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A Fuzzy-Sets Based Approach for Modelling Uncertainties in Quantitative Risk Assessment of Industrial Plants Under Seismic Actions

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This paper describes a fuzzy set based approach for dealing with uncertainties in the assessment of “NaTech” events triggered by earthquakes: and in particular with those related to seismic hazard and fragilities of the industrial plant components.
The effects of these uncertainties on the Quantitative Risk Assessment (QRA) of local and societal risk indexes, caused by accidental scenarios triggered by seismic events, are evaluated for a case study refinery. The adopted QRA methodology allows for identification and consequence assessment of all the possible scenarios, including possible domino events. The procedure has been implemented in a GIS-based software tool in order to manage the high number of event sequences that are likely to be generated in large industrial facilities.

1. Introduction

The impact of seismic events in industrial plants may trigger accidental scenarios involving the release of hazardous substances. Fires, explosion, toxic releases, water pollution are often the consequence of seismic events in industrial areas. In spite of the importance of these so called “Na-Tech” accidents, scarce attention was devoted until now to the assessment of risk due to major accidents triggered by seismic events (Renni et al., 2010). A comprehensive approach to the risk assessment and the emergency planning in industrial sites able to include the possible external hazard factors is still needed (Cozzani, 2010).
In the present study, a specific approach has been developed for the assessment of “NaTech” events triggered by earthquakes. The methodology has been integrated within a general framework developed for the assessment of external hazard factors in industrial sites. The developed procedure requires to perform *i*) a Probabilistic Seismic Hazard Analysis (PSHA) at the site considered and *ii*) to evaluate the damage probability for the equipment due to seismic events. The large uncertainties related to these data are taken into account in the form of fuzzy numbers (Möller and Beer, 2004).
Finally seismic–hazard and fragility curves are used to perform a Quantitative Risk Assessment (QRA) of local and societal risk indexes caused by accidental scenarios triggered by seismic events. The methodology developed allows for the identification and the consequence assessment of all the possible scenarios that may follow the seismic events, including possible domino events and has been

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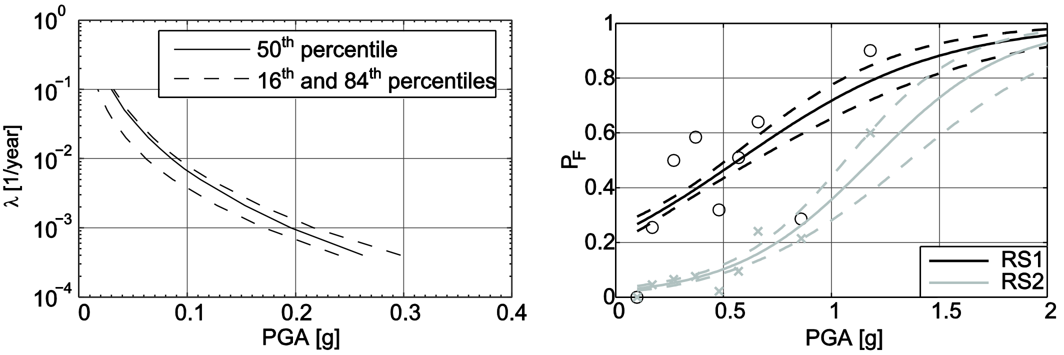

Figure 1: Seismic hazard curves (left) and fragility curves obtained by logistic regression (right). Solid lines indicate the mean curves, dotted lines indicate 68 % confidence intervals and dots and crosses indicate observational data.

implemented in a GIS-based software tool in order to manage the high number of event sequences that are likely to be generated in large industrial facilities.
The application of the methodology to one case-study selected in the Sicilia region evidenced that scenarios initiated by seismic events may be important in the comprehensive assessment of the industrial risk. The results thus confirmed that a robust risk and emergency management should include accidental scenarios that may be triggered by external events as well.

2. Input data and sources of uncertainty

2.1 Seismic hazard

Seismic hazard could be defined, in the most general sense, as the possibility of potentially destructive earthquake effects occurring at a particular location. It is normally estimated through a Probabilistic Seismic Hazard Analysis (PSHA). An example of seismic hazard curve is given in Figure 1.
The PSHA methodology is capable of accounting for aleatory variability. However, there is another important component of uncertainty that must also be accounted for – the uncertainty associated with not knowing the applicability of available methods (Abrahamson and Bommer, 2005). This type of uncertainty is known as epistemic uncertainty within the context of PSHA and is normally evaluated using logic trees. In this case the range of ground-motion values corresponding to a given hazard level may vary considerably but commonly in design only the median value is used. Each aspect of the overall uncertainty must be treated prudently and must be approached in a different manner – in the present work epistemic uncertainty is described by fuzzy sets.

2.2 Seismic damage on refinery equipment

Because of to their structural vulnerability, large atmospheric vessels used for the storage of liquid hydrocarbons, are the categories of equipment more frequently damaged by the seismic events. The damage of this category of tanks following an earthquake often resulted in a loss of containment (LOC) followed by a tank or pool fire if flammable substances were released triggering fires or environmental contamination (Campedel et al., 2008).
The framework of risk assessment suggests adopting a simplified approach to state the damage extension of equipment, based on a number of discrete damage states (DS). With this aim, in the present study, data collected by Salzano et al. (2003) were used. These authors provide data organized in terms of discrete Risk States (RS), with specific reference to the loss of containment The first class, defined here as RS0, corresponds to earthquakes slightly affecting the structure of the tank, with no or negligible loss of containment. A structural damage of the shell, or of a auxiliary equipment, giving rise to a “slight loss of content”, identifies RS1. Finally, a consistent and rapid loss of content following has been identified as RS2. In the present study only RS2 was considered, since this risk state, due to the higher LOC intensities and to the more severe final scenarios involved, is that having the more important influence on the industrial risk caused by seismic events.

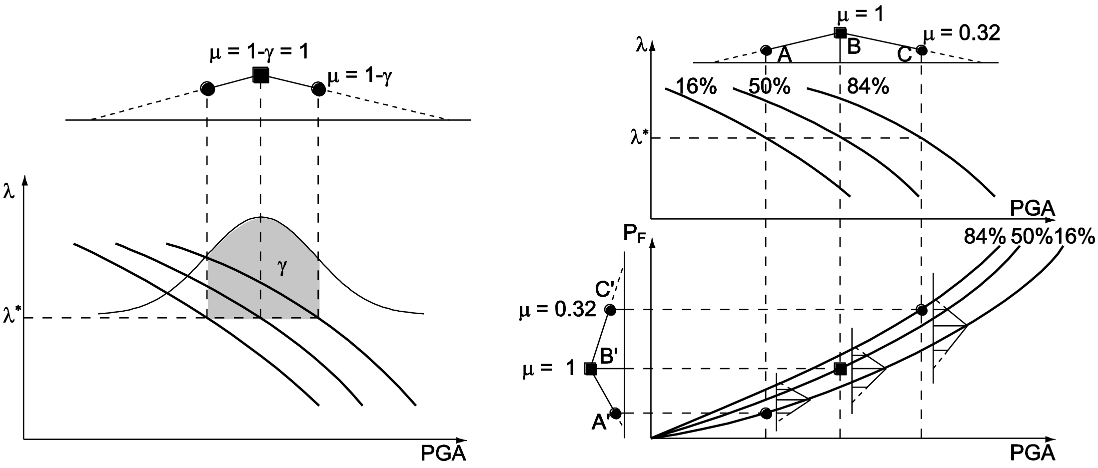

Figure 2: Definition of membership function from confidence intervals (left panel) and fuzzy number giving the PGA associated with a value λ of annual exceedance frequency, and procedure to obtain the fuzzy number giving the probability of failure through the fragility curves (right panel).*

2.3 Fragility Curves

In performing a seismic risk analysis of a system, it is mandatory to identify the seismic vulnerability of components for the various states of damage. For the QRA of an industrial plant, the fragility curve quantifies the probability that a certain release state will be achieved or exceeded as a function of Peak Ground Acceleration (PGA). In the present work, the fragility curves for atmospheric storage tanks have been calibrated starting from the data described in the previous Section.

Logistic regression was used to obtain the fragility curves for RS1 and RS2. The obtained fragility curves, representing the probability of being in or exceeding risk state RS given a peak ground acceleration, are given in Figure 1 together with their 68 % confidence intervals, which are defined by the 16^{th} and the 84^{th} percentile curves. The fragility curves obtained by observational data are be affected by implicit error due to the lack of knowledge, because of no sufficient data or errors in the definition of observational damage, also this source of uncertainty is modeled by means of fuzzy sets.

3. Modeling uncertain variables through fuzzy sets

3.1 Definition of membership functions

The fuzzy number method is considered a very efficient method to define variables in the case of very uncertain data (Möller and Beer, 2004). Probabilistic methods (e.g. cannot be directly used without introducing arbitrary assumptions. Non-probabilistic methods, such as those based on fuzzy sets or interval analysis can be more appropriate as well as simpler. Further details can be found in (Buratti et al., 2010). Confidence intervals of the probability distributions can be used to define the membership functions of the fuzzy sets, and simple fuzzy number operations can then be used instead of probability operations. The fuzzy membership functions are defined as follows. Considering a random variable together with its γ–level probability confidence curves it is possible to define, for a given value λ^* of the variable, the interval $I^{\gamma}(\lambda^*) = U^{\gamma}(\lambda^*) - L^{\gamma}(\lambda^*)$, the extremities of which are obtained from the curves giving the 0.5 − γ/2 and 0.5 + γ/2 confidence intervals (see Figure 2). The value γ of probability is associated to the interval $I^{\gamma}(\lambda^*)$.

In the framework of the fuzzy set theory, the membership μ = 1 − γ is associated with the interval *I*. According to this representation, the vertex of the fuzzy number (μ = 1) is associated with the value of probability given by the mean curve.

3.2 Uncertainty propagation

First of all, seismic hazard curves are obtained for the site under consideration. In particular, the median curves (50^{th} percentile) and those corresponding to the 16^{th} and the 64^{th} percentiles are obtained, in terms of the annual frequency of exceedance λ (these percentiles are here chosen as an

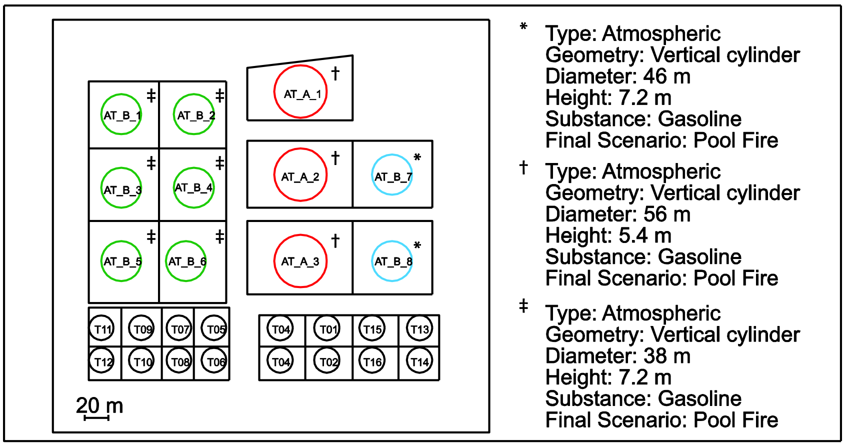

Figure 3: Layout of refinery of the case study refinery.

example but the procedure described is general). Then, chosen a value λ^*, the PGA values corresponding to the vertex and the confidence interval with membership μ = 0.32 are defined. Making use of the fragility curves of the tank (median curve and 16^{th} and 84^{th} confidence curves), the extension principle is used to obtain the fuzzy number representing the probability of failure of the tank (see Figure 2. For the sake of simplicity, a single interval to represent the uncertainty in the definition of the probabilistic variables (seismic hazard and fragility) has been used, and the triangular representation of the fuzzy numbers is used. The membership function is then extended in the figures up to the fuzzy number support (μ = 0). That interval has clearly no probabilistic meaning, but can be used to define two (upper and lower) bounds for the probability of failure to be used for technical purposes

4. Consequence assessment

The final consequences of the releases are due to the accident scenarios that follow the LOC. These may be due to fire, toxic dispersion or environmental contamination depending on the substance hazard and physical state after the release. In order to assess the consequences of a single scenario, physical models are available to define the source term and the physical effects (e.g. radiation intensity with respect to distance in the case of a fire) of the scenario. Even if the application of an event tree technique to assess possible alternative final scenarios was feasible, in the present approach, for the sake of simplicity, a single final scenario was assumed for each LOC event (e.g. a pool fire or a vapor cloud explosion), having a given probability conditioned to the LOC. Conventional models for consequence assessment were used to evaluate the toxic concentration, thermal radiation and blast wave maps following the final event (Van Den Bosh and Weterings, 1997). Consequence maps were then converted in vulnerability (probability of fatality) maps using the conventional human vulnerability models based on Probit functions (Van Den Bosh et al., 1989).
However, an important complication with respect to standard QRA is present in the case of seismic events affecting an industrial site. In fact, because of the action of an earthquake, it is necessary to consider that more than one LOC event (and thus more than one final scenario) may take place simultaneously, and their effects may be synergetic. Moreover, the physical effects may be different (e.g. thermal radiation from a fire and a toxic release). Thus, the actual overall final scenario due to an earthquake may involve a combination of simultaneous final scenario due to single LOC events. This requires the development of a specific approach to the calculation of the vulnerability maps of all the possible overall final scenarios, and the development of a specific approach to the calculation of the frequencies of each overall scenario. The procedures analyses domino effects and allows the identification and the calculation of frequencies of the overall final scenarios due to seismic events. More details on the procedure are provided in Antonioni and Cozzani (2007).
The development of a software tool was a necessary step in order to apply the methodology discussed above. A specific software package was added to the Aripar-GIS software. The Aripar-GIS software

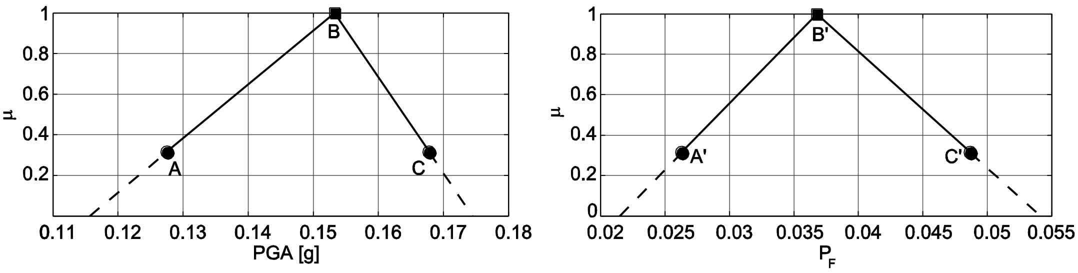

Figure 4: Membership function of PGA for T= 475 y generated starting from confidential levels of PSHA (left) and membership function of the conditional probability of failure for RS2 (right).

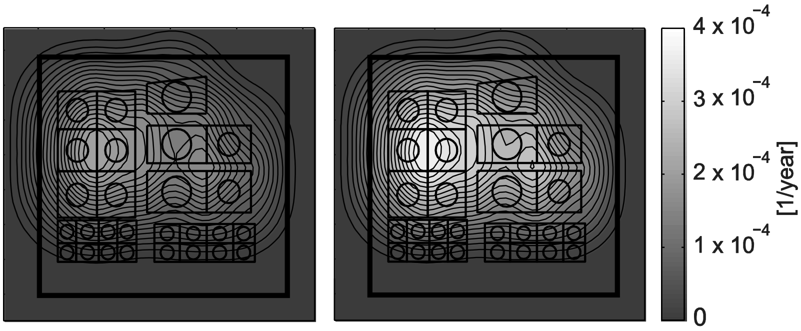

Figure 5: Individual-risk maps obtained using: the fragility value represented by the left point – A' in Figure 4 – (left) and the right point –C' in Figure 4 – of the μ=0.32 interval.

allows the assessment of three standard risk indexes used in the QRA of industrial processes, individual and societal risk: individual risk, societal risk, and Potential Life Loss (Lees, 1996).
The software allows individual and societal risk calculation due both to fixed risk sources and to risk sources associated to transport systems. The "seismic package" was developed in order to apply the above procedure to the analysis of large industrial plants or of extended industrial areas. The software automatically generates all the possible overall final scenarios and performs the quantitative evaluation of the risk in the area of interest on the basis of a simplified layout that should be implemented in a GIS environment. Further details are reported elsewhere (Antonioni and Cozzani, 2007).
The layout defined for the case study is reported in Figure 3. The layout reports the number, position, and catch basin of the units considered in the analysis. The boundaries of the plant section considered are also evidenced. Following usual design standards, each unit in the layout is identified by a unit identification code. Tanks labeled with T in Figure 3 were not considered in the analysis for the sake of simplicity. For the sake of simplicity, a single risk state, RS2, was assumed in the analysis of LOCs triggered by seismic events. In the analysis of LOCs triggered by seismic events, only the worst-case scenarios were considered. A conservative value was assumed for ignition probability (100 %) in order to take into account the very high ignition probability suggested by past accident analysis.

4.1 Uncertainty modeling by fuzzy numbers

The seismic hazard data used in the present work was produced by the workgroup MPS 2004, and is available through the web-site developed by Progetto S1 (Istituto Nazionale di Geofisica e Vulcanologia, 2007). These curves were obtained using a logic tree with sixteen branches to describe epistemic uncertainties related to: *i*) the procedures used to define the completeness of the earthquake catalogue; *ii*) the definitions of seismicity ratios; and *iii*) the choice of attenuation relationships. As described in Section 3.1, the median hazard curve is used to define the vertex of the fuzzy number (μ = 1) and the curves corresponding to the 16th and the 84th percentiles are used to define the μ = 0.32 level interval (see Figure 1 and Figure 4). In the present work the 16th and the 84th percentiles were used because no further data is provided by Progetto S1 and no specific PSHA for the site under consideration was carried out in the present work. Nevertheless the procedure described is general.

Once the fuzzy number representing the PGA is defined, it is possible to obtain a second fuzzy number representing the fragility, as was discussed in Section 3.2. In the case study presented, only the Risk State RS = 2 was considered. The so obtained fuzzy number is depicted in Figure 4. The procedure described in Section 4 was used to calculate Individual-Risk (IR) maps for the case study refinery. Figure 5 depicts the maps of IR corresponding to two different fragility values considered, i.e. points A', and C' in Figure 4. Comparing the two panels of Figure 5, it can be observed data uncertainty can have a significantly influence on IR values.

5. Conclusions

The present work presented a fuzzy-number based procedure for modelling data uncertainty in quantitative risk assessment analysis. Epistemic uncertainties on seismic hazard, obtained through probabilistic seismic hazard assessment analysis, and on seismic fragility curves were modelled by fuzzy set theory. This approach gives a very simple framework to threat uncertainties

The effects of uncertainties on Quantitative Risk Assessment (QRA) of local and societal risk indexes, caused by accidental scenarios triggered by seismic events, were evaluated for a case study refinery. The adopted QRA methodology allows for identification and the consequence assessment of all the possible scenarios, including possible domino events. The procedure was implemented in a GIS-based software tool in order to manage the high number of event sequences that are likely to be generated in large industrial facilities. The developed methodology requires a limited amount of additional data with respect to those used in a conventional QRA.

References

Abrahamson N.A., Bommer J.J., 2005, Probability and Uncertainty in Seismic Hazard Analysis, Earthquake Spectra, 21, 603-607, DOI: 10.1193/1.1899158.

Antonioni G., Cozzani V., 2007, A methodology for the Quantitative Risk Assessment of major accidents triggered by seismic events, Journal of Hazaurdous Materials, 75, 48-59, DOI: 10.1016/j.jhazmat.2006.12.043.

Buratti N., Ferracuti B., Savoia M., Antonioni G., and Cozzani V., 2010, Quantitative Risk Analysis of an Industrial Plant Under Seismic Action, XIV European Conference on Earthquake Engineering, 30 August - 3 September, Ohrid, Republic of Macedonia.

Campedel M., Cozzani V., Garcia-Agreda A., Salzano E., 2008, Extending the quantitative assessment of industrial risks to earthquake effects, Risk analysis, 28, 1231-1246, DOI: 10.1111/j.1539-6924.2008.01092.x.

Cozzani V., 2010, Towards the inclusion of external factors in quantitative risk assessment: the analysi of NaTech accident scenarios, Chemical Engineering Transactions, 19, 1-6, DOI: 10.3303/CET1019001.

Istituto Nazionale di Geofisica e Vulcanologia, 2007, Interactive Seismic Hazard Maps <esse1-gis.mi.ingv.it> Accessed 27.03.2012.

Lees F.P., 1996, Loss prevention in the process industries (II ed.), Butterwoth-Heineman, Oxford, UK.

Möller B., Beer M., 2004, Fuzzy Randomness: Ucertainty in Civil Engineering and Computational Mechanics, Springer-Verlag, Berlin, Germany.

Renni E., Basco A., Busini V., Cozzani V., Krausmann E., Rota R., Salzano E., 2010, Awareness and mitigation of NaTech accidents: Toward a methodology for risk assessment, Chemical Engineering Transactions, 19, 383-389, DOI: 10.3303/CET1019063.

Salzano E., Iervolino I., Fabbrocino E., 2003, Seismic risk of atmospheric storage tanks in the framework of quantitative risk analysis, Journal of Loss Prevention in the Process Industries, 16, 403-409, DOI: 10.1016/S0950-4230(03)00052-4.

Van Den Bosh C.J.H., Merx W.P.M., Jansen C.M.A., De Wager D., Reuzel P.G.J., Leeuwen D.V., Blom-Bruggerman J.M., 1989, Methods for the calculation of possible damage (green book), Committee for the Prevention of Disasters, The Hague, The Netherlands.

Van Den Bosh C.J.H., Weterings R.A.P.M., 1997, Methods for the calculation of physical effects (Yellow book), Committee for the Prevention of Disasters, The Hague, The Netherlands.