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A short-cut methodology for the selection of critical units in major-hazard plants under seismic loading

Silvia Alessandri[a], Riccardo Bandini[b], Daniele Corritore[a], Fabrizio Paolacci[a], Maria Giulia Sotgiu
[a] *Dipartimento di Ingegneria, Università degli Studi Roma Tre, Via Vito Volterra 62, 00143 Roma, Italy*
b TEA Sistemi Spa, Ponte a Piglieri 8, 56122, Pisa, Italy

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ABSTRACT

Major-Hazard plants are known to be particularly vulnerable to earthquakes, which may trigger technological accidents, also known as Na-Tech events, leading to equipment damage and release of dangerous substances. The scientific community is currently focusing on efficient methodologies for the Seismic Quantitative Seismic Risk Analysis of this kind of plants, but without converging toward a consolidated approach. In fact, several analytical and numerical methods have been proposed and validated through representative case studies. Nevertheless, the complexity of this matter renders their applicability difficult, especially for a rapid identification of the critical components of a plant, which may induce hazardous material release and thus severe consequence for the environment and the community. Accordingly, in this paper a short-cut methodology is proposed for a rapid selection of the most critical components of a major-hazard plant under seismic loading. It is based on a closed-form evaluation of the probability of damage for all components, based on an analytical representation of the seismic hazard and fragility curves of the equipment. At this purpose, fragility curves currently available in literature are used, whereas, the parameters of the seismic hazard curve are estimated based on the regional seismicity. The representative damage states are selected based on specific Damage/Loss of Containment (LOC) matrices, which are used to individuate the most probable LOC events. The potential release of hazardous material is instead quantified by event trees, which provide the probability of occurrence of different physical effects. Consequently, an exposition Index IE is used to quantify the potential effects on the people. In addition, domino effects can be included, using an empirical approach. Finally, the probability of damage P(d) and the exposition index (IE) are re-combined to evaluate the potential risk of each equipment. This allows to build a ranking of the most hazardous components that will be analyzed in a subsequent analysis level. The applicability of the method is shown using a representative case study.

1 INTRODUCTION

Classical consequence-based methods for risk assessment are largely employed for the evaluation of the risk of process industries (Uijt De Haag and Ale 2005). Such methods well fit conditions in which events that imply the release of material and the relevant consequences occur, starting from failure and malfunctioning of single equipment, during service conditions.

In presence of Na-Tech events, such as earthquakes, these methods loss their applicability because of additional complexities as the simultaneous damage of more units, the different structural damage conditions and loss of containment, as well as the development of multiple accidental chains (Young et al. 2004, Caputo 2015). Several attempts to modify the classical quantitative risk analysis methods to account for these aspects are available in the literature, but without converging toward a unified approach (Fabbrocino et al. 2005, Antonioni et al. 2007).

A new probabilistic method for the seismic risk assessment in the process industry, based on the Monte Carlo simulations technique (Rubinstein and Kroese 2008), has been recently proposed by Alessandri et al. (2018).

This methodology, beyond the advantage of automatically generating all possible damage scenarios, appears very flexible, because can be easily adapted to different necessities, including economic loss evaluation, business continuity analysis and death risk analysis. The procedure is based on a multilevel approach (Caputo 2015, Caputo 2016). Each propagation level includes a series of process units directly damaged by the units belonging to the previous level. The analysis starts with the "level 0" in which only units directly damaged by the seismic event are considered. The physical effects generated by LOC events are used for the damage propagation (domino effects) to the subsequent levels by means of Probit functions (TNO 1992).

Generally, it is quite prohibitive to expect that the plant manager might include in the risk analysis the domino effects, given the recognized complexity of these operations, due to the high uncertainty of the models and the interpretation of the results. Therefore, it is usually required to assess only the risk of the single equipment with respect to damage states that generate LOC events.

Accordingly, in this paper a short-cut methodology is proposed for a preliminary selection of the most critical units and the assessment of their seismic risk based on a simple closed form solution.

2 MAIN ISSUES IN SEISMIC RISK ASSESSMENT OF MAJOR-HAZARD FACILITIES

Quantitative Risk Analysis (QRA) of major-hazard process plants is a well-recognized group of techniques devoted to the risk assessment of existing facilities with a high level of potential consequences on people and the environment. Single events characterized by release of content are typically accounted for in consequence analysis to evaluate physical effects like overpressure or thermal radiation able to cause injuries and environmental damages. These methods considers single predefined events generated by human errors or malfunctioning of the equipment. The frequency of these events is also predefined, so that, based on selected event trees the frequency of the physical effects can be quantified and, using specific Probit functions, the consequence on human beings and the environment can be determined (TNO 1992).

Unfortunately, Na-Tech events (technological effect triggered by natural hazard as earthquakes) could induce structural damages that are not known a priori as well as their frequency of occurrence. Consequently, it is not possible to predetermine the worst release conditions and evaluate their consequences. In addition, contemporary damage in the equipment could generate multiple damage conditions and domino effect difficult to be predicted.

All these aspects have been recently summarized in (Caputo et al. 2019). The authors identified the most critical aspects of the quantitative seismic risk analysis (QSRA) including hazard analysis, seismic vulnerability of the plant units and the risk assessment in presence of seismic loading with the related domino effects.

Seismic Hazard analysis and the definition of seismic input is a delicate matter that for major-hazard plants becomes more and more crucial because of the high potential consequences that a seismic damage could ingenerate. Usually PSHA are used, which are based on full probabilistic approaches incorporating site effects and proper ranges of frequencies (Cornell 1968). Nevertheless, several issues are still under discussion. For example, the definition of the nominal life is a controversial point that should be analysed with the due attention because of the extreme harsh conditions in which the equipment of a process plant usually works. Typically, an importance factor is adopted to account for the criticality of these structures, even though this does not help to harmonize the desired uniform risk conditions required by the codes (Koller and Kolz 2014). The return periods of the seismic action is another issue related to the seismic design and the assessment of process plant. Bursi et al. (2016) tried to clarify this aspect, defining two different limit states called Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE), the first one associate to the well-known life safety (SLV) and the second one to the collapse conditions (SLC). This approach, that has been borrowed by the well-known performance-based approach, need more clarification concerning the meaning of the limit states in terms of consequences.

Fragility Analysis of industrial equipment and relevant loss of containment conditions are crucial for a credible risk and consequence-based analysis of process plants. A large number of methodologies for deriving fragility curves, especially for the most diffused equipment like storage tanks, can be found in the literature (Salzano et al. 2003, HAZUS 2001, Buratti et al. 2014,Bakalis et al. 2015, Iervolino et al. 2004, Paolacci et a. 2015, Phan et al. 2016, Kaynia 2013). Nevertheless, few contributions were focused on the possible LOC events and potential consequences (Paolacci et al. 2018). Therefore, the definition of proper damage states/LOC (DS/LOC) relationship is still an open issue. For example, Alessandri et al (2018) proposed the adoption of specific DS/LOC matrices. This is crucial in the consequence analysis, which strongly depends on the amount of released material and the generated physical effects (TNO 1992).

Finally, the risk analysis of a process plant can be quantified by combining Seismic Hazard, Vulnerability and consequence analyses. In addition, given that the seismic action could generate a multiplicity of damage conditions the mutual interaction should also be accounted for, including the possible domino effects (Alessandri et al. 2018, Caputo 2016).

A seismic QRA methodology, including in a realistic manner all these steps is not yet available, despite many years of research. In fact, while the literature about seismic risk assessment of process plants is scarce, as compared to other sectors, recently the attention toward this issue increased as demonstrated by the funding of dedicated international research projects, such as LESSLOSS (2004), STREST (2016), INDUSE (Karamanos et al. 2013), INDUSE-2-SAFETY (2013), and XP-Resilience (2016).

All the above-mentioned aspects demonstrate the complexity of this matter and the need to simplify the approach for practical applications. Consequently, in what follows, a short-cut methodology of a decision making analysis implying the selection of critical components of major-hazard industries is proposed and applied to a realistic case study.

3 A SHORT-CUT METHDOLOGY FOR THE SELECTION OF CRITICAL UNITS IN MAJOR-HAZARD INDUSTRIAL PLANT

In this section a new short-cut methodology for a preliminary selection of critical equipment is proposed, which is based on the idea of using synthetic indexes to account for seismic hazard, vulnerability and exposition (consequences). A ranking of the critical equipment is then built, which allows to identify the most critical units.

Subsequently, the mean annual frequency of their most relevant damage states is calculated using a closed form solution for seismic hazard and vulnerability. Based on possible LOC events, it is possible to quantify then the consequence class to which the analysed equipment belongs and which critical events need to be controlled trough proper mitigation strategies.

The proposed method is based on the following steps:

1. Preliminary identification of the critical units
2. Seismic hazard assessment
3. Fragility analysis of the equipment
4. Identification of DS/LOC matrices
5. Evaluation of the mean annual frequency of LOC events
6. Decision Making analysis and mitigation strategy selection

Figure 1 shows the flow-chart of the method, whose single steps will be analysed and discussed in the next sections.

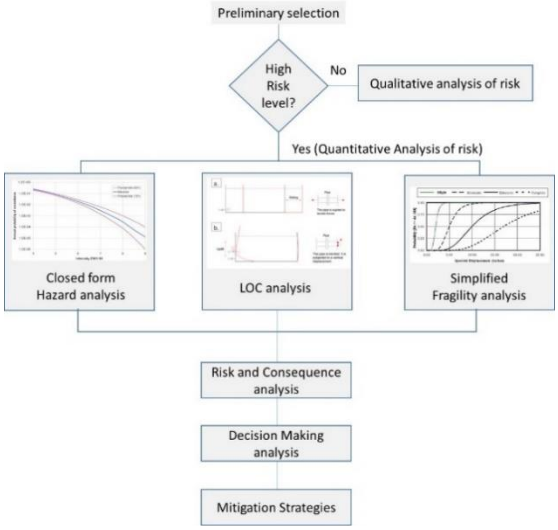

Figure 1 Short-Cut Methodology for damage scenarios assessment of Major-Hazard plants

3.1 *Preliminary identification of the critical units*

The identification of the most critical equipment of a major-hazard industrial plant depends on several factors:

- Level of expected seismic hazard
- Seismic design and vulnerability of the equipment
- Physical effects related to the dangerousness of the stored material
- Exposition to the external zones
- Domino effects

A reasonable selection criterion should necessary integrate all these aspects in a rational manner. At this end, the international literature provides at least three methods (Caputo et al. 2019):

- Preliminary calculation of the damage probability for each equipment and evaluation of the relevant consequences and risk re-composition (Girgin et al. 213).
- Use of vulnerability forms ([30])
- Risk Index methods ([31])

The first two methods require a high level of information and analysis that is not suitable for a rapid screening of numerous equipment. For this reason, a model based on risk indices appears more reasonable. Starting from the definition of seismic risk, whose main ingredients are hazard, vulnerability and exposure, a synthetic IR index can be defined, which can be expressed in a conventional manner as follows:

$$I_R : I_P \times I_V \times I_E \qquad (1)$$

where:

I_R: Risk Index
I_P: Seismic Hazard Index
I_V: Seismic Vulnerability Index
I_E: Exposition Index

Usually, the seismic hazard index I_P should be used to characterize and compare the risk of different seismic zones. In presence of a plant placed in a specific seismic zone, it becomes meaningless and can be omitted.

The seismic vulnerability Index I_V depends on aspects of different nature, of which:

- Equipment typology
- State of preservation
- Degradation phenomena
- Typical states of damage

The most direct way to quantify I_V is to identify vulnerability classes. At this purpose, it is possible to use the fragility curves available in the literature for the different structural categories (HAZUS 2001, PEC 2017). Because the significant damage states for the risk analysis of a process plant are those associable to a material release (LOC), it is reasonable to adopt fragility curves related to an "extensive damage state" that could reasonably generate a loss of containment, (HAZUS 2001).

Table 1 reports the association between structural categories (Paolacci et al. 2013, Figure 2) and the seismic vulnerably classes. The highest class represents structures with the highest seismic vulnerability. Given that each structural category could be characterized by a certain geometrical and mechanical variability, it has been deemed necessary individuate, for each of structural category, more vulnerability classes. For example, the highest columns are typically more vulnerable than the other (PEC 2017).

Finally, the exposition index I_E is defined in such a way to account for the criteria related to the standard major-hazard accidental conditions.

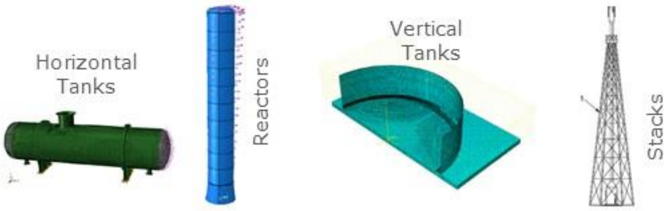

Figure 2. Structural typologies of process plant units

The Seveso III European directive on the Control of Major-Accident Hazards Involving Dangerous Substances (Directive 2012/18/EU, 2012) suggests a preliminary screening based on the standard safety report of the major-hazard plants. Consequently, an index I_E has been developed, which can be determined using the analysis results for standard technological accidental conditions. In particular, the highest value of I_E is associated to the equipment with the highest probability to generate, in case of accident, scenarios with possible consequences outside the plant.

Table 1. Vulnerability classes of process plant equipment

		Vulnerability class			
	Typology	**4**	**3**	**2**	**1**
Slim Vessels	columns	▨	▨		
	stacks			▨	▨
	horizontal tanks		▨		
Squat Equipment placed on the ground	unachored tanks		▨		
	anchored tanks				▨
	unachored tanks		▨		
Equipment on support structures	Compressors		▨	▨	
	Heat Exchangers		▨	▨	
	Support Structures			▨	
Piping systems	Pipes and racks			▨	▨

In particular, $I_E = 1$ for events with limited impact, $I_E = 2$ for events confined in the reference area of the units (D < 50 m), $I_E = 3$ for events with impact in a large zones of the plant (D > 50 m), and finally, $I_E = 4$ for events with consequences in the surrounding community.

In order to identify the most critical units and assuming I_P=1 (it is excluded a comparison of the risk level for different seismic zones), the following risk matrix is proposed:

Table 2. Risk matrix for process plant equipment

Risk Index	Risk level
$12 < I_R \leq 16$	High risk
$9 < I_R \leq 12$	Medium Risk
$6 < I_R \leq 9$	Low risk
$0 < I_R \leq 6$	Limited risk

Once the equipment with medium/high risk level are selected, the quantitative evaluation of their seismic risk is performed in order to recognize structural and nonstructural deficiencies that could generate severe consequences. In this work, such evaluation is confined only to the structures that can be directly damaged by the earthquake, neglecting eventual damage propagation effects (Alessandri et al. 2018).

3.2 Probabilistic Seismic hazard analysis of the site

The seismic hazard of a site is usually analysed in a probabilistic manner and it is measured in terms of mean annual frequency of exceeding a certain intensity measure (IM). The seismic hazard curve is typically expressed in terms of peak ground acceleration (PGA) and can be derived using different approaches, as the one proposed by Cornell (1968). In addition, local seismic analyses are often performed to better characterize soil and to derive possible amplification phenomena.

As alternative, many codes, as the Italian Technical Code (D.M. 17.01.2018) or the Eurocodes (Eurocode 8 – EN (1998)), provides, for different limit states, the return period of the earthquake and thus the mean annual frequency of exceeding the PGA. Consequently, a linear piece-wise seismic hazard curve representation can be used.

It is convenient to linearize the hazard curve in the log-log plane, whose equation in the ordinary plan can be expressed as:

$$\lambda(PGA)=k_0 PGA^{-k} \tag{2}$$

where k_0 and k are the parameters of the straigh line. This linearization can be performed in the range of seismic intensity corresponding to the limit states imposed by the codes, as discussed in the previous section. An example of linerized seismic hazard curve is shown in Figure 8.

3.3 Fragility analysis of the equipment

The seismic vulnerability of a process plant equipment can be effectively described using the fragility curves. The fragility functions provide the probability of exceeding a given limit state, given a ground shaking intensity. For this type of structures, the PGA is usually considered an efficient and sufficient intensity measure (Kaynia 2013, Phan and Paolacci 2016), fully consistent with the seismic hazard analysis. One of the most diffused techniques for fragility functions analysis, which conjugate reduced computational effort and easiness, is the so called “Cloud Analysis (Mackie and Stojadinovic 2005). This technique utilizes the results of proper numerical models to build a probabilistic model based on a regression analysis. Usually, a lognormal distribution is adopted so that the probability of exceeding a specific limit state con be estimated with a normal standard cumulative distribution function:

$$\mathrm{P}(D_{EDP}>LS|IM=x)=1-Ø\left(\frac{ln(LS_m)-ln(D_m)}{\sqrt{\beta^2_{D|IM}+\beta^2_{LS}}}\right) \tag{3}$$

in cui:
$Ø$: standard normal distribution function;
LS_m: median of the limit state;
D_m: median of the demand;
$\beta_{D|IM}$: response dispersion;
β_{LS}: dispersion of the capacity (here neglected)

In this paper, response spectral analyses carried out with proper linear elastic FE models of the equipment, are used to build fragility curves. For a given number of return period, consistent with the expected damages, a minimum number of 7 accelerograms have been selected and used to derive the parameters of the linear regression in the log-log plane as follows:

$$D_m=a\, IM^{\,b} \tag{4}$$

$$\beta_{D|IM}=\sqrt{\frac{\sum_{i=1}^{n}[ln(d_i)\text{-}ln(D_m]^2}{n\text{-}2}} \tag{5}$$

The limit states of the different equipment have been defined both according to the structural behaviour and the possible loss of hazardous containment in the several pipe-equipment connections. Concerning the first ones, a particular attention is paid in the collapse limit state (SSE), which could entail a catastrophic failure of the equipment and thus the instantaneous release of the content (liquid or gas). The collapse condition, as defined in the codes, refers to conditions that potentially could provoke a structural collapse. Specific collapse fragility curves have been introduced recently, which are based on models able to follow the structural collapse step-by-step. Therefore, the term “collapse” must be intended not as blown collapse, but as a condition of potential collapse. This conservative choice guarantees appropriate margins with respect to phenomena considered more disastrous of the mere collapse, being involved potential catastrophic consequences with the release of hazardous material.

Concerning the limit states associated to the failure of pipes connected to the equipment and coming from other units, literature definitions have been adopted, which are associated to standard LOC conditions often used in the QRA of process industries. In particular, three different LOC events are adopted, whose definition is reported in Table 3.

These limits must necessarily be related to specific structural damage states. To this end, the results of an experimental campaign were used, in which different types of flanged joints were tested (Karamanos et al. 2013).

Table 3. 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 of 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

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.

Table 4. 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

These values can be considered rather conservative because of the high dispersion of the results. These values 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 3 for a horizontal tank.

The above-defined limit states have also been used for the definition of the response parameters D_m, as reported in Table 3.

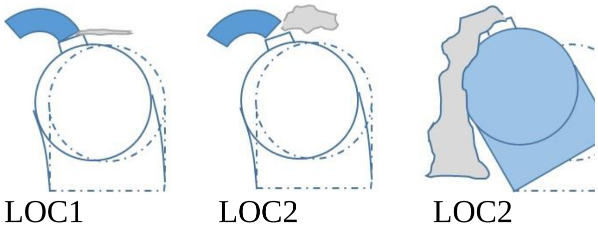

Figure 3. Definition of LOC events for a horizontal tank

3.4 Evaluation of the mean annual frequency of exceeding LOC events

The mean annual frequency of exceeding a given damage state can be performed by applying the total probability theorem, combining the seismic hazard curve with the fragility curves. The general equation is the following:

$$\lambda_{DS}(d)=P[DS>d]=\int P[D>d\,|PGA=PGA_0]d\lambda(PGA) \qquad (6)$$

where λ_{DS} is the mean annual frequency of exceeding the damage d, $P[D>d|PGA=PGA_0]$ is the fragility curve and $d\lambda$ is the differential of the seismic hazard curve. Taking into account that the fragility curve can be expressed analytically using the Cloud Analysis, as well as the hazard curve, the previous integral assumes the following closed form, as suggested by Jalayier and Cornell (2003):

$$\lambda_{DS}(d)=\lambda(PGA_{50\%})e^{\frac{1}{2}(k\beta_{Ed})^2} \qquad (7)$$

where $\lambda(PGA_{50\%})$ represents the hazard corresponding to a probability of 50% of exceeding the damage d, which is derived by the fragility curves, whereas, k represents the slope of the linearized seismic hazard curve. β_{Ed} represents the logarithmic standard deviation of the response due to the seismic action. This latter can be increased to account for epistemic uncertainty (e.g. model imprecision). The total standard deviation becomes the following:

$$\beta_{TOT}=\sqrt{\beta_{Ed}^2+\beta_E^2} \qquad (8)$$

Consequently, the risk calculation can be estimated using the following formula:

$$\lambda_{DS}(d)=\lambda(PGA_{50\%})e^{\frac{1}{2}(k\beta_{TOT})^2} \qquad (9)$$

Thus, the calculation of the mean annual frequency of exceeding the damage can be immediately derived, as the fragility curves and the parameters of the hazard curve are known.

Finally, by means of specific DS/LOC matrices it is possible to obtain the annual frequency of exceeding the LOC events (LOC1, 2 and 3) and thus to evaluate the degree of exposure of the equipment.

An example of DS/LOC matrix concerning storage tanks can be found in (Alessandri et al. 2018).

3.5 *Decision Making analysis and ranking scenarios*

From the calculation of the mean annual frequency of exceeding the LOCs, it is possible to derive a ranking of the most critical components, identifying the most critical conditions for which it may be necessary to intervene with appropriate mitigation systems.

The reference values of the LOC probability are not easily identifiable from the literature. In the present work, it is suggested to operate with an index approach that allows to draw up a list of critical issues. On the basis of performance matrices, it is possible to associate the consequences of a given LOC event based on the associated event tree.

Once the frequency of the different scenarios is known, it is possible to evaluate a risk index based on their consequences. For this purpose, it may refer to the probability classes shown in Table 5 (D.P.C.M. 31.03.89).

Table 5. Probability classes (D.P.C.M 31.03.89)

Mean annual frequency of an event				
$< 10^{-6}$ Rare	$10^{-6}<p< 10^{-4}$ Rather unlikely	$10^{-4} < p < 10^{-3}$ Unlikely	$10^{-3} < p < 10^{-1}$ Quite Likely	$p > 10^{-1}$ Likely
1	2	3	4	5

The consequence classes can be associated to probability classes, as illustrated, for example, in Table 6, which is related to damage thresholds for thermal radiation.

By associating each class of probability to the damage index, it is possible to derive a global index (product of the two) which provides a measure of the severity of the event. Since each LOC event is associated to different possible (mutually exclusive) scenarios, a global risk index can be defined as the sum of the indexes of each of the scenarios. This index can be used to create a ranking of events with decreasing level of risk and draw up a list of priorities. These priorities can be further refined by identifying some additional parameters as, for example, the impact of the intervention, including implementation time, plant shutdown, etc.

Table 6. Damage thresholds for thermal radiation and consequence index

Damage thresholds (Decree 9 May 2001)				
Accidental scenario	High Lethality and Structural damage	Initial Lethality	Irreversible Injury	Reversible Injury
Stationary Thermal Radiation	12.5 kW/m2	7.0 kW/m2	5.0 kW/m2	3.0 kW/m2
Flash-Fire	LFL	½ LFL	-	-
UVCE	0.3 bar	0.14 bar	0.07 bar	0.03 bar
Toxic release	LC50	-	IDLH	-
Damage Index	5	4	3	2

4 APPLICATION TO A REPRESENTATIVE CASE STUDY

The proposed short-cut methodology has been applied to an idealized case study. It represents a treatment plant for the separation of the crude oil from gas and water.

The plant contains different lines for the oil treatment, which includes several equipment as slug catchers, oil/water and gas/water separators, oil stabilization columns, gas treatment columns, heat exchangers, oil storage tanks, piping systems and many others.

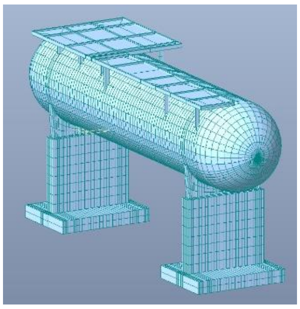

Figure 4. Slugh Catcher

Figure 5. Elevated heat exchanger

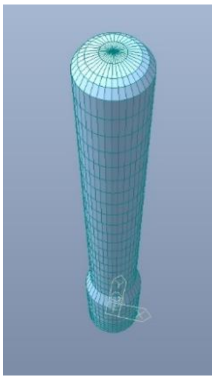

Figure 6. Oil stabilization column

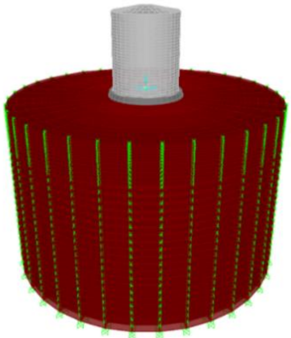

Figure 7. Crude Oil storage tank

In addition, the plant is equipped with an emergency system, which includes a blown down pipeline and a fire protection system with compressors, water storage tanks and a buried pipeline network.

The plant is located in a seismic zone characterized by the hazard curve shown in Figure 8. A series of 7 return periods (Tr=60, 75, 101, 712, 949, 1950 and 2475 yeas) have been used to generate as many response spectra. Thus, for each return period a set of 7 natural accelerograms have been selected from the European Strong Motion Database (Luzi et al. 2016) and used to perform the cloud analysis.

For the application of the short cut methodology, the safety report has been firstly analyzed, which allows to extract a list of more than 400 units characterized by a high release hazard. Subsequently, a sub-list of about 40 units has been identified, which are characterized by a risk index $I_R > 9$; it includes mainly columns, oil/water separators, a broad crude oil storage tank, and a series of elevated equipment, as heat exchangers and vertical separators.

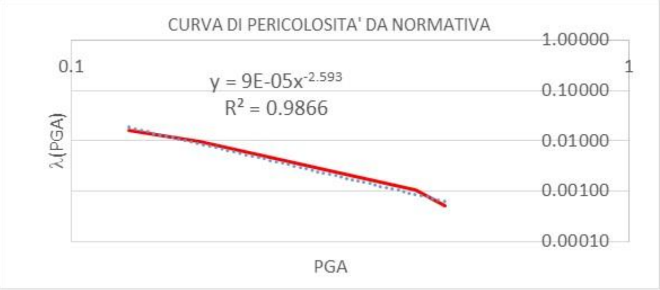

Figure 8. Hazard curve of the site

For each equipment refined FE models have been built using MIDAS software. Some of them are illustrated in Figure 4-5-6-7. As a matter of fact, the stabilization oil columns (Figure 6) have been modeled using shell elements, including the column vessel and the skirt at the column base. The bottom flange joint has been modeled as suggested in Cook et al. 2001, where a nonlinear rotational spring is defined through two different damage mechanisms in which either the plasticization of the flange or the anchor bolts is involved (PEC 2017).

In the present work, a linear response spectrum analysis has been performed. The engineering demand parameters, the damage and limit states are reported in Table 7, where the LOC events are also recognized.

They have been used to build fragility curves by means of the Cloud Analysis. Examples of fragility curves for one of stabilization oil columns are shown in Figure 9–10. The column is clearly characterized by a high vulnerability due to the weakness of its base (50% of probability of exceeding yielding and collapse corresponds respectively to a PGA=0.4g and 0.75g), which corresponds to a LOC3 event.

Table 7. Engineering Demand Parameters, DS, LS and LOC events of a column

Damage State (DS)	Engin. Demand Param. (EDP)	Limit State (LS)	LOC1	LOC2	LOC3
Structural collapse	Rotation of the column base	Complete plasticization	No	Yes	No
Excessive rotation of pipe flanges	Column rotation of the pipe joint	First leakage Rotation	Yes	No	No
Excessive rotation of pipe flanges	Column rotation of the pipe joint	Failure of the flange	No	Yes	No

Figure 10 shows the fragility curve for excessive rotation (failure) at the flange joint of the outlet acid gas pipe that, according to Table 7, corresponds to a LOC2.

The last step of the procedure allowed the calculation of the mean annual frequencies of exceeding the LOC1, 2 and 3 events. They have been reported in Table 8 for some of the critical units. The results show that the slug catcher is extremely vulnerable against damage conditions that implies structural collapse (LOC3). This is due to the weakness of the anchor bolts of the foundation, whereas LOC1 and LOC2 events are less frequent. In fact, the structure itself is particularly rigid and high rotations of the bolted flange joints are unlikely. Differently, the columns are more flexible and this indicates a more likely excessive rotation of the bolted flange joints at the pipe-column connections. As a matter of fact, LOC1 has the highest frequency.

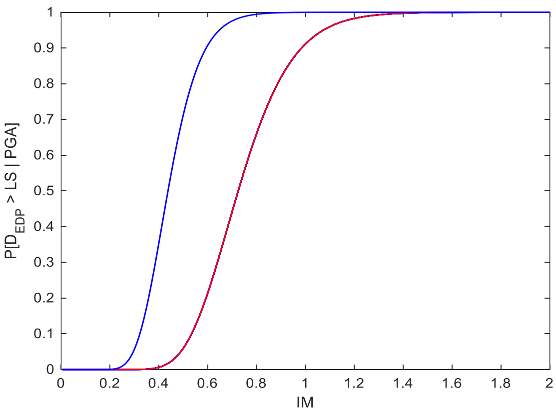

Figure 9. Fragility curves of a stabilization oil column - excessive rotation of the columns base: blue line – yielding, red line – collapse.

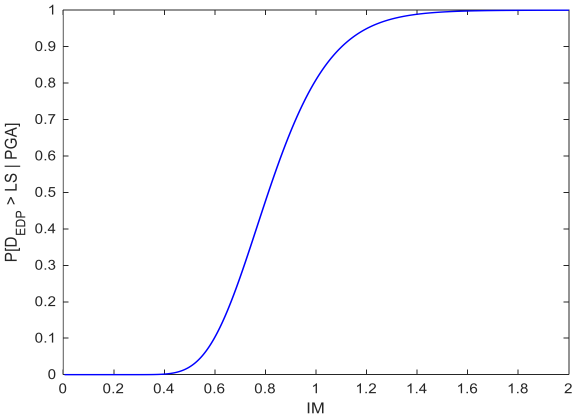

Figure 10. Fragility curves of a stabilization oil column: Excessive rotation at the flange joint of the outlet acid gas pipe

Table 8. Mean annual frequency of the occurrence of LOC events

Units	LOC1	LOC2	LOC3
Column	1.90E-03	5.37E-05	6.62E-04
Slug Catcher	3.30E-09	2.91E-09	7.53E-03
Oil Storage tank	--	3.34E-04	7.94E-06
Vertical separator	1.43E-03	4.74E-04	7.46E-04
Elevated heat exchanger	2.55E-03	4.74E-04	7.46E-04

Elevated equipment could result vulnerable to earthquakes due to the filtering effect of the support structure. For example, the heat exchanger of Figure 5 is extremely vulnerable with respect to all LOC events. This is due to the flexible support structure that amplifies the floor displacements and ingenerates excessive rotation of the pipe flange joints. The support structure is seismically vulnerable as well.

It is clear for this framework that the plant contains equipment particularly vulnerable to earthquake that could generate severe scenarios with important consequences. Therefore, a dedicated decision-making analysis with the indication of the most suitable mitigation strategies would be necessary. This is the last step of the procedure that is still under development and will be presented in the next future.

5 CONCLUSIONS

The paper deals with a new short-cut methodology for a rapid selection and risk analysis of critical process plants components under seismic loading. An index approach is proposed which synthetize the information of the most critical damage scenarios that entails hazardous material release.

Afterwards, using closed form solutions for seismic hazard and fragility analysis a simplified closed form solution for the risk analysis of the most critical units is suggested. Based on predefined new damage states (DS) / loss of containment (LOC) matrices it is possible to identify the mean annual frequency of standardized LOC events based on their seriousness. Finally, a decision making analysis based on simple risk-consequence matrix will help in identifying the most suitable mitigation strategies. A realistic case study has been used to test the proposed methodology demonstrating its simplicity and novelty in evaluating the most frequent LOC events and identifying the most critical scenarios that could generate serious consequences. Future developments will concern the application of the last stage of the method and the application of more rigorous method to validate the proposed methodology.

In the knowledge of the authors this is the first attempt to summarize in a simplified framework a complex matter as the risk assessment of existing process plants under seismic loading.

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