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INNOVATIVE APPROACHES FOR SEISMIC FRAGILITY ANALYSIS WITHIN METIS PROJECT

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ABSTRACT

The building and structure related part of the Euratom funded Project METIS (metis-h2020.eu) (Figure 1) is focused on the evaluation of fragility curves, giving failure probabilities for increasing ground motion intensity, intensity measure selection, uncertainty quantification and bayesian updating of fragility curves. While METIS improves the methodologies for the seismic assessment of NPPs, work package 6 (WP) focuses on the structural part of the project delivering the methodologies for specific, detailed fragility curves and applying these to the case study. The work will finalize in guidelines for the application of the developed methodologies. In the following, first work within the fragility analysis part of the project and future topics will be presented. For an overall overview of METIS project, see SMIRT-26 2022 Publication "Challenges and innovation in tools and methods for seismic risk assessment of NPP addressed by METIS project" from I. Zentner et al. (Zentner 2022).

Figure 1.: METIS project logo

INTRODUCTION

Work package 6 is located in the middle of the Project, between the time history selection and site response within WP5 and the seismic probabilistic risk assessment within WP7 (Figure 2). WP6 consists of in total 9 tasks each with several actions. The tasks range from the SSC selection and process of nonlinear model creation over fragility curve creation to application to the case study and implementation of guidelines. For each a deliverable will be created including the relevant new approaches and investigations. An overview of the tasks is presented in Table 1. In the next passages, the recent work of some of the first tasks is presented.

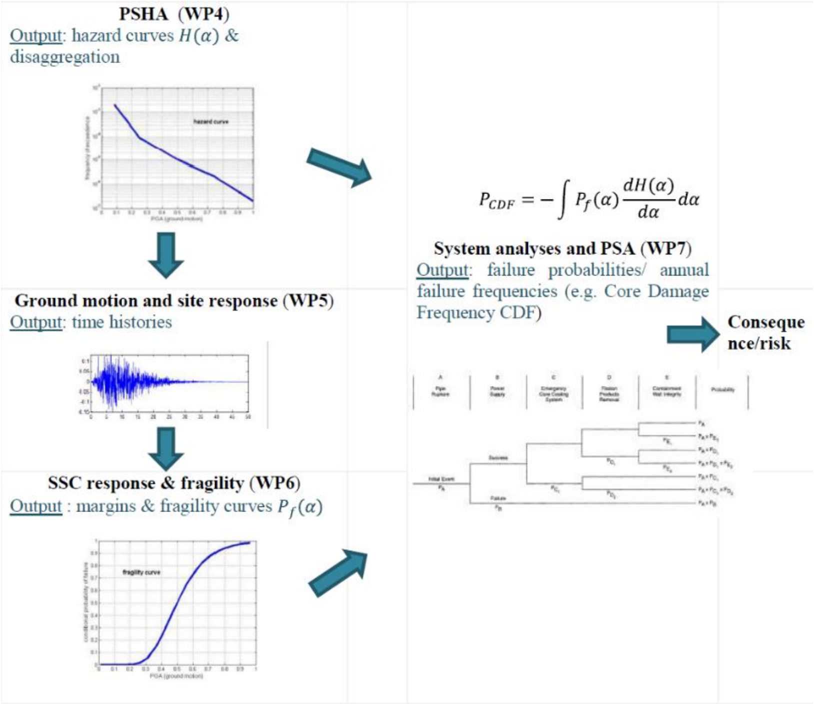


Figure 2: Workflow of METIS for the scientific WPs

Table 1: Tasks within WP6

Task	Topic	Leader
6.1	Definition and classification of SSCs and development of reliable mechanical models	ER
6.2	Verification and validation of models and failure criteria	IRSN
6.3	Determination of damage/failure relevant ground motion intensity measures and record selection	UL
6.4	Uncertainty quantification and propagation	NTUA
6.5	Seismic fragility evaluation of relevant SSCs	TUK
6.6	Bayesian updating of models and fragilities	IRSN
6.7	Influence of aftershocks and clustered seismicity on seismic fragility	IUSS
6.8	Sensitivity analyses and methods and parameters for beyond design assessments	IRSN
6.9	Application to METIS case study and guidelines	TUK

SSC SELECTION

Approach for definition and classification of systems, structures and components, in order to perform generic fragility analysis or detailed specific fragility analysis was proposed (Figure 3). It includes the definition of process for identification of SSC, as well as technical recommendations to develop seismic equipment list; qualitative and quantitative criteria to screen out SSC from further consideration (e.g., identification of inherently seismically rugged SSC and definition of low-significant SSC); quantitative criteria to decide which fragility analysis (Tier 1 - detailed plant specific study or Tier 2 – generic analysis) should be performed for SSC.

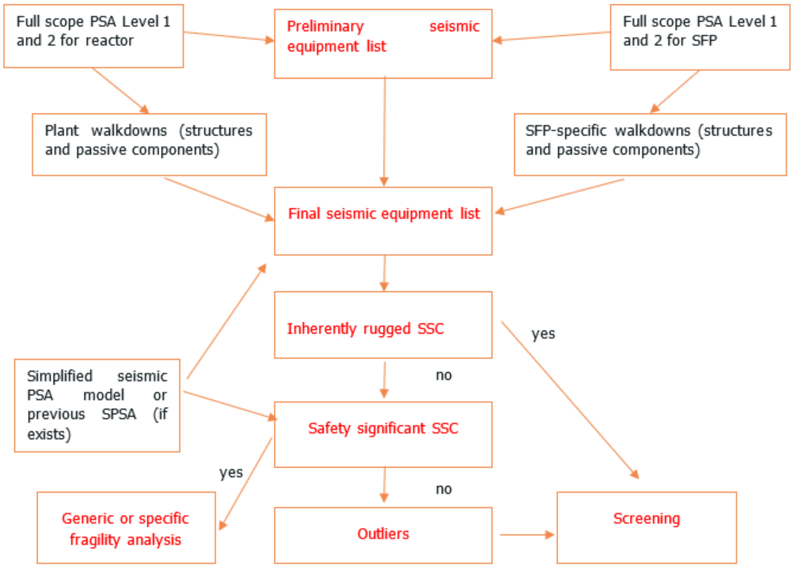


Figure 3.: Definition of SSCs for fragility analysis

Criteria to define low-significant SSC and to distribute SSC between two types of fragility analysis were developed using risk-informed approach. It utilizes combination of different importance measures (Fussely-Vesely, risk achievement worth, Birnbaum) calculated at existent PSA for NPP in question (see Figure 4 for illustration). Important aspects (as well as limitations) that should be accounted for during development and adjustment of seismic equipment list are also identified and discussed.

The approach was applied for Zaporizhzhia NPP Unit 1, which is chosen as the METIS case study. 16 SSCs groups important to prevent core damage at reactor facility and 9 SSCs groups important to prevent fuel damage at spent fuel pool are proposed for inclusion into Tier 1. These lists will be used as basis for further selection of SSCs for detailed fragility evaluation under METIS project, depending on availability and completeness of plant-specific documentation and data needed for fragility analysis.

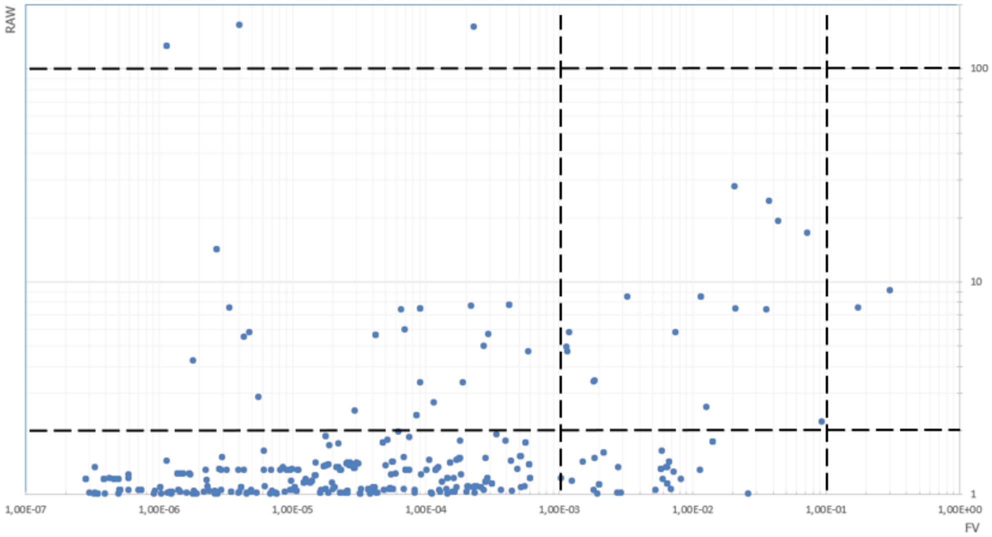


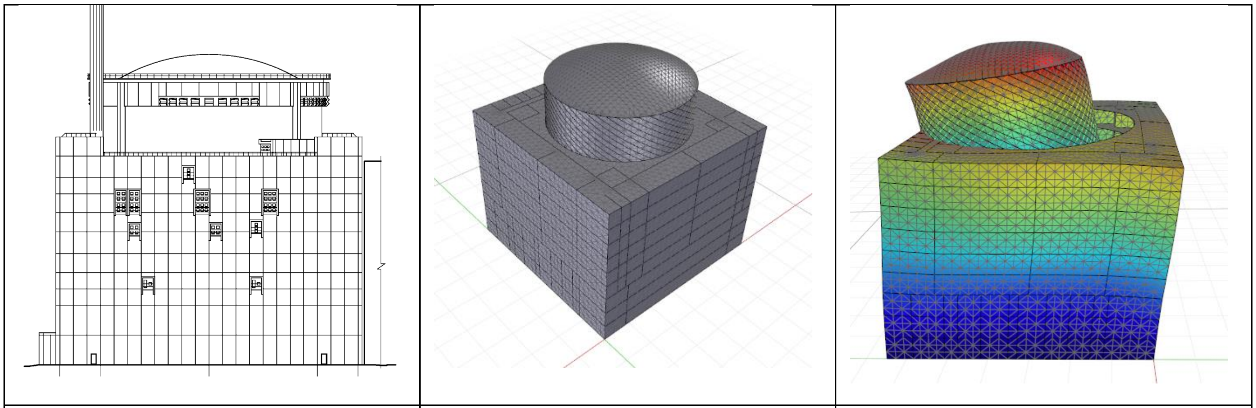
Figure 4.: ZNPP Unit 1 SSCs categorization by importance measures

CASE STUDY

For verification of the developed methodologies and comparison with other approaches a case study is part of the METIS project. To ensure a case comparable to European Nuclear Power Plants (NPP) a hybrid case study was selected. The structural part will be represented by the Zaporizhzhia NPP in Ukraine (Figure 5). It is one of the largest NPPs in the world and the largest in Europa by capacity.

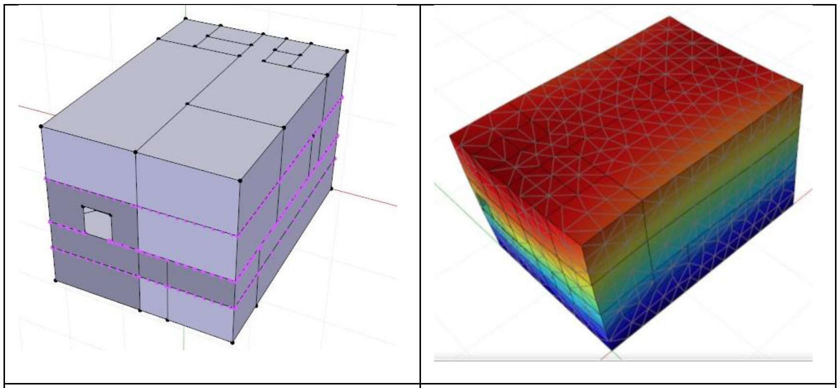
Figure 5: Zaporizhzhia NPP, the two cooling towers and the 6 VVER reactor buildings (Ralf 2009)

For the site an area in the region of Albinia in Tuscany, Italy was selected. The higher earthquake hazard in this region combined with the high amount of available data allows specific seismic calculations. Based on the SSC selection methodology the reactor building (Figure 6) and diesel generator building (Figure 7) have been selected as structures of interest. For these finite element (FE) models have been created. The reactor building consists of a foundation, an outer building and a prestressed containment.



Façade view	Shell model	Eigenmode

Figure 6: Finite element model created for the reactor building



Shell model

Eigenmode

Figure 7: Finite element model created for the diesel generator building

Since complex FE models are computational expensive, the possibility to derive surrogate models to be used for fragility analysis is analysed within the project. In further steps special attention is paid to identify and quantify sources of uncertainty of reduced-order or surrogate models, using cross validation to make sure that the reduction to surrogacy does not inadvertently introduce errors, but instead helps reducing epistemic uncertainty by allowing a cost-effective exploration of a large parameter space. For a first step the use of machine learning approaches like feedforward neural networks (FNN), Convolutional neural network (CNN) and Long short-term memory (LSTM) networks are investigated. While FNN allow only the prediction of values, CNNs and LSTMs also allow the prediction of full response time series (Figure 8) allowing wider application.

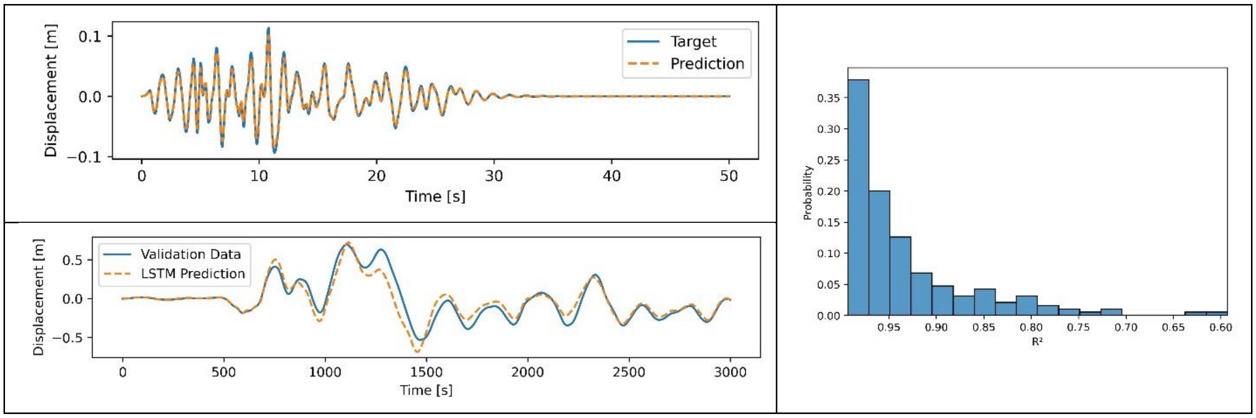
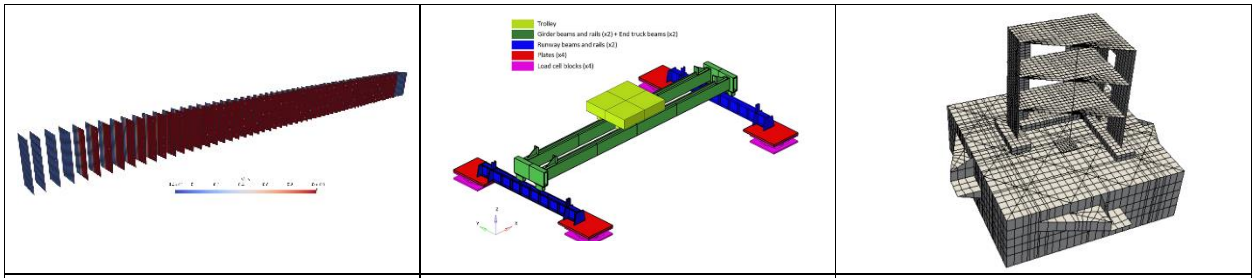


Figure 8: Prediction of response time series by LSTM model with validation data

VERIFICATION MODELS

Regarding task 6.1, detailed deterministic mechanical models of three SSCs (Figure 9): a reinforced concrete beam, a crane bridge mock-up and a three-story reinforced concrete structure have been developed. These three SSCs have been selected because they were subjected to seismic shaking table tests in the TAMARIS experimental facility between 2013 and 2015. The development of the models is now finished, and calibration tests have been carried out. Depending on the seismic input intensity, the experimental/numerical comparisons show a good agreement.



Reinforced concrete beam model | Crane bridge mock-up model | SMART 2013 model

Figure 9: IDEFIX, SOCRAT and SMART 2013 models where experimental data is available and will be used for validation and verification

Regarding task 6.2, a verification and validation (V&V) methodology has been developed based upon similar technical in other scientific field such as fluid mechanics or aerospace engineering. The proposed method has been codified under two sequential flowcharts, one being simplified and the other one being detailed. The full methodology is now being declined to the reinforced concrete beams modelled within the task 6.1.

DETERMINATION OF DAMAGE/FAILURE RELEVANT GROUND MOTION INTENSITY MEASURES AND RECORD SELECTION

For task 6.3, in anticipation of the final characterization of the SSCs, fragility curves for a wide array of SDOF systems have been developed, with a range of periods between 0.2 and 2.0 seconds, and with two different material models also presented in figure 11: degradation and elastic-hardening. These fragility curves were derived for three damage states, representing ductility levels of 2, 5 and 8. The SDOF models were evaluated for different sets of hazard consistent ground motions with intensity levels representing probabilities of exceedance ranging from 70% to 0.2% in 50 years and using both SaT1 and AvgSa as conditioning IMs (Figure 10). The different record sets tested were used to evaluate the variability and bias produced by using ground motions coming from either soil stations, synthetic records or highly scaled ground motions in lieu of recorded, unscaled rock ground motions.

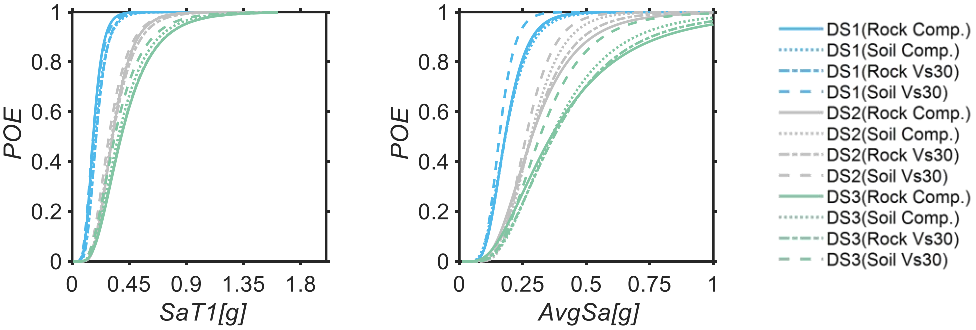


Figure 10: Degradation system 1.0s, AvgSa and SaT1 results.

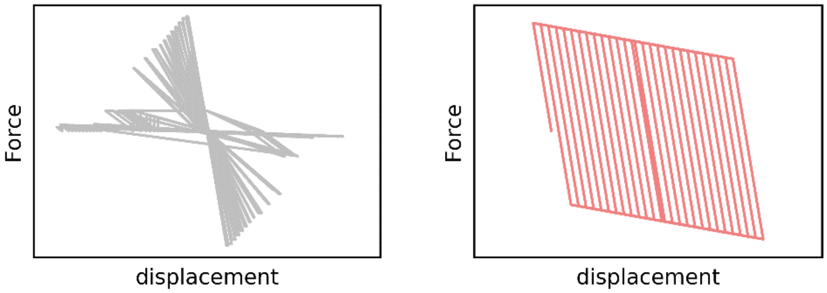


Figure 11: SDOF material models: degradation and elastic-hardening

A parametric seismic fragility evaluation for a number of idealized non-structural components of a simple stick NPP model has been performed. The structural modelling data are taken from EPRI (EPRI 2005) based on the AP 1000 advanced reactor design. The damage assessment of the components is performed by characterizing the influence of several features: (a) different locations of components in the powerplant, (b) the period of the component, (c) the capacity of the component, and (d) different intensity measures (IMs). The numerical results demonstrate that the same demand is recorded for the anchored components regardless of their location, owing to the high stiffness of the supporting structure. Furthermore, concerning the effect of the IMs it is concluded that the (geomean) average spectral acceleration over the short period range would be a useful intensity measure in terms of both efficiency (Figure 12) and sufficiency (Figure 13), regardless of component location, period or capacity. Nevertheless, peak ground acceleration remains a very close contender, as it leads to results of low dispersion and little bias for such stiff structures and short-period components.

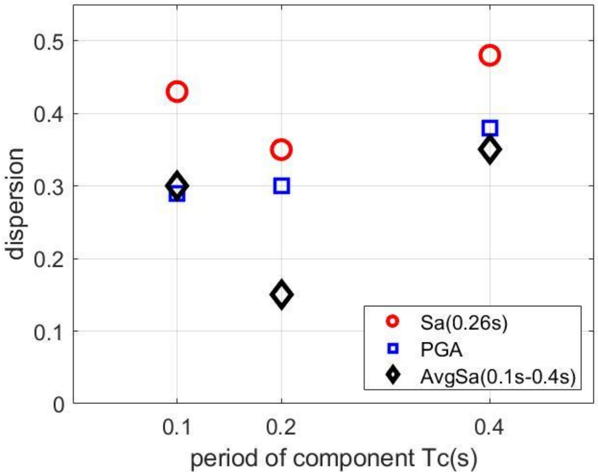


Figure 12.: Efficiency of components for the candidate IMs.

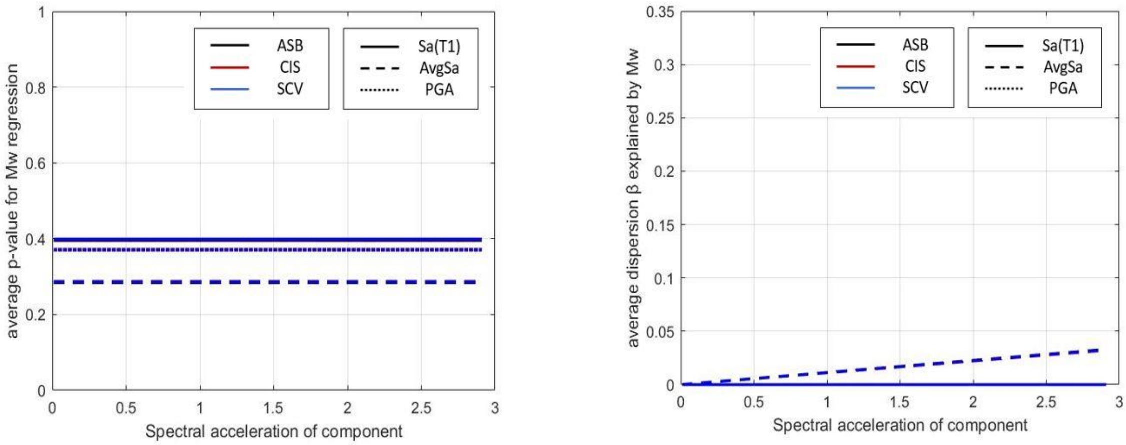


Figure 13.: Sufficiency statistical tests for a component of period 0.2s.

OUTLOOK

Currently most of the tasks from WP6 are in the middle of their work. Based on the already fulfilled work, future actions will cover the application of Bayesian techniques to update input parameters of SSCs nonlinear models based on experience feedback, numerical results coming from advanced simulations and measured data coming from either in-site measurements or laboratory experiments such as shaking table tests. By this, seismic fragilities will be updated by means of nonlinear best estimate plus uncertainty analyses and experience feedback. Also, damage-state dependent fragility evaluation procedures for clustered seismicity will be develop and the effects of clustered seismicity on the resulting fragility curves will be determined and quantified. Additionally, required parameters and simplified models for beyond design assessments (design extension earthquake/best estimate plus uncertainty) based on the results of the detailed probabilistic seismic fragility analysis will be determination. The results will also be used for the development of simplified pragmatic conservative deterministic failure margin assessment schemes. At the end, the previously developed models and methods will be applied to the METIS case study. The results of the simplified methods will be verified by detailed seismic fragility analysis and compared to results by applying EPRI methods/parameters. Practice oriented guidelines will be developed for detailed seismic fragility analysis, simplified beyond design assessments (DEE/BEPU), seismic margin assessment and simplified pragmatic conservative deterministic failure margin assessment schemes.

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