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COMPARATIVE ANALYSIS OF TECHNOLOGICAL AND NATECH RISK FOR TWO PETROLEUM PRODUCT TANKS LOCATED IN SEISMIC AREA

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Abstract

The failure of process equipment due to the impact of natural hazards, the so-called Natech events, have generated several industrial accidents, such as Fukushima, Japan - 2011, Ichihara, Japan - 2011, Tupras, Turkey - 1999, Northridge, US - 1994 etc., causing the release of large quantities of hazardous materials in the environment. Earthquakes occupy a leading position in the list of natural hazards with Natech potential, causing serious damage and the loss of containment in process equipment. The present study reveals the importance of Natech risk analyses for industrial sites. The aim of the study is to compare the Individual Risk (IR) and Societal Risk (SR) results between conventional technological risk and Natech risk, related to a possible Natech event triggered by an earthquake for two petroleum products storage tanks, located in an urban area in the South-Eastern part of Romania. The results show an increase of approximately one order of magnitude in the Natech risk compared to technological risk for the selected study area. Results highlight the fact that Natech scenarios should be included in the risk analysis process for technological sites located in natural hazard prone areas and applied for land-use planning purposes as well.

Key words: earthquake, individual risk, land-use planning, Natech, risk assessment

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1. Introduction

During the last years there has been an increase in the number of natural hazards, which causes concerns about the possible effects of these phenomena on industrial activities (EM-DAT, 2013; Ozunu et al., 2011). Hazardous industrial sites themselves have always presented a threat for the community, being a common reality in urban areas, often provoking major accidents which affect the communities in the surrounding areas. Several well-known Natech events occurred in the last years, such as the fires and explosions at chemical facilities following the Tohoku earthquake, Japan – 2011 (Krausmann and Cruz, 2013), Tupras, Turkey – 1999 (Girgin, 2011; Steinberg et al., 2001), Northridge, US – 1994 (Lindell and Perry, 1998; Rose and Lim, 2002) etc., releasing large quantities of hazardous materials in the environment.

The natural hazards which can trigger technological accidents include earthquakes, floods and flash floods, tsunamis, volcanic eruptions,

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landslides, tornadoes, wildfires, extreme snowing etc. If the industrial sites are located in any of these natural hazard-prone areas, then the Natech events may increase the impact, the overall damage and the size of the affected areas (Furdu et al., 2013; Ozunu et al., 2011; Petrova, 2011). Furthermore, Natech events can cause indirect damage, generating the delay of response actions, depending on the complexity of the phenomena. Adequate preparedness, proper emergency planning and effective response are crucial for the management of Natech events and for the mitigation of the consequences (Boca et al., 2010; Cozzani et al., 2006).

The last three years were characterized by a record in the number and scale of natural hazards, demonstrating once again the potential of natural hazards to harm the human society and the vulnerability that characterizes society in terms of people and property affected by natural hazards. Among these hazards, earthquakes and their aftermath are a leading cause for this unfortunate record in terms of consequences, causing serious damage and the loss of containment in the process equipment (Antonioni et al., 2007). As such, in 2010 and the first semester of 2011 natural disasters accounted for the death of more than 320000 people worldwide and economic losses that reached 320 billion US$ (Petrova and Krausmann, 2011).

The site taken into consideration for the case study in the present paper is located in one of the highest earthquake risk areas of Europe, namely the Vrancea area in Romania (Burtiev, 2011; Sokolov et. al. 2007; Toma-Danila, 2012). The aim of the present study is to compare the location-based Individual Risk (IR) and Societal Risk (SR) results between pure technological risk and total risk (including Natech and technological risks). The Natech event is assumed to be triggered by an earthquake on two hydrocarbon storage tanks located in an urban area in the South-Eastern part of Romania. The tanks pertain to a refinery and the reason behind selecting these particular tanks for the analysis is that the tanks contain n-hexane, a highly flammable hydrocarbon, and are located at a very short distance (less than 40m) from a residential area. This raises awareness on the necessity of Natech risk analysis used for land-use planning (LUP) purposes in this case.

2. Risk assessment approach

The risk assessment procedure includes both the qualitative identification and analysis of hazards and the quantitative estimation of risk. The combined use of these methods is considered to be the most appropriate for the estimation of risk, taking into account the high level of experience and knowledge in this field and the state of the art in the computer based modeling and simulation.

At European level there are three main risk assessment approaches used, namely the consequence-based approach, risk-based approach and deterministic approach methods with implicit judgment of risk (Christou et al., 2006). The consequence-based approach focuses on the estimation of safety distances at which different consequences of credible accident scenarios can occur, without the quantitative estimation of the likelihood. The risk-based approach is based on the quantitative estimation and combination of likelihood and consequences. The final risk is represented using individual risk contours and societal risk F-N (Cumulative Frequency - Number of fatalities) curve. The deterministic approach is based on the concept that sufficient safety measures must exist at the establishment to protect the population from an accident. Hybrid methods have been also developed, which are based on quantitative consequence analysis combined with qualitative frequency estimation (Cozzani et al., 2006).

Quantitative risk analysis includes the use of numerical data and mathematical modeling in the estimation of accident likelihood and consequences. The quantitative results can be highly affected by the precision and validity of the input parameters, therefore, the results should be taken into consideration as estimates, with a variable scale depending on data quality.

The risk analysis presented in the study includes the determination of the possible accidental scenarios, the estimation of damage probabilities in case of an earthquake, modeling of physical effects using Effects software, calculation of conventional technological IR (location-based risk) and SR using ARIPAR-GIS modeling software and comparison with calculated total IR and SR (including Natech and conventional technological scenarios). The location-based IR assumes the risk of death, as a result of an accident within an establishment, for an unprotected person who is permanently present at a given location.

The acceptable IR limit values used for LUP purposes, accepted in several EU member states (UK, The Netherlands, Hungary, Czech Republic), are 10^{-5} y^{-1} upper and 10^{-6} y^{-1} lower limits (Duijm, 2009; Trbojevic, 2005). These values were considered in this paper for the analysis of LUP criteria. It has to be mentioned that in Romania the acceptable IR limit values used for LUP purposes have not yet been implemented in legislation.

3. Case study application

The earthquake risk in Romania is one of the highest in Europe. The Vrancea seismic area (at the Eastern Carpathian arc bend) is mostly characterized by intermediate-depth earthquakes, and accounts for Romania's high level of seismic hazard. During the last century four major earthquakes occurred: on November 10th 1940 (MW = 7.7), March 4th 1977 (MW = 7.4), August 30th 1986 (MW = 7.1) and on May 30th 1990 (MW = 6.9). During the 1977 event 1570 people died, 11300 were injured and 32500 residential and 763 industrial units were destroyed or seriously damaged (Ardeleanu et al., 2005).

The selected site is located approx. 120 km South-West of the center of Vrancea seismic region. Considering a 475 years return period, the Peak Ground Acceleration (PGA) in the area of the studied site can reach up to 3.5 m/s^2 with an intensity of approx. 8.5 MSK (Ardeleanu et al., 2005; Leydecker et al., 2008; Sokolov et al., 2007). The tanks selected for the risk analysis are vertical cylindrical stainless steel single wall tanks with different storage capacities, approximately 800 m^3 and 2000 m^3 respectively, placed together in a retention bund. For a conservative approach in the risk analysis, a maximum filling degree of 80% of the tanks is considered. The surface of the retention vat is 1740.5 m^2. The tanks are located at a distance of approximately 40 m north of a residential area. The residential area is comprised of single story houses and has an estimated population density of 39.13 inhabitants/ha, constituted of refinery workers and their families.

The substance stored in the selected tanks is n-hexane, known as highly flammable and harmful (risk phrases: R11 – highly flammable, R38- irritating to skin, R48/20 - harmful: danger of serious damage to health by prolonged exposure through inhalation etc.). The analyzed scenarios are as follows:

A. Conventional technological failures:

A.I. Damage state 3 (DS 3) - catastrophic rupture of the tank due to internal technological causes and the release of the entire amount of n-hexane in the retention vat (G.1.a. scenario according to Uijt de Haag and Ale, (2005)). The possible outcomes of the release can be: Flash fire or VCE (Vapor Cloud Explosion) due to pool evaporation; Pool fire in the retention vat; Domino effect: internal vapor cloud explosion in the second tank in the vapor space above liquid (due to the heat effect of the pool fire in the retention vat);

A.II. DS 2 - continuous release from a hole on the tank wall with an effective diameter of 10 mm, due to internal technological causes (G.3.a. scenario according to Uijt de Haag and Ale, 2005). It was considered a release time of 10 minutes, in which an intervention can be made. The possible outcomes of the release are qualitatively similar to case A.I.

B. Failure due to seismic events:

B.I. DS 3 - catastrophic rupture of one or both tanks due to seismic event and the release of the entire amount of n-hexane in the retention vat. The possible outcomes of the release can be qualitatively similar to case A.I., but also the possibility of simultaneous damage of the tanks is considered.

B.II. DS 2 - continuous release from a hole on the tank wall with an effective diameter of 10 mm, due to seismic event. It was considered a release time of 10 minutes, in which an intervention can be made. The possible outcomes of the release are qualitatively similar to case B.I.

Two different meteorological conditions were used in the modeling, calculated from hourly data for the year 2011, as such stability class D with wind speed of 4 m/s and stability class F+G with wind speed of 1 m/s.

The simulation results for the determination of physical effects (using Effects software) show that VCEs are not possible due to the low congestion of the lay-out considered, while Flash Fires are negligible since the resulted concentration of n-hexane at 50.4 m downwind from the center of the source (at 0 m height) is 27350 mg/m^3, which is lower than the LFL (Lower Flammable Limit): 37623 mg/m^3. The internal explosion simulation of the 2000 m^3 tank resulted a distance of 32 m for the 140 mbar threshold limit, corresponding to the beginning of lethal effects (Török et al., 2011), therefore this scenario was considered in the IR and SR analysis. The pool fire in the retention vat scenarios in case of DS 3 show significant heat radiation effect reaching the residential area, therefore these scenarios were also considered in the IR and SR calculations. The pool fire – DS 2 scenarios presented much lower heat radiation effects, the maximum pool radius resulted to be 4.1 m.

The parameters that are the most significant in the analysis are the surface of the retention vat, wind speed and wind direction.

The loss of containment (LOC) frequencies, $F1 = 5\cdot10^{-6}\ y^{-1}$, for the G.1.a scenario and $F2 = 1\cdot10^{-4}\ y^{-1}$ for the G.3.a scenario due to technological (internal) causes were selected from Purple Book, pp. 3.6 (Uijt De Haag and Ale, 2005).

The LOC frequencies for the DS 2 and DS 3 of a tank due to the seismic event were calculated based on data for a reference seismic event with a recurrence period of 475 years ($f_{eq} = 2.11\cdot10^{-3}\ y^{-1}$) and a PGA of 3 m/s^2 (0.306 g) (Ardeleanu et al., 2005; Sokolov et al., 2007). The PGA was estimated based on a PSHA (Probabilistic Seismic Hazard Analysis) map developed for Romania by Ardeleanu et al. (2005). The k_1 and k_2 coefficients values selected for the Probit functions, see (Eq. 1), are presented in Table 1:

$$Pr_{DS,i} = k_{1,i} + k_{2,i} \cdot ln(PGA) \tag{1}$$

The coefficient values were selected based on a near full filling level for anchored atmospheric tanks. The calculated damage probabilities (P_d) in case of an earthquake resulted to be: $1.52\cdot10^{-2}$ for DS 3 and 5.13 10^{-1} for DS 2.

Table 1. Values of the Probit constants in (Eq. 1) for different damage states (Antonioni et al., 2009)

Damage state	k_1	k_2
DS 2	7.01	1.64
DS 3	4.66	1.54

Considering, that two tanks are present in the same retention bund the LOC frequency combinations were estimated using the domino effect methodology presented by Cozzani et al. (2005), see Table 2. The probability of damage combinations P_{comb} can be estimated with (Eq. 2):

$$P_{comb} = P_d^{\,n} (1-P_d)^{(N-n)} \qquad (2)$$

where: P_d – probability of damage due to the earthquake; n – no. of simultaneously damaged tanks; N – total number of tanks;

The combined LOC frequency is the product of the combined damage probability and the frequency of the seismic event (Eq. 3):

$$f_{comb} = P_{comb}\, f_{eq} \qquad (3)$$

The total LOC frequency for DS 3 due to seismic OR (logical gate) conventional technological event, considering the damage of one (n = 1) OR two tanks (n= 2) is resulted to be $3.708\cdot10^{-5}$ y^{-1} and it was calculated by the addition of conventional technological failure frequency F1 to the combined LOC frequencies (Table 2). Proceeding in the same way for the DS 2 a total LOC frequency of $1.18\cdot10^{-3}$ y^{-1} was obtained. The pool fire and internal explosion scenarios were analyzed using Effects software for the determination of physical effects versus distance. The "Pool fire on land" and "Multi-Energy" models used in the study are briefly described in the Yellow Book of TNO (Van den Bosch and Weterings, 2005). The results of the simulations were introduced in the ARIPAR-GIS Software for the determination of the individual and Societal risk (Antonioni et al., 2007; Egidi et al., 1995; Spadoni et al., 2000).

The consequence models are based on the use of Probit functions for the determination of the probability of death of a person exposed to heat radiation and overpressure effects (Uijt de Haag and Ale, 2005).

4. Results and discussion

The results of the IR calculations are represented in Figs. 1 and 2, using individual risk curves. Fig. 1 represents the IR for the conventional technological accident scenarios. One can note that the lower limit IR value of 10^{-6} y^{-1} exceeds the boundary of the residential area, but the upper IR limit value of 10^{-5} y^{-1} was reached only inside the site's boundaries. Comparing the results of IR represented in Figs. 1 and 2, one can conclude that including the Natech scenario in the risk analysis the IR increased with one order of magnitude and has reached the unacceptable threshold in a part of the residential area.

Fig. 3 represents the SR results, calculated for the conventional technological accident scenarios, respectively the total risk including technological and Natech scenarios. Considering only the technological accident scenarios the SR curve is below the lower ALARA (As Low As Reasonably Achievable) limit, but adding the Natech scenarios the SR increased approximately with one order of magnitude and the F-N curve enters in the ALARA zone.

The results of the case study show that, if the earthquake hazard is considered in the risk assessment procedure, this specific site does not fulfill the safety requirements (regarding IR) for LUP purposes.

Table 2. Frequencies of tank failure combinations for DS 2 and DS 3

Damage state	*n*	P_{comb}	f_{comb} *(ev./year)*	*No. of combinations*
2	0	0.2371	$5.00\cdot10^{-4}$	1
	1	0.2498	$5.25\cdot10^{-4}$	2
	2	0.2631	$5.54\cdot10^{-4}$	1
3	0	0.9698	$2.05\cdot10^{-3}$	1
	1	0.0149	$3.16\cdot10^{-5}$	2
	2	0.0002	$4.87\cdot10^{-7}$	1

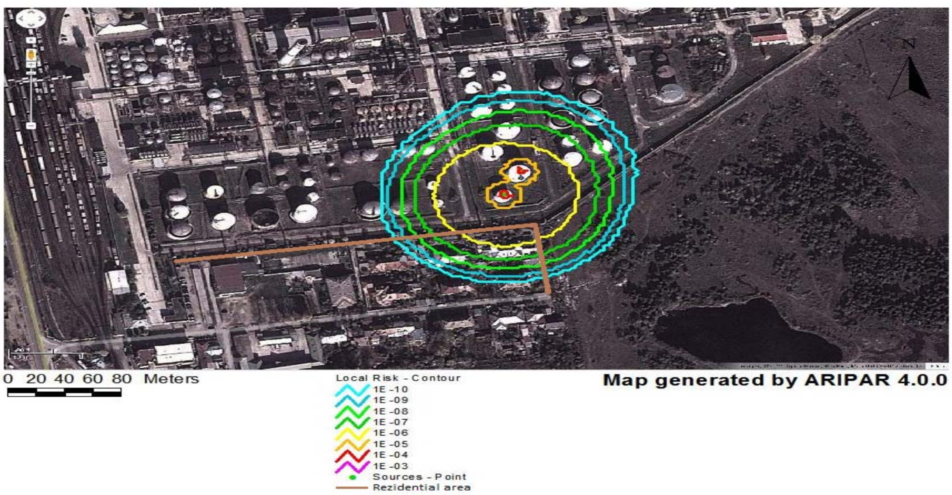

Fig. 1. Individual risk curves for conventional technological accident scenarios

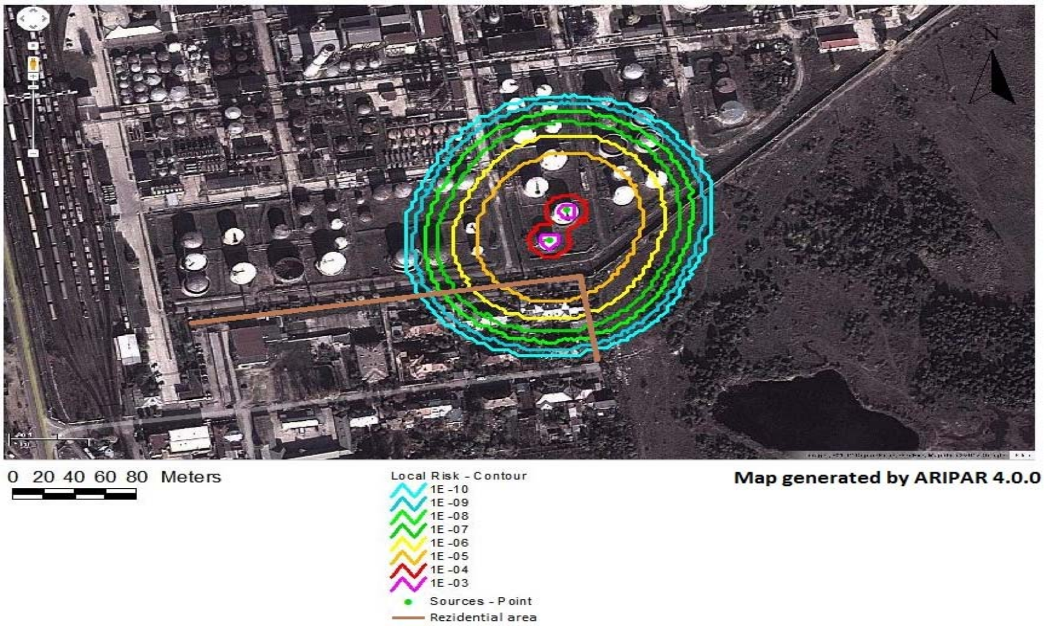

Fig. 2. Individual risk curves for total risk, including technological accident and Natech scenarios

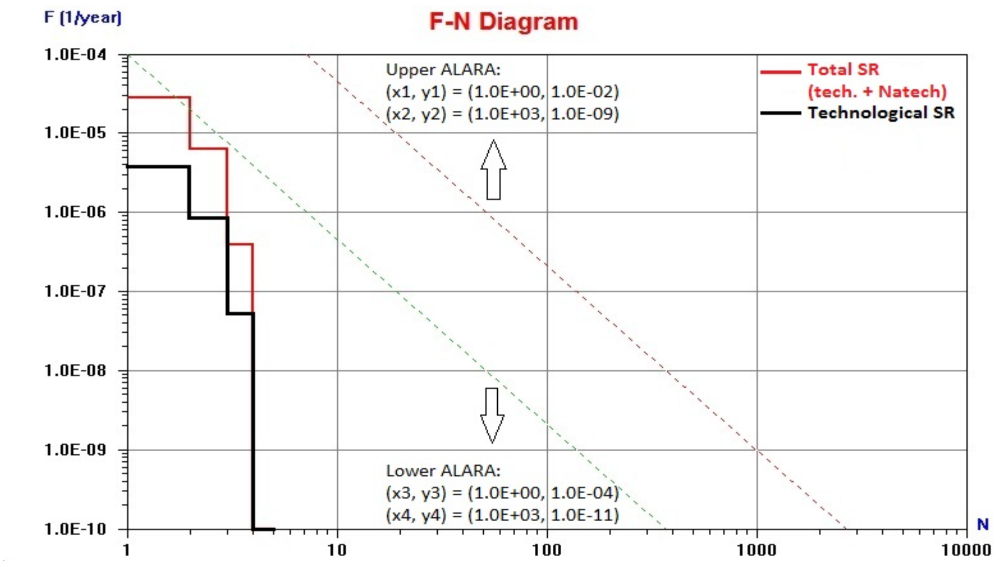

Fig. 3. Societal risk F-N curves for conventional technological accident scenarios and Natech scenarios

5. Conclusions

The study reveals the importance of considering Natech events when performing risk analyses for LUP purposes in case of industrial sites located in natural hazard prone areas.

A more detailed analysis for this site is recommended, in order to consider all the storage tanks and other equipment, including a domino effect analysis and finally a further escalation triggered by Natech events (second level domino effect). Thus risk reduction measures can be implemented if the scenarios (or combinations of them) with the highest contribution to overall risk are identified.

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