



Harmonized approach to stress tests for critical infrastructures against natural hazards

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INTRODUCTION

Critical infrastructures 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 critical infrastructures 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 critical infrastructures. Among the most important tools are the stress tests, designed to test the vulnerability and resilience of critical infrastructures 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 classes of critical infrastructures.

The 'Harmonized approach to stress tests for critical infrastructures against natural hazards' (STREST) project, funded by the European Community's Seventh Framework Programme, aims at designing an **innovative stress test framework for non-nuclear critical infrastructures**, with the development of models for the hazard, risk and resilience assessment of extreme events, and with applications to six critical infrastructures.

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

- Lessons learned from past regulations and research projects;
- Hazard assessment of extreme events;
- Vulnerability of critical infrastructures and their performance to extreme events;
- Development of the STREST stress test methodology and framework;
- Exploratory applications on six key representative critical infrastructures in Europe.

Objectives

The consistent design of stress tests and their application to specific infrastructures, to classes of infrastructures as well as to 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 critical infrastructures 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 the implementation of future European Union policies for the systematic enactment of stress tests for non-nuclear critical infrastructures:

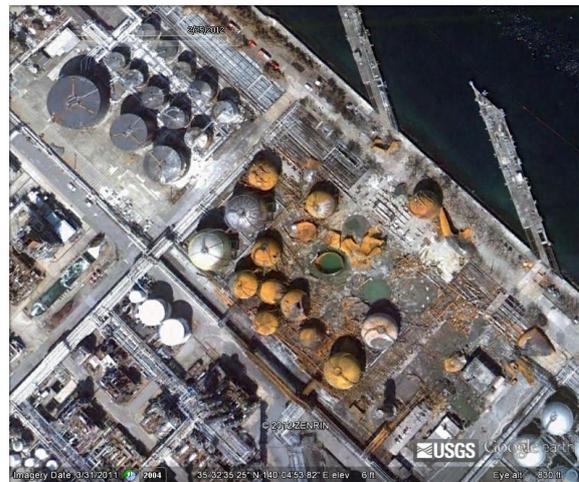
1. Establish a common and consistent **taxonomy** of critical infrastructures, their risk profiles and their interdependencies, with respect to the resilience to natural hazard events.
2. Develop a rigorous common methodology and a consistent modelling approach to **hazard, vulnerability, risk and resilience assessment of low-probability high-consequence 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 critical infrastructures as well as to address the first level of interdependencies among critical infrastructures from local and regional perspectives.
4. Work with key European critical infrastructures to **apply and test** the developed stress test framework and models to specific real infrastructures chosen to typify general classes of critical infrastructures.
5. Develop standardised protocols and operational **guidelines for stress tests**, disseminate the findings of STREST, and facilitate their implementation in practice.

STATE-OF-THE-ART AND LESSONS LEARNED

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 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 events, considering common cause failures for multiple sites.

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. State-of-the-art guidelines for risk assessment are available, which have to be considered by governments and operators, and provide quantitative, semi-quantitative and qualitative concepts.

The LPG tank farm at the Chiba refinery after the earthquake-triggered fires and explosions (©2012 Google, ZENRIN)



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. The review of past 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 natural hazard.

LOW PROBABILITY-HIGH CONSEQUENCE HAZARD ASSESSMENT

A coherent process was developed to ensure a robust **management of epistemic uncertainty** within a stress test. It ensures a standardised treatment of the epistemic uncertainty emerging from hazard and 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 seismic 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.

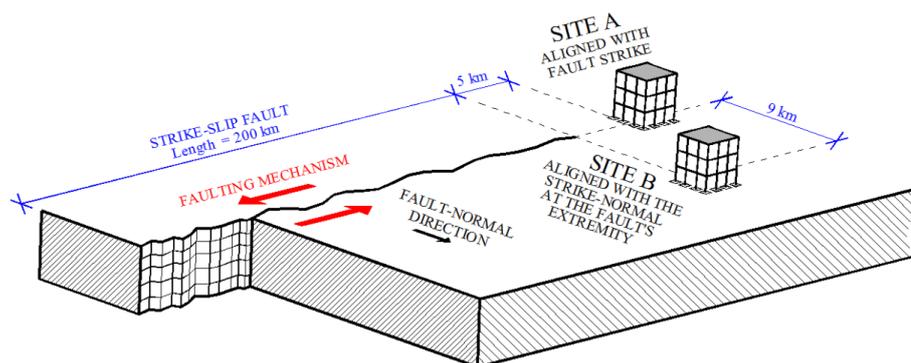
Seismic hazard measures and extreme event scenarios for **geographically extended lifeline systems** were defined. Multi-scale random fields and Monte Carlo simulation techniques were implemented for computing the annual exceedance rates of dynamic ground-motion intensity measures as well as permanent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

The stochastic dependence among the processes counting multiple exceedances of intensity measures was also studied for geographically extended structures. 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 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 one example application for the Euroseistest site (euroseisdb.civil.auth.gr). The results of the application were then used to formulate recommendations for an 'optimal' approach depending on the available information.

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. 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.

Schematic representation of site-source configuration



A methodology for **site-specific tsunami hazard assessment method** was developed for inclusion in stress tests. 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.

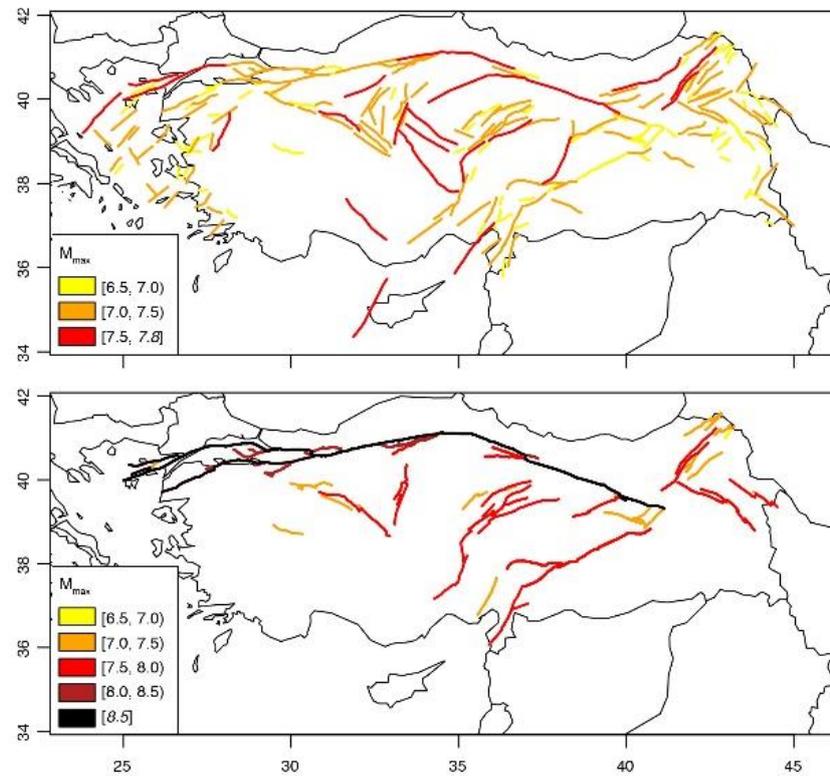
Site-specific tsunami inundation modelling results on a high resolution grid of the application in the port of Thessaloniki



Probabilistic multi-hazard scenarios, where cascades of events emerged from three types of hazard interactions, were generated for three different cases, emphasising the richness of processes potentially leading to extremes:

- (i) **'Intra-event'** earthquake triggering, based on concepts of dynamic stress, allowed evaluating the maximum magnitude M_{max} of cascading fault ruptures. Once fault rupture cascading is considered, higher M_{max} values follow, which may have an impact on pipeline stress tests for instance.

M_{max} maps of the strike-slip faults in the Anatolian Peninsula: recomputed from the SHARE fault database (top) and with rupture propagation across segments (bottom)



- (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.

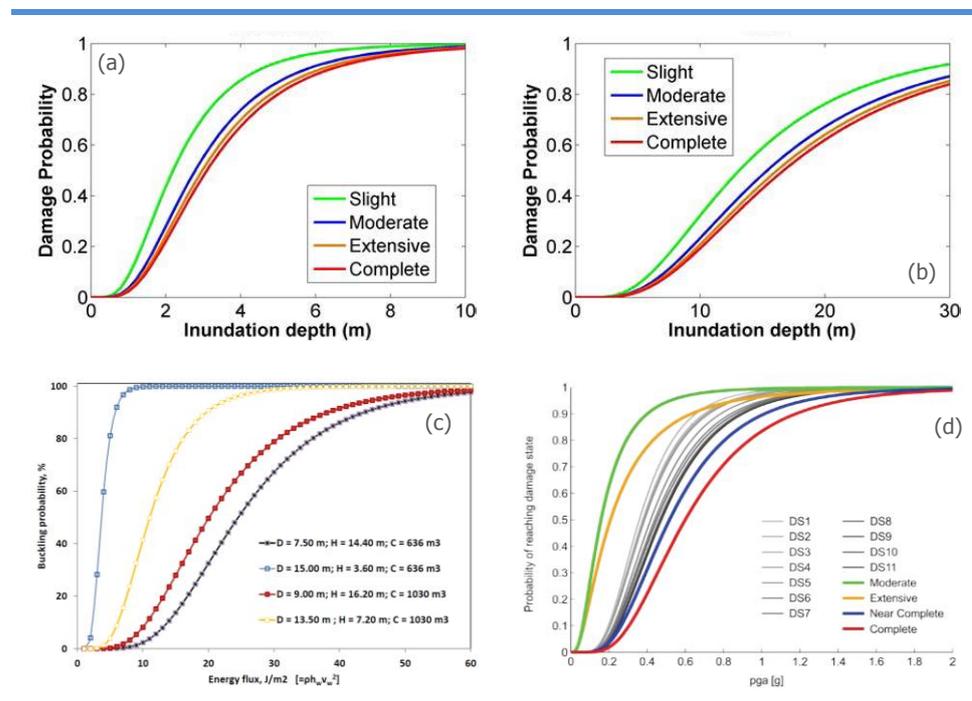
- (iii) **'Inter-hazard'** interactions were considered at hydropower dams to examine the combined impact of earthquakes, floods, internal erosion, malfunctions on the dam and foundation, spillway, etc.

The characteristics of the cascades were investigated under various parametric conditions with a view to discussing their possible inclusion in stress tests. All hazard interactions were modelled using the Generic Multi-Risk (GenMR) framework.

VULNERABILITY MODELS FOR PERFORMANCE AND CONSEQUENCES ASSESSMENT

Regarding single-site critical infrastructures, standardised procedures were developed for the hazard assessment and consequence analysis of petrochemical plants, dams and harbours. **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**.

Fragility functions for warehouses (a), cranes (b) and atmospheric tanks (c) for tsunami hazard and structural and non-structural components of industrial buildings (d) for earthquake hazard



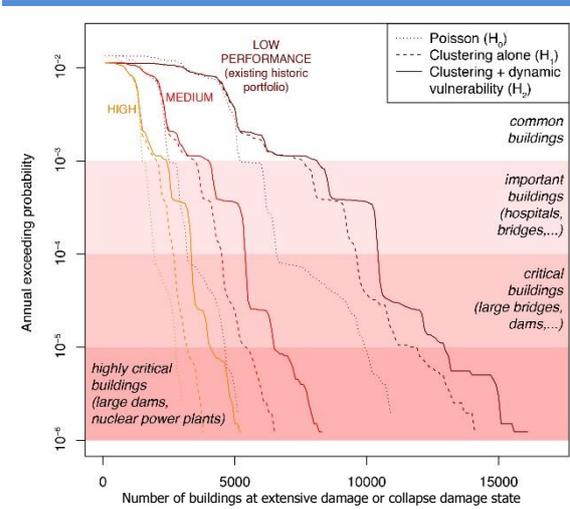
Similarly, tools (e.g., fragility curves, response and vulnerability analysis models) and specifications were provided for the three geographically distributed critical infrastructures. The interdependencies in the port of Thessaloniki were investigated, with the aim to develop a conceptual framework on factors influencing the resilience of geographically distributed critical infrastructures 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 non-nuclear critical infrastructures. Precast concrete warehouses 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**.

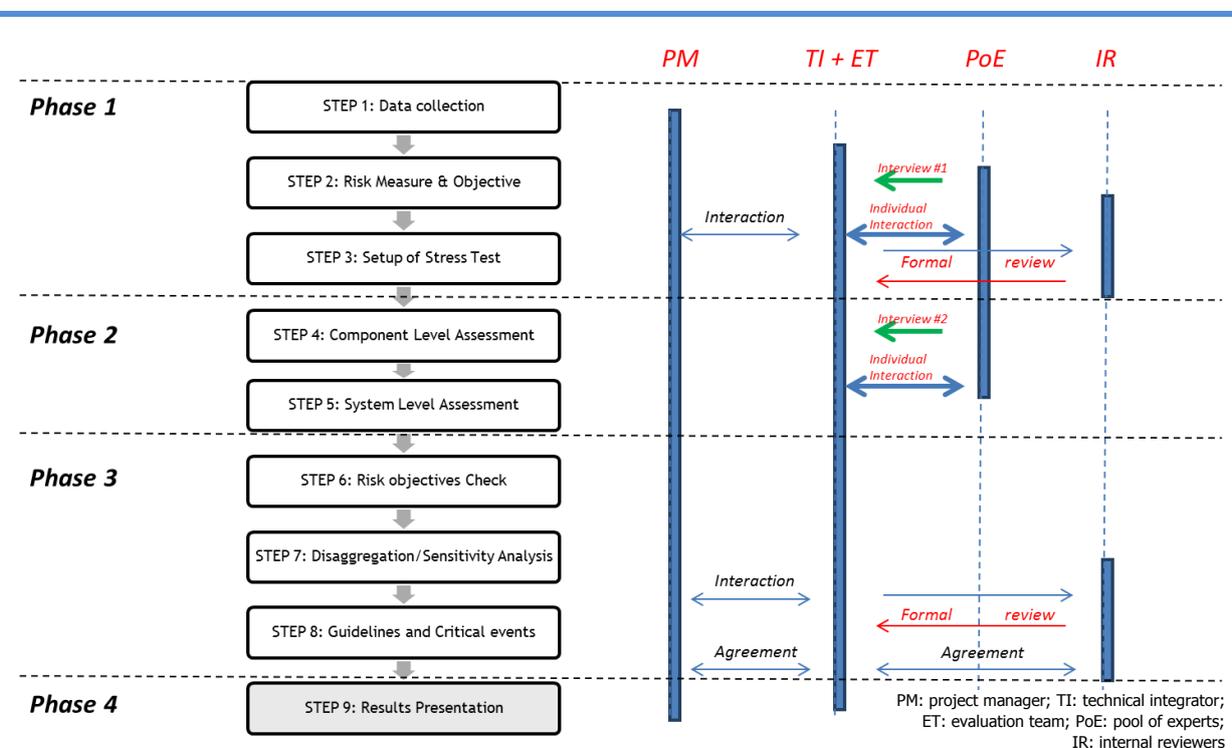
Finally, structural methods for probabilistic performance assessment in the case of state-dependent seismic damage accumulation were developed based on Markov chains. **Damage-dependent vulnerability** was also combined to earthquake clustering in Northern Italy and the impact on risk was investigated. In simple terms, the risk increases as additional physical processes are considered, such as event clustering and dynamic vulnerability.

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



DESIGNING STRESS TESTS FOR CRITICAL INFRASTRUCTURES

The engineering risk-based multi-level stress test, **ST@STREST**, that was developed in the project and applied in the exploratory applications, aims to enhance the procedures for evaluation of the risk exposure of critical non-nuclear infrastructures against natural hazards. To account for diverse types of infrastructures, the potential consequences 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.



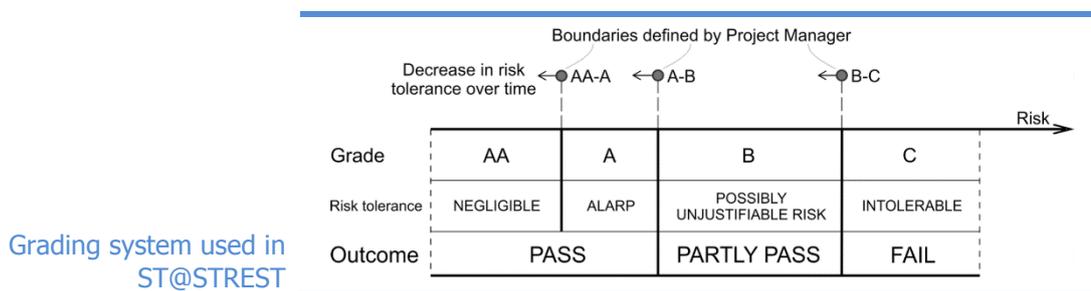
Workflow of the ST@STREST methodology and interaction among the main actors

The workflow of the stress test methodology includes four phases:

1. In the **Pre-Assessment Phase**, the data available on the critical infrastructure 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.
2. In the **Assessment Phase**, 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 critical infrastructure is performed (using, for

instance, the hazard and risk methods developed in STREST for the modelling of extreme events).

3. In the **Decision Phase**, results of the Assessment phase are compared to the risk objectives defined in the Pre-Assessment Phase. This comparison results in a grade that informs about the magnitude of the risk posed by the infrastructure, and, if the risk is unjustifiable or intolerable, how much the safety of the critical infrastructure 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.



4. In the **Report Phase**, 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.

Stress test levels

Due to the diversity of types of critical infrastructures and the potential consequence of failure, the types of hazards and the available resources for conducting the stress tests, it is not optimal to require the most general form of the stress test for all possible situations. Therefore, three stress test variants, termed Stress Test Levels (ST-Ls) are proposed:

- **Level 1 (ST-L1):** single-hazard component check;
- **Level 2 (ST-L2):** single-hazard system-wide risk assessment;
- **Level 3 (ST-L3):** multi-hazard system-wide risk assessment.

Within these levels, potentially different implementations are possible. The quantification of epistemic uncertainty may not be performed (sub-level a). If performed, it may be based either on the evaluations of a single expert (sub-level b) or of multiple experts (sub-level c). Complementary scenario-based analysis (sub-level d) may be performed.

EXPLORATORY APPLICATIONS TO CRITICAL INFRASTRUCTURES

Selection of sites for pilot study

In order to develop and test the harmonised methodologies, which can be implemented in practice, STREST worked together with critical infrastructure partners and applied the STREST methodology in six pilot sites deemed representative of three classes of critical infrastructures:

- 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;
- C** Distributed, multiple-site infrastructures with low individual impact but large collective impact or dependencies.

The selected critical infrastructures for the **exploratory applications** were:

- ENI/Kuwait oil refinery and petrochemical plant, Milazzo, Italy (CI-A1);
- Large dams in the Valais region of Switzerland (CI-A2);
- Baku-Tbilisi-Ceyhan hydrocarbon pipelines, Turkey (CI-B1);
- Gasunie national gas storage and distribution network, the Netherlands (CI-B2);
- Port infrastructures of Thessaloniki, Greece (CI-B3);
- Industrial district of the Tuscany Region, Italy (CI-C1).



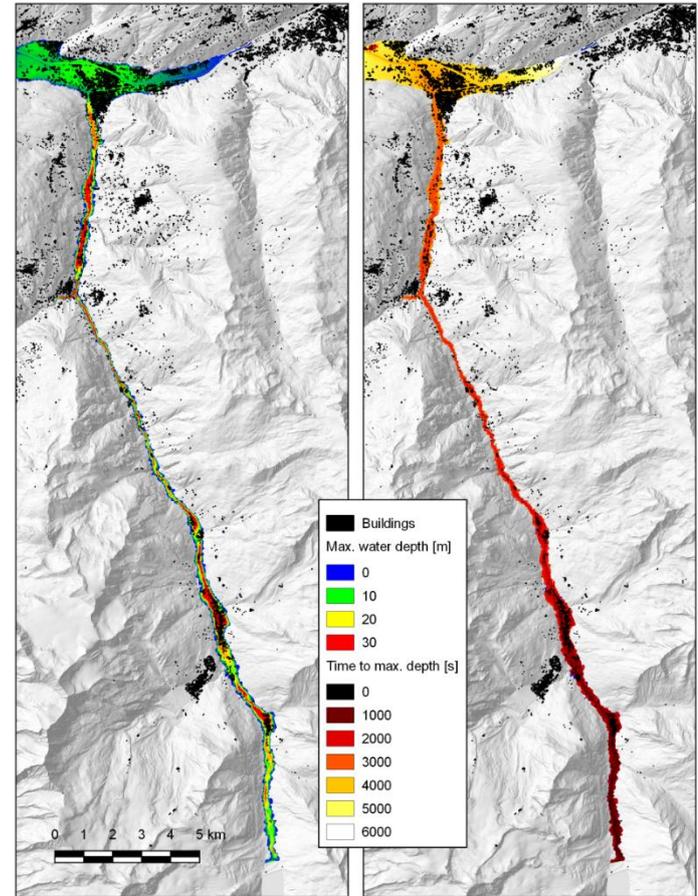
The table below combines all the obtained stress test grades for comparison not only of the risk posed by these critical infrastructures but also of the stress test levels used in these exploratory applications. Note that, while a significant effort was invested to develop the best possible stress test for each considered infrastructure, the obtained results do not reflect the actual safety or risk posed by these infrastructures, because the data considered in this project was limited for safety or business reasons. Therefore, these results should be read with due caution.

Stress test results in terms of grades by pilot site and level of detail

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	-	-	-	-	-	-

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

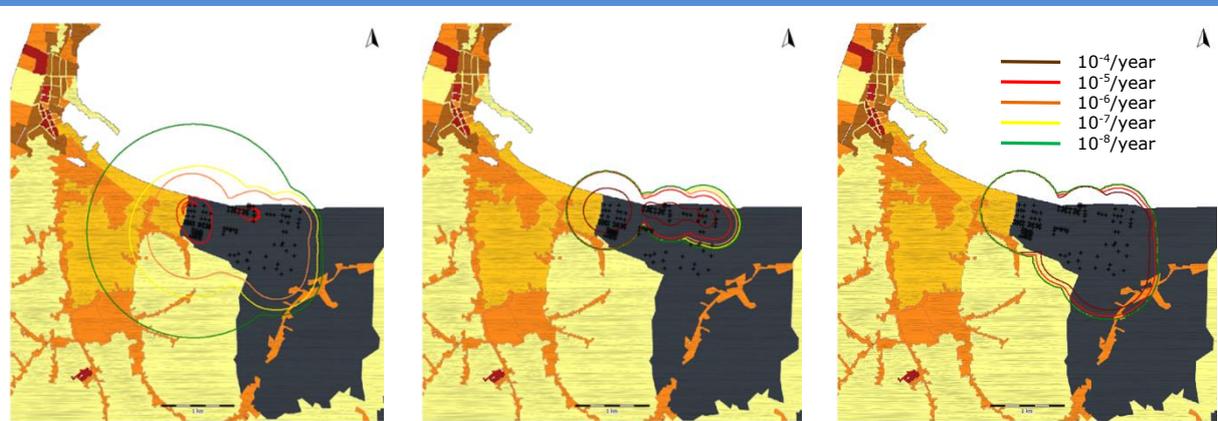
For a **conceptual dam system**, it was shown that accounting for component fragility functions and epistemic uncertainty affecting hazards, components, and their interactions, increased four-fold the frequency of failures (yet remaining, in the examined case, below existing dam safety margins). In order 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 can be used to plan which buildings at risk to reinforce, provide with shelters, or relocate.



Inundation resulting from overtopping of the conceptual-dam application

Quantitative risk assessment of the **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.

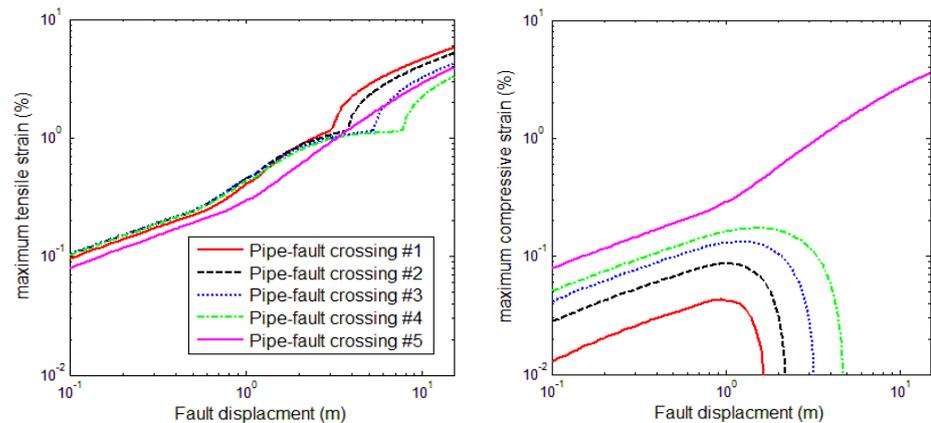


Risk contours for industrial (a), tsunami (b) and earthquake (c) risk in the petrochemical plant

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

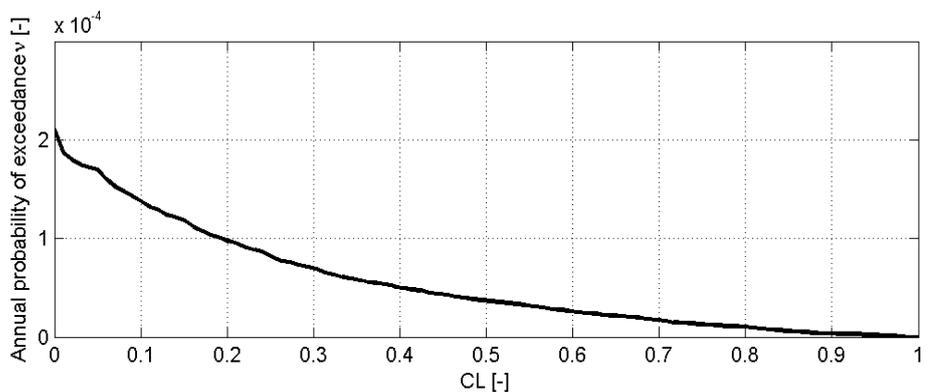
The stress test of the **oil pipeline** crossing five faults was performed considering the failure at the intersections as perfectly correlated or statistically independent and spotted the three most critical intersections to be retrofitted. The proposed change of the pipe-fault intersection angle reduced the probability of failure to less than 2% in 2475 years and the overall risk to negligible.

Maximum tensile (left) and compressive (right) pipe strains for the pipes at pipe-fault crossings for different intersection angles

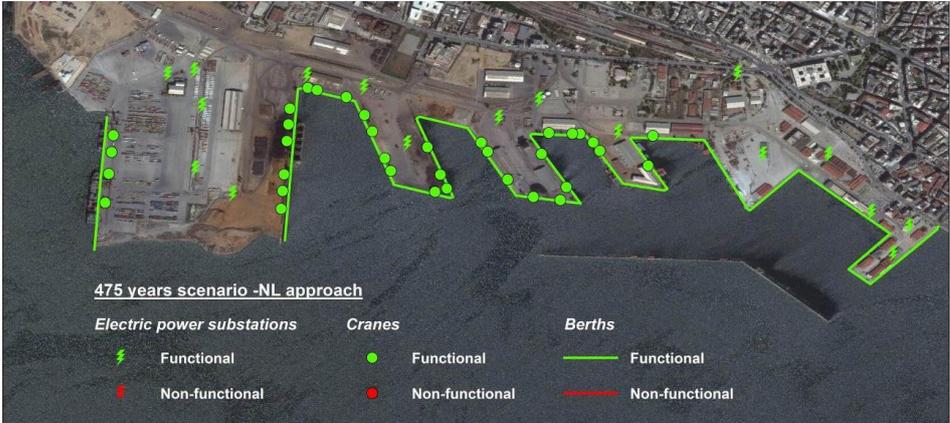
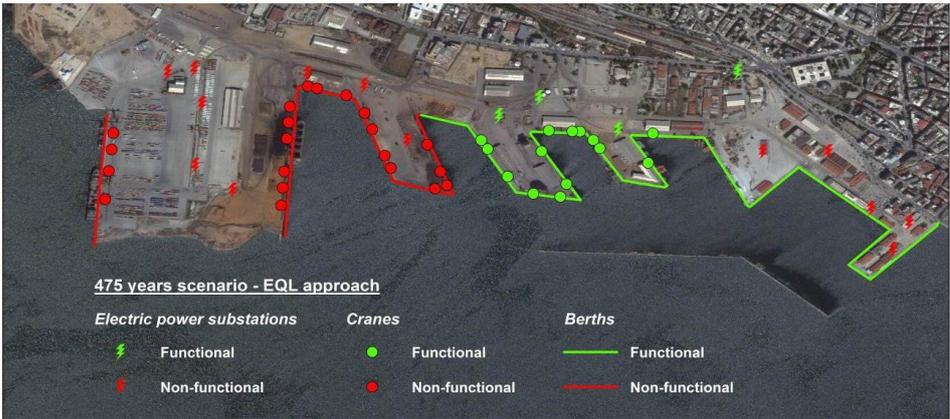


The stress test for a sub-network of the **Groningen field** in the Netherlands was performed using a risk-based approach for individual stations and pipe segments and a full probabilistic risk analysis with Monte Carlo simulations for the network analysis. Earthquakes induced by gas extraction were the main hazard source. The stress test results show 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.

Annual probability of exceedance of network connectivity loss (CL) of the natural gas distribution network



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 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.

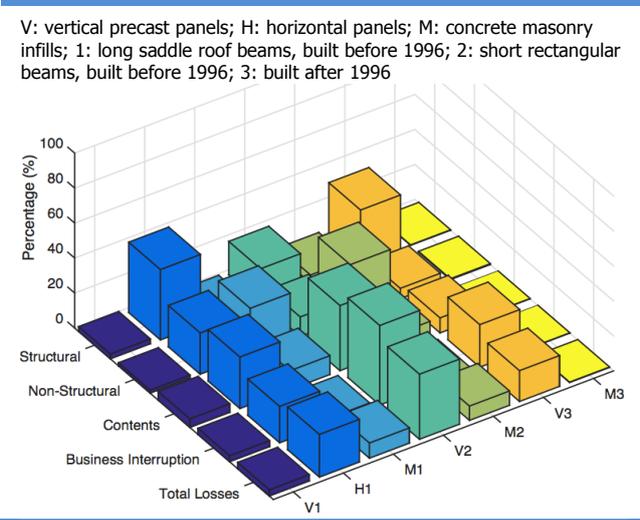


Functionality of components in the harbour application for an earthquake scenario with 475 years return period, for equivalent linear (top) and nonlinear analysis approach (bottom)

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. 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.

Disaggregation of average annual loss in the industrial district application, according to building sub-class for each component of loss



CLOSING REMARKS

Major achievements

STREST developed innovative **hazard models to include in stress tests** of non-nuclear critical infrastructures to tackle the problem of extreme events, with focus on large earthquakes, floods and domino effects. Epistemic uncertainties, cascade effects and inter-hazard interactions were considered.

The project also developed **fragility functions** for components of petrochemical plants, dams, harbours, gas/oil distribution networks and common industrial buildings with respect to earthquakes, floods and tsunamis, and demonstrated how these component fragilities can be integrated at the system level.

The engineering **risk-based multi-level stress test methodology** developed by STREST enhances the evaluation of the risk exposure of critical non-nuclear infrastructures against natural hazards. Each stress test level is characterised by a different scope and by a different complexity of the risk analysis. The outcome of a critical infrastructure stress test is a grade conveying where the risk is with respect to pre-determined risk acceptance criteria.

Exploratory applications to six critical infrastructures illustrated how the developed tools were able to identify extremes, disaggregate risks to specific hazards and component failures, and to support decision-making on cost-effective mitigation measures.

Impact

STREST seeks to improve the security and resilience of critical infrastructures against low-probability high-consequence natural hazards, in support of the implementation of the European policies for **disaster risk reduction** and the **protection of critical infrastructures**. The results contribute also to the Sendai Framework target for reducing disaster damage to critical infrastructures and to the UN Sustainable Development Goal for regional and transnational resilient infrastructures.

The knowledge, methodologies and tools produced by the project provide the basis for a master plan for the coordinated implementation of stress tests for classes of critical infrastructures and systems thereof. They are useful for owners and operators of CIs to

optimise maintenance, develop security plans and risk/vulnerability reports, and for authorities and urban planners to develop and update their **national risk assessments**.

The networking with key organisations and programs in the USA, Asia and Japan ensures the **international perspective**, harmonisation and knowledge transfer. **Clustering activities** with previous and on-going projects on related issues give added value to the European Framework Programme for research.

The long-term impacts refer to the reinforced European safety assessment capacity, improved and more reliable stress tests for critical infrastructures, support for decision-making and prioritisation of mitigation options and support for preparedness and communication, all leading to increased public acceptance of risk and societal **resilience**.

Recommendations

- 1. Include uncertainties, cascade effects, multiple hazards** in stress tests.
- Initiate a dialogue between European critical infrastructure operators, regulators and users to establish, where needed, and **harmonise the risk tolerance objectives**.
- 3. Investigate technical aspects** relevant to risk assessment of critical infrastructures:
i) loss data for model calibration; ii) fragility curves for loss of containment in components of petrochemical plants, for dam components and systems, for pipelines in case of liquefaction; and iii) cumulative damage and long-term degradation.
- 4. Promote the application of the methodology**, taking benefit of the exploratory applications on six European critical infrastructures.
- 5. Initiate the drafting of guidelines** for the application of harmonised stress tests, making use of the knowledge base and tools developed within STREST.
- 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, in the development of guidelines.

SCIENTIFIC PUBLICATIONS

Peer-reviewed articles

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15. Trevelopoulos, K. and P. Guéguen (2016), Period elongation-based framework for operative assessment of the variation of seismic vulnerability of reinforced concrete buildings during aftershock sequences, *Soil Dynamics and Earthquake Engineering*, doi: 10.1016/j.soildyn.2016.02.009
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1. State-of-the-art and lessons learned from advanced safety studies and stress-tests for critical infrastructures
2. Guidelines for harmonized hazard assessment for low-probability and high-consequence events
3. Guidelines for harmonized vulnerability and risk assessment for non-nuclear critical infrastructures
4. Guidelines for stress-test design for non-nuclear critical infrastructures and systems: Methodology
5. Guidelines for stress-test design for non-nuclear critical infrastructures and systems: Applications
6. STREST project policy brief

The STREST project produced more than 30 deliverables, including the six Reference Reports, which are available to download from the Results section of the project website: www.strest-eu.org.

CONSORTIUM



Partner institutions

The STREST Consortium has a broad and diverse expertise in hazard and risk assessment, as well as in stress test procedures, making it a solid and dynamic team for the purpose of the project. The STREST Consortium includes key organizations and specialists, securing specific strengths covering all the required important expertise.

- Eidgenössische 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, Greece;
- Kandilli Observatory and Earthquake Research Institute – KOERI, Turkey;
- Ljubljana University, Slovenia;
- Joint Research Centre – JRC, Belgium.

Associated Industry Partners

The Board of Associated Industry Partners is 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;
- 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;
- Regione Toscana, Italy.

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