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Guidelines for harmonized hazard assessment for LP-HC events

STREST Reference Report 2

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SEVENTH FRAMEWORK PROGRAMME

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Abstract

This report describes the main conclusions of the STREST project (and associated guidelines) to evaluate hazard of Low-Probability High-Consequences (LP-HC) events used to define stress tests for non-nuclear Critical Infrastructures (CIs). Several new approaches have been developed to assess these extreme hazard scenarios and to evaluate the associated uncertainties.

This report presents a summary of the developments, results and products issued from Work Package 3 (WP3) of STREST. It is given as a set of "recommendations" for potential users responsible of the estimation of hazard for a particular non-nuclear CI in the European Union and other countries. The methods and guidelines are dedicated to two different target-users: project managers and hazard experts.

It poses the main differences with a traditional Probabilistic Hazard Assessment analysis, the benefits and extra challenges, and the particular information requirements for the three selected infrastructure classes covered in STREST.

In a simple and understandable manner, it summarizes the principal available tools, the main references and the application examples issued from the project in order to help the users in the realization of theirs studies.

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1. Introduction

The 2010 Tohoku (Japan) earthquake and tsunami that triggered the Fukushima power plant disaster recalled emergency planers, decision makers, stakeholders and the entire community that these infrastructures present an ever-evolving risk to modern societies. The nuclear industry has developed and improved tools to evaluate the hazards and assess the risk of their power plants. Among the most important tools are the stress tests, designed to test the vulnerability and resilience of the nuclear infrastructures.

However, these tests are often too complex and costly to be applied to other infrastructures that are also critical, since damage or failure of their structures or components can potentially have important socioeconomics effects at a regional or even global scale. In order to mitigate this risk and increase resilience to natural hazards, improved and standardized tools for hazard and risk assessment are required, together with a systematic application of these new tools to various classes of CIs.

With this idea in mind, WP3 of the STREST project aimed on developing innovative approaches for the hazard evaluation to be used for the risk assessments of non-nuclear CIs. The three selected infrastructure classes in the project are:

- A - Individual, single-site infrastructures with high risk and high potential impacts at a regional or global scale;
- B - Distributed and/or geographically-extended infrastructures with potentially high economic and environmental impacts;
- C - Distributed, multiple-site infrastructures with low individual impact but large collective impact or dependencies.

Due to the inherent characteristics and risks associated to these kinds of infrastructures, these analyses must go beyond the classical Probabilistic Hazard Assessment (PHA).

Particularly, they should include the assessment of "unlikely" (rare) events, i.e. events with a low probability of occurrence that can produce significant unwanted consequences due to damage in a CI. Assessing these LP-HC events presents several challenges compared to conventional PHA, particularly related to the scarcity of data on extreme events and the handling of the associated uncertainties.

In addition, these stress tests should incorporate the analysis of potential "cascades" of events from natural hazard correlations usually not considered in PHA (e.g., earthquakes triggering other earthquakes, tsunamis or landslides).

The main goal of this report is to present these differences, challenges and benefits and to summarize guidelines to tackle them affordably and effectively. This will guide new stress tests hazard studies in the short term and facilitate the appropriate data collection, the monitoring or investigations which might help better assessing (when possible, reducing) the uncertainties for future analyses in the long term.

In the first part of this report a summary table is presented which recapitulates the key developments, available tools and databases and the application examples of the STREST project. The second part lists and describes these developments in a simple and understandable way, together with the main references in order to guide potential users responsible of the hazard assessments for their respective CIs. For more detailed information the reader is directed to the corresponding documents.

2. Multi-hazard assessment of low-probability-high-consequences events

2.1 Summary tables

The estimation of hazard to be used for the risk assessment of a CI must include the analysis of extreme events, i.e., those events having a low probability of occurrence but potentially large impacts on the infrastructures. Table 2.1 is directed to the managers in charge of the project and Table 2.2 to the hazard experts. These tables recapitulate the different developments and results issued from the STREST project. The main available tools, references and application examples are also presented. In addition, the particular application to each type of infrastructure is proposed.

The STREST project considered the following hazards: earthquake shaking, surface fault rupture, tsunami and flooding (Table 2.3). New guidelines in uncertainty assessment apply to all hazards while most site-specific models apply to earthquakes only. Flooding is only considered in the case of overtopping at dams, limiting the STREST findings to this specific type of infrastructure. All other processes considered in STREST may apply to any type of CI (including gas and oil pipelines, petrochemical plants, harbors, industrial districts, etc.).

Table 2.1 For project operator / manager. Summary of new developments, guidelines, references and application examples for the hazard assessment in the risk evaluation of critical infrastructures issued from the STREST project

For project operator / manager					
Infrastructure Type	**Challenges compared to classical PHA**	**New developments. Solutions**	**Developed / Available tools**	**Useful references**	**Application examples in STREST**
All types	Selection of participants and stress test level Procedural guidance	EU@STREST process Multiple Expert Integration	Guidelines	STREST D 3.1	-
All types	Reduction of uncertainties in seismic hazard assessment	Monitoring Soil profiles Fault studies	Guidelines	STREST D 3.4	-
All types	Reduction of uncertainties in tsunami hazard assessment	Bathymetry	Guidelines	STREST D 3.4	-

Table 2.2 For hazard experts. Summary of new developments, tools and references and application examples for the hazard assessment in the risk evaluation of critical infrastructures issued from WP3 of the STREST project

For Hazard Experts							
Challenges compared to classical PHA	**New developments**	**Available tools and databases**	**Useful References**	**Application and examples**	**Infrastructure type**		
					A	**B**	**C**
Procedure to organize experts interactions and the review process	EU@STREST procedural guidance	Guidelines, forms and questionnaires	STREST D 3.1	Port infrastructure, Thessaloniki	✓	✓	✓
Inclusion of low probability (unlikely) events. Full exploration of epistemic uncertainty	EU@STREST treatment of epistemic uncertainty	Guidelines, forms and questionnaires	STREST D 3.1 Marzocchi et al (2015)	Gas storage & distribution network, Netherlands Port infrastructure, Thessaloniki	✓	✓	✓
Multi-hazard assessments and analysis of potential "cascades" of events from natural hazard correlations	Multi-hazard and multi-risk assessment method. Methods to prioritize natural hazards Generic multi-risk framework (genMR)	Forms and questionnaires (Hazard correlation matrix)	STREST D 3.5 Mignan et al (in press) Mignan et al (2014) MATRIX project	Large dams, Switzerland (A2). Gas storage & distribution network, Netherlands Port infrastructure, Thessaloniki Industrial district, Italy	✓	✓	✓
Inclusion of detailed tsunami hazard assessment and exploration of epistemic uncertainty	Refined methodology to reduce computational cost allowing a full quantification of epistemic uncertainties	Guidelines	Lorito et al (2015) Selva et al (2016) STREST D 3.4 STREST D 3.7	Oil refinery & petrochemical plant, Milazzo Port infrastructure, Thessaloniki	✓	✓	✓
Inclusion of specific site analysis in PSHA	Comparisons of methods Host to target adjustments Non-ergodic PSHA	Guidelines	STREST D 3.4	Oil refinery & petrochemical plant, Milazzo Port infrastructure, Thessaloniki Euroseistest	✓	✓	✓
Near fault hazard assessment	Assessment of near-source directivity effects	OpenQuake-engine	Baltzopoulos et al (2013, 2015) STREST D 3.3	Oil refinery & petrochemical plant, Milazzo Major hydrocarbon pipelines, Turkey	✓	✓	✓

Inclusion of fault permanent displacement	Probabilistic fault permanent displacement hazard using Monte-Carlo simulations techniques	Matlab routines	STREST D 3.2 Chen and Akkar (2015)	Major hydrocarbon pipelines, Turkey	✓	✓	✓
Spatial variability of ground motion assessment	Monte-Carlo simulations techniques for computing dynamic ground-motion intensity measures	OpenQuake-engine (ePSHA workflow) Matlab routines	STREST D 3.2 Chen and Akkar (2015)	Major hydrocarbon pipelines, Turkey Port infrastructure, Thessaloniki Industrial district, Italy		✓	✓
Spectral period cross-correlation assessment	Magnitude-dependent cross-correlation coefficients	Coefficients for Europe	STREST D 3.7 Kotha et al. 2016a	Oil refinery & petrochemical plant, Milazzo	✓	✓	✓
Earthquake rupture propagation analysis (maximum magnitude)	Algorithm to estimate M_{max} due to rupture propagation using dynamic stress considerations	Algorithm in appendix of Mignan et al (2015)	STREST D 3.5 Mignan et al (2015)	Anatolian Peninsula	✓	✓	✓
Inclusion of potential human-induced hazards (induced seismicity)	Induced seismicity PSHA	OpenQuake-engine	STREST 3.6	Gas storage & distribution network, Netherlands	✓	✓	✓

Table 2.3 Natural hazards included in STREST and the application of new developments

Perils	**New developments and guidelines**		
	Stochastic (uncertainties)	**Site-Specific**	**Physical (interaction)**
Earthquake	✓	✓	✓
Surface fault rupture	✓	✓	
Tsunami	✓	✓	✓
Flood	✓		✓

As it is described in these tables, many developments for seismic hazard evaluation have been implemented on the OpenQuake-engine developed by the Global Earthquake Model foundation (GEM).

The GEM foundation is a public-private partnership that drives a global collaborative effort to develop resources for transparent assessment of earthquake risk and to facilitate their application for risk management around the globe (GEM site – www.globalquakemodel.org). GEM developed (starting in 2009) an open-source software named OpenQuake (www.openquake.org), for estimating seismic hazard and losses.

OpenQuake-engine includes four main modules or calculators (Silva et al 2014):

- M1: a scenario risk and a scenario damage calculators;

- M2: a probabilistic event-based risk calculator;
- M3: a classical PSHA-based risk calculator;
- M4: a retrofitting benefit-cost ratio calculator.

Exposure-related data is stored in what is called the Global Exposure Database (GED) (Vinay et al 2013), which provides a spatial inventory of exposed assets for the purposes of catastrophe modelling and loss estimation.

Since GEM is a global collaborative project developing open-source tools to evaluate seismic risk, the OpenQuake tool is becoming relevant for hazard experts internationally (as well as risk analysts).

Including the new developments of the STREST project directly in an increasingly used tool is therefore very convenient.

2.2 Description of main developments and guidelines

In this section the approaches developed in WP3 are briefly described. These descriptions serve as recommendations for the hazard assessments in stress tests for all different CIs. The reader is directed to the detailed documents where precise information is available. Fig. *2.1* shows the locations of CIs selected to test these new methods and apply these guidelines.

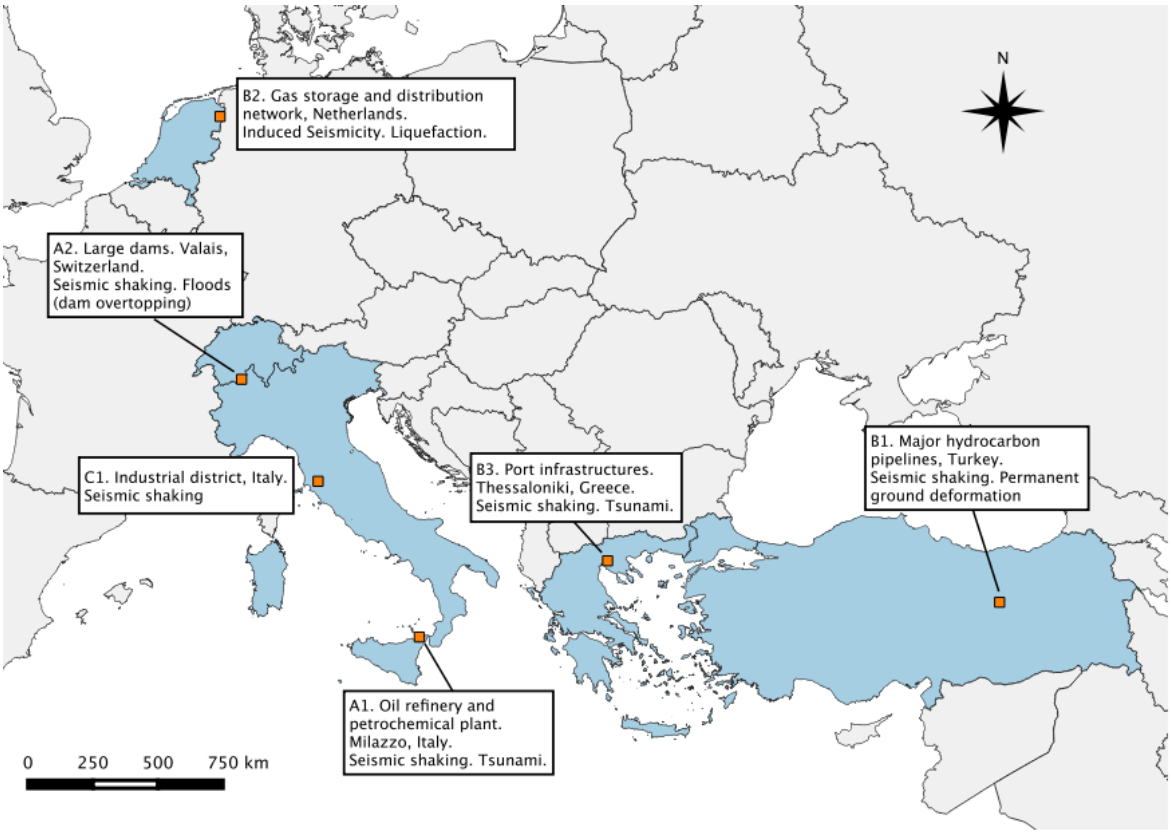


Fig. 2.1 Location of Critical Infrastructures selected by the STREST project and associated hazard evaluation methods and guidelines developed by the project

2.2.1 EU@STREST process (epistemic uncertainty in STREST)

The lack of available data on extreme events requires a full exploration of the epistemic uncertainties. EU@STREST is a coherent process to ensure an improved, standardized

and robust management of this uncertainty within a project aimed to perform a stress test.

The process deals with the uncertainty emerging from the hazard selection, the implementation of alternative models and the exploration of the tails of distributions. It also takes into account the different views and opinions of the involved experts and the potential budget limitation of stress tests for non-nuclear CIs.

EU@STREST defines a general framework for the assessment of these uncertainties in order to increase the reliability of stress test results. The treatment and quantification is usually performed by means of well-known methods like Logic Trees (LT) and Bayesian/Ensemble Approach (BEA) (Marzocchi et al 2015).

It is important however that these results do not depend on specific subjective choices of the practitioner performing the assessment. In order to avoid an a priori control of the results, it is required that a minimum level of involvement of multiple experts is guaranteed both in setting up the methodological framework of the study and in performing the calculations. The quantification of epistemic uncertainties should not be dependent on a specific analyst (it must be objective).

Due to budget limitations, the inclusion of a very large number of experts is generally not conceivable. Based on different expert judgment techniques (Classical Expert Elicitation – cEE – and Multiple Expert Integration – MEI), the process guarantees the minimum required level of involvement of multiple experts from the community and accounting for this economical limitation of stress tests.

EU@STREST follows the state-of-the-art methodological and procedural guidance from ENSREG (European Nuclear Safety Regulation Group) (ENSERG, 2013) and IAEA (International Atomic Energy Agency) (see: http://www-ns.iaea.org/standars/). The participants playing a core role in the process are: (i) the Technical Integrator team (TI), (ii) the Review Panel (RP), and (iii) the Panel of Experts (PoE). With the goals of transparency, independence between the participants and responsibility during the stress tests, the process is divided in four main stages: Phase 0: Preparation, Phase 1: Evaluation, Phase 2: Integration, and Phase 3: Finalization.

Guidelines, forms and questionnaires are available in Deliverable D 3.1 and the reader is directed to that document for further details.

In terms of the selection of hazards and hazardous phenomena to be included in the analysis, regulatory concerns and available sources in the nuclear sector might allow considering the treatment of most of the hazards, but it might not be possible in the non-nuclear sector due to low regulatory concerns and available funding. It is then imperative to prioritize the natural hazards/phenomena of interest. In this regard, a multi-hazard and multi-risk assessment method is presented in WP3 of STREST, built upon results from the MATRIX project (Mignan et al 2014) and developed further here (Matos et al 2015; Mignan et al 2016; in press) (see also Section 2.2.2 below).

2.2.2 Analysis of cascading events and multi-hazard probabilistic scenarios

Many analyses of natural hazards take a single-hazard approach, treating hazards as being separate and independent. Past experiences have shown however that natural hazard interaction as well as other cascading effects can have a major impact. These interactions may lead to “domino effects” where an initial event will trigger a chain of additional hazardous events. Many examples exist through history.

Due to the population growth, the rising concentration of economics assets and people living in urban areas and the high level of interconnection and complexity in modern society networks, multi-hazard assessment becomes fundamental for risk mitigation.

CIs being a vital component of societies, the analysis of potential cascading effects is required when performing stress tests. In order to do it, a generic multi-risk framework (genMR) has been proposed in the scope of the New Multi-Hazard and Multi-Risk Assessment Methods for Europe (MATRIX) project (Mignan et al 2014) and further developed in STREST (Matos et al 2015; Mignan et al 2016; in press). The aim of genMR is to help better understanding the different aspects of multi-hazard and multi-risk, to define a common terminology and to guide the integration of knowledge from various types of models into the same framework. The methodology is based on the sequential Monte Carlo method and on a variant of a Markov chain to simulate cascading event scenarios.

In this project focus was made on three types of hazard interactions: (1) "intra-event" earthquake triggering to evaluate the maximum magnitude Mmax of cascading fault ruptures (Mignan et al 2015), (2) "intra-hazard" earthquake triggering to evaluate earthquake spatio-temporal clustering (i.e., large aftershocks) (Mignan et al in press) and (3) various "inter-hazard" interactions at dams (impact of earthquakes, floods, internal erosion, and malfunctions on dam and foundation, spillway, bottom outlet and hydropower system) (Matos et al 2015).

The Hazard correlation matrix (HCM) is part of the GenMR framework and can be used as a form/questionnaire to generate multi-hazard scenarios (Mignan et al 2016). An algorithm to estimate Mmax due to rupture propagation is presented in appendix of Mignan et al (2015) (see also Deliverable 3.5).

2.2.3 Near-fault seismic hazard assessment

Near the source of earthquakes (relative to the rupture's size) the seismic demand can be systematically different and larger than that of so-called ordinary records, which accordingly affect the structural response of constructions. These phenomena are generally called as near-source (NS) effects.

NS seismic effects include, among others, forward-directivity. This effect is a constructive interference of waves that delivers in preferential directions most of the seismic energy in a single pulse-like ground motions at low frequency, which is very detrimental for structures.

If critical structures are close to active faults, a particular attention is required due to these NS effects.

In NS conditions both ground motion and seismic structural response may show systematic spatial variability, which classical Probabilistic Seismic Hazard Assessment (PSHA) is not able to explicitly capture. The STREST project presents a framework and new guidelines for taking forward-directivity into account in PSHA (i.e., NS-PSHA) and non-linear static procedures with respect to the inelastic demand associated with forward-directivity.

In this context, a methodology is presented for the implementation of the Displacement Coefficient Method (DCM) towards estimating NS seismic demand, by making use of the results of NS-PSHA and a semi-empirical equation for NS-FD inelastic displacement ratio.

Application of the proposed approach showed that forward-directivity could have an important impact on near-source structural demand, which corroborates the need of this analysis for CIs located near active seismic faults.

The reader is directed to Baltzopoulos et al (2014) for further details.

Near-fault ground-motion databases are however still rather poor. Because of this lack of data, the understanding of near fault shaking effects (e.g. hanging wall effects, high frequency directivity effects) needs to be improved. New methods used to evaluate these near-fault effects will then be developed and it is recommended to carefully take into

account these future new developments. Most of the new methods will likely be implemented within the OpenQuake software.

2.2.4 Spatial variability of ground motion and fault permanent displacement

When performing stress tests and seismic hazard analyses for distributed and/or geographically extended infrastructures or lifeline systems, several particular aspects of the ground motion behaviour need to be accounted for.

For these infrastructures types (B and C), the consideration of site-to-site variation (spatial correlation) in dynamic ground motion intensity measures (GMIMs) (e.g., PGA, Sa) is important for realistic probabilistic seismic hazard and risk assessment. The interdependency between the GMIMs (cross-correlation) is also relevant for such structural systems because the vulnerability of some of their components is sensitive to the conditional occurrence of multiple GMIMs. In addition to these two phenomena, the proper amplitude estimations of static (permanent fault displacement) and dynamic GMIMs are crucial for geographically distributed buildings or geographically extended lifelines located in the close proximity to fault segments.

Monte Carlo (MC) simulation techniques have become appealing in probabilistic hazard and risk calculations as an alternative to conventional PSHA. They provide some flexibility, transparency and robustness to the consideration of above stated physical models.

Deliverable D3.2 provides the theory and application of MC simulation technique for probabilistic seismic hazard assessment of geographically distributed and extended structural systems. The methodology uses multi-scale random fields (MSRFs) technique to incorporate spatial correlation and near-fault directivity while generating MC simulations to assess the probabilistic seismic hazard of dynamic GMIMs.

The MC-based simulations are also implemented to permanent fault displacement hazard by using the model provided in Petersen et al (2011). The implementation of MC simulations for permanent fault displacement hazard accounts for surface rupture, mapping accuracy and occurrence probabilities of on- and off-fault displacements.

These steps are implemented via a suite of codes developed on the MATLAB™ platform. The spatial variability of ground motion assessment has been implemented in the open-source code for probabilistic seismic hazard and risk analysis OpenQuake-engine (ePSHA workflow).

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 (Giorgio and Iervolino, 2016).

2.2.5 Human-induced hazards (induced seismicity)

In recent years, the increased occurrence of induced seismicity has heightened public concern. Induced earthquakes can now occur in regions where little or no natural seismicity was expected. In those regions, the building stock is usually more vulnerable, since no earthquake design rules were to be applied. This seismicity, due to a wide range of anthropogenic activities such as fluid injection and extraction, hydraulic fracturing and mining, can have an important impact on the built environment (Bommer et al 2015).

Within the STREST project, the open-source code for probabilistic seismic hazard and risk analysis OpenQuake-Engine has been adapted for application to induced seismicity hazard.

The work adapts OpenQuake to produce a Monte Carlo based probabilistic seismic hazard assessment in which the rate, location and magnitude of the earthquakes vary in

response to a dynamically changing pressure field. In the present implementation this adopts the approach of geomechanical seed model proposed by Goertz-Allmann & Wiemer (2013) and Gischig & Wiemer (2013).

Within these adaptations, some were largely centred upon the implementation of several new ground-motion models, developed specifically for induced seismicity applications and into adapting the engine for a Geomechanical Seed Model Seismic Hazard Calculation (Deliverable 3.5).

The open source tool is already available.

2.2.6 Site-specific PSHA

Seismic site effects are related to the modification of seismic waves (e.g., amplitudes, durations) in the superficial layers due to local geological or topographical conditions. These variations can strongly influence the nature and severity of shaking at a given site.

It is therefore essential to assess these local effects for any CI since the damages due to an earthquake may be locally aggravated. The degree of complexity (and associated necessary funding) of available site effects evaluation methods is however highly variable.

STREST presents different approaches and guidelines for the consideration of site effects with an increasing level of detail and complexity.

Levels 0 or 0.5 are generic or partially site-specific methodologies where the site effect is taken into account by proxy and correction factors based on the direct use of the site amplification defined within the Ground Motion Prediction Equations (GMPE) (usually Vs30) or a posteriori modification of the site term using Site Amplification Prediction Equations (SAPE). Generic simplified approaches are usually used for regional hazard assessments and are then not recommended for CI hazard estimation. The STREST results show that the main drawback of these approaches, from a safety concern, is the risk to severely underestimate the specific amplification of the site under study (Deliverable 3.4).

For Levels 1 or 2, the whole amplification complexity is studied in the hazard definition. They are based on a complete consideration of the local site response and relative uncertainties. These approaches require therefore, a detailed characterisation of sites and also need host-to-target adjustments.

They may be based on an instrumental approach where seismological instrumentation on the site and its vicinity measures and records ground motions from “real” earthquakes, allowing the implementation of empirical models.

The amplification or the resulting site-specific ground motion can also be assessed through a numerical simulation of the wave propagation phenomena occurring in the site. A linear simulation is recommended for the simpler local geology and moderate seismic activity, but numerical simulations allow the consideration of “extreme” cases going much beyond the soil linear behaviour. For those cases, the use of non-linear simulation is the only way to estimate the modifications of site response linked with soil non-linearity.

Of course, the level of complexity of characterization/instrumentation depends on the choice of site effect evaluation method, but characterization/instrumentation is also mandatory to get the minimum information to help on the choice of site evaluation method itself, the whole process is therefore iterative. In-situ instrumentation provides an invaluable feedback.

2.2.7 Site-specific tsunami hazard assessment

A site-specific Probabilistic Tsunami Hazard Assessment (PTHA) involves a very heavy computational effort since it encompasses the production of a full source-to-site numerical tsunami simulation on a high-resolution digital elevation model for each and every potential source scenario considered. In the case of earthquake-induced tsunamis (SPTHA) the computational burden is heavily increased since both local and distant sources, as well as the full aleatory variability of the seismic source, must be taken into account. At the same time, the analysis of the epistemic uncertainties becomes critical.

The STREST developments include a refined methodology to reduce the computational cost, which allows a full quantification of epistemic uncertainties.

The procedure is based on the approach by Lorito et al (2015). This methodology allows a significant and consistent reduction of the epistemic uncertainty associated to probabilistic inundation maps, as it balances between the completeness of the earthquake model and the computational feasibility. It allows in fact performing high-resolution inundation simulations on realistic topo-bathymetry only for the relevant seismic sources.

The Lorito et al (2015) method is included into an ensemble modelling approach (Marzocchi et al 2015, D 3.1), allowing a full quantification of epistemic uncertainty.

3. Conclusions and key recommendations

Due to the large regional or even global socioeconomics impacts that could potentially derive from damage to critical infrastructures, the hazard assessment of low-probability-high-consequences events, to be considered in the risk analysis of these structures (stress tests), needs to go beyond a classical probabilistic hazard assessment. These studies increase in complexity and involve a somehow large team of experts. The detailed evaluation of epistemic uncertainties becomes also fundamental for the validation and coherency of the results. At the same time, these analyses need to be simpler, cheaper and less time consuming than the stress tests prepared for the nuclear industry.

This report presented the new developments and guidelines issued from the STREST project. The main challenges compared to a classical probabilistic hazard assessment were detailed. The new developments and the available tools were simply described in order to guide the person in charge of the hazard assessment for a non-nuclear critical infrastructure in Europe and other countries. The reader was directed to the corresponding documents and references for detailed descriptions of each particular assessment. This document may also give a starting point, with a simple and clear overview, of the analyses that need to be carried on for the hazard assessments of critical infrastructures. Four key recommendations have been identified.

3.1 Recommendation 1: Epistemic uncertainties need to be evaluated

STREST site-specific hazard case studies show that epistemic uncertainties remain large (Fig. *3.1*). New computation schemes give a new opportunity to reduce computation costs (even for physics-based site-specific hazard evaluation) and perform sensitivity analysis. These sensitivity analyses are important to identify key model input parameters and explore the associated uncertainties.

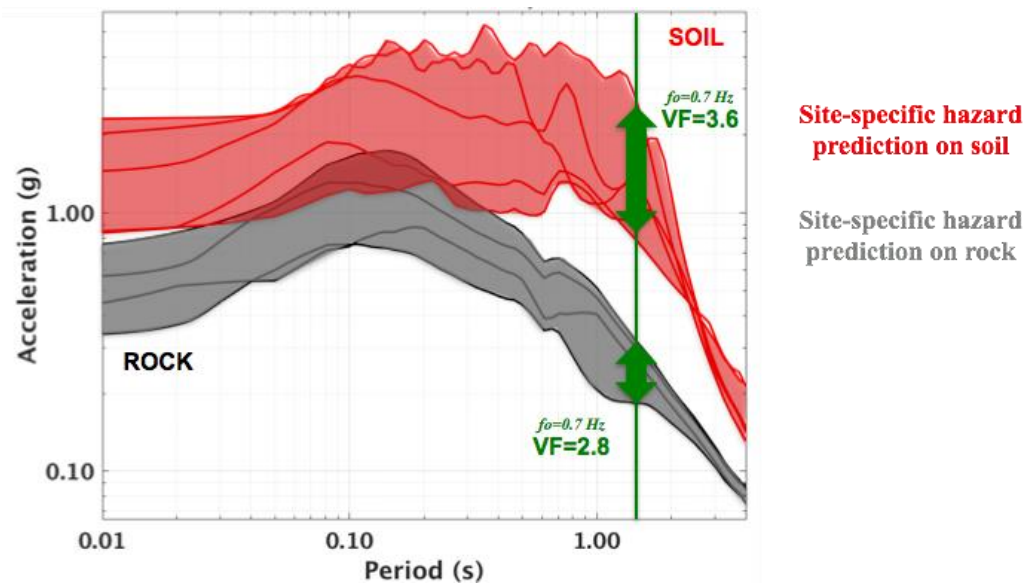


Fig. 3.1 Site-specific hazard predictions (5000 years return period Uniform Hazard spectrum, Euroseistest, Greece). Four different methods (red and gray lines) have been used to predict the rock and soil site-specific hazards. The red and gray areas illustrate the large epistemic uncertainties of the predictions (STREST deliverable 3.4)

STREST provides a multiple-expert integration process for managing epistemic uncertainties. The STREST results show that to guarantee robust results while reducing

the financial costs of stress tests, a smart combination of more than one method to assess epistemic uncertainties must be discussed: (i) multiple-expert procedures, required to guarantee results applicable for regulatory concerns, (ii) logic trees or Bayesian/ensemble approaches, and (iii) classical expert elicitation, to prioritize actions in stress tests.

3.2 Recommendation 2: Cascading effects and integrated multihazard assesments need to be taken into account

Several STREST test cases show the needs to consider cascading effects for CI's hazard studies and perform integrated multi-hazard studies:

- The maximum magnitude M_{max} in Turkey increases from 8.1 to ~8.5, once fault rupture cascading is considered, which may have an impact on pipeline stress tests (Mignan et al 2015; Fig. *3.2*).
- In the case of strong earthquake clustering in Northern Italy, it has been shown that the risk migrates towards lower-probabilities–higher-consequences risk scenarios (Mignan et al in press).
- The coherency between seismic and tsunami hazard analyses needs to be granted as well as much as possible, through the coherency between the seismic source databases used.

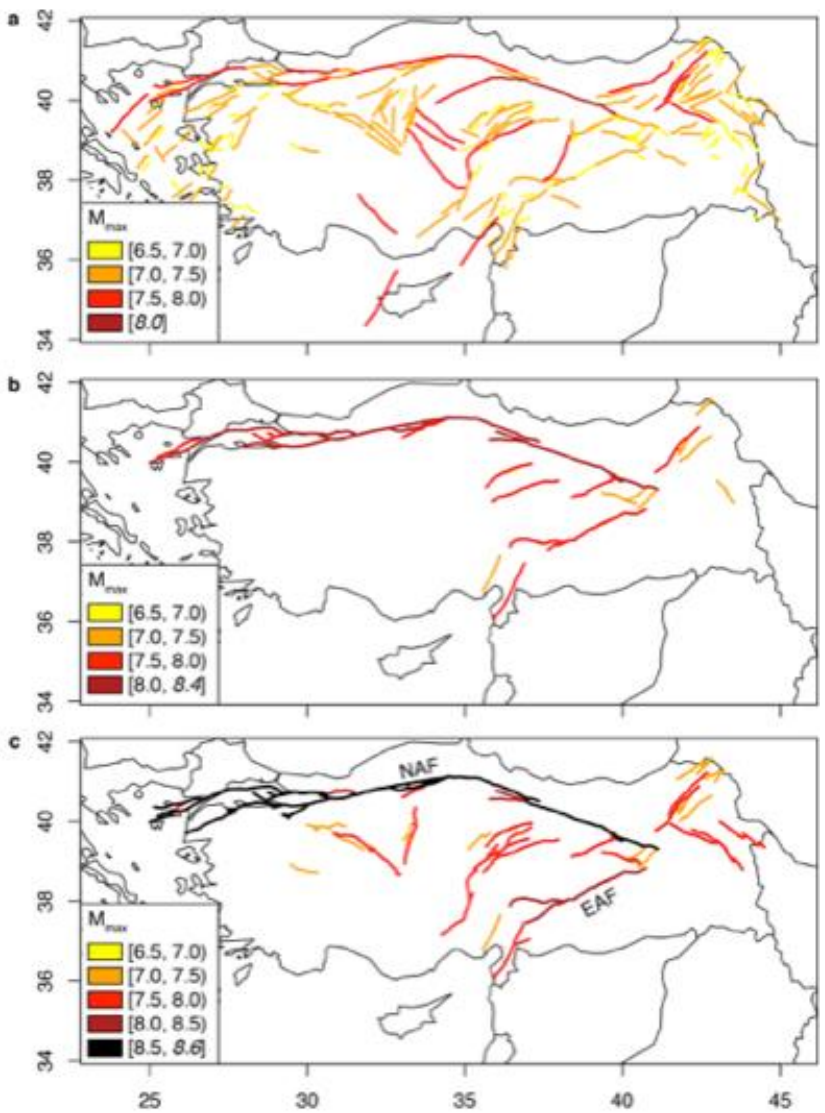


Fig. 3.2 The maximum magnitude Mmax in Turkey increases from 8.1 to ~8.5, once fault rupture cascading (bottom) is considered (Mignan et al 2015)

3.3 Recommendation 3: Consider Near-faults effects

The STREST results show the needs to consider carefully near-fault effects:

- The permanent fault displacements for the designated pipe performance levels will be the result of very rare events for continuous pipelines crossing the fault segments closer to their edges. Relatively more frequent earthquakes should be of concern for performance evaluation of continuous pipelines when their fault crossings are more likely to occur at the middle portion of fault segments.
- Results of Near-Source Probabilistic Seismic Hazard Analysis confirm that forward directivity could have an important impact on near-source structural demand.
- The STREST results (Milazzo and Istanbul site studies) show that near-fault/site geometries may have a large impact on hazard. Precise fault geometries are needed to reduce the uncertainties.

3.4 Recommendation 4: On site monitoring is essential

STREST clearly shows the importance of performing site-specific hazard analysis for CIs. A systematic comparison of site specific (Level 1a according to Deliverable 3.4) and non-specific hazard assessment (Level 0 according to Deliverable 3.4) has been performed for 80 sites in Europe (Kotha et al 2016b). The results (Fig. *3.3*) show that differences as large as 50% are observed.

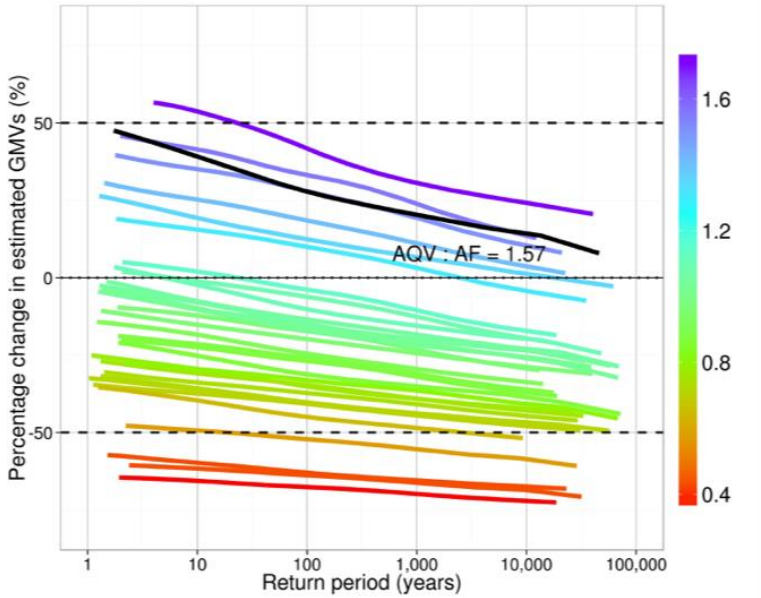
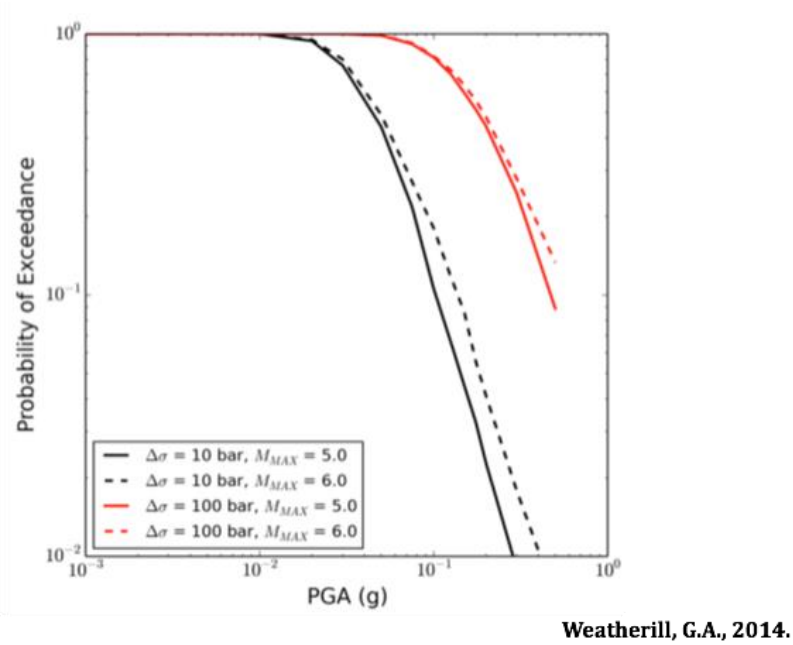


Fig. 3.3 Comparison of site specific (Level 1a according to Deliverable 3.4) and non-specific seismic hazard assessment (Level 0 according to Deliverable 3.4) for 80 sites in Europe (Kotha et al 2016b)

The STREST test cases show that in-situ seismological instrumentation, when properly designed, has multiple advantages, including setting constraints on numerical simulation estimates, and thus limiting the cost of either extensive site surveys to feed the site models for numerical simulation, or of comprehensive sensitivity studies. In-situ instrumentation will, in the long run, provide an invaluable feedback from all instrumented industrial sites, and allow to carefully assessing the practical pros and cons, and the cost.

3.5 Recommendation 5: Consider high-level, validated and open-source softwares

High level, validated and open-source codes have been developed for probabilistic seismic hazard and risk analysis. The OpenQuake-engine (GEM foundation) is a key example of such software platform, which can be used for CI's seismic hazard evaluations. Within the STREST project, this open-source software has been successfully used to model induced earthquake hazard (Fig. *3.4*). The STREST codes developed to predict tsunami hazard will also be part of an open-source platform initiative (www.globaltsunamimodel.org)



Weatherill, G.A., 2014.

Fig. 3.4 Application of OpenQuake (An Open-Source Software for Seismic Hazard and Risk Assessment) to Induced Seismicity Hazard Analysis (STREST deliverable 3.5)

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