are a reference to optimize future numerical analyses. Observing post-earthquake damages to tanks show the influence of few parameters on seismic performance of tanks (H/D ratio; Filling percentage; anchoring/foundation type).

To speed up the process and improve the usefulness of results is suggested to consider producing only two groups of curves about anchored and unanchored tanks. In each group at least two/three curves have to be analyzed for different H/D ratios (i.e. $H/D\leq1$; $1<H/D<2$; $HD\geq2$). Only filling level $\geq50\%$ seems to be effective to vulnerability. For tanks with lightweight roof maybe filling level and H/D parameters can be fused into one that is H_{filled}/D ratio. Comparison of fragility obtained in this and in the previous way can test the applicability of this simplification. If applicable, this new factor allow to reduce the number of parameters involved in tanks vulnerability problem improving usefulness of developed curves.

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