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Rapid Natech Risk Assessment and Mapping Tool for Earthquakes: RAPID-N

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Natural-hazard triggered accidents at industrial facilities (natechs) are recognized as an emerging risk with possibly serious consequences. Risk maps are helpful to identify natech hot spots. However, recent surveys showed that hardly any natech risk maps exist in the OECD and EU. A probabilistic natech risk mapping methodology for earthquakes was developed to fill this gap and was implemented as a web-based software tool: RAPID-N. The tool allows rapid natech risk assessment and mapping with minimum data input. It can calculate on-site natural hazard parameters and estimate site, process equipment, and substance properties. A basic set of damage states and fragility curves is provided for damage assessment. Custom damage states and fragility curves can also be defined for different process equipment. Conditional probabilistic relationships can be specified between damage states and possible natech event scenarios. The consequences of the natech events are assessed using the Risk Management Program methodology of US EPA and the results are presented as summary reports and interactive risk maps. The tool can be used for land-use and emergency planning.

1. Introduction

Major accidents at chemical process industries, which are triggered by natural hazards and result in the release of hazardous materials, can have serious consequences on the population, the environment, and the economy (Young et al. 2004; Girgin, 2011). Termed natechs, the risk of such accidents is expected to increase in the future due to the growing number of industries, the occurrence of larger-scale natural hazards due to emerging factors such as climate change, and the vulnerability of the society that is becoming more interconnected (iNTeg-Risk, 2010). Adequate preparedness and proper emergency planning are needed to prevent natechs and mitigate their consequences. For this purpose, natech-prone areas should be identified and natech risks must be assessed in a methodical way. Recent surveys have shown that hardly any natech risk maps exist within the EU or OECD. Where existing, natech risk maps simply overlay natural and technological hazards without considering site-specific features or the interaction of hazards (Krausmann and Baranzini, 2009; Krausmann, 2010). The need for a systematic natech risk-mapping methodology is therefore evident. In order to fill this gap, a probabilistic natech risk-mapping methodology was developed, which is applicable for earthquakes. The methodology is based on the calculation of on-site hazard parameters from earthquake scenarios and the use of fragility curves to determine damage probabilities of process equipment (including storage units) for different damage states. Damage states are converted into risk states that define probable consequence scenarios resulting from the earthquake-triggered damage. Finally, the risk and the severity of the potential consequences are calculated by using consequence models and the results are converted into natech risk maps.

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The methodology is implemented as a web-based application entitled RAPID-N, which features an integrated framework for natech risk assessment by providing advanced data management, estimation, and analysis tools. In the following sections RAPID-N and its modules are described in more detail.

2. The RAPID-N tool

RAPID-N is a multilingual, collaborative application publicly available at http://rapid-n.jrc.ec.europa.eu. It is composed of four main modules. The *Scientific tools* module supports scientific calculations, GIS analyses, and bibliographic citations. The *Natural hazards* module includes source and site-specific natural hazard information. The *Facilities and process equipment* module provides data on industrial facilities, process equipment, and hazardous substances. Finally, the *Risk assessment* module covers all functionalities required for natech risk assessment, including damage classifications, fragility curves, risk states, and consequence modeling tools. Google Maps is used to visualize geo-referenced data.

2.1 Scientific tools module

The scientific tools module supports bibliographic citations and GIS analyses. It also includes a property definition and estimation framework, which is a key component of the tool. There are four major entities in RAPID-N, which are natural hazards, industrial facilities, process equipment, and chemical substances. Natech risk assessment calculations depend on the properties of these entities, i.e. the severity parameters of the natural hazards, site characteristics of the facilities, the physical characteristics of the process equipment, and the chemical properties of the substances. RAPID-N provides a common framework to define entity properties. Numerical and tabular (pre-defined) property data are supported. Scientific units are used to define scales of numerical values and unit conversion is done automatically using an extendable unit conversion library. The tool supports fuzzy arithmetic and allows uncertainty in numerical data to be specified by trapezoidal fuzzy numbers with constant slopes (Buckley, 2006). Five fuzzy number classes are supported, which describe less than (e.g. < 1.2), greater than (e.g. > 3.4), in between (e.g. 5-7), about (e.g. ~8) and exact value (e.g. 9) conditions.

User-defined property values are used as input to risk assessment calculations. However, such data may be incomplete or even unavailable for many cases. To make calculations possible with minimum data input, the tool features a generic property estimation framework to complete missing data. The framework relies on value estimators indicated explicitly by (fuzzy) numerical or tabular values, and function estimators in the form of mathematical expressions or complex functions involving other properties, internal functions, and control structures (e.g. if-conditions, loops). RAPID-N allows validity conditions to be specified for each estimator to control their applicability. For example, a process equipment volume estimator can be made restricted to a certain shape. Validity conditions are defined by using entity properties. Multiple conditional values can be specified for each property. Fuzzy numbers are supported and evaluated as range expressions. The dependence of estimators on geographic locations is also considered. Validity regions can be indicated by using countries or Flinn-Engdahl seismic regions (Young et al., 1996). The framework takes available user-defined property data as input and tries to calculate missing properties by using existing property estimators and their validity conditions. The estimation procedure is continued recursively until no further properties can be estimated with the available data, including values estimated in the previous steps. Property estimators reduce the amount of data that should be entered by the user and increases flexibility. Many calculations that should normally be hard-coded in RAPID-N are carried out using property estimators. For example, there are no built-in functions for the calculation of on-site ground motion parameters. All ground motion-related calculations are performed using property estimators. Hence, there is no need to modify the tool to support a new ground motion equation; defining a new estimator is simply sufficient.

2.2 Natural hazards module

The natural hazards module contains source and site-specific earthquake data required for the natech risk assessment. Both historical and scenario earthquakes are supported. Source data includes date, geographic location, extent, and characteristics of the earthquake, which can be specified by using the property definition framework. RAPID-N monitors on-line earthquake catalogs to retrieve and update source-specific earthquake data. The European Mediterranean Seismological Centre (EMSC, 2010), U.S. National Earthquake Information Center (NEIC, 2010), and U.S. Geological Survey (USGS, 2011) earthquake catalogs are supported. The tool is loaded with data of M > 5.5 earthquakes that occurred since the 1970s. Source-specific hazard data is used to estimate on-site hazard data by using the property estimation framework. More precise on-site hazard parameter data can be specified in the form of hazard maps. Multiple hazard parameters are allowed for each map and on-site values are estimated by spatial interpolation. Currently, ShakeMaps of the USGS are supported (Wald et al., 2005). RAPID-N monitors the ShakeMaps archive of the USGS and makes recent ShakeMaps available for natech risk assessment calculations.

2.3 Facilities and process equipment module

The natech risk assessment methodology of RAPID-N is based on the estimation of earthquake damage probabilities of process equipment located at industrial facilities. Although there are different types of process equipment, natech risk assessment methodologies developed so far mainly focused on storage tanks (Salzano et al., 2003; Fabbrocino et al., 2005). RAPID-N supports not only storage tanks, but also other process equipment that may cause natechs. A special mapping tool is provided to delineate facility boundaries, mark process equipment, and determine their dimensions. Equipment characteristics (e.g. storage conditions) can be indicated by using the property definition framework. Chemical substances contained in process equipment can be specified. Multiple substances can be entered by denoting their amounts in percent of the process equipment volume. If the exact amounts are not known, they can be specified as fuzzy numbers. RAPID-N features an extendable substance database that includes information on physical, structural, toxic, and flammable properties of substances. The basic data on substances include name, identifiers (e.g. CAS No) and structure data (e.g. chemical formula). The properties of substances cover common physical and chemical properties (e.g. boiling point) and RMP parameters (e.g. toxic endpoint) (EPA, 1999). The property estimation framework can calculate missing properties. Data on industrial facilities contain industrial activity, location, operator information, and site characteristics including construction-related properties (e.g. construction year) and environment factors (e.g. topography). They are defined by using the property definition framework and can be estimated by site-specific property estimators. Site characteristics are inherited to process equipment. For example, soil type of a storage tank is taken from the soil type property of the facility.

2.4 Risk assessment module

The risk assessment module includes damage classifications used to define natural hazard related damage states at process equipment; fragility curves used to calculate probabilities of the damage states; risk states which describe possible natech event scenarios triggered by the damage states; and the analysis tools used to describe and evaluate natech risk scenarios and their consequences.

Because the extent of damage to an engineered structure may vary significantly from case to case, a simplification is necessary to facilitate the damage assessment. Generally, this is done by grouping similar damage types into a pre-defined set of damage states, ranging gradually from none to complete damage (FEMA, 1997). RAPID-N contains various damage classifications composed of damage states frequently used for earthquake damage assessment. Custom damage classifications can also be defined for specific process equipment. RAPID-N uses fragility curves to assess the probabilistic natural hazard damage. They are plots relating a hazard severity parameter (e.g. PGA) to the damage probability of a structure for a certain damage state (FEMA, 1997; O'Rourke and So, 2000). A generic fragility curve framework is provided for defining fragility curves for different damage classifications and process equipment. Four different forms of fragility curves are supported, which are mean log-normal, median log-normal, probit functions, and probability datasets with quadratic interpolation. Curves are entered for each damage state separately. Like the property estimators, validity conditions can be indicated to restrict fragility curves to specific process equipment (e.g. floating roof tank with H/D > 1.5).

In order to estimate the natech risk, the damage states have to be related to possible consequence scenarios. Similar to the simplification for the damage states, the consequence scenarios are also simplified in the form of risk states, which describe possible natech event, its conditional probability, volume of process equipment involved, and validity conditions. Simple relations were used in the past to relate damage states to risk states (Salzano et al., 2003; Fabbrocino et al., 2005). RAPID-N supports conditional relations, which allow different natech scenarios to be defined for a certain damage state, depending on process equipment and substance properties. The natech scenarios are based on RMP scenarios, which include 10-min and 60-min releases for toxic substances, and vapor cloud fire, pool fire, BLEVE, and vapor cloud explosion for flammable substances (EPA, 1999). Worst-case scenario can be automatically determined by the tool. The conditional probability of the natech event can be indicated and multiplied by the damage probability to obtain the overall natech probability. In order to calculate the amount of substance involved in the event, % volume of the substance is multiplied by the process equipment volume, filling level, and the % volume of the process equipment involved. The possibility to indicate the conditional natech event probability and the % volume involved in the event allows a more realistic assessment of certain cases, such as damage to piping (generally regarded as minor structural damage) or elephant-foot buckling with minor loss of content (generally regarded as major structural damage). Classical relationships assuming “higher structural damage state implies higher risk state” result in the over- or under-estimation of natech risk in such cases. RAPID-N also allows conditional risk states to be defined by indicating validity conditions using process equipment and substance properties. For example, risk states can be defined for floating-roof tanks constructed before a certain year and storing substances with high heat of combustion.

The natech risk assessment and mapping is performed in two phases. In the first phase, structural damage probabilities of process equipment located at industrial facilities are calculated by using an earthquake scenario as input. Facilities that should be included in the risk assessment location-wise are determined automatically. A cut off distance measured from the hazard origin can be provided to exclude facilities not of interest. The analysis can also be limited to certain facilities by selecting them explicitly. On-site hazard parameters are calculated by using hazard property estimators or by using pre-calculated values available in hazard maps. They can also be specified manually. Damage probabilities of process equipment are calculated for possible damage states by using fragility curves. The tool is capable of selecting the most suitable damage classification and fragility curve for each process equipment. By default, fragility curves are assigned to process equipment individually, considering the equipment type, damage classification, and validity conditions. A certain damage classification or fragility curve can also be used for all process equipment. For facilities without process equipment data, on-site hazard parameters are calculated and hypothetical damage probabilities are reported for a typical atmospheric storage tank assumed to be located on-site.

In the second phase of the risk assessment, the probable consequence scenarios are identified using risk states that relate the damage states to natech events, and their severity is calculated. If the damage probabilities calculated for process equipment are < 10 %, the unit is excluded from the risk assessment as the main interest is in the main accident initiators. If there is no information on the substances contained in the process equipment, only damage probabilities are reported and the unit is also not further considered in the risk assessment. For other process equipment and for each damage state having an occurrence probability ≥ 10 %, the risk state corresponding to the damage state is determined by evaluating the validity conditions of the risk states available for the designated damage state. Both process equipment and substance properties are considered during the evaluation to select the most appropriate risk state. According to the consequence scenario of the selected risk state, the distance to the endpoint is calculated using the simple modeling approach of the Risk Management Program of US EPA, details of which are given in (EPA, 1999). Chemical substance properties and weather conditions (e.g. stability) are taken into consideration during calculations. The results of the risk assessment are presented as summary reports and interactive risk maps showing natech event probabilities and the areas possibly affected by the events. A sample risk assessment report with corresponding risk map is given in Figure 1.

3. Conclusions

RAPID-N features a web-based, integrated framework for natech risk assessment and mapping for earthquakes. It provides a user-friendly interface and advanced data management, estimation, and analysis functionalities, allowing the rapid assessment of natech risks at a regional scale with minimum data input. Owing to its flexible framework, the tool can be extended easily to support a wide variety of damage classifications, fragility curves, process equipment, hazardous substances, and hazard parameter estimation methods. The results of the damage and consequence assessment are shown as easily understandable risk maps and reports.

Name:	Sample Natech Risk Assessment, Turkey
Date:	2011/06/12
Type:	Public

Hazard Information

Hazard:	Scenario Earthquake, 2011/05/27 (7.6 Mw – 40° 44' 52.800", 29° 51' 50.400")
Hazard Map:	None

Risk Assessment Settings

Weather Condition:	F Stability, Wind Speed 1.5 m/s
Damage Classification:	Auto
Fragility Curve:	Auto
Facilities:	Auto
Cutoff Distance:	200 km

Results

1.

Facility:	Facility A, Turkey
Distance:	8.73 km

ⓘ No process equipment information.

Damage Assessment

Fragility Curve	Damage Probability
O'Rourke and So (2000)	≥ DS2: 71.76 % ≥ DS3: 30.80 % ≥ DS4: 11.59 %

2.

Facility:	Facility B, Turkey
Distance:	25.98 km

Process Equipment

No	Type	Code	Distance	Fragility Curve	Damage Probability	Consequence Probability	Consequence Distance
1.	Storage Tank	ST01	25.65 km	O'Rourke and So (2000)	≥ DS2: 50.48 % ≥ DS3: 18.26 %	Pool Fire: 25.24 % Pool Fire: 13.70 %	56 m 56 m
2.	Storage Tank	ST02	25.88 km	O'Rourke and So (2000)	≥ DS2: 50.43 % ≥ DS3: 18.22 %	Pool Fire: 25.21 % Pool Fire: 13.66 %	79 m 79 m
3.	Storage Tank	ST03	26.01 km	Seligson et al. (1996)	≥ DS2: 65.23 % ≥ DS3: 26.79 %	60-minute release: 21.53 % 60-minute release: 6.69 %	6.65 km 14.25 km

3.

Facility:	Facility C, Turkey
Distance:	156.75 km

ⓘ No damage.

Figure 1: Sample natech risk assessment report and risk map

RAPID-N can be used at different stages of the natech risk management process. In the preparation phase, it can be used to assess the potential consequences of different natech scenarios to develop natech risk maps useful for land-use and emergency planning purposes. In the response phase, it can be used for rapid earthquake damage assessment based on actual earthquake parameters. By monitoring on-line earthquake catalogs and the ShakeMap archive, RAPID-N keeps track of recent earthquakes which may trigger natechs. An automated analysis function will be implemented to assess natech risk for facilities available in the database immediately after the occurrence of such an earthquake, so that the results can be quickly reported to the responsible authorities, first responders and other interested parties. The natech risk assessment methodology in RAPID-N is generic and can also be used to assess the risk due to natural hazards other than earthquakes. Hazard parameter estimation methods are available in the literature for other natural hazards. However, studies on the associated natech-related damage states and fragility curves are scarce and further in-depth analyses are required. Currently, work is underway to extend the tool to include floods. Furthermore, it is planned to also support pipeline natech risk assessment in addition to fixed industrial facilities and process equipment.

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