INDUSE2-SAFETY

Component fragility evaluation and seismic safety assessment of "special risk petrochemical plants under design basis and beyond design basis accidents, Grant No: RFS-PR-13056

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Outline

• Premises
• **INDUSE2-SAFETY** : Origin
• **INDUSE2-SAFETY** : Architecture
• **INDUSE2-SAFETY** : A Novel Fragility-Based methodology for QsRA of process plants
  • Main aspects and criticisms
• **PRIAMUS**: a new tool for QsRA of process plants
• Conclusions
• What else?
In a world that has a continuous need of materials transformation industries, an important role is played by process plants and in particular Petrochemical Plants.

Once discovered, drilled and brought to the earth’s surface, crude oil is transported to a refinery by pipeline, ship or both. At the refinery, it is treated and converted into consumer and industrial products.

A petroleum refinery is a complex assembly of individual process plants interconnected with piping and tanks.
Premises

Several accidents (Na-Tech events) occurred in the last decades in industrial sites have evidenced that naturals phenomena may cause severe damages to equipment items, resulting in losses of containment, thus in multiple and extended releases of hazardous substances.

Database: MHIDAS

Past accidents analysis evidences that structural damage to the equipment directly struck by lightning is the more frequent cause of loss of containments accidents, but generally seismic events produces severe consequence because increases the likelihood of multiple and simultaneous failures of industrial components.

Kobe Earthquake, Japan, 1995

Tupras Refinery, Turkey 1999

Chiba Refinery, Japan, 2011
The Kocaeli earthquake caused significant structural damages to the Tupras refinery itself and associated tank farm with crude oil and product jetties and triggered multiple fires in the refinery’s naphtha tank farms.

Kocaeli earthquake (Turkey) - 17 August 1999 - Magnitudes 7.4

- The majority of the floating roof tanks (30 out of 45) were damaged;
- 250,000 m³ crude oil and 100,000 m³ oil product having been exposed to the atmosphere and partially pouring out of the tanks;
- Evacuation order was issued by the crisis centre for a zone of 5 km around the refinery;
- Considerable oil pollution occurred during the incident;
- Total damage is estimated to be around US$ 350 million

Lession from the past: Extreme vulnerability of the tank farm, importance of the domino effect, damaging of the services and security systems.
2011 Pacific Coast of Tohoku Earthquake (Mw9.0), Japan
What about Europe?

SEVESO III

European Union Law: DIRECTIVE 2012/18/EU (amendments of 96/82/EC) on the control of major-accident hazards involving dangerous substances

Annex II: Minimum data and information to be considered in the safety report referred to in Article 10

4. Identification and accidental risks analysis and prevention methods:
(a) detailed description of the possible major-accident scenarios and their probability or the conditions under which they occur including a summary of the events which may play a role in triggering each of these scenarios, the causes being internal or external to the installation; including in particular:
   (i) operational causes;
   (ii) external causes, such as those related to domino effects, sites that fall outside the scope of this Directive, areas and developments that could be the source of, or increase the risk or consequences of a major accident;
   (iii) natural causes, for example earthquakes or floods;
What are the Actions in USA/EUROPE?

PREVIOUS RELATED RESEARCH PROJECTS

- Structural safety of industrial steel tanks, pressure vessels and piping systems under seismic loading (INDUSE)
- Development of INnovative DEvices for Seismic Protection of PeTrocHemical Facilities (INDEPTH)
- Integrated European industrial risk reduction system (IRIS)
- Seismic-Initiated events risk mitigation in LEad-cooled Reactors (SILER)
- Enhancing resilience of communities and territories facing natural and na-tech hazards (ENSURE)
- Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain (SYNER-G)
**Premises**

**What are the Actions in USA/EUROPE?**

Onshore structures inside the scope of EN1998. Target reliability that depends on consequences of failure. In operational terms one multiply the reference seismic action by the importance factor $\gamma_I$.

<table>
<thead>
<tr>
<th>Country</th>
<th>Importance Factor, $\gamma$ (for special risk structures)</th>
<th>National Return Period $T_R$ (Years)</th>
<th>Return Period calculated using Eurocode 8 based on $T_L$ (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>2.2</td>
<td>5000</td>
<td>5057</td>
</tr>
<tr>
<td>Germany</td>
<td>1.65</td>
<td>-</td>
<td>2133</td>
</tr>
<tr>
<td>Italy</td>
<td>2</td>
<td>1950</td>
<td>3800</td>
</tr>
<tr>
<td>Norway</td>
<td>1.8</td>
<td>2000</td>
<td>2770</td>
</tr>
</tbody>
</table>

*Inconsistent Return Period values*
What are the Actions in USA/EUROPE?

The Seismic Task Committee of ASCE Energy Division issued specific Guidelines for Seismic Evaluation and Design of Petrochemical Facilities (1997, 2011), in order to provide practical guidance to engineers involved in seismic design and evaluation. Though these Guidelines are largely based on qualitative seismic risk concepts and deterministic approaches, no corresponding European technical document exists in this respect. In addition, also the requests to CEN/TC 250 for Eurocode amendments do not include specific issues for process plants (CEN/TC 250, 2013).

INDUSE2-SAFETY PROJECT: Origin

INDUSE

Structural safety of industrial steel tanks, pressure vessels and piping systems under seismic loading

COMPONENT LEVEL

COMPONENT FRAGILITY EVALUATION AND SEISMIC SAFETY ASSESSMENT OF "SPECIAL RISK" PETROCHEMICAL PLANTS UNDER DESIGN BASIS AND BEYOND DESIGN BASIS ACCIDENTS (INDUSE-2-SAFETY)

PROJECT DURATION: JULY 2014-JUNE 2017

PLANT LEVEL

XP-Resilience: extreme loading analysis of petrochemical plants and design of metamaterial-based shields for enhanced resilience

COMMUNITY LEVEL

....a clear (three steps) strategy
INDUSE2-SAFETY PROJECT: Partnership

1. UNIVERSITA DEGLI STUDI DI TRENTO, Prof. Oreste S. BURSI, Dr. Nicola TONDINI
2. CENTRO SVILUPPO MATERIALI SPA, Eng. Elisabetta Mecozzi
3. COMMISSARIAT Á L’ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES, Alain LE MAOULT, Philippe MONGABURE
4. RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN, GERMANY Prof. Benno Hoffmeister, Eng. Jonas Korndšrfer
5. PANEPISTIMIO THESSALIAS (UNIVERSITY OF THESSALY), GREECE Prof Spyros A Karamanos, Eng. Maria Vathi
6. UNIVERSITA DEGLI STUDI ROMA TRE, Dr. Fabrizio PAOLACCI
7. THE UNIVERSITY OF LIVERPOOL, UK, Prof Alexander MOVCHAN
8. WALTER TOSTO SPA, ITALY, Eng. Patrizio DI LILLO
9. ING.-GES. DR.-ING. FISCHBACH MBH, GERMANY Dr. Gunter FISCHBACH
INDUSE2-SAFETY was conceived based on the above-mentioned framework with a multiplity of objectives:

1. Assessment of the actual risk of potentially dangerous onshore petrochemical plants, for seismic loss prevention and inside the scope of EN 1998.

2. Development of full a probabilistic QSRA using a consequence-based methodology (cascading effect fashion).
**INDUSE2-SAFETY project: Objectives**

**INDUSE2-SAFETY** was conceived based on the above-mentioned framework with a multiplicity of objectives:

3. Evaluation of fragility curves of main structures and components needed for the QSRA analysis based on numerical and experimental approaches

4. Issuing of quantitative risk assessment provisions for seismic loss prevention of onshore “special risk” petrochemical facilities within the scope of EN 1998
INDUSE2-SAFETY project: Objectives

INDUSE2-SAFETY was conceived based on the above-mentioned framework with a multiplicity of objectives:

5. Issue of enhanced design recommendations for the improvement of Eurocodes (EC8) and recognized standards for petrochemical components (EN13480)
INDUSE2-SAFETY project: Architecture

INDUSE2-SAFETY is subdivided in 7 technical Work Packages.

WP1 to WP5 are dedicated to the definition of the main ingredients of the QsRA fully developed in WP6.

WP6 concerns the development of a new multi-level approach in which the domino effect is considered (cascading effect).

WP7 is finally devoted to guidelines for risk-assessment of Petrochemical plants.
INDUSE2-SAFETY project: Motivations for a new QsRA procedure

Performance-based seismic analysis

Well recognized for civil structures

What are the performances for a process plant?

Recognized Limit States for NPP

OBE
operating basis earthquake

SSE
safe shutdown earthquake

How to calculate the probability of occurrence of an earthquake related to these two Limit States?
NPP versus Non NPP

All possible scenarios, involving:
• A set of units damaged by the earthquake
• One or more chains of accidents

INDUSE2-SAFETY project: Motivations for a new QsRA procedure

What are the main issues in the probabilistic risk calculation of a Petrochemical Plant?
Classical Quantitative Risk Assessment (QRA) methods cannot be applied to evaluate consequence in case of earthquakes, because of the presence of multi-damage conditions, simultaneously involving more than one equipment.

The proposal method is an extension of the classical QRA procedure, with the introduction of some fundamentals aspects: the seismic hazard of the site, the specific seismic vulnerability of the components, the Domino effect based on a multi-level approach.
INDUSE2-SAFETY project: main aspects

Improvement of numerical models

Solid Lagrangian

ABOVE GROUND ANCHORED & UNANCHORED TANKS

PRESSURE VESSELS

ELEVATED TANKS
INDUSE2-SAFETY project: main aspects

Improvement of numerical models
INDUSE2-SAFeTY project: main aspects

Experimental evaluation of the seismic response and damage states

REAL-TIME TESTING

SHAKING TABLE TESTS

PIPING SYSTEMS

STORAGE TANKS
INDUSE2-SAFETY project: main aspects

Different methods for Fragility analysis methods based in numerical and experimental analysis have been investigated along with an efficiency-sufficiency analysis for the determination of the best Intensity measure. Accordingly a collection of Fragility curves has been provided for QsRA.

Numerical and experimental evaluation of fragility curves for the QsRA.
INDUSE2-SAFETY project: main aspects

Determination of loss of containment (LOC) events for each component damaged by the earthquake according to damage states (DS). This relationship is considered deterministic as illustrated in the DS/LOC matrix reported below, valid for anchored and unanchored tanks.

<table>
<thead>
<tr>
<th>Damage Type</th>
<th>Engineering Demand Parameter (EDP)</th>
<th>Limit State Threshold (LS)</th>
<th>LOC1 Continuous release from a 10mm hole</th>
<th>LOC2 Continuous release from a full bore of the pipe</th>
<th>LOC3 Instantaneous release of full content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elephant Foot Buckling</td>
<td>Meridional Stress $G_M$</td>
<td>Buckling limit $G_M$</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Shell Fracture</td>
<td>Hoop Stress $G_H$</td>
<td>Buckling limit $G_H$</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Sliding</td>
<td>Total Base Shear $F_{slidex}$ $\mu W$</td>
<td></td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Overturning</td>
<td>Overturning Moment</td>
<td>Overturning Moment limit</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Base plate fracture</td>
<td>Max local strain</td>
<td>Strain limit</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Roof Damage</td>
<td>Max vertical displacement of liquid</td>
<td>Free-board height</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Of course, more than one LOC could be triggered by the same LS, but, conservatively, only the most severe is herein considered. A refinement of this relationship, in a probabilistic sense, is under investigation, and will be object of further researches.
INDUSE2-SAFETY project: main aspects

EVENT TREE

Physical Effects (Yellow Book)

Estimation of source terms and physical effects (Consequences)
For each seismically damaged unit, after the quantification of the physical effects (pressure, thermal radiation, etc.) due to a LOC event, the procedure includes the damage evaluation in the remaining undamaged units.

**INDUSE2-SAFETY project: main aspects**

**Damage propagation effects (Domino effect)**
It is assumed that the accidents sequence may be represented with a multi-level approach based by a sequence of propagation “levels”. Each propagation level includes a subset of process units directly damaged by units belonging to the previous levels.

- A propagation sequence, starts from “Level 0” where seismically damaged units are presents;

- “Level 1” includes units directly damaged by the units seismically damaged at “level 0”; 

- At a “Level 2” are presents the units directly damaged by the units damaged at level “0” and “level 1” and so on.

MCS approach represents one of the most suitable methodologies because of its capability to simulate step-by-step all critical phases of the damage propagation, with the identification of the main starting damage scenarios and the rate of occurrence of the most critical accidental chains.
PRIAMUS has been developed in MATLAB environment for a full probabilistic QsRA for petrochemicals plants based on Monte Carlo Simulations.
The proposed procedure allows three different types of seismic analysis of the plant:

- **Scenario**
- **Fragility**
- **Risk Analysis**

**Scenario**: defines the seismic scenario corresponding to the occurrence of an earthquake with a given magnitude $M$ at a given distance $D$ from the site with soil conditions.

**Fragility**: consists in calculating the probability of occurrence of damage scenarios and consequence for a given set of IMs.

**Risk Analysis**: is a complete risk analysis of the plant, integrating over the whole set of IMs, with their probability of exceedance, the probability of occurrence of each scenario and related consequences in a given time period.
INDUSE2-SAFETY project: PRIAMUS a new tool for QsRA

“Tank information” - This section is dedicated to the definition of the characteristics of the storage tank farm: number of tanks, locations, geometries, typology of content, economic value. The software allows the input of the data through prompt or excel files.

“Vulnerability of tanks”- in this section user can define the typology of each tank (anchored, unanchored or elevated, with fix or floating roof). For each structural damage typology that causes loss of containment, user must define the parameters of fragility curves (medium value and standard deviation).

“Plant information”- This part is dedicated to the definition of the vertex of obstructed area, the volume of components inside and the component maximum height inside the zone for the definition of VCE effects.

“Atmospheric information”: the statistics of atmospheric conditions are entered. Monthly mean value of air humidity, air temperature and wind velocity are needed. The wind direction is defined in terms of probability for each month.

“Analysis information”: user can choose the typology of seismic analysis (risk analysis, scenario analysis, analysis for a range of intensity measure).
SITE: PRIOLO GARGALLO (SR) - ITALY

TANK FARM SELECTED

CHARACTERISTICS OF TANKS

<table>
<thead>
<tr>
<th></th>
<th>TK1</th>
<th>TK2</th>
<th>TK3</th>
<th>TK4</th>
<th>TK5</th>
<th>TK6</th>
<th>TK7</th>
<th>TK8</th>
<th>TK9</th>
<th>TK10</th>
<th>TK11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (m)</td>
<td>37.96</td>
<td>37.96</td>
<td>37.96</td>
<td>41.26</td>
<td>54.86</td>
<td>41.26</td>
<td>54.86</td>
<td>65.4</td>
<td>81.46</td>
<td>81.46</td>
<td>54.86</td>
</tr>
<tr>
<td>Liquid Level (m)</td>
<td>11.3</td>
<td>11.3</td>
<td>11.3</td>
<td>12</td>
<td>15.3</td>
<td>12</td>
<td>15.3</td>
<td>10</td>
<td>21.6</td>
<td>21.6</td>
<td>15.3</td>
</tr>
<tr>
<td>Height (m)</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>15</td>
<td>18</td>
<td>15</td>
<td>18</td>
<td>14</td>
<td>25</td>
<td>25</td>
<td>18</td>
</tr>
<tr>
<td>Yielding strength (MPa)</td>
<td>345</td>
<td>345</td>
<td>345</td>
<td>345</td>
<td>345</td>
<td>345</td>
<td>345</td>
<td>345</td>
<td>345</td>
<td>345</td>
<td>345</td>
</tr>
<tr>
<td>Shell equiv. thick. (m)</td>
<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
<td>0.0185</td>
<td>0.013</td>
<td>0.0185</td>
<td>0.014</td>
<td>0.026</td>
<td>0.026</td>
<td>0.0185</td>
</tr>
<tr>
<td>Shell base thick. (m)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.0295</td>
<td>0.02</td>
<td>0.0295</td>
<td>0.0295</td>
<td>0.04</td>
<td>0.04</td>
<td>0.0295</td>
</tr>
<tr>
<td>Annular plate thick. (m)</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.016</td>
<td>0.016</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Content: Crude oil

CASE STUDY
The most likely seismic damage scenarios (Level 0) along with the relevant frequency of occurrence together to the more likely chain of accidents can be identified.
The most likely seismic damage scenarios (Level 0) along with the relevant frequency of occurrence together to the more likely chain of accidents can be identified.
Conclusions

• The need to quantify the Seismic Risk of process plants has been recognized.
• Specific actions have been identified in order to integrate the existing European codes on seismic risk of process plants.
• The DIRECTIVE 2012/18/EU (Seveso III) on the control of major-accident hazards involving dangerous substances imposes the quantification of the NaTech risk, and in particular the seismic risk.
• Process plants, and more in particular Petrochemical plants, have been highly exposed in the past to seismic action resulting in a large amount of economic losses both direct and indirect.
Conclusions

• INDUSE2-SAFETY has been conceived on these premises and proposes a **new tool for the QsRA** of process plants based on fragility curves and domino effects (Cascading effects).
• This method fully integrate the structural and the industrial plants engineering knowledge.
• A new tool (PRIAMUS) has been proposed to expedite the QsRA of process plants in a simple manner but recognizing all the critical aspects that characterize this complex problem.
• The proposed methodology is easily extendable to other types of NaTech events.
XP-Resilience: extreme loading analysis of petrochemical plants and design of metamaterial-based shields for enhanced resilience

XP-RESILIENCE is an inter/multi-disciplinary programme including seven academic partners, one Institute of Applied Science and seven private companies from ten different European countries.

XP-RESILIENCE intends to establish a network of individual research projects working towards Advanced Modelling and Protection—via metamaterial based isolators/layouts of Complex Engineering Systems for Disaster Reduction and Resilient Communities.
XP-Resilience: extreme loading analysis of petrochemical plants and design of metamaterial-based shields for enhanced resilience

The objective of XP-RESILIENCE is to train researchers combining a robust academic foundation in reliability/resilience with practical experiences, technological expertise with awareness of the socio-economical context and conviction to furthering research with an entrepreneurial spirit.

It aims at offering innovative research training ground as well as attractive career development and knowledge exchange opportunities for 14 Early Stage Researchers (ESRs) through cross-border and cross-sector mobility for future growth in Europe.
Thank you for your attention!

Questions?

http://www.induse2safety.unitn.it