Seismic vulnerability analysis of storage tanks for oil and gas industry

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OIL AND GAS TRANSPORTATION LINE components are particularly vulnerable to natural hazard events. Steel tanks are recognized as the most vulnerable equipment to seismic action, whose damage may result in the release of materials and thus the increase of overall damage to nearby areas. The seismic vulnerability of tanks is commonly expressed by fragility curves, which are conditional probability statements of potential levels of damage over a range of earthquake intensities. This paper aims to present an appropriate procedure for analytically deriving fragility curves of tanks with the treatment of uncertainties. At first, the analysis of critical damage states of steel storage tanks observed during past earthquakes is presented. Possible numerical models of tanks subjected to earthquakes are then discussed. An overview of seismic fragility methodologies for tanks is next presented. Attention is paid to an analytical method, i.e. cloud method, which is conducted by using a probabilistic seismic demand model and non-linear time-history analyses. A broad tank, which is located in a refinery in Italy, is considered for the fragility evaluation. Resulting fragility curves for critical damage states of the tank, such as the plastic rotation of the shell-to-bottom plate joint, the buckling of the bottom shell course, and the material yielding of the shell plate, show a high seismic vulnerability of the tank.

Keywords: steel storage tank, damage identification, seismic vulnerability analysis, numerical model

Introduction

Oil and gas transportation lines components can be considered particularly vulnerable to natural-hazard events, in particular earthquakes. Due to the interaction between the natural events and the industrial risk, several effects take place in the plant, and in particular the storage site, causing damage to pipelines and equipment like storage tanks, and consequently, the release of hazardous materials. Since a large amount of flammable materials is often handled by storage equipment, e.g., piping, vessels, and tanks, the consequences of failures can affect wide surrounding areas.

There are different types of natural event triggering industrial accidents, e.g., landslides, hurricanes, high winds, tsunamis, floods, earthquakes, etc. Several industrial accidents occurring in the last decades demonstrated that earthquakes might cause severe damage to storage equipment items, resulting in losses of contents, and in multiple and extended releases of hazardous substances.

Earthquake damage in recent decades (e.g. 1995 Hyogoken-Nanbu Japan, 1999 İzmit Turkey, 2003 Tokachi-oki Japan, 2008 Wenchuan China, 2011 Great East Japan, 2012 Emilia Italy, etc.) has revealed that storage tanks are one of the most vulnerable components in industrial plants. Damage to tanks can cause significant disruption to the facility operation. Seriously, the extensive seismic-induced uncontrolled fires, when flammable materials or hazardous chemicals leak, naturally increase the overall damage to nearby areas.

Prediction and prevention of possible accidental scenarios depends upon

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Fig.1. Typical tanks in an oil and gas industrial storage facilities (l-r): (a) broad tank, (b) slender tank, and (c) spherical LNG tank.

the reliability of available tools for the structural design and assessment. Unfortunately, despite the continuous evolution of the knowledge on this matter, there is a lack of standard and established procedures to evaluate the effects of the seismic action on equipment. An emerging tool, i.e. seismic fragility curves, provides valuable support for seismic risk assessment of equipment used in industrial installations. These curves are conditional probability statements of potential levels of damage over a range of earthquake intensities and can be used as initial fragility-based damage scenarios in the seismic risk assessment procedure [1]. The availability of reliable fragility curves would allow for assessment of the effects of various failure conditions, which are associated with the loss of contents, on the performance of equipment. Such curves are essential tools for decision-support frameworks such as performance-based and cost-benefit analyses.

This paper aims to provide an enhanced understanding of the impact of natural disasters, especially earthquakes, on the performance of steel storage tanks in oil and gas industry. A primary objective is to introduce a reliable procedure for vulnerability assessment of steel storage tanks in seismic-prone areas. This procedure is then applied to a case study of the oil storage tank. The vulnerability of the tank is represented by resulting fragility curves for different damage states.

Seismic damage to storage tanks in the oil and gas industry

The storage of material received form oil and gas transportation lines can be considered a particularly critical facility in seismic-prone areas, because cylindrical steel storage tanks, usually adopted to storage raw and refined material, have been recognized as highly vulnerable components. They are characterized by aspect ratios ranging between 0.2 and 2, as shown in Figs 1a and 1b. The roof can be welded to the shell (i.e. a fixed conic roof) or floating over the contained liquid. The operating volume varies from some tens to 200,000 m^3. The typical damage states associated to these structures are related to buckling phenomena of the wall such as elephant's foot buckling or elastic-plastic buckling (Fig.2) and diamond-shaped buckling or elastic buckling (Fig.3).

Another damage to tanks is related to excessive sloshing motion, especially in the presence of floating roofs, which can cause liquid overtopping and fire due to the crash between the roof itself and the wall. For example, during the 1999 Izmit and 2003 Tokachi-Oki earthquakes, most of the tanks were destroyed due to the

Fig.2. Shell elephant's foot buckling or elastic-plastic bucking.

Fig.3. Shell diamond-shaped buckling or elastic buckling.

Fig.4. Floating-roof damage.

Fig.5. Detachment of the pipe due to sliding and shell buckling.

excessive sloshing motion (Fig.4). Damage involving the rupture of the pipes attached to the tank is also rather common. This is due to the excessive relative displacement between the pipe and the tank wall, which is caused by the uplift, sliding, or shell buckling (Fig.5).

Another important category of tanks for the oil and gas industry is represented by spherical storage vessels, which are essentially used to store pressure-liquefied gases. They are generally elevated with respect to the ground, using steel columns placed along the circumference and welded to the shell at the equatorial level and normally linked each other by diagonal braces, as shown in Fig.1c. Vertical large storage vessels for cryogenic liquefied gases are also common in gas industry; their configuration is similar to that of the large atmospheric storage vessels for liquids, but their walls are formed of a double shell, in the inner-space of which an efficient thermal insulation is located, and their bases are anchored to a concrete plates, supported by short reinforced concrete columns. This equipment is used to heat or vapourize large amounts of liquid products. For these tanks, collapse is mainly due to the soft-story phenomenon caused by the shear failure of the columns [2].

The above framework offers an easy guideline to individuate the typical seismic damage conditions in storage tanks for oil and gas industry. This is particularly useful to identify the criticality concerning the loss of containment (LOC) and damage propagation effects. It is important to note that the occurrence of these damage states can result in LOC events with different degrees of severity. This is necessary in order to perform a reliable quantification of the risk of storage plants in seismic prone areas [1].

Main issues in seismic vulnerability analysis of storage tanks

Seismic vulnerability of structures and equipment is traditionally expressed in the form of fragility curves. A lognormal cumulative distribution function is often used to define a fragility function:

$$P\left[D_{EDP} > LS \middle| IM\right] = \Phi\left\{\frac{\ln\left(IM/\mu\right)}{\beta}\right\} \qquad (1)$$

where:

$P[D_{EDP} > LS|IM]$ is the probability that a ground motion with intensity measure IM will cause a demand D_{EDP} exceeding a selected structural limit state LS

$\Phi(.)$ is the standard normal cumulative distribution function

μ is the median of the fragility function, and

β is the standard deviation of ln(IM).

Seismic fragility curves are commonly generated using a non-linear time-history analysis approach. Although this type of approach tends to be the most computationally expensive, it is also one of the most reliable methodologies available. The general procedure of this approach is the following:

- The first step is to obtain a suite of ground motions that is appropriate and representative of the target geographic area, and captures the uncertainty inherent in ground motions. The characteristics of ground motions are usually based on the magnitude, the source-to-site distance, and the site condition.

- Next, based on a reliable numerical model of tanks, the peak structural responses are obtained from non-linear time-history analyses, which are performed using a set of selected ground-motion records, to generate a probabilistic seismic demand model (PSDM).

- The capacity or limit state of each component is determined using expert-based, experimental, and/or analytical methods.

- Finally, the seismic demand and the structural capacity models are combined assuming a log-normal distribution, as shown in Equn 1.

The above procedure clearly shows five distinct aspects in developing fragility curves:

- definition of reliable numerical models of storage tanks;
- definition of seismic hazard-consistent input signals and selection of proper seismic intensity measures (IMs);
- selection of a set of representative engineering demand parameters (EDPs) and EDP-consistent damage states along with the corresponding limit states; and
- selection of proper fragility analysis and fitting methods.

In what follows, all these aspects are critically examined.

Numerical modelling of storage tanks

The seismic response of above-ground storage tanks subjected to earthquakes has been widely studied in the past [3]. The analysis procedure has been commonly based on three possible models:

- the simplified spring-mass model in which the impulsive and convective components are modelled as SDOF systems;
- the added-mass model in which the impulsive and convective forces are converted to equivalent masses along the height of the shell and bottom plate; and
- the full non-linear finite-element model in which the real interaction between fluid and structure is considered.

The simplified approach has been widely used thanks to its efficiency in reducing the computational effort, especially in a probabilistic manner. The basic idea is based mainly on the spring-mounted masses analogy proposed by Housner (1963) [4]. The liquid mass is ideally subdivided into two parts: an impulsive component, which accounts for the base motion and the deformability of the tank wall, and a convective component, whose oscillations cause superficial waves of different frequency frequencies. While the impulsive mass moves rigidly with the tank wall, the convective mass oscillates in different modes. As mentioned in

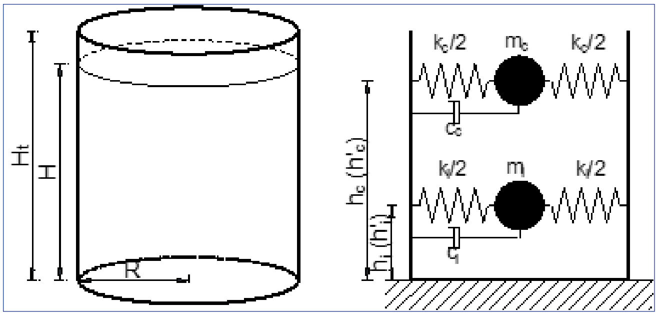

Fig.6. Lumped mass model of above-ground anchored tanks.

literature, it is enough to consider only the first convective mode to reproduce correctly the sloshing effect of the liquid [5]. The possible numerical model of the anchored tank represented by two viscoelastic oscillators is shown in Fig.6. In particular, the impulsive and convective masses (m_i and m_c, respectively) are connected to the tank wall by equivalent one-dimensional spring-dashpot systems at heights h_i (or h'_i) and h_c (or h'_c). The calculations of mass, height and natural period for each system can be obtained by the method presented by Malhotra *et al.* (2000) [6]. This procedure has been adopted by Eurocode 8 (EN 1998-4 2006) [7].

In the case of unanchored tanks, the partial uplift of the bottom plate occurs when the tanks are subjected to strong seismic excitations. The uplift mechanism of the tanks can be simulated by a rotation spring that represents the rocking resistance of the base, as shown in Fig.7. The behaviour of the resistance spring can be obtained using either the simplified approach presented by Malhotra and Veletsos (1994) [8] or the more refined approach presented by Phan *et al.* (2018) [9].

Selection of seismic-hazard-consistent input signals

The selection of seismic-hazard-consistent input signals to perform linear and non-linear analyses of tanks is an important issue which the scientific community is still discussing. For the construction of fragility curves, it is often necessary to use non-linear analysis, which requires seismic motion records. If a scalar IM is used, such as PGA, the correlation with the response is generally very low. As an alternative, accelerograms whose spectrum individually matches the target seismic-response spectrum could be used. These records can be artificially built or obtained by modifying the frequency content of records. The first approach has been completely abandoned while the second one still represents an interesting alternative.

To reduce the dispersion of the response without modifying the spectral content of the records, Shome *et al.* (1998) [10] proposed to use the response spectrum at the most significant vibration period of the structure as an IM. This criterion works properly only if the structural response depends mainly on one

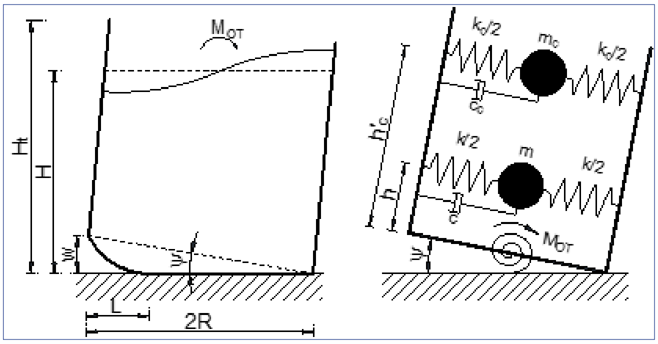

Fig.7. Lumped mass model of above-ground unanchored tanks.

Table 1. Critical EDPs and EDP-consistent damage states for steel storage tanks.

	EDP	Damage state
1	Maximum sloshing wave height	Sloshing damage of the roof and fracture of the shell-to-roof joint
2	Hoop hydrodynamic stress	Material yielding of the shell and bottom plate
3	Compressive meridional stress	Elastic and elastic-plastic buckling of the shell plate
4	Plastic rotation of the shell-to-bottom joint	Fracture and fatigue of the shell-to-bottom joint
5	Overturning moment	Uplift
6	Total base shear	Sliding

vibration mode and behaves elastically. To overcome this approximation, Baker (2011) [11] proposed to use the conditional mean spectrum (CMS), which is obtained by taking into account the correlation between the spectral ordinates at different periods. The accelerograms are then selected so that the average of their spectra approximates the CMS and their dispersion is contained within the CMS 1 standard deviation.

Oil and gas transportation lines and storage components are often characterized by a variegate frequency content. Therefore, the above record-selection criteria could fail. For example, storage tanks, which are among the most vulnerable components, exhibit at least two significantly different natural periods, due to impulsive and convective motions. This clearly complicates the problem of the accelerograms selection. In civil engineering, where complex structures exhibit similar problems, vector-valued IMs have been defined. However, in many applications, this approach shows a limited effectiveness, whereas a much more complicated procedure is required by including the necessity of performing a vector probabilistic seismic hazard analysis (Bazzurro and Cornell 2002) [12].

Selection of EDPs and EDP-consistent damage states

The definition of proper EDPs and EDP-consistent damage states represents another delicate aspect of the fragility analysis; however, a limited number of contributions has been offered in the literature. For example, an interesting contribution by Vathi *et al.* (2015) [13] provided the performance criteria for the design of storage tanks and piping systems, which identify the most critical failure modes for each structural category. The definition of damage states and the calculation of limit-state capacities are also presented in the current seismic design guidelines, e.g. Eurocode 8 (EN 1998-4) [7], API 650 (API 650 2007) [14], NZSEE (NZSEE 2009) [15]. The critical EDPs and EDP-consistent damage states for steel storage tanks are summarized in Table 1.

Fragility analysis methods

As mentioned in literature, different analytical methods to build fragility curves have been proposed either considering or not the randomness of structural characteristics. The most common use is the cloud analysis (CA). This method implements non-linear dynamic analyses through (linear) regression-based probabilistic model (Shome et al. 1998) [10]. A second common approach is the incremental dynamic analysis (IDA), where a suite of ground motions are repeatedly scaled to find the IM level at which each ground motion causes the exceeding of a certain limit state (Vamvatsikos and Cornell 2002) [16]. For the same computational effort, the CA method provides a good estimate of the first two PSDM moments across the range

	Property	Design value
Tank	Density (kg/m^3)	7850
	Young's modulus (MPa)	200,000
	Poisson's ratio	0.3
	Yield strength (MPa)	235
	Radius of tank (m)	27.432
	Height of tank (m)	15.6
	Bottom plate thickness (mm)	33, 29.5, 25.5, 21.5, 17.5, 14, 10, 8, 8, 10
	Shell plate thickness (mm)	8
Liquid	Density (kg/m^3)	900
	Liquid level (m)	14

Table 2. Nominal material and geometry properties of the tank.

of intensities considered in the suite of ground motions. IDA provides the same information; however, it is subjected to scaling issues and requires more computational effort. With a prudent selection of ground motions, both CA and IDA provide robust estimates of the median and dispersion across a range of ground motion intensities. A detailed discussion about the two approaches for the fragility analysis of steel storage tanks can be found in Phan *et al.* (2016, 2017) [2, 17, 18], where the priority of the CA method was demonstrated.

Fragility analysis example of an existing fuel storage tank

Description of case study

An existing tank ideally installed in a refinery in Sicily (Italy), which well represents a broad geometry, is selected for this study. The tank is a 54.8-m diameter cylindrical steel tank and unanchored with respect to the foundation. The tank height is 15.6 m, and the capacity of the tank is 37,044 m^3. The tank is provided with a floating roof; however, the effect of the floating roof is neglected in this study. The shell thickness has been designed varying from 8 mm at the top shell course to 33 mm at the bottom one. The bottom plate has a uniform thickness of 8 mm. The tank is filled with crude oil at a filling level of 14 m (i.e. 90% of the tank height). Both shell and bottom plate are structured in S235 carbon structural steel having a yield strength of 235 MPa. A detail of nominal material and geometry properties is illustrated Table 2.

Numerical modelling

The hydrodynamic pressures caused by the liquid motion can be expressed by sum of two components:

(i) an impulsive component which represents the effect of the part of the liquid that moves unison with the shell plate; and
(ii) a convective component which represents the effect of the part of liquid undergoing a sloshing motion.

The sloshing effects are characterized by long period oscillations, whereas the impulsive ones are dominated by oscillations of a shorter period. The contribution of the convective component to the response is small and can be neglected. Therefore, the tank-liquid system may be considered to respond as a single degree-of-freedom (SDOF) system, as shown in Fig.8.

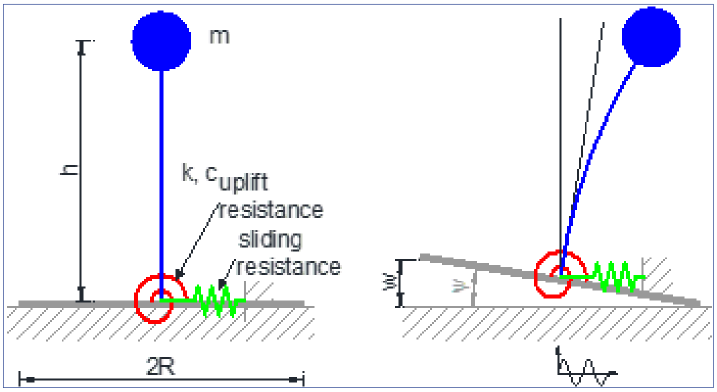

Fig.8. Spring-mass model of the tank.

The uplift resistance is represented by the M-ψ curve. This curve is obtained from the static analysis of the above refined finite element model and implemented in OpenSees using an elastic multilinear material. In fact, cyclic analyses demonstrated that a limited hysteresis is present and thus its effect has been here neglected, preserving only the geometrical non-linearity. The horizontal spring for the sliding resistance is a pure friction element with a constant friction coefficient, μ= 0.4.

Calculation of limit-state capacities

The commonly observed failure modes of unanchored steel liquid storage tanks during past earthquakes involved elephant's foot buckling of the bottom shell course and plastic rotation of the shell-to-bottom plate joint (Malhotra and Veletsos 1994) [8]. These failure modes have occasionally resulted in the loss of contents due to the weld or piping fracture (Alessandri *et al.* 2017) [1]. The elephant's foot buckling is caused by the concentration and high magnitude of the compressive stress developed in the shell when the tank base is uplifted from the ground support. The maximum compressive meridional stress in the shell (s_z) is calculated using the formulas provided in Malhotra and Veletsos (1994) [8]. The critical buckling stress is calculated using the formula developed by Rotter (1985) [19]. It is noticed that the buckling stress limit is in terms of the maximum pressure response of the seismic analysis. Thus it is conditioned on the IM. The median estimate of the EFB limit can also be predicted by the power function.

The second common failure mode developed at the joint of the shell and bottom plate is due to the plastic rotation of the joint caused by the base uplift. The rotation demand of the shell-to-bottom plate joint (θ) associated with an uplift at the edge and a base separation is given in Eurocode 8 (EN 1998-4) [14], which should be less than the estimated rotation capacity of 0.2 radians.

The third common failure mode is the material yielding of the shell plate due to the excessive hoop hydrodynamic stress (σ_h). As described in API 650 (2007) [14], the maximum allowable hoop tension membrane stress is the lesser of the basic allowable membrane for the shell plate material increased by 33% or 0.9 σ_y, where σ_y is the yielding strength of the steel.

Selection of ground motions

A total of 120 accelerograms has been selected based on six target uniform hazard spectra (UHS), which were obtained from the seismic hazard analysis of the selected site. The selection procedure is conducted with the following parameters: moment magnitude: 4.5-7.5, source-to-site distance: 3-80 km, soil type: B, and period interval: 0.001-4 s. The records of each set are selected so that the mean response spectrum and its 84% fractile have the best fit to those of the target UHS. An

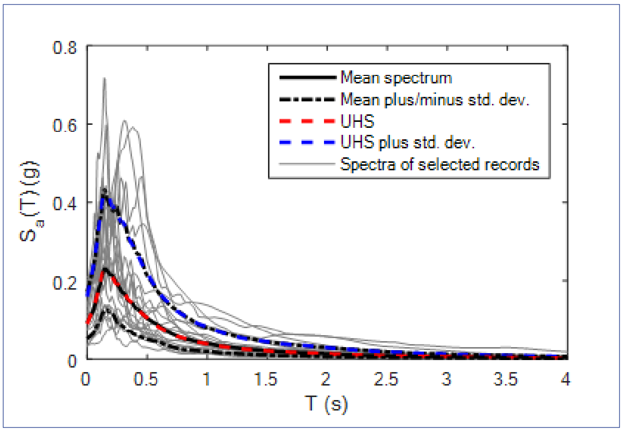

Fig.9. Example of ground motion selection.

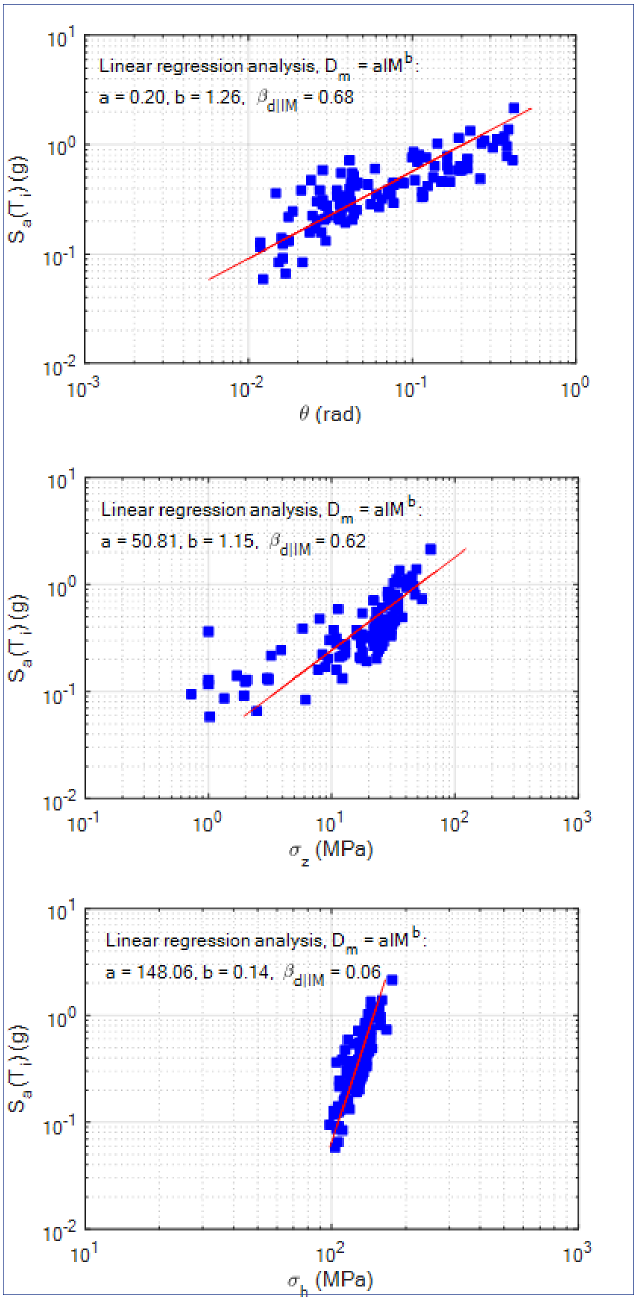

Fig.10. Linear regression analysis results (top-bottom):

(a) joint rotation demand;
(b) shell meridional stress; and
(c) shell hoop stress.

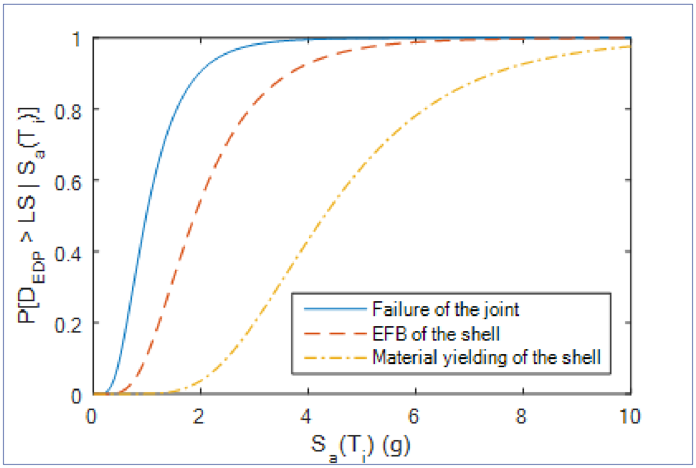

Fig.11. Fragility curves of the tank.

example of the selected ground motions for a UHS with a return period of 75 years is shown in Fig.9.

Fragility analysis

The seismic demand placed on each component is assessed against its capacity, or limit state, which is modelled by a lognormal distribution. The regression analysis results for the two demands are shown in Fig.10. The spectra acceleration at the impulsive period $S_a(T_i)$ is selected as IM of the regression analysis, which is based on the suggestion by Phan and Paolacci (2016) [18]. The fragility curve for each failure mode is then generated. The plot of fragility curves is shown in Fig.11.

It is observed that the failure of the shell-to-bottom plate joint in the examined unanchored tank is more frequent, with a failure probability of 50% at $S_a(T_i)$ = 1.0 g. The results show a high seismic demand of the shell-to-bottom plate joint rotation when the uplift occurs. The probability of exceeding the design buckling stress in the bottom shell course is also significant. A high seismic demand (50%) related to the shell buckling failure mode can be recognised when $S_a(T_i) > 2.0$ g. The occurrence of the material yielding of the shell plate is instead limited. A probability under 5% is recognized at a IM level $S_a(T_i)$ = 2 g.

Conclusions

The main objective of this study was to develop an appropriate methodology for the treatment of uncertainties for the fragility curve evaluation of steel tanks for oil and gas storage facilities. From an overview of past earthquake damage to steel liquid-storage tanks, critical failure modes of the tanks have been analysed. The most critical damage was classified as elastic and elastic-plastic buckling of the shell wall, sloshing damage of the roof, failure of the attached piping system, etc. The comprehensive analysis procedure of the fragility evaluation was then presented with the attention paid to four aspects: the numerical modelling, the selection of seismic hazard-consistent input signals, the selection of EDPs and EDP-consistent damage states, and the selection of proper fragility analysis and fitting methods. Finally, an application of the procedure to an unanchored oil storage tank in a refinery in Italy was presented. The fragility curves of three critical damage states of the tank - the plastic rotation of the shell-to-bottom plate joint, the buckling of the bottom shell course, and the material yielding of the shell plate - were obtained. The curves show a high vulnerability of the tank in terms of the failure of the joint and the buckling of the bottom shell course.

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