Structural issues in seismic risk assessment of existing oil storage tanks

G. Fabbrocino, I. Iervolino, G. Manfredi
Department of Structural Analysis and Design
University of Naples Federico II

Abstract

Large regions in many countries are exposed to earthquakes, thus seismic risk evaluation is a relevant issue and requires specific knowledge development and integration between different skills. Failure of critical constructions can have direct and indirect influence on public safety; in fact, pollution or damages due to explosions can be related to collapse of industrial facilities.
In the present paper, after a review of available data concerning industrial plants in Italy with specific reference to their exposure to earthquake actions, the main aspects related to structural design and seismic evaluation of existing facilities for oil storage are discussed and the main features of probabilistic procedures able to give fragility curves of structures and components to be used in seismic risk assessment are outlined.

1 Introduction

Italian large industrial facilities are often located in seismic areas. In particular, many existing plants consist of large steel tanks with short relative distance and piping systems for oil distribution. Seismic performance assessment of such layouts is critical, thus traditional force-stress approaches are generally unsatisfactory and probability based procedures have to be used. The latter are aimed to establish reliable correlations between dynamic behaviour and failure probability of each structural element due to their logical and physical connections with quantitative methods as Failure Modes and Effect Analysis

(FMEA/FMECA) [1].
Failure probability in seismic reliability analysis is related to earthquake intensity and nature and is evaluated depending on the set of main parameters; in particular, the cumulative function of the probabilistic distribution is commonly called fragility curve. Fragility takes into account many different epistemological uncertainties about materials constraints and dynamic behaviour.
In last years different full probabilistic approach have been developed to get fragility taking into account randomness of both *demand* and *capacity* for structures in time-dependent cases. Any procedure needs a dynamic model optimisation and a reliable analytical formulation of failure modes to fit the study aims. Fragility curves are a very powerful tool for risk assessment since they are take account of typical structural arrangements and can represent a very high number of existing facilities. Petrochemical facilities observations show a consolidated fabrication standard for oil storage tanks worldwide, resulting in a standardised dynamic behaviour. In the following seismic/industrial Italian situation is analysed considering oil storage facilities and procedures for steel tanks seismic limit states definition and vulnerability assessment are proposed.

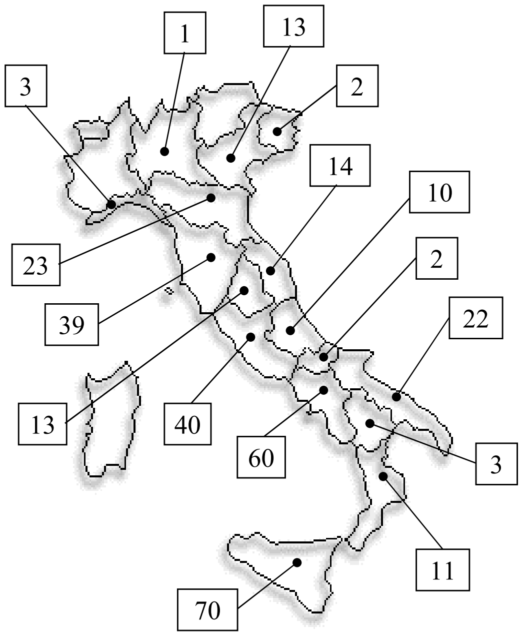
2 Existing petrochemical facilities in seismic areas

One of main environmental hazards for Italian national country comes from industrial plants and the related risk of relevant incidents. Many industrial facilities in Italy are located in seismic areas often near to urban zones due to former policies of industrial development and increase of population with the consequent unplanned extension of residential areas. From a structural viewpoint, many plants have been designed without suitable seismic rules because building location have been classified as seismic zones only in last few years. Recently Italian Environmental Department have been released guidelines for assessment of risks related to industrial plants.
In 1999 decree 334 provided 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 were registered in Italy, about 50% of them are considered as *relevant industrial risk plants*. It has been estimated that risk can involve the health of five millions of citizens and five thousand hundred can be direct victims [2]. 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 kilometre 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 stored material (inflammable, explosive, toxic) and the stored quantity within the area [3]. Risk assessment guidelines do not provide any provision to take account explicitly of structure performances, probably due to lack of information about real plants layout and structural detailing of

components and systems. If large storage tanks are concerned, damages can be induced by concurrent fire and pollution effects due to oil release in water or soil, and even explosions can be generated. The review of seismic hazard data provided by Italian national 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 per cent of them is located in seismic area.

Table 1. Seismic risk exposed plants.

	#	%
Relevant Risk Plants	406	39
Risk Plants	688	61
Chem/Petroch. 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



3 Fabrication standards of welded steel tanks for oil storage

Storage petrochemical facilities consist of atmospheric storage steel tanks. These structures can be very large even one hundred meters in diameters and twenty meters height. They are simple structures similar to tanks for water storage not only due to geometry, but also for initial performance checks that are carried out using water as tank filling. Starting from 30's same types of steel tanks were fabricated as riveted, welded or bolted (especially for low values of height over radius ratio), conversely in the last decades they were basically welded worldwide. According to consolidated design and construction standards [4÷8]

these types of tanks exhibit strong structural similarities.
Base plate is generally flat or conical shaped, its minimum thickness is six millimetres and it includes dragging pipes connections. Shell consist of different steel courses approximately one meters and a half tall, their thickness is height decreasing 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 made of a floating panel for vapour control, Figure 1. Main difference between roofs is supporting type, in fact they can be self or columns supported in case of large diameters. International guidelines in shell design provide minimum roof plate thickness and geometrical calculation (i.e. cone inclination depending from tank's diameter). Tanks can be *anchored* or *unanchored*; 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 is seismic areas but their effectiveness needs more investigations.

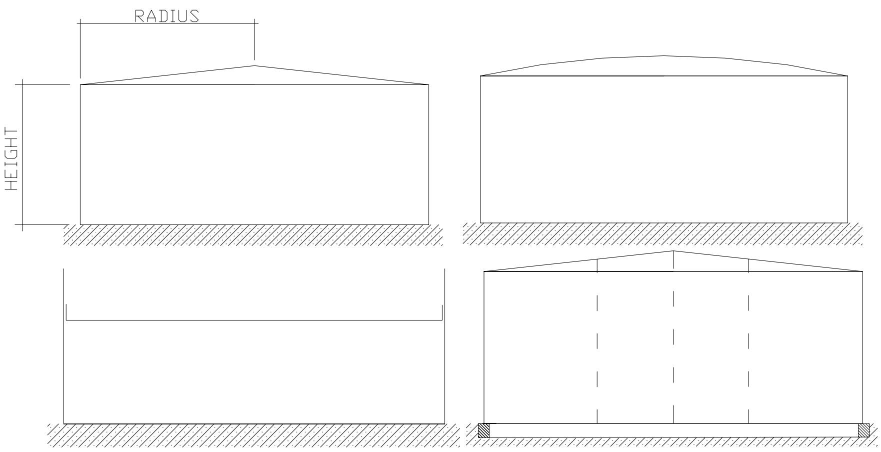


Figure 1: (a-c) different self-supporting roof types; (d) large tank with columns-supported roof and founded on reinforced concrete ring.

A key issue in steel tanks design is welding, this is why welds are a weak point for structural systems is many conditions, in fact they are sensitive to corrosion and can lead to content loss and often experienced wide cracks during earthquake events in particular in the shell/roof and shell/base plate joint zones.
Another critical aspect that can strongly influence the seismic behaviour of tanks is the type of foundation. Seismic damages observation analysis [9÷11] pointed out the effects of foundation on collapse mechanisms and strength performances of the structure; in fact assuming the same filling level and nominal dimensions, gravel rested tanks are subjected to uplifting and/or sliding motion, but if higher

displacement capacity can avoid elephant foot buckling, tear of pipes connection can be activated in case of strong motions triggering domino effect. As a consequence, anchored tanks seems to be more reliable since detaching of painting on anchoring bolts in case of seismic actions clearly show the structural response type and can give direct contributions to modelling of the structure. However, more investigations are needed on the subject due to the beneficial increase of system deformation given by uplifting motions.

4 Observed seismic damages to steel tanks

Dynamic behaviour of tanks is characterised by two predominant vibrating modes: one is related to the mass that rigidly moves with the tank (*impulsive*), the other one correspond to the liquid's sloshing (*convective*). Liquid sloshing during earthquake action provokes several damages and is the main cause of collapse in high filling level tanks. As recorded by many international studies since 1933 earthquakes can induce damages to petrochemical production and storage facilities with sub sequential fires and explosions or environmental pollution.

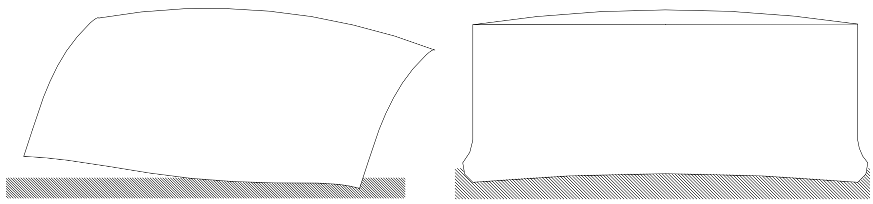


Figure 2: unanchored tank subjected to uplifting and "elephant foot" buckling.

Due to their similarity and with on grade water steel tanks, during the last century it was possible to collect significant numbers of data about seismic behaviour and damages related to seismic events in U.S.A. (California, Alaska) and Japan. One of main outcomes of these observations is that the main parameters ruling dynamic behaviour of tanks are height over radius ratio and filling level. Only full or nearly full tanks experienced failure. Low H/r ratios tank suffered cracks in conical roof connection or damage on floating panel sinking. Most common shell's damage is elephant foot buckling and its probability increase with H/r increasing.
If base plate can uplift (unanchored tanks with H/r<0.8) elephant foot is not experienced but base plate/shell connection can fail causing spillage or content complete loss (see fig.2). For unanchored tank another limit state is the shell and plate connection failure due to their direct attachment and lack of flexibility. It is worth noting that anchoring tanks seems to be a good seismic provisions for tank also avoid piping connections detaching and to eliminate uplifting risk, but unanchored tank increase their oscillating period reducing seismic action power, therefore trade off balance have to be found.

5 Structural Models for seismic analysis and design

Due to similarity between steel tanks for oil and storage, main international standards considered by engineers in design are provided by American Petroleum Institute and American Water Works Association. As discussed before, static loads design guidelines provided by API and AWWA use simplified design methods. Only since the 1994 Alaska earthquake structural engineers started to consider seismic design of tanks, therefore guidelines are less detailed in seismic design than in static loads design.
Both AWWA D100-D103 and API Standard 620-650 refers to same background studies for seismic analysis and design of steel tanks [12-13]. The procedures filter all theory background and do not prescribe any dynamic analysis and evaluate effects of seismic actions only in terms of overturning moment and total base shear. The pivot parameter is the longitudinal stress in the shell without taking into account any other possible failure mode.
In last few years Eurocode 8 referring to these standards and more advanced studies [14] developed the more comprehensive and integrated guidelines to chemical facilities design. A full stress analysis is certainly the more accurate way to design and/or assess steel tanks under seismic loads.
This approach leads to the direct computation of the interaction between sheel deformations and content motion during earthquakes. Tank seismic global behaviour is different if anchored tanks or unanchored tanks are concerned.
For base constrained tanks a complete seismic analysis requires solution of Laplace's equation for motion of contained liquid. Solution of the latter equation has to be carried to obtain the pressure on the tank's shell. In rigid tanks liquid motion is made of two contributions "impulsive" and "convective", for flexible tank a "deformative" term have to be added. These three terms can be treated separately due to weak interactions. Total pressure's time history is summation of three time histories. Maximum pressure terms has to be found (i.e. using response spectra), thus the main resulting complexity is related to the unknown combination of each maximum term in equation (1) for base shear.

$$Q(t) = m_i A_g(t) + \sum_{n=1}^{\infty} m_{cn} A_n(t) + m_f A_f(t) \tag{1}$$

$$Q(t) = m_i (A_f(t) + A_g(t)) + \sum_{n=1}^{\infty} m_{cn} A_n(t) \tag{2}$$

$$Q(t) = (m_i - m_f) A_g(t) + \sum_{n=1}^{\infty} m_{cn} A_n(t) + m_f A_{fa}(t) \tag{3}$$

Alternative ways to solve this problem have been proposed. Veletsos et al. (2) have upper bounded pressure considering impulsive mass acceleration due to deformative tank amplified response [12-13]. Housner et al. (3) manipulated equation to use easy to reach accelerations by spectra. Malhotra [15] using multisingle degrees of freedom system corresponding to impulsive and convective masse suggested a simplified approach. This method quickly provides the base shear and overturning moment depending from H/r ratio (see fig.3).

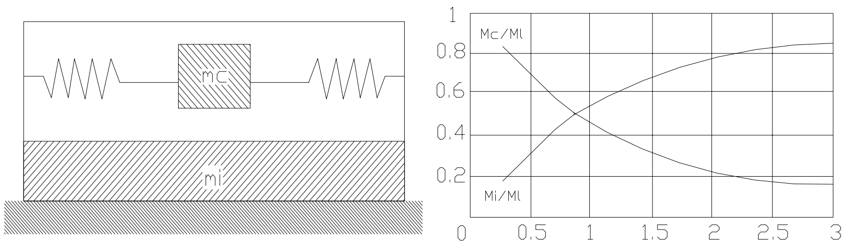


Figure 3: Dynamic model of steel tanks for oil storage.

Unanchored tanks are subjected to uplifting but also to sliding. Uplifting can crack base plate connection but adds flexibility to the system, this is why design procedure consider the tank as anchored on the safety side. Before publication of Eurocode 8 American Water Works Association was the reference guidelines for seismic design. AWWA D-100 and API 650 focussed their attention on base shear and overturning moment after Malhotra [15] and provided methods to take account of geometrical parameters of the tank and the seismic zone classification factors

$$M = Z(C_1 W_S X_S + C_1 W_r H_t + C_1 W_1 X_1 + C_2 W_2 X_2) \tag{4}$$

In equation (4) Z is the seismic factor (ground acceleration), C_i are determined as vibrating period functions, W_i and X_i represent the masses and the positions of centres of gravity for shell (W_s; X_s), roof (W_r; H_t), impulsive mass (W_1; X_1) and convective mass (W_2; X_2) depending from H/r ratio.
Established the expected overturning moment and base shear for unanchored tanks seismic resistant mechanisms consist of a “resistant annulus” that is a shell reinforcement at the bottom course. AWWA guidelines provide simplified formulas to calculate maximum shell’s longitudinal compression, to avoid elephant foot buckling and determine uplifting condition. Annular reinforcement is recommended when maximum longitudinal stress is greater than the “seismic allowable compression stress” that is simply 1,333 times the material’s allowable stress for unanchored tanks and is the same plus 1,333 times the “critical stress increase” for avoid buckling depending form young modulus and radius.

6 Risk assessment and fragility curves

According to the classical approach, risk is given by product of two terms: *hazard* depending on hexogen environmental variables and *vulnerability* depending on system related factors. This general definition is specialized for seismic risk considering specific tools for hazard and vulnerability assessment.

Evaluation of structural vulnerability results in the definition of the system failure probability according to selected limit state functions and hazard parameters. A full probabilistic approach in vulnerability assessment can be oriented to two different objectives:

- definition of the *fragility of structure*, that if of the probability of failure for a given seismic intensity (5)

$$fragility = P[f \mid a] \tag{5}$$

- evaluation of the *total risk* (6) that is the probability of exceeding a certain structural demand in a given period of time for the probability of random capacity threshold, integrated over all possible values [18]

$$totalrisk = \int_0^\infty [1 - F_D(a)] f(a) da \tag{6}$$

Fragility is useful in vulnerability assessment problems for existing structures due to its definition, conversely total risk evaluation is recommended by many guidelines for design of new structures due to its relation with the hazard of the construction site. Seismic reliability analysis results are often expressed by fragility curves. Fragility can take account of all possible epistemological uncertainties about a type of structure (i.e. materials, constraints, etc.).

Many methods have been developed to get fragility for seismic problems in last years, most easy to manage are based on observational data fitting [16-17], but do not allow to investigate deeply seismic behaviour of steel tanks as a dynamic based analyses can do. Any full probabilistic seismic analysis method requires an effective dynamic model that enables to monitor all displacement and stress parameters related to the selected limit state function. The latter contain the random variables related to the uncertainties present in the analysed phenomena describing the bound between the safe and failure domains in the space of chosen random variables.

In steel tanks dynamic analysis the considered failure conditions are not yet completely defined. A possible approach to evaluation of failure parameters and consequent limit state function can be based on the available data concerning major damages during earthquake. Shell worst damages correspond to elephant foot buckling and base plate/shell joints welds failure. Elephant foot is dependent on shell longitudinal compression stress that can be compared with material yielding stress as guidelines suggests. Unanchored tanks that experience uplifting often were subjected to detachment of rigid piping connection so the absolute shell's displacement and base plate rotation constitute another limit state. Due to the number and the different nature of the mentioned failure mechanisms, the structural model choice seems to be critical. According to these failure modes a suitable dynamic model can be a 3D generalisation of the multi SDOF proposed by Malhotra and previously discussed. This model considers a F.E. 3D model of tanks including shell, roof and base plate (see fig.4). The simulation of content sloshing is done using the convective mass (point condensate) that is connected to the shell by radial springs with a specific stiffness related to the convective sloshing period determined by the SDOF analysis. All the parameters of the model as masses position and ratios depend only on the H/r ratio and filling level.

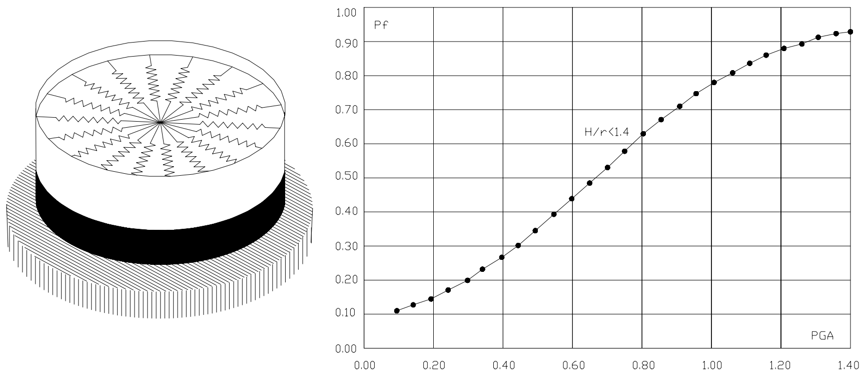


Figure 4: 3D dynamic model and empirical fragility for steel tanks.

Final remarks

Industrial risk is a very dangerous aspect of earthquakes; failure of critical constructions can have relevant influence on public safety especially in high populated regions like Italy. A large number of risk plants consists of steel tanks for oil storage and is located in seismic areas. Design and construction of existing storage facilities are generally based on long-established US standards used worldwide that take into account seismic actions only in terms of global forces. On the other hand, vulnerability assessment of tanks requires a reliability analysis resulting in failure probability related to seismic hazard. To this end optimised structural models are needed to match requirements for physical relevance of calculations and definition of limit state functions including uncertainties about materials and systems.

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