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Probabilistic Fault Tree Analysis of Refinery Plant Components subject to Earthquake Scenarios

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The aim of this paper is to present a probabilistic framework useful for the risk assessment of refinery plant components located in areas prone to seismic hazard. The classical quantitative risk analysis (QRA) in fact allows to evaluate a mean frequency value of a potential release as a function of the fault tree diagram without taking into account uncertainties related in the estimation of temporal occurrence of each singular initiator event. In addition, natural hazards are not frequently considered in QRAs due to challenges related to the evaluation of their consequences in the chemical process industry. For these reasons, this work presents a probabilistic framework to be applied in the fault tree analysis (FTA) to estimate the occurrence probabilities of small, medium and large release from an atmospheric steel tank belonging to a chemical plant located northeast Italy, a national area particularly prone to seismic risk.

1. Introduction

The use of chemical substances in refinery plants is a quite simple process but at the same time characterized by high risks related to transportation, handling and storage of hazardous and flammable materials. To improve site safety, quantitative risk assessment (QRA) methodology was developed over years with the aim to calculate individual, environmental, employee and public risk levels and compare them with threshold values associated to specific regulatory risk criteria. In other terms, QRA can be defined as the formal and systematic approach for the identification of potentially hazardous events, estimating their likelihood and consequences, and expressing the results as risk to people, the environment or the infrastructures. A general classification of methodologies used for risk assessment was provided by Dziubinski et al. (2006). The methodologies of quantitative risk analysis (Center for Chemical Process Safety, 1999) are usually structured as follows:

- description of the system;
- risk identification;
- estimation of failure frequency;
- estimation of consequences.

The main result of a QRA is the estimation of failure frequency values, which usually is derived by coupling results provided by the fault tree analysis (FTA), which mainly takes into account anomalies of mechanical components, control and protective device as main failure cause, and the event tree analysis (ETA), performed to define potential damage consequences induced by each identified top-event. The QRA approach is deterministic since a mean value of failure frequency is taken into account for each initiator event. In addition, natural hazardous events are not specifically taken into account in the classical methodology but are simply embedded in the general frequency estimates of each initiator event.
The main aim of this work is therefore the proposal of a probabilistic fault tree framework to be used for the quantification of occurrence probabilities of each potential top-event, considering also site seismic hazard. The proposal is illustrated and subsequently applied on a case study represented by an atmospheric steel tank of a chemical plant located in Osoppo, northeast Italy. Results obtained from the analyses are finally compared and critically discussed.

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2. Probabilistic fault tree framework

In a QRA one of the objectives is the identification of the sequence of events that lead to undesired consequences and lead to the process failure. The first event in such a sequence is commonly named the initiator event: examples of initiator events are pipe or a vessel breaks, a plant upset or a human error. Consequences of the initiator events are then assessed with reference to other process components or built environment which could be affected by the initiator event occurrence.

Once defined the potential failure sequences, the following crucial step of a QRA is to calculate the probability of occurrence of each accident sequence which leads to an undesired consequence. A method to calculate this occurrence probability is represented by the use of the so-called Fault Tree Analysis (FTA). The FTA methodology is a top down deductive failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine a series of lower-level events.

2.1 Primary failure probability estimates

The commonly used techniques to estimate primary failure probabilities are mainly based on generic data available in literature, specific studies and reliability models (Center for Chemical Process Safety, 1999; ; Schüller, 2005; API, 2008). Data are deterministic, so failure frequencies are average values derived from dataset of past accidents, without taking into account any variability in frequency estimation.

In the probabilistic fault tree framework, frequency mean value data and related standard deviations are indeed used to build probability density functions of the frequency values associated to each initiator event. A lognormal function has been assumed for each initiator event frequency. A set of *n* simulations has then been performed for estimating component release probabilities.

For each random simulation, a i^{th} frequency value λ_i has been sampled from each frequency probability density function. Finally the probability values $P_i(\lambda_i)$ are subdivided according to LNE Department (2009) into three possible release states (*RS*) as follows:

- $P_{i,RS1}(\lambda_i)$ corresponding to *RS1*, (i.e. small release), estimated as 84% of $P_i(\lambda_i)$;
- $P_{i,RS2}(\lambda_i)$ corresponding to *RS2*, (i.e. moderate release), estimated as 8% of $P_i(\lambda_i)$;
- $P_{i,RS3}(\lambda_i)$ corresponding to *RS3*, (i.e. high release), estimated as 8% of $P_i(\lambda_i)$.

2.2 Seismic probability estimates

Chemical plants can be subject to an increase of failure rate if located in areas prone to seismic hazard. In such cases, release can be a direct consequence of earthquake-induced structural failure of tanks, pipes and other elements drift- or acceleration- sensitive. Hence, seismic hazard must be adequately taken into account in probabilistic terms since earthquakes can occur at several sites and can be characterized by different magnitudes following specific recurrence laws.

In this paper an alternative approach for including seismic hazard in risk analysis is presented. If a structural component is located in a site, it is possible to define its seismic hazard curve according to the results provided in the National Building Codes with regard to Probabilistic Seismic Hazard Analysis (*PSHA*). The goal of *PSHA* is to estimate the probability of exceeding various ground-motion levels given all possible earthquakes that could affect the site of interest in a preset time window *T*.

For each ground motion level, by fixing a preset time window and selecting a specific intensity measure, it is possible to perform the seismic hazard disaggregation analysis. Seismic hazard disaggregation allows engineers to identify the values of some characteristics earthquakes that provide the largest contributions to the hazard at a specific site of interest. These events can be viewed in probabilistic terms as the *k* earthquakes dominating the seismic hazard of a site (Iervolino et al. 2011).

Once identified such *k* scenarios in terms of event magnitude *M* and epicenter distance *R* from the site of interest, it is possible to define for each of them a lognormal probability distribution of the selected intensity measure through a Ground Motion Prediction Equation (*GMPE*). On such basis, also in this case, a set of *n* simulations are performed for estimating component release probabilities. For each i^{th} simulation, *k* intensity measure values $IM_{i,x}$ are randomly sampled by respective *GMPE* probability density functions.

Once desaggregated seismic hazard, the following step is the assessment of probabilities of detecting a certain damage state: in this regard, seismic vulnerability of chemical plant component can be described through fragility functions, representative of exceedance probability values for a set of possible damage states as a function of a specific intensity measure value to which an element is subject during an earthquake.

In the framework of the *QRA*, the estimation of loss of hazardous materials is the most challenging issue but it is necessary for properly assess consequences of potential failures. Hence, structural damage states must be converted in terms of release states *RS*, which are the same of that previously described. In such way fragility curves in terms of exceedance probability of a set of possible release states (*RS1*, *RS2*, *RS3*) are taken into account, adopting fragility coefficients reported in Salzano et al. (2003).
So for each intensity measure value $IM_{i,x}$, *RS1*, *RS2* and *RS3* release state probabilities $P_{i,RSj}$ ($IM_{i,x}$) are computed: for each i^{th} simulation, all these values are then condensed taking into account disaggregation percent contributions $\%_x$ of each k^{th} considered event, as follows:

$$P_{i,RS_j} = \sum_{x=1}^{k} (\%_x) \cdot P_{i,RS_j}(IM_{i,x}) \cdot \frac{1}{T_{R,x}} \quad (2)$$

where $T_{R,x}$ is the return time of each considered event.

2.3 Final probability aggregation

The last step of the probabilistic fault tree analysis method herein proposed is the aggregation of probability values derived from the primary and the seismic failure estimates. Release probability values derived in the i^{th} simulation from the electro-mechanical initiator events branch and earthquake occurrence branch are thus processed according to the fault tree diagram (taking into account logical operators AND, OR) to derive a final set of aggregate release probability values for *RS1*, *RS2* and *RS3*. The analysis is repeated performing *n* simulations and thus leading to define release probability value distributions for each release state analysed.

3. Procedure application

The probabilistic fault tree analysis procedure previously described has been subsequently applied to a case study represented by an atmospheric steel tank located in Osoppo, northeast Italy. The case study was selected since the area is highly prone to seismic hazard and was recently subject to the M_w 6.4 1976 Friuli earthquake. The first step of the procedure was the identification of the fault tree logic scheme for the analysed atmospheric steel tank: Figure 1 shows the synthetic fault tree scheme adopted for taking into account possible initiator events for the atmospheric tank case study.

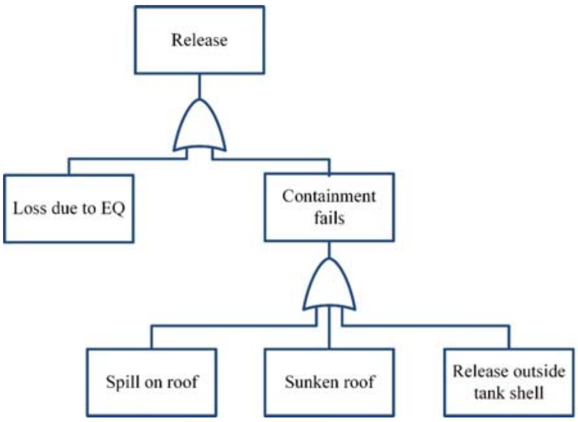

Figure 1: Fault tree scheme adopted for the analysed case study.

The second step was represented by the identification of the failure frequencies values associated to the tank mechanical components: mean values and standard deviations were derived from the Handbook of failure frequency (LNE Department, 2009) and are listed in Table 1.

Table 1: Failure frequencies for mechanical components

Type of release	Mean	Lower bound	Upper bound
Spill on roof	0.0016	0.0011	0.0023
Sunken roof	0.0011	0.0007	0.0016
Release outside tank shell	0.0028	0.0021	0.0037

Peak ground acceleration (PGA) was assumed as relevant intensity measure for the analysed case study. Hence, the seismic hazard curve of the Osoppo site was then retrieved from the Italian Institute of Geophisychs and Vulcanology (*INGV*) with reference to the 10% in 50 years *PGA* hazard map. The value of 50 years was taken into account to define the operating time of failure rates estimation.

On this basis, disaggregation analysis was then performed with the aim to identify the couples of *M*, *R* values representative of the earthquake scenarios mostly contributing to the seismic hazard of the site of interest. Figure 2 illustrates the results of the disaggregation analysis, evidencing how the highest contributions to seismic hazard at the site are given by near-field (0-10km) earthquakes with magnitude values ranging from M_w 4.5 to M_w 6.5.

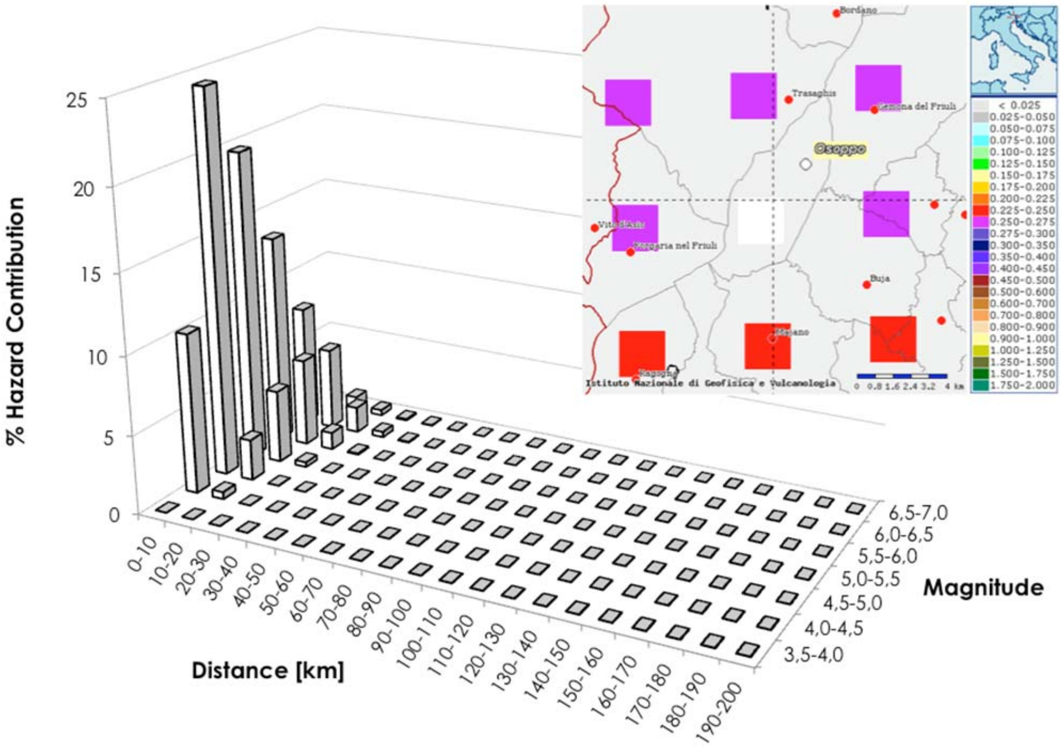

Figure 2: Disaggregation results for the Osoppo site.

For each earthquake scenario characterized by a specific magnitude M_w, epicenter distance *R* and percent contribution to the seismic hazard of the site of interest, the PGA probability density function was derived through the use of the regional *GMPE* of Slejko and Bragato (2008). The return time $T_{R,x}$ values associated to each PGA probability density function were defined according to the recurrence laws of the seismogenic sources contributing to the seismic hazard of the area.

Once desaggregated seismic hazard, the following step is the assessment of probabilities of detecting a certain damage state: in this study, the fragility functions for athmospheric steel tanks proposed by Salzano et al. (2003) were adopted for characterizing seismic vulnerability of the tank under analysis.

Subsequently, for each i^{th} simulation, a $PGA_{i,x}$ value was sampled, and for each k^{th} scenario it was used for define release probability values $P_{i,RSj}$ ($PGA_{i,x}$). Probability values for the *RS1*, *RS2* and *RS3* release states were then combined in each i^{th} simulation with mechanical failure frequencies according to the synthetic fault tree scheme adopted (Figure 1).

A total number of 2000 simulation were performed with the aim of stocastically taking into account all the potential combinations of probability values. Figures 3-5 illustrate the resulting *RS1*, *RS2* and *RS3* release states distributions respectively calculated for mechanical failures (Figure 3), releases induced only by earthquake scenario occurrences (Figure 4) and finally the aggregated top-event probabilities (Figure 5).

Figure 3 shows how taking into account only potential failures induced by electro-mechanical leads to failure probabilities ranging between 10^{-4} and 10^{-3}. As expected higher probability values are associated to lower release states (e.g. *RS*1) whereas lower probabilities characterize more critical release states (e.g. *RS*3). A comparison between probability values obtained with the classical deterministic FTA methodology (black line) and the median ones (blue line) derived with the proposed probabilistic FTA are also reported in Figure 3: it

can be noted how the probabilistic approach leads to higher probability values than those deterministically assessed.
With reference to only earthquake-induced failures, significantly higher release states probability values were observed (Figure 4), ranging from 10^{-2} to 10^{-1}. Also in this case higher probability values are related to lower release states whereas lower probabilities are associated to more risky release states. However, for RS1 and RS2 damage states the median probability estimates are lower than the deterministic ones, whereas for RS3 the probabilistic assessment lead to higher values than those obtained from the classical deterministic approach.

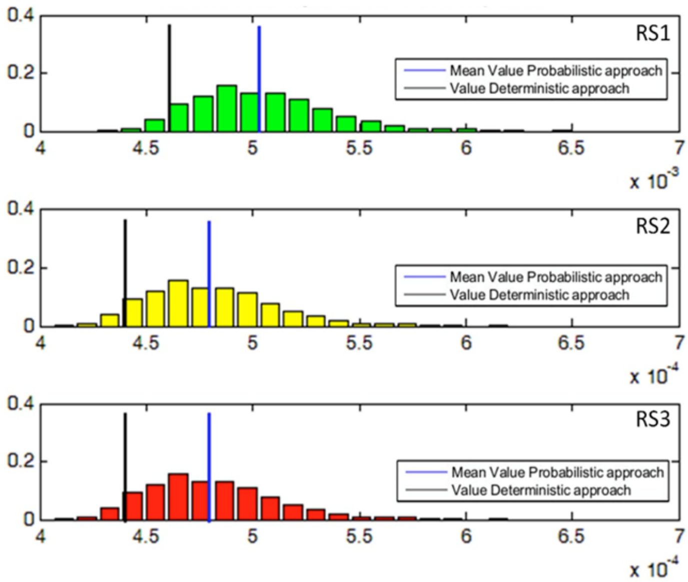

Figure 3: RS1, RS2 and RS3 probability distributions related to mechanical components failure.

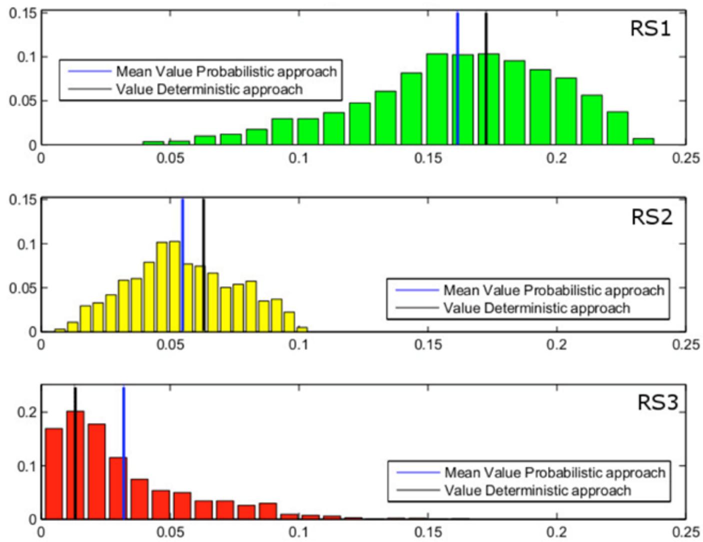

Figure 4: RS1, RS2 and RS3 probability distributions related to failure induced by earthquake scenario occurrences.

Finally, Figure 5 illustrates the results obtained from tha aggregation of classical electro-mechanical failures and damages induced by earthquake occurrence: it can be observed how the latter mainly contributes to the final probability values for the specific case study analysed. Also in this case probability values range from 10-2 to 10-1. The comparison between probabilistic and deterministic results evidenced the same conclusions related to the only earthquake-induced results, i.e. *RS*1 and *RS*2 damage states the median probability estimates are lower than the deterministic ones, whereas for RS3 the probabilistic assessment lead to higher values than those obtained from the classical deterministic approach.

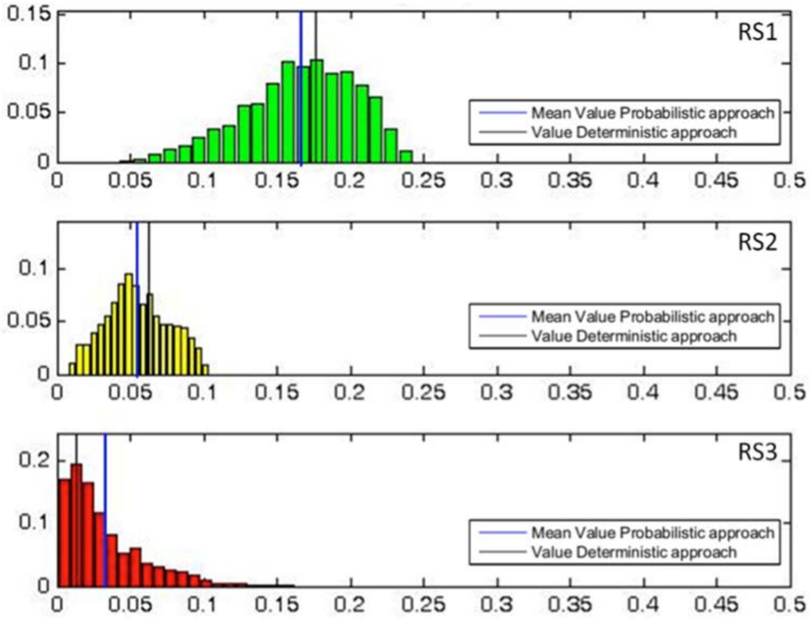

Figure 5: RS1, RS2 and RS3 aggregated probabilities of top-event occurrence.

4. Conclusions

Results have highlighted how taking into account earthquake occurrence is a crucial step in defining release occurrence probabilities in areas prone to seismic hazard. Top-event release probabilities significantly grows up with respect to a fault tree analysis in which seismic hazard is not considered as potential initiator event. When dealing with seismic risk, a probabilistic approach might thus be preferred due to significant uncertainties that are involved in the analysis. This work proposed a method to extend probabilistic approaches also to the classic *QRA* analysis with the aim to formalize a probabilistic fault tree analysis to be perfomed when seismic risk has to be faced.

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