# Seismic failure modes and damage state/loss of containment relationship of industrial equipment

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ABSTRACT
Major accidents in industrial plants and storage sites may be triggered by seismic events, due to the damage of process equipment resulting in a loss of containment. A quantitative seismic risk analysis is used to demonstrate the risks (individual, societal, economic, and environmental) caused by an activity involving dangerous substances, in case of earthquakes. In particular, starting from the seismic hazard curve of the site in which the plant is placed, the risk is evaluated through the seismic vulnerability assessment of the equipment, expressed in the form of fragility curves, and the relationship damage state/loss of containment. For each critical unit, a set of relevant failure modes and damage state associated to the release of material should be defined. While for steel storage tanks, these failure modes and relationship damage state/loss of containment are available and used, the same cannot be said for the other typologies of industrial equipment as columns, horizontal vessels, compressors, furnaces, etc… The aim of this paper is to provide a criterion to determine damage states and loss of containment resulting from the structural seismic damage for different categories of industrial equipment. The problem has been solved by introducing a “damage state/loss of containment” correlation matrix.

## 1 INTRODUCTION

A process industry is composed of a large number of different equipment; a seismic damage to some of them can produce the leakage of dangerous substances with serious consequences for people and environment and the possible activation of accidental chains.

A seismic risk analysis of a process plant, aimed at quantifying the risk of structural damage to equipment, especially in relation to Loss of Containment (LOC), should start from the seismic behavior of equipment, identifying the Damage States (DS) that can produce losses.

LOCs defined in the classic Quantitative Risk Analysis of a plant are conventional LOCs related to internal failures, such as human error or equipment failure, and neglect structural collapse or external events, which is commonplace in the case of natural hazards. Instead, in seismic QRA, the actual LOC events should be correlated to structural LOC events.

Based on the experience derived by post-earthquake inspections it's possible to collect critical units in a limited number of categories, identified on the basis of geometric and mechanical similarity criteria. In this way it's possible to characterize the seismic structural behaviour and identify the Loss of Containment (LOC) events.

In this paper the critical aspects of some of this kind of equipment are analysed, and the DS and the relevant LOC are individuated.

## 2 STRUCTURAL CLASSIFICATION OF PLANT EQUIPMENT

The main equipment of a process plant can be classified into a restricted number of categories (Paolacci et al., 2013):

1. slim vessels,
2. above-ground squat equipment,
3. equipment on support structure,
4. piping systems.

The slim vessels category includes cylindrical equipment with a large height-to-diameter ratio (usually from 5 to 30). Slim vessels can be vertical elements, anchored to the foundation, both free and restrained along the height, or horizontal vessels on saddle supports.

Above-ground squat equipment are characterized by comparable dimensions in the three directions and high masses; the most important category is that of tanks.

The category of equipment on support structure includes equipment supported by columns (furnaces, spherical tanks, compressors, tanks on legs, etc..), or elevated equipment, placed on metallic frames.

Figure 1. Slim vessels

Figure 2. Above-ground squat equipment

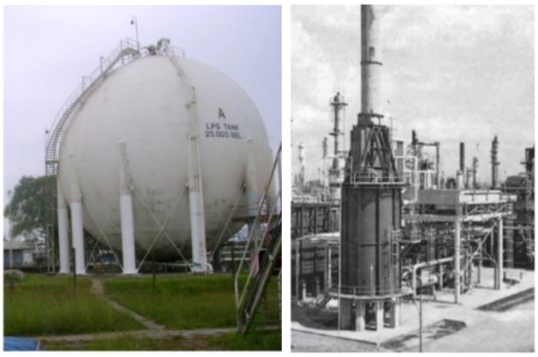

Figure 3. Slim or squat equipment supported by columns

## 3 DAMAGE STATES AND ASSOCIATED LOC

In order to evaluate the seismic vulnerability of equipment, the limit states (LS) must be identified The LS for equipment are defined both respect to the structural behaviour and the release of dangerous materials from the pipes connected to them.

With regard to the former, particular attention must be paid to the collapse limit state which could lead to a potential catastrophic failure of the entire equipment and therefore an instantaneous release of all the content.

The collapse condition, as defined in the codes, refers to conditions that potentially could provoke a structural collapse. Here the term “collapse” is intended as a condition of potential collapse, in order to guarantees appropriate margins with respect to phenomena considered more disastrous than the mere collapse, being involved potential catastrophic consequences with the release of hazardous material. The collapse limit states for each category are listed in Table 1. In the same table the Engineering Demand Parameter (EDP) through which each limit state can be analytically evaluated is also individuated.

Table 1. Definition of EDP and collapse limit states for process plant units

| **Class of Equipment** | **Type of Equipment** | **Collapse LS ($LS_m$)** | **EDP ($D_m$)** |
|---|---|---|---|
| Slim vessels | Columns | Plastic rotation of the bolted flange joint at the columns base | Rotation of the bolted flange joint |
| | Pressurized Horizzontal tanks | Saddles or anchor bolts Failure | Maximum anchor forces or Maximum stress in the saddles |
| Squat Equipment placed on the ground | Storage tanks | Overturning | Overturning moment |
| Equipment on support structures | Elevated tanks or pressure vessels | Failure of the support structure | Maximum displacement of the support |
| Pipes | Stress in the pipe fittings | Craks of the pipe fittings | Maximum stress in the pipe |

Starting from the LOC definition contained in the Purple Book (TNO 1992), assumed as reference, three levels of LOC, ranging from moderate to complete loss of content are considered (Table 2). These LOC must be associated to LS that must necessarily be related to specific structural DS. The first level (LOC1) is associated to the plasticization of the pipe flange joint at the connection to the equipment, able to produce a moderate loss from a small break. A serious loss (LOC2) is associated to the excessive rotation of the flanged joints of pipes connected to the equipment. Finally, the instantaneous release of full content, here identified as LOC3, is associated to the collapse LS.

Table 2. Definition of LOC events in process plant equipment

| | LOC 1 | LOC 2 | LOC 3 |
|---|---|---|---|
| Definition | Continuous release from a 10 mm hole | Continuous release from a full bore of the pipe | Instantaneous release of full content |
| Effects | Limited damage of the structure and limited material release | Consistent damages and release, with possible domino effects. | Structural collapse, catastrophic losses and domino effects |

For the definition of the LOC from the pipes, the results of an experimental campaign are here used, in which different types of flanged joints were tested (Karamanos et al. 2013).

Accordingly, the rotation of pipes with a large diameter (8-14 "), corresponding to the first release of materials are around 0.01 rad, while the complete breaking of the joint occurs for 0.03 rad.

These values can be considered rather conservative because of the high dispersion of the results and are referred to conditions in which the pipes are considered rigidly connected to equipment. In different conditions, the previously defined limits should be appropriately increased. A graphical definition of LOC events is shown in Figure 4 for a horizontal tank.

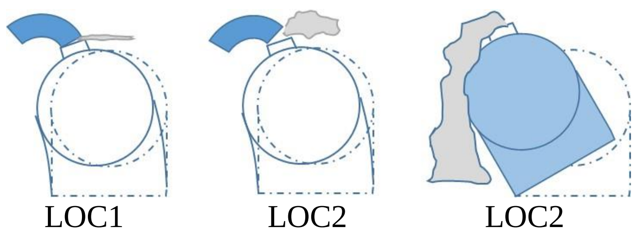

Figure 4. Definition of LOC events for a horizontal tank

The above-defined limit states have also be used for the definition of the response parameters $D_m$, as reported in Table 1.

In the following the DS and the relevant LOC are analysed for the different categories.

## 3.1 *Slim vessels*

### 3.1.1 *Columns*

LOC may occur due to the excessive rotation of pipe flanged joints or to the collapse of anchors; the first one is caused by the column deformation and to the plasticization of the base plate and/or of the skirt. Because of high and slimness of this kind of equipment, small base rotations can cause high displacement at the top with consequent excessive rotations of pipes connected to them (Figure 5).

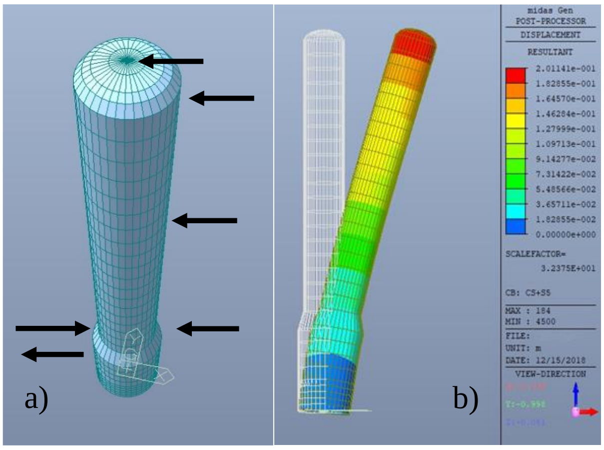

Figure 5. Connections point of pipes (a) and deformed shape of column (b).

The structural response of columns can be analyzed in terms of rotations of the bolted flange joints of pipes and the plastic rotation of the bolted flange joint at the columns base.

In the former case the equality of the rotation of the pipes to those of the column in the point of attachment of the pipe itself can be assumed.

As regards the limit states corresponding to the rotation at the base of the column, in the literature two possible limits have also been identified (Cook et al 2011). The first corresponds to the first plasticization of the flanged connection to the foundation, $\theta_y$, and the second to its full break, corresponding to a rotation equal $2\theta_y$.

The collapse of the column base connection is related to the instantaneous release of the whole content, while the LOC2 and LOC1 conditions can be associated to the deformation of the pipes connections.

In Table 3 the DS/LOC correlation matrix is showed.

Table 3. Correlation DS/LOC for columns

| Damage state (DS) | Eng. demand parameter (EDP) | Limit state (LS) | LOC1<br>Continuous release from a 10mm hole | LOC2<br>Continuous release from the connected pipe section | LOC3<br>Instantaneous release of the whole content |
|---|---|---|---|---|---|
| Collapse of columns base connections | Column base rotation | Complete plasticization rotation (structural collapse) | NO | NO | YES |
| Excessive rotation of pipe flange joint | Column rotation in at the pipe attachment | First release rotation | YES | NO | NO |
| Excessive rotation of pipe flange joint | Column rotation in at the pipe attachment | Collapse rotation | NO | YES | NO |

### 3.2 *Horizontal vessels*

Two Damage States (DS) connected to release of content can be considered for horizontal vessels: the rotations of the bolted flange joints of main pipes in the point of attachment to the equipment, and the collapse of anchor bolts with following overturning and loss of the full content.

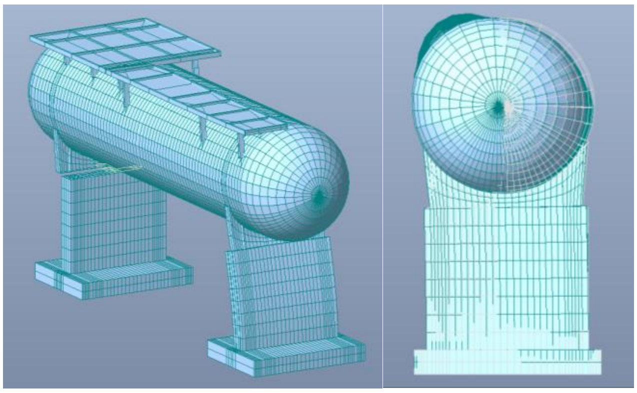

Figure 6. Modes of vibration of an horizontal vessel

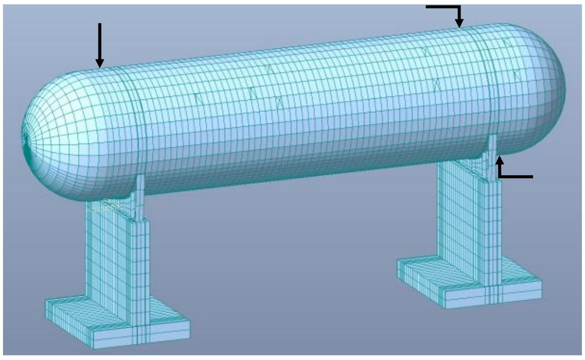

Figure 7. Pipes connections point for an horizontal vessel

Table 4. Correlation DS/LOC for horizontal vessels

| Damage state (DS) | Eng. demand parameter (EDP) | Limit state (LS) | LOC1 Continuous release from a 10mm hole | LOC2 Continuous release from the connected pipe section | LOC3 Instant. release of the whole content |
|---|---|---|---|---|---|
| Anchor bolts | Shear and tension capacity | Complete plasticization (structural collapse) | NO | NO | YES |
| Excessive rotation of pipe flange joint | Vessel rotation in at the pipe attachment | First release rotation | YES | NO | NO |
| Excessive rotation of pipe flange joint | Vessel rotation in at the pipe attachment | Collapse rotation | NO | YES | NO |

For both directions the collapse mechanism can be expressed in terms of demand/capacity ratio, considering both the shear and the tension in the anchor bolts evaluated with the assumption of a rigid behaviour of the steel vessel and that the connections react with a push–pull mechanism. An equivalent simplified static system for the vessel can be considered as described by Moss (Moss, 2012) to calculate the overturning moment. In Table 4 the DS/LOC correlation matrix is showed.

### 3.3 *Equipment on support structures*

For this kind of equipment the DS mainly related to the LOC are the excessive rotation of pipe connection and the failure of the support structure, with following overturning and loss of all content.

For vessels on legs the capacity can be expressed in terms of chord rotation $\theta$ (Figure 8).

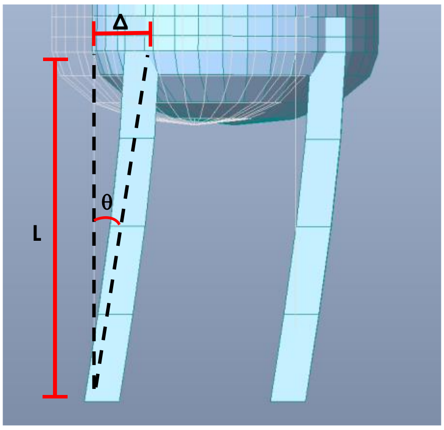


Figure 8. Chord rotation for vessel's legs

For the definition of the rotation at yield and collapse, reference can be made to the indications of FEMA 356 (2000) according to which the limit value of the 'drift' is set at 2.5% for the limit state of Life Safe and 5% for the collapse. The LS causing loss of containment is that associated to collapse. In Table 5Table 3 the DS/LOC correlation matrix is showed.

Table 5. Correlation DS/LOC for vessels on legs and equipment on support structure

| Damage state (DS) | Eng. demand parameter (EDP) | Limit state (LS) | LOC1 Continuous release from a 10mm hole | LOC2 Continuous release from the connected pipe section | LOC3 Instantaneous release of the whole content |
|---|---|---|---|---|---|
| Support legs break due to excessive plast. | Drift | Complete plasticization (structural collapse) | NO | NO | YES |
| Excessive rotation of pipe flange joint | Vessel rotation in at the pipe attachment | First release rotation | YES | NO | NO |
| Excessive rotation of pipe flange joint | Vessel rotation in at the pipe attachment | Collapse rotation | NO | YES | NO |

For elevated equipment it is necessary to consider the collapse both of the supporting structure and of the connection between the equipment and the supporting structure, in addition to the excessive rotation of pipe flanged joints.

### *3.4 Squat equipment placed on the ground*

Squat equipment placed on ground are mainly represented by tanks. For this kind of equipment the following DS can be defined:

- Roof damage caused by sloshing.
- Elastic buckling (EB).
- Elephant-foot buckling (EFB).
- Tensile failure of the wall
- Sliding
- Overturning

Only the DSs able to induce hazardous LOC events and potential consequences are considered. In particular, in storage tanks four types of damage can be envisaged:

- Loss of containment due to the detachment of pipes from the tank wall;
- Loss of containment due to the wall cracking for excessive hoop stress or due to buckling phenomena;
- Loss of containment due to excessive motion of the floating roof;
- Loss of containment due to the cracking for excessive tensile stress or low-fatigue phenomena in the base plate.
- Loss of containing due to the tank overturning.

In Table 6Table 3 the DS/LOC correlation matrix is showed.

Table 6. Correlation DS/LOC for tanks

| Damage state (DS) | Eng. demand parameter (EDP) | Limit state (LS) | LOC1 Continuous release from a 10mm hole | LOC2 Continuous release from the connected pipe section | LOC3 Instant. release of the whole content |
|---|---|---|---|---|---|
| Roof damage | Maximum vertical displacement of liquid | Free-board height | NO | NO | NO |
| Elastic buckling (EB) | Meridional stress | Buckling limit | NO | YES | NO |
| Elephant foot buckling (EFB) | Meridional stress | Buckling limit | NO | YES | NO |
| Tensile failure of the wall | Hoop stress | Tensile strength | NO | NO | NO |
| Sliding | Total base shear | Sliding force | NO | YES | NO |
| Overturning | Overt. moment | Overt. moment limit | NO | NO | YES |

To the category of squat equipment on ground belong also pumps and compressors. For what concerns the pumps, the DS and relevant LOC are associated to anchor bolts damage; to this DS no LOC is associated.

For what concerns the compressors, the DS are defined in terms of rotations of the bolted flange joints of main pipes in the point of attachment to the equipment, and the collapse of anchor bolts, as defined in Table 4 for horizontal vessels.

### *3.5 Pipes and rack*

The definition of DS for rack is carried out in terms of lateral deformation, considering the maximum drift as reference parameter, in accordance with the provisions of the codes. The LS can be defined assuming the reference values in the FEMA356 and ASME41 codes, as listed in Table 7.

Table 7. Drift values for the definition of LS of supporting structures.

| Damage state (DS) | Transversal frames (Moment Frames) | Longitudinal frames (Braced Frames) |
|---|---|---|
| Plasticization | 0.7% | 0.5% |
| Moderate damage | 1.5% | 1.0% |
| Severe damage | 2.5% | 1.5% |
| Collapse | 5.0% | 2.0% |

Operational conditions for pipe-rack and pipes can be associated whit high deformations which do not allow the regular functionality of the structure, but which, in any case, do not compromise structural integrity. This level is related to the yielding.

Collapse of supporting structure is associated with the cut of the pipes and the instantaneous release of all the content (LOC3).

The rupture tension achievement in pipes is related to a severe loss (LOC2), while at the plasticization is associated a less severe loss (LOC1).

No leakage is associated to the plasticization of the supporting structure.

In Table 8Table 3 the DS/LOC correlation matrix is showed.

Table 8. Correlation DS/LOC for pipes and rack

| Damage state (DS) | Eng. demand parameter (EDP) | Limit state (LS) | LOC1 Continuous release from a 10mm hole | LOC2 Continuous release from the connected pipe section | LOC3 Instant. release of the whole content |
|---|---|---|---|---|---|
| Yielding of pipe | Stess | Yielding stress | YES | NO | NO |

| | | | | | |
|---|---|---|---|---|---|
| Collapse of pipe | Vessel rotation in at the pipe attachment | Ultimate stress | NO | YES | NO |
| Support structure break due to excessive plast. | Drift | Drift limit | NO | NO | NO |

## 4 CASE STUDIES

Fragility curves in terms of LOC have been evaluated for equipment of different categories belonging to a plant ideally placed in Priolo Gargallo (Italy). According to the seismic hazard of the place the mean annual frequencies of LOCs are then evaluated.

Four columns have been analysed, with different high to diameter ratio. The main characteristics of the columns are listed in Table 9.

Table 9. Geometric characteristics of analysed columns

| Colum number | Height (m) | Height/Diameter |
|---|---|---|
| 1 | 28 | 9 |
| 2 | 10.8 | 7.7 |
| 3 | 25.3 | 23.3 |
| 4 | 8.7 | 7 |

For each column the fragility function has been evaluated, for each of the DS, by applying to a FEM model a set of 49 ground motion records, selected from the European Strong Motion Database (Luzi et al. 2016) according to 7 site specific response spectra with increasing value of the return period ($T_r$=60, 75, 101, 712, 949, 1950 and 2475 yeas). For each column, according to Table 3, the DS related to the column base and the main pipes have been considered.

The FEM of the columns with indication of the position of the main pipes are showed in Figure 9.

By the Cloud Analysis method (Jalayer and Cornell, 2003) the median value (θ) of the PGA that cause the exceedance of the LS have been evaluated together to the logarithmic standard deviation (Alessandri et al., 2019); they are listed in Table 10.

Given the parameters of the fragility functions and the hazard the mean annual frequency of the occurrence of LOC events can be evaluated (Alessandri et al., 2019). They are listed in Table 11.

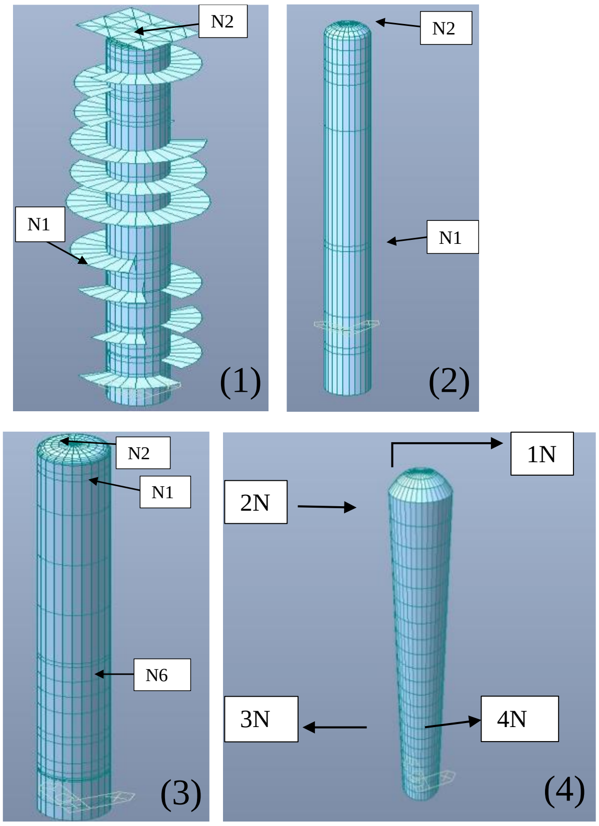


Figure 9. FEM model of columns and connections point of pipes.

Table 10. Parameters of fragility functions for columns.

| Colum number | Median PGA (g) LOC1 | | Median PGA (g) LOC2 | | LOC3 | Log st.dev. |
|---|---|---|---|---|---|---|
| 1 | N1 | 0.48 | N1 | 1.09 | 0.146 | 0.34 |
| | N2 | 0.46 | N2 | 1.03 | | |
| 2 | N1 | 1.60 | N1 | >2.0 | 0.42 | 0.32 |
| | N2 | 1.34 | N2 | >2.0 | | |
| 3 | N1 | 0.51 | N1 | 1.80 | 0.72 | 0.24 |
| | N2 | 0.51 | N2 | 1.80 | | |
| | N6 | 0.60 | N6 | >2.0 | | |
| 4 | N1 | >2.0 | N1 | >2.0 | 1.30 | 0.36 |
| | N2 | >2.0 | N2 | >2.0 | | |
| | N3 | >2.0 | N3 | >2.0 | | |

Table 11. Mean annual frequency of the occurrence of LOC events.

| Colum number | LOC1 | | LOC2 | | LOC3 |
|---|---|---|---|---|---|
| 1 | N1 | 3.0E-04 | N1 | 2.9E-05 | 8.8E-03 |
| | N2 | 3.4E-04 | N2 | 3.4E-05 | |
| 2 | N1 | 1.2E-05 | N1 | 6.7E-06 | 5.6E-04 |
| | N2 | 2.1E-05 | N2 | 6.7E-06 | |
| 3 | N1 | 2.4E-04 | N1 | 6.7E-05 | 9.0E-05 |
| | N2 | 2.4E-04 | N2 | 6.7E-05 | |
| | N6 | 1.5E-04 | N6 | >4.1E-06 | |
| 4 | N1 | >5.5E-06 | N1 | >5.5E-06 | 1.9E-05 |
| | N2 | >5.5E-06 | N2 | >5.5E-06 | |
| | N3 | >5.5E-06 | N3 | >5.5E-06 | |

In the same way the mean annual frequencies of LOC have been evaluated for two horizontal vessels on saddle support and three vertical vessels on legs, they are summarized in the following tables.

Table 12. Parameters of fragility functions for horizontal vessel.

| Vessel number | Median PGA (g) | | | | | Log st.dev. |
|---|---|---|---|---|---|---|
| | LOC1 | | LOC2 | | LOC3 | |
| 1 | N1 | >2.0 | N1 | >2.0 | 0.31 | 0.24 |
| | N2 | >2.0 | N2 | >2.0 | | |
| 2 | N1 | >2.0 | N1 | >2.0 | 0.89 | 0.46 |
| | N2 | >2.0 | N2 | >2.0 | | |

Table 13. Mean annual frequency of the occurrence of LOC events for horizontal vessels.

| Vessel number | LOC1 | | LOC2 | | LOC3 |
|---|---|---|---|---|---|
| 1 | N1 | >4.0E-06 | N1 | >4.0E-06 | 8.2E-04 |
| | N2 | >4.0E-06 | N2 | >4.0E-06 | |
| 2 | N1 | >7.7E-06 | N1 | >7.7E-06 | 7.6E-05 |
| | N2 | >7.7E-06 | N2 | >7.7E-06 | |

Table 14. Geometric characteristics of vertical vessels on legs

| Equipment number | Height (m) | Legs | Weight (kN) |
|---|---|---|---|
| 1 | 5.1 | 4L 100x10x1690 | 41 |
| 2 | 5.3 | 4L 100x10x1790 | 69 |
| 3 | 4.2 | 4L 150x14x1790 | 83 |

Table 15. Parameters of fragility functions for vertical vessels on legs.

| Vessel number | Median PGA (g) | | | | | Log st.dev. |
|---|---|---|---|---|---|---|
| | LOC1 | | LOC2 | | LOC3 | |
| 1 | N1 | >1.5 | N1 | >1.5 | 0.81 | 0.26 |
| | N2 | >1.5 | N2 | >1.5 | | |
| 2 | N1 | >1.5 | N1 | >2.0 | 0.44 | 0.20 |
| | N2 | >1.5 | N2 | >2.0 | | |
| 3 | N1 | >1.5 | N1 | >1.5 | >1.5 | 0.35 |
| | N2 | >1.5 | N2 | >1.5 | | |

Table 16. Mean annual frequency of the occurrence of LOC events for horizontal vessels.

| Vessel number | LOC1 | | LOC2 | | LOC3 |
|---|---|---|---|---|---|
| 1 | N1 | >9.7E-06 | N1 | >9.7E-06 | 5.6E-05 |
| | N2 | >9.7E-06 | N2 | >9.7E-06 | |
| 2 | N1 | >8.7E-06 | N1 | >3.8E-06 | 2.8E-04 |
| | N2 | >8.7E-06 | N2 | >3.8E-06 | |
| 3 | N1 | >1.2E-05 | N1 | >1.2E-05 | >1.2E-05 |
| | N2 | >1.2E-05 | N2 | >1.2E-05 | |

From the previous Tables it's clear that columns can be equally vulnerable to all LOCs events; they are flexible and this indicates a more likely excessive rotation of the bolted flange joints; horizontal vessels are usually more rigid and are characterized by more frequent LOC3 events caused by collapse of anchor bolts, while LOCs due to rotation of the bolted flange joints have a negligible frequency. Most frequent LOC events for vertical vessels on legs are also due to structural collapse and are also a mainly related to the legs slenderness and the supported mass.

## 5 CONCLUSIONS

The aim of this paper is to provide a criterion to determine damage states and loss of containment for different categories of industrial equipment, related to the evaluation of the seismic risk of a process plant, in terms of damage to the equipment that can produce the leakage of dangerous substances with serious consequences for people and environment and the possible activation of accidental chains.

The problem has been solved by introducing a "damage state/loss of containment" correlation matrix for each one of the main categories in which the equipment can be subdivided. The criterion has been developed in order to evaluate the seismic risk of the equipment of a plant ideally placed in Priolo Gargallo.

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