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# A PROBABILISTIC APPROACH FOR THE ASSESSMENT OF LOC EVENTS IN STEEL STORAGE TANKS UNDER SEISMIC LOADING

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## ABSTRACT

The damage states in a storage tank subjected to seismic loading can induce loss of containment (LOC) with possible consequences (fire, explosion, etc..) both for the surrounding units and people. This aspect is particularly crucial for the Quantitative Risk Analysis (QRA) of industrial plants subjected to earthquakes. Classical QRA methodologies are based on standard LOC conditions whose frequency of occurrence is mainly related to technological accident rather than natural events and are thus useless. Therefore, it is evident the necessity of establishing new procedures for the evaluation of the frequencies of occurrence of LOC events in storage tanks when subjected to an earthquake.

Consequently, in this work a simple procedure founded on a probabilistic linear regression-based model is proposed, which uses simplified numerical models typically adopted for the seismic response of above ground storage tanks. Based on a set of predetermined LOC events (e.g. damage in the pipes, damage in the nozzles, etc..), whose probabilistic relationship with the local response (stress level, etc..) derives from experimental tests, the probabilistic relationship of selected response parameters with the seismic intensity measure (IM) is established. As result, for each LOC event, the cloud analysis method is used to derive the related fragility curve.

## INTRODUCTION

*Background and motivation*

The interest of the scientific community in developing reliable methodologies for the seismic risk analysis of hazardous industrial plants like chemical/petrochemical plants has seen a rapid increasing during the last few years [1], [2].

It is well known that the seismic risk can be defined as the convolution of seismic hazard and structural vulnerability. However, in case of chemical plants the risk calculation necessary involves also the effects of the content release from a critical unit, (e.g. tank, pipe, etc..), which can provoke important effects on the surrounding elements and community [3]. In this respect, the probability of loss of containment for a given level of seismic damage must be calculated.

Nevertheless, the contributions in this directions have been particularly limited. The few contributions present in literature are typically based on empirical approaches, [4], [5], in which the relationship between loss of containment and seismic damage is defined on accident databases and is generally considered as deterministic. For example, in [5] the authors defined proper Risk States (RS) that correspond to a certain level of material loss. The first class correspond to a slight seismic damage and a negligible LOC. The second class corresponds to a slight LOC, whereas the third one refers to the extended or catastrophic damage of tank resulting in the rapid total loss of containment. A similar approach has been adopted in [6].

While this approach can be successfully applied for a large scale risk analysis of a process plants, in which steel storage tanks are present, this is not suitable when specific storage tanks need to be analyzed and the related seismic risk quantified. In fact, the causes of LOC can be different, because related to different local mechanisms and diverse type of consequences, which cannot be synthetized in few RS.

From the above framework it is evident the necessity to identify an analytical criterion for defining in a more rational way the frequencies of hazardous material release in storage tanks located in seismic prone area.


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*Scope of the work*

The present paper deals a probabilistic approach for the assessment of LOC events in steel storage tanks under seismic loading. With the use of simple mechanical models for the simulation of the seismic response of storage tanks and experimental data for the LOC/Damage relationship, a simple procedure is proposed for building fragility curves in terms of LOC.

## DAMAGE STATES AND LOC EVENTS IN STEEL STORAGE TANKS

Steel storage tanks has been recognized as one of the most critical unit of process plants because in case of earthquakes the release of hazardous liquid could cause serious accidents and consequences to the plant, workers and the surrounding communities.

Despite of the need of filling the gap for the quantification of the frequency of occurrence of LOC events and the related consequences, only few contributions have been provided in literature. The current approach consists in defining the amount of released material using an empirical approach, which is based on data, coming from recognized accident databases [7], [8]. The percentage of the released material is typically subdivided in groups that correspond to different risk states, based on which the risk of the plant can be quantified [5].

Even though interesting, this approach contains some drawbacks that make it feasible only for a rough estimation of the risk. In particular:

- The limited number of accidents due to the seismic action make the statistic incomplete;
- The risk states (RS) are based on arbitrary definition of released material quantity (negligible, slight, etc…);
- Using only data concerning the amount of the released material is inadequate to reliably quantify consequences given that they depend on several other parameters, including the time of release, temperature, etc.;
- The LOC/DS relationship is not deterministic, even if this aspect has been neglected in many literature contributions.

Consequently, a different approach is here proposed, which is based on a specific mechanical model able to provide a direct relationship between damage and loss of containment, which is fully described in the next section.

In this section, the set of damage states (DS) able to induce hazardous LOC events and potential consequences are described. In particular, in storage tanks four types of damage can be envisaged:

a) Loss of containment due to the detachment of pipes from the tanks wall;
b) Loss of containment due to the wall cracking for excessive hoop stress or due to buckling phenomena;
c) Loss of containment due to excessive motion of the floating roof;
d) Loss of containment due to the cracking for excessive tensile stress or low-fatigue phenomena in the base plate.

In this paper, only the first typology will be examined in detail, suggesting for each damage state the associated limit states and the definition of possible LOC phenomena. The remaining LOC events are under investigation and will be illustrated in future publications.

**Loss of containment due to the detachment of pipes from the tanks wall**

For this type of damage there are at least three type of actions capable to provoke a detachment of the pipe from the tank wall, as illustrated synthetically in Fig. 1.

The case a) is mainly related to possible sliding phenomena in unanchored tanks. In fact, the horizontal movement of the tank induces tensile/compression forces in the attached pipe. In tensile conditions it is possible to have partial/complete failure of bolted flange joints or the failure of the pipe nozzle in the pipe-tank wall connection. Limited studies, especially in the experimental field, have been conducted on these phenomena [9]. The main failure conditions are herein summarized.

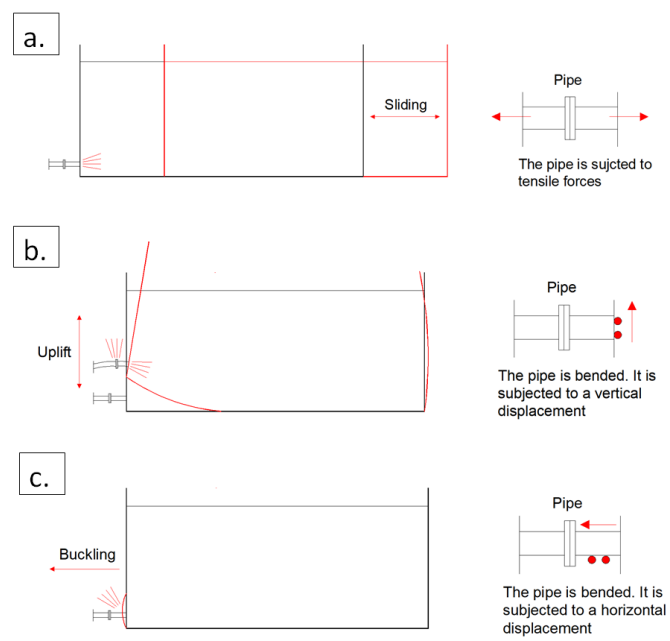


**Figure 1. Type of damages in storage tanks due to the detachment of pipes**

*LOC conditions in bolted flange joint (BFJ)*

Regarding this particular component, being interested in the leakage limit state and missing of code prescriptions about a threshold value, experimental data were used to find out a reference [10].

The aim of the experimental test was to investigate standard and non-standard bolted flange joint behavior of an 8” pipe with


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Schedule 40 under bending moments with an internal pressure of 1.5 MPa. Internal pressure has been obtained by means of water.

In order to guarantee a constant bending moment over the gasket and over the middle section, a 4-point bending configuration was adopted (Fig. 2). The results obtained during the several tests can be considered to obtain a reference threshold.

To generalize these results Bursi et al, [11], provided a simple closed-form formulation for the predictions of leakage conditions in Bolted Flange Joints (BFJ) based on the EN 1591-2009 standard, [12]. In particular, a dimensionless leakage interaction (axial and shear load) domain for a generic BFJ angle was provided.

**Figure 2. Four points test on flanged joints [10]**

*LOC conditions in pipe elbows*

Regarding pipe elbows, being interested in the leakage limit state and missing of code prescriptions about a threshold value, experimental data were used to find out a reference. For the experimental results, attention can be paid about few test conducted in [13]. In this experimental campaign, several elbows were tested in opening/closing mode. The results are presented in Table 1.

**Table 1. Experimental results on elbows [13]**

| Exp. Ref. | Mode | Load [kN] |
|---|---|---|
| 1 | Opening | 112 |
| 2 | Opening | 92 |
| 2 | Closing | 125 |

The first two rows of Table 1 show the maximum load that leads to a crack initiation on the intrados side due to an opening mode force hence, the reference limit state is average value F = 102 KN. In Table 1, the third row shows the maximum load that leads to a crack initiation on the extrados side due to a closing mode force. The reference limit state is F = 125 KN.

Other useful tests were performed within the European project INDUSE, where a series of bending tests on elbows were carried out at the University of Delft, [9]. In these tests the number of cycles until failure, and thus leakage, was provided, along with the corresponding force.

*LOC conditions in the pipes*

These performance levels for piping systems in terms of damage has been treated in, [14]. The authors defined the leakage condition in pipes as function of specific failure modes (DS). In particular, tensile failure, local buckling and fatigue cracking failure were considered. Accordingly, DS, in terms of maximum strain or fatigue measure, were proposed to evaluate leakage conditions.

In particular, for tensile fracture a tensile strain $\geq 2$ corresponds to leakage. Similarly, a compression tensile strain equal or greater than of 5 times the ultimate strain is symptom of leakage. For the fatigue phenomenon the authors referred to a damage factor related to the fatigue theory.

*LOC conditions for rupture of the pipe nozzles*

This particular type of rupture is not frequent. However, possible leakage phenomena could happen. In this respect a very limited number of contributions are present in literature, which are often focused on the mechanical behavior of the nozzle rather than to the leakage condition. For example, in [15] the authors tested a tank nozzle for different set of loading conditions, in particular longitudinal and transverse load directions as they can be expected under seismic actions. Another of the few test campaigns were presented in [16]. From the tests emerged that nozzles have a rather high plastic capacity and that under cyclic loading they are mostly safe. Unfortunately, no tests in presence of pressure have been conducted and thus no leakage conditions were detected.

## A PROBABILISTIC APPROACH FOR THE SEISMIC ASSESSMENT OF LOC EVENTS IN STORAGE TANKS

The proposed method consists in using simple models for the evaluation of the dynamic response of tanks and experimental results for the LOC events in the pipes, [9]. Once the displacement of the tank due to sliding and/or to uplifting are known, the stresses and the deformations on the pipe are automatically evaluated and according to the above-defined limit states it is possible to determine if they are exceeded or not.

As a matter of fact, let's consider an unanchored storage tank subjected to a seismic action. In this case, a possible dynamic model is illustrated in Fig. 3.

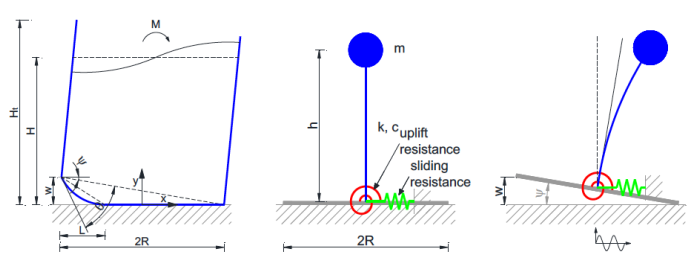


**Figure 3. Lumped mass model of unanchored tanks**


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Neglecting the convective motion effects, the dynamic of the fluid can be simply represented by linear cantilever with a mass equal to the impulsive one, [17].

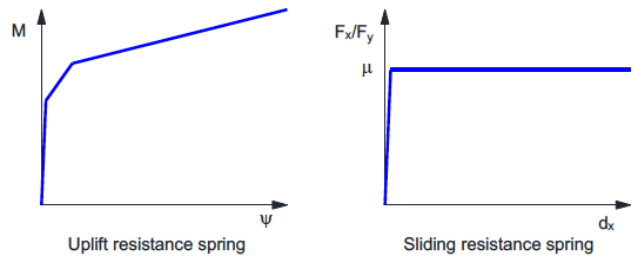


**Figure 4. Non-linear springs behavior**

The sliding phenomenon can be modeled considering the SDOF freely moving on the ground and attached to a pure friction element with constant $\mu$, whose constitutive law is illustrated in Fig. 4.

The uplifting phenomenon is more involved, to which recently a certain number of work have been devoted [18], [19]. The simplest model proposed in literature is represented by a SDOF model (impulsive liquid motion) rotating with respect to the ground through a rotational spring whose resistance law can be expressed in terms of moment (M) – Rotation ($\psi$). For the definition of the kinematic parameter $\psi$ see Fig. 3. The parameters of this law can be determined through a pushover analysis on 3D FEM elements of the tank [18]. An example is illustrated in Fig. 5.

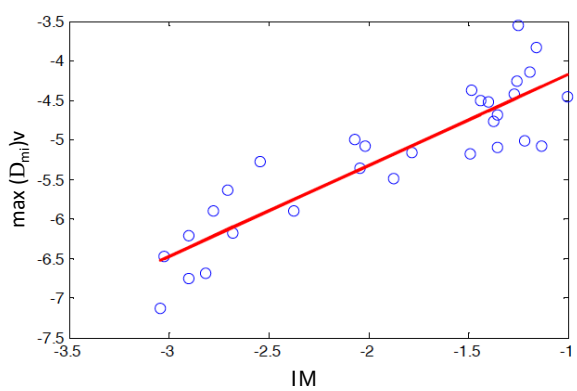


**Figure 5. Probabilistic response model (CA)**

Given that the pipe has a limited influence on the dynamic response of the tanks, this is not included in the model of Fig. 3.

Once the model has been defined and the ground motion signals selected, the statistics of the maximum displacement ($D_m$) of the tanks in correspondence of the tank-pipe attachment generated by a set of $n$ ground motions can be determined. At this purpose, the use of the Cloud Analysis (CA) methods is here suggested [20]. According to this method, the cloud of points in the plane $D_m$-$IM$, where $IM$ is the seismic intensity measure can be plotted and the points interpolated in the log-log plane (Fig. 5).

The red line in Fig. 5 represents the median values of the $\delta_m$-IM relationship that can be expressed as:

$$D_m = a\, IM^b \tag{1}$$

where $a$ and $b$ are the regression coefficients. The standard deviation can be calculated according to the Eq(2), where $d_i$ is the maximum displacement recorded for the *i-th* ground motion.

$$\beta_{d|IM} = \sqrt{\frac{\sum_{i=1}^{n}\left[\ln(d_i) - \ln\left(aIM_i^b\right)\right]^2}{n-2}} \tag{2}$$

Under the hypotesis that the seismic demand $D_m$ and the structural limit states ($LS_m$) follow a lognormal distribution with dispersion $\beta$, the probability of exceeding a specific limit state $LS$ can be estimated with the lognormal cumulative distribution function, given as:

$$P\left[D_{EDP} > LS \mid IM\right] = 1 - \Phi\left(\frac{\ln(LS_m) - \ln(D_m)}{\sqrt{\beta_{d|IM}^2 + \beta_{LS}^2}}\right) \tag{3}$$

As already explained, the mean and the standard deviation ($LS_m$ and $\beta_{LS}$) of the leakage limit state in the pipe come usually from experimental tests, even though some authors provided analytical formulations, at least for $LS_m$, [14].

Eq.(3) represents the leakage fragility curve of the tank, that is the probability of occurrence of the leakage in case of rupture of the pipes attached to the tanks as function of IM. Given that different $LS$ can be contemporary present, the mutual correlations should be considered. However, in the present work they are considered as indipendent, leaving to future researches to investigate about the coupling effect.

## APPLICATION TO A CASE STUDY

As case study, a real storage tank (TK-1) belonging to a petrochemical plant, is chosen for the application of the proposed approach for the probabilistic seismic assessment of the LOC events. The facility is supposed to be ideally placed in one of the most seismically active zones in Sicily (Italy), just closed to Priolo Gragallo city and characterized by a soil condition B. Steel outgoing 8” pipe of raw material is attached to the tank shell bottom and transfer the oil to start the processing.

In order to show the methodology, only a possible loss of containment event due to the detachment of the flanged joints is herein considered. This problem is typically associated with the sliding of the tank due to the seismic action that could cause tensile stresses, plastic deformation and leakage of material from the flanged joints.


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## Description of the case study

The tank TK-1, containing crude oil of density ρ equal to 917 kg/m$^3$, consist of steel shell with equivalent thickness of 13.0mm and yield strength $f_y$ of 345 MPa. The tank has a diameter D of 37.96 m and a clear height H between the bottom slab and the top cover of about 14.0 m; the maximum filling level $H_{FL}$ is set at 11.30 m (Fig. 6). The tank is unanchored and directly resting on the ground with a friction coefficient assumed equal to 0.4. A steel pipe with diameter of 8" and thickness 18 mm is attached to the tank shell, near the base and continues its path in the ground, a flanged joint is present between the two extreme points. According to [21], the most probable damage state in the analyzed tank is associated to the sliding with respect to the ground.

## Modeling issues

Dynamic analysis of a liquid-filled tank with a pipe attached, are carried out using the concept of generalized single degree of freedom (SDOF) systems, representing the impulsive and convective vibration modes of the tank liquid system (Fig.7).

Numerical model is implemented in the finite element platform OpenSEES, [22].

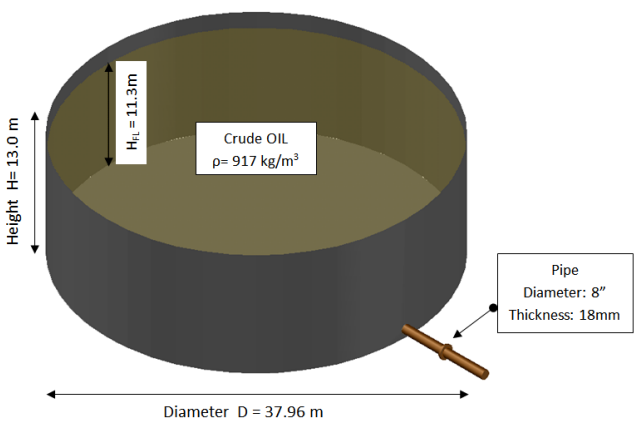


**Figure 6. Geometric charactheristics of the tank TK-1**

Mass, height, natural period and stiffness of each SDOF system are obtained by following existing methods, [17], and reported in Table 2, in which, $h_i$ and $h_c$ are the heights of the centroids of impulsive and convective SDOF models, $T_i$ and $T_c$ are the natural vibration periods of the impulsive and convective modal response with the corresponding damping ratios, $\xi_i$ and $\xi_c$.

**Table 2. Dynamic characteristics of the tank**

| Liquid Components | | |
|---|---|---|
| | Impulsive | Convective |
| Mass (m) | $m_i$=4.206 t | $m_c$= 7.521 t |
| Height (h) | $h_i$= 13.41 m | $h_c$= 13.25 m |
| Damping ratio (ξ) | $\xi_i$= 2% | $\xi_c$= 0.5% |
| Period (T) | $T_i$= 0.21 s | $T_c$= 7.32 s |
| Stiffness (k) | $k_i$= 3740560 kN/m | $k_c$= 5.527 kN/m |

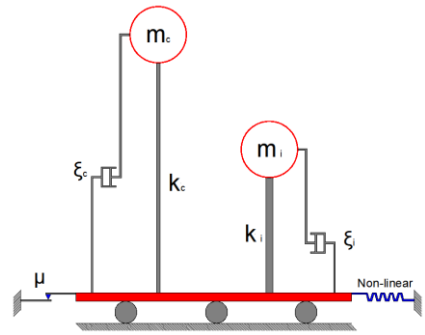


**Figure 7. Simplified FE numerical model of the tank**

The tank TK-1 is free to slip on the ground surface but only when the seismic base shear force is greater than the friction resistance. So, a Coulomb friction model is introduced utilizing a flat slider bearing element with a friction coefficient equal to 0.4 (Fig.7).

The pipe is attached to the tank and is numerically modelled as a twoNode link element with a uniaxialMaterial Parallel behavior. In fact, the non-linear behavior, as demonstrated in the several experimental tests on the pipe, [10], is very different in tension and compression domain. Consequently, the behavior of the pipe joint has been modelled with a bilinear uniaxial material in tension and a uniaxial elastic-no tension material in compression. The comparison with the experimental test in tension are shown in Fig. 8.

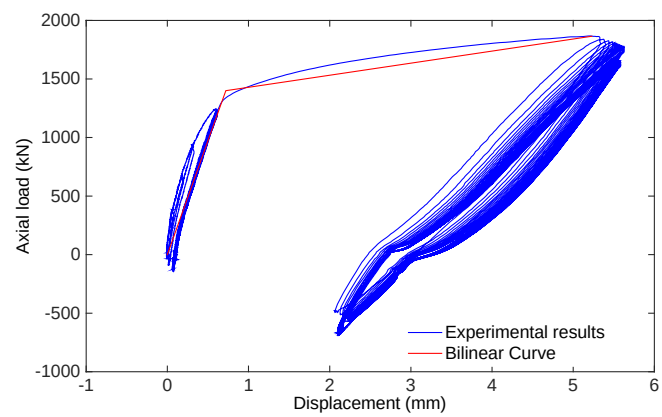


**Figure 8. Axial Load-displacement curve: numerical-experimental comparison**

## Evaluation of LOC events in the pipe due to sliding

Probabilistic seismic hazard analysis of Priolo Gargallo is conducted with reference to a Latitude LA=37.17°, a Longitude LG= 15.17° and Radius Ra=100 km. A set of 140 accelerograms are selected according to the criteria indicated in [21], and seismic dynamic analysis of the simplified system are conducted with the final goal to obtain the maximum displacement in the bolted flange joint (BFJ) to evaluate the leakage conditions. In particular, the onset of leakage in the pipe due to tensile action is


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here considered, which corresponds to a mean displacement of 0.6 mm, considered as deterministic. An example of time-history of the tank displacement due to the sliding is shown in Fig. 9.

## Calculation of the LOC Fragility curves

The LOC fragility curves are calculated with Cloud Analysis method that implements the nonlinear dynamic analysis results in a linear regression-based probabilistic model. When the seismic demand and the structural limit states are assumed to follow a lognormal distribution, the probability of exceeding a specific damage state for a particular component can be estimated with the standard normal cumulative distribution function. The maximum displacement of a pipe due to the sliding of the tank is evaluated for each time-history analysis, then the estimate of the median demand is predicted by the power function of Eq. (1), (Fig. 10). The dispersion of the demand conditioned on the PGA is estimated from the regression analysis of the seismic demands (Eq. (2)).

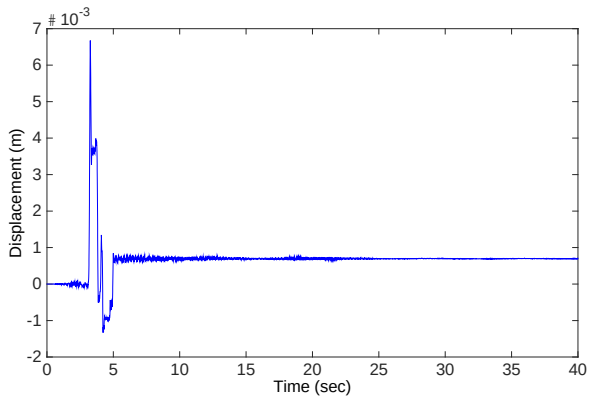


**Figure 9. Time-History of the tank displacement at the tank base due to sliding**

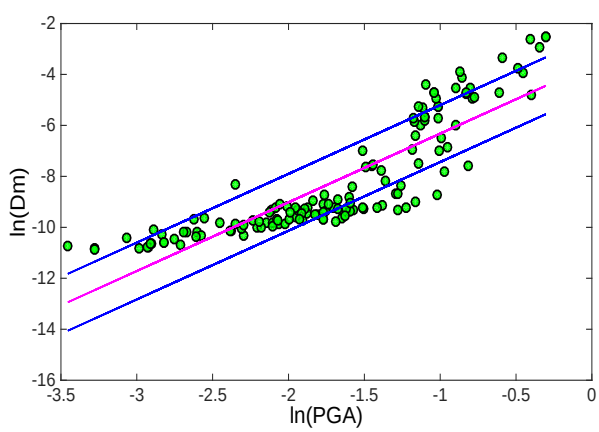


**Figure 10. Regression analysis of the seismic demand (displacement at tank-to-pipe connection)**

Once the definition of the limit state from the experimental test has been established, that is the value of the joint pipe displacement at which the loss of containment is detected, the fragility curves can be calculated using Eq.(3) and directly expressed in terms of LOC.

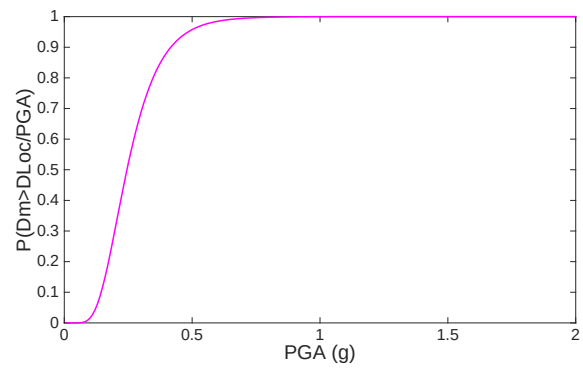


**Figure 11. LOC Fragility curve at the onset of the leakage in the BFJ of pipe due to the tank sliding**

In Fig. 11 is illustrated the fragility curve of the considered storage tank (TK-1) at the onset of leakage in the attached pipe due to the tank sliding. It is possible to note that for a peak ground acceleration of 0.2g the probability is about 20%, which increases rapidly. For example, at 0.4g the probability of LOC is about 80%.

This simple example shows all the potentialities of the proposed method.

## CONCLUSIONS

In the present paper a simple procedure for the evaluation of fragility curves for above-ground storage tanks in terms of loss of containments has been proposed.

Assuming, for simplicity, the LOC/Damage relationship as deterministic and represented by the mean value of the displacement of the pipe at the onset of leakage for tensile condition (experimentally evaluated), the probability of occurrence of the leakage condition and thus the LOC fragility curve has been built by using a probabilistic regression-based model (Cloud Analysis).

The procedure has been applied to a representative case study: a broad tank in which the sliding problem were predominant. From the analysis, the displacement at the onset of leakage in the attached 8” pipe appears frequently exceeded. The fragility curve showed clearly that the leakage can occur with high probability since low values of PGA and increase rapidly.

This paper represents a preliminary attempt to evaluate the probability of LOC for different Damage State in storage tanks located in seismic areas, which is crucial in Quantitative Seismic Risk Analysis, in order to determine the probability of fluid release and related consequences.

The extension to different LOC events, with random characteristics too, will be the object of further researches.


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## REFERENCES

[1] Caputo A.C., Giannini R., Paolacci F., (2015), Quantitative seismic risk assessment of process plants. state of the art review and directions for future research, ASME 2015 Pressure Vessels & Piping Conference PVP2015, July 19-23, 2015, Boston, Massachusetts, USA, DOI: 10.1115/PVP2015-45374

[2] Krausmann E., Cruz A.M., Salzano E., (2017), Natech Risk Assessment and Management, Reducing the Risk of Natural-Hazard Impact on Hazardous Installations, Elsevier, 2017, ISBN 9780128038079

[3] STREST, 2016. Harmonized approach to stress tests for critical infrastructures against natural hazards. In: Tsionis, G., Pinto, A., Giardini, D., Mignan, A. (Eds.), Report on lessons learned from recent catastrophic events, http://dx.doi.org/10.2788/17066.

[4] Antonioni, G., Spadoni, G., Cozzani, V., 2007. A methodology for the quantitative risk assessment of major accidents triggered by seismic events. J. Hazard Mater. 147 (1–2), 48–59.

[5] Salzano, E., Iervolino, I., Fabbrocino, G., 2003. Seismic risk of atmospheric storage tanks in the framework of quantitative risk analysis. J. Loss Prev. Process. Ind. 16, 403.

[6] Lipovics, T., Czakó, S., Kelemen, I. et al. Acta Geod. Geoph. Hung (2008) 43: 449.

[7] Major Accident Reporting System (MARS). (2006). European commission, joint research centre, institute for the protection and security of the citizen, major accident hazards bureau. http://mahbsrv.jrc.it/. Cited 29 August 2006.

[8] ICHEME. (2004). The accident database. Version 4.1. United Kindgdom: Institution of Chemical Engineers

[9] Karamanos, S., Pappa, P., Varelis, G., et al., 2013. Structural Safety of Industrial Steel Tanks, Pressure Vessels and Piping Systems under Seismic Loading. RFSC funds, Grant No: RFSR-CT-2009–20000022, Final Report.

[10] Reza Md, O.S. Bursi, Paolacci F., Kumar A., (2014), Performance of non-standard bolted flange joints in industrial piping systems subjected to seismic loading, Journal of Loss Prevention in the Process Industries, Vol. 30 July, Pages 124–136, DOI: 10.1016/j.jlp.2014.05.011

[11] Bursi, O.S., Di Filippo, R., La Salandra, V., Pedot, M., Reza, Md.S., (2017). Probabilistic Seismic Analysis of an LNG Subplant. Journal of Loss Prevention in the Process Industries Available online 16 October 2017. DOI:10.1016/j.jlp.2017.10.009.

[12] EN 1591-1, (20099. Flanges and Their Joints – Design Rules for a Gasketed Circular Flange Connection – Part 1: Calculation Method.

[13] Chattopadhyay J., Kushwaha H.S., Roos E., (2006), "Some recent developments on integrity assessment of pipes and elbows. Part II: Experimental investigations". International Journal of Solids and Structures.Vol. 43, Issue 10, pp. 2932–2958

[14] Vathi, M., Karamanos, S.A., Kapogiannis, I.A., Spiliopoulos, K.V., (2016). Performance criteria for liquid storage tanks and piping systems subjected to seismic loading. J. Pressure Vessel Technol. 139 (5). DOI: 10.1115/1.4036916. Paper No: PVT-16–1045.

[15] Wieschollek M., Hoffmeister B., Feldmann M., (2013). "Experimental and Numerical Investigation on Nozzle Reinforcements", ASME 2013 PVP Conference, Paris, France.

[16] Aiba M., Grashi K.I, Akiyama H. Chiba T., (2000), Test of nozzles at wall of cylindrical tank for severe loads under earthquake, 12WCEE, Auckalnd, New Zealand.

[17] Malhotra PK, Wenk T, Wieland M (2000) Simple procedure for seismic analysis of liquid-storage tanks. Struct Eng Int 10(3):197–201.

[18] Vathi, M., Karamanos, S.A., 2017. A Simple and Efficient Model for Seismic Response and Low-cycle Fatigue Assessment of Uplifting Liquid Storage Tanks. Journal of Loss Prevention in the Process Industries Available online 5 August 2017.. DOI:10.1016/j.jlp.2017.08.003

[19] Phan H.N., Paolacci F., (2018), Fluid-structure interaction problems: an application to anchored and unanchored steel storage tanks subjected to seismic loadings, 16th European Conference on Earthquake Engineering, Thessaloniki, Greece, 18-21 June 2018

[20] Mackie, K.R., Stojadinovic, B., 2005. Comparison of Incremental Dynamic, Cloud, and Stripe Methods for Computing Probabilistic Seismic Demand Models. Structure Congress 2005.

[21] Alessandri S., Caputo A., Corritore D., Giannini R., Paolacci F., Phan H.N., (2018), Probabilistic Risk Analysis of Process plants under Seismic loading based on Monte Carlo Simulations, Journal of Loss Prevention in the process Industries, Published on-line 30 December 2017, DOI: 10.1016/j.jlp.2017.12.013

[22] McKenna F, Fenves GL, Scott MH (2007) OpenSees: open system for earthquake engineering simulation. PEER, University of California, Berkeley, CA



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