European Commission

# JRC TECHNICAL REPORTS

# State-of-the-art and lessons learned from safety studies and stress-tests for critical infrastructures

*STREST Reference Report 1*

Editors: Georgios Tsionis, Peter Zwicky
Contributors: Bekir Özer Ay, Maximilian Billmaier, Helen Crowley, Mustafa Erdik, Simona Esposito, Domenico Giardini, Iunio Iervolino, Kalliopi Kakderi, Elisabeth Krausmann, Giovanni Lanzano, Arnaud Mignan, Roberta Piccinelli, Achilleas Pistolas, Dimitris Pitilakis, Kyriazis Pitilakis, Johan Reinders, Ernesto Salzano, Raphael Steenbergen, Eren Uckan
Reviewer: Jacopo Selva

2016


EUR 27806 EN

# State-of-the-art and lessons learned from safety studies and stress-tests for critical infrastructures

**Contact information**
Name: Georgios Tsionis
Address: Joint Research Centre, Via E. Fermi 2749, Ispra (VA) 21027, Italy
E-mail: georgios.tsionis@jrc.ec.europa.eu
Tel.: +39 03 32 78 94 84

**JRC Science Hub**
https://ec.europa.eu/jrc

JRC100946

EUR 27806 EN

ISBN 978-92-79-57502-0 (PDF)
ISBN 978-92-79-57566-2 (print)

ISSN 1831-9424 (online)
ISSN 1018-5593 (print)

doi:10.2788/036273 (online)
doi:10.2788/703813 (print)



Printed in Italy

How to cite: Georgios Tsionis, Peter Zwicky, Bekir Özer Ay, Maximilian Billmaier, Helen Crowley, Mustafa Erdik, Simona Esposito, Domenico Giardini, Iunio Iervolino, Kalliopi Kakderi, Elisabeth Krausmann, Giovanni Lanzano, Arnaud Mignan, Roberta Piccinelli, Achilleas Pistolas, Dimitris Pitilakis, Kyriazis Pitilakis, Johan Reinders, Ernesto Salzano, Jacopo Selva, Raphael Steenbergen, Eren Uckan; State-of-the-art and lessons learned from safety studies and stress-tests for critical infrastructures; EUR 27806 EN; doi 10.2788/036273

STREST

# D 7.6.1

DELIVERABLE

PROJECT INFORMATION

| | |
|---|---|
| Project Title: | Harmonized approach to stress tests for critical infrastructures against natural hazards |
| Acronym: | STREST |
| Project N°: | 603389 |
| Call N°: | FP7-ENV-2013-two-stage |
| Project start: | 01 October 2013 |
| Duration: | 36 months |

DELIVERABLE INFORMATION

| | |
|---|---|
| Deliverable Title: | State-of-the-art and lessons learned from advanced safety studies and stress-tests for critical infrastructures |
| Date of issue: | 18 March 2016 |
| Work Package: | WP7 – Dissemination and stakeholder interaction |
| Authors: | Georgios Tsionis<br>(Joint Research Centre)<br>Peter Zwicky<br>(Basler & Hofmann AG) |
| Reviewer: | Jacopo Selva<br>(Instituto Nazionale di Geofisica e Vulcanologia) |

REVISION: Final

SEVENTH FRAMEWORK PROGRAMME


| | |
|---|---|
| Project Coordinator: | Prof. Domenico Giardini |
| Institution: | ETH Zürich |
| e-mail: | giardini@sed.ethz.ch |
| fax: | + 41 446331065 |
| telephone: | + 41 446332610 |

# Table of contents

Abstract ........................................................................................... iii
Acknowledgments ................................................................................... v
Deliverable contributors ........................................................................ vii
1. Introduction .................................................................................... 1
2. Lessons learned from stress tests of nuclear facilities ....................................... 3
2.1 Stress tests on European nuclear power plants ........................................... 3
2.1.1 Background and requirements .................................................... 3
2.1.2 Findings of the safety assessments ............................................... 4
2.2 IAEA advanced safety assessment studies ................................................ 6
3. State-of-the-art in hazard and risk assessment of non-nuclear critical infrastructures ............................................................................................ 7
3.1 Critical infrastructure protection in Europe ............................................... 7
3.1.1 Legislative background ............................................................... 7
3.1.2 European and international guidelines for risk assessment ................. 8
3.2 National guidelines for protection against chemical hazards .......................... 9
3.3 Guidelines related to the STREST test sites ............................................. 11
3.3.1 Large dams ............................................................................. 11
3.3.2 Hydrocarbon pipelines, gas storage and distribution networks .......... 12
3.3.3 Industrial districts ................................................................... 14
4. Lessons learned from recent catastrophic events related to the STREST case studies 15
4.1 Refineries and petrochemical facilities .................................................... 15
4.1.1 Lessons learned from earthquakes ............................................... 15
4.1.2 Lessons learned from tsunamis ................................................... 17
4.2 Large dams ........................................................................................ 18
4.2.1 Lessons learned from earthquakes ............................................... 18
4.2.2 Lessons learned from floods ....................................................... 19
4.3 Hydrocarbon pipelines .......................................................................... 20
4.3.1 Lessons learned from earthquakes ............................................... 20
4.4 Gas storage and distribution networks .................................................... 21
4.4.1 Lessons learned from earthquakes ............................................... 21
4.5 Ports ................................................................................................ 21
4.5.1 Lessons learned from earthquakes ............................................... 21
4.5.2 Lessons learned from tsunamis ................................................... 23
4.6 Industrial districts ............................................................................... 24
4.6.1 Lessons learned from earthquakes ............................................... 24
4.6.2 Lessons learned from floods ....................................................... 25

5. Summary and recommendations ........ 27
A Bibliography on stress tests for nuclear power plants ........ 29
A.1 European Commission and ENSREG documents on the EU stress tests for nuclear power plants ........ 29
A.2 EU Stress Test Country Reports ........ 29
A.3 EU Stress Test Peer Review Reports ........ 30
A.4 National Action Plans Resulting from EU Stress tests ........ 30
A.5 Western European Nuclear Regulators Association (WENRA) reference levels 31
A.6 Selected IAEA guidelines and reports ........ 31
A.7 European and US Seismic Hazard Studies ........ 32
B Risk assessment methods ........ 33
B.1 Hazard and operability study (HAZOP) ........ 33
B.2 Failure mode and effects analysis (FMEA) ........ 33
B.3 Fault-tree analysis (FTA) ........ 33
B.4 Event-tree analysis (ETA) ........ 33
B.5 Risk matrix (RM) ........ 34
References ........ 35
List of abbreviations ........ 41
List of figures ........ 43
List of tables ........ 45

## Abstract

Critical infrastructures are the backbone of modern society and provide many essential goods and services. Recent events have highlighted the vulnerability of these infrastructures to natural hazards and the risk for cascade effects with potentially major and extended socio-economic impacts. The STREST project aims at developing a stress test framework to determine the vulnerability and resilience of non-nuclear critical infrastructures.

This report summarizes the state-of-the-art and the lessons learned from post-Fukushima stress tests and safety assessment studies for nuclear power plants, from guidelines for hazard and risk assessment of critical infrastructures, and finally from recent catastrophic events.

The turn from 'absolute safety', which is unreachable, to the more realistic concept of 'risk awareness' has been made and several methods for risk assessment are implemented. Further efforts are required towards the harmonisation of methods for the identification of natural hazards for critical infrastructures and for the safety assessment in case of beyond-design (cliff-edge) events, considering common cause failures for multiple unit sites and multiple sites as well as cascade effects in interdependent systems. Where necessary, for instance in the case of floods, hazard assessment should include climate-change projections. Enriched knowledge on the vulnerability of key critical infrastructures and their components together with improved preparedness are key to avoiding future disasters.

## Acknowledgments

The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 603389.

## Deliverable contributors

| | |
|---|---|
| Basler & Hofmann AG | Peter Zwicky |
| | Maximilian Billmaier |
| EUCENTRE | Bekir Özer Ay |
| | Helen Crowley |
| AMRA | Giovanni Lanzano |
| | Ernesto Salzano |
| | Iunio Iervolino |
| | Simona Esposito |
| TNO | Johan Reinders |
| | Raphael Steenbergen |
| AUTH | Achilleas Pistolas |
| | Kalliopi Kakderi |
| | Dimitris Pitilakis |
| | Kyriazis Pitilakis |
| KOERI | Eren Uckan |
| | Mustafa Erdik |
| Joint Research Centre | Elisabeth Krausmann |
| | Roberta Piccinelli |
| | Georgios Tsionis |
| ETH Zurich | Arnaud Mignan |
| | Domenico Giardini |

# 1. Introduction

Critical infrastructures are the backbone of modern society and provide many essential goods and services, e.g. electrical power, telecommunications, water, etc. These infrastructures are highly integrated and often interdependent. Recently, natural events impacting critical infrastructures have highlighted the vulnerability of these infrastructures to natural hazards. They have also revealed the risk of cascading failures with potentially major and extended societal and economic consequences. This risk is bound to increase in the future. On the one hand, global warming is already changing the severity and frequency of hydro-meteorological hazards, and growing industrialisation increases technological hazards. On the other hand, exposure and vulnerability are growing due to industry and community encroachment on natural-hazard prone areas and the increasing interconnectedness of society.

Given the risks associated with the impact of natural hazards on critical infrastructures, the move towards a safer and more resilient society requires the development and application of an improved risk assessment framework to address high-impact-low-probability events. In this context, the STREST project aims at developing a stress test framework to determine the vulnerability and resilience of critical infrastructures.

The present report summarizes the state-of-the-art and the lessons learned from advanced safety studies and stress tests for critical infrastructures, which serves as the basis for the development of a framework for the future testing of critical infrastructures. It provides a review of the methodologies and findings from:

- post-Fukushima stress tests and advanced plant safety assessment studies for nuclear power plants (Zwicky 2014);
- national standards for hazard and risk assessment and for stress tests for different classes of critical infrastructures (Billmaier and Reinders 2014);
- recent catastrophic events (Krausmann 2014).

Chapter 2 provides a review of the methodologies and findings from post-Fukushima stress tests and advanced safety assessment studies for nuclear power plants. Findings are extracted from the specifications and the summary reports of the European stress test project for nuclear power plants and from a selection of relevant guidelines and reports on plant safety assessments elaborated by the International Atomic Energy Agency (IAEA).

The harmonization of national approaches to risk assessment of non-nuclear critical infrastructures has been emphasized in the European Union in order to standardize guidance and increase safety levels in terms of risks emitted by natural hazards and critical infrastructure. Chapter 3 gives a literature survey of national regulations and guidelines used in European countries. Available national and European documents dealing with the six types of critical infrastructures investigated in the STREST project are presented and examined. Conclusions and recommended approaches to conduct risk assessment are discussed.

Chapter 4 provides case-study descriptions of past incidents to shed light on the vulnerability of critical infrastructures to natural hazards. More specifically, incidents at refineries, large dams, hydrocarbon pipelines, natural gas storage and distribution networks, ports and industrial districts are analysed to better understand impact dynamics, system weaknesses, potential consequences and contributing factors. Based on the experience from the case studies, lessons are derived regarding system weaknesses and critical components, potential for propagation, severity and extent of consequences, and protection systems and measures.

# 2. Lessons learned from stress tests of nuclear facilities

## 2.1 Stress tests on European nuclear power plants

### 2.1.1 Background and requirements

In the light of the Fukushima reactor accident in March 2011, the European Council of 24/25 March 2011 requested that the safety of all nuclear plants in the European Union (EU) should be reviewed on the basis of a comprehensive and transparent risk and safety assessment (stress tests). These stress tests are defined as targeted re-assessments of the safety margins of nuclear power plants. All the operators of nuclear power plants in the EU had to review the response of their nuclear plants to those extreme situations. National reports on the stress tests were produced by 17 countries: Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, Lithuania, Netherlands, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine and the United Kingdom.

The assessments are based on the specifications largely prepared by the Western European Nuclear Regulators Association (WENRA). They cover extraordinary triggering events like earthquakes and flooding, and the consequences of any other initiating events potentially leading to multiple loss of safety functions requiring severe accident management. Human and organisational factors are part of these assessments.

The technical scope of the stress tests has been defined (ENSREG 2011) considering the issues that have been highlighted by the events that occurred at Fukushima, including combination of initiating events and failures. It covers the structures, systems and components, which are essential for the safety of the nuclear power plants. The focus is placed on the following issues:

- initiating events (earthquake, flooding);
- consequence of loss of safety functions from any initiating event conceivable at the plant site;
- severe accident management issues.

Furthermore, the assessment of consequences of loss of safety functions is relevant also if the situation is provoked by indirect initiating events, for instance large disturbance from the electrical power grid impacting power distribution systems, forest fire or airplane crash.

Three main areas to be assessed were defined (EC 2012):

1. For the extreme natural events (earthquake, flooding, extreme weather conditions): hazard assessment, design basis events, protection measures, vulnerabilities, evaluation of design and beyond-design events, safety margins for beyond-design events, with special emphasis on cliff-edge effects, recommended upgrades and safety enhancements. The quantification of safety margins is based on the 'success path concept', which identifies scenarios for safe plant conditions in case of emergency and the corresponding system components needed to remain available.
2. Response of the plants to prolonged loss of electric power including station blackout and/or loss of the ultimate heat sink, irrespective of the initiating cause.
3. Severe accident management: means to protect from and to manage loss of core cooling function, loss of cooling function in the fuel storage pools and loss of containment integrity.

The safety assessments are organised in three phases:

1. Self-assessments by nuclear operators;
2. Review of the self-assessments by national regulators;
3. Peer reviews of the national reports.

The review of the severe accident management issues focuses on the licensee's provisions but it may also comprise relevant planned off-site support for maintaining the safety functions of the plant. Although the feedback from the Fukushima accident may include the emergency preparedness measures managed by the relevant off-site services for public protection (e.g. fire-fighters, police, health services), this topic is out of the scope of these stress tests.

For each plant, the assessment reports on the response of the plant and on the effectiveness of the preventive measures, noting any potential weak point and cliff-edge effect, for each of the considered extreme situations. This is to evaluate the robustness of the defence-in-depth.

### 2.1.2 Findings of the safety assessments

The stress tests have confirmed that all the 17 participating countries perform periodic safety reviews at least every 10 years, including a reassessment of the external hazards. External hazards (e.g. earthquake, flooding and extreme weather) and robustness of the plants against them should be reassessed as often as appropriate but at least every 10 years.

Almost all countries consider for the design basis earthquake and flood an event with an exceedance probability of $10^{-4}$/year as a minimum. However, the evaluation of beyond-design-basis margins is not consistent in the 17 participating countries. Additional guidance on natural hazards should be developed, as well as on the assessment of margins beyond the design basis and cliff-edge effects. Regulators and operators should consider developing standards to address qualified plant walk-downs with regards to earthquake, flooding and extreme weather.

All the countries estimated the cliff-edge effects related to various combinations of losses of electrical power and/or cooling water and identified improvements related to hardware and procedures. At most multi-unit sites, an accident simultaneously occurring at several units was not considered in the original design.

Fire-fighting equipment, diesel pumps, generators, emergency lighting, etc. is normally readily available at the plants. Nevertheless, a systematic selection and acquisition of the equipment that would provide a variety of power and pressure levels and that is safely stored on-site and/or offsite still needs to be done.

Bunkered systems are qualified to expected external events and equipped with independent diesel-driven pumps and water storage to ensure heat sink, and electrical power supply to vital consumers for at least 24 hours. Bunkered systems are already installed as a standard design feature in only a few nuclear power plants.

Effective implementation of severe accident management requires that adequate hardware provisions are in place, such as additional diesel generators (or combustion turbines), mobile generators, centralised storage of emergency equipment and instrumentation and communication means which are qualified for design basis accidents. Main Control Rooms of the plants have been designed against design basis accidents and most of the countries have proposed additional measures to improve the habitability of Main Control and Emergency Control Rooms in case of severe accidents.

As a key result of the EU stress tests, each of the participating countries has developed a national action plan, listed in Table 2.1. The action plans contain a detailed list and schedule for all decided measures, and provide an implementation tool for the utilities and the national regulators.

Table 2.1 National action plans

| **Country** | **Authority** | **Report title** |
|---|---|---|
| Belgium | Federal agency for nuclear control | Belgian stress tests, national action plan for nuclear power plants |
| Bulgaria | Nuclear regulatory agency | European 'Stress Tests' Kozloduy NPP, national action plan of Bulgaria |
| Czech Republic | State office for nuclear safety | Post Fukushima national action plan on strengthening nuclear safety of nuclear facilities in the Czech Republic |
| Finland | Radiation and nuclear safety authority | European stress tests for nuclear power plants, national action plan Finland |
| France | Autorité de sûreté nucléaire | Complementary safety assessments follow-up to the French nuclear power plant stress tests, national action plan of the French nuclear safety authority |
| Germany | Federal ministry for the environment, nature conservation and nuclear safety | German action plan for the implementation of measures after the Fukushima Daiichi reactor accident |
| Hungary | Atomic energy authority | National action plan of Hungary on the implementation actions decided upon the lessons learned from the Fukushima Daiichi accident |
| Lithuania | State nuclear power safety inspectorate | Plan of strengthening nuclear safety in Lithuania, follow-up of the 'stress tests' performed in European Union |
| Netherlands | Ministry of economic affairs, agriculture and innovation | Netherlands' national action plan for the follow-up of post-Fukushima Daiichi related activities |
| Romania | National commission for nuclear activities control | Romanian national action plan post-Fukushima |
| Slovakia | Nuclear regulatory authority | National action plan of the Slovak Republic, regarding actions to comply with the conclusions from the stress tests performed on nuclear power plants |
| Slovenia | Nuclear safety administration | Slovenian post-Fukushima national action plan |
| Spain | Nuclear safety council | Post-Fukushima European action plan, Spain, national action plan |
| Sweden | Radiation safety authority | Swedish action plan for nuclear power plants |
| Switzerland | Swiss nuclear safety authority | EU stress test: Swiss national action plan |
| Ukraine | State nuclear regulatory inspectorate | National Action Plan |
| United Kingdom | Office for nuclear regulation | ONR ENSREG related 'national action plan' |

## 2.2 IAEA advanced safety assessment studies

The International Atomic Energy Agency provides technical guidance on nuclear safety issues. Following the Fukushima event, IAEA organized an international meeting of expert with the objectives to:

- share lessons learned from recent extreme earthquakes and tsunamis;
- exchange information on the development of recent technologies and the results of on-going research programmes relating to site evaluation and nuclear power plant safety;
- identify issues that should be further investigated.

The key issues relevant to the scope of this report are summarised in the following. Further details are available elsewhere (IAEA 2012).

There is a large uncertainty in the estimated seismic hazard, which regulators need to understand and address. The uncertainty related to the lack of knowledge, i.e. the epistemic uncertainty, may be reduced by the use of increasingly refined ground motion prediction models, whereas the inherent variability in ground motions does not lend itself to easy quantification. Furthermore, historical data are not sufficient to capture the long-term hazards and investigations to collect prehistoric data are needed. Considering that seismic hazard evaluations will likely not remain valid over the life of the power plant, periodic updates of the seismic hazard are to be carried out to take advantage of the impressive amount of new ground motion data that is being collected and of the new methods that are being developed. In this context, the use of probabilistic seismic hazard assessment methods is encouraged.

Similarly, tsunami hazard assessment should take into account recent advances in deterministic and probabilistic approaches, modelling, prehistoric and historical data gathering, data analysis, field investigations, etc.

The potential for flooding to affect multiple units and possibly multiple sites needs to be comprehensively investigated for new and existing nuclear power plants, using a probabilistic approach to identify any severe cliff-edge effects. Where needed, protection measures should follow the ‘dry site’ concept.

The safety goal should be defined considering different natural hazards and their combination in a probabilistic safety assessment that provides qualitative and quantitative output. The latter may be frequencies of plant damage states or releases to the environment, expressed as mean estimates with associated uncertainty distributions. The combination should cover all extreme external natural hazards that can potentially affect the site, either as concomitant or physically separated events. To this end, methodologies for the calculation of the available safety margins should be developed, with preference for probabilistic and site-specific approaches, and the failure modes of critical structures, systems and components need to be clearly understood. The design process and the re-evaluation of the safety of existing nuclear installations should also consider external event scenarios beyond the design basis, taking into account the uncertainties associated with natural events. Seismic isolation is a technique to be further considered for design basis and beyond-design basis scenarios.

A list of the country reports and selected IAEA guidelines, together with specific findings from the country reports and a detailed case study of the Krško nuclear power station in Slovenia may be found in the corresponding deliverable of the STREST project (Zwicky 2014).

# 3. State-of-the-art in hazard and risk assessment of non-nuclear critical infrastructures

A critical infrastructure is an asset or system, which is essential for society and the environment. Because of the critical infrastructures' high integration and dependencies in Europe, a failure of a superregional critical infrastructure facility could cause large-scale effects. Therefore, measures are taken to increase the protection of society and the environment in the European Union. A survey about state-of-the-art methods and guidelines in terms of risk assessment in European countries and in the entire EU is presented in this Chapter with a view to examine the way different countries deal with risks related to critical infrastructures and to evaluate specific standards for the types of critical infrastructures defined in STREST.

## 3.1 Critical infrastructure protection in Europe

### 3.1.1 Legislative background

The principles of the European programme for critical infrastructure protection propose different concepts on risk evaluation and risk analysis (EC 2006). According to the Directive[1] on European critical infrastructures (ECIs), ECIs have cross-border influences on society and environment. The Directive deals with the assessment, categorization and evaluation of ECIs and refers to different measures to increase the protection of ECIs. Terrorism is defined as a major threat. Additionally, the vulnerability of CIs to natural hazards is examined and discussed. A step-by-step approach for the protection of ECIs is described in Fig. 3.1.

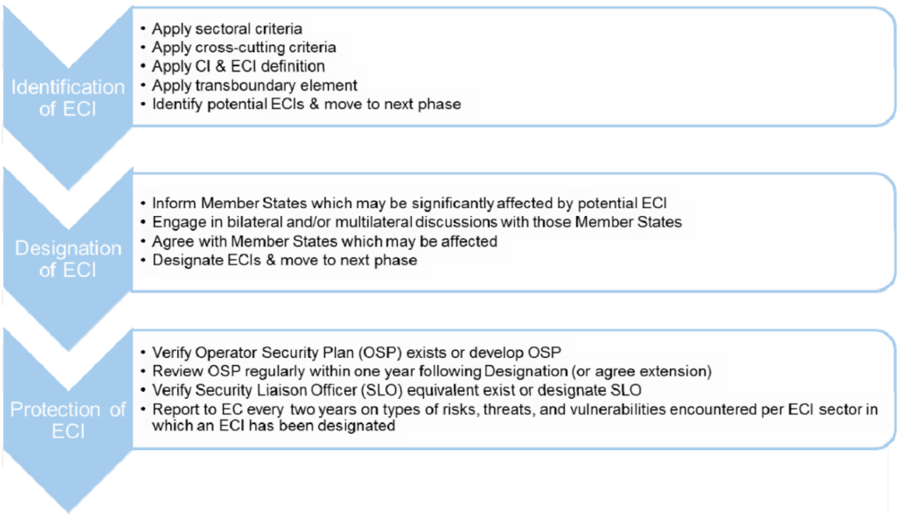


Fig. 3.1 The European Critical Infrastructure process (EC 2012)

A proposal for the implementation of a critical infrastructure warning information network introduces multi-hazard events and cascading failures of critical structures, with the objective to enforce risk management, especially after the occurrence of hazards (EC 2008).

[1] Council Directive 2008/114/EC on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection

The 'Seveso III' Directive[2] concerns the treatment of chemical substances in the European Union. The main objectives are firstly to prevent major accidents involving dangerous substances and secondly to limit consequences for citizens and the environment. Cascading failures are dealt with in terms of domino effects.

The Directive on the assessment and management of flood risks[3] requests EU Member States to prepare national flood hazard maps considering scenarios of low, medium and high probability and to establish risk management plans with appropriate measures. The Directive recalls the possibility to grant rapid financial assistance in the event of a major disaster to help the people, natural zones, regions and countries.

Within the EU internal security strategy, an all-hazard approach to risk assessment is introduced for natural and man-made disasters (EC 2010a). The objective is to improve the long-standing disaster management practices in terms of efficiency and coherence and ultimately to increase Europe's resilience to disasters. Guidelines for risk assessment and mapping are proposed (EC 2010b), building on the experience in the practical implementations of national risk assessments and mapping, taking full account of existing EU legislation, considering the Eurocodes for structural design, gathering results from most recent research in the area and seeking a better comparability between Member States.

### 3.1.2 European and international guidelines for risk assessment

The EN Eurocodes are a series of 10 European Standards, EN 1990 – EN 1999, providing a common approach for the design of buildings and other civil engineering works and construction products. They apply to structural design of buildings and other civil engineering works including geotechnical aspects, structural fire design and situations including earthquakes, execution and temporary structures. Table 3.1 lists the Eurocodes that are relevant for a number of natural and industrial disasters. Location-specific actions (snow, wind, earthquakes) are defined in national annexes. The Eurocodes provide principles and rules for the design of buildings and other civil engineering works against earthquakes, fires and explosions.

Table 3.1 Eurocodes relevant for different types of disasters (EC 2010b)

| Disaster | Technical / normative framework |
|---|---|
| Forest fires | Eurocode 1 defines protective design measures against fire for buildings made of various materials, e.g. steel, concrete, wood, masonry |
| Ground movements | Eurocode 7 defines calculation and design rules for the stability of buildings according to the geotechnical conditions of the site |
| Earthquakes | Eurocode 8 covers general rules and seismic actions, assessment and retrofitting of buildings, design of silos, tanks, pipelines, foundations, towers, masts and chimneys |
| Storms, hurricanes | Eurocode 1 defines wind actions |
| Industrial and technological hazards | Eurocode 1 defines principles for the design of structures against explosions |

[2] Directive 2012/18/of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC

[3] Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks

ISO 31000 'Risk management – Principles and guidelines' (ISO 2009a) provides principles, framework and a process for managing risk, to be used by any organization regardless of its size, activity or sector. ISO 31000 can help organizations increase the likelihood of achieving objectives, improve the identification of opportunities and threats and effectively allocate and use resources for risk treatment. The ISO Guide 73 (ISO 2009b) complements ISO 31000 by providing a collection of terms and definitions relating to the management of risk. These documents are further complemented by ISO/IEC 31010 that focuses on risk assessment concepts, processes and techniques to help decision makers understand the risks that could affect the achievement of objectives as well as the adequacy of the controls already in place.

A brief description of a number of methodologies for risk assessment of critical infrastructures is given in Annex B (Giannopoulos et al 2012).

## 3.2 National guidelines for protection against chemical hazards

This section presents the risk methods used in a number of countries, mainly the 'early adapters' to the 'Seveso' Directives that largely served as a template for countries that developed their methods in a later stage. These countries are Austria, Belgium, Finland, France, Germany, Greece, Italy, the Netherlands, Spain, Sweden, Switzerland and the United Kingdom. Information is also given on the USA. An overview is given in the following, while further details are given elsewhere (Billmaier and Reinders 2013).

The Austrian national safety research program for hazards of critical infrastructures (BMVIT 2008) is based on the principles proposed by the European Programme for Critical Infrastructure Protection. A publicly accessible hazard map (www.hora.gv.at) is meant to assist with the assessment of risks, to which selected regions in Austria are exposed. The topic of flood risks is up-to-date in Austria, because of their occurrence in the past years. The Austrian 'Industrial Accident Guidelines' (BKA 2013) deal with accidents in industrial plants and waste treatment facilities, including cross-border accidents. Key points are safety concepts, information systems, safety reports and the inclusion of consequences on the environment. Public announcements in any case of accidents in important industrial facilities are compulsory.

The deterministic risk assessment approach is applied in the industry related to dangerous chemicals in Finland. Risks are often evaluated in a coarse way by using a semi-quantitative assessment, e.g. a risk matrix. The competent authority requires a description and the control of possible hazards at the plant, as well as measures for protection and intervention for the limitation of the consequences of accidents. The results of risk analysis are also used for emergency response planning by the local rescue services.

The initial deterministic approach of the French regulations changed after the Toulouse tragedy in 2001, where a series of explosions of ammonium nitrate caused about 20 fatalities, many injuries and extensive property damage. Guidelines are available for land use, types of loss of containment, selection of relevant scenarios, analytical equations for assessing consequence distances for typical events, and presentation of the results (MESD 2003, MLPE 2004). The French government has assigned a number of independent experts to assist in the evaluation of safety reports submitted by the plant owners.

The German approach for risk assessment is a fully deterministic one. The hazard identification process makes use of structured techniques like hazard and operability (HAZOP) studies, failure mode and effects analysis (FMEA), checklists, accident history and expert opinions. The guidelines for risk analysis (BKK 2011) define three approaches to risk analysis: i) the 'qualitative approach' that can be applied in order to derive 'critical criteria' analysis; ii) the 'semi-quantitative approach' where numbers are assigned to theoretical risk values in order to achieve comparability; and iii) the 'quantitative approach' that is based on simulation models. The German ordinance that regulates exceptional industrial hazards and critical infrastructures which deal with dangerous substances (BMJ 2013) specifies three grades of impact: effect on a major group of humans, particular danger for some humans and the possible general effect on animals and environment. An important issue is the demand for emergency plans and the related communication with federal governments and institutions, also in the case of possible cross-border effects.

The requirements for safety reports in Greece are limited to common interpretations of the Seveso II text, and thus neither quantitative risk analysis nor environmental risk studies are required. A zoning system with certain consequence criteria has been proposed by the Ministry of Environment for the external emergency plan of industrial areas. It comprises three levels of consequences that are based on damage criteria.

Specific features are included in the Seveso II guidelines in Italy (DL 2015). The Port Safety Report gives a summary of all major hazardous activities, defines the carrier of a critical infrastructure as a possible source of hazard and requests port authorities to prepare emergency plans. Integrated Area Safety Reports are used to coordinate risk assessment in areas in which critical infrastructures are situated, aiming to reduce the risks of domino effects and cascading hazards.

The Netherlands have developed one of the most extensive and fully quantified probabilistic risk assessment methods. It is also one of the most prescriptive: installations, types and frequencies of loss of containment, calculation methods, risk acceptance criteria and even the computer programme to use are prescribed. Guidelines are available on: i) statistical methods to determine loss of containment (CPD 2005a); ii) models for physical effect calculations for the release, evaporation and dispersion of hazardous materials and for assessing thermal radiation due to fire, overpressures due to explosion and exposure to toxic dose (CPD 2005b); iii) models for assessing the potential damage (CPD 1992); and iv) standardised procedures for a quantitative risk assessment, including reference scenarios and their frequency of occurrence (CPD 2005c).

The Dutch approach is strongly related to the one adopted in the Flanders region of Belgium, where the Dutch CPR guidelines are recommended as standard.

The approach for risk analysis in Spain is basically a deterministic one. For a number of accident scenarios, the consequence areas (distances) have to be assessed and mapped for a set of prescribed effect values like heat radiation and explosion overpressure. Not only areas for fatalities are required, but also areas with potential injuries. Regional differences are observed in Spain. In the province of Catalonia for instance, the regional authorities often require a probabilistic assessment to be provided in addition to the national requirements. Use of the Dutch tools is encouraged.

Decision support in Sweden is based on a risk matrix approach, in which semi-quantitative classification of consequence severity and incident likelihood are presented. Consequences are expressed in human life, damage to the environment and financial loss of property. The results are used to prioritise risks in municipalities, to evaluate possibilities for accident prevention and to plan for emergencies.

The Ordinance on Protection against Major Accidents (OMA 1994) in Switzerland reflects well-established procedures in risk control, in particular those used in the Netherlands in the context of the environment control policy, e.g. the quantitative risk approach. At the same time, it requires implementation of the state-of-the-art technology in agreement with the German practice. Assessment of hazard potential and risks is done in a two-steps procedure: a summary report by the facility owner, followed by a quantitative risk assessment, in case the summary report shows that major accidents and serious damage must be expected. Guidance is available on risk analysis process and risk evaluation, manuals for specific types of installation, typical accident scenarios, prototypes for fault- and event-tree analyses, case studies for fictitious facilities, etc.

The intention of the Swiss ordinance dealing with hazardous events in critical infrastructures (BAFU 2013) is to protect humans and the environment and makes compulsory the definition of hazard and emergency plans. Risk assessment has to be conducted with a risk analysis report, examined by the enforcement agency that decides whether further actions have to be considered. Even if risks exist within acceptable thresholds, stakeholders have to reduce them if necessary actions can be accepted in economic terms.

In the United Kingdom, a quantified risk assessment is required according to a probabilistic risk analysis approach, as described in guidance documents for assisting the risk analysts (HSE 2001, 2002, 2003). The quantitative risk assessment procedure is according to 'proportionality', which means that the extent of detail of the assessment shall be proportional to the risk generated and/or to the complexity of the process/installation in question. In decision-making, the 'as low as reasonably practicable' rule applies, meaning that residual risk shall be as low as reasonably practicable, thus a further reduction of the risk would be disproportional costly.

In the USA, the Environmental Protection Agency developed the relevant policy that requires major hazard industries to submit a risk management plan document (EPA 1999) and the requirements for information to be provided for emergency response planning. A deterministic approach is followed and at least two scenarios have to be evaluated and quantified in terms of consequence distances: a major or catastrophic incident and a 'more likely serious incident', to be defined by the operator. The Agency provides guidance documents and consequence assessment software to support a consistent and uniform application of the matter.

## 3.3 Guidelines related to the STREST test sites

### 3.3.1 Large dams

Large dams are built for the production of electrical power and serve also for the absorption of flood events. Because of their high filling level and size, they have a great damage potential due to natural hazards such as earthquakes, landslides and floods. The International Commission on Large Dams (ICOLD) is a worldwide organization that involves the majority of the European countries, and has issued guidelines for risk assessment that aim to increase the safety of large dams (ICOLD 2005).

The most recent version of Germany's standard on water-retaining structures was introduced in 2004 (DIN 2004) and proposed a classification of individual dam sites based on risk assessment for specified design cases: floods and earthquakes. The concept for the structural reliability of large dams combines uncertainties of the external inputs and of the structural resistance and considers partial risks. The system comprising the bearing structure and foundation has to resist the design input without any damage, but may experience structural damages in case of a more unlikely extreme event. Monitoring and maintenance are important, while additional rules (e.g. on preparedness and on the competence of planners) cover so-called 'other risks' and reduce tolerance levels.

Large dams under the guidance of the Swiss Federal Office of Energy (SFOE) are subject to the Water Retaining Facilities Decree (BFE 2013a) and the Water Retaining Facilities Act (BFE 2013b). The consequences of a potential failure are discussed, but the probabilities of occurrence of an extreme event are not evaluated. Natural hazards are defined as any change of performance, mass movements in terms of landslides, floods, earthquakes and inputs such as explosions. These extreme events are highly unlikely but physically possible to occur. Risks are assessed with a concept of three pillars: i) planning and design, ii) monitoring and maintenance while in operation, and iii) emergency plans in case of an extreme event.

Monitoring is one key point for dam safety in the Austrian guidelines for structural safety (BMLFUW 1996), where earthquake hazard is mentioned with reference to the 'maximum conceivable earthquake event', but risk assessment or management is not directly addressed. Dam sites which have a runoff in existing river runways are considered as less affected by flood hazards.

Garbe (2007) examined the national standards in 21 countries and compared how risks of large dams are assessed. Table 3.2 summarises the results of a survey consisting of four different criteria to assess and treat the remaining risks in a number of European countries. Apparently, risk analysis and management is obligatory in the majority of the examined countries.

Table 3.2 Criteria to assess and deal with disclosed risks of dam hazards

| Country | Risk analysis and treatment | Flood wave and break of a dam | Emergency plans | Alarm systems |
|---|---|---|---|---|
| Austria | supplemental | supplemental | supplemental | no declaration |
| Czech Republic | obligatory | no declaration | no declaration | no declaration |
| France | obligatory | obligatory | obligatory | obligatory |
| Germany | obligatory | obligatory | obligatory | obligatory |
| Italy | obligatory | obligatory | obligatory | obligatory |
| Norway | obligatory | obligatory | obligatory | supplemental |
| Portugal | obligatory | supplemental | obligatory | supplemental |
| Spain | obligatory | obligatory | obligatory | supplemental |
| Switzerland | obligatory | obligatory | obligatory | obligatory |

### 3.3.2 Hydrocarbon pipelines, gas storage and distribution networks

The hydrocarbon pipelines for gas and oil products that are examined in STREST cross different fault zones in Turkey. Low-pressure pipelines in the Netherlands are also studied, where the gas distribution network is an interconnected system that spans across approximately 100 gas fields. Possible hazards are earthquakes, floods, changes of soil conditions and collapse of tall structures, such as wind turbines and electrical power lines, which could fall on elements of the gas distribution network.

A number of European legislative acts [1,4,5] and standards, such as EN 14161 for pipeline transportation systems (CEN 2011) and EN 1594 (CEN 2013) for pipelines for maximum operating pressure over 16 bar, are relevant to oil and gas pipelines. Besides, the majority of European countries define national guidelines and recommendations dealing with oil and gas pipelines, as shown in Fig. 3.2. Other international guidelines also cover the safety of pipelines (BAFU 1963, BAFU 2007, HSE 1996, UNECE 2008, ASME 2014).

[4] Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment

[5] Directive 2014/68/EU of the European Parliament and of the Council of 15 May 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of pressure equipment

| Country | Safety management systems | Risk assessment | External emergency plans | Land use planning | Information to the public | Third-party issues | Technical safety requirements |
|---|---|---|---|---|---|---|---|
| Belgium | ++ | ++ | ++ | ++ | + | +++ | ++ |
| Czech Republic | + | 0 | +++ | ++ | + | +++ | ++ |
| Denmark | 0 | ++ | ++ | + | 0 | ++ | +++ |
| Estonia | 0 | ++ | 0 | + | 0 | ++ | ++ |
| Finland | +++ | ++ | ++ | ++ | + | ++ | +++ |
| France | +++ | ++ | +++ | ++ | + | +++ | ++ |
| Germany | ++ | ++ | +++ | ++ | + | +++ | +++ |
| Ireland | +++ | ++ | +++ | | + | +++ | 0 |
| Italy | + | ++ | 0 | + | + | ++ | +++ |
| Netherlands | ++ | ++ | +++ | + | + | +++ | Duty of care |
| Poland | +++ | + | 0 | + | + | + | +++ |
| Portugal | +++ | ++ | 0 | + | + | +++ | +++ |
| Romania | +++ | ++ | +++ | + | + | 0 | ++ |
| Spain[23] | + + | + + | + | + + + | + | + | + + |
| Sweden | ++ | 0 | + | 0 | 0 | + | ++ |
| UK | +++ | ++ | ++ | ++ | 0 | + | Duty of care |
| Croatia | ++ | +++ | ++ | ++ | + | ++ | +++ |
| Turkey | ++ | +++ | +++ | ++ | + | ++ | +++ |
| Norway | ++ | +++ | +++ | ++ | + | ++ | +++ |

Legend: 0: no provision in place +: basic provision, ++ several provisions
+++ many provisions

Fig. 3.2 Overview of legislative coverage in Europe (DG ENV 2012)

The Seveso guidelines are the basis for risk assessment of gas storage and transportation systems in the Netherlands, involving several ministries for the overall coordination, disaster response and principal safety concerns. Companies must submit a safety report, including quantities of hazardous substances. Flood risks are typically evaluated, while other hazards such as natural fires and earthquakes can be examined. A detailed guideline for risk assessment (RIVM 2009) governs critical infrastructures and the surrounding areas.

Turkey has introduced numerous recommendations and guidelines on oil and gas pipelines. Besides the national laws, international standards that comply with national regulations are in use. Therefore pipelines conform to relevant EN and ASME standards.

### 3.3.3 Industrial districts

The industrial district located in the Emilia region of northern Italy was selected as a test site because of its economic importance and the widespread damage due to the multiple earthquakes in 2012. The earthquake series had major economic consequences for the entire region's industry; losses were estimated to exceed 15 billion Euros.

Eurocode 8 (CEN 2004) covers earthquake resistant design of structures and included regional seismic hazard maps in National Annexes. The studied industrial district in the Emilia region, indicated with a star symbol in the map of seismic zones shown in Fig. 3.3, has not been identified to be seismically sensitive prior to 2003, therefore buildings were not designed to withstand earthquake shaking.

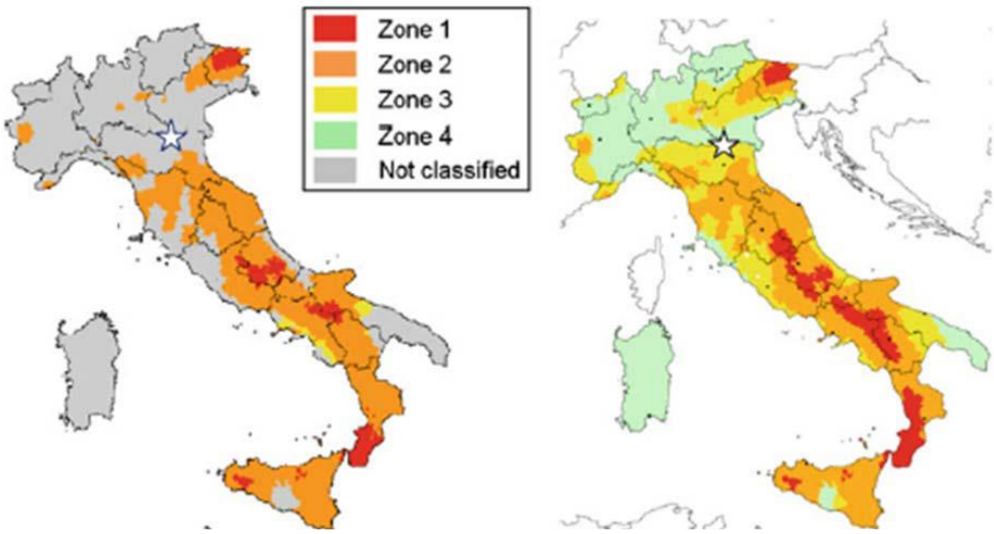


Fig. 3.3 Seismic zones in Italy before (MLP 1984) (left) and after 2003 (PCM 2003) (right)

# 4. Lessons learned from recent catastrophic events related to the STREST case studies

This Chapter provides case-study descriptions of past incidents to shed light on the vulnerability of critical infrastructures to selected natural hazards. More specifically, incidents at refineries, large dams, hydrocarbon pipelines, natural gas storage and distribution, ports and industrial districts are analysed to better understand impact dynamics, system weaknesses, potential consequences and contributing factors. The examined past events and their impact on different types of critical infrastructures are summarised in Table 4.1. Based on the case histories and experience from similar incidents, lessons learned are derived for system weaknesses and critical components, potential for propagation, consequence severity and extent and protection systems and measures.

Table 4.1 Natural events and types of affected critical infrastructures

| Event | Petrochemical facility | Large dams | Hydrocarbon pipelines | Gas storage and distribution networks | Ports | Industrial districts |
|---|---|---|---|---|---|---|
| Northridge earthquake, USA, 17/01/1994 | X | | X | X | | X |
| Hyogo-Ken Nanbu (Kobe) earthquake, Japan, 17/01/1995 | | | | | X | |
| Kocaeli earthquake, Turkey, 17/08/1999 | X | | | | X | X |
| Wenchuan earthquake, China, 12/05/2008 | | X | | | | |
| L'Aquila earthquake, Italy, 6/04/ 2009 | | | | X | | |
| Central Europe floods, Poland, 7/08/2010 | | X | | | | |
| Christchurch earthquake, Australia, 22/02/2011 | | | | | | X |
| Great East Japan (Tohoku) earthquake and tsunami, Japan, 11/03/2011 | X | | | | X | |
| Thai Floods, Thailand, 2011 | | | | | | X |
| Emilia Romagna earthquakes, Italy, 20-29/05/2012 | | | | | | X |

## 4.1 Refineries and petrochemical facilities

### 4.1.1 Lessons learned from earthquakes

The examined cases suggest that non-anchored storage tanks are particularly vulnerable to earthquake-induced shaking. Major accidents were caused by tank deformation, e.g. as shown in Fig. 4.1, and failure with losses from the tank shell or the roof top due to liquid sloshing, and breaking of flanges and pipe-tank connections. This is in agreement with the findings of several other studies related to earthquake-triggered Natech accidents (Krausmann et al 2010, 2011; Salzano et al 2003, Steinberg and Cruz 2004). Pressurised tanks generally perform better during earthquakes as their operating conditions require a higher shell thickness than for atmospheric tanks. This renders them more resistant to earthquake shaking. Liquid sloshing, in particular for full or nearly full tanks, is an important contributing factor for tank collapse which can lead to the instantaneous release of the complete tank inventory (Ballantyne and Crouse 1997). The dynamic loading on the tank wall should be considered in the risk assessment in earthquake-prone areas. On-site piping and pipelines are also vulnerable to earthquake shaking.

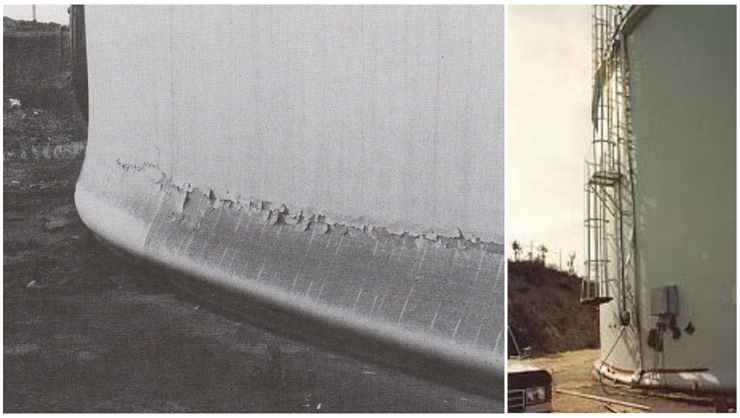

Fig. 4.1 Elephant foot buckling of a bolted steel tank

The risk of cascading effects is very high. On the one hand, earthquakes can trigger multiple releases at a single chemical facility or from several affected hazardous installations at the same time, potentially overloading emergency response. On the other hand, the ignition probability is extremely high when flammables are released. Furthermore, in the case of explosions, missile projection could cause secondary accidents in neighbouring installations. Land-use and emergency-response planning decisions should consider this potential for domino effects.

Since storage tanks usually hold large quantities of hazardous materials, the risk of severe and extended consequences can be high in case of damage. Furthermore, historical analyses showed that several equipment items of the same type can be damaged or destroyed per earthquake event, as well as more than one equipment type. This is compounded by the likely loss of lifelines needed e.g. for cooling processes or for combating fires. On-site emergency planning needs to take this into account and standalone backup plans for accident prevention and mitigation should be developed in earthquake-prone areas. These backup plans should not rely on the availability of off-site emergency-response resources as they might be needed elsewhere to fight the consequences of the earthquake on the population. At the same time, off-site emergency plans should take into account the possible impact of hazardous-materials releases on rescue operations.

Economic losses can be major due to damage to equipment, raw materials and products. Costs related to business interruption and the suspension of production can exacerbate a company's losses.

Seismic building codes based on a realistic assessment of the expected earthquake severity and the resultant seismic loading on structures need to be implemented and compliance monitored. Where not mandatory, it might also be beneficial to extend seismic design codes to equipment rather than only buildings. Since also safety barriers may fail under earthquake loading, critical active and passive safety barriers should also be designed to resist the design earthquake. Furthermore, it is crucial that functioning safety-management oversight in companies and effective control mechanisms by authorities are in place to ensure the correct implementation of safety regulations.

Structural protection measures to increase the resistance of the most vulnerable equipment to earthquake shaking exist, such as adequate anchoring or restraining of tanks and other types of equipment to avert lateral displacement and/or uplifting and flexible pipe-tank connections.

With warning times ranging from only a few seconds to a couple of minutes, the implementation of early-warning and rapid-response systems at facilities is of only limited use. At most, automatic valve closure and emergency shutdown upon activation of a sensor net could be envisaged.

### 4.1.2 Lessons learned from tsunamis

Unanchored tanks and other equipment are vulnerable to floating and displacement due to buoyancy and overturning. These phenomena can lead to the breaking of pipe connections, ripping off of valves, and destruction of equipment, and hence to releases of possibly toxic and/or flammable materials. Debris impact can result in additional damage or destruction.

Refinery port terminals are also identified as vulnerable to tsunami impact, in particular when tankers are docked when the tsunami hits. Tankers engaged in product transfer activities and connected to the (un)loading arm can tear loose upon wave impact, thereby breaking pipe connections or the (un)loading arms which results in hazardous-materials releases, as observed during the tsunami triggered by the Kocaeli earthquake in 1999 (Steinberg and Cruz 2004). In this context, the interconnectedness with the power grid needs to be highlighted. During the Tohoku earthquake, tankers moored at the terminals in the Kashima industrial park could not disconnect from the (un)loading arms due to the power outage. When the tsunami arrived, the arms broke and the ships floated off, causing damage to berths.

Multiple and simultaneous hazardous-materials releases are to be expected. In addition, the tsunami waters can disperse flammable spills (including releases from a preceding earthquake) over wide areas, thereby increasing the risk of ignition and severe secondary consequences. This risk is particularly important in situations where failed land-use planning puts industrial facilities in proximity to residential areas or where distances between facilities are insufficient. In addition, the potentially wide-scale disruption of lifelines can hamper effective emergency response, e.g. due to a loss of fire-fighting or cooling water. Loss of lifelines can also significantly decrease a facility's production capacity even if it did not suffer damage by the tsunami.

Land-use-planning restrictions should ascertain that industrial development is limited in tsunami-prone areas. However, this is difficult to implement retroactively, in which case supplementary measures are required to protect a hazardous installation, such as offshore break walls or onshore barriers. The latter can also help to keep tsunami-driven debris from washing into a facility where it can cause significant damage due to collisions with equipment containing hazardous materials. In addition, structures or equipment containing hazardous substances, as well as safety-critical systems should be protected from water intrusion or wave-load damage. Anchoring of tanks or equipment in general should keep it from floating off its foundations under most conditions. If critical structures cannot be hardened to tsunami impact, relocation (e.g. to higher elevations on the site) should be considered and might be more cost-effective. Containment dykes around storage tanks could provide some flood protection in case they are not overtopped or eroded, but their primary purpose is to retain accidental releases of hazardous substances rather than keep the flood waters out.

Structural protection measures need to be supplemented by organisational measures to reduce the risk of tsunami impact. Tsunami hazard management plans should be drawn up at both plant and community level, and construction practises and compliance with building codes need to be monitored. The damaging effects of a possibly preceding earthquake should be considered, as weakened shore-protection systems and industrial facilities have less resistance to an impacting tsunami wave (Cruz et al 2011). In addition, the vulnerability of emergency resources should be assessed, as they might also be affected by the tsunami.

Timely early warning prior to a tsunami would enable operators to take protective measures, such as safety valve isolation, plant shutdown, depressurisation of equipment, de-inventorying of equipment and transfer of hazardous substances to safer locations. The necessary time for action depends on the type of potentially impacted equipment, the substance it contains, operating or storage conditions, as well as associated actions of people and systems. If the propagation time of the tsunami is long enough, tankers moored at a refinery's oil terminal will be able safely stop (un)loading and move into deeper waters.

## 4.2 Large dams

### 4.2.1 Lessons learned from earthquakes

The dam body's structural integrity needs to be ensured after an earthquake, as well as the operability of certain elements that are considered safety critical. These are, for instance, bottom outlets, spillways and related hydro- and electromechanical equipment (Wieland 2012). Damage to these components can hamper the capability to release pressure on the dam by discharging water from the reservoir and therefore seriously endanger the dam's integrity. Earthquake impact on appurtenant structures, such as powerhouses, switchyards, etc. do not pose a threat to the dam itself but damage will lead to service disruption and economic losses.

Earthquakes pose a risk not only due to ground shaking but also because of potential fault movements, landslides, rockfalls, and liquefaction etc. The Wenchuan earthquake demonstrated this: what aggravated the recovery situation was the blocking of access roads by rockfalls, making it impossible for construction equipment to reach several dam sites for several months (Wieland 2012). This means that damaged dams might have to remain safe for an extended time span before rehabilitation can begin.

The risk of cascading effects can be significant when dams are impacted by multiple earthquake shocks. On the one hand, failure of the dam endangers the downstream environment, potentially causing a high number of fatalities. On the other hand, many dams may be subjected to strong ground shaking at the same time. The earthquake-induced failure of upstream dams and the subsequent water masses rushing downstream might exceed a downstream dam's capacity for dealing with the extra water load, potentially causing it to fail under the additional pressure. Furthermore, there is a risk of landslides that enter a dam's reservoir, which may increase the risk of overtopping.

Seismic dam design exists since the 1930s and large dams generally have a good seismic safety record (ICOLD 2010a). There is only a single case where lives were lost in a dam failure triggered by the Tohoku earthquake in 2011 (Matsumoto et al 2011). Until now, only embankment dams have suffered complete failure due to seismic loading, while large concrete dams exposed to strong earthquakes were damaged but did not fail (Wieland and Brenner 2008). Seismic design guidelines are available that should ensure the safe performance of large dams (ICOLD 2010b). They introduce modern seismic design criteria, different levels of design earthquake intensities as a function of safety criticality of the dam component, and dynamic analyses to calculate the inelastic seismic response of embankment and concrete dams.

There is concern related to existing large dams whose construction dates back to a time when design criteria and analysis methodologies differed significantly from what is considered adequate nowadays. Where unacceptable performance is predicted, retrofitting measures can improve the situation. For embankment dams, in situ soil improvement, removal and replacement of weak soils, embankment buttressing and combinations of these methods have been proposed (ASDSO 2014). Concrete dams can be retrofitted, e.g. through anchoring and buttressing.

### 4.2.2 Lessons learned from floods

Dams are at risk when the water inflow into the reservoir greatly exceeds the outflow capacity because of inadequate spillway design or where there is no emergency spillway. This can lead to failure of the dam by overtopping and scouring of the embankment or foundation, as shown in Fig. 4.2. In the US, about 30% of dam failures over the last 75 years were caused by overtopping of embankment dams (USDOI 2012). Where spillways are gated, there is the additional risk of gateway malfunction due to mechanical failures, loss of power or gate binding. Gates can also be blocked by floating debris, landslides or rockfalls. Embankment dams are vulnerable to even low levels of overtopping, if sustained, while concrete dams would likely be able to withstand a certain level of overtopping due to their rock foundations (USDOI 2012). The depth and duration of the overtopping is a key factor in determining the risk, as well as the erodibility of the embankment material or foundations.

Fig. 4.2 Failure of the Niedow dam in Poland due to flooding (Fry et al 2012)

Considering that large rivers usually have a network of multiple dams, there can be a risk of cascading failure triggered by the collapse of an upstream dam. This can be of concern during flood conditions when downstream reservoirs might already have reached their flood retention capacity and where they consequently might not be able to accommodate the water volume approaching from the reservoir of a failed upstream dam. Safe dam design in addition to considering the need for excess storage capacity for flood conditions ensures that this risk remains low. Another cascading scenario, although of extremely low probability, exists in situations where multiple dam failures occur within a short time interval in the same river basin affected by floods.

The consequences of dam failure to downstream settlements can be both disastrous and spatially extended. Sensible land-use planning should therefore restrict settlements in high-hazard areas, and early-warning systems linked with evacuation plans will reduce the risk for existing towns and villages.

Dam safety during flood conditions is ensured by designing the dam to withstand the probable maximum flood (PMF). This is a flood volume which can be spilled (and partly stored) without endangering dam stability (Lempérière and Vigny 2005). Definition of the PMF requires a good knowledge of the hydrological situation at the site which can change over time, e.g. due to global warming. Furthermore, time series for flood statistics may have been too short or not representative and as a consequence, older dams may have been designed for floods that no longer represent the magnitude of the PMF (USDOI, 2012). It is therefore important to update the PMF and to link it with retrofitting measures. In cases where retrofitting is not feasible, either due to technological challenges or because costs are prohibitive, the reservoirs would have to be operated at a lower level to safely manage PMF inflow by retention. A safety check flood of very low probability is proposed in replacement of the design flood with 1.000

years return period (ICOLD 1992, Lempérière and Vigny 2005). The safety check flood is the most extreme flood that the dam can withstand without failure but also with a low safety margin. It provides a more realistic approach to dam safety design and is more cost effective. Many countries have implemented for a long time the above-mentioned dual concept of design flood and safety check flood.

Safe dam design is the most important factor for controlling risks from large dams. Additional factors are maintenance, regular inspection and repair, as well as the preparation of emergency plans downstream of the dam. With sometimes substantial warning times, the implementation of early-warning systems coupled with evacuation plans, can contribute substantially to reducing the risks to the downstream environment.

## 4.3 Hydrocarbon pipelines

### 4.3.1 Lessons learned from earthquakes

Old pipelines made of non-ductile materials with oxy-acetylene welds are the system component most vulnerable to ground motion, e.g. Fig. 4.3 (left), and weld fractures are the most common failure mode. Replacement pipelines using newer materials, joint types and welding techniques show a much higher resistance to earthquake shaking. However, also newer pipelines are vulnerable to soil liquefaction with lateral spreading and fault movement, while discontinuities like supports and valves and connections to pump stations are also vulnerable. Buried continuous pipelines generally perform better than above-ground (ground supported) steel pipes due to inertial effects and the potential for unseating from their supports, e.g. Fig. 4.3 (right). Furthermore, above-ground pipelines and exposed sections of buried pipelines can be subject to earthquake-triggered landslides in mountainous areas.

Fig. 4.3 Buckled steel pipe connection (left) (Bilham et al 2003) and fall of ground-supported unseated pipeline from the supports at TUPRAS refinery due to inertial effects (left) (courtesy of Tupras 2000)

Since hydrocarbon pipelines transport flammable materials, the risk of ignition is high. Therefore, there is the danger of accident propagation if the affected pipeline is traversing residential areas. Furthermore, the earthquake can damage one pipeline in several places, or impact many pipelines at the same time. This increases the likelihood of cascading effects. Spills from liquid-fuel pipelines are more problematic in terms of spatial extent and impact on people and the environment (Girgin and Krausmann 2014). Crude-oil and petroleum-product releases on the ground can flow into storm drains that empty into rivers, potentially causing major environmental damage. Flammable spills can ignite and spread over wide areas, posing a risk to the population and property.

One of the most effective and economical ways to protect pipelines and associated facilities is adequate siting. Design safety is the most important pipeline protection mechanism that relies on the implementation of modern design standards, including the use of more resistant pipe materials and novel techniques for strengthening joints against earthquake shaking. Additional measures are required for pipelines in liquefaction-induced permanent ground deformation zones or at fault crossings. The installation of strong-motion detectors on the pipelines can be an additional measure to support quick operator action, e.g. reducing flow in the pipeline or shutting it down.

## 4.4 Gas storage and distribution networks

### 4.4.1 Lessons learned from earthquakes

Pipelines appear to be the weakest link in the natural gas storage and distribution network in case of strong ground motion and ground failure. Pipe materials and joint detailing critically influence the resistance of the natural gas system to earthquake loading (Lanzano et al 2013). Old steel pipelines with oxy-acetylene weld joints are particularly susceptible to earthquake damage compared to electric arc welds, chemical welds and mechanical joints (O'Rourke and Palmer 1996). Furthermore, small-diameter (low pressure) pipes are more vulnerable to seismic loading than medium-diameter (medium pressure) ones. Newer pipelines made of polyethylene are more resistant to earthquake impact compared to steel pipes. Construction of pipes according to the latest design standards is the most effective protection measure. Gas meters can be damaged due to debris impact from building collapse. Storage facilities are also subject to earthquake damage, in particular where tanks are supported by R/C columns, are not anchored or have hard pipe connections.

In case of natural gas release, the risk of explosions or spreading of fires to surrounding structures, in particular in urban areas, can be significant. In situations like these, it is of paramount importance that the gas network be immediately shut down to avoid any escalation of the event. Automatic gas shutoff systems are usually used as a protection measure in gas storage-distribution plants. Contemporary earthquake damage to fire-fighting structures or the breaking of water mains, can constitute a problem in case of fires in the natural gas network.

## 4.5 Ports

### 4.5.1 Lessons learned from earthquakes

Strong earthquakes can affect all port facilities, ranging from quay walls, docks, warehouses and cranes, e.g. Fig. 4.4 (left), to piles beneath jetties, pipelines and industrial manufacturing and storage activities. Evidence from past earthquakes suggests that most damage to port structures is associated with significant deformation of a soft or liquefiable soil deposit e.g. Fig. 4.4 (right). Damage can be severe because at the time of construction of port facilities, neither all the important response behaviours, such as soil liquefaction, nor a realistic approach of the seismic loading might have been considered in design.

Fig. 4.4 Crane damage at Sendai Port (TCLEE 2012) (left) and damage at the navy port in Gölcük (Bilham et al 2003) (right)

Experience from past earthquakes shows that properly designed cranes perform well if the foundations and soils perform well. Damages to cranes after earthquake events could be attributed not only to ground shaking, but also due to movement of rail foundations caused by ground failure, resulting in bending of their members (PIANC 2001). Cranes that are restrained or anchored to foundation rails are vulnerable to failure due to bending and ground shaking. Cranes may overturn due to liquefaction of underlying soil fills or/and the occurrence of differential settlements, or they may be induced to bending type of failure due to ground detachment of a foundation member (PIANC 2001). Overturned cranes can induce damage to adjacent structures and other facilities. Today's larger jumbo cranes are more susceptible to earthquake damage than early container cranes that are lighter and hence would be subjected to lower seismic forces (Soderberg et al 2009).

In case of earthquake-triggered hazardous-materials releases at industry sited at the port, fires and explosions can occur that could propagate to adjacent facilities, if adequate separation distances are not observed.

Analysing interdependencies between infrastructures during earthquakes highlights that ports can either be affected by the disruption of other infrastructures or their closure can impact other infrastructures (Tsuruta et al 2008). Interruption of the electric power and gas supply, waterworks, telecommunication and transport networks will have adverse effects on port operations, as illustrated for instance in the application of the SYNER-G methodology for systemic vulnerability analysis considering inter-dependencies (Kakderi et al 2012) to the Thessaloniki harbour (Kakderi et al 2013). Conversely, the closure of a port due to earthquake damage can affect gas delivery and administration infrastructures. With respect to the resilience of lifelines based on lessons learned from the Kobe earthquake, Casari and Wilkie (2004) indicated that the timing of lifeline repairs has a considerable impact on social welfare and that decentralised decisions by lifelines firms are not socially optimal.

An effective solution to protect port facilities from earthquake impact is to harden their critical elements. The seismic design of the structures and infrastructure components of a port should consider, as far as possible, a realistic evaluation of the seismic behaviour of the materials in situ and the seismic loads as well as the interaction between all the elements of the facilities/infrastructures. Where liquefaction can be an issue, implementing appropriate remediation measures against the phenomenon can effectively increase the seismic performance of port structures. Strategic decisions can be made to design important port operations to resist higher earthquake loading than others.

### 4.5.2 Lessons learned from tsunamis

All port facilities are at risk from tsunami impact due to their heightened exposure compared to other infrastructures. Non-anchored equipment or pieces of cargo, see Fig. 4.5 (left), can be moved or carried away with the tsunami waters, becoming debris that can collide with other structures and cause significant damage. In fact, ships that have broken their moorings due to tsunami inundation and began drifting have been identified as a major source of damage risk in port areas. Drifting ships caused various problems during the Tohoku earthquake either because of damage to the ships themselves, collision with other structures, and because they can constitute and obstacle for restoration, see Fig. 4.5 (right). Therefore, it is important for disaster prevention purposes to predict the drifting motion and route of a large ship driven by tsunami current (Suga et al 2013).

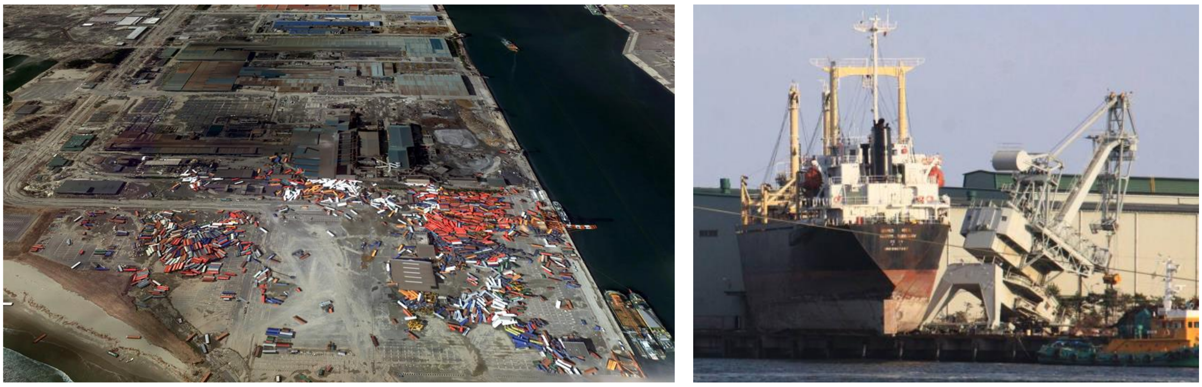

Fig. 4.5 Scattered containers at Sendai Port after the tsunami (Tomita and Yoem 2012) (left) and container ship swept ashore by tsunami at Sendai Port and damage on crane (TCLEE 2012) (right)

Cascading effects from tsunami impact at port facilities would be mostly economic, caused by the disruption of the supply chain from damage and facility downtime. The generation of disaster debris can exacerbate the damage due to collision with structures or equipment.

Many ports are home to manufacturing or storage activities involving hazardous materials. The risk of releases from these industries during a tsunami is high. Should flammable substances be accidentally released by tsunami impact, they can ignite and the fires can spread with the tsunami waters over wide areas, increasing the risk of accident propagation to other parts of the port.

The availability of a tsunami early warning system should help avoid major human losses at ports, provided that evacuation times are sufficient to reach higher ground and timely evacuation orders are given by the port authorities. The main tsunami losses at ports would then be caused by possibly unavoidable damage to structural and non-structural components, and the associated downtime of port operations.

Although the Tohoku region was in principle well prepared for tsunamis in general, the Great East Japan earthquake tsunami highlighted that structural measures cannot completely prevent tsunami disasters. However, a study commissioned by the World Bank found that while many dikes and breakwaters were destroyed by the tsunami, they were nevertheless somewhat effective in mitigating damage (Ishiwatari and Sagara 2012). The study also concludes that it is unrealistic to build protection structures large enough to safeguard people and assets from the largest conceivable events. Instead, the resilience of conventional structures should be enhanced to mitigate damage even when the design hazard level is exceeded and the concept of failure should be incorporated into the design of structures as a way to consider unforeseen events. It is noted that probabilistic tsunami hazard/risk assessment methods are based on this principle, but still less common in literature.

## 4.6 Industrial districts

### 4.6.1 Lessons learned from earthquakes

Earthquakes have caused widespread damage that included many tilt-up and steel frame industrial buildings. In the case of tilt-up buildings, connections between floor diaphragms and wall panels, inadequate steel reinforcement of members and large out-of-plane deformation demands of wall panels reduced the seismic performance of this kind of industrial facilities. These weaknesses usually caused partial roof collapse or suspended ceiling failures. Poor seismic performance of inadequately designed panel-structure connections was the primary reason for wall damage whereas pounding of roof and column members to the cladding wall panels also caused damage (Magliulo et al 2014).

Compared to the damage to tilt-up construction, steel frame buildings performed relatively better at first glance during the Northridge earthquake. However, detailed investigations revealed brittle fractures in welded beam-column connections which were usually hidden with architectural cladding elements (Mahin 1998).

During the Kocaeli earthquake, precast industrial facilities built before 1998 were vulnerable to seismic loading due to the relatively low design forces prescribed by the code and insufficient reinforcement detailing. In addition, inadequate precast member connections, irregularities causing short-column behaviour, unsettlement of beams due to excessive lateral deformations and inadequate diaphragm floors/roofs increased the vulnerability of industrial building stock (Saatçioğlu et al 2001).

In the industrial districts affected by the L'Aquila earthquake structural weaknesses such as vertical irregularities prone to causing soft-storey behaviour or significant movement of the beam and column support were identified (GRM 2009). Reasons for failure included heavy roof systems and improper design of beam-column connections. Damage and failure of columns observed during the Emilia Romagna earthquakes were due to low longitudinal reinforcement ratio, large spacing of stirrups, weak column pocket sockets and irregularities such as adjacent stiff members or partly infilled walls (Liberatore et al 2013). Common damage to beam and roof elements occurred because of either unseating or pounding with adjacent structural elements. Additionally, an insufficient diaphragmatic behaviour and individual column footings are other factors that contributed to the structural damage. Examples of observed damage after the Emilia Romagna earthquakes are given in Fig. 4.6.


Fig. 4.6 Observed damage to industrial buildings after the Emilia Romagna earthquakes of 20 and 29 May 2012 (Liberatore et al 2013)

Even without significant structural damage, cascading effects can be observed in industrial facilities. Earthquakes have highlighted the vulnerability of industrial facilities that contain chemical substances, and hazardous material incidents involving fires or explosions can cascade onto other infrastructures. Besides, Tang (2000) highlights the weakening effects of corrosion, chemical attack and low maintenance on originally earthquake-resistant industrial facilities and their components. In addition, it was observed that chemical containment systems can be more fragile than the buildings in which they are placed, and thus the performance of these components should also be considered when designing industrial facilities that house or process hazardous materials.

Cascading effects to a region’s or country’s economy are also possible where strong earthquakes affect extended areas that are heavily industrialised. These effects can be caused by structural damage and production downtimes, as well as via a ripple effect due to supply-chain interruption in otherwise undamaged facilities.

The socio-economic impact of earthquakes on industrial districts can be severe and stems from structural and non-structural damage, as well as from damage to raw materials or products to a potentially high number of individual businesses over a large area. In addition, industrial facilities might not able to get back to business immediately after the event due to damage to utilities that provide services to these facilities or disruption of other infrastructures, e.g. access roads and communication systems.

Much of the damage and destruction in past earthquakes can be attributed to insufficient or inadequate design requirements. Furthermore, past earthquakes have shown a need for a better quantification of the seismic hazard (Kaiser et al 2012) and a better understanding of soil-structure interaction, particularly liquefaction (Kam et al 2011). The Northridge earthquake highlighted that design codes should also consider the serviceability limit states, and not just life-safety, because non-structural damage can be even more important than structural damage for business interruption and cascading effects. In addition to implementing retrofitting measures where possible and financially viable, current design approaches should be revised to consider inherent ground-motion uncertainties more rigorously. For new structures, the need for a better seismic design approach for panel-structure connections is evident.

### 4.6.2 Lessons learned from floods

In the case of slowly-rising river floods, structural damage to industrial buildings is unlikely. However, non-structural components, such as partition walls, and equipment, stocks and products sensitive to water intrusion or high humidity, are at risk of irreparable damage. The risk of global cascading effects is high due to weaknesses in the global supply chain (supply and demand) management of industrial facilities. The modelling of industrial facilities as components of a larger system is complex but deserves further attention to avoid cascading economic effects similar to those seen during the Thai floods (Fig. 4.7) to occur in future events.


Fig. 4.7 Inundation level at industrial estates near northern Bangkok (www.bbc.co.uk/news/world-asia-pacific-15335721)

Losses can be severe due to damage caused by the inundation itself and costs associated with business interruption. Where companies escape a flood unscathed there is still the risk of suffering downtime via supply-chain effects from affected industry that limit the availability of raw materials needed for production.

Improved urban planning that keeps assets out of harm's way, is a tool that should be used to mitigate future losses. In addition, embankments around industrial estates should be built in conformity with worst-case flood severity predictions and best practices for constructing sturdy protection barriers. Diversifying procurement sources will help businesses reduce their downtime.

# 5. Summary and recommendations

Stress test results of nuclear facilities clearly indicate that particular attention needs to be paid to periodic safety reviews, including the re-assessment of hazards. The European and international authorities (WENRA and IAEA respectively) promote the use of probabilistic methods for seismic and flood hazard assessment, in order to define the design ground motion and flood. However, the design and operation of each plant must be able to deal also with unforeseen hazards (e.g. earthquake, flooding, extreme weather and accidents) which were not considered in the original design. The review of stress tests on nuclear facilities indicates that further efforts are required towards the harmonisation, across the European countries, of the methods for the identification of natural hazards for critical infrastructures and for the safety assessment in case of beyond-design (cliff-edge) events, considering common cause failures for multiple unit sites and multiple sites.

Measures that are implemented in nuclear facilities and may be used in non-nuclear critical infrastructures include:

- bunkered system or hardened safety core, designed to resist anticipated external events and equipped with all components necessary to provide power and cooling capacities in case of failure of the primary safety systems;
- the 'dry site' concept for the plant layout, as a defence against flooding;
- active tsunami warning system at coastal sites, coupled with the provision for immediate operator action;
- seismic monitoring systems for warning.

The topics of risk and hazard are introduced in national provisions in European countries, principally in relation to the use, storage and transport of dangerous substances under the 'Seveso' Directive and in a number of countries also with respect to the protection of critical infrastructures. Overall, the turn from 'absolute safety', which is unreachable, to the more realistic concept of 'risk awareness' has been made. State-of-the-art guidelines are available, which have to be considered by governments and operators, and provide quantitative, semi-quantitative and qualitative concepts for risk assessment. Where methods are prescribed, they comprise the following steps:

1. identify the hazards;
2. identify the threat or cause that might release the hazards, e.g. industrial accident, natural or man-made disaster, and assess its likelihood;
3. assess the extent of damage in terms of casualties, disruption of service, economic losses, etc.;
4. evaluate the scenarios, considering the likelihood of occurrence and the severity of the consequences, and the need to implement any measures;
5. decide which actions should be taken to deal with the risk.

Natural hazards are partly covered by the Eurocodes, which prescribe actions on structures and rules for structural design. Regarding earthquakes in particular, seismic hazard is defined in the National Annexes to Eurocode 8, while the SHARE project represents a trend-setting approach on the seismic hazard harmonization in Europe. The harmonized approach for stress tests that is developed by the STREST project and is comparable to the Eurocodes in the building industry, will significantly increase public awareness of risks related to critical infrastructures in the European Union and will provide tools for risk assessment.

Recent events have highlighted the potential for catastrophic natural-hazard impact on critical infrastructures, with consequences ranging from health impacts and environmental degradation to major economic losses due to damage to assets and business interruption. For major earthquakes, floods and tsunamis, there is a high risk of multiple and simultaneous impacts at a single infrastructure or to several infrastructures over a potentially large area. This review also highlighted the major risk of cascading effects, such as the release and dispersion of flammable substances and the reduction of production due to impacts at suppliers of raw materials or because products cannot be delivered where major transport hubs are affected by the natural hazard. Although the ripple effects on the economy may reach global proportions, resulting in a shortage of raw materials or intermediate products in the manufacturing industry and causing price hikes, the vulnerability introduced into infrastructure systems by interconnectedness is not routinely assessed. Besides, emergency response in case of large-scale natural-hazard impact usually suffers from a competition for scarce response resources, where the highest priority is given to preserving human life and recovering essential infrastructures.

The severity of some of the analysed natural hazards was unexpected but not impossible to foresee, in most of cases. Nevertheless, they caused a significant amount of damage and infrastructure service outage. This indicates an underestimation of the risk that resulted in siting in natural-hazard prone areas, insufficient design, not adequately updated hazard analyses and a lack of preparedness. In order to avoid future disasters, the vulnerability of key critical infrastructures to natural hazards and the consequences of impact should be determined. Furthermore, it is essential to implement a scheme of regular updating (e.g. every five or ten years) of hazard and risk analyses. Risk analysis is required to understand system weaknesses and to prioritise prevention and mitigation measures. This should be coupled with a cost-benefit analysis. This risk assessment needs to be based on the realistic assessment of a natural hazard’s severity that includes, where necessary, for instance in the case of floods, climate-change projections.

# A Bibliography on stress tests for nuclear power plants

## A.1 European Commission and ENSREG documents on the EU stress tests for nuclear power plants

1. European Commission, 2012a. Communication from the Commission to the Council and the European Parliament on the comprehensive risk and safety assessments ("stress tests") of nuclear power plants in the European Union and related activities, Staff Working Document SWD(2012) 287 final
2. European Commission, 2012b. Technical summary on the implementation of comprehensive risk and safety assessments of nuclear power plants in the European Union; Accompanying the document "Communication from the Commission to the Council and the European Parliament" on the comprehensive risk and safety assessments ("stress tests") of nuclear power plants in the European Union and related activities, Staff Working Document SWD(2012) 571 final
3. European Nuclear Safety Regulators Group (ENSREG), 2011. Declaration of ENSREG, with Annex "EU Stress tests" specifications
4. European Nuclear Safety Regulators Group (ENSREG), 2012a. Compilation of recommendations and suggestions, Peer review of stress tests performed on European nuclear power plants
5. European Nuclear Safety Regulators Group (ENSREG), 2012b. Action plan, Follow-up of the peer review of the stress tests performed on European nuclear power plants European Nuclear Safety Regulators Group (ENSREG), 2012c. Stress tests and Peer Review Process, Joint statement of ENSREG and the European Commission
6. European Nuclear Safety Regulators Group (ENSREG), 2013. ENSREG, National Action Plans Workshop, Summary Report

## A.2 EU Stress Test Country Reports

1. Belgian Federal Agency for Nuclear Control FANC, 2011. Belgian stress tests, National report for nuclear power plants
2. Bulgarian Nuclear Regulatory Agency, 2011. European "Stress Tests" for Nuclear Power Plants, National Report of Bulgaria
3. State Office for Nuclear Safety Czech Republic, 2011. National Report on „Stress Tests‟ NPP Dukovany and NPP Temelín
4. Radiation and Nuclear Safety Authority STUK, Finland, 2011. European Stress Tests for Nuclear Power Plants, National Report Finland
5. Autorité de Sûreté Nucléaire, France, 2011. Complementary Safety Assessments of the French Nuclear Power Plants (European "Stress Tests"), Report by the French Nuclear Safety Authority
6. German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2011. EU Stresstest, National Report of Germany, Implementation of the EU Stress Tests in Germany
7. Hungarian Atomic Energy Authority, 2011. National Report of Hungary on the Targeted Safety Re-assessment of Paks Nuclear Power Plant
8. Republic of Lithuania, State Nuclear Power Safety Inspectorate, 2011. National Final Report on "Stress Tests"

9. Ministry of Economic Affairs, Agriculture & Innovation, Netherlands, 2011. Netherlands' National report on the Post-Fukushima Stress Test for the Borssele Nuclear Power Plant

10. Romania National Commission for Nuclear Activities Control, 2011. National Report on the Implementation of the Stress Tests

11. Nuclear Regulatory Authority of the Slovak Republic, 2011. National Report on the Stress Tests for Nuclear Power Plants in Slovakia

12. Republic of Slovenia, Ministry of the Environment and Spatial Planning, Slovenian Nuclear Safety Administration, 2011. Slovenian National Report on Nuclear Stress Tests, Final Report

13. Spanish Nuclear Safety Council CSN, 2011. Stress tests carried out by the Spanish nuclear power plants, Final Report

14. Swedish Radiation Safety Authority, 2011. European stress tests for nuclear power plants, The Swedish National Report

15. Swiss Nuclear Safety Authority ENSI, 2011. EU Stress Test, Swiss National Report, ENSI Review of the Operator's Reports

16. State Nuclear Regulatory Inspectorate of Ukraine, 2011. National Report of Ukraine, Stress Test Results

17. Office for Nuclear Regulation, UK, 2011. European Council “Stress Tests” for UK nuclear power plants, National Final Report

## A.3 EU Stress Test Peer Review Reports

1. European Nuclear Safety Regulators Group (ENSREG), Stress Test Peer Review Board, 2012a. Peer review Report, Stress tests performed on European nuclear power plants

2. European Nuclear Safety Regulators Group (ENSREG), Stress Test Peer Review Board, 2012b. Peer review country report, Stress tests performed on European nuclear power plants, Reports are available for the following countries: Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, Lithuania, Netherlands, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine and United Kingdom

## A.4 National Action Plans Resulting from EU Stress tests

1. Belgian Federal Agency for Nuclear Control FANC, 2012. Belgian stress tests, National action plan for nuclear power plants

2. Bulgarian Nuclear Regulatory Agency, 2012. European "Stress Tests" Kozloduy NPP, National Action Plan of Bulgaria

3. State Office for Nuclear Safety Czech Republic, 2012. Post Fukushima National Action Plan (NAcP) on Strengthening Nuclear Safety of Nuclear Facilities in the Czech Republic Radiation and Nuclear Safety Authority STUK, Finland, 2012. European Stress Tests for Nuclear Power Plants, National Action Plan Finland

4. Autorité de Sûreté Nucléaire, France, 2012. Complementary Safety Assessments Follow-up to the French Nuclear Power Plant Stress Tests, National Action Plan of the French Nuclear Safety Authority

5. German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2012. German Action Plan for the implementation of measures after the Fukushima Daiichi reactor accident

6. Hungarian Atomic Energy Authority, 2012. National Action Plan of Hungary on the implementation actions decided upon the lessons learned from the Fukushima Daiichi accident

7. Republic of Lithuania, State Nuclear Power Safety Inspectorate, 2012. Plan of Strengthening Nuclear Safety in Lithuania, Follow-up of the "stress tests" performed in European Union

8. Ministry of Economic Affairs, Agriculture & Innovation, Netherlands, 2012. Netherlands' National Action Plan (NAcP) for the follow-up of post-Fukushima Daiichi related activities

9. Romania National Commission for Nuclear Activities Control, 2012. Romanian National Action Plan post - Fukushima

10. Nuclear Regulatory Authority of the Slovak Republic, 2012. National Action Plan of the Slovak Republic, regarding actions to comply with the conclusions from the stress tests performed on nuclear power plants

11. Republic of Slovenia, Ministry of the Environment and Spatial Planning, Slovenian Nuclear Safety Administration, 2012. Slovenian Post-Fukushima National Action Plan

12. Spanish Nuclear Safety Council CSN, 2012. Post-Fukushima European Action Plan, Spain, National Action Plan

13. Swedish Radiation Safety Authority, 2012. Swedish action plan for nuclear power plants Swiss Nuclear Safety Authority ENSI, 2012. EU Stress Test: Swiss National Action Plan

14. State Nuclear Regulatory Inspectorate of Ukraine, 2013. National Action Plan Office for Nuclear Regulation ONR, UK, 2012. UK ONR ENSREG Related 'National Action Plan'

## A.5 Western European Nuclear Regulators Association (WENRA) reference levels

1. Western European Nuclear Regulators' Association, 2008. Reactor Harmonization Working Group, WENRA Reactor Safety Reference Levels (document is under updating revision)

## A.6 Selected IAEA guidelines and reports

1. International Atomic Energy Agency IAEA, 2012a. Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant", International Experts Meeting, 4-7 September 2012, Vienna, Austria

2. International Atomic Energy Agency IAEA, 2012b. Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant

3. International Atomic Energy Agency IAEA, 2011a. Action Plan on Nuclear Safety, Report by the Director General

4. International Atomic Energy Agency IAEA, 2011b. International Nuclear Safety Group; „A Framework for an Integrated Risk Informed Decision Making Process", INSAG-25

5. International Atomic Energy Agency IAEA, 2011c. Earthquake Preparedness and Response for Nuclear Power Plants, Safety Reports Series No. 66

6. International Atomic Energy Agency IAEA, 2010. Seismic Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-9

7. International Atomic Energy Agency IAEA, 2003a. Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. NS-R-3

8. International Atomic Energy Agency IAEA, 2003b. Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-18

9. International Atomic Energy Agency IAEA, 2003c. Periodic Safety Review of Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-2.10

## A.7 European and US Seismic Hazard Studies

1. SHARE, 2013. Seismic Hazard Harmonization in Europe, www.share-eu.org

2. Swissnuclear, 2013. PEGASOS Refinement Project, Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites (report not public)

3. Senior Seismic Hazard Analysis Committee (SSHAC), 1997. Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts,

4. NUREG/CR-6372, Volumes 1 and 2 NRC, 2010. Generic Issue 199 (GI-199): Implications Of Updated Probabilistic Seismic Hazard Estimates in Central And Eastern United States on Existing Plants Safety/Risk Assessment, ADAMS Doc. No. ML100270639

# B Risk assessment methods

## B.1 Hazard and operability study (HAZOP)

The HAZOP assessment method is a structured and systematic examination method to identify and evaluate incidents, which emanate risks. The method deals in principle with the terms "prediction", "locating causes" and "estimating the consequences" of risks. Counteractive measures are applied. The comparison with the allocated targets and the actual targets is made. The HAZOP method is executed under the guidance of experts and conducted in structured discussions. Thus, the method not only depends, but also relies, on experience of involved people. The HAZOP team then determines possible significant deviations from any defined measures, which likely cause and result in negative consequences. It is then decided whether existing and designed safeguards are sufficient, or if additional actions are required to reduce risks to an acceptable level. The HAZOP method to assess risks is a qualitative method.

## B.2 Failure mode and effects analysis (FMEA)

The FMEA method involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes. This is done with analytic methods to assess reliabilities. Its basic principle is to avoid failures already prior to their appearance. Selections and discussions are led by teams of experts.

Classification numbers ("consequences", "probability of occurrence" and "probability of discovery") are the basis for the risk evaluation. These numbers represent values in an ordinal scale between 1 and 10 and are defined based on rating recommendations. The "risk-potential-number" is then defined by the multiplication of the three factors, resulting in a possible value to classify and arrange risks. The expressions of estimated risks are assigned from the perspective of society/environment that would be affected by consequences. FMEA is a "bottom-up" method.

## B.3 Fault-tree analysis (FTA)

The FTA method is based on Boolean decision-making with the intention to evaluate blackout probabilities. These could be caused by initiating faults and events in complex systems. Based on logic relations (the system is either in the status functional deficiency or functional capability), the branches in the fault tree are identified, which yield the highest risks and/or worst consequences.

Fault trees can be based on large numbers of event occasion combinations, which are then evaluated with the use of computer software. The analysis has been used in probabilistic approaches in the nuclear industry. In Germany, the DIN 25424 covers the FTA method. It is a "top-down" method.

## B.4 Event-tree analysis (ETA)

The ETA method is used to find a path to assess probabilities of outcomes and overall system analysis. It is based on the occurrence of both a functioning or not functioning system, given that an event has occurred. The ET analysis works by tracing forward in time, which is in difference to the FT analysis. Similarly, the two methods are both based on analytical diagrams using Boolean logic. The ET analysis is a "bottom-up" method.

An event-tree is built up on possible paths of events. From these, probabilities of occurrence can be estimated. The event, which results in the highest risks and/or consequences can be easily identified. Additionally, measures can to taken in order to avoid the occurrence and/or their effect can be graphically and mathematically estimated.

## B.5 Risk matrix (RM)

The risk matrix defines the relationship between the likelihood of an incident and the consequences caused by this incident. A diagram is assembled, in which the first axis shows the possible amount of damage and the second axis shows the probabilities of this events occurrence. In the diagram, classifications are made based on priority rating. Based on these ratings, priority decisions can be made.

# References


1. Zwicky P (2014) Lessons learned from stress tests of nuclear facilities. STREST project deliverable D2.1
2. Billmaier M, Reinders J (2014) State-of-the-art in hazard and risk assessment of non-nuclear critical infrastructures. STREST project deliverable D2.2
3. Krausmann E (2014) Report on lessons learned from recent catastrophic events. STREST project deliverable D2.3
4. ENSREG (2011) Declaration of ENSREG about stress tests, Annex I - EU 'stress test' specifications. European Nuclear Safety Regulators Group
5. EC (2012) Comprehensive risk and safety assessments ('stress tests') of nuclear power plants in the European Union and related activities. Communication from the Commission to the Council and the European Parliament COM(2012) 571 final
6. IAEA (2012). Protection against extreme earthquakes and tsunamis in the light of the accident at the Fukushima Daiichi nuclear power plant. International Experts Meeting, 4-7 September 2012, Vienna, Austria
7. EC (2006) A European programme for critical infrastructure protection. Communication from the Commission COM(2006) 786 final
8. EC (2012) The review of the European programme for critical infrastructure protection (EPCIP). Commission staff working document SWD(2012) 190 final
9. EC (2008) A critical infrastructure warning information network (CIWIN). Proposal for a Council Decision COM(2008) 676 final
10. EC (2010a) The EU Internal Security Strategy in Action: Five steps towards a more secure Europe. Communication from the Commission to the European Parliament and the Council COM(2010) 0673 final
11. EC (2010b) Risk assessment and mapping guidelines for disaster management. Commission staff working paper SEC(2010) 1626 final
12. ISO (2009a) ISO 31000:2009 Risk management - Principles and guidelines. International Organization for Standardization, Geneva
13. ISO (2009b) ISO Guide 73:2009 Risk management – Vocabulary. International Organization for Standardization, Geneva
14. Giannopoulos G, Filippini R, Schimmer M (2012). Risk assessment methodologies for critical infrastructure protection. Part I: A state of the art. JRC Technical Note EUR 25286 EN
15. BMVIT (2008) Masterplan: Österreichisches Programm zum Schutz Kritischer Infrastruktur (APCIP).Bundesministerium für Verkehr, Innovation und Technologie
16. BKA (2013) Industrieunfallverordnung IUV. Fassung vom 03.12.2013, Bundeskanzleramt
17. MESD (2003) Policy and action programme as concerns the prevention of industrial risks. Ministry of Ecology and Sustainable Development
18. MLPE (2004) Principes généraux pour l'élaboration et la lecture des études de danger. Ministry for Land-use Planning and the Environment
19. BKK (2011) Schutz Kritischer Infrastrukturen - Risiko- und Krisenmanagement. Bundesministerium des Innern
20. BMJ (2013) 12. BImSchV: Stoerfall-Verordnung. Bundesministerium der Justiz

21. DL (2015) Attuazione della direttiva 2012/18/UE relativa al controllo del pericolo di incidenti rilevanti connessi con sostanze pericolose. Decreto legislativo 26 giugno 2015, n. 105
22. CPD (2005a) Methods for determining and processing probabilities. Committee for the Prevention of Disasters
23. CPD (2005b) Methods for the calculation of physical effects due to releases of hazardous materials (liquids and gases). Committee for the Prevention of Disasters
24. CPD (1992) Methods for the determination of possible damage to people and objects resulting from releases of hazardous materials. Committee for the Prevention of Disasters
25. CPD (2005c) Guidelines for quantitative risk assessment. Committee for the Prevention of Disasters
26. OMA (1994) Swiss ordinance on protection against major accidents. SR 814.012 Berne
27. BAFU (2013) Stoerfallverordnung. Die Bundesbehörden der Schweizerischen Eidgenossenschaft
28. HSE (2001) Safety report assessment guide: criteria. Health and Safety Executive of UK
29. HSE (2002) COMAH safety reports: information about the extent and severity of the consequences of identified major accidents. Health and Safety Executive of UK, www.hse.gov.uk/comah/circular/perm06.htm
30. HSE (2003). COMAH safety report assessment manual: how to use the criteria for assessing the information in a safety report during its examination. Health and Safety Executive of UK, www.hse.gov.uk/hid/land/comah2/pt2ch1a.htm
31. EPA (1999) Risk management program guidance for offsite consequence analysis. United States Environmental Protection Agency
32. CEN (2004) EN 1998-1 Eurocode 8: Design of structures for earthquake resistance -Part 1: General rules, seismic actions and rules for buildings. Comité Européen de Normalisation, Brussels
33. ICOLD (2005) Risk assessment in dam safety management - A reconnaissance of benefits, methods and current applications. Bulletin 130. International Commission on Large Dams
34. Garbe F (2007). Internationaler Vergleich zur Handhabung verbleibender Risiken von Talsperren. Siegen, Bezirksregierung Arnsberg
35. DIN (2004) DIN 19700 Stauanlagen. Deutsches Institut fuer Normung
36. BFE (2013a) Verordnung über die sicherheit der stauanlagen, (Stauanlagenverordnung, StAV). Bundesamt fuer Energie
37. BFE (2013b) Bundesgesetz für stauanlagen (Stauanlagengesetz, StAG). Die Bundesversammlung der Schweizerischen Eidgenossenschaft
38. BMLFUW (1996) Richtlinie zum Nachweis der Standsicherheit von Staudaemmen. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Oesterreichische Staubeckenkommission
39. CEN (2011) EN 14161 Petroleum and natural gas industries - Pipeline transportation systems. Comité Européen de Normalisation, Brussels
40. CEN (2013) EN 1594 Gas infrastructure - Pipelines for maximum operating pressure over 16 bar - Functional requirements. Comité Européen de Normalisation, Brussels

41. BAFU (1963) Rohrleitungsgesetz, RLG. Bundesamt fuer Umwelt

42. BAFU (2007) Verordnung ueber Sicherheitsvorschriften fuer Rohrleitungsanlagen, RLSV. Bundesamt fuer Umwelt

43. HSE (1996) Pipelines safety regulations. Health and Safety Executive

44. UNECE (2008) Safety guidelines and good practices for pipelines. United Nations Economic Commission for Europe, Geneva

45. ASME (2014) Gas transmission and distributing piping systems. American Society of Mechanical Engineers

46. DG ENV (2012) Assessing the case for EU legislation on the safety of pipelines and the possible impacts of such an initiative. European Commission, Directorate-General Environment, Final Report ENV.G.1/FRA/2006/0073

47. RIVM (2009) Reference manual Bevi risk assessments. National Institute of Public Health and the Environment , Centre for External Safety, Bilthoven

48. MLP (1984) Classificazione sismica del territorio italiano (1984). Decreto Ministero dei Lavori Publici dell 14/07/1984

49. PCM (2003) Primi elementi in materia di criteri generali per la clasdsificazione sismica del territorio nazionale e normative tecniche per le costruzioni in zona sismica. Ordinanza del Presidente del Consiglio dei Ministri n. 3274 del 20 marzo 2003

50. Krausmann E, Cruz AM, Affeltranger B (2010) The impact of the 12 May 2008 Wenchuan earthquake on industrial facilities. Journal of Loss Prevention in the Process Industries 23(2): 242-248

51. Krausmann E, Renni E, Campedel M, Cozzani V (2011) Industrial accidents triggered by earthquakes, floods and lightning: lessons learned from a database analysis. Natural hazards 59(1): 285-300

52. Salzano E, Iervolino I, Fabbrocino G (2003) Seismic risk of atmospheric storage tanks in the framework of quantitative risk analysis. Journal of Loss Prevention in the Process Industries 16(5): 403-409

53. Steinberg LJ, Cruz AM (2004) When natural and technological disasters collide: lessons from the Turkey earthquake of August 17, 1999. Natural Hazards Review 5(3): 121-130

54. Ballantyne D, Crouse C (1997) Reliability and restoration of water supply systems for fire suppression and drinking following earthquakes. National Institute of Standards and Technology, NIST GCR 97-720

55. Cruz AM, Krausmann E, Franchello G (2011) Analysis of tsunami impact scenarios at an oil refinery. Natural Hazards 58(1): 141-162

56. Wieland M (2012) Seismic design and performance criteria for large storage dams, In 15th World Conference on Earthquake Engineering, Lisbon, Portugal

57. ICOLD (2010a) Dam safety and earthquakes. Water Power & Dam Construction http://www.waterpowermagazine.com/features/featuredam-safety-and-earthquakes

58. Matsumoto N, Sasaki T, Ohmachi T (2011). The 2011 Tohoku earthquake and dams. In: Schleiss AJ, Boes RM (eds) International Symposium on Dams and Reservoirs under Changing Challenges, ICOLD 79th Annual Meeting, Lucerne, Switzerland

59. Wieland M, Brenner RP (2008) Current seismic safety requirements for large dams and their implication on existing dams. ICOLD 76th Annual Meeting, Sofia, Bulgaria

60. ICOLD (2010b) Selecting seismic parameters for large dams., International Commission on Large Dams, Bulletin 148

61. ASDSO (2014). Association of State Dam Officials, United States, http://www.damsafety.org/resources/?p=bb3013ce-98ee-47ef-9bdf-d6dbb9dbad86

62. USDOI (2012) Overtopping failure – Best practices. US Department of the Interior, Bureau of Reclamation

63. Fry J-J, Vogel A, Royet P, Courivaud J-R (2012) Dam failures by erosion: Lessons from ERINOH data bases. 6th International Conference on Scour and Erosion, Paris, France

64. Lempérière F, Vigny JP (2005) Shall we forget the traditional "design flood"? International Journal on Hydropower & Dams 2

65. ICOLD (1992). Selection of design flood. Bulletin 82, International Commission on Large Dams

66. Bilham R, Doyle P, Evans R, Greening P, May R, Stewart A, Teymur B, Vince D (2003) The Kocaeli, Turkey Earthquake of 17 August 1999: A Field Report by EEFIT. Institution of Structural Engineers Earthquake Engineering Field Investigation Team

67. TUPRAS (2000) TUPRAS Refinery damage report, 1999 Kocaeli Earthquake

68. Girgin S, Krausmann E (2014) Analysis of pipeline accidents induced by natural hazards. JRC Technical Report 88410, European Commission, Joint Research Centre

69. Lanzano G, Salzano E, Santucci de Magistris F, Fabbrocino G (2013) Seismic vulnerability of natural gas pipelines. Reliability Engineering & System Safety 117: 73-80

70. O'Rourke TD, Palmer MC (1996) Earthquake performance of gas transmission pipelines. Earthquake Spectra 12(3): 493-527

71. TCLEE (2012) Report of the 11 March 2011 Mw 9.0 Tohoku, Japan, earthquake and tsunami. Technical Council on Lifeline Earthquake Engineering

72. PIANC (2001) Seismic design guidelines for port structures. World Association for Waterborne Transport Infrastructure

73. Soderberg E, Hsieh J, Dix A (2009). Seismic guidelines for container cranes. Technical Council on Lifeline Earthquake Engineering Conference, Oakland, USA

74. Tsuruta M, Goto Y, Shoji Y, Kataoka S (2008) Damage propagation caused by interdependency among critical infrastructures. 14th World Conference on Earthquake Engineering, Beijing, China

75. Kakderi K, Selva J, Argyroudis S, Fotopoulou S, Pitilakis K (2012) Systemic vulnerability and loss for harbors. SYNER-G deliverable D5.6

76. Kakderi K, Selva J, Argyroudis S, Pitilakis K, Anastasiadis A, Alexoudi M, Souli A, Fotopoulou S, Rovithis M, Senetakis K (2013) Application and validation study to a harbor system (Thessaloniki, Greece). SYNER-G deliverable D6.6

77. Casari M, Wilkie SJ (2004) Sequencing repairs after an earthquake: An economic approach. PEER Report 2003/09, Pacific Earthquake Engineering Research Center, Berkeley

78. Suga Y, Koshimura S, Kobayashi E (2013) Risk evaluation of drifting ship by tsunami. Journal of Disaster Research 8(4): 573-583

79. Tomita T, Yoem G (2012) Tsunami damage in ports by the 2011 off Pacific Coast of Tohoku-Oki earthquake. International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake, 1-4, Tokyo, Japan

80. Ishiwatari M, Sagara J (2012) Knowledge note 1-1 Cluster 1: Structural measures – Structural measures against tsunamis. The World Bank

81. Magliulo G, Ercolino M, Petrone C, Coppola O, Manfredi G (2014) Emilia earthquake: the seismic performance of precast RC buildings. Earthquake Spectra 30(2): 891-912

82. Mahin SA (1998) Lessons from damage to steel buildings during the Northridge earthquake. Engineering Structures 20(4-6): 261–270

83. Saatcioglu M, Mitchell D, Tinawi R, Gardner NJ, Gillies AG, Ghobarah A, Anderson DL, Lau D (2001) The August 17, 1999, Kocaeli (Turkey) earthquake - damage to structures. Canadian Journal of Civil Engineering 28(4): 715-737

84. GRM (2009) M6.3 L'Aquila Italy earthquake field investigation report. Global Risk Miyamoto, Lafayette, http://www.grmcat.com/images/Italy-EQ-Report.pdf

85. Liberatore L, Sorrentino L, Liberatore D, Decanini LD (2013) Failure of industrial structures induced by the Emilia (Italy) 2012 earthquakes. Engineering Failure Analysis 34: 629-647

86. Tang AK (2000) İzmit (Kocaeli), Turkey, earthquake of August 17, 1999 including Düzce earthquake of November 12, 1999: lifeline performance. ASCE Technical Council on Lifeline Earthquake Engineering Monograph No. 17

87. Kaiser AE, Holden C, Beavan RJ, Beetham RD, Benites RA, Celentano A, Collet D, Cousins WJ, Cubrinovski M, Dellow GD, Denys P, Fielding E, Fry B, Gerstenberger MC, Langridge RM, Massey CI, Motagh M, McVerry GH, Pondard N, Ristau J, Stirling MW, Thomas J, Uma SR, Zhao JX (2012) The Mw 6.2 Christchurch earthquake of February 2011: preliminary report. New Zealand Journal of Geology and Geophysics 55(1): 67-90

88. Kam WE, Pampanin S, Elwood K (2011) Seismic performance of reinforced concrete buildings in the 22 February Christchurch (Lyttelton) Earthquake. Bulletin of the New Zealand Society of Earthquake Engineering 44(4): 239-278

## List of abbreviations

| | |
|---|---|
| ASME | American Society of Mechanical Engineers |
| ECI | European critical infrastructure |
| EN | European standard |
| ETA | event-tree analysis |
| EU | European Union |
| FMEA | failure mode and effects analysis |
| FP7 | Seventh Framework Programme |
| FTA | fault-tree analysis |
| HAZOP | hazard and operability |
| IAEA | Atomic Energy Agency |
| ICOLD | International Commission on Large Dams |
| PMF | probable maximum flood |
| RM | risk matrix |
| SFOE | Swiss Federal Office of Energy |
| WENRA | Western European Nuclear Regulators Association |

## List of figures

Fig. 3.1 The European Critical Infrastructure process (EC 2012) ................................ 7

Fig. 3.2 Overview of legislative coverage in Europe (DG ENV 2012) ......................... 13

Fig. 3.3 Seismic zones in Italy before (MLP 1984) (left) and after 2003 (PCM 2003) (right) ............................................................................................................ 14

Fig. 4.1 Elephant foot buckling of a bolted steel tank ............................................ 16

Fig. 4.2 Failure of the Niedow dam in Poland due to flooding (Fry et al 2012) ........... 19

Fig. 4.3 Buckled steel pipe connection (left) (Bilham et al 2003) and fall of ground-supported unseated pipeline from the supports at TUPRAS refinery due to inertial effects (left) (courtesy of Tupras 2000) ....................................................................... 20

Fig. 4.4 Crane damage at Sendai Port (TCLEE 2012) (left) and damage at the navy port in Gölcük (Bilham et al 2003) (right) .................................................................. 22

Fig. 4.5 Scattered containers at Sendai Port after the tsunami (Tomita and Yoem 2012) (left) and container ship swept ashore by tsunami at Sendai Port and damage on crane (TCLEE 2012) (right) ............................................................................................ 23

Fig. 4.6 Observed damage to industrial buildings after the Emilia Romagna earthquakes of 20 and 29 May 2012 (Liberatore et al 2013) ...................................................... 24

Fig. 4.7 Inundation level at industrial estates near northern Bangkok (www.bbc.co.uk/news/world-asia-pacific-15335721) ............................................... 26

## List of tables

Table 2.1 National action plans ........................................................................ 5
Table 3.1 Eurocodes relevant for different types of disasters (EC 2010b) ..................... 8
Table 3.2 Criteria to assess and deal with disclosed risks of dam hazards .................. 12
Table 4.1 Natural events and types of affected critical infrastructures ....................... 15

LB-NA-27806-EN-N

## JRC Mission

As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new methods, tools and standards, and sharing its know-how with the Member States, the scientific community and international partners.

*Serving society*
*Stimulating innovation*
*Supporting legislation*

Publications Office

doi:10.2788/036273

ISBN 978-92-79-57502-0