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SEVENTH FRAMEWORK PROGRAMME

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Abstract

The main objective of Work Package 3 (WP3) of the STREST project was to construct a common methodology and a consistent modeling approach 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 comparative analysis and a summary of the developments, results and products issued from WP3. 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. 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 realisation of theirs studies.

Keywords: Recommendations, Hazard Assessment, Low-Probability-High-Consequences Events, Critical Infrastructures, WP3 Summary.

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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 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 socioeconomical 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 the whole 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 Assessments (PHA).

Particularly, they should include the assessment of “unlikely” (rare) events, that is, events with a low probability of occurrence that can produce significant unwanted consequences due to damage in a CI. Assessing these LP-HC hazards presents several challenges compared to conventional PHA, particularly related to the scarcity of data on rare 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 goals of Task 3.7 are to present these differences, challenges and benefits and to summarize the new developments issued from WP3 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. This summary includes the works performed in tasks 3.1 to 3.6.

In the first part of this report a summary table is presented which gives an overview of the works performed in WP3. This table 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 rare events, i.e., those events having a low probability of occurrence but potentially large impacts on the infrastructures. Table 1 is directed to the managers in charge of the project and Table 2 to the hazard experts. These tables recapitulate the different developments and results issued from WP3 of 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. It should be noted that the pool of participants selected by the project manager (Table 1) includes hazard experts who in turn can use the STREST hazard guidelines (Table 2).

The STREST project considered the following hazards: earthquake shaking, surface fault rupture, tsunami and flooding (Table 3). New developments 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 1: For project operator / manager. Summary of new developments, tools, references and application examples for the hazard assessment in the risk evaluation of critical infrastructures issued from WP3 of 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	Deliverable STREST D 3.1	-
All types	Reduction of uncertainties in seismic hazard assessment	Monitoring Soil profiles Fault studies	Guidelines	Deliverable STREST D 3.4	-
All types	Reduction of uncertainties in tsunami hazard assessment	Bathymetry	Guidelines	Deliverable STREST D 3.4	-

Table 2: For hazard experts. Summary of new developments, tools, 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	Deliverable STREST D 3.1	Port infrastructures, Thessaloniki (B3).	★	★	★
Inclusion of low probability (unlikely) events. Full exploration of epistemic uncertainty	EU@STREST treatment of epistemic uncertainty	Guidelines, forms and questionnaires	Deliverable STREST D 3.1 Marzocchi et al. (2015)	Gas storage & distribution network, Netherlands (B2). Port infrastructures, Thessaloniki (B3).	★	★	★
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)	Deliverable STREST D 3.1 Deliverable STREST D 3.5 Mignan et al. (2014) MATRIX project	Large dams, Switzerland (A2). Gas storage & distribution network, Netherlands (B2). Port infrastructures, Thessaloniki (B3). Industrial district, Italy (C1).	★	★	★
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) Deliverable STREST D 3.4 Deliverable STREST D 3.7	Oil refinery & petrochemical plant, Milazzo (A1). Port infrastructures, Thessaloniki (B3).	★	★	★
Inclusion of specific site analysis in PSHA	Comparisons of methods. Host to target adjustments. Non-ergodic PSHA	Guidelines	Deliverable STREST D 3.4	Oil refinery & petrochemical plant, Milazzo (A1). Port infrastructures, Thessaloniki (B3). Euroseistest.	★	★	★
Near fault hazard assessment	Assessment of near-source directivity effects	OpenQuake-engine	Baltzopoulos et al. (2014) Deliverable STREST D 3.3	Oil refinery & petrochemical plant, Milazzo (A1). Major hydrocarbon pipelines, Turkey (B1).	★	★	★
Inclusion of fault permanent displacement	Probabilistic fault permanent displacement hazard using Monte-Carlo simulations techniques	Matlab routines	Deliverable STREST D 3.2 Chen and Akkar (2015)	Major hydrocarbon pipelines, Turkey (B1).	★	★	★
Spatial variability of ground motion assessment	Monte-Carlo simulations techniques for computing dynamic ground-motion intensity measures	OpenQuake-engine (ePSHA workflow) Matlab routines	Deliverable STREST D 3.2 Chen and Akkar (2015)	Major hydrocarbon pipelines, Turkey (B1). Port infrastructures, Thessaloniki (B3). Industrial district, Italy (C1).		★	★
Spectral period cross-correlation assessment	Magnitude-dependent cross-correlation coefficients	Coefficients for Europe	Deliverable STREST D 3.7	Oil refinery & petrochemical plant, Milazzo (A1).	★	★	★
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)	Deliverable STREST D 3.5 Mignan et al. (2015)	Anatolian Peninsula (B1).	★	★	★
Inclusion of potential human-induced hazards (induced seismicity)	Induced seismicity PSHA	OpenQuake-engine	Deliverable STREST 3.6	Gas storage & distribution network, Netherlands (B2).	★	★	★

Table 3: Natural hazards included in STREST and the application of new developments

Perils	New developments		
	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 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.

We also point out that a similar effort to GEM, the GLOBAL TSUNAMI MODEL (GTM) is being promoted by the tsunami scientific community (www.globaltsunamimodel.org, website under construction).

The GTM has now received the endorsement of the United Nations Office for Disaster Risk Reduction (UNISDR) and of the World Bank Global Facility for Disaster Reduction and Recovery (GFDRR).

The GTM will provide tools for tsunami hazard and risk analysis, and certainly the developments achieved by STREST in this context will be considered for inclusion in GTM tools.

2.2 DESCRIPTION OF MAIN DEVELOPMENTS

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.

2.2.1 EU@STREST process (Epistemic Uncertainty in STREST)

The lack of available data on rare 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. 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 limited available funding. It is then imperative to prioritize the natural hazards/phenomena of interest. Different strategies are possible in this respect, from the use of expert elicitation processes (see Deliverable D3.1 for the Method; Deliverable D6.1 for a exemplificative application in the case of the harbor of Thessaloniki), or more complicated multi-hazard and multi-risk assessment method, such as the one presented in WP3 of STREST, developed upon results from the MATRIX project (Mignan et al., 2014). (See also Section 2.2.2 in this report).

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/standards/). 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 three main stages: Phase 0: Pre-assessment, Phase 1: Assessment, Phase 2: Decision.

Guidelines, forms and questionnaires are available in Deliverables D 3.1 and D6.1, and the reader is directed to that document for further details.

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 interactions 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 assessments becomes fundamental for risk mitigation.

Critical infrastructures being a vital component of societies, the analysis of potential cascading effects is required when performing stress tests. In order do it, a generic multi-risk framework (GenMR) is presented in Deliverable D 3.5 of the STREST project, originally developed 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; Mignan et al., 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 integrate 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 (Deliverable D 3.5) focus was made on three types of hazard interactions: (1) “intra-event” earthquake triggering based on concepts of dynamic stress to evaluate the maximum magnitude Mmax of cascading fault ruptures (Mignan et al., 2015), (2) “intra-hazard” earthquake triggering based on the theory of Coulomb stress transfer to evaluate earthquake spatiotemporal 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), which is part of the GenMR framework and can be used as a form/questionnaire to generate multi-hazard scenarios, is presented in Deliverable D 3.5 (Mignan et al., 2016). An algorithm to estimate Mmax due to rupture propagation is presented in appendix of Mignan et al. (2015).

The reader is directed to Deliverable D 3.5 and to Mignan et al. (2014; 2015; 2016; in press) for further details.

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 high frequency, which is very detrimental for structures.

Careful characterization of seismic hazard is especially important for the design of critical facilities. If critical structures are close to active faults, a particular attention is required due to these NS effects.

In NS conditions both ground motions and seismic structural response may show systematic spatial variability, which classical Probabilistic Seismic Hazard Assessment (PSHA) is not able to explicitly capture. Deliverable D 3.3 presents a framework 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.

The methodology has been implemented in the OpenQuake-engine.

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

The reader is directed to Baltzopoulos et al. (2014) and Deliverable STREST D 3.3 for further details.

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 infrastructure 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 of these two phenomena, the proper amplitude estimations of static (permanent fault displacement) and dynamic GMIMs is 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 D 3.2 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).

The reader is directed to Deliverable D 3.2 and Chen and Akkar (2015) for further details.

2.2.5 Human-induced hazards (induced seismicity)

In recent years, the increased occurrence of induced seismicity has heightened public concern. Tremors 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).

In Deliverable D 3.6 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 GMPEs, developed specifically for induced seismicity applications and into adapting the engine for a Geomechanical Seed Model Seismic Hazard Calculation.

The open source tool is already available, and the reader is directed to Deliverable D 3.6 for further details.

2.2.6 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.

Deliverable D 3.4 presents a refined methodology to reduce the computational cost which allows a full quantification of uncertainties.

The procedure is based on the approach by Lorito et al. (2015) and Selva et al. (2016). 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) & Selva et al. (2016) method is based into an ensemble modelling approach (Marzocchi et al., 2015, D 3.1), allowing a full quantification of epistemic uncertainty.The methodology is presented in Deliverable D 3.4, Lorito et al., (2015), and Selva et al. (2016).

2.2.7 Site specific PSHA

Site effects are related to the modification of seismic waves (e.g., amplitudes, duration, frequency content, among others) in the superficial layers due to local geology 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 site effects for any CIs since the damages due to an earthquake, may be locally affected and could underestimated or overestimated.

Table 4 : Main characteristics of the approaches for consideration of site effects in SHA.

		Generic or partially site-specific		Site-specific				
		Level 0	Level 0.5	Level 1 (linear)			Level 2 (NL site response	
Method for site-effects estimation		Site effect by proxy in GMPEs (VVS30, measured or inferred, L or NL)	Site effect by proxy in GMPEs + amplification factor based on simplified approaches (Vs,i + f_0, + other possible proxies)	1a Site specific residual (δS2S,s from GMPEs)	Site response analysis 1b Instrumental (spectral ratio wrt local reference)	1c Numerical (any kind: nD, linear)	Nonlinear site response analysis (Nonlinear amplification function) 2a NL site response analysis after disaggregation for the considered return period	2b Full convolution PSHArock *AF(pga)
Prerequisite : rock hazard		Not necessary	"standard rock" (e.g;, V_{S30} = 800 M/S	"Standard rock"	Site specific bedrock		Site specific bedrock	Site specific bedrock
GMPEs host-to-target adjustment		No	No	No	Yes		Yes	Yes
Uncertainty in GMPEs for rock hazard		Total Sigma (measured or inferred site proxies)		Single-station sigma				
Site response uncertainties	Aleatory	No additional uncertainty	No uncertainties (Level 0)	$\Phi_{SS,s}$, no additional variability	$\Phi_{SS,s}$ or Φ_{SS}, no additional variability		$\Phi_{SS,s}$ or Φ_{SS}, no additional variability	$\Phi_{SS,s}$ or Φ_{SS}, no additional variability
	Epistemic	No additional branch	Various SAPE	Uncertainty on δS2S,s	None unless clear evidence	Various profiles or models	Various profiles or models (possibility of…)	

It presents an overview of the available approaches for site-specific probabilistic seismic hazard assessment in terms of ground motion estimates, together with some examples of applications on a particular site.

Deliverable D 3.4 intends to summarize robust operational recommendations in order to study, evaluate and take into account the local conditions of sites within the seismic hazard assessment.

Among the mentioned document, different approaches and their examples of application were studied, and the main target was to include site effects on a probabilistic seismic hazard assessment with an increasing level of detail and complexity. The described methodologies are better explained in Table 4.

Level 0 or 0.5 are generic or partially site-specific methodologies where the site effect are taken into account by proxies and correction factors based on the direct use of the site amplification defined within the Ground Motion Prediction Equations (GMPE) (usually Vs30) or an a posteriori modification of the site term using Site Amplification Prediction Equations (SAPE).

For Level 1 and 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 in some cases; host-to-target adjustments are necessary to account for particular site conditions such as very high shear wave velocity of the bedrock, a parameter that cannot be accounted on the applicability range of the ground motion prediction equations and which is very important since it affects significantly the ground motion at the surface.

The site amplification functions or transfer functions used to transform the shaking at the bedrock to obtain the shaking at the surface, can be derived rather instrumentally or numerically, and can also considered linear or nonlinear behaviour of the soil column.

The site-specific amplification can be estimated in a purely empirical way on the basis of a dedicated instrumentation, and various approaches, using or not a reference site. By “seismological instrumentation”, we designate instruments that allow to record, on the studied site and/or in its vicinity, ground motions induced by real, local or regional or even teleseismic earthquakes. Based, on these recordings, a number of "instrumental" approaches can be implemented such as: Site-specific residuals approach and SSR approach.

The local site amplification or the resulting site-specific ground motion can also be assessed through a numerical simulation of the wave propagation phenomena occurring at the site. A linear simulation is recommended for the simpler local geology and moderate seismic activity. However, numerical simulations allowing the consideration of “extreme” cases, where the soil properties are demanded beyond the soil linear behaviour, a linear approximation is not anymore accurate and does not represent the real soil behaviour, for this reason, the need of a nonlinear model appears on this document.

For very large level of accelerations where the soil is demanded beyond its linear range, the use of nonlinear simulations is the only way to estimate the site amplification, since normally there is no available data to derive empirically or instrumentally the local site amplification.

Deliverable D 3.4 presents a comparison using different approaches; applying host-to-target adjustments when needed and using single station sigma of GMPEs when possible to perform a site-specific host to target corrected non-ergodic PSHA.

A systematic comparison of site specific (Level 1a according to table 4) and non-specific hazard assessment (Level 0) has also been performed for 80 sites in Europe (Kotha et al., 2016a, 2016b). Differences as large as 50% are observed.

3 Conclusions

Due to the large regional or even global socioeconomical 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 that the stress tests prepared for the nuclear industry.

This report presented the new developments issued from WP3 of 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. The reader was directed to the corresponding documents and references for detailed descriptions of each particular assessment. This document, other than giving a summary of the works performed in WP3, may also give a starting point, with a simple and clear overview, of the analyses that needs to be carried on for the hazard assessments of critical infrastructures in Europe.

4 References

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