

# Release of Hazardous Substance Due to Seismic Loads: Influence of Pipe to Tank Connection in Fragility Estimation

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The damage observed during past earthquakes demonstrated the need for the seismic vulnerability assessment of industrial plants to reduce the risk of major accidents and to develop detailing for risk mitigation. If damaged by a seismic event, industrial plants might be affected by a domino effect with the consequent interruption of plant serviceability and severe economic losses; at the same time, toxic substances could be released due to the damage of pipelines and tanks, causing environmental damages and loss of lives.

This preliminary study investigates the influence of the dynamic properties of pressurised tanks on the industrial plant seismic vulnerability, focusing on the possible issues to which the pipelines connecting the tanks are prone. To this purpose, numerical analyses are conducted aimed at identifying the most critical conditions in terms of displacements and stress state to which the pipelines are subjected. At the same time, a framework for the definition of fragility functions including the damage states related to piping connections, is also presented.

## 1. Introduction

Industrial facilities and their components are particularly vulnerable to natural events, such as floods, hurricanes, earthquakes, landslides and extreme temperature events. The interaction between natural hazards and industrial risk may trigger major hazard accidents, called “Na-Tech” events (Natural Hazard Triggering Technological Disasters) (Campedel, 2008). In industrial plants, these events can cause loss of containment with consequent structural collapses, explosions, fires or toxic cloud emissions, leading to environmental damage and loss of human life. Focusing on Na-Tech events, Campedel (2008) analysed 78 records reporting that atmospheric storage tanks, pipe-works and pipelines are the most frequently damaged equipment during a seismic event in industrial plants. Furthermore, only in 26% of the analysed cases the structural and non-structural damage was not associated with a loss of containment.

To overcome this issue, in Italy, the so-called major hazard industrial plants are subjected to seismic safety assessment according to the Italian Technical Standards of Construction (NTC 2018) and to Na-Tech risk analysis according to Italian Legislative Decree no. 105 of 2015 (Ciucci et al., 2021). The structural analyses are based on semi-probabilistic methods and aim at the seismic verification of structural and supporting components. On the other hand, the risk analyses are based on probabilistic approaches and are devoted to estimating the probability of occurrence of Na-Tech incidents, which also account for releasing hazardous substances (Marino et al., 2019).

In risk analysis, the development of accurate fragility functions for all the components characterising an industrial plant is of paramount importance. A fragility function specifies the probability of achievement of a defined limit state as a function of an intensity measure, IM. The parameter IM is often quantified by a peak ground acceleration or a spectral acceleration with a specified period and damping if the fragility function is referred to a structure or a tank, while it can be associated with a peak floor acceleration or with a floor spectral acceleration in the case of suspended elements, such as piping networks. A key issue in developing the fragility functions of industrial plant components concerns the identification of the correct engineering demand parameters and their

threshold for each considered limit state. To deal with this issue, in this paper, the typical damages to which pipelines are prone are described by analysing different pipe-to-tank connections; at the same time, a methodology for developing specific fragility functions for pipe connections in industrial plants is described.

### 1.1 Typical seismic damages

A typical industrial plant consists of storage tanks, process equipment, piping systems and flares (Paolacci et al., 2012). Each of these components could be damaged by earthquake triggering a domino effect with consequent interruption of plant serviceability, release of toxic containment, structural collapses, environmental damage and loss of human life. The analysis of damages observed in industrial plants during past earthquakes, allows to identify the more critical features in industrial plants and it can guide in the development of mitigation detailing. In order to define a macro-classification of the damages to which industrial plants are prone, it is possible to identify three main categories: damage to supporting structures, tanks and pipelines. The damage to supporting structures is mainly related to the structural typology (steel or concrete structures) and it depends on the adopted construction criteria. Concerning storage tanks, typical damages are the “elephant’s foot” buckling, the “diamond buckling” or the failure of wall-bottom plate joint. If the storage vessel is supported by short columns, it can be affected by shear failure due to seismic loads (Vathi et al., 2017). In the case of tanks with floating roofs, possible damages are due to the fluid-structure interaction (sloshing), which can lead to damage or to liquid overtopping.

Pipelines, pipe-to-pipe and pipe-to-tank connections are affected by seismic events. Tanks and pipes are characterised by non-negligible differences in terms of dynamic properties, leading to possible relative displacements close to the pipe-to-tank connections and to the consequent failure of the piping joints (Figure 1b and 1c). Tensional states are also influenced by the position of the pipe connection along the tank wall and by the presence of elbows. Excessive compressive stresses can lead to a pipeline failure due to local buckling (Figure 1a) or to a punching failure of pipe-to-tank connection. On the other hand, excessive tensile stresses can cause the damage to flanged or welded joints connecting two pipes or connecting the pipeline to the tank (Vathi et al., 2017). It is worth noting that pipelines are also identified as the main cause of the release of hazardous substances following seismic events; for this reason, their seismic vulnerability should be accounted for in risk analysis by defining fragility curves, including damage limit states able to account for their seismic performance.



Figure 1: a) local buckling in a pipe (Karamanos et al., 2003), b) failure of the tank to pipe connection (Reza Manshoori, 2011), c) damage on a flanged joint (Paolacci et al., 2012)

## 2. Seismic response of pipe-to-tank connections

### 2.1 Case studies and numerical modelling

In this preliminary study, a parametric analysis is carried out in order to investigate the seismic response of pipe-to-tank connections and the pipeline itself. The analysed parameters are the path of the pipeline connecting the tanks and the dynamic response of the tanks, analysed by varying their height and mass. The study aims to identify the configurations that can lead to an amplification of the relative displacements at which the pipes are prone and to the consequent failure of the pipe-to-tank connections. The tanks are modelled by adopting an inverse pendulum modelling approach, assuming a fixed base connection.

Four configurations are considered, namely configuration 1.A and 2.A in which two tanks are connected by a pipeline with elbows and configurations 1.B and 2.B in which the two tanks are connected using a linear pipeline (Figure 2). By varying the mass and the height of the tanks, seven case studies are identified for each configuration previously described, as reported in Table 1. In the evaluation of the mass, it is considered that the tanks are filled with a substance characterised by a density equal to  $10 \text{ kN/m}^3$ . Pipe and tank material is characterized by  $\sigma_y = 460 \text{ Mpa}$ ,  $\rho = 0.07698 \text{ N/cm}^3$ ,  $\nu = 0.3$ ,  $\Delta T = 6.6667e^{-6} 1/F$ ,  $\zeta = 0.02$  and  $E = 2.1e^{+7} \text{ N/cm}^2$ . Table 2 reports the geometrical properties of the adopted pipelines (linear or with elbows). In particular,  $D_{\text{ext}}$  and  $D_{\text{int}}$  are, respectively, the outside and inside pipe diameter,  $R_c$  is the radius of curvature of the pipe with elbows,

$t_w$  is the pipe thickness,  $l_1$  and  $l_2$  are the lengths of horizontal branches and  $h$  is the vertical branch length. The diameter of analysed tanks is equal to 10 m with a wall thickness of 4.66 mm.

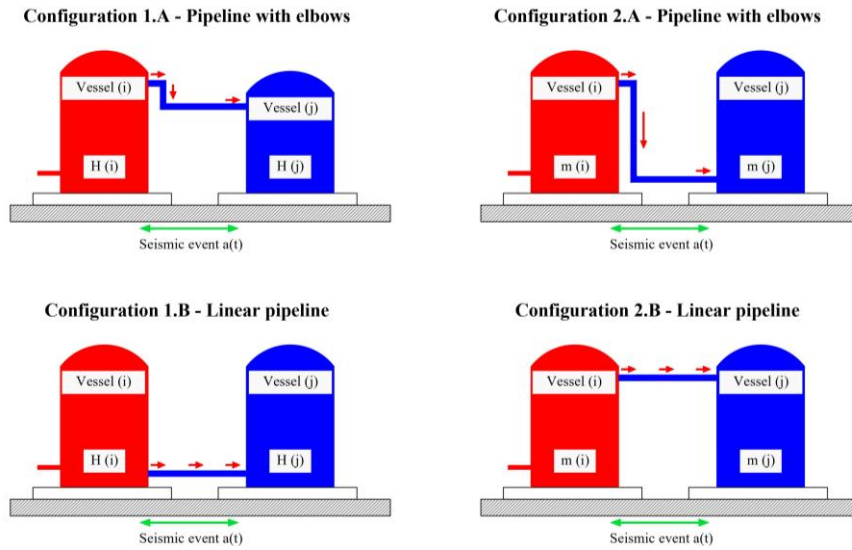


Figure 2: Tanks configurations adopted in the parametric analysis

Table 1: Properties of the analysed tanks

Configuration 1 Change of stiffness		Configuration 2 Change of mass	
Case	H[m]; $m=1500$ kN/g	Case	M [kN/g]; H=15 m
M <sub>1</sub>	20	M <sub>2</sub>	1500
M <sub>2</sub>	15	M <sub>5</sub>	1000
M <sub>3</sub>	10	M <sub>6</sub>	600
M <sub>4</sub>	5	M <sub>7</sub>	500

Table 2: Geometric properties of pipelines

Pipeline	Type [inch]	$D_{ext}$ [mm]	$t_w$ [mm]	$D_{int}$ [mm]	$R_c^{90^\circ}$	$l_1$ [mm]	$l_2$ [mm]	$h$ [mm]
Elbow	14"	355.6	3.96	347.68	533	1050	5000	13410
Elbow	14"	355.6	3.96	347.68	533	1050	5000	3410
Linear	14"	355.6	3.96	347.68	-	7000	-	-

A cascading approach has been adopted to analyse the response of the pipelines and of the pipe-to-tank connections. Firstly, the numerical models of the four analysed configurations have been developed to identify the relative displacements at which the pipelines are prone; then, detailed numerical models of the pipelines were developed to investigate in detail the response of the pipelines when subjected to the seismic input derived from the global analyses. The global models were developed in Midas GEN, while the detailed models of the pipelines were developed in Midas FEA. In this preliminary study, only one ground motion record was considered for the time history analyses. The ground motion was selected according to the selection criteria provided by NTC18, and a site characterised by a PGA equal to about 0.16g for a return period equal to 475 years on soil type B was assumed.

## 2.2 Results

Because the stiffness of the pipelines is negligible with respect to the stiffness of the tanks, estimating the maximum displacements of the tanks to be used for the analysis of the pipelines is only required to perform the analysis for one of the four configurations reported in Figure 2. Considering all the combinations of the parameters reported in Table 1, a total of 21 combinations were analysed. Figure 3 reports the maximum displacements obtained from the time history analyses for each combination. The maximum displacement was calculated by comparing the absolute displacement time histories of the two tanks considered in each combination in order to account for the counter-phase displacements. Among all the combinations, the worst conditions are obtained for combinations M<sub>1</sub>-M<sub>2</sub> and M<sub>2</sub>-M<sub>6</sub>.

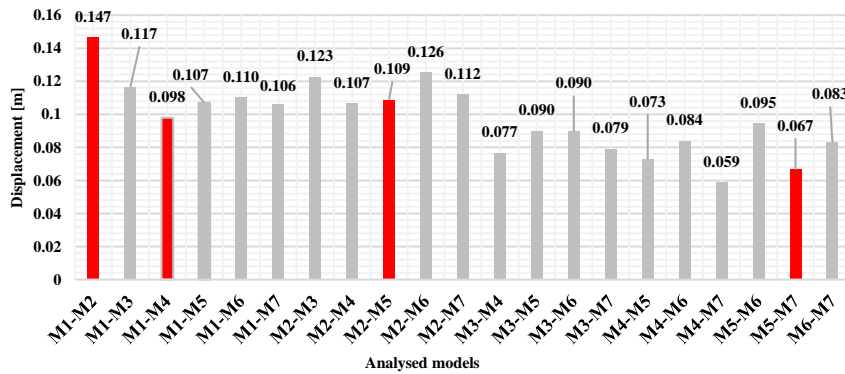


Figure 3: Maximum displacements of coupled models

Four combinations, cases M1-M2, M2-M5, M1-M4, M5-M7 (marked in red in Figure 4), were selected to perform the detailed analyses of the pipelines for the different configurations reported in Figure 2. The performance of the pipelines was investigated in terms of stress state, adopting the von Mises-Maxwell criterion for the failure assessment. Examples of the stress state in configuration 1.A, 2.A and 2.B are reported in Figure 4.

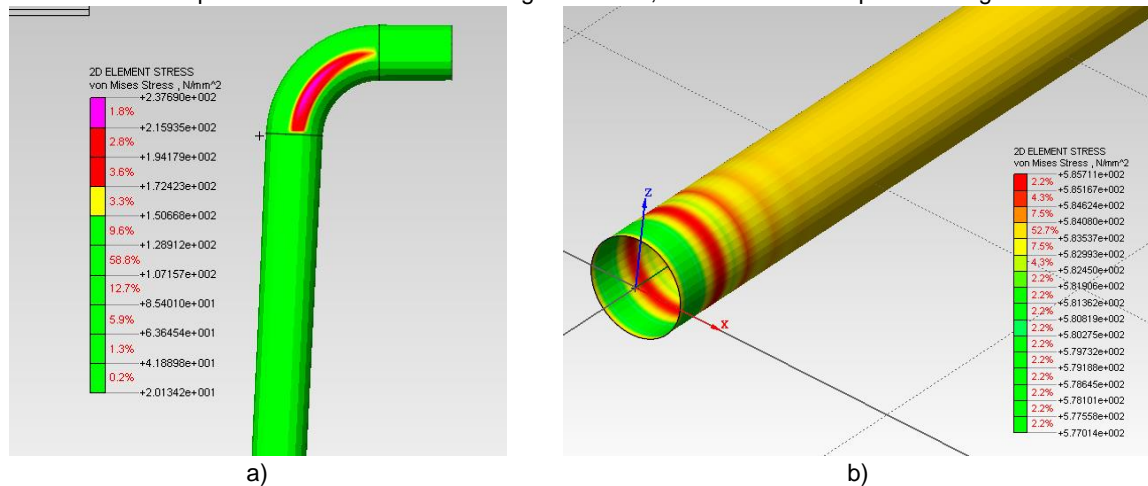


Figure 4: Examples of stress state achieved during the analysis: a) Configuration 2.A, case M1-M4, pipeline with elbow b) Configuration 2.B, case M2-M5, linear pipeline.

The global stress state for Configuration 2.A, case M1-M4, is depicted in Figure 4a. For this combination, the pipe with elbows does not reach the yield strength and a scaling factor of about 2.6 is required to achieve the failure of the pipe, assuming an elastic behaviour up to the collapse. For Combination 2.B, case M2-M5, the failure of linear pipe-to-tank connection is achieved for a displacement lower than the maximum displacement recorded during the global analysis of the tanks, as shown in Figure 4b. After analysing all the results, it is possible to state that Configuration 2.B represents the worst-case scenario, followed by Configuration 1.A. In configuration 2.A the effects due to the seismic input can be geometrically mitigated through a more flexible pipe with elbows. As a result, the effects of the earthquake on the pipes (weak elements of the system) can be mitigated geometrically by the presence of elbows or by changing the connection position along the tank wall. In these cases, the critical point could be related to the elbows and the stress concentration in these elements could be mitigated by adopting flexible joints.

### 3. Seismic risk analysis

In general terms, risk analysis describes the relationship between the probability of a given outcome and a measure of the degree of that given outcome. In the case of seismic risk, this relationship is determined by:

- Exposure, which represents the assets exposed to loss. The asset definition includes locations, values exposed to loss, and the characteristics necessary to estimate vulnerability.
- Hazard, in this case, seismic events characterised by their intensity (i.e., how strong they are).

- Damageability, which determines the affectation to a component of interest and is represented by either fragility (i.e., probability of exceeding a defined limit state given an intensity) or vulnerability (i.e., the expected value of loss and the conditional distribution of loss given many intensity levels).

Currently, existing standards and guidelines lack explicit methodologies for conducting risk analyses concerning the release of hazardous substances due to equipment and pipe leaks, breaks, or failures.

A prevalent methodology for seismic risk assessment in major hazard industrial facilities initiates with the dual characterisation of the seismic event, assessing site-specific hazards, and the response of the equipment/pipe to evaluate seismic vulnerability. Subsequent steps involve identifying critical structural and non-structural components, which then facilitate the delineation of potential accident scenarios involving hazardous substances using a variety of complementary techniques. Following scenario identification, two analytical processes are essential to estimate the frequency of an incidental scenario:

- Fault Tree Analysis (FTA) is utilised to estimate the likelihood of incidental scenarios, beginning with root causes and preventive measures.
- Event Tree Analysis (ETA) serves to evaluate and assign expected frequencies to all potential outcomes of an event, taking into account protective measures as well.

The ultimate goal of seismic risk analysis is to quantify the risk and, if deemed unacceptable, to propose improvements to mitigate it (Salimbeni et al., 2022).

### 3.1 Fragility functions

A fragility function represents the probability that the seismic demand ( $D_{EDP}$  – demand in terms of an Engineering Demand Parameter) on a system exceeds the Limit State (LS) as an undesirable condition for a specific Intensity Measure (IM). There are three methods for deriving fragility curves:

- The empirical or observational approach employs statistical procedures to derive fragility functions, which characterise the probability of sustaining or exceeding specific damage levels as a function of earthquake intensity.
- The analytical approach facilitates the development of site-specific fragility curves based on structural analysis performed using an appropriately modelled representation of the structure. The behaviour of the structure is determined by certain basic variable vectors, which influence both the seismic demand and the capacity of the structure. After defining the limit function or limit state, the probability that these limit states will be exceeded is computed.
- The expert judgment-based approach involves constructing fragility curves for structures based on expert evaluations of the likelihood of failure as a function of seismic intensity.

Although tank-to-pipe connections play a crucial role in the risk assessment of industrial plants, few studies have focused on the matter. This can be explained by the high variability of configurations, conditions, materials, typologies, requirements, etc., which makes it difficult to generalise such connections. However, some studies can provide useful insights for the analysis of the fragility of tank to pipe connections. For instance, Danesi (2015) studied the seismic risk of pipe racks in industrial plants using incremental dynamic analysis. Tadinada and Gupta (2017) proposed structural fragility functions for T-joint connections of large-scale piping systems. Wang et al. (2019) obtained experimental data for the formulation of fragility functions of piping systems connected by grooved fit joints. Hosseini et al. (2020) developed double-variable seismic fragility functions for industrial piping systems. Corritore et al. (2021) proposed a methodology for the identification of critical units in industrial plants using seismic fragility.

Due to the lack of general fragility functions for tank to pipe connections, the development of individual and specific fragility functions can be carried out analytically, taking into account the following aspects:

- Actual State: It is essential to account for the actual condition of the tank-to-pipe connection. Factors such as fabrication defects, inadequate maintenance, ageing, and material degradation can significantly alter the performance of connections compared to their newly constructed counterparts.
- Numerical Model: The model used must accurately represent the physical and mechanical properties of the connection, taking into account complexities and variabilities in geometry, material properties, and boundary conditions.
- Types of Structural Analysis and Related Seismic Input: Different methods of structural analysis may be applied, each requiring appropriate seismic input data that reflect likely ground motion characteristics specific to the site.
- Damage or Limit State: The relationship between seismic actions and the resulting damage is often categorised using standardised damage categories such as those defined by HAZUS (FEMA, 2003). Alternatively, damage states can be defined based on ranges of Engineering Demand Parameters (EDP) that describe specific damage modes (Paolacci et al., 2015).

- Damage-Related EDP: When damage states are established based on EDP value ranges, it is crucial to select an EDP that accurately characterises the specific mode of damage being assessed.
- Input Intensity Measure: The selection of an appropriate intensity measure (e.g., peak ground acceleration, spectral acceleration) is critical, as it directly influences the accuracy of the fragility functions.
- Probability Distribution for Random Variables: Typically, seismic fragility functions adopt a lognormal cumulative distribution function (CDF) due to its straightforward, parametric form, which facilitates the estimation of mean and standard deviation.

These considerations are pivotal in ensuring that the analytical fragility curves developed are robust and reflective of the actual seismic vulnerability of the structure under study. In addition, to consider the real geometrical and mechanical conditions of the structure, it is appropriate to define several fragility functions, each considering different conditions that differ from the actual design.

#### 4. Conclusions

In the risk assessment of industrial plants, the pipelines connecting adjacent tanks can play an important role. In this preliminary study, different pipe-to-tank connections have been analysed in order to provide insight into possible critical configurations and possible mitigation detailing. The obtained results pointed out that the adoption of connecting pipelines with elbows could be beneficial; however, practitioners should pay attention to the stress concentration in the elbows by adopting flexible joints. At the same time, the importance of accounting for the fragility of these elements in the risk assessment has been emphasised. The parametric analysis carried out in this study will be extended in the future in order to account for both record-to-record variability and of the epistemic uncertainties to provide useful fragility functions to be implemented in risk assessment frameworks.

#### References

- Campedel M., 2008, Analysis of major industrial accidents triggered by natural events reported in the principal available chemical accident databases, JRC Scientific and Technical Reports, JRC42281.
- Caputo A.C., Paolacci F., Bursi O.S., Giannini R., 2019, Problems and Perspectives in Seismic Quantitative Risk Analysis of Chemical Process Plants, *J. Press. Vessel Technol.*, 141(1), 010901.
- Ciucci M., Barbieri Vita L., Marino A., 2021, Rischio NaTech da sisma negli stabilimenti con Pericolo di Incidente Rilevante: metodologie di valutazione e gestione, SAFAP 2021.
- Corritore D., Paolacci F., Caprinuzzi S., 2021, A Screening Methodology for the Identification of Critical Units in Major-Hazard Facilities Under Seismic Loading, *Front. Built Environ.*, 7, 1-16.
- Danesi R.J., 2015, Seismic risk of industrial plants: assessment of a petrochemical piperack using incremental dynamic analysis, Master's thesis, IUSS Pavia, Italy.
- FEMA, 2003, HAZUS Multi-Hazard Loss Estimation Methodology – Earthquake Model, Federal Emergency Management Agency, Washington.
- Hosseini M., Ghalyani E., Ghorbani Amirabad N., 2020, Development of double-variable seismic fragility functions for oil refinery piping systems, *J. Loss Prev. Process Ind.*, 68.
- Karamanos S. A., Giakoumatos E., Gresnigt A. M., 2003, Nonlinear Response and Failure of Steel Elbows Under In-Plane Bending and Pressure, *J. Press. Vessel Technol.*, 125(4), 393-402.
- Marino A., Ciucci M., Barbieri Vita L., Palermo O., Quinci G., 2019, Valutazione e gestione del rischio sismico negli stabilimenti con pericolo di incidente rilevante, XVIII Convegno Anidis - L'ingegneria sismica in Italia.
- Paolacci F., Giannini R., De Angelis M., 2012, Analysis of the Seismic Risk of Major-Hazard Industrial Plants and Applicability of Innovative Seismic Protection Systems, *Petrochemicals*.
- Paolacci F., Phan H. N., Corritore D., Alessandri S., Bursi O. S., Reza M. S., 2015, Seismic fragility analysis of steel storage tanks, COMPDYN 2015 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering.
- Piccinelli R., Krausmann E., 2013, Analysis of natech risk for pipelines: A review, JRC Scientific and Policy Reports, Report EUR 26371 EN, European Commission.
- Reza Manshoori M., 2011, Evaluation of Seismic Vulnerability and Failure Modes for Pipelines, *Procedia Eng.*, 14, 3042-3049.
- Salimbeni M., De Angelis M., Ciucci M., 2022, Earthquake NaTech risk assessment in major-hazard industrial plants, a case study: cylindrical liquid storage tank with floating roof, *Chem. Eng. Trans.*, 91, 193-198.
- Tadinada S.K., Gupta A., 2017, Structural fragility of T-joint connections in large-scale piping systems using equivalent elastic time-history simulations, *Struct. Saf.*, 65, 49–59.
- Vathi M., Karamanos S., Kapogiannis I.A., Spiliopoulos K.V., Performance Criteria for Liquid Storage Tanks and Piping Systems Subjected to Seismic Loading, *J. Press. Vessel Technol.*, 139(5), 051801.
- Wang T., Shang Q., Chen X., Li J., 2019, Experiments and Fragility Analyses of Piping System Connected by Grooved Fit Joints With Large Deformability, *Front. Built Environ.*, 5, 1-14.