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Harmonized approach to stress tests for critical infrastructures against natural hazards

STREST Reference Report 6

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An innovative stress test framework for non-nuclear critical infrastructures
The STREST project developed a stress test methodology and a modelling approach to hazard, vulnerability, risk and resilience assessment of low-probability high-consequence events. The project contributes to the Sendai Framework for risk reduction, the improved protection of European and national critical infrastructures and the resilience of society to natural disasters.

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DELIVERABLE

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Executive summary

Policy context

This report summarises the research results of the STREST FP7 project and its impact on the application of stress tests for non-nuclear critical infrastructures (CIs). It answers to the European Programme for Critical Infrastructure Protection and the Internal Security Strategy to develop guidelines for multi-hazard disaster management, aiming to improve the protection of European and national critical infrastructures and the resilience of society to natural and man-made disasters. Furthermore, STREST takes into account the requirements prescribed by the Directive for the reduction of the consequences of accidents involving dangerous substances. Improved effectiveness of systems for preventing, preparing for and responding to natural and man-made disasters is also the aim of the European Union Civil Protection Mechanism. At the global level, the substantial reduction of disaster damage to CIs and disruption of basic services is one of the seven targets of the Sendai Framework for disaster risk reduction. This makes the STREST project a key component to prepare for potential European Union policy changes in the areas of infrastructure, disaster risk reduction and societal resilience.

Key conclusions

Recent events have confirmed the potential for the catastrophic **impact of natural hazards** on CIs, with consequences ranging from health impacts and environmental degradation to major economic losses, with a major role of cascading effects on risk.

STREST developed innovative hazard models to include in stress tests of CIs to tackle the problem of extreme events, with focus on **earthquakes, floods** (tsunamis, dam failures) and **domino effects** (Natech, system failures). Earthquake models considered epistemic uncertainties, earthquake rupture directivity, cascading and clustering, spatial correlations, site/geotechnical effects, and permanent ground displacement. Inter-hazard interactions included flooding from dam failure, tsunamis due to earthquakes, and industrial accidents due to both earthquakes and tsunamis.

Probabilistic risk models and tools are essential for analysing and quantifying the consequences of critical infrastructure damage due to extreme natural events. Yet, they are not widely used in risk management of non-nuclear CIs. The project filled this gap by producing fragility functions for components of petrochemical plants, dams, harbours, gas/oil distribution networks (e.g. storage tanks, cranes, pipelines, hydropower systems) and common industrial buildings with respect to earthquakes, floods and tsunamis, and demonstrating how these component fragilities can be integrated at the system level.

The **interdependencies** within a CI and possible **cascading failures** may have an important **impact on the society** (public safety and higher-level societal functions) beyond the critical infrastructure itself, as observed in past events and demonstrated in the STREST exploratory applications. Societal resilience definition, models, probabilistic assessment and acceptance criteria remain as yet in the research domain.

The engineering **risk-based multi-level stress test methodology** developed by STREST enhances the evaluation of the risk exposure of CIs against natural hazards. In order to account for the diversity of CIs, the wide range of potential consequences of failure, the types of hazards and the available human and financial resources, each stress test level is characterised by a different scope (component or system) and by a different complexity of the risk analysis. The outcome of stress tests is a grade convening where the risk posed is with respect to pre-determined risk acceptance criteria. The grading system is based on different hazard and risk metrics and is independent of the class of the infrastructure and/or of the underlying hazard and risk drivers.

A petrochemical plant (IT), a hydropower dam (CH), hydrocarbon pipelines (TK), a gas storage and distribution network (NL), a harbour (GR) and an industrial district (IT) were selected for exploratory applications of the stress test methodology, which illustrated how the developed tools were able to identify extremes and **disaggregate risks** to specific scenarios of hazard and component failures. Furthermore, the method was built to **support decision-making on cost-effective mitigation measures**.

Main findings

The STREST project produced fundamental knowledge beyond the state-of-the-art in hazard, vulnerability, risk and resilience assessment of non-nuclear CIs and systems of infrastructures for extreme natural events. The main achievements, some case-dependent, are: (1) a probabilistic multi-hazard/risk assessment framework including cascade scenarios; (2) a harmonised treatment of uncertainties and mechanics of hazard assessment; (3) a consistent taxonomy of classes of CIs including intensity measures, engineering demand parameters and performance indicators; (4) probabilistic models for fragility, vulnerability and consequence assessment; (5) an integrated risk assessment of geographically distributed CIs considering interdependencies and cascading effects; (6) probabilistic structural and systemic performance models to determine losses; and (7) an engineering risk-based multi-level stress test methodology, with workflow and tools.

Related and future JRC work

The activities of the STREST project are well aligned with the JRC established experience and expert capability in assessment of natural and man-made hazards, risk mitigation measures, and protection of critical infrastructures. The JRC will continue – within institutional and collaborative projects – to provide European policy makers and other stakeholders with scientific and technical advice on improving resilience against natural, technological and man-made disasters, by performing research, developing tools and guidelines, and also through the Disaster Risk Management Knowledge Centre.

Quick guide

Critical infrastructures are the backbone of modern society and provide many essential goods and services, e.g. electrical power, telecommunications, water, etc. As such, they have been highly integrated and intertwined. These growing interdependencies make our complex evolving society more vulnerable to natural hazards. Recent events, such as the 2011 Fukushima disaster, have shown that cascading failures of CIs have the potential for multi-infrastructure collapse and widespread socioeconomic consequences.

Moving toward a safer and more resilient society requires improved and standardised tools for hazard and risk assessment of low-probability high-consequences events and the systematic application of these new tools to whole classes of CIs. Among the most important tools are the stress tests, designed to test CI vulnerability. Following the stress tests recently performed for the European nuclear power plants, it is urgent to carry out appropriate stress tests for all other CI classes.

The ‘Harmonized approach to stress tests for critical infrastructures against natural hazards’ (STREST) project, funded by the European Community’s Seventh Framework Programme, designed a new stress test framework for non-nuclear CIs, with the development of innovative models for the hazard, risk and resilience assessment of extreme events (earthquake, tsunami, flood), and with applications to six CIs (www.strest-eu.org). The results of STREST shall enable the implementation of European Union policies for the systematic enactment of societal risk governance.

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1. Introduction

Critical infrastructures (CIs) are the backbone of modern society and provide many essential goods and services, e.g. electrical power, telecommunications, water, etc. As so, they have been highly integrated and intertwined. These growing interdependencies make our complex evolving society more vulnerable to natural hazards. Recent events, such as the 2011 Fukushima disaster, have shown that cascading failures of CIs have the potential for multi-infrastructure collapse and widespread socioeconomic consequences. Moving toward a safer and more resilient society requires i) improved and standardised tools for hazard and risk assessment, in particular for low-probability high-consequences events (so-called extreme events), and ii) a systematic application of these new procedures to whole classes of CIs. Among the most important tools are the stress tests, designed to test the vulnerability and resilience of CIs to extreme conditions. Following the stress tests recently performed for the European nuclear power plants, it is urgent to carry out appropriate stress tests for all other CI classes.

The 'Harmonized approach to stress tests for critical infrastructures against natural hazards' (STREST) project (www.strest-eu.org), funded by the European Community's Seventh Framework Programme, designed an innovative stress test framework for non-nuclear CIs, with the development of models for the hazard, risk and resilience assessment of extreme events, and with applications to six specific CIs. The results of STREST shall enable the implementation of new European policies for the systematic enactment of stress tests.

Focusing on earthquakes, tsunamis, geotechnical effects, floods and various domino effects, STREST tackled the following themes:

i) Lessons learned from past regulations and research projects (Tsionis et al 2016);

ii) Hazard assessment of extreme events (Cotton et al 2016);

iii) Vulnerability of CIs and their performance to extreme events (Iervolino et al 2016); and

iv) Development of the STREST stress test methodology and framework (Stojadinović et al 2016).

The proposed methods were integrated in exploratory applications on six representative CIs (Pitilakis et al 2016):

i) Petrochemical plant in Milazzo, Italy (A1);

ii) Hydropower dam of the Valais region, Switzerland (A2);

iii) Hydrocarbon pipelines, Turkey (B1);

iv) National gas storage and distribution network, Netherlands (B2);

v) Port infrastructure of Thessaloniki, Greece (B3); and

vi) Industrial district in Tuscany, Italy (C1).

Those CIs were categorised into three classes in the early phase of the project: (A) individual, single-site infrastructures with high risk and potential for high local impact and regional or global consequences; (B) distributed and/or geographically-extended infrastructures with potentially high economic and environmental impact; and (C) distributed, multiple-site infrastructures with low individual impact but large collective impact or dependencies. While the project concluded that such a classification was not necessary to apply the proposed stress test methodology, classes A-B-C are kept in this report for sake of clarity.

This report is the final part of a set of six Reference Reports that provide guidelines covering all the steps for a coherent hazard/risk assessment and stress test design together with the reports on the implementation on the six test sites (Tsionis et al 2016, Cotton et al 2016, Iervolino et al 2016, Stojadinović et al 2016, Pitilakis et al 2016). It is a policy brief, addressed mainly to owners and operators of CIs, regulators and other national and European authorities, as well as Civil Protection departments. It describes the policy context, state-of-the-art in stress tests and the objectives of the STREST project (Chapter 2), the key research results and findings from the exploratory applications (Chapter 3) and the impact of the project on the implementation of European policies for risk reduction and protection of CIs, the production and exchange of knowledge and the public acceptance of CIs (Chapter 4). Lastly, a number of short- and mid-term recommendations for the implementation of stress test policies are proposed (Chapter 5). The participating institutions and associated industry partners are listed in Annex A.

2. Why STREST

2.1 Policy objectives for critical infrastructures

The European Programme for Critical Infrastructure Protection[1] adopts an all-hazards approach with the general objective to improve the protection of CIs in the European Union. The planned actions include the collection of best practices, risk assessment tools and methodologies, studies concerning interdependencies, identification and reduction of vulnerabilities. Besides, increasing Europe's resilience to natural and man-made disasters is among the strategic objectives of the Internal Security Strategy[2], which asks for the development of guidelines for all-hazards disaster management and the establishment of a risk management policy.

In this perspective, the Directive on the identification and designation of European critical infrastructures[3] aims to improve these infrastructures to better protect the safety, and fulfil the needs, of citizens. For each European CI, an operator security plan must be put in place and reviewed regularly. Member States are to report every two years on the risks, threats and vulnerabilities the different European CI sectors are facing.

The 'Seveso' Directive[4], on the other hand, lays down rules for the prevention of accidents involving dangerous substances and the limitation of their consequences for human health and the environment. Operators are requested to produce and regularly update safety reports, which include, inter alia, the identification and analysis of risks, as well as measures to limit the consequences of a major accident.

Aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods, the Floods Directive[5] requires the development of flood hazard and risk maps and of risk management plans.

Lastly, the Union Civil Protection Mechanism[6] aims to improve the effectiveness of systems for preventing, preparing for and responding to natural and man-made disasters. The specific common objectives are to: i) achieve a high level of protection against all kinds of natural and man-made disasters; ii) enhance preparedness to respond to disasters; iii) facilitate rapid and efficient response; and iv) increase public awareness and preparedness for disasters.

At the global level, the substantial reduction of disaster damage to CIs and disruption of basic services is one the seven targets of the Sendai Framework for disaster risk reduction (UNISDR 2015). Besides, the STREST project contributes to the development of sustainable and resilient infrastructures, both regional and transnational, which is a

[1] Communication from the Commission on a European programme for critical infrastructure protection. COM(2006) 786 final

[2] Communication from the Commission to the European Parliament and the Council. The EU internal security strategy in action: Five steps towards a more secure Europe. COM(2010) 673 final

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

[4] Directive 2012/18/EU of the European Parliament and of the Council on the control of major-accident hazards involving dangerous substances

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

[6] Decision No 1313/2013/EU of the European Parliament and of the Council of 17 December 2013 on a Union Civil Protection Mechanism

specific target of the UN Sustainable Development[7] Goal 9 'Build resilient infrastructure, promote sustainable industrialization and foster innovation'.

2.2 The need for stress tests and new knowledge

CIs are vulnerable to natural hazards. Retrospective analyses of selected major industrial accident databases showed that 2 to 5 % of reported accidents with hazardous materials releases, fires or explosions were caused by natural hazards. More specifically, these analyses identified 79 records of accidents triggered by earthquakes in the 1930-2007 period and 272 records of accidents triggered by flooding in the 1960-2007 period (Cozzani et al 2010, Krausmann et al 2011).

Modern strategies to reduce vulnerabilities and increase the resilience, adaptive capacity and efficiency of CIs – as well as the provision of related analytical instruments – have to follow an integrative approach. However, CIs are usually engineered and operated in an isolated manner and insufficient attention has been devoted to the interdependencies between them, as well as to the interplay with their social and economic environment. Therefore, little is known about how to model and eventually improve their resilience. This requires a profound systemic understanding of the intertwined infrastructures and their collective performance.

Moving toward a safer and more resilient society requires improved and standardised tools for hazard and risk assessment of low probability-high consequence (so-called extreme) events, and their systematic application to whole classes of CIs, targeting integrated risk mitigation strategies.

Previous research projects and studies advanced the knowledge in seismic, tsunami, permanent ground displacement, induced seismicity and flood hazard assessment, considering concatenated events and geographically extended areas. The STREST project targeted specific knowledge gaps identified in recent disciplinary hazard studies with the goal of harmonising hazard assessment conducted at different scales (local and regional) and for different natural hazards initiators, including potential extreme events.

The vulnerability and risk assessment within the framework of performance-based earthquake engineering has received a great deal of research attention in recent years, especially for buildings. STREST addressed the need to develop vulnerability and loss models for CIs considering multiple hazards and cascading effects.

An engineering risk-based multi-level stress test methodology for non-nuclear CIs was developed by STREST. In order to account for the diversity of CIs, the wide range of potential consequences of failure, the types of hazards and the available human and financial resources, each stress test level is characterised by a different scope (component or system) and by a different complexity of the risk analysis. The outcome of a critical infrastructure stress test is a grade convening where the risk posed by the critical infrastructure is with respect to pre-determined risk acceptance criteria.

Concerning resilience, fundamental research is needed to include it in stress tests for CIs. STREST developed a conceptual framework to address the resilience of infrastructures, defined quantitative resilience metrics and proposed a method to assess them.

At the European level, the state-of-the-art for stress tests is defined by the post-Fukushima stress tests for nuclear power plants and by the Seveso Directive for major-accident hazards involving dangerous substances. The STREST project advances the state-of-the-art by proposing a multi-level stress test methodology and framework, built on a harmonised approach to hazard and vulnerability assessment and quantification.

[7] www.un.org/sustainabledevelopment

2.3 Objectives of the STREST project

The consistent design of stress tests and their application to specific infrastructures, to classes of infrastructures as well as to whole systems of interconnected infrastructures, is a first step required to verify the safety and resilience of individual components as well as of whole systems. Obtaining such knowledge by carrying out appropriate stress tests for all classes of CIs is a clear goal and urgent need for Europe.

STREST followed five overarching objectives, to improve the state of knowledge and to provide the basis for future European Union policies for the systematic implementation of stress tests for non-nuclear CIs. The STREST objectives were to:

1. Establish a common and consistent taxonomy of CIs, their risk profiles and their interdependencies, with respect to the resilience to natural hazard events;
2. Develop a rigorous common methodology and a consistent modelling approach to hazard, vulnerability, risk and resilience assessment of low-probability high-consequence (i.e., extreme) events used to define stress tests;
3. Design a stress test methodology and framework, including a grading system (A – pass to C – fail), and apply it to assess the vulnerability and resilience of individual CIs as well as to address the first level of interdependencies among critical infrastructures from local and regional perspectives;
4. Work with key European CIs to apply and test the developed stress test framework and models to specific real infrastructures chosen to typify general classes of CIs;
5. Develop standardised protocols and operational guidelines for stress tests, disseminate the findings of STREST, and facilitate their implementation in practice.

3. Progress beyond the state-of-the-art and key research findings

The STREST project produced fundamental knowledge beyond the state-of-the-art in hazard, vulnerability, risk and resilience assessment of non-nuclear CIs and systems of infrastructures for low-probability and high-consequence natural hazards. The main achievements are summarised below and described in more detail in the following sections:

- Multi-hazard/risk framework for generating probabilistic hazard and/or risk scenarios, which properly accounts for cascading events;
- Harmonised treatment of uncertainties and mechanics of hazard assessment;
- Consistent taxonomy of classes of CIs, including intensity measures, engineering demand parameters and performance indicators;
- Probabilistic models for fragility, vulnerability and consequence assessment of CIs, including geographically distributed ones;
- Integrated risk of geographically distributed infrastructures considering cascading effects and interdependencies;
- Probabilistic structural and systemic performance models to determine CI losses;
- An engineering risk-based multi-level stress test methodology, with workflow and tools.

3.1 Background

Several measures that are implemented in nuclear facilities may be used in non-nuclear CIs, such as bunkered systems, 'dry site' concept for the plant layout against flooding, seismic monitoring and tsunami warning systems coupled with provisions for operator action. Besides, state-of-the-art guidelines are available and provide qualitative, semi-quantitative and quantitative concepts for risk assessment. Regarding earthquakes in particular, seismic hazard is defined in the national annexes to Eurocode 8 (CEN 2004), while the SHARE project (Woessner et al 2015) represents the most recent approach on the seismic hazard harmonisation in Europe.

Recent events have highlighted the potential for catastrophic impact of natural hazards on CIs, 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. The review of recent events 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 disaster.

3.2 Low-probability high-consequence hazard assessment

Extreme events can be considered as the consequence of three different processes (Mignan et al 2017): (i) they can emerge naturally from randomness - those are events that occur by 'lack of chance' and populate the tail of statistical distributions; (ii) extremes can be due to physical processes that amplify their severity, for example domino effects; (iii) they finally can be due to site-specific conditions that again amplify severity locally. These three general processes, which can be intertwined, have been considered in STREST by investigating the themes described in the following.

A coherent process was developed to ensure a robust management of epistemic uncertainty within a stress test (so-called EU@STREST; Marzocchi et al 2015, Selva et al 2016). The process ensures a standardised and robust treatment of the epistemic uncertainty emerging from hazardous phenomena selection, alternative models implementation and exploration of the tails of distributions. It takes into account the diverse range of views and expert opinions, the budget limitations and the regulatory impact. This process allows a rigorous and meaningful validation of any probabilistic hazard analysis and provides a clear description of epistemic uncertainty. Although developed and tested for seismic and tsunami hazard assessment, the method is easily portable to other perils.

Seismic hazard measures and extreme event scenarios for geographically extended lifeline systems were defined (Akkar and Cheng 2016). Multi-scale random fields and Monte Carlo simulation techniques were implemented for computing the annual exceedance rates of dynamic ground-motion intensity measures as well as permanent fault displacement. The developed techniques allow considering a number of seismological factors, which are important for a proper hazard assessment of geographically extended CIs in a computationally efficient way.

The stochastic dependence among the processes counting multiple exceedances of intensity measures was also studied for geographically extended structures (Giorgio and Iervolino 2016). Closed-form solutions for multi-site probabilistic seismic hazard analysis were developed and probabilistically rigorous insights into the form of dependence among hazards at multiple sites were derived.

Several approaches are available for site-specific probabilistic seismic hazard assessment, including the use of proxies, e.g. V_{s30}, in ground motion prediction equations, proxies and amplifications factors, linear site-specific residual, instrumental linear site response analysis and numerical linear or nonlinear response analysis. The variability of the results from these approaches was reviewed and illustrated on the Euroseistest site in Greece (http://euroseisdb.civil.auth.gr). The results of the application were then used to formulate recommendations for an 'optimal' approach depending on the available information (Aristizábal et al 2016). A systematic comparison of site specific and non-specific hazard assessment has also been performed for 80 sites in Europe (Kotha et al 2016a, 2016b). Differences as large as 50 % are observed.

Near-source ground motions can carry seismic demand systematically larger than that of so-called ordinary records, due to phenomena such as rupture forward directivity. A framework for considering forward directivity in structural design was developed, as schematically represented in Fig. 3.1. The displacement coefficient method was implemented for estimating near-source seismic demand, by making use of the results of near-source probabilistic hazard analysis and a semi-empirical equation for near-source forward directivity inelastic displacement ratio (Baltzopoulos et al 2015).

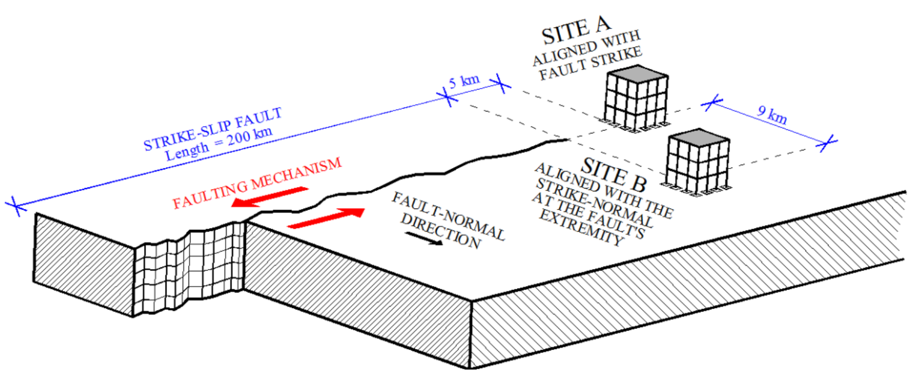


Fig. 3.1 Schematic representation of site-source configuration (Iervolino 2015)

Probabilistic multi-hazard scenarios were generated for three different cases, emphasizing the richness of processes potentially leading to extremes (see also Mignan et al 2016a):

(i) 'Intra-event' earthquake triggering, based on concepts of dynamic stress, allowed evaluating the maximum magnitude Mmax of cascading fault ruptures (Mignan et al 2015). Once fault rupture cascading is considered, as observed in Nature, higher Mmax values follow (see Fig. 3.2 for the Anatolian region), which may have an impact on pipeline stress tests for instance.

(ii) 'Intra-hazard' earthquake triggering, based on the theory of Coulomb stress transfer, allowed evaluating earthquake spatiotemporal clustering and its role in damage-dependent vulnerability (Mignan et al 2016b) (see consequences at the risk level in section 3.3).

(iii) 'Inter-hazard' interactions were considered at hydropower dams to examine the combined impact of earthquakes, floods, internal erosion, malfunctions on the dam and foundation, spillway, etc.

The characteristics of the cascades were investigated under various parametric conditions with a view to discussing their possible inclusion in stress tests (Matos et al 2015) (see also section 3.5.1). All hazard interactions were modelled using the Generic Multi-Risk (GenMR) framework described in Mignan et al (2014).

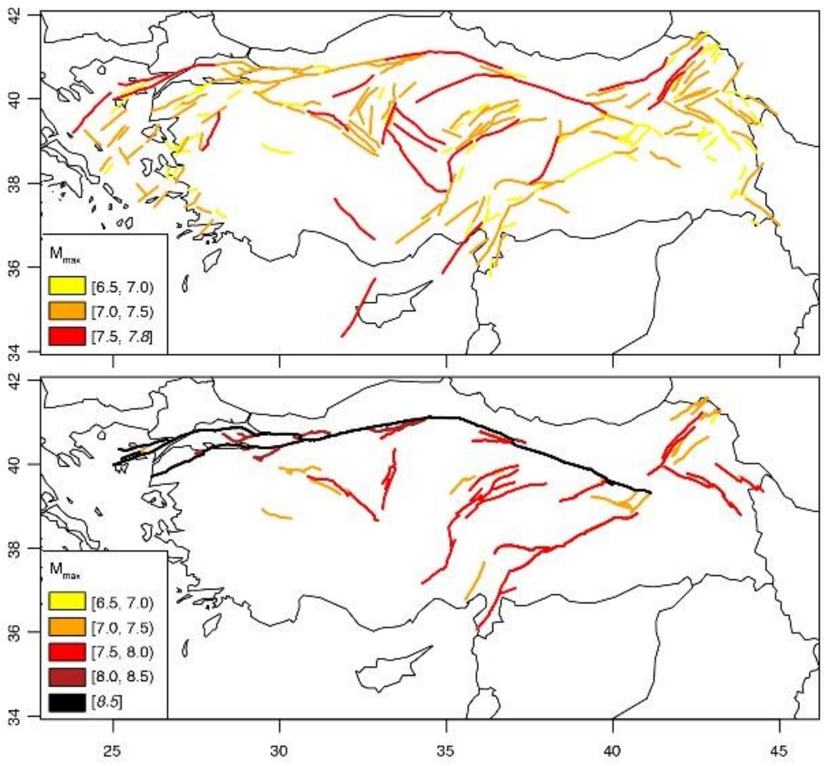


Fig. 3.2 $M_{\max}$ maps of the strike-slip faults in the Anatolian region: recomputed from the SHARE fault database (top) and with rupture propagation across segments (bottom) (Mignan et al 2015)

A site-specific tsunami hazard assessment method was developed for inclusion in stress tests (Selva et al 2016). It makes use of an event tree and performs a separate treatment of subduction and background (crustal) earthquakes, which allows for a more focused use of available information and for avoiding significant biases. For the application in the Thessaloniki area, full simulations have been conducted at the regional scale using the complete event tree. Example results of tsunami inundation modelling are shown in Fig. 3.3.

Fig. 3.3 Site-specific tsunami inundation modelling results on a high-resolution grid of the application in the port of Thessaloniki (Selva et al 2016; Pitilakis et al 2016)

3.3 Vulnerability models for stress tests of critical infrastructures

Regarding single-site CIs, standardised procedures were developed for the hazard assessment and consequence analysis of petrochemical plants (Salzano et al 2015), dams (Matos et al 2015) and harbours (Pitilakis 2015). Structural vulnerability functions for all elements at risk (such as storage tanks and pipelines; foundation, spillway and hydropower system in dams; and buildings and cranes in harbours) were defined with respect to earthquakes, tsunamis and floods. Indicative examples are shown in Fig. 3.4.

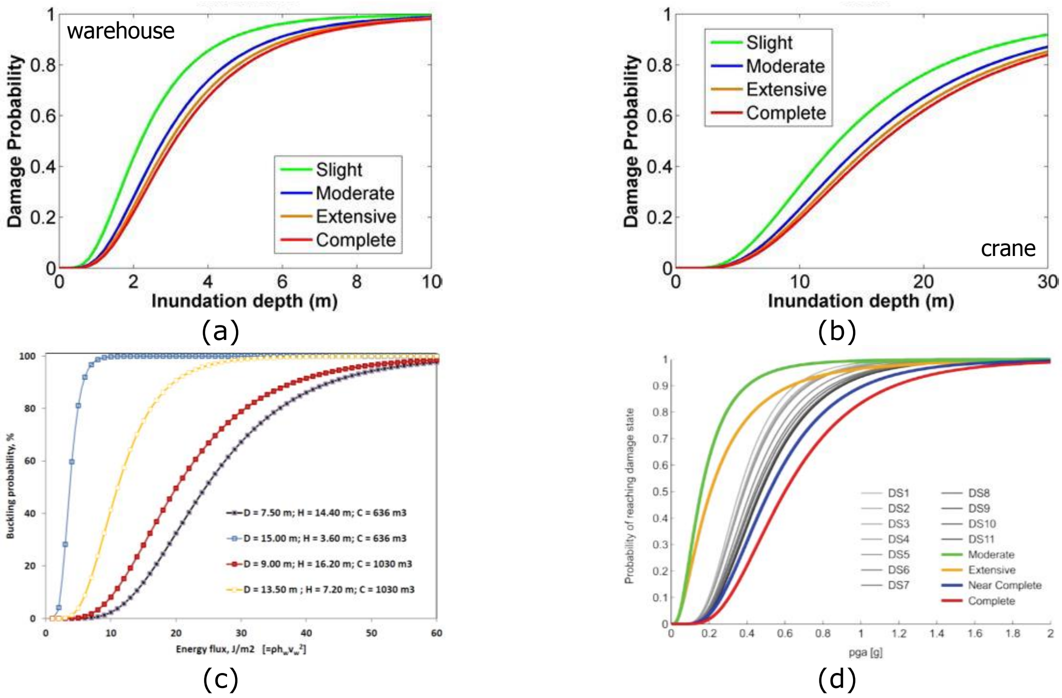


Fig. 3.4 Fragility functions for (a) warehouses, (b) cranes (Karafagka et al 2016) and (c) atmospheric tanks (Salzano, 2015) for tsunami hazard and (d) structural and non-structural components of industrial buildings for earthquake hazard (Crowley 2015)

Similarly, tools (e.g., fragility curves, response and vulnerability analysis models) and specifications were provided for the three geographically distributed CIs (Miraglia et al 2015, Uckan et al 2015, Trevlopoulos and Guéguen 2016). The interdependencies in the port of Thessaloniki were investigated, with the aim to develop a conceptual framework on factors influencing the resilience of geographically distributed CIs and to define stress tests at a regional scale that account for the consequences of cascading failures.

Industrial districts have been selected as an example of multiple-site, low-risk high-impact CIs. Precast concrete warehouses and other industrial buildings that are typically found in industrial districts in Europe, and that have demonstrated high levels of damage in past earthquakes, were used as an application of the guidelines for developing a probabilistic risk model that includes fragility functions for structural and non-structural components and contents, and modelling the consequences of damage with a focus on monetary losses (Babič and Dolšek 2014, Casotto et al 2015).

Finally, structural methods for probabilistic performance assessment in the case of state-dependent seismic damage accumulation were developed based on Markov chains (Iervolino et al 2016). Damage-dependent vulnerability was also combined to earthquake clustering in northern Italy and the impact on risk investigated (Mignan et al 2016b). Results are shown in Fig. 3.5. In simple terms, risk increases as additional physical processes are considered, such as event clustering and dynamic vulnerability.

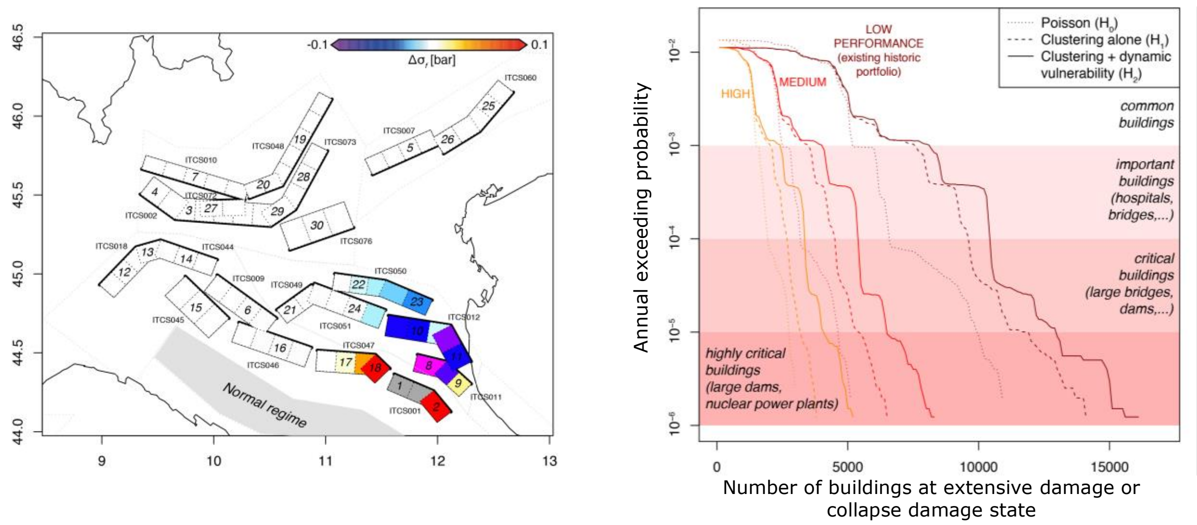


Fig. 3.5 Seismic risk curves in a conceptual example in northern Italy, with amplification of risk due to the combination of earthquake clustering and damage-dependent vulnerability of buildings (Mignan et al 2016b)

3.4 Stress test methodology for non-nuclear critical infrastructures

The engineering risk-based multi-level stress test, ST@STREST (Stojadinović et al 2016, Esposito et al 2017), that was developed in the project and applied in the exploratory applications, aims to enhance the procedures for evaluation of the risk exposure of non-nuclear CIs against natural hazards. To account for diverse types of infrastructures, the potential consequence of failure, the types of hazards and the available resources for conducting the stress test, each stress test level is characterised by a different scope (component or system) and by a different complexity of the risk analysis. The workflow is presented in Fig. 3.6.

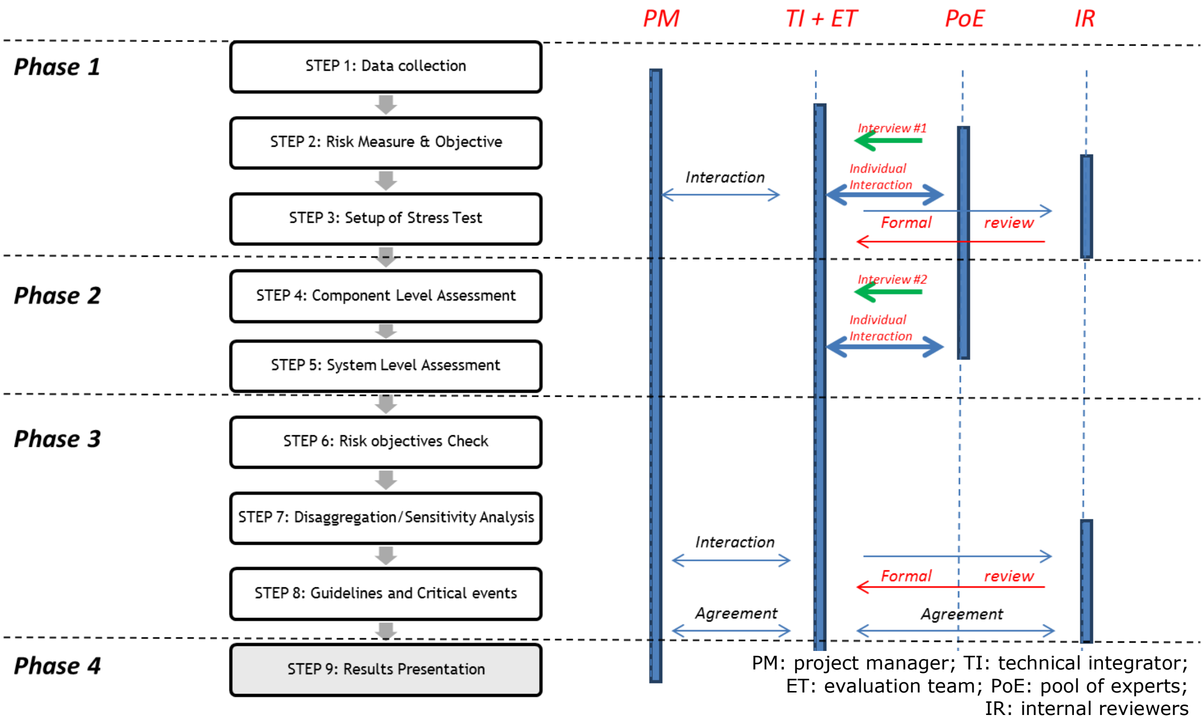


Fig. 3.6 Workflow of the ST@STREST methodology and interaction among the main actors during the multiple-expert process (Esposito et al 2017)

In the Pre-Assessment phase (Phase 1), the data available on the CI and hazard are collected. Then, the risk measures and objectives, the time frame, the total costs of the stress test and the most appropriate stress test level are defined.

In the Assessment phase (Phase 2), initial design demand levels for each component are compared with the best available information about their capacity and then, a systemic probabilistic risk analysis of the entire CI is performed (using, for instance, the hazard and risk methods developed in STREST for the modelling of extreme events – sections 3.2-3.3).

In the Decision phase (Phase 3), results of the Assessment phase are compared to the risk objectives defined in the Pre-Assessment phase. This comparison results in a grade (Fig. 3.7) that informs about the magnitude of the risk posed by the critical infrastructure, and, if the risk is possibly unjustifiable or intolerable, how much the safety of the CI should be improved until the next periodical verification. Critical events that most likely cause the exceedance of a loss value of interest are identified through a disaggregation analysis. Risk mitigation strategies and guidelines are formulated based on the identified critical events.

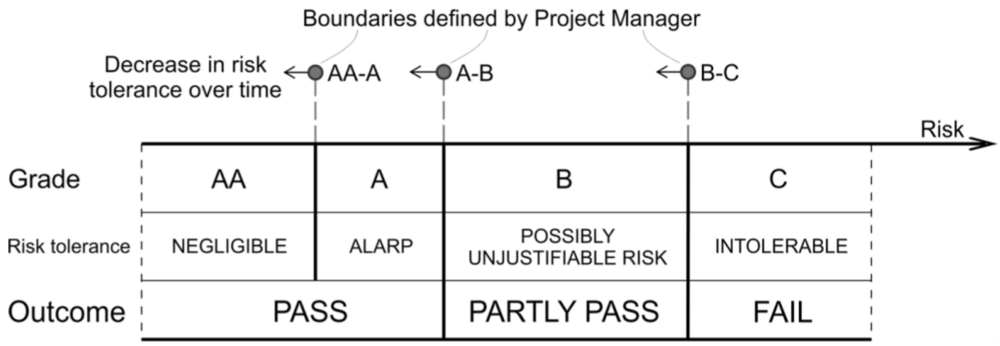


Fig. 3.7 Grading system used in ST@STREST (Esposito et al 2016)

In the Report Phase (Phase 4), the experts present the stress test results to authorities and regulators. The presentation includes the outcome of stress test in terms of the grade, the critical trigger events, the guidelines for risk mitigation, and the accuracy of the methods adopted in the stress test.

3.5 Exploratory applications of new stress test concept

This section provides a brief summary of the results of stress tests performed at the six pilot sites considered in the STREST project, separated in three classes A (section 3.5.1), B (section 3.5.2) and C (section 3.5.3). For a detailed description of the results, the reader is invited to consult Pitilakis et al (2016). Fig. 3.8 combines all the obtained stress test grades (Fig. 3.7) for comparison not only of the risk posed by these critical infrastructures but also of the stress test levels used in these example applications. Note that, while a significant effort was invested to develop the best possible stress test for each considered critical infrastructure, the obtained results do not reflect the actual safety or risk posed by these critical infrastructures because the data considered in this public project was limited for safety or business reasons.

Case study	Hazard	Grading range								
		ST-L1a	ST-L2a	ST-L2b	ST-L2c	ST-L2d	ST-L3a	ST-L3b	ST-L3c	ST-L3d
CI-A1	Earthquake	AA-C	-	AA-C	-	AA-C	-	-	-	-
	Tsunami	AA-C	-	AA-C	-	AA-C	-	-	-	-
CI-A2	Earthquake/ Flood/ Internal erosion/ Outlet malfunction/ Hydropower system malfunction	AA-A	-	AA-A	-	AA-A	-	-	AA-A	AA-A
CI-B1	Earthquake	B	B	-	-	-	-	-	-	-
CI-B2	Earthquake/ Liquefaction	AA-A	AA-A	-	-	-	-	-	-	-
CI-B3	Earthquake	C	-	-	-	-	-	-	-	-
	Tsunami	AA-C	-	AA	-	-	-	-	-	-
	Earthquake/ Liquefaction	-	-	B	-	AA-C	-	-	-	AA-C
CI-C1	Earthquake	B-C	-	B-C	-	-	-	-	-	-

Fig. 3.8 Stress test results in terms of grades by pilot site and level of detail (Pitilakis et al 2016). ST-Lxx labels represent the different levels of ST@STREST and CI-xx the site classes and numbers

3.5.1 Individual, single-site infrastructures with high risk and potential for high local impact and regional or global consequences

For a conceptual dam system, it was shown that accounting for component fragility functions and epistemic uncertainty affecting hazards, components, and their interactions (Matos et al 2015) increased four-fold the frequency of failures (yet remaining in the examined case below existing dam safety margins). In order to characterise losses in the downstream area, inundation scenarios were generated based on a 2-D hydraulic model, capturing the uncertainty in the dam-break wave propagation and the probabilistic response of buildings to the flood. Resulting maps, as the one shown in Fig. 3.9, can be used to plan which buildings at risk to reinforce, provide with shelters, or relocate.

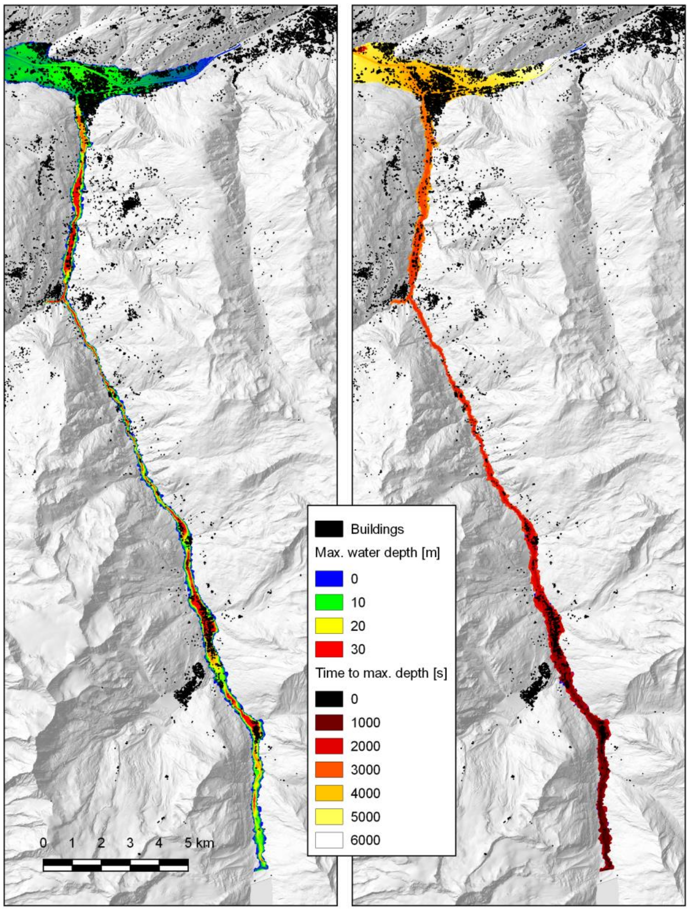


Fig. 3.9 Inundation resulting from overtopping of the conceptual-dam application (Pitilakis et al 2016, work by EPFL and ETH Zurich)

Quantitative risk assessment of an oil refinery impacted by earthquakes and tsunamis was performed. For this specific site, tsunamis damaged a limited number of atmospheric storage vessels along the shoreline, while earthquakes increased the failure frequency of atmospheric storage tanks. However, societal risk was mainly caused by damage to LPG tanks, which failed due to industrial-related causes, and therefore the impact of the natural hazards was limited. Fig. 3.10 presents the probabilistic risk contours separately for the three types of hazards examined.

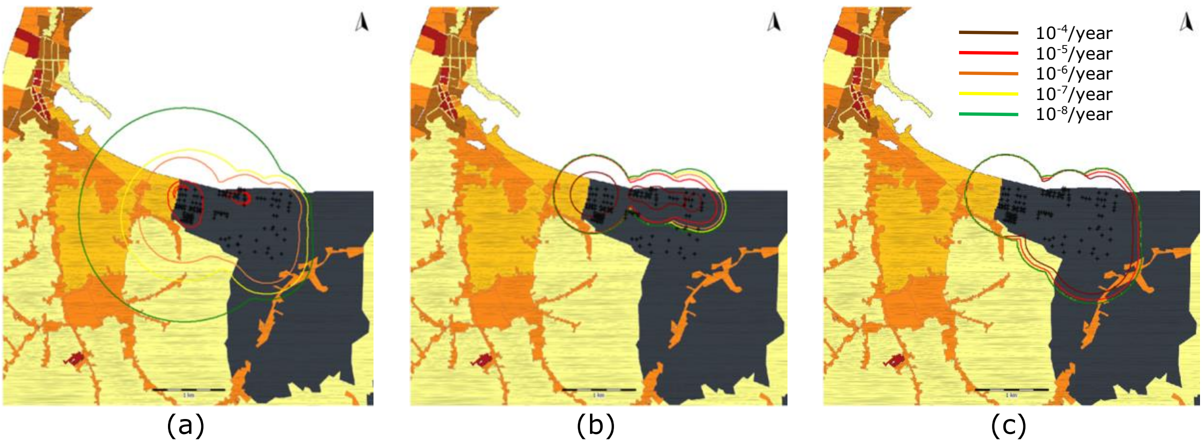


Fig. 3.10 Probabilistic risk contours for (a) industrial, (b) tsunami and (c) earthquake triggers in the petrochemical plant application (Pitilakis et al 2016, work by AMRA & INGV)

3.5.2 Distributed and/or geographically-extended infrastructures with potentially high economic and environmental impact

A stress test of an oil pipeline crossing five faults was performed considering the failure at the intersections as perfectly correlated or statistically independent and spotting the three most critical intersections to be retrofitted. The calculated maximum tensile and compressive strains of the pipe at the five crossings are shown in Fig. 3.11. The proposed change of the pipe-fault intersection angle reduced the probability of failure to less than 2 % in 2475 years and the overall risk to negligible.

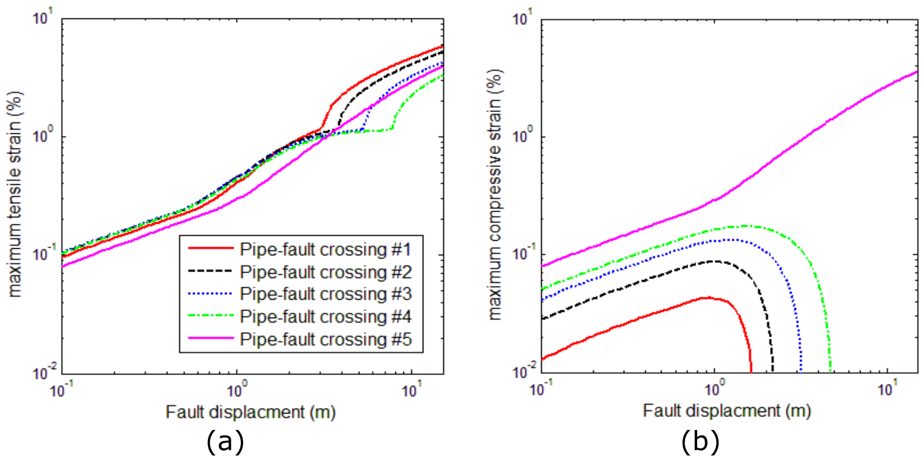


Fig. 3.11 Maximum tensile (a) and compressive (b) pipe strains for the pipes at pipe-fault crossings for to different intersection angles (Pitilakis et al 2016, work by KOERI)

A stress test for a sub-network of the Groningen field in the Netherlands was performed using a risk-based approach for individual stations and pipe segments and a full probabilistic risk analysis with Monte Carlo simulations for the network analysis. Earthquakes induced by gas extraction were the main hazard source. Fig. 3.12 shows low risk of high connectivity loss (i.e. the average reduction in the ability of endpoints to receive flow in the damaged network with respect to the original conditions). These results were obtained under a number of conservative assumptions for the seismic demand and the component fragilities.

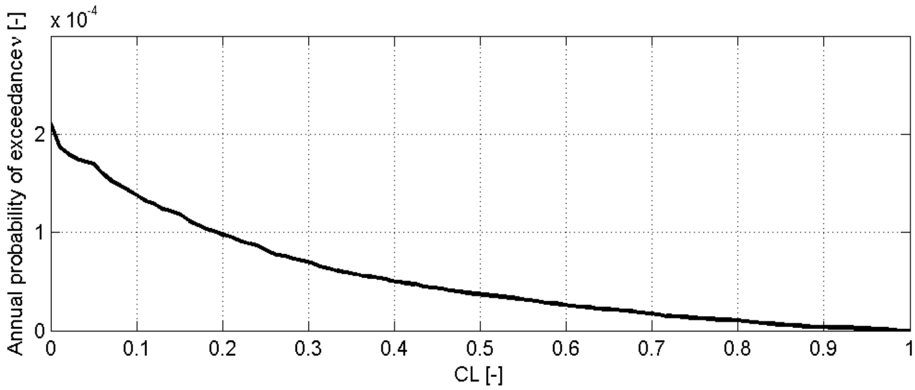


Fig. 3.12 Annual probability of exceedance of network connectivity loss (CL) of the natural gas distribution network (Pitilakis et al 2016, work by TNO)

The application to the port facility showed that it might pass, partly pass or fail a stress test depending on the seismic scenario, analysis approach (see Fig. 3.13) and risk metric. Several electric power distribution substations, which presented high failure risk and contributed significantly to the performance loss of the port due to loss of power supply to the cranes, should be considered for upgrading or/and provided with alternative power sources. Although the systemic risk for the tsunami hazard was very low, it was recommended to investigate the effect of floating ships that may hit the harbour components.

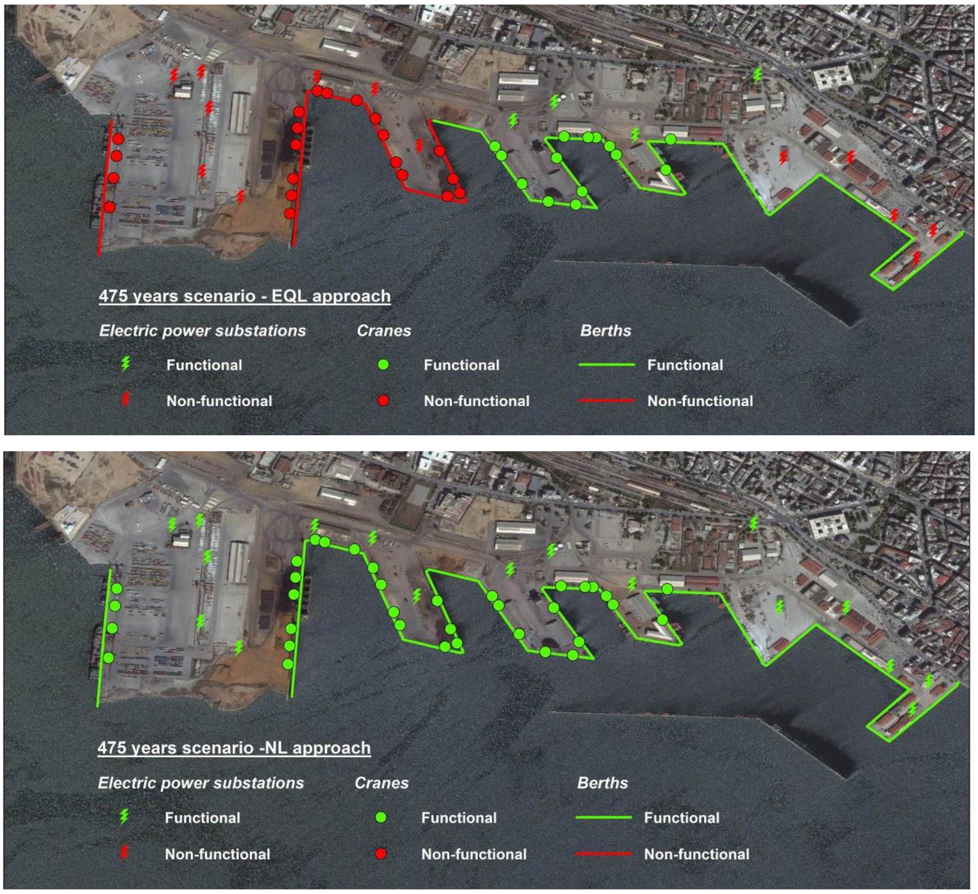
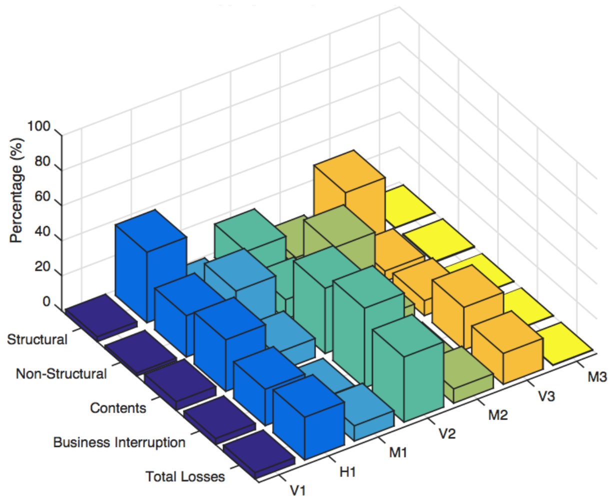


Fig. 3.13 Functionality of components in the harbour application for an earthquake scenario with 475 years return period, for equivalent linear (top) and nonlinear analysis approach (bottom) (Pitilakis et al 2016, work by AUTH and INGV)

3.5.3 Distributed, multiple-site infrastructures with low individual impact but large collective impact or dependencies

The limited budget for a stress test of the industrial district has conditioned the level of detail and complexity of the stress test, which considered only seismic hazard as the predominant hazard. The results showed that several facilities failed the component level assessment and identified the sub-typologies that contributed most to the total average annual losses, as illustrated in Fig. 3.14. The event disaggregation implied that business interruption losses were not just driven by the rare events, and thus mitigation efforts related to structural and non-structural retrofitting should be given high priority.



V: vertical precast panels
H: horizontal panels
M: concrete masonry infills
1: long saddle roof beams, built before 1996
2: short rectangular beams, built before 1996
3: built after 1996

Fig. 3.14 Disaggregation of average annual loss in the industrial district application, according to building sub-class for each component of loss (Pitilakis et al 2016, work by EUCENTRE and UL)

4. Policy impact of STREST

STREST seeks to improve the security and resilience of CIs against low-probability high-consequence natural hazards. The fundamental knowledge, methodologies and tools produced by the project provide the basis for a master plan for the coordinated implementation of stress tests for whole classes of CIs and systems thereof. The long-term impacts originating from the project, which will outlast its duration and ensure a structuring effect in Europe, refer to the reinforced European safety assessment capacity, improved and more reliable stress tests for CIs, support for decision making and prioritisation of mitigation options and support for preparedness, all leading to increased societal resilience.

STREST provides best practices and robust methodologies for stress tests, in particular for the systematic identification of major hazards and potential extremes, infrastructure vulnerabilities and interdependencies, and systematic technology-neutral risk-based stress test workflow, in support of the implementation of the European policies for disaster risk reduction and the protection of national and European CIs. Furthermore, the correct assessment of risk is a pre-requisite of any long-term strategy for industrial and energy production in Europe. In a wider context, the results produced in STREST contribute to the faster attainment of the Sendai Framework target for reducing disaster damage to CIs.

The knowledge, procedures and tools developed by the project are useful on one hand for owners and operators of CIs to optimise CI maintenance and/or partial or complete replacement, develop the operator security plan and draft the regular reports on risks and vulnerability, and on the other hand for Member States authorities and urban/community planners to develop and update their national risk assessments, with the ultimate goal of increasing the resilience of CIs and societies to the effects of extreme events.

The networking with key organisations and programs in the USA, Asia and Japan ensures the international perspective, harmonisation and knowledge transfer for the development of truly novel standards. In addition, clustering activities with previous and on-going projects (SHARE, SYNER-G, MATRIX, INFRARISK, RAIN, INTACT) on related issues gives added value to the European framework programme for research by defining a common understanding of terminology, sharing of good practice and harmonising indicators, metrics and methods. Furthermore, STREST benefits from the direct participation of representatives of a broad range of CIs and industry to ensure the relevance of the products and outcomes, and the communication to the wider community.

STREST conceived a dissemination plan to transform the results and new methodologies developed by the project in protocols and reference guidelines for the wider application of stress tests. The planned activities are a key instrument for dissemination to the scientific and technical communities, as well as to policy and decision makers at European, national, regional and local levels. Overall, these activities will have an impact on the society at large, by incorporating stress test methodologies in current management and long-term planning of non-nuclear CIs, and ultimately by the enhancement of societal resilience.

Public acceptance of existing and new technologies in CIs has been eroded by a number of technical accidents and failures initiated by natural events. The coherent assessment of risk and safety enabled by the implementation of the STREST methodology and framework will allow increasing public acceptance for critical technologies and infrastructures, whereas the test applications illustrate the benefits of improved hazard and risk assessment for key critical sites in Europe. Moreover, the sensitivity analyses conducted on advanced hazard studies combining regional and site-specific assessments will enable to develop guidelines for improved surveillance capacity at CI sites and for future CI design and construction plans as well.

5. Recommendations for the implementation of stress test policies

STREST developed a harmonised multi-hazard and risk process for stress tests and advanced the state-of-the-art in hazard and vulnerability assessment of non-nuclear CIs against low-probability high-consequence natural events (and implicitly against the more common events). It is recommended to:

1) Promote the application of the methodology (Section 3.4), taking benefit of the exploratory applications on six CIs.
2) Initiate a dialogue (possibly via workshops) between European critical infrastructure operators, regulators and users to establish, where needed, and harmonize the societal risk tolerance objectives. Indeed, a key issue that emerged from the exploratory applications is the fact that a critical infrastructure may pass or fail a stress test, depending on the adopted risk targets.
3) Initiate the drafting of guidelines for the application of harmonised stress tests, making use of the knowledge base and tools developed within STREST.
4) Include uncertainties, cascade effects and multiple hazards in stress tests.
5) Investigate technical aspects relevant to risk assessment of critical infrastructures.
6) Continue coordination among research projects to capitalise on the wealth of knowledge produced within the European Union's Framework Programme for Research and Innovation, for instance through the harmonisation of methodologies and exploratory applications in different sites.
7) Promote transnational cooperation and the wider involvement of stakeholders, mainly operators and regulators of critical infrastructures.

The guidelines provide the best practices and methodologies, together with new scientific developments, for hazard and risk assessment. They will ultimately contribute to the objectives of the European policies for increased resilience of CIs and of the Sendai Framework for the reduction of disaster damage.

The work performed within STREST highlighted a number of technical aspects relevant to hazard and vulnerability assessment of critical infrastructures that should be further developed in future studies. Firstly, uncertainties, cascade effects and multiple hazards were shown to be important aspects that need to be properly included in stress tests. The exploratory applications revealed in some cases lack of input data to perform the stress tests and lack of loss data for the calibration of models, e.g. for loss of life following damage to critical infrastructures. Regarding vulnerability assessment, fragility curves need to be developed for loss of containment in components of petrochemical plants, for dam components and systems, for pipelines in case of liquefaction and to include the effect of cumulative damage. With a view to the life-cycle management and planning of interventions in critical infrastructures, it is advisable to account for the long-term degradation of components. Lastly, it is recommended to use high-level, validated and preferably open-source software to perform the calculations needed for stress tests.

STREST established technical dialogue with relevant ongoing FP7 and H2020 projects and identified areas where common work would be beneficial. These include a common approach to uncertainty estimation, review of good practice in risk analysis, and harmonisation of hazard indicators and risk metrics. The interaction is planned to continue through the participation to different project meetings and if possible in future projects. A coordinated support action from the European Commission would be needed to capitalise on the wealth of knowledge and tools produced within the EU Framework Programme for Research and Innovation. This would allow achieving results at inter-project level, for instance a harmonised taxonomy across projects and types of CIs (e.g. combining energy and transportation networks), a common method for cascade modelling (e.g. applied to both geological and hydrological hazards and industrial risks), and a harmonized set of risk tolerance objectives applicable across the range of critical infrastructure types and across Europe.

A panel of experts could help making sure that the methods developed in different projects are compatible and investigate whether they can be transposed to additional exploratory applications in different sites. Moreover, the panel could investigate the causes of possible discrepancies between the results of different projects, with a view to harmonised stress test methods.

Further actions to promote transnational cooperation and the wider involvement of stakeholders, mainly operators and regulators of CIs, in all stages of the development and implementation of stress tests should be undertaken. Such actions should present how the state-of-the-art tools that were produced by STREST and other recent and on-going research projects may be used to provide scientific evidence for decision-makers to achieve a higher level of protection against the effects of extreme natural hazards, to communicate risk and mitigation measures to authorities and the general public, and to comply with the legal requirements. Through their participation, stakeholders will have the opportunity to provide feedback on their needs and experience, and thus contribute to the development of guidelines. Their cooperation is also valuable for the collection of input data and the definition of common risk levels. STREST has already identified a number of European associations of CI operators.

A The consortium

Twelve institutions were involved in the STREST project (see Fig. A.1):

- Eidgenossische Technische Hochschule Zurich – ETH Zurich, Switzerland;
- Ecole Polytechnique Fédérale de Lausanne – EPFL, Switzerland;
- Basler & Hofmann, Consulting Engineers, Zurich, Switzerland;
- European Centre for Training and Research in Earthquake Engineering – EUCENTRE, Italy;
- Analisi e Monitoraggio del Rischio Ambientale – AMRA, Italy;
- Istituto Nazionale di Geofisica e Vulcanologia – INGV, Italy;
- Toegepast Natuurwetenschappelijk Onderzoek – TNO, Netherlands;
- Institut des Sciences de la Terre, Université Joseph Fourier– ISTerre, UJF, France;
- Aristotle University of Thessaloniki- AUTH, Greece;
- Kandilli Observatory and Earthquake Research Institute – KOERI, Turkey;
- Ljubljana University, Slovenia;
- Joint Research Centre – JRC, Belgium.

Fig. A.1 STREST participants

The Board of Associated Industry Partners was formed of a representative of each of the six critical infrastructures considered in the project:

- CNR and AMRA, risk consultants for the ENI/Kuwait Milazzo petrochemical plant, Italy;
- The Swiss Federal Office of Energy, regulator for the Valais dams of Switzerland;
- BOTAS International Ltd., operator of the Baku-Tbilisi-Ceyhan Crude Oil Pipeline, Turkey;
- Gasunie Transport Services, owner of the national natural gas pipeline system, the Netherlands;
- Thessaloniki Port Authority SA, Greece;
- Tuscany Region, Italy.

B Reference Reports and technical deliverables

B.1 Reference Reports

STREST produced an integrated set of Reference Reports with technical guidelines and recommendations concerning the assessment and protection of critical infrastructures, written specifically for end-users, regulators and plant operators. This set includes the following Reference Reports that are available to download from the project web site (www.strest-eu.org):

RR-1: State-of-the-art and lessons learned from advanced safety studies and stress-tests for CIs

RR-2: Guidelines for harmonized hazard assessment for LP-HC events

RR-3: Guidelines for harmonized vulnerability and risk assessment for CIs

RR-4: Guidelines for stress-test design for non-nuclear critical infrastructures and systems: Methodology

RR-5: Guidelines for stress-test design for non-nuclear critical infrastructures and systems: Applications

RR-6: STREST project policy brief

B.2 Technical deliverables

The scientific output of the project is described in the technical deliverables listed below. The deliverables are available to download from the project web site.

D2.1: Report summarizing the analysis and systematic classification of the results from hazard assessment and stress tests for NPPs

D2.2: Report on state-of-the-art in hazard assessment and stress tests for non-nuclear CIs

D2.3: Report on lessons learned from recent catastrophic events

D2.4: Report on lessons learned from on-going and completed EU projects

D3.1: Report on the effects of epistemic uncertainties on the definition of LP-HC events

D3.2: Report on the definition of extreme hazard scenarios for geographically-extended facilities

D3.3: Report on near-source hazard assessment and definition of reference scenarios for stress tests

D3.4: Guidelines and case studies of site monitoring to reduce the uncertainties affecting site-specific earthquake hazard assessment

D3.5: Report on cascading events and multi-hazard probabilistic hazard scenarios

D3.6: New software package incorporating induced seismicity hazard in PSHA

D3.7: Integrated report on the comparative analysis and sensitivity tests of multi-hazard assessment of LP-HC events for the six selected application areas

D4.1: Guidelines for performance and consequences assessment of single-site, high-risk, non-nuclear critical infrastructures exposed to multiple natural hazards

D4.2: Guidelines for performance and consequences assessment of geographically distributed, non-nuclear critical infrastructures exposed to multiple natural hazards

D4.3: Guidelines for performance and consequences assessment of multiple-site, low-risk, high-impact, non-nuclear critical infrastructures exposed to multiple natural hazards

D4.4: Report on the proposed taxonomy of CIs based on their vulnerability characteristics and exposure to natural hazard initiating events

D4.5: Report on development of a coherent definition of societal resilience and its attributes

D5.1: Report on the proposed engineering risk assessment methodology for stress tests of non-nuclear CIs

D5.2: Report on the proposed Bayesian network framework for conducting stress tests of non-nuclear CIs

D5.3: Tools and strategies to incorporate stress tests into the long-term planning and life cycle management of non-nuclear CIs

D5.4: Report on strategies for stress test implementation at community level and strategies to enhance societal resilience using stress tests

D6.1: Integrated report detailing analyses, results and proposed hierarchical set of stress tests for the six CIs covered in STREST

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