METIS
Research and Innovation Action (RIA)

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Project final handbook

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Project officer: Katerina PTACKOVA

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Summary

This project final handbook serves as an essential guide to understanding and implementing the methodologies, technologies, and best practices developed under this Horizon 2020 project. It is designed to provide stakeholders with a thorough overview of the project?s objectives, key components, conclusions and recommendations to mitigating seismic risks. This document aims to foster the transfer and the implementation of the results across the wider community beyond the lifetime of the project.

Approval

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2025-05-28 17:48:31	Philippe MARTINUZZI (EDF Energy)
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METIS

Seismic Risk Assessment
for Nuclear Safety

Research & Innovation Action

NFRP-2019-2020

Project final handbook

Deliverable D2.5

Version N°0.3

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Disclaimer

Document Information

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N°0.2	Philippe Martinuzzi	EAB	16/05/2025	Version sent for internal review
N°0.3	Philippe Martinuzzi	LGI (Raffaella Canu)	28/05/2025	Final version

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Abbreviations and Acronyms

Acronym	Description
AS	Aftershock
AvgSa	Average Spectral Acceleration
BE	Best Estimate
BEU	Best Estimate including Uncertainty
BBP	Broadband Platform
CCDP	Conditional Core Damage Probability
CDF	Core Damage Frequency
CLHS	Classic Latin Hypercube Sampling
CMC	Control Monitor Cabinet
CMS	Conditional Mean Spectrum
CS	Conditional-Spectrum
CS-MR	Conditional Spectrum with Magnitude and Distance parameters
DGB	Diesel Generator Building
DRM	Domain Reduction Method
EAB	External Advisory Board
EDPs	Engineering Demand Parameters
EGF	Empirical Green's Functions
ESM	Engineering Strong-Motion
ETAS	Epidemic-Type Aftershock Sequence
EUG	End User Group
FCVs	Filter Containment Venting System
FEM	Finite Element Method
FFBC	Free-Field Boundary Condition
FOSM	First Order Second-Moment
GCIM	Generalized Conditional Intensity Measure
GMM	Ground Motion Models
GIT	Generalised Inversion Technique
HCLPF	High Confidence Low Probability of Failure
IDA	Incremental Dynamic Analysis
IM	Intensity Measures

IML	Intensity Measures Level
IMT	Intensity Measure Type
KK NNP	Kashiwazaki-Kariwa Nuclear Power Plant
LHS	Latin Hypercube Sampling
METIS	Methodologies and Tools Innovation for Seismic Risk Assessment
MDOF	multi-degree-of-freedom
MFT	Master Fault Tree
MS	Mainshock
MSA	Multiple Stripes Analysis
MSAS	Mainshock Aftershock
NESS	Near-Source Strong-motion database
NGA-West2	Next Generation Attenuation – West2 Models
NLTHA	Non-Linear Time History Analysis
NPP	Nuclear Power Plant
OPSAMEF	Open-PSA Model Exchange Format
OQ	OpenQuake
PBEE	Performance-Based Earthquake Engineering
PGA	Peak Ground Acceleration
PLHS	Progressive Latin Hypercube Sampling
POS	Plant Operational States
PSA	Probabilistic Safety Assessment
PSHA	Probabilistic Seismic Hazard Analysis
PWR	Pressurized Water Reactor
RB	Reactor Building
R&D	Research and Development
SCEC	Southern California Earthquake Center
SPSA	Seismic Probabilistic Safety Assessment
SSHAC	Senior Seismic Hazard Analysis Committee
SDB	Synthetic/Simulated ground motion Database
SGMSM	Stochastic Ground Motion Simulation Method
Sa	Spectral Acceleration
SDOF	Single-Degree-Of-Freedom

SSC	Seismic Site Characterization
SSCs	Structures, Systems, and Components
SSE	Sum of Square Errors
SSI	Soil-Structure Interaction
SWP	Service Water Pump
UHS	Uniform Hazard Spectrum
VPSHA	Vector-Valued Probabilistic Seismic Hazard Analysis
Vp	Primary-wave velocity
Vs	Shear-wave velocity
VVER	Water-Water Energetic Reactor
WP	Work Package
ZNPP	Zaporizhzhia Nuclear Power Plant

Summary

This project final handbook serves as an essential guide to understanding and implementing the methodologies, technologies, and best practices developed under this Horizon 2020 project. It is designed to provide stakeholders with a thorough overview of the project's objectives, key components, conclusions and recommendations to mitigating seismic risks. This document aims to foster the transfer and the implementation of the results across the wider community beyond the lifetime of the project.

Keywords

METIS, seismic, hazard, fragility, risk, assessment, nuclear, power plant, communication, dissemination, exploitation and knowledge transfer, case study, seismic hazard assessment, fragility curves, seismic probabilistic safety assessment.

Introduction

In a world increasingly reliant on nuclear energy for sustainable power generation, ensuring the safety and integrity of nuclear facilities is paramount. One of the most significant threats to these installations is seismic activity. Earthquakes, with their unpredictable nature and potentially devastating impacts, pose a critical risk to nuclear power plants and related infrastructures. Recognizing this challenge, the Horizon 2020 program has launched the Methodologies and Tools Innovation for Seismic Risk Assessment (METIS) project; a comprehensive initiative dedicated to the seismic risk assessment for nuclear safety.

The METIS project aims to respond to the need of having a European consensus on best practices for the seismic safety assessment of nuclear power plants and clear guidelines regarding uncertainty assessments and the interpretation of their results. Therefore, METIS focuses on the three facets of seismic risk assessment of nuclear reactors: hazard - fragility - consequence to improve tools and methodologies employed in seismic safety assessments of nuclear reactors and translate this research into practice for industry use. The project enables also to develop common guidelines to facilitate periodic safety reviews, promote good practices under the Nuclear Safety Directive and enable risk-informed decision-making, and as a result, directly contribute to the safety and competitiveness of the European nuclear industry.

The project is delivered by an international consortium comprising of energy companies and research organization from France, Germany, Italy, Greece, UK, Ukraine and Slovenia alongside with 3 organizations from US and Japan.

METIS project is articulated in the following seven Work Packages:

- WP1 Management
- WP2 Dissemination, exploitation & training
- WP3 Case study for the implementation & application of METIS results
- WP4 Seismic hazard analysis
- WP5 Ground motion selection engineering analyses including site response
- WP6 Beyond design & fragility analysis
- WP7 PSA tools & methodologies

Description of Project Partners and Main Contributions

Electricité de France – EDF (France)

Electricité de France (EDF) was set up in 1946 out of the desire to have a national electrical utility that could help rebuild the country after the Second World War. Since its creation, the company has had the responsibility for generating, transmitting, and distributing electricity in France. EDF remains one of the European utilities with a significant research and development (R&D) activity and effort on innovation. Around 2500 people are presently employed at EDF R&D, amongst which, 70% are researchers and executives. EDF is today one of the leading energy companies, with solid positions in major European countries.

EDF is committed to creating long term, low carbon affordable energy and the safety and sustained performance of nuclear and hydraulic plants is one of the key issues in this regard. EDF participates in the project through its R&D unit. EDF R&D has the mission to contribute to increasing performance, efficiency and safety of operating units of EDF Group. Collaborative research projects are a vital component for EDF, creating an invaluable forum for exchange and knowledge-sharing. Through them, innovations are developed, disseminated, and industrialized. EDF R&D is also a major national player in opensource simulation software development and dissemination. In particular, it develops and disseminates code_aster opensource Finite Elements Software www.code-aster.org.

In METIS, EDF is project coordinator, WP leader and contributor. As coordinator, EDF brings in a global vision on the industrial problem at hand, as well as experience on the approaches pursued in the different work-packages in this multi-disciplinary project, engineering seismology, geophysics, fragility analyses and risk assessment. To deal with these topics, 3 different departments of EDF R&D as well EDF's engineering divisions are involved in the project.

EDF has a proven track record in conducting national and international collaborative projects. As a project contributor, EDF has a leading role in the definition of the industrial case study and has strong contributions in the fields of PSHA and seismic PSA computation, as well as integration and application. Via its activities in international organization IAEA and OCDE, EDF also provides a strong vector of dissemination with high visibility.

Website address: https://www.edf.fr

EDF Energy UK R&D – UKC (United Kingdom)

EDF Energy UK R&D is an integral part of the Group R&D network and is responsible for leading research and development activities in the UK. As of today, our 100-strong fully international team is engaged in projects of various sizes in support of EDF Energy and works across all energy aspects including Nuclear, Offshore Wind, Energy management, Energy Efficiency, Smart Meters, Electric Vehicles and Digital Innovation. The Centre plays a key role in increasing EDF visibility, disseminate knowledge, promote EDF Group tools, influence the UK scientific community and manage long term relationships with research organizations and it benefits from UK public sector funding and initiatives.

In METIS, UKC is Leader of WP2.

Website address: https://www.edfenergy.com/about/research-development

Energorisk - ER (Ukraine)

ENERGORISK is a nuclear service-oriented company, founded in 1992, which provides services on nuclear facilities safety analysis, risk assessment, design works and associated peer review activities.

Energorisk, Ltd. was one of the first companies in Ukraine that obtained a license for safety-related engineering works for nuclear facilities. It is included in the list of recommended suppliers of the National nuclear operator, NNEGC "Energoatom". The company products are expert and consulting services; research and developments; design works; analytical and computational studies in the area of safety assessments for potentially hazardous industrial facilities. Activities of Energorisk, Ltd. mainly relate to safety and security of various types of nuclear facilities: nuclear power plants; research reactors and facilities; spent fuel storage facilities; nuclear fuel cycle facilities; radioactive waste management, addressing different stages of their life cycles (construction, commissioning, operation, decommissioning, etc.).

During over twenty years of intense activity, the company has established itself as a leader in the field of safety assessment of nuclear facilities in Ukraine. It completed many tens of major research projects related to nuclear power plants, NNEGC "Energoatom" and Operators of other nuclear facilities, and a number of large-scale international projects for all nuclear power plants in Ukraine. It also provided services to a number of foreign and international customers – EC, U.S. DOE and its Laboratories, IAEA, EBRD and several well-known European nuclear engineering companies and institutions. Today "Energorisk" performs the following: comprehensive safety analysis of nuclear reactor facilities, spent fuel storage and nuclear fuel cycle facilities with the use of modern analytical software and advanced deterministic and probabilistic methods of research; development of safety analysis reports and periodic safety review reports for operating NPPs and other nuclear facilities; development of the design and operational documentation for nuclear facilities, upgrade of safety important equipment and systems; analytical and scientific and technical support activities for the nuclear operators and regulatory authority, development of design and operational documentation; deterministic analyses on nuclear and radiation safety including analyses of design basis accidents, beyond design basis accidents (design extension conditions) and severe accidents; emergency response and accident management, development and justification of emergency procedures and severe accident management guidelines; full-scope PSA, PSA application and risk-informed decision making; external and internal hazards evaluation; radiation protection, environmental impact assessment of nuclear installations on the environment and population; scientific and technical support for decommissioning and radioactive waste management.

Leading Energorisk specialists have many-year experience of participating in large international research projects, including IAEA coordinated research projects, US DOE In-depth Safety Assessment projects, EC International Nuclear Safety Program (INSP), FP7 and HORIZON 2020.

In METIS, Energorisk is Contributor in WP6 and WP7.

Website address: www.energorisk.com.ua

Fondazione GEM - GEM (Italy)

GEM is a non-profit foundation and UN approved Non-Governmental Organization. GEM has extensive experience in the development of tools for probabilistic seismic hazard and risk analysis, collection and processing of hazard and risk data, and generation of risk information for disaster risk managers. All the tools and models created by GEM are open source and open access.

In METIS, GEM is coordinating WP4 (Seismic Hazard Assessment) and is also participating into WP3 and WP6. GEM implements into the open-source software OpenQuake Engine various innovative methodologies for the calculation of hazard and for the construction and testing of components of probabilistic seismic hazard and risk models. GEM also extensively applies the new implemented features in the context of the activities carried out within WP3.

Website address: www.globalquakemodel.org

HELMHOLTZ ZENTRUM POTSDAM DEUTSCHESGEOFORSCHUNGSZENTRUM - GFZ (Germany)

The GFZ is member of the Helmholtz Association of National Research Centers. GFZ is a public law foundation and it is Germany's premier institute for the geosciences. Research in 37 sections of the GFZ ranges across the full breadth of the Earth Sciences, from the dynamics of Earth's deep interior to the remote observation of its active surface. The GFZ employs almost 1,300 people. The GFZ is the responsible institution for the assessment of seismic hazard in Germany and a key participant in many seismic hazard assessments worldwide. A key product in of the GFZ in this domain is the European Macroseismic Scale EMS-98, and it has participated in design of the German building codes. Moreover, GFZ maintains a close cooperation with relevant researchers and institutes worldwide as well as relevant end-users through the participation of political and administrative stakeholders up to the ministerial level in many of its international projects. Section 2.6 (Seismic Hazard and Risk Dynamics) is coordinating GFZ's participation in METIS. This section employs a group of more than 20 scientists working in the field of seismic hazard and risk, covering the whole timeframe from earthquake early warning, earthquake characterization/assessment and rupture simulation via ground-motion predictions, to exposure and risk modelling. In the field of testing, GFZ is pioneering the testing and validation of seismic hazard and risk models and their components, i.e. earthquake forecast models, earthquake ground-motion predictions, and exposure models.

In METIS, GFZ was involved in WP4 related to the methodological development and case studies of testing seismic hazard models and ground motion models.

Website address: www.gfz-potsdam.de

Geodynamique et Structure - GDS and SEISTER (France)

GÉODYNAMIQUE & STRUCTURE (GDS) is an Engineering Firm specializing in the analysis of soils, structures, equipment and their interactions under cyclic (wave and tidal forces, vibration), dynamic (earthquake, explosions) and thermomechanical (pressure, temperature) loads with over 35 years of continuous activity in these areas. GDS's know-how thus covers most particularly: seismic analyses of structures and equipment; nonlinear finite element modelling for statics and dynamics; development of nonlinear constitutive models and analysis methods; advanced modelling procedures together with in-house built applications for pre- and post-processing; seismic hazard analyses with definition of design strong motions for civil and industrial structures; probabilistic studies of risk assessment for all sorts of nuclear and industrial facilities.

SEISTER is a consulting company specialized in the fields of geosciences, geological and seismic engineering. Founded in 2018 it is formed by a team of internationally recognized experts providing client-focused innovative solutions for seismic hazard and risk studies for large projects.

GDS and SEISTER is a complementary group which gathers the experience of both Companies.

In METIS their contributions concerns WP4 and WP7.

Website address: www.geodynamique.com, www.seister.fr

Institut de Radioprotection et de Sûreté Nucléaire – IRSN[*] (France)

The Institute for Radiological Protection and Nuclear Safety (IRSN) was created by law 2001-398 of 9 May 2001. As a public entity specialized in risk assessment, IRSN contributes to publics policies relating to nuclear safety and protection of human health and environment with respect to ionizing radiation. It collaborates with all stakeholders involved in these policies. The IRSN activities covers the entire scope of civilian or defense nuclear activities: safety of nuclear facilities, safe transportation of radioactive and fissile material, employee protection against ionizing radiations, protection of people and the environment, protection against risk of proliferation or malicious acts, monitoring of radioactive sources, emergency preparedness through its Technical Centre. IRSN has more than 1600 employees including over a thousand specialists and researchers and allocate about 40% of its resources to research and 35% to the technical support for the authorities or public service mission.

IRSN contributes to the METIS project on four different topics. First, IRSN enables METIS project to benefit from its experience in seismic hazard assessment by sharing with project partners in the WP5. IRSN mainly contributed in the WP6 by developing mechanical model testing and verification/validation process are derived in order to ensure their representativeness. IRSN also developed Bayesian approaches for fragility assessment. Then, IRSN is involved in WP7 by providing academic partners with guidance and recommendations regarding the software developments planned.

*On January 1st 2025, IRSN has merged with the Autorité de Sûreté Nucléaire (ASN) to become the ASNR (Autorité de Sûreté Nucléaire et de Radioprotection)

Website address: www.asnr.fr

Istituto Universitario di Studi Superiori di Pavia - IUSS (Italy)

The University School for Advanced Studies IUSS Pavia is an Italian Public Institution devoted to research and higher education. Since 1997, IUSS fulfils an advanced teaching and research model successfully implemented by two other prestigious institutions in Italy: the Scuola Normale Superiore and the Scuola Sant'Anna located in Pisa. The mission of IUSS is to contribute to the academic growth of a small number of students by offering them, at any step of their higher education, qualified programs that enhance every technical skill and knowledge. IUSS offers a variety of educational and training paths based on a strong interdisciplinary approach. The School is committed to scientific progress by preparing young researchers and developing scientific research programs.

IUSS is the leader of WP5, the work package devoted to hazard consistent ground motion record selection. This package provides the necessary link from the hazard to the fragility computations of SSCs. IUSS also significantly contributes to WP4 and WP6.

Website address: http://www.iusspavia.it/

LGI Sustainable Innovation - LGI (France)

Founded in 2005 by its current CEO, LGI is an independent consultancy headquartered in Paris with a team of 75, present in Lyon, Grenoble, Aix-Marseille, Montpellier, Strasbourg, Toulouse, Rouen, Lille, Le Mans, Nantes, Biarritz, Saint-Etienne, and Valencia.

Through sustainable innovation, LGI aims to address some of the most urgent challenges facing our world today: climate change, resource depletion and biodiversity loss. With over 20 years of experience, LGI has successfully contributed to more than 600 projects and coordinated 5 of them, fostering long-standing relationships with stakeholders across France, Europe and internationally.

LGI intends to make a difference in several ways:

- Guiding sustainable innovation strategies: LGI provides predictive market analysis, international benchmarking, business model innovation and deployment roadmaps.
- Association management: LGI supports the origination, constitution, and operations of membership-based organisations.
- Informing public action. We produce studies of value chains, stakeholder mapping and forward- looking scenarios, and formulate recommendations for public strategy.
- Facilitating collective intelligence. LGI runs Innovation Camps and other ideation workshops, using a combination of techniques (BMC, LEGO Serious Play, Value Proposition Design, Metaplan, etc.) to characterise challenges and harness collective intelligence.
- Setting up and managing R&D and innovation projects. Our team brings its multidisciplinary expertise in setting up and managing complex projects, particularly those involving multiple players at international scale.

In METIS, LGI is a participant involved in exploitation, dissemination, communication and as PMO.

Website address: https://lgi.earth/

National Technical University of Athens - NTUA (Greece)

The National Technical University of Athens (NTUA), is the oldest (founded in 1837) and most prestigious Engineering University in Greece with a large involvement and participation in research projects both in a National and European level. NTUA has been ranked at the 10th position among all the European Universities in terms of research funded by the EU and at the 17th position among all the research centers in Europe. In METIS, the Department of Structural Engineering, Institute of Steel Structures is involved. The Department was founded in 1965 and it is active in education, research, and analytical as well as experimental support of technological development in the broad area of structural engineering, with emphasis on steel structures and steel-reinforced concrete composite construction. Particular emphasis is placed on evaluating the vulnerability, risk and performance of civil structures, infrastructure, networks and systems subjected to extreme environmental or man-made actions under the influence of uncertainties. To that effect, a combined experimental, numerical and analytical approach is employed. The Institute’s activity is characterized by strong participation in national and international funded research projects, large number of research publications and corresponding citations and close cooperation with the industry in the above-mentioned fields.

In METIS, NTUA contributes to training, dissemination and research in fragility and vulnerability assessment of structural and non-structural components of power-plants.

Website address: http://labmetalstructures.civil.ntua.gr/cms/en/

State Scientific and Technical Center for Nuclear and Radiation Safety – SSTC NRS (Ukraine)

SSTC NRS was established in 1992 as part of the national regulatory infrastructure, which currently is managed by the State Nuclear Regulatory Inspectorate of Ukraine (SNRIU). SSTC NRS specializes in scientific, engineering and expert support to regulator in all safety-related areas to ensure protection of public health and safety, and protection of the environment. Thus, SSTC NRS carries out its statutory function as a Technical Safety Organization (TSO) by:

- contributing to the improvement of the national regulatory system, particularly by converging the Ukrainian and the EU regulatory bases and safety practices
- supporting regulatory decision-making in a licensing process

- ensuring the oversight function of regulation
- carrying out applied research related to safety issues and implementing advanced approaches, methodologies and practices into regulatory, licensing and safety assurance activities.

In 2019, about 140 nuclear engineers and researchers of SSTC NRS were involved in expert activities and scientific and technical projects. SSTC NRS as a research entity is associated with the National Academy of Sciences of Ukraine.

SSTC NRS has been closely supporting regulatory activities aiming at re-assessment of site seismic hazards (performed by deterministic and probabilistic methods) and seismic resistance of structures, systems and components (SSC) of Ukrainian NPPs in operation (including Seismic PSA). This applied research has the normative and methodological basis, which is permanently updated to account for state-of-art safety approaches (IAEA, WENRA, US NRC, etc.) and advanced international experience and practices.

SSTC NRS has vast experience of international cooperation, participation in the EU INSC and EBRD projects, in the Euratom R&D Framework Programs and in multilateral (IAEA) and bilateral activities. SSTC NRS is an associated member of the European TSOs' Network (ETSON) and member of NUGENIA.

The SSTC NRS Management System has been certified by the TUV NORD as complying with the requirements of the ISO 9001:2015, with the Certificate valid until 2020.

In METIS, the SSTC NRS is contributor to the project activities of WP2, WP3, WP6 and WP7.

TECHNISCHE UNIVERSITAT KAISERSLAUTERN - TUK (Germany)

The Technische Universität Kaiserslautern (TUK) is a medium sized university founded in 1970 and hosts departments of natural sciences, engineering, and social sciences. It has about 14,000 students from nations world-wide, approx. 4000 of whom are remote study students. The university has received excellence awards for developing teaching concepts, concepts of work-family-life-balance, and is scientifically recognized as center of prestigious coordinated research consortia. TUK is a part of a dynamically evolving alliance of universities at the border between France, Belgium, Luxemburg, and Germany (Universität der Großregion, UniGR) cooperating in research, teaching, and development. The university conducts a number of international collaborations, successfully participated in projects funded under several EU Framework Programs and has gathered comprehensive experience both as coordinator and partner in research networks and projects. Besides projects with national funding, TUK is also very active in the field of international research. In this context, the funding instruments available in the EU Framework Programs play an important role. TUK is partner or coordinator to 15 projects conducted under Horizon 2020. Four further individual projects funded by ERC are being also coordinated by researchers at TUK. TUK has procured more than 13.5 million Euros under the 7th FP.

The Institute of Structural Analysis and Dynamics is part of the department of civil engineering at TUK and is specialized in dynamic nonlinear analysis and earthquake engineering. The institute has also conducted numerous experimental research works and analytical studies to investigate the seismic vulnerability of existing structures, seismic risk analysis, and probabilistic determination of seismic damage to buildings.

In METIS, TUK leads WP6 and contributes to offering training, dissemination and research in seismic hazard, fragility (including SMA/BEPU) and risk assessment of structural and non-structural components of power-plants via vector intensity measures.

Univerza v Ljubljani - UL (Slovenia)

The University of Ljubljana (Univerza v Ljubljani, UL) was established in 1919 and it encompasses 23 faculties and 3 art academies. UL ranks among the top 500 universities according to the ARWU Shanghai ranking and among the top 3% Universities in the world according to the Times ranking. It has more than 40.000 undergraduate and postgraduate students and employs approximately 5.600 higher education teachers, researchers, assistants and administrative staff. The UL is very active in international research and educational programs and projects, especially in the EU Framework Programs. In terms of the number of research projects, it ranks among the top of universities and research organizations from the new EU Member States (EU 13).

The Faculty of Civil and Geodetic Engineering (UL FGG) was one of the constitutional members of the UL. The UL FGG performs educational, research, development, professional and consulting activities in the areas of civil engineering, environmental engineering and geodesy and takes care of the development of these scientific areas. The UL FGG performs undergraduate and postgraduate education by offering study programs from different areas of Civil Engineering, Environmental Engineering and Geodesy. The UL FGG is actively involved in the development of the relevant legislation (European standards) and its application to practice. In 2019, UL FGG was involved in 40 European projects (10 of them are H2020 projects). In METIS, the work will be performed by the Institute of Structural Engineering, Earthquake Engineering and Construction IT (IKPIR), which is part of UL FGG and has around 40 years of experience in studies related to the performance assessment and design of nuclear-safety-related structures.

In METIS, UL contributes to WPs 2, 3, 5, 6 and 7.

Website addresses: UL: www.uni-lj.si/eng/, https://www.en.fgg.uni-lj.si/

Geo-Research Institute – GRI (Japan)

GRI was established in 1960 and is a general incorporation foundation specialized in the fields of geosciences, geological and earthquake engineering. To prepare for inevitable major earthquakes, the most effective advanced methods for the earthquake disaster mitigation involve considering a specific fault in a targeted area of examination, preparing a source model of that fault's potential activity, and predicting strong ground motions near the fault in time domain. For this purpose, our foundation is engaged in developing methods to predict strong ground motion (Irikura's Recipe) and conducting corresponding basic research.

In METIS, GRI is involved in WP4 (Seismic hazard Analysis) and WP5 (Site response & Ground motion for engineering). GRI provides the ground motion time histories using Irikura's recipe, and these time histories, calculated on the physics-based simulations, can be used to develop simulation-based GMMs that provide response spectra in near-site fault area.

Website address: https://www.geor.or.jp/eng/index.html

North Carolina State University – NCSU (United States of America)

The mission of the Centre for Nuclear Energy Facilities and Structures (CNEFS) is to perform research on innovative but rigorous solutions to problems in nuclear energy related facilities and to transfer this technology to the industry. These solutions reduce uncertainty, increase safety and reduce the cost of operating existing plants and of building new ones. Educating and training the next generation of work force in state-of-the-art methodologies is a related objective.

In METIS, NCSU is involved in WP4 and WP6

Website address: https://www.ccee.ncsu.edu/cnefs/

The Regents of the University of California – PEER (United States of America)

PEER is the main earthquake engineering research center for California and the western United States. The PEER research program aims to provide data, models, and software tools to support a formalized performance-based earthquake engineering methodology. Within PEER, the PEER lifelines program is focused on seismic hazard and seismic risk for lifelines systems.

Collaboration of research in the PEER lifelines program with the METIS funded research. Topic areas for collaboration include seismic hazard methods, uncertainty propagation, time histories, testing of PHSA, and use of numerical simulations of ground-motions.

Website address: peer.berkeley.edu

Project End User Group (EUG) and External Advisory Board (EAB)

The EAB is composed of experts from international organizations and safety authorities (IAEA, EPRI, ENSI, ETSI, STUK) and 2 independent senior experts with long standing and recognized expertise in their field:

- Robert Budnitz, senior seismic risk expert, retired from Lawrence Berkeley National Laboratory
- Nilesh Chokshi, senior seismic risk expert, former USNRC
- Paolo Contri, IAEA
- Zeynep Gulerce, IAEA
- Abhinav Gupta, professor, NCSU
- John Richards, EPRI
- Tadeusz Szczesiak, ENSI
- Gernot Thuma, ETSON
- Pekka Välikangas, STUK

METIS End Users group

- GEN ENERGIJA, Slovenia
- Nuclear Power Plant Krško, Slovenia
- IPP Centre, Ukraine
- Principia, Spain
- Swissnuclear, Switzerland
- ORANO, France
- TÜV, Germany
- Framatome Germany
- ENGIE, Belgium
- Bel V, Begium

- Mott MacDonald, Bulgaria
- Lloyd's Register
- SED Engineering, Germany

List of Deliverables

Below is the list of the deliverables produced by the METIS consortium

- WP1
  - D1.1 Detailed work plan (EDF)
  - D1.2 Project quality plan (LGI)
  - D1.3 Summary of EAB Review Meetings (EDF)
  - D1.4 Data Management Plan (LGI)
- WP2
  - D2.1 Project branding, document templates, Project presentation brochure, base public website and collaborative tools (LGI)
  - D2.2 Communication and Dissemination plan report (UKC)
  - D2.3 Project website on-line (LGI)
  - D2.4 End-users survey report (UKC)
  - D2.5 Project final handbook (UKC)
- WP3
  - D3.1 Case study for implementation and application of METIS results (EDF)
  - D3.2 Peer-review of METIS case-study: technical and organizational points (EDF)
  - D3.3 Recommendations from peer-review group for METIS case-study (EDF)
- WP4
  - D4.1 Methodology for the declustering of earthquake catalogs (GEM)
  - D4.2 Methodologies for physics-based simulation of ground motion (EDF)
  - D4.3 Methodologies for physics-based simulation of ground motion (EDF)
  - D4.4 Extended PSHA methodology and tools (GEM)
  - D4.5 Developments and Tools for PSHA to Data Comparison (GFZ)
  - D4.6 Preparation of the METIS study case (WP4) and application (GEM)
  - D4.7 Summary of WP4 activities and insights (GEM)
- WP5
  - D5.1 Methodology for site-specific rockhazard-consistent record selection for mainshock-only seismicity (IUSS)

  - D5.2 Methodology for selecting ensembles of rock-hazard-consistent ground motions suitable for fragility curve computations for clustered seismicity and datasets for WP6 (IUSS)
  - D5.3 Strategies for response modelling development of surface ground motions from rockhazard consistent ground motions (UL)
  - D5.4 Hazard-consistent surface ground motion time histories for METIS case study (IUSS)
  - D5.5 Ensembles of hazard consistent surface ground motions for clustered seismicity (IUSS)
- WP6
  - D6.1 Definition and classification scheme of SSCs for specific and generic seismic fragility evaluation (ENERGORISK)
  - D6.2 Verification & Validation of nonlinear mechanical model on SMART2013 campaign (IRSN)
  - D6.3 Damage/failure relevant ground motion intensity measures, record selection/generation and site response analysis schemes (UL)
  - D6.4 Report on efficient uncertainty quantification and propagation techniques (NTUA)
  - D6.5 Report on scalar and multi-dimensional (vector-based) fragility evaluation methods (TUK)
  - D6.6 Application of Bayesian updating techniques to the seismic fragility of nuclear structures – case of SMART2013 mock-up (IRSN)
  - D6.7 Influence of aftershocks and clustered seismicity on seismic fragility (IUSS)
  - D6.8 Fragility curves for METIS case study (TUK)
  - D6.9 Guidelines for beyond design assessments (DEE/BEPU) and fragility evaluation (Technical report) (TUK)
- WP7
  - D7.1 Development of an open-source representation format for PSA models (EDF)
  - D7.2 Seismic PSA Database tool - User Manual (IRSN)
  - D7.3 Seismic PSA Tool for the risk quantification - SCRAM – Andromeda (IRSN)
  - D7.4 Strategy for consideration of aftershocks in seismic PSA (SSTC NRS)
  - D7.5 New tool for uncertainty propagation in seismic PRA (EDF)
  - D7.6 Benchmark of PSA models (SSTC NRS)
  - D7.7 Assessment of new or improved PSA approaches (ENERGORISK)
  - D7.8 Report on Risk Testing methodology and outcome (GEM)
  - D7.9 Application to METIS study case (WP7) (ENERGORISK)
  - D7.10 Recommendations to conduct seismic PSA (ENERGORISK)

1. Motivations, Objectives and Organization of the METIS project

1.1. The project

The METIS project aims to innovate methods and tools for seismic risk assessment of nuclear power plants. The seismic risk assessment chain includes seismic hazard assessment, SSCs response analysis to compute fragility curves, and the use of these curves to compute plant failure probabilities and evaluate risk.

The METIS project has obtained funding from EURATOM Horizon 2020 program and runs until May 2025. Its goal is to propose innovations in tools and methods used in the seismic probabilistic safety assessment analysis chain covering: 1) seismic hazard; 2) structural and equipment fragility analyses and 3) risk quantification to determine plant failure probabilities.

The overall workflow and organization of the METIS project into work packages is illustrated in **Figure 1** below:

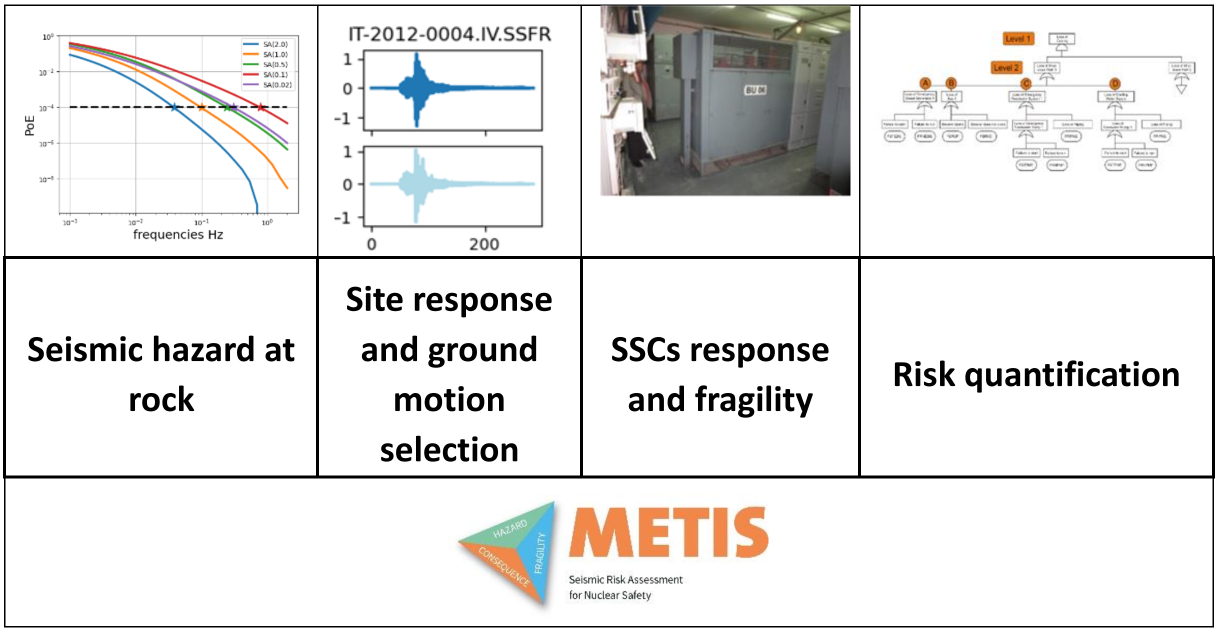

Figure 1. Organization and workflow of METIS project.

1.2. Current practice for seismic risk assessment and integrated approach developed in METIS

Probabilistic and performance-based assessments are becoming the state-of-the-art methods for seismic assessment and design of civil and infrastructures in the US and worldwide. Regarding probabilistic risk-informed assessments for NPP, the seismic PSA approach was developed in the late 70’s in the USA and is now applied worldwide. Nevertheless, deterministic (scenario-based) assessments are often preferred in Europe.

Concurrently, the Performance-Based Earthquake Engineering (PBEE), developed for critical infrastructures and industrial installations in 2000 (pioneered by Cornell & Krawinkler, 2000) aims to evaluate how structures will perform under different earthquake intensities in a probabilistic framework.

Similar to seismic PSA, this approach separates seismic hazard analysis and structural response analysis to estimate the probability of different damage levels.

In seismic risk assessment, seismic hazard is defined as the annual probability of exceeding certain levels of ground motion intensity at a given site, an approach known as Probabilistic Seismic Hazard Analysis (PSHA). PSHA calculates this probability using data from all relevant earthquake sources and scenarios affecting a site.

The seismic risk assessment of nuclear power plants includes seismic hazard, fragility, and system assessment.

The strategy developed in the METIS project is to develop seismic hazard on rock conditions and to consider the impact of the surrounding soil and site conditions as part of the structural analysis. The advantage of this approach is that it enables the development of site response tailored specifically to the engineer's scenarios of interest. This means that this strategy requires much fewer analyzes than those that would be required for introducing detailed site response in hazard curves and avoids double counting related uncertainties.

In the current nuclear practice and most regulations, seismic hazard is defined at the free-field, where site response is accounted for in a simplified way through Ground Motion Models (GMM). It is then modelled in more detail during the structural response and Soil-Structure Interaction (SSI) modelling step. This approach often leads to double counting and potential bias due to conservative assumptions at the interface between hazard and structural response. To overcome this, a unified approach can be developed where seismic hazard is computed for bedrock conditions while site response is introduced in the structural modelling step. This is illustrated in **Figure 2**. The soil-profile and soil surface ground motion pairs are then used to compute the structural floor response including Soil Structure Interaction.

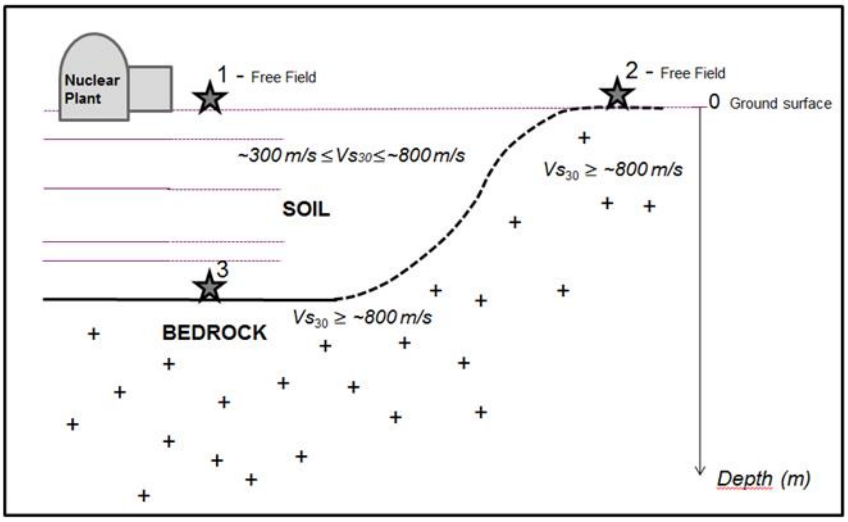

Figure 2. Schematic view of the site configuration and the definition of the « reference or control point » on bedrock (3) and free field (1,2). Figure from (Berge-Thierry, et al., 2017).

The approach presented here is fully in line with findings from SINAPS@ project (Berge-Thierry, et al., 2017) and (Laurendeau, et al., 2017) where a control point at the bedrock level and elaboration of specific GMM for rock site condition are proposed.

Defining the hazard for rock and bedrock conditions requires the availability of appropriate rock GMM. In this respect, it is interesting to acknowledge the recent efforts to develop rock GMM for the computation of hazard on rock and bedrock conditions. For example, Shible et al (2023) recently developed ground motion for rock sites from deconvolved ground-motion models using site response from generalized inversion techniques. Concurrently, recent GMM developers (Al Atik & Abrahamson 2021) provide compatible generic soil profiles that would allow to determine the reference bedrock motion from surface motion. Obviously, despite increasing effort in site characterization, the soil conditions and the parameters governing the seismic wave propagation are not perfectly known. Therefore, it is paramount to carefully assess and propagate uncertainties in the framework of the site response analysis.

1.3. Description of the METIS case study

The goal of METIS case study was to provide a common framework to assess all METIS developments, scientific and engineering results.

The feasibility and benefits of new and improved approaches developed in METIS are assessed, and as much as possible compared to current practice, through application in the METIS case study.

The METIS case study is a hybrid test case involving the relocation of a plant from Ukraine (ZNPP, SSI, SSCs' fragility) to a site in the Tuscany region of Italy (hazard and site response) as described in **Figure 3**. More precisely, the METIS case study site is located in Tuscany, Italy, facing the Tyrrhenian Sea.

Figure 3. Picture of the ZNPP (left) and site location (right) used in the METIS case study

1.4. Opensource tools and data

METIS project builds on existing and new opensource codes, developed within the project (see **Figure 4**). This facilitates dissemination, cross-fertilization and uptake of new methods and tools developed within the project. Sharing knowledge and training new generations of engineers through summer schools, workshops and training sessions is a natural part of the project.

OPENQUAKE calculate share explore	code_aster	salome_meca EXPERIENCE OPEN SIMULATION	OpenSees	SCRAM
Hazard	Multipurpose FEM	Simulation platform (meshing, pre- and post-processing, analysis)	Earthquake engineering FEM	Risk

Figure 4. Existing opensource codes used and developed in METIS project.

- OpenQuake engine is a PSHA code developed and disseminated by partner GEM. It is now used worldwide for PSHA, mainly at national or regional scale. OpenQuake also offers an integrated risk modelling toolkit, to assess exposure to earthquakes of people, livelihoods, and property. The tool is currently used for regional assessments for example in the insurance sector.
- code_aster is a multi-purpose FEM code available with salome_meca platform developed and disseminated by partner EDF since 1989. The opensource code is used and shared with numerous industrial and academic partners, mainly in Europe.
- OpenSees, developed by the University of California at Berkeley since 1989, is a FEM software dedicated to simulating the performance of structural and geotechnical systems subjected to earthquakes. The goal of the OpenSees development is to improve the modelling and computational simulation in earthquake engineering through open-source development. It is used by industry for engineering studies but also by academia for research purposes.
- SCRAM is a command-line Risk Analysis Multi-tool allowing for fault and event tree analyses used for PSA of NPP. It has been further developed and used to develop new opensource tool SCRAM++ and SCRAM_NG by METIS partners to assess new approaches perform prototype PSA computations for METIS case study.

New codes are made available on the openMETIS GitLab repository: https://gitlab.pam-retd.fr/openmetis.

New opensource tools available on the openMETIS GitLab repository include:

- PyPSHATest, a new tool for Testing and comparing PSHA output to observations is now available on openMETIS. It can be readily used for any hazard model developed with OpenQuake. More tools for ground motion simulation and vector PSHA will be added (METIS D4.5).
- FRAGREG: Fragility computation by the cloud-regression approach (METIS D6.8)
- PRA tool (METIS D7.5)

Data and reports are available at openMETIS on ZENODO: Search EURATOM METIS

2. Seismic hazard analysis on rock

In this Chapter, we outline the main objectives and achievements undertaken within METIS WP4. The reader interested in a broader illustration of the results achieved within this WP can refer to METIS Deliverable D4.7 "Summary of WP4 activities and insights".

2.1. Objectives

The objective of WP4 was to improve and expand our capabilities to forecast the expected levels of shaking by enhancing various components of seismic hazard analyses for nuclear installations.

We focused the research on improving components of both probabilistic and physics-based approaches. Given the extensive literature on this subject endorsed by the scientific and technical communities, we did not concentrate on procedural aspects of PSHA. Given the project's constraints, we did not manage to follow the SSHAC process while implementing the hazard model for the METIS case study. Nonetheless, the site-specific study endorsed the principles of the SSHAC philosophy of capturing the center, body, and range of technically defensible interpretations with the time and resources available.

The first task of WP4 was to improve the approaches currently used to decluster catalogues to create collections of historical events whose occurrence can be considered independent from other earthquakes. Our goal has been to reduce the subjective component of choosing a declustering algorithm, as currently done while characterizing earthquake occurrence using statistical approaches.

A second broader task pertained to extending and improving the approaches to compute probabilistic seismic hazard. We wanted to describe hazard results more comprehensively by implementing the most advanced methodology for computing the Conditional-Spectrum (CS), in the OpenQuake Engine. We also aimed to find new methods for computing Vector-Valued PSHA (VPSHA) that are more computationally efficient than the available approaches. Overall, the ambition was to provide a more robust and consistent characterization of the frequency content of the hazard computed and - most of all - allow for a more efficient selection of hazard-consistent time histories.

In traditional PSHA, the contribution of aftershocks is usually neglected as the calculation considers only the contribution of mainshocks. Recent events showed a non-negligible contribution to the overall level of shaking observed during an earthquake sequence. Therefore, we wanted to test the extent to which the contribution of aftershocks can be substantial when assessing the risk of a nuclear installation. For this purpose, we aimed to implement various approaches to incorporate the contribution of aftershocks into seismic hazard.

While developing PSHA models for nuclear installations, significant importance is placed on capturing the whole spectrum of epistemic uncertainty to represent the center, body, and range of technically defensible interpretations. Still, calculating hazard for the millions of individual realizations of the resultant composite logic tree is not feasible. Therefore, sampling this complete logic tree becomes necessary to calculate hazard estimates for only a subset of the realizations. To improve the computational aspects of PSHA, a task was devoted to enhancing the propagation and computation of epistemic uncertainties.

The importance of testing PSHA models and the challenges associated with this testing are well recognized in the current scientific literature (Gerstenberger et al., 2020, and references therein). Generally, testing the hazard at a single site is not feasible due to the limited time window of direct and/or indirect ground motion measurements. To overcome the issue of data paucity, it is usually necessary to trade space for time and utilize observed exceedances of ground motion across many sites to provide a dataset large enough to calculate the fit of models to data for return periods of engineering relevance. This space-time substitution, the ergodic assumption, was adopted within WP4 to develop a full suite of methods to check hazard models against observations.

Current strong-ground motion databases contain limited recordings for many magnitude-distance combinations relevant to seismic hazard analysis. This limitation can be partially overcome by replacing observed time histories with simulated ones. In the literature, we find various approaches to performing physics-based analyses. In WP4, we dedicated a task to comparing and testing different methodologies and checking the extent to which the computed time histories match engineering requirements.

2.2. Methodologies

We developed a new method to test and quantify the Poissonian nature of an earthquake catalogue and compare the performance of alternative declustering algorithms. This information allows an informed decision about the relative balance between the number of earthquakes retained by a given declustering algorithm and the Poisson nature of the resulting declustered catalogue. This can be used to select the declustering algorithm(s) to characterize the seismic sources.

The proposed testing method considers whether the seismicity's temporal and spatial distribution in a declustered catalogue has statistical properties like that of a synthetic Poisson catalogue (that has the same temporal and spatial distribution and contains the same number of earthquakes). Specifically, this new method computes the inter-earthquake spatiotemporal distances between each event in each catalogue, described as a probability mass density function for the catalogue. A strongly clustered catalogue will have more similar inter-earthquake spatiotemporal distances than a synthetic Poisson catalogue. Using this difference, we calculate a Poisson test score for a catalogue between 0 and 1, where a higher value indicates a more Poisson nature.

We improved the logic tree processing in PSHA. We incorporated an option into the OpenQuake Engine to utilize a Latin Hypercube sampling method instead of a traditional Monte Carlo approach. Furthermore, we added the possibility of using the weights before or after the sampling. In the second phase, we developed a new approach that computes seismic hazards for each single source-specific logic tree and combines the results using discrete distributions via a convolution approach. Correlated uncertainties, for example, as implied by two faults sharing the same variability of the seismogenic thickness, are explicitly accounted for by splitting the sources into groups, where each group contains the sources sharing correlated epistemic uncertainties. This new method for propagating epistemic uncertainties provides results consistent with traditional approaches and computes results more efficiently.

We developed two new methodologies for computing VPSHA. The first approach expands the indirect approach proposed by Bazzurro et al. (2010). We improve calculation efficiency by reducing the size of the multidimensional matrix traditionally used to store the disaggregation results concerning GMMs explanatory variables. In this new method, we store the occurrence rates of discrete combinations of the median values and corresponding standard deviations of the two intensity measure types selected into a four-dimensional kernel matrix. This approach operates as a post-processing tool that reuses the results of a previous classical PSHA for the same site and set of IMTs. The second approach for VPSHA is a handy yet rigorous approach that allows for obtaining vector hazard using the copula approach. This approach only requires scalar hazard curves and the correlation coefficient between the intensity measure types considered to compute vector hazard in a post-processing step.

We added to the OpenQuake Engine method 4, the most complex approach proposed by Lin et al. (2013) to compute the conditional spectrum. This approach integrates the contributions from the ruptures in all the realizations admitted by the hazard model logic tree.

We implemented two distinct approaches to account for the contributions of aftershocks in probabilistic seismic hazard. The first one adjusts the occurrence rates in hazard models based on mainshocks to account for the contribution of aftershocks. This method assumes that all the aftershocks occur on ruptures within the mainshock-based seismic source model. The second approach implemented computes hazard for an aftershock sequence given the occurrence of a mainshock. The mainshock can be either an earthquake that occurred in the past or an event selected using traditional results of hazard disaggregation, such as a magnitude-distance disaggregation matrix.

We developed methods to quantitatively compare the results of alternative seismic hazard models for a region and assess whether the PSHA model estimates are consistent with observed ground motions (see Weatherill et al., 2024). We collected the methods implemented into the PyPSHATest toolkit, an open-source Python toolkit for quantitative model-to-model and model-to-observation comparison probabilistic seismic hazard results. The toolkit is available on the openMETIS GitLab (see https://gitlab.pam-retd.fr/groups/openmetis).

To model seismic hazards using physics-based approaches, we introduced various simulation methods and used them to generate synthetic ground motion time histories on bedrock. We then compared the results of a suite of open-source tools for performing physics-based simulations, including stochastic, empirical, and hybrid models, focusing on engineering applications.

The following approaches were analyzed alongside the validations presented by their authors:

1. The Irikura recipe uses Empirical Green's Functions (EGF). This approach is used worldwide to simulate large crustal earthquakes and in Japan for seismic safety evaluations of nuclear power plants (IAEA 2015). It was validated using the 2007 Mw 6.6 Chuetsu-Oki earthquake and the strong ground motions recorded at the Kashiwazaki-Kariwa Nuclear Power Plant (KK NPP) site.
2. A 3-D stochastic physics-based approach using the Southern California Earthquake Center (SCEC) Broadband Platform (BBP) and tailored for Europe. We validated the approach by comparing the simulated ground motions with the recorded and empirical GMM of the 2016 Mw 6.2 Amatrice earthquake of Central Italy. Second, the consistency of the variability (standard deviation) of the simulations with empirical GMM estimates using a database with simulated ground motion time histories based on a stochastic catalogue of ruptures for the Rhine Graben area.
3. We validated a stochastic ground motion simulation approach based on an enhanced Otarola method by comparing the simulations with recordings from various events. We used this methodology to produce a database of simulated time histories for the METIS test site.
4. Recorded ground motions corrected for the site term. This approach applies a physics-based correction to remove site effects from surface recordings to obtain the underlying bedrock motion. We validated this approach by comparing results against recordings at downhole sensors at KiK-net sites.
5. The combination of spectral decomposition of ground motion with empirical Green's function simulation techniques to simulate region-specific reference bedrock time histories. This method is referred to in D4.3 as the "Seister approach". This approach was validated based on a large set of earthquake recordings in Central Italy (Ameri et al., 2024)

2.3. Case Study Application

For the purpose of METIS case study applications, a site on the western coast of Tuscany, Italy has been chosen (as described in section 1.3). Due to the lack of an existing site-specific seismic hazard study for the METIS hybrid site, a relatively simple seismic hazard model was produced to test and apply the various methods and tools developed in the METIS project.

The newly developed catalogue Poisson test method was applied to investigate the performance of different declustering algorithms for an earthquake catalogue relevant to the METIS case study site in Central Italy. Five established declustering algorithms, including window and nearest neighbor approaches, and the new declustering algorithm developed within subtask 4.11 were applied to the International Seismological Centre bulletin catalogue of Mw≥3.5 earthquake events between 1960 and 2020. These inter-earthquake spatiotemporal distances of each declustered catalogue were compared to a synthetic Poisson catalogue generated for the region, and Poisson test scores were determined for each declustered catalogue.

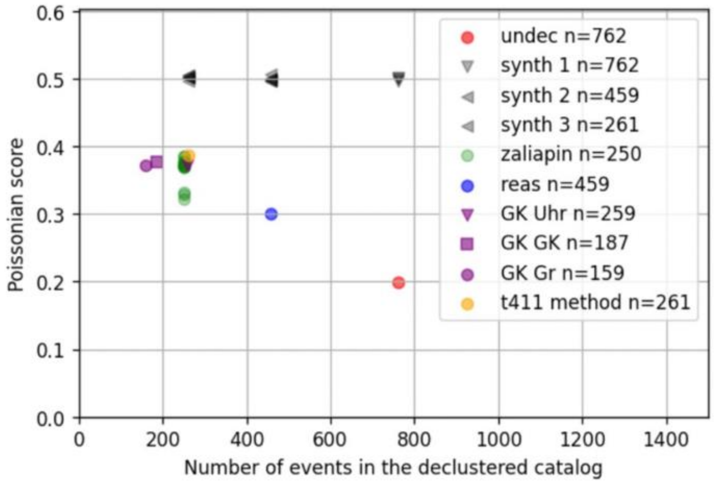

Figure 5. Poisson test score for the METIS case study site undeclustered catalogue (red circle) each investigated declustering algorithm (colored circles and triangle) as well as for two sets of synthetic catalogues with three different numbers of events (grey triangles).

To demonstrate the benefit to PSHA from the information gained by the catalogue Poisson test score, each of the six declustered catalogues was developed into the seismic source characterization for the METIS case study and a site within the Apennine chain (see **Figure 5**). The European Seismic Hazard Model 2020 (Danciu et al., 2024) area source geometries were used, and hazard calculated using the OQ Engine and various modelling options. The results revealed that the impact of the declustering approach on the hazard results is greater for the site located in the more seismically active region, closer to many earthquake clusters, than for the site in the stable region where the declustering removes only a few earthquakes. Therefore, the Poisson test score method developed during this METIS work package is most valuable when assessing the hazard of areas with higher past seismicity. Nonetheless, this methodology was applied to construct the seismic source characterization for the METIS case study.

All the methodologies developed within WP4 to enhance PSHA calculations were tested in the METIS case study. A conditional spectrum, with conditional mean and standard deviation, was calculated for a given spectral acceleration period, integrating contributions from the ruptures in all realizations admitted by the hazard model logic tree (Lin et al., 2013). The analysis was conducted for a spectral acceleration at a period of 0.2 s and for an annual probability of exceedance of 0.001 (1,000 years return period, approximately) and then 0.0001 (10,000 years return period, approximately) using the cross-correlation model of Baker and Jayaram (2008).

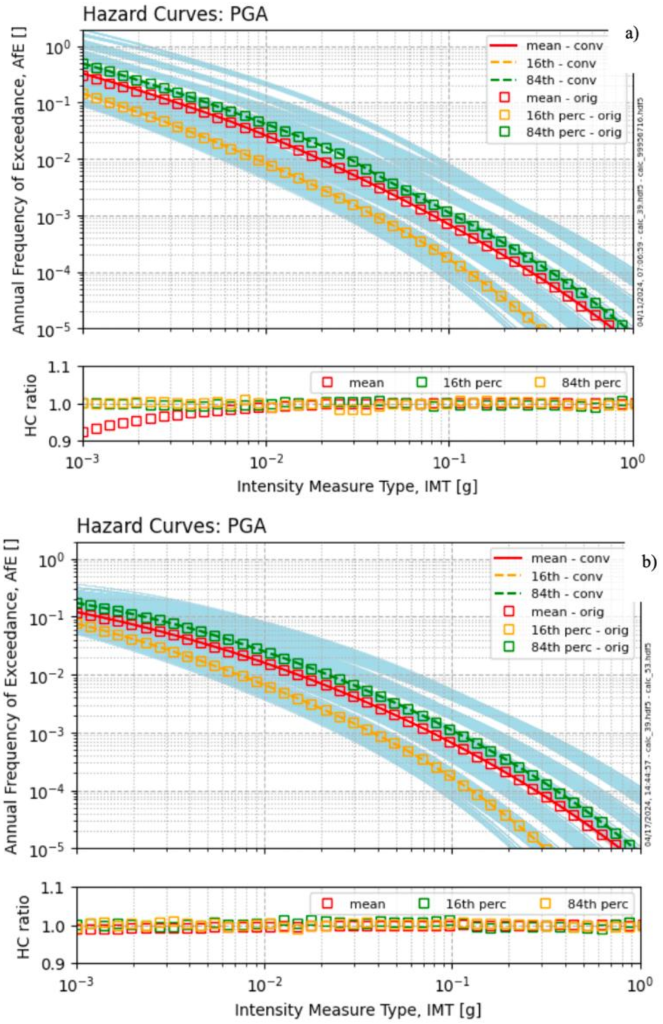

Figure 6. Comparison between the mean, 16th, and 84th percentile hazard curves for PGA representing the annual frequency of exceedance at the METIS test site as obtained from the OpenQuake Engine with the traditional calculation approach and the new approach proposed for the propagation of epistemic uncertainty. In both plots, the lower panel compares the ratio of the original result over the corresponding one computed using the proposed new approach. [a] Comparison computed considering all the sources [b] Comparison computed considering only the area source encompassing the site TSZ050.

We computed hazard results for the METIS case study using the new method for propagating epistemic uncertainty. **Figure 6** compares the hazard curves computed using the OpenQuake Engine and the ones obtained using this new approach to propagate epistemic uncertainty. Panel a) shows the comparison between the mean hazard curve computed with the OQ Engine and the histograms representing the distribution of the probability of exceedance using all the sources included in the hazard model. Plot b) shows the same comparison but only considers the results obtained using the zone encompassing the site, TSZ050. This is the zone that controls almost entirely the hazard at the site. Overall, the proposed methodology's performance and implementation appear successful. However, further improvements and tests will be added to check for possible error leakage for very low shaking values (not of engineering relevance).

The methods developed for considering aftershocks were applied to the hazard model for the site, and the impact on the hazard results of incorporating aftershocks into the PSHA model was investigated. The hazard curves for the METIS case study site show a substantial increase in seismic hazard when aftershocks are considered, compared to conventional PSHA without considering aftershocks. The increase varies with the return period and the maximum magnitude of the aftershock. Within WP6 and WP7 of the METIS project, it has been decided that to account for the contribution of aftershocks while performing the Probabilistic Safety Analyses (PSA) of nuclear power plants, it is more appropriate to compute the conditional hazard produced by the aftershock sequence triggered by a mainshock. To provide results compatible with this requirement, we developed an ad-hoc methodology that computed the hazard from a sequence of aftershocks given the occurrence of a mainshock. **Figure 7** shows an example of the results computed using the newly developed methodology for the calculation of conditional aftershock hazard.

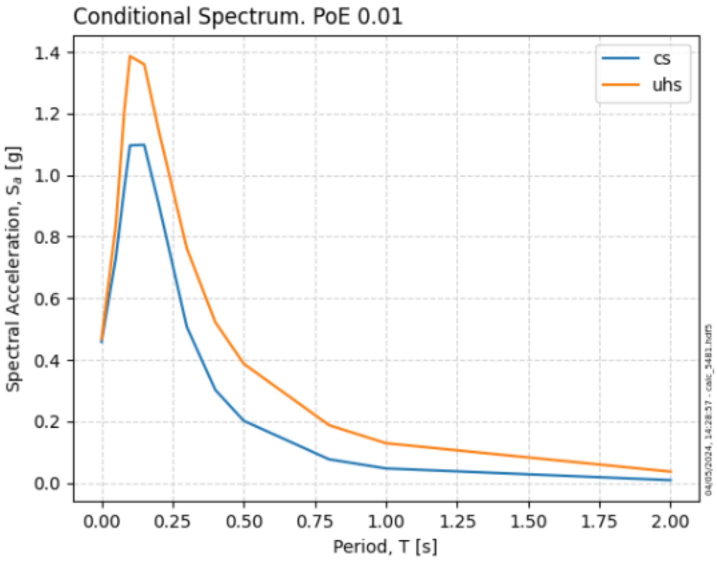

Figure 7. Conditional spectrum with a 1% probability of being exceeded in the 30 hours following the occurrence of the mainshock. The model used to compute this, is the mean model of the many simulations of the aftershock sequence. The mainshock is the rupture, which makes the largest contribution to the mainshock hazard for PGA, with a return period of 1e4 years. The conditioning period is PGA.

The enhanced Otarola and Seister approaches, respectively, were selected as the preferred approaches and applied to the METIS case study site, where the moderate seismicity of the region is characterized by a limited amount of data and available rock motions. A series of steps were followed to generate the database of simulated ground motions for the METIS case study using the Otarola approach. First, a set of input parameters (for a similar model) was obtained from the literature for the region of interest. Next, a set of ground motions recorded in the region of interest was selected for its use as a reference in calibrating these input parameters to accommodate the differences with the enhanced Otarola method. Finally, the calibrated model was used to generate a database of simulated ground motions populated with new earthquake scenarios consistent with those obtained from the disaggregation of the hazard computed for the METIS case study. **Figure 7** compares the spectral accelerations at different frequencies for simulated and recorded scenarios and the ground motion models considered in the PSHA of the METIS case study. In the Seister approach, first, the nonparametric spectral decomposition approach (also called the Generalized Inversion Technique, GIT) was applied to separate the contribution of source, path, and site from the observed Fourier spectra of a dataset of recordings covering central Italy. The average source and site effects are removed from observed small-magnitude recordings in the target region through deconvolution in the Fourier domain. This way, the obtained deconvolved signals represent path term only (effectively EGFs). Then, we couple the EGFs with k-2 kinematic rupture models for target scenario events. For each target magnitude, a set of rupture models following a ω-squared source spectrum is generated by sampling the uncertainties in kinematic source parameters. The proposed approach is validated using recorded ground motions at reference sites from multiple earthquakes in Central Italy (Ameri et al. 2024). The power of this approach lies in its ability to map the path-specific effects into the ground-motion field, providing 3-component time histories covering a wide frequency range without the need for computationally expensive approaches. The simulated spectral accelerations from the synthetic time histories were compared to the empirical Lanzano et al. 2019 and 2022 GMMs for Italy.

2.4. Results and Findings

The results obtained in WP4 align with the original goals of the METIS project.

The various groups involved successfully completed the planned activities. In addition to the original plan, work was done to address the lack of a site-specific seismic hazard model and implement a second methodology for assessing the aftershock hazard that better aligns with the probabilistic approach currently used to evaluate the risk of nuclear installations.

Most of the new methodologies implemented were effectively applied at the METIS test site, either for constructing components of the hazard input model or calculating various hazard results.

One analysis is insufficient to exhaustively verify the effectiveness and efficiency of a newly developed approach. Nonetheless, many of the new methods proposed received considerable interest and will be further developed in subsequent projects.

The research on physics-based strong motion simulation for engineering applications, considered a wide spectrum of approaches. The Otarola and Seister methods helped build a database of simulated time histories alternative to collections of recordings from real events.

2.5. Best Practices and Lessons Learnt

The methodology developed for testing catalogue declustering is a first step towards abandoning the current practice of relying on methods that—although extensively used—should be considered outdated, even just for the limited information on which they are based. The methodology proposed in METIS offers the possibility of more comprehensively analyzing the impact of declustering on the mean occurrence rates and, ultimately, on the computed values of seismic hazard.

The methodologies implemented in the OpenQuake Engine to propagate epistemic uncertainty expand the software's current capabilities. The new approach, which computes the hazard at each site independently for each source, aligns with the strategies already adopted in some of the in-house software used in site-specific projects and improves efficiency in dealing with large logic tree structures. It also offers opportunities to reduce the current separation between the hazard models used to assess hazard at a national scale and site-specific studies.

The proposed methods for computing vector-valued PSHA provide valid and computationally efficient alternatives to traditional approaches published over the last two decades. Overall, their application at the METIS test site demonstrated adequate flexibility and computational efficiency. The availability of VPSHA in publicly accessible code (the OpenQuake Engine) will hopefully encourage broader adoption of vector-valued methods for seismic hazard analysis. The implementation in the OQ Engine of the most sophisticated algorithm for computing the conditional spectrum extends the suite of results that can be used to assess hazard at a specific site more comprehensively.

Along the same line, the methods proposed to assess the hazard by incorporating the contribution of aftershocks offer new opportunities for a more comprehensive characterization of seismic hazards. The approach that computes the hazard conditionally to the occurrence of a mainshock, offers opportunities for more widespread integration of physics-based components modelling the spatial distribution of aftershocks and—potentially—of the shaking.

Hazard testing methods expand the current capabilities of comparing forecasted hazard values against observations and more accurately defining and designing benchmark tests.

Finally, the extensive analysis of various physics-based methods currently available for simulating ground motion identified some promising methodologies that, on one side, could be used more to complement the database of empirical observations and, on the other one, to directly compute the expected levels of shaking (at least for certain frequency ranges).

2.6. Dissemination, Other Resources and Impact

Deliverables 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, and 4.7 of the METIS project provide detailed information about the analysis, methodologies, and tests completed within WP4.

Conference proceedings:

- Pagani, M. et al. (2024) - METIS Project: GEM's contributions to the Hazard Work Package. Proceedings of the *18th World Conference on Earthquake Engineering*.
- Weatherill G., et al. (2022). "Comparing and Testing Probabilistic Seismic Hazard Models at National and Regional Scale: Examples from France, Germany, and the ESHM20". In Proceedings of the *3rd European Conference on Earthquake Engineering & Seismology*, Bucharest, Romania
- Zentner, I., Pagani, M., Daniel, G, Bazzurro, P., (2024) METIS Methods and Tools Innovation for Seismic risk assessment –new approaches to perform vector hazard analysis and possible applications in seismic risk assessment. *SMiRT27*, Yokohama, Japan

Papers published in scientific journals:

- Ameri, G., Shible, H. & Baumont, D. Simulation of region-specific ground motions at bedrock by combining spectral decomposition and empirical Green's functions approaches. *Bull Earthquake Eng*, 22, 5863–5890 (2024). https://doi.org/10.1007/s10518-024-01988-9
- Pagani, M. et al. (2025) - POINT: A New Computationally Efficient Methodology for the Propagation of Epistemic Uncertainty in Probabilistic Seismic Hazard Analysis. *In preparation*
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Results available on the METIS area on Zenodo:

- OpenQuake Engine METIS test study seismic hazard output datastore (https://zenodo.org/records/10932901)
- METIS case study synthetic scenario ground motion database (https://zenodo.org/records/10692783)

Webinars:

- Pagani, M. (2023). New tools in OpenQuake Engine. METIS webinar, June 30, 2023.
- Weatherill, G. (2023). PSHA (Probabilistic Seismic Hazard Assessment) Testing. METIS webinar, July 7, 2023.

2.7. Key Contacts

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3. Rock ground motion selection for engineering analyses and site response

3.1. Objectives

Ground motion record selection plays a crucial role in evaluating seismic risk, as it is the link between the seismic hazard at a site (likelihood of experiencing an earthquake ground motion intensity) to the expected structural response and potential damage to structures. These ground motion records contain the acceleration information of different events and can be characterised by different Intensity Measures (IMs). Here, the task is to ensure that selected records are "hazard consistent," meaning that they realistically represent those that can be generated by the seismic events likely to occur nearby the specific location of interest.

In seismic risk assessment, structural response is typically assessed using “fragility functions,” which predict the probability of reaching or exceeding specific damage states for a given ground motion intensity. These functions can be developed either empirically, based on observations or experiments, or analytically, through the use of numerical models. Developing accurate analytical fragility functions requires running simulations that use real earthquake records, chosen to be hazard-consistent with the site. This ensures that these records are representative of the site’s seismic hazard. Hazard-consistent ground motions minimize the potential of obtaining biased fragility functions and, in turn, biased risk estimates, and help engineers to accurately predict structural performance under realistic seismic conditions.

The primary objective of this work package (WP5) is to implement new approaches for scenario-based record selection and apply them to the METIS case study. We aim to provide ground motion sets that reflect the seismic hazard at the METIS project site under rock site conditions. The previous work package (WP4) describes the PSHA work which was performed to characterise the rock hazard at the METIS case study location, setting the basis for selecting appropriate ground motions for rock conditions. These sets are then utilized as input to site response analysis to obtain the soil surface ground motion sets following the METIS strategy that will be described later in this section. The surface records are then used for Non-Linear Time History Analysis (NLTHA) of numerical models of SSCs, providing a detailed understanding of the responses of nuclear facility structures to seismic events controlling the hazard at the site (WP6).

A major task within this objective is to ensure hazard consistency on rock conditions using advanced record selection techniques. As discussed in the next subsection, one such technique is the Conditional Spectrum (CS) method, which accurately captures the variability in ground motion by considering the unique shape and spectral characteristics of seismic waves at the site. This approach helps capture the potential range of seismic intensities and frequencies a site might experience, thereby providing more complete and reliable risk estimates. An extensive description of this and other methods can be found in Deliverable D5.1. Sensitivity and parametric studies have been performed with simple structures (SDOF) to compare the fragility functions obtained using different hazard-consistent ground motion sets. For instance, it evaluates the legitimacy of utilizing also ground motions recorded at soil sites, scaled ground motions (adjusted in amplitude to match certain intensities), and synthetic ground motions. This assessment, extensively described in D5.1, provides flexibility in situations where rock site records may be limited, which is often the case especially for the larger intensities that are expected to be observed very rarely. These alternative record selection and simulation techniques are explored in WP6 to understand their impact on fragility functions of SSCs and, therefore, beyond the simple SDOFs considered here.

Another objective involves the development of ground motions sets that could be generated by earthquake sequences or clusters to be used for structural analysis of SSCs. Recent damaging sequences—such as those observed in Christchurch, Central Italy, and Turkey—have underscored the need to account for aftershocks (AS) and triggered events, which often follow mainshocks (MS) and can contribute to increasing risk. In this work package, mainshock-aftershock (MS-AS) ground motion sets are prepared to capture these sequence effects and enable back-to-back structural response assessment, supporting the derivation of fragility curves that reflect cumulative damage potential. The ground motion selection for clustered seismicity is elaborated on in Deliverable D5.2, with the final set of motions described in D5.5.

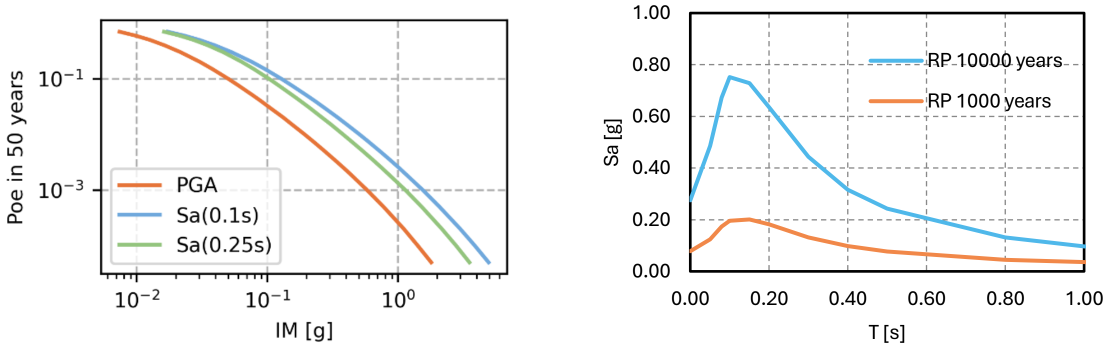
As mentioned earlier, in addition to selecting site-specific rock hazard-consistent records, this work package also addresses site response to obtain soil surface ground motion sets for engineering studies. The overall methodology with different approaches for 1D, 2D and 3D site response and criteria to decide whether 1D or multidimensional analysis are required for a specific site are presented in deliverable D5.3. In particular, for the METIS case study, which was identified as a 1D configuration, we have developed and implemented a comprehensive strategy for the propagation of soil and ground motion uncertainty in 1D linear equivalent (LEQ) site response analysis. To establish this, we performed an extensive suite of parametric analyses by comparing the 1D LEQ site response to nonlinear 1D and 2D analyses. The detailed analyses and case study application results are presented in the Deliverable D5.4.

3.2. Methodologies

3.2.1. Ground motion selection methods

This subsection presents key methods for selecting ground motion records that reflect the site's hazard and examines their basis in the probabilistic seismic hazard analysis (PSHA) conducted in the METIS project.

The results of hazard analysis are traditionally represented through the hazard curve (**Figure 8a**), which relates the probability of exceeding a certain value of intensity in a certain time interval (usually 50 years). The hazard curve can be computed for different intensities, such as the spectral acceleration values at different periods, denoted as $S_a(T)$, or the peak acceleration of the ground motion (Peak Ground Acceleration or PGA). Taking all the values of different periods for the same probability of exceedance (or return period) results in the Uniform Hazard Spectrum (UHS, see **Figure 8b**). However, this UHS does not have the shape of spectra of realistic ground motions, as it represents the aggregate of all events for all periods simultaneously. Therefore, to generate realistic spectral shapes, one must understand the types of events that cause the different intensities at each return period. This is done through the disaggregation of the seismic hazard, which provides insight into the most contributing magnitudes (M) and distances (R) of earthquakes that might affect the site for that intensity level.



(a) (b)

Figure 8. (a) Hazard curve for PGA, Sa(0.1) and Sa(0.25) and (b) Uniform Hazard Spectra for 1,000 and 100,000 year return periods.

Different methods with different levels of accuracy and sophistication have been used in the past to select ground motions that are faithful to the earthquake scenarios controlling the hazard. Among these, those that provide a ground motions with higher fidelity of hazard consistency are the Conditional Mean Spectrum (CMS), Conditional Spectrum (CS), Generalized Conditional Intensity Measure (GCIM), and Conditional Spectrum with Magnitude and Distance parameters (CS-MR) (see Deliverable D5.1 for details). These methods use Ground Motion Models (GMMs) to generate a possible mean spectral shape and its associated dispersion based on both the event and site's characteristics. Each of the aforementioned methods are briefly described below:

1. **Conditional Mean Spectrum (CMS)**: The CMS approach (Baker, 2011) can be utilized to select ground motions that possess a given value of a pre-selected IM and a mean spectral shape that aligns with the site's expected spectral accelerations based on the earthquake scenarios controlling that level of hazard as per the PSHA. This method allows the selection of ground motions that, on average, are representative of the hazard-controlling earthquakes but does not provide the means to account for the variability of their spectral content.

2. **Conditional Spectrum (CS)**: The CS method (Jayaram et al., 2011) builds on the CMS by incorporating variability across spectral accelerations at various periods, thereby providing a more realistic depiction of the potential ground motions consistent with the a specified IM level. The CS uses a broad range of events in PSHA disaggregation to create a target spectrum that includes mean values and variability for each spectral ordinate.

3. **Generalized Conditional Intensity Measure (GCIM)**: The GCIM approach (Bradley, 2010) expands the CS to include to consistency of other intensity measures beyond spectral acceleration, such as Arias Intensity (AI), Cumulative Absolute Velocity (CAV), and duration. This method allows for the selection of ground motions with distributions of multiple IMs consistent with the hazard at the site, capturing additional characteristics of ground motion that may significantly affect structural response.

4. **Conditional Spectrum with Magnitude and Distance Parameters (CS-MR)**: The CS-MR (Spillatura et al., 2021) further refines the CS method by accounting directly for the M-R parameters identified in PSHA disaggregation. By doing so, it incorporates the effects of the parameters of causative earthquakes as proxy for selecting records with duration and other M-R-dependent metrics beyond spectral content consistent with the events that may affect the site.

In the METIS project, the Conditional Spectrum (CS) method was chosen because it ensures a spectral shape that reflects both the mean and variability in spectral accelerations at various periods and it is a compromise between simpler but less accurate methods (e.g., CMS) and more complex ones (GCIM and CS-MR). The hazard consistency is achieved through several steps:

1. Initial PSHA provides the spectral acceleration, $S_a(T^*)$, at the target reference oscillator period for the desired hazard level. Disaggregation then identifies representative earthquake scenarios (magnitude, distance, and epsilon values) that contribute most to the occurrence of $S_a(T^*)$ at this hazard level, creating a basis for conditioning the target spectrum. This target spectrum is generated using a GMM that takes as an input the different earthquake scenarios characteristics. Alternatively and preferably, as done in this study, one may consider the contribution of all scenarios contributing to that intensity level, and not just the most prominent.

2. Using the selected conditional period T*, the CS is computed by deriving conditional means and standard deviations across all other vibration periods. These are calculated based on the correlation between each spectral ordinates $S_a(T_i)$ and the conditioning period $S_a(T^*)$, allowing variability to be incorporated.

3. This results in a target spectrum that reflects both the expected response spectrum mean and variability as shown by the black curves of **Figure 9**, offering a full picture of ground motions more relevant for the specified intensity level.
4. After defining the CS target, a pre-defined number of records are selected from a database to best match the mean and variability of this spectrum. An iterative "greedy" optimization technique is then applied, where records are systematically evaluated and replaced if needed to improve the match with the CS target. The Sum of Squared Errors (SSE) that evaluated the discrepancies in both mean and standard deviation is a common metric to quantify the misfit.

This operation results in a set of ground motions with different spectral shapes that when used together has the same distributions as the targets defined, as shown in **Figure 9a**. This way it is ensured that these records are aligned, in a spectral sense, with the results of the probabilistic hazard analysis and can be used to accurately assess the structural demands of the structures and equipment located at the site for which the hazard was computed.

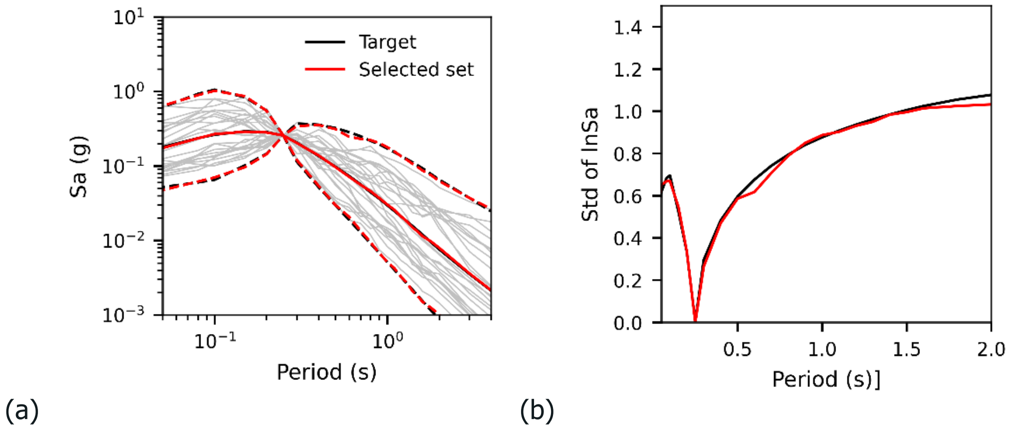


Figure 9. (a) Target mean spectrum and bounds with selection and (b) target and selected dispersion.

3.2.2. Record selection for clustered seismicity

For clustered seismicity, the aim is to represent complete seismic sequences, including both mainshocks and other related earthquake (i.e., foreshocks, aftershocks, and triggered events) instead of treating the largest-magnitude events only as independent occurrences. This process integrates the Conditional Spectrum (CS) for mainshocks, while generating realistic aftershock sequences using the Epidemic-Type Aftershock Sequence (ETAS) model using the methodology described next:

1. As explained in Subsection 3.1.1, the same CS approach is used to select mainshock ground motions that match the spectral shape associated with the hazard at a specific intensity level. This involves PSHA disaggregation to identify key parameters such as magnitude (M), distance (R), and epsilon (ε), which help determine the target spectral shape.
2. For each mainshock, aftershock sequences are simulated using the ETAS model proposed by Ogata (1988). This model simulates aftershock sequences by assuming that each mainshock (or "parent" event) triggers a series of ("children") earthquakes, which can in turn trigger additional events. The model is stochastic, and aftershocks are generated based on the magnitude and location following some region-specific parameters. To ensure the relevance of the aftershocks for engineering purposes, only those above a certain magnitude and within an appropriate distance range are retained.
3. For each mainshock ground motion selected using a CS approach as explained above, aftershock ground motions are then selected using the MSAS-CS approach. This approach ensures that the response spectrum of the aftershock of given M and R is statistically consistent with the spectral

shape of the corresponding mainshock ground motions. This step is needed following the observations of the work presented in (Papadopolous et al 2020) which showed that the spectral shape of the aftershock ground motion is positively correlated to that of the mainshock.

The MS-AS-CS consists of generating a target AS conditional spectrum based on the aftershock's causative parameters (M and R, coming from ETAS), as well as the response spectrum of the MS ground motion along with its causative M and R parameters. The process, thoroughly explained in the Deliverable D5.2, modifies the mean spectrum coming from the GMM depending on the MS's ground motion response spectrum shape, using the correlations statistically derived between the spectral ordinates of past MS and AS ground motions, to give it a more realistic shape. This results in an MS consistent AS conditional mean spectrum.

4. Finally, a single ground motion is selected to match the target MS-AS CS. This is repeated for each AS in the sequence.

This exercise results in sets of MS consistent and site hazard consistent MS-AS ground motion pairs that can be used to perform back-to-back dynamic analyses on structures. For more information, please refer to Deliverables D5.2 and D5.5.

3.2.3. Site response to obtain surface ground motions

Once the ground motions at surface rock are selected, they are converted to surface soil ground motions by (i) obtaining an equivalent bedrock motion including rock attenuation and (ii) running a numerical model representing the characteristic soil profile of the site. The modelling approaches varies according to the geometrical complexity of soil stratigraphy and soil/bedrock interface across the site as well as the nonlinearity level developed in the soil shallow layers. The state of the practice in this domain is to consider the ground motion at the bedrock as vertically propagating plane wave and horizontally layered soil stratigraphy. Under these hypotheses, surface ground motions can be obtained by a 1D wave propagation model. However, for most configurations soil non-linear behaviour develops even for moderate seismic loads which is why it has to be accounted for. In addition, despite ever increasing increase in knowledge and available field data, the uncertainty related to the site configurations (layers and properties) needs to be considered in a probabilistic framework, in addition to the variability of the seismic ground motion.

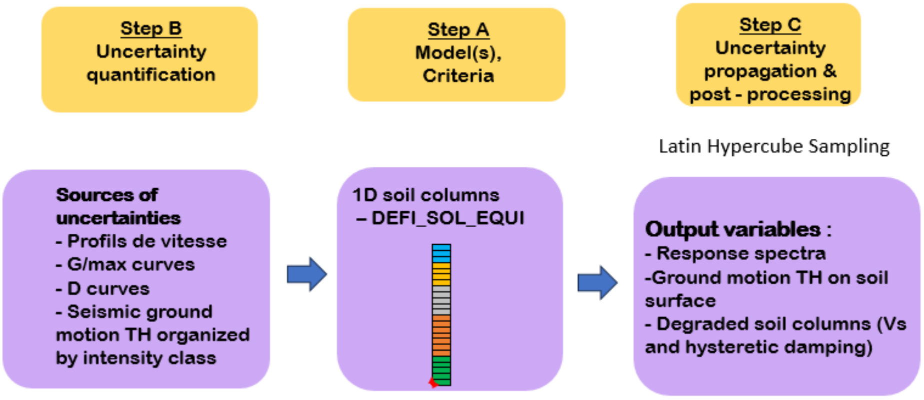


Figure 10. Overall view of the uncertainty analysis with the 3 steps: model definition, uncertainty quantification & propagation and post-processing of probabilistic results.

In addition, 1D vertical wave propagation conditions are not met for every site and more complex modelling approaches (both in terms of wave propagation modelling and site geometrical configuration) can be deployed. The project has also proposed strategies to assess the validity of the 1D assumption and to investigate the ability to identify 2D and 3D site effects have been proposed:

- using earthquake-based criteria when seismic records but no site-specific information is available
- and using transfer function variability when additional site-specific information is available.

This is described with more detail in D5.3. In addition, the project has developed or tested with FE solver code_aster two main approaches for this case:

- **Vertical incidence plane wave excitation and the Free-Field Boundary Condition (FFBC):** The ground motion of reference can be defined in a form of an acceleration time history at bedrock, either directly from a PSHA analysis (selection/generation of accelerograms, in correspondence with the strategy developed on the METIS project), or from a physics-based simulation. In this case, vertically polarized plane waves are considered for the base of the model, along with the FFBC (on the lateral boundaries of the domain.
- **3D ground motion excitation and the Domain Reduction Method (DRM) approach:** A more advanced 3D boundary condition that allows the consideration of the spatial variability of the ground motion as an input to the numerical model, was initially introduced as the Domain Reduction Method (DRM) approach. It consists of a two-steps weak coupling approach where the complete 3D wave field obtained from a source-to-site auxiliary domain simulation is replaced by equivalent nodal forces to be exerted on the boundary surface of a reduced domain, providing a realistic 3D definition of the seismic excitation. In practise, the advantage of the DRM approach lies in the fact that each step of the simulation can be solved separately with an appropriate numerical tool and based on the limitations of each problem. The spectral element method (SEM) coupled to finite element method (FEM) as implemented in (Korres, et al., 2022), was used and the FEM modelling part was adapted during the project for HPC under a domain decomposition framework (Tardieu, Alves Fernandes, & Devesa, 2019), where the whole domain is partitioned into several overlapping sub-domains, and each sub-domain is processed separately by a MPI process.

For small to moderate shear strains, soil nonlinearity can be considered in a simplified manner by a classical Linear Equivalent approach, which also relies on a 1D modelling hypothesis. Nonlinear soil models may be necessary if large strains are developed in soil during shaking. Total or effective stress soil models can be considered in this case, depending on the susceptibility of the soil to develop volumetric strains and liquefaction risk assessment.

3.2.4. Novelty and Challenges of the methodology

Traditional approaches for record selection generally rely on spectral matching of ground motion records to match the UHS at specific return periods. While this approach ensures a direct match to hazard levels, it requires modifying records in ways that distort their natural characteristics. As explained earlier, this is because the UHS is an envelope of spectral ordinates generated by many earthquake scenarios and does not have a realistic spectral shape of any ground motion generated by a future earthquake event. In contrast, this project proposes the use of a hazard-consistent methodology, that is the Conditional Spectrum approach, to preserve the spectral shape and statistical properties of ground motions (except the amplitude because some level of scaling is required). This represents a more physical and realistic approach to defining seismic ground motion for fragility analysis.

In addition, this project integrates aftershock sequences into the analysis. However, this advancement comes with its own set of challenges, particularly the increased computational demands. Incorporating seismic sequences requires analyzing larger datasets for MS and AS combinations, longer back-to-back simulations, and complex interactions, all of which demand substantial additional computational efforts. These aftershock sequences have been used in WP6 for structural response and fragility analysis while in WP7 the impact of aftershock sequences on the risk estimates has been studied. Preliminary risk assessments performed in WP7 including aftershock sequences showed negligible impact on plant risk estimates, however this needs to be corroborated by further analysis and requires further research.

These advanced methodologies necessitate a greater number of ground motion analyses compared to conventional practices. This is mainly due to the consideration of a set of hazard levels instead of the hazard at only one return period, as conventionally done in practice. While it is expected that rock spectral shapes differ only very little with the return period when considering diffuse seismicity, the site response analysis need to be carried out for each intensity level to capture the nonlinear soil behaviour, and the soil uncertainty propagation increases generally the number of analyses. By emphasizing hazard-consistent selection across multiple intensity measure levels, this project highlights the variability that is naturally present in seismic hazard.

The nuclear industry is governed by extensive and stringent regulations designed to ensure the highest levels of safety and reliability. Probabilistic approaches are not accepted by all regulators in European countries. Introducing changes to well-established practices can face resistance due to the sensitivity of these structures and the perceived risk of deviating from conservative assumptions. Introducing changes to well-established practices requires careful cost benefit analyses. Balancing innovation with regulatory compliance requires clear communication of the scientific validity and safety benefits of these methods.

Since the parametric testing used to evaluate the proposed methodologies requires a large number of analyses, it can be challenging to conduct them using complex numerical models. This highlights the need for simplified structural models, like those presented in this section. More advanced and state-of-the-art models are developed within WP6 and are intended for downstream applications. These allow for comparisons with more conventional fragility assessment approaches—such as the safety factor method—within the context of the METIS case study applications.

3.3. Case Study Application

The methods described previously were then used to select hazard consistent ground motions for the METIS case study site, located in Italy at the Southern tip of the Tuscany Region (**Figure 11**) described in chapter 2. This zone is considered a low to moderate seismicity region, where historical data shows only 32 events with magnitude above 5.

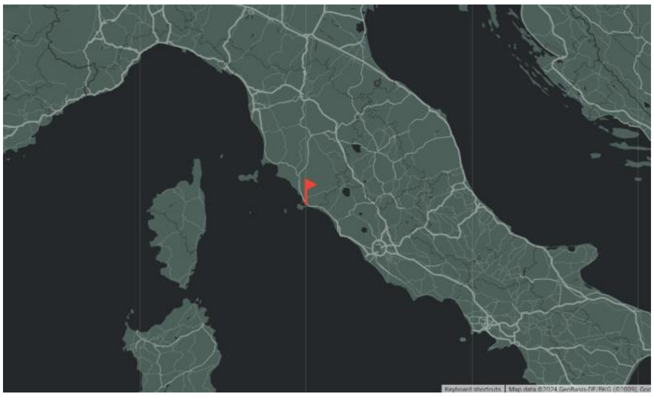


Figure 11. METIS case study site

The results of hazard analysis were used to compute spectral accelerations for ten Intensity Measure Levels (or IMLs) for a set of different spectral ordinates which represent different oscillator periods that can be representative for several types of structures and components. The spectral ordinates considered as IMs were: peak ground acceleration (PGA), spectral acceleration at a period of 0.1s, namely Sa(0.1s), spectral acceleration at 0.25s, Sa(0.25s), and finally average spectral acceleration (AvgSa) which encompasses the average values of the spectral acceleration ordinates in the range between 0.1 and 0.4 seconds. It must be noted that given that no correlation structures exist for PGA (i.e., a period of 0s), a proxy value of 0.01s was used instead for record selection, as this is the lowest period for which correlation structures are available. For the case of the IMLs, they range from low-intensity of very high intensity levels (from 40 up to a 100,000-year return periods). For consistency with outcropping rock conditions on the case study site, hazard calculations at the rock level were performed for the METIS case study assuming a shear wave velocity (Vs30) of 1000 m/s at bedrock level.

3.3.1. Database of ground motions

For the METIS project, a comprehensive database of over 30,000 ground motion records from various sources and regions worldwide was compiled, as illustrated in **Figure 12**. This database was developed to enable record selection algorithms to choose ground motions based on their spectral shape from a broad dataset, enhancing the likelihood of achieving a precise match to target values for all IMs and IMLs, as explained earlier. For more details, please refer to Deliverable D5.1.

The database was compiled using the flatfiles from various data repositories, including the Engineering Strong-Motion (ESM) database (Lanzano et al., 2019), NGA-West2 (Ancheta et al., 2014), the New Zealand Strong-Motion database (Van Houtte et al., 2017), and the updated version of the Near-Source Strong-motion (NESS) database (Sgobba et al., 2021). Ground motions from NGA-West2 and NESS are kept only if recorded outside the geographic regions covered by the other two databases to avoid duplication. This database was used for record selection.

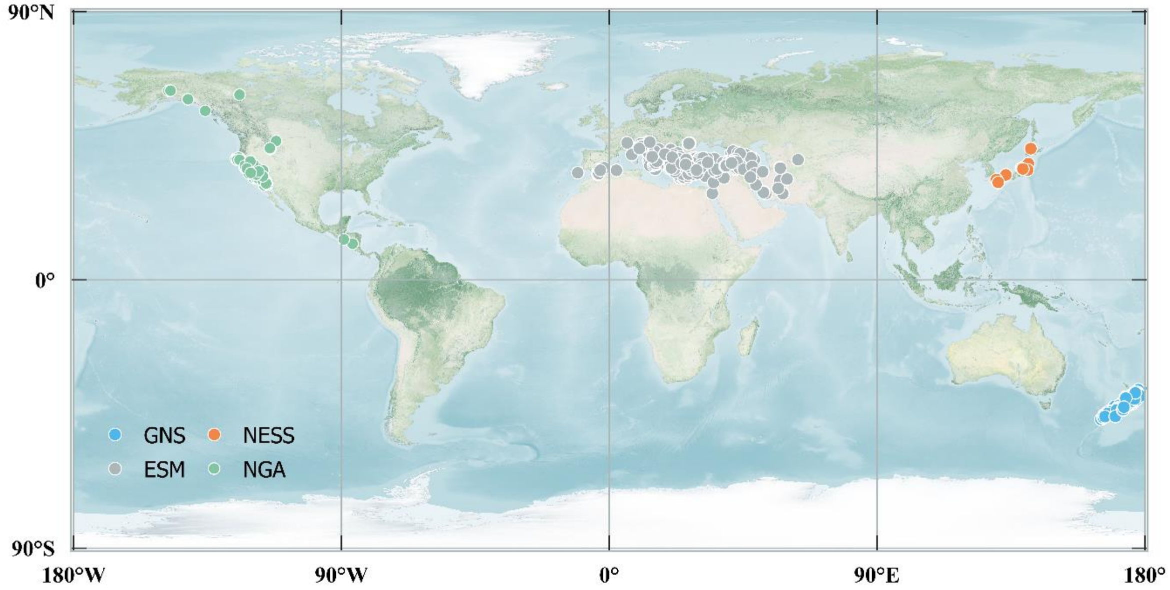


Figure 12. Sources of the record database.

Additionally, a database of synthetic or simulated ground motions (SDB) was generated using the method developed by Alvarez et al. (2022) to test its ability to generate realistic earthquake scenarios. The SDB was calibrated to match a subset of the Engineering Strong-Motion (ESM) database, focusing on events with magnitudes between 4 and 8, hypocentral distances under 100 km, and sites with a shear wave velocity above 400 m/s. The Stochastic Ground Motion Simulation Method (SGMSM) was used for the simulation to produce coherent three-component time histories. After calibration, the SDB was populated using Monte Carlo sampling of key ground motion features (magnitude, hypocentral distance, and depth) to maintain consistency with the original ESM subset. The final simulated database was evaluated for its ability to replicate recorded ground motion characteristics. More extensive information about the methods and performance of the synthetic ground motions can be found on D4.2 et D5.1. The further analysis of the simulated ground motions for 3D site response revealed inconsistencies in the vertical component that needs to be fixed before further applications. In consequence, the synthetic records were not used for METIS case study applications.

3.3.2. Record selection

For this application, record selection was performed to be consistent with the specific characteristics and seismic hazard at the bedrock level for the METIS site. Records were selected across ten intensity levels, as well as for varying intensity measures, to ensure that a broad range of seismic inputs suitable for diverse structures would be accurately represented. OpenQuake software was used to generate the target spectra, incorporating the Conditional Spectrum (CS) approach and including all seismic sources. This process followed the approach by Lin et al. (2013), enabling a fully hazard-consistent target spectra across all IM levels.

Record selection was conducted with a focus on the four conditioning IMs: PGA, Sa(0.1s), Sa(0.25s), and AvgSa between 0.1 and 0.4 seconds. These IMs were prioritized due to their importance for structural analysis within the METIS project (Deliverable 6.3). In the case of PGA, it was represented instead by the spectral acceleration at 0.01 seconds, as this is the shortest period for which correlation values were available (Baker and Jayaram, 2008). The ground motions were selected based on their two horizontal components, while the vertical component is also available for the pair but was not considered during the target matching procedure.

Due to the limited availability of high-intensity rock-level ground motion records, certain acceptance criteria for the non-rock and scaled ground motions had to be defined. Some records from sites with Vs30 values as low as 400 m/s were included, along with amplitude scaling of ground motions to match the desired intensity levels. Scaling factors were generally capped at 10, except for the highest intensity level when scaling up to 12 was allowed. These tolerances, while complying with the maximum 0.12 SSE tolerance limit (set based on METIS D5.1 findings), are expected to minimize the bias in the analysis while ensuring realistic representations of high-intensity motions. The possible influence of these inclusions was explored within the METIS project and will be elaborated on in a following subsection.

Selection was performed incrementally for different record set sizes to allow flexibility in subsequent numerical analyses. This approach ensures that sets, ranging from 9, 11, and 13 records to up to 25 records per IML, remain fully hazard-consistent for rock conditions when used in their entirety across each IM and intensity level. Hence, they provide a robust foundation for further structural assessment. The methodology and structure of record selection is more amply described in Deliverable D5.4. The site response analysis requires a larger number of analyses to fully cover the uncertainty and obtain converged estimations (here 100 soil columns); also a minimum of 30 time histories is generally used to propagate uncertainty in probabilistic analysis in nuclear safety. In consequence, only the sets of 25 time histories were used for METIS case study as described with more detail in D5.4.

3.3.3. Record selection for clustered seismicity

For the clustered seismicity application, the record selection process was performed across the same ten predefined ground motion intensity measure levels focusing on the average spectral acceleration (AvgSa) as the preferred intensity measure. This choice of AvgSa is particularly suited for clustered seismicity since structures are likely to experience vibration period elongation as they accumulate damage from multiple events. In addition, in probabilistic seismic risk assessments this measure accommodates the variability in fundamental periods across diverse structural components, regardless of whether damaged or not (Kohrangi et al., 2017; De Biasio et al., 2014, 2015).

For each IML, selection was performed for 20 mainshock (MS) records that matched the Conditional Spectrum (CS) target to ensure a robust basis for subsequent aftershock (AS) sequence simulation. This selection aimed to maintain enough MS-AS ground motion sequences to accurately represent high-intensity aftershock impacts on structures. The ETAS model, calibrated with parameters specific to Central Italy (Šipčić et al., 2022), was then applied to simulate aftershocks sequences for each MS event.

Aftershock ground motions were further filtered to include only those above a minimum magnitude of 3.5 and source-to-site distance within 100 km. Additional filtering criteria was set to retain only those with peak ground accelerations (PGA) above 0.05g to ensure that only significant aftershocks (i.e., capable of causing damage) were included in the structural assessment. The different intensities of the sequences are represented in

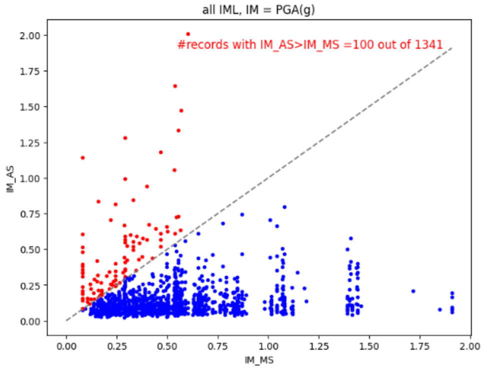


Figure 13 (left), which shows the MS AvgSa values as defined stripes given the enforced CS selection at the different IMLs, while the AS intensities are scattered vertically, as they represent the values of the individual events of the sequences. Additional details can be found in Deliverable D5.5. In addition, **Figure 13** (right) also shows PGA MS-AS pairs, highlighting that further research is required to better understand and validate the ETAS model for structural analysis in moderate seismicity regions.

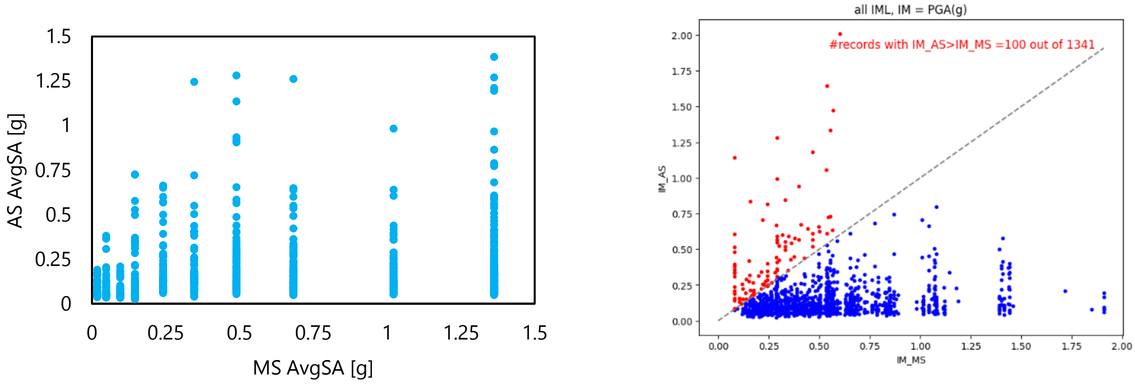


Figure 13. MS and AS intensity pairs for AvgSA (left) and PGA (right).

3.3.4. Site characterization including uncertainties to obtain ground motion on soil surface

The METIS case study considered a 1D soil profile characterized by four distinct geotechnical layers, with a prominent change in Vs value between the bottom of the first layer (composed of different sublayers with stratified soils) and the second layer (a more homogeneous but softer silty clay material), as well as a variable increasing with depth Vs value. The soil 1D profile has been calibrated based on geotechnical and geophysical campaigns already conducted previously to the METIS project. Results from downhole measurements (**Figure 14**) also pointed out a variable depth of the bedrock interface.

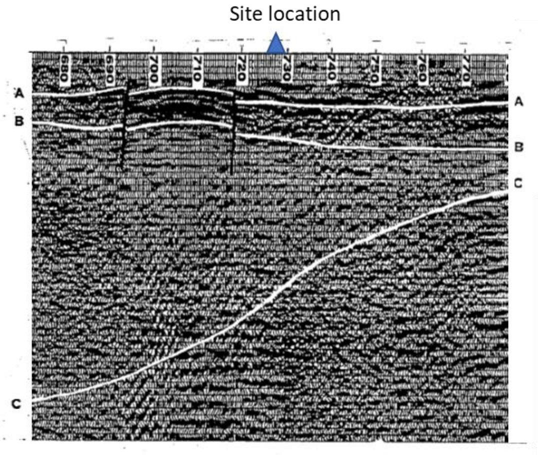


Figure 14. Synthetic view of one down-hole measurement performed at the site.

Soil nonlinear properties characterized by their secant modulus reduction and damping curves were obtained based on laboratory test results previously conducted with soil samples from geotechnical boreholes at the site. The obtained data presented a maximum shear strain of 3.10^{-4} and served as a basis for fitting a standard hyperbolic for secant modulus reduction and damping models proposed by Darendeli (2001) and Zhang et al. (2004).

Uncertainties are considered both for the Vs profile and nonlinear properties. Vs at each layer/sublayer is considered as following a lognormal distribution with β_{Vs}= 0.175, which allows associating the deterministic interval (0.5, 2) to 2.3%-97.7% confidence intervals of the lognormal distribution. We enforce correlation between adjacent layers to obtain realistic samples of the Vs profile (**Figure 15**). No vertical Vs variation within a layer/sublayer is considered for the Vs profile. Uncertainties in the nonlinear properties are considered based on standard deviation values from the Darendeli (2001). Latin Hypercube is used to obtain 100 samples of 1D Vs profile and nonlinear properties that were then considered for site response analysis at the different Intensity Measure Levels and spectral ordinates.

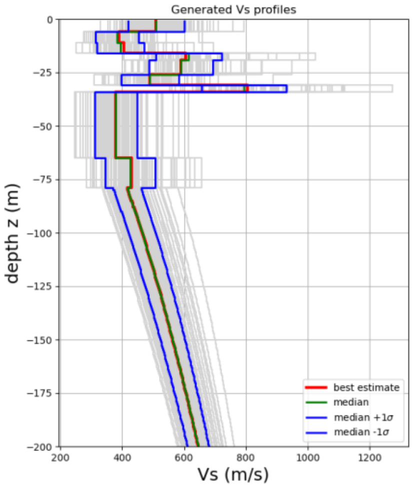


Figure 15. Set of N=100 probabilistic Vs profiles

3.3.5. Exploring the suitability of scaled soil and synthetic ground motions

In cases where it is necessary to include records for long return periods, analysts often face limited options in terms of purely rock ground motions that meet the intensity levels required. This limitation generally leads to the inclusion of records that are scaled in their amplitude to match the hazard level, recorded on soil rather than rock. For the specific METIS case study, the scaling had to be applied to the selection of ground motions both in the recorded (D5.1) and the synthetic (D4.2) database. This section outlines the types of tests conducted to assess potential biases in the fragility functions of simple structures introduced by these record modifications in hazard-consistent analyses.

The primary objective of these tests, thoroughly described in D5.1, was to investigate whether scaling, soil-recorded motions, or synthetic records could introduce biases that impact the accuracy of structural response and fragility assessments. For hazard-consistent record selection, it is critical to use records that match the desired distributions of spectral accelerations across the intended intensity measures (IMs) to ensure robust structural response assessment. Ideally, ground motions would be recorded at rock sites with similar site characteristics. However, due to database limitations, achieving this exclusively with natural, unscaled, rock-recorded ground motions is still unfeasible, particularly for high hazard levels. Therefore, it was required to explore and evaluate the legitimacy of using scaled, soil, and synthetic records.

The first battery of tests examined the effect of scaling by comparing two extreme sets of CS-based hazard-consistent ground motions: one with high scaling factors (7-10) and another with low scaling factors (1-2). Both sets included records selected to match the Conditional Spectrum at various conditioning IMs and IMLs. These motions were tested on nonlinear single-degree-of-freedom (SDOF) systems with various natural periods, as well as a multi-degree-of-freedom (MDOF) system representing a 5-story reinforced concrete building. Responses were evaluated in terms of maximum ductility (or inter-story drift for the MDOF model), comparing the effects of high vs. low scaling factors. Additionally, several representative IMs were tested, to evaluate if any significant and systematic differences were present in the responses generated by the ground motions in the two groups.

A similar battery of tests was conducted to assess the effects of using soil-recorded motions at a rock site. Two classification schemes were considered, resulting in four sets of records, two consisting exclusively of rock and two exclusively of soil motions. One classification scheme was established based solely on Vs30, which was referred to as the Vs30-method, and another incorporating more complex proxies (while still considering Vs30), which was referred to as the complex-method. This exercise led to four distinct rock and soil ground motion groups. Using the same structures and analysis parameters as in the scaling tests, these soil and rock records were evaluated to explore whether using soil-recorded motions could bias the response metrics.

Finally, another set of tests were performed comparing hazard-consistent records selected from a real ground motion database to those selected from the simulated database. This test aimed to determine whether the simulated ground motions—generated to match the same site characteristics and intensity measures as real records—could serve as viable alternatives without introducing bias in structural responses. Real and simulated records were applied to the same structures as previously mentioned to evaluate their responses. This comparison offers valuable insights into the reliability of simulated records in supplementing real data, particularly at higher magnitudes and for specific scenarios where actual recorded motions are limited. The additional analysis of the simulated ground motions for 3D site response carried out in the project revealed inconsistencies in the amplitudes of the vertical component that was not in agreement with recorded data and expected physical behaviour. Consequently, the synthetic records were not used for the METIS case study applications.

The findings of these batteries of tests are highlighted in Subsection 3.3.4.

3.4. Results and Findings

3.4.1. Rock ground motion database

The finalised database of CS-based selected real ground motions is accessible in the METIS repositories, facilitating their use for further analysis and reference. The organization of these datasets is shown in detail in D5.4. Record sets are classified according to the length of the group ranging from 9 to 25 per intensity level. Comprehensive metadata is available for each ground motion in the database, including the file names for the two horizontal and vertical components, the source database, applied scaling factors, spectral shape, and time step interval (dt). These data points ensure that each record's source, modifications, and characteristics are well-documented, facilitating hazard-consistent applications and analyses tailored to assessing structural demands across a range of scenarios.

Most of the time histories have a very long total duration (around 100s) including noise and they would require some post-processing to extract the part of the signal that is useful for engineering purposes. In order not to introduce subjective decisions this has not been done here but this step is necessary for industrial applications when many time-consuming analyses are performed with complex nonlinear models.

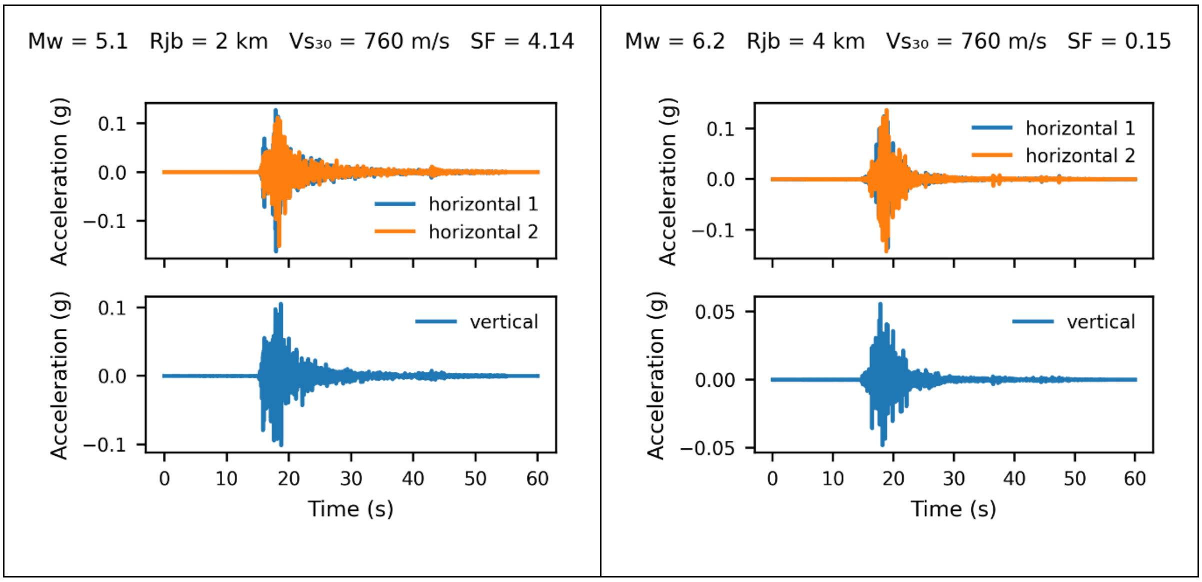


Figure 16. Selected records example.

3.4.2. Surface ground motion database

The obtained 3-component surface motions and related equivalent soil properties database for best estimate 1D soil profile (BE) and including uncertainties (BEU) are available at METIS repositories for conditioning IMs PGA and Sa(0.25s), and Intensity Measure Levels from 5 to 9. Report D5.4 discusses in detail the main characteristics of this dataset. These surface motions and equivalent soil properties can be directly used to Soil-Structure Interaction (SSI) studies and fragility analysis.

3.4.3. Clustered seismicity records

The clustered seismicity ground motion dataset is also accessible in the METIS repositories as described in D5.5. This set includes mainshock (MS) and aftershock (AS) ground motion pairs, arranged sequentially with 10-second intervals between signals. This interval allows the structural response to the MS motion to dissipate before the aftershock motion begins. Each record in the dataset includes metadata on the source, scaling factors, and spectral shape, along with details on the resampling performed to standardize the time step interval (dt) between MS and AS signals. This resampling was necessary for a reliable response analysis since these ground motions were often recorded at different stations with different native time steps.

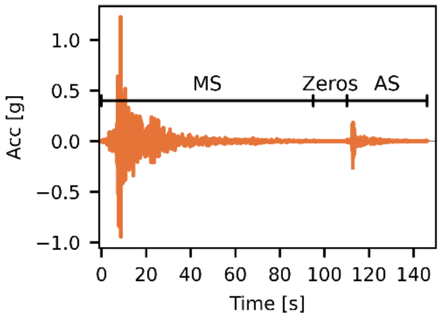


Figure 17. Example of MS AS sequence.

3.4.4. Influence of scaled soil and synthetic ground motions.

The results of the tests performed on the simple aforementioned structures to investigate the suitability of scaled, soil and synthetic ground motions indicate that enforcing hazard consistency through the conditional spectrum (CS) approach can lead to similar responses and fragility functions as real, unscaled rock motions. This enables the effective use of ground motions with scaling factors up to 10 and allows for the inclusion of ground motions recorded at soil sites alongside those recorded on rock. This conclusion is based on responses of single degree of freedom oscillators as well as of a multi-degree-of-freedom (MDOF) system representing a 5-story reinforced concrete building. It is worthwhile noting that these are controlled "worst-case" scenario tests, where datasets consisted exclusively of either highly scaled records or soil-recorded ground motions. In applications, record selection would generally prioritize real rock ground motions with mild scaling, sparingly supplementing them with soil motions or highly scaled rock records. Given that these extreme scenarios exhibited no significant bias in structural response or fragility, with only some differences appearing only at the highest ductility levels, it can be inferred that carefully curated selections—including scaled and soil motions—are unlikely to introduce statistically significant bias when hazard consistency and spectral shape are carefully maintained via a CS-matching approach.

Similarly, tests comparing real and simulated ground motions selected using the CS approach showed largely consistent results, with differences arising mainly at high ductility levels, unlikely to be ever reached in nuclear SSCs. In addition, minor discrepancies in the duration of simulated records were observed, as the higher intensity levels often yielded longer duration simulated ground motions which could influence responses of structures sensitive to cumulative loading in scenarios with prolonged or repeated ground motion sequences. While simulated records are a valuable alternative when real data is limited, caution is advised when used for assessing structural response metrics sensitive to duration.

Note that the battery of tests carried out on simulated ground motions mentioned here and detailed in Deliverable D5.1 only considered single horizontal components of ground motion. However, real life applications require using 3-component time histories to compute SSCs response. Hence, it is recommended to extend the tests performed here to further qualify different sets of records and simulated ground motions for engineering needs. The additional analysis of the simulated ground motions for 3D site response carried out in the project revealed inconsistencies in the amplitudes of the vertical component that was not in agreement with recorded data and expected physical behaviour. Consequently, the synthetic records were not used for the METIS case study applications.

3.4.5. Influence of bedrock variable depth on surface motions

Complementary to the 1D model conducted for a large dataset of ground motions, a reduced number of 2D wave propagation numerical simulations were performed based on the FFBC approach. The numerical model considered the realistic variable bedrock depth along the site, but horizontally constant Vs values at each layer (i.e. no lateral variability of Vs in each layer). Different model sizes allowed to ensure the adequacy of the lateral free-field hypothesis of the FFBC approach. The obtained results interestingly showed that for the location with the same bedrock depth, the 1D soil column results are in very good agreement to the 2D model. However, as expected spatial variability of the horizontal ground motions is observed on nearby locations (points P1-4 in **Figure 18**), which is not captured by the simplified 1D model.

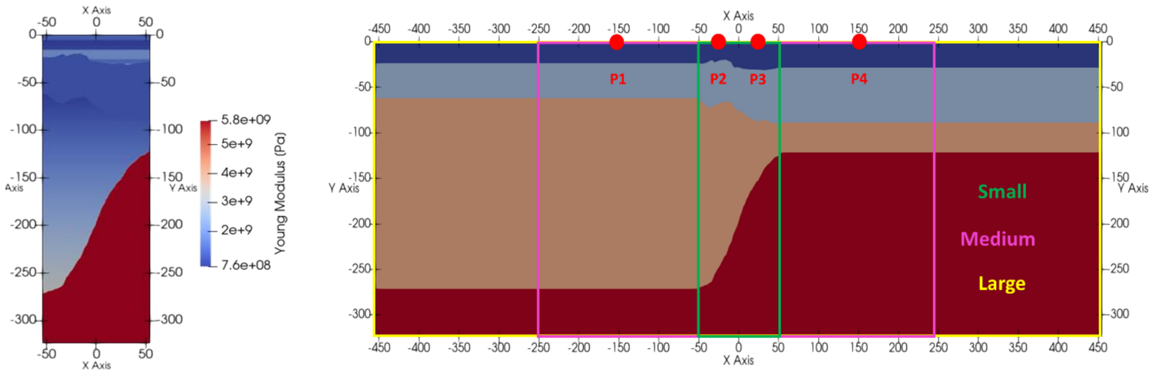


Figure 18. Spatial variability of the Young's modulus for the small model (left), and the three different sizes of the 2D soil profile (right).

3.5. Best Practices and Lessons Learnt

- Hazard consistency of ground motions is important to accurately assess seismic risk of structures located at a specific site. Enforcing it through record selection allows to properly link the hazard of the site with the response of the structures located there. The Conditional Spectrum (CS) approach proved to be a robust method for selecting hazard-consistent ground motion sets, preserving the statistical properties of the site-specific seismic hazard on rock. However, it was found that the interpolation at a specific vibration period of rotd50[1] spectral acceleration values from the metadata, instead of recomputing the exact values from the time histories, can introduce errors. Hence, it is not recommended to interpolate the rotd50 values at a specific vibration period from the database but rather using the values at the closest period provided.
- A large and diverse database of ground motions is essential to achieve an accurate match with target spectra. This enables to achieve a proper hazard consistent set with different numbers of motions through a sufficiently large collection of spectral shapes and amplitudes. In future applications, it is recommended to include seismological scenario parameters in the selection procedure (at least M, R, and if possible, an additional site parameter), to ensure hazard consistency beyond spectral values.
- Using scaled and soil-site ground motions instead of real rock motions in the selection process is generally acceptable, provided that hazard consistency is strictly maintained. This can be achieved by applying the CS method and tracking the error in both the mean and the dispersion. Including some of these apparently spurious ground motion types is often preferable to ensure a better match with the target spectral distribution, rather than excluding them and ending up with a poorer fit. Only minor differences were observed at the highest ductility levels, and primarily in the most extreme scenarios (e.g., especially using only synthetic motions).
- In cases where the bedrock depth varies significantly across the site, spatial variability of surface ground motions is expected. In cases where a common substratum cannot be defined, specific

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[1] RotD50 is the median value of resultants of two horizontal components of ground motions as computed over each angle of rotation from 1 to 180°

1D soil column models for different site locations may be considered, although these differences can only be properly assessed across the site by conducting 2D or 3D site response models.

- It is recommended to visualize the selected ground motion time histories and to assess the suitability of the waveforms before using them to conduct risk assessment studies for the site under study. Some time histories require further post-processing to focus the duration on the seismic ground motion and exclude noise portions not relevant for engineering purposes, in particular when time consuming nonlinear analyses have to be performed.
- The site response analysis highlighted that the deconvolution step is required to ensure consistency of bedrock input motion and to account for the soil column depth. Introducing the deconvolution decreases inconsistencies when considering different soil column heights in cases where no significant bedrock contrast is present.

3.6. Dissemination, Other Resources and Impact

All the detailed information about the analysis, methodologies and tests discussed herein can be found in Deliverables 5.1, 5.2, 5.3, 5.4 and 5.4 of the METIS project. Additionally, the following journal and conference publications were based on this work:

- Álvarez-Sánchez, L. G., Iñárritu, P. G. de Q., Šipčić, N., Kohrangi, M., & Bazzurro, P. (2023). Hazard-consistent simulated earthquake ground motions for PBEE applications on stiff soil and rock sites. Earthquake Engineering and Structural Dynamics, 52(15), 4900–4918. https://doi.org/10.1002/eqe.3987
- Alvarez Sanchez, L., & Zentner, I. (2024). Simulation Of A Scenario Database Of Consistent Ground Motions For Site Specific Earthquake Response. 18th World Conference on Earthquake Engineering. Milan, Italy.
- García de Quevedo Iñarritu, P. G., Šipčić, N., Alvarez-Sanchez, L., Kohrangi, M., & Bazzurro, P. (2023). A closer look at hazard-consistent ground motion record selection for building-specific risk assessment: Effect of soil characteristics and accelerograms' scaling. Earthquake Spectra, 39(3), 1683–1720. https://doi.org/10.1177/87552930231173713
- Šipčić, N., García De Quevedo Iñarritu, P., Álvarez, L, Bazzurro, P. (2022). A preliminary evaluation of using hazard-consistent real and simulated ground motions for structural response assessment. 3rd European Conference on Earthquake Engineering and Engineering Seismology. Bucharest, Romania.
- Šipčić, N., Kohrangi, M., Papadopoulos, A.N., Marzocchi, W., Bazzurro, P.; (2022) The Effect of Seismic Sequences in Probabilistic Seismic Hazard Analysis. Bulletin of the Seismological Society of America 2022;; 112 (3): 1694–1709. doi: https://doi.org/10.1785/0120210208
- Šipčić, N., García De Quevedo Iñarritu, P., Kohrangi, M., & Bazzurro, P. (2024). Importance of hazard-consistent record selection for the risk assessment of NPP components. 18th World Conference on Earthquake Engineering. Milan, Italy.
- Alves Fernandes, V., Korres, M., Zentner. I. (2024) Framework to introduce site response in seismic risk assessment and application to METIS case study. 18th World Conference on Earthquake Engineering. Milan, Italy.
- Zentner, I. (2024) Different ways to implement the conditional spectra approach in nuclear engineering - computational costs and possible benefits for seismic risk assessment SMiRT27, Yokohama, Japan

3.7. Key Contacts

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4. Beyond design & fragility analysis

4.1. Objectives

The primary objectives of work (WP6) within the METIS project are to evaluate the probability of the failure of ZNPP nuclear power plant (NPP) SSCs identified in 6.1. using numerical simulation based approaches. The fragility analysis is the link between seismic hazard characterization and overall plant risk assessment. To develop seismic fragilities, several key tasks must be undertaken, including the selection of appropriate seismic intensity measures (IMs), development of robust numerical models to represent structure and component behaviors, identification and propagation of all relevant sources of uncertainty, inclusion of dynamic interaction effects such as soil-structure interaction (SSI), and the selection of a fragility methodology that is both efficient and site specific.

4.1.1. Identification and Selection of Critical SSCs

NPPs include numerous components, all of which must operate reliably over the plant's lifetime. These components include, but are not limited to transformers 400kV/27kV, 10kV switchgear, 200V DC cabinets, solenoid valves, shutdown panels, storage tanks, heat exchangers, filter containment systems, and motor-operated valves. These components are typically located in NPP civil structures, such as the diesel generator building or the reactor building. More details can be found on Deliverable 6.1 on the criteria for the selection of the SSCs for METIS case study.

4.1.2. Selection and Evaluation of Seismic Intensity Measures (IMs)

Given that seismic fragility curves are typically represented by lognormal distributions relating to the seismic IM to the conditional probability of failure, we have studied the question of the choice of an optimal IM. The objective here is to identify the IM that minimizes the dispersion in the resulting fragility curve, thereby improving the reliability of the risk assessment. Deliverable D6.3 addresses this by studying various IMs and evaluating their efficiency, ultimately guiding the selection of the most suitable IM for fragility analysis.

4.1.3. Quantification and Propagation of Uncertainty

Accurate fragility analysis requires careful treatment of both aleatory (inherent randomness) and epistemic (knowledge-based) uncertainties. These arise from various sources, such as variability in ground motion characteristics, structural properties, and modelling assumptions. This objective involves identifying relevant sources of uncertainty and applying suitable sampling techniques (e.g., Monte Carlo, Latin Hypercube Sampling, etc.) to propagate them through different steps of the analysis. Deliverable D6.4 provides an examination of these uncertainty sources and evaluates the most efficient sampling approaches for fragility assessment.

4.1.4. Incorporation of Soil-Structure Interaction (SSI)

To realistically simulate the seismic response of NPP structures, it is essential to account for soil-structure interaction effects which are responsible for transferring seismic inputs to structures and subsequently to their components. SSI can significantly alter the dynamic characteristics of the structure, typically resulting in a softer system response and modified force distributions compared to fixed-base assumptions. This objective ensures that the models used in fragility analysis adequately represent these phenomena, enhancing the accuracy of the failure prediction of the relevant SSCs.

4.1.5. Evaluation of Fragility Methodologies

Numerous methodologies exist for conducting fragility analysis, ranging from simplified approach such as the EPRI method, where no or few numerical computations are required, to more advanced techniques like Incremental Dynamic Analysis (IDA), Cloud-Regression or Multiple Stripes Analysis (MSA), where the latter involves extensive simulations at various intensity levels. The objective is to assess the relative merits of these methods in terms of accuracy, computational efficiency, and consistency with hazard data. The goal is to select a methodology that best captures the essential fragility parameters while remaining practical for application across different NPP scenarios.

4.2. Methodologies

In order to achieve the list of objectives mentioned in the previous section, the following methodologies were employed:

4.2.1. Selection of Critical SSCs

The selection of SSCs (Structures, Systems, and Components) for seismic fragility analysis involves an initial walk-down and screening of high seismic capacity SSCs that are not major contributors to risk, followed by detailed analyses of components identified as significant risk contributors. The High Confidence of Low Probability of Failure (HCLPF) values are key criteria for initial screening, incorporating considerations of variability among component types, and utilizing recommended reference values from EPRI guidelines. SSCs are classified into tiers considering factors like accuracy of fragility estimates, significance in probabilistic safety assessments (PSA), and potential uncertainties in generic data. Special attention is given to relays susceptible to seismic chatter, requiring targeted screening, and specific mitigation strategies to ensure safety functions remain robust. For Zaporizhzhia NPP, the relevant SSCs were selected for their critical roles in the functioning of the nuclear power plant. These SSCs include the Reactor Building (RB), Diesel Generator Building (DGB), Filter Containment Venting System (FCVs), transformers, Control Monitor Cabinet (CMC), and Service Water Pump (SWP). Each of these components plays a vital role in the safe and efficient operation of the NPP under seismic load (more details on main contributors to risk for METIS cases study can be found in deliverable METIS D6.1).

4.2.2. Optimal Intensity Measure

To determine the most appropriate ground motion intensity measure (IM) for fragility analysis of nuclear power plant structures, Deliverable D6.3 adopted a comprehensive evaluation focusing on both scalar and vector-valued IMs. The study began with a detailed literature review and classification of both scalar and vector-valued IMs, emphasizing their role in predicting structural response and supporting hazard-consistent fragility curves. Several case studies were conducted, including analyses on the AP1000 reactor and METIS case structures, to evaluate IM performance using approaches such as Incremental Dynamic Analysis (IDA), Regression and Multiple Stripe Analysis (MSA). These methods enabled sensitivity assessments of Engineering Demand Parameters (EDPs) to various IMs. Efficiency was primarily assessed through the reduction of dispersion in EDPs conditioned on each IM. The study concluded that the optimal IM is case-dependent, but structure-specific spectral measures—particularly spectral acceleration at the fundamental period, Sa(T1), and averaged spectral acceleration over a range, AvgSa—exhibited superior performance in terms of both efficiency and hazard consistency for the evaluated NPP components compared to the selected IMs.

4.2.3. Quantification and Propagation of Uncertainty

To effectively quantify and propagate uncertainties in the seismic fragility assessment of nuclear power plant structures and components, Deliverable D6.4 employed several advanced sampling and analytical techniques. The primary focus was on propagating both aleatory and epistemic uncertainties through fragility models using simulation-based approaches. The study implemented and compared various uncertainty propagation methods, including Latin Hypercube Sampling (LHS), Sobol sequences, and the First Order Second-Moment (FOSM) method. These methods were evaluated through two case studies: a nonlinear single-degree-of-freedom (SDOF) system and a service water pump located on an AP1000 reactor building. The sampling techniques were integrated with Incremental Dynamic Analysis (IDA) to evaluate structural response across a range of seismic intensities. Among the methods, Progressive Latin Hypercube Sampling (PLHS) allows for increasing the sample size by using former results, which can be useful for convergence and sensitivity analysis. Sobol sequences also offered good convergence properties for high-dimensional problems. For smaller-scale models, all the sampling techniques proved effective, but LHS and Sobol showed the lowest dispersion and estimation errors in fragility parameters. Overall, the methodologies provide a robust framework for assessing how uncertainties influence structural response and fragility curves, enabling hazard-consistent and efficient seismic risk evaluations for nuclear facilities.

4.2.4. Vector Fragility Assessment

One of the objectives in this work framework is to evaluate the scalar and vector intensity measures (IMs) in fragility analysis for both linear and nonlinear structural responses, using the Diesel Generator Building at the Zaporizhzhia Nuclear Power Plant as a case study. A simplified structural model was developed and validated against a complex model. Fragility assessments were performed using Cloud Regression Analysis and Incremental Dynamic Analysis (IDA), with drift and acceleration as Engineering Demand Parameters (EDPs), applying Multiple Linear Regression (MLR) and Maximum Likelihood Estimation (MLH). Scalar IMs were assessed using dispersion (β), Akaike Information Criterion (AIC), and Area Under the Curve (AUC), with spectral acceleration at the fundamental period, Sa(T1), consistently emerging as the most effective. Vector IMs, particularly combinations like (Sa(T1), Np), further reduced uncertainty, especially for nonlinear responses. Roof drift showed lower dispersion than roof acceleration, indicating its greater reliability.

In summary, the report highlights the importance of selecting suitable IMs and EDPs, showing that while Sa(T1) is a strong scalar IM, vector IMs offer improved accuracy in nonlinear scenarios. For more details, please refer to the deliverable D6.4 of the project.

4.2.5.Soil structure interaction and fragility analysis

The soil-structure interaction was considered using a simplified approach (distributed spring elements representing the properties of the soil). This approach was considered to be suitable for the purpose of the case study considering its relatively simple application. To take into consideration soil-structure interaction while maintaining computational simplicity, the widely recognized methodology of distributed springs was employed to model the soil response, which proved its efficiency with respect to the other rigorous methods. To determine the properties of the spring elements and dashpots, the Federal Emergency Management Agency (FEMA) guidelines were used (ATC 2020). For more advanced nuclear safety analyses, it is recommended to assess the appropriateness of simplified SSI approaches.

Various approaches are available in literature to conduct fragility analysis. One approach is cloud regression analysis, which involves generating a "cloud" of data points through numerous nonlinear dynamic analyses, with each point representing a different seismic event and the corresponding structural response taking into account the variability of the parameters of the numerical model. Another method is incremental dynamic analysis (IDA), where structures are subjected to a series of ground motion records scaled to increasing intensity levels to assess their seismic performance. Additionally, multiple-stripe analysis (MSA) evaluates structural performance by analyzing responses to ground motion records at different pre-selected or scaled intensity levels, referred to as "stripes," differing from IDA, which uses incrementally scaled motions.

For nuclear power plants are concerned, Multiple-Stripe Analysis (MSA) faces significant limitations in fragility analysis. The high median capacities of SSCs (Structures, Systems, and Components) in these facilities often result in few, if any, observable failures within the MSA stripes, making it challenging to derive accurate fragility parameters. This is particularly problematic in realistic scenarios, where seismic demands usually fall below the failure threshold, reducing the effectiveness of MSA. Also, the limited number of results per stripe affects the robustness of the failure probability estimations per stripe. On the other hand, the IDA approach seems to be a suitable method for this task because it enables us to explore the structural behavior under extreme loading, but with a high computational cost.

In contrast, the cloud regression method offers a more practical and reliable approach for nuclear applications. It allows for useful visualization of structural behavior as a function of ground motion intensity and extrapolation to higher values, even when there is limited failure data, making it feasible to generate meaningful fragility estimates. By utilizing a lognormal model, the regression method effectively handles the high-capacity values typical in nuclear systems, ensuring that the analysis remains both accurate and applicable. This makes the cloud regression method a more robust and suitable tool for fragility analysis in the nuclear industry, especially when compared to the challenges associated with MSA. For this reason, the cloud regression method was used to conduct fragility analysis of ZNPP components.

The cloud regression method utilizes nonlinear time history analysis to create a data sample for fragility curve evaluation. This involves representing the seismic load with a set of N triplets of ground motion histories tailored to the site-specific seismic hazard. In conjunction with the regression method, Latin Hypercube Sampling is employed to account for variability at the structural level, including factors such as strength, stiffness, and damping, as well as soil parameters like stiffness and damping in the soil model. This approach effectively propagates uncertainty through the mechanical model and optimizes the exploration of the entire space of possible parameter values.

The regression method (Zentner, 2018) requires a sample of N input-output pairs, (α_i, y_i) , i=1,….,N , where the input is the ground motion indicator or seismic intensity level α_i (such as PGA) and the output is the continuous damage measure y_i.The continuous damage measure variable Y is modelled as lognormal random variable:

$$Y = b\alpha^c\eta$$

where η is a lognormal random variable with a median of 1 and a logarithmic standard deviation σ. It is assumed that the structure fails or reaches a certain damage level when the variable Y exceeds a threshold D_S such that $P_f(\alpha)=P(Y>D_S|\alpha)$. The parameters b, c, and σ can be conveniently determined by linear regression in log-space:

$$\ln Y = \ln b + c \ln \alpha + \sigma\varepsilon$$

Where $\sigma\varepsilon = \ln\eta$, is a centered normal random variable with standard deviation s, the latter is obtained as the standard deviation (std) of the regression error. Moreover, defining $D_S = bA_m^c$, we have:

$$A_m = \exp\left(\frac{\ln\left(\frac{D_S}{b}\right)}{c}\right)$$

In consequence, the fragility curve is described by a lognormal distribution with a median equal to the seismic capacity Am and the lognormal standard deviation $\beta = \sigma/c$ such as:

$$p_f(\alpha) = \Phi\left(\frac{c\ln\left(\frac{\alpha}{A_m}\right)}{\sigma}\right) = \Phi\left(\frac{\ln\left(\frac{\alpha}{A_m}\right)}{\sigma/c}\right)$$

One key advantage of the cloud regression approach is its ability to be utilized even when no or few failures are observed. It doesn't inherently require the scaling of accelerograms and remains effective, even with smaller sample sizes. Although linear regression can be applied to any dataset, it does involve extrapolating the behavior in cases where no failures are observed.

4.2.6.Mainshock–Aftershock Fragility Assessment

Another important focus of this framework is to develop damage-state-dependent fragility curves that account for clustered seismicity, specifically the effects of mainshock–aftershock (MS–AS) sequences on structural components.

The methodology involved a hazard-consistent approach to selecting MS–AS ground motion records, using procedures from Deliverable D5.2 to derive target spectra for aftershocks based on the mainshock hazard at a given site. These MS and AS records are assembled in a back-to-back sequence and used in nonlinear time history analyses of safety-significant components (SSCs). Structural responses are classified by the level of damage sustained after the mainshock, and fragility curves are then developed using the intensity of the aftershock ground motion. This approach was applied to a simplified model of a Service Water Pump located within a reactor building. The results show a reduction in the component's capacity under MS–AS loading compared to MS-only scenarios, with the extent of reduction influenced by the definitions of intermediate and collapse damage thresholds. More details can be found in deliverable 6.7.

4.3. Case Study Application

The cloud regression approach discussed above, was applied to numerical models representing the structure, systems, and components of the Zaporizhzhia Nuclear Power Plant, assumed to be theoretically situated in Tuscany, Italy.

A total of six numerical models were developed, including comprehensive models for two structures—the reactor and diesel generator buildings—as well as the filter containment venting system. Components such as the transformers, control monitor cabinet, and service water pump were modeled in a simplified manner, focusing on capturing their failure mechanisms and dynamic characteristics.

According to the ZNPP configurations, transformers are located in both the reactor and diesel generator buildings, while both FCV systems and the control monitor cabinet are situated in the reactor building. The diesel generator building hosts both the service water pump and one of the transformers. More details can be found in D6.8, Table 1.1.

4.3.1. Reactor Building

The reactor building at the Zaporizhzhia Nuclear Power Plant consists of a containment structure, an outer building, and a common foundation. The cylindrical section of the containment is prestressed with diagonal tendons. For seismic analyses, the reactor building was modeled using OpenSees software with multilayer shell elements capable to represent reinforced concrete shear walls and their nonlinear behavior. The model incorporates prestressing effects using fiber sections and initial stress elements. Concrete and steel materials were represented with nonlinear stress-strain models (DamageTC3D and Steel02). The final numerical model, illustrated in **Figure 19**, consists of approximately 145,000 degrees of freedom.

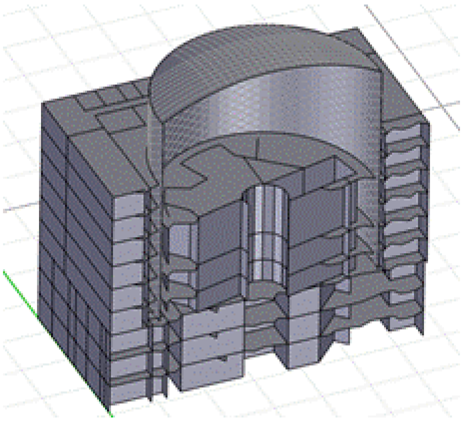


Figure 19. Finite Element (FE) Model of the Reactor Building with Detailed Internal Structures

The numerical validation of the reactor building's finite element model was conducted using the modal analysis results of the first six modes for the fixed base conditions. These included translational modes in the range of 3.85–3.91 Hz and rotational modes at higher frequencies. The computed results closely aligned with reference data, showing deviations of less than 5%. Incorporating soil-structure interaction (in particular soil stiffness) had, as expected, a significant impact, reducing the fundamental frequencies from 3.89 Hz to 2.01 Hz in the first mode, and from 4.02 Hz to 2.09 Hz in the second mode.

4.3.2. Diesel Generator Building

The Diesel Generator Building (DGB) of Unit No. 1 at Zaporizhzhia NPP comprises three identical reinforced concrete structures, each accommodating a diesel generator. One structure (1DGB-1) is individually housed, while the other two (1DGB-2 and 1DGB-3) share a combined three-block-cell structure. The numerical modeling of DGB, illustrated in **Figure 20**, applied the same approach as the reactor building, including nonlinear materials and multilayer shell elements. To optimize computational resources, only the representative diesel generator building (1DGB-1) with single cell structure modeled.

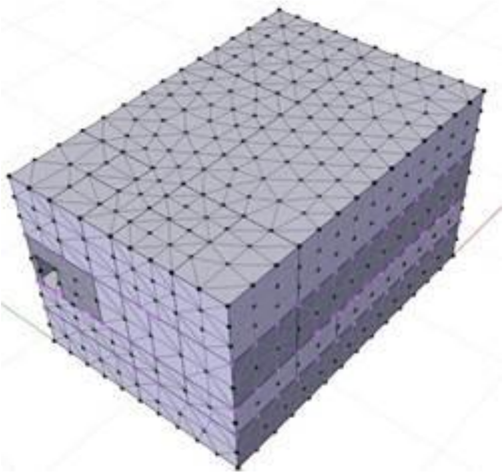


Figure 20. Finite Element (FE) model of the Diesel Generator Building

The numerical validation of the diesel generator building (DGB) at Zaporizhzhia NPP involved modal analysis performed with OpenSees software. The analysis identified the first six mode shapes, revealing a predominantly translational response at frequencies between approximately 12.00 Hz and 16.27 Hz, with significant rotational contributions at higher modes up to around 28.88 Hz. Comparison with reference data showed close agreement, with deviations generally below 5%. When soil-structure interaction (SSI) was incorporated, the fundamental frequencies notably decreased, with the first mode frequency reducing from 12.00 Hz (without SSI) to 8.45 Hz (with SSI).

4.3.3. Filter Containment Venting System

The filter containment venting System (FCVs) is a critical piping system within nuclear power plants, designed to manage and prevent overpressure in the reactor containment. The FCV system primarily consists of DN 300.0 pipes with varying thicknesses with some insulation which was included as extra mass within certain regions of the model.

Given the system goes through multiple floors, the numerical model, illustrated in **Figure 21**, incorporates several distinct support points, including fixed points, sliding bearings, wall ducts, and spring hangers, each with specified stiffness characteristics. Nonlinear behavior under seismic loading was captured using fiber section modeling applied to representative pipe segments, reflecting different pipe cross-sectional properties.

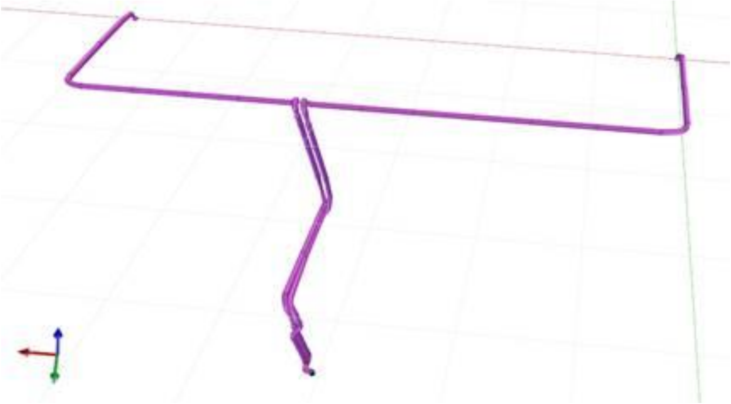


Figure 21. FCV System Numerical Model

The numerical validation of the filter containment venting system (FCVs) at Zaporizhzhia NPP was conducted using modal analysis via OpenSees software. This piping system demonstrated significant flexibility due to its geometry, with fundamental frequencies ranging from 0.957 Hz to 4.404 Hz for the first six mode shapes. The comparison with reference data from a German nuclear plant indicated a good match in the fundamental modes (less than 3% difference).

4.3.4. Transformer

Transformers, which ensure efficient transmission of electricity generated by nuclear power plants, are located within both the reactor building and the diesel generator building at Zaporizhzhia NPP, **Figure 22**. Each transformer weighs approximately 2420 kg, anchored and supported by clamped connections made from C100x50x8 steel sections.

The modelling of the transformer component, which has a frequency of 7.5 Hz, specifically targeted capturing the most likely mode of structural failure during seismic events, modeling nonlinearity explicitly in the supporting clamp elements (C100x50x8 sections). The overall transformer model was simplified, maintaining essential accuracy to reflect the actual behavior of the critical structural elements under seismic loading conditions.

Figure 22. Transformer Component located at Zaporizhzhia Nuclear Power Plant (NPP)

4.3.5. Control Monitor Cabinet

The control monitor cabinet (CMC), situated within reactor buildings at the Zaporizhzhia NPP, is crucial for safely monitoring and managing reactor operations. Each cabinet weighs about 227 kg and is secured to the floor using expansion anchors connected through steel angles (40x40x3 mm) spaced 310 mm apart.

In developing a numerical model, emphasis was placed on accurately capturing potential seismic failure modes. Nonlinear analyses of the anchoring steel angles determined their ultimate capacity, and this data was integrated into simplified hinge models. The resulting simplified model exhibits a natural frequency of approximately 7.5 Hz, reflecting the dynamic behavior of the cabinet under seismic loading.

Figure 23. Control Monitor Cabinet located at Zaporizhzhia Nuclear Power Plant (NPP)

4.3.6.Service Water Pump

The service water pump, **Figure 24**, is modeled as a long-column vertical pump anchored to the floor using expansion bolts, with component properties aligned with those specified in the EPRI guidelines. The full model includes the pump column, shaft, motor stand, and motor, all represented with beam elements. A simplified model was also developed to capture the most critical failure mode, specifically of the motor stand, using a 3D stick model with an elasto-plastic rotational spring at its base. This simplified model exhibits a natural frequency of approximately 10 Hz and replicates the nonlinear hysteretic behavior under cyclic loading, ensuring accurate representation of the system's seismic response.

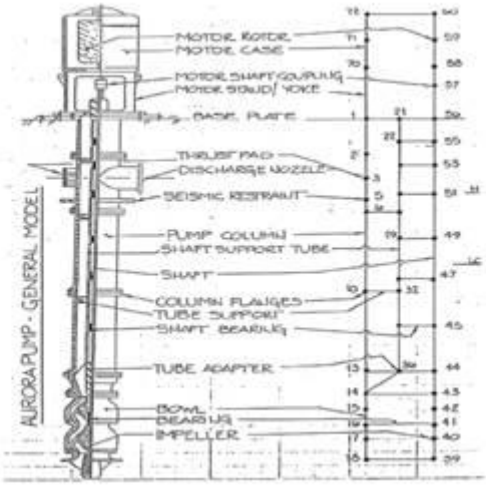
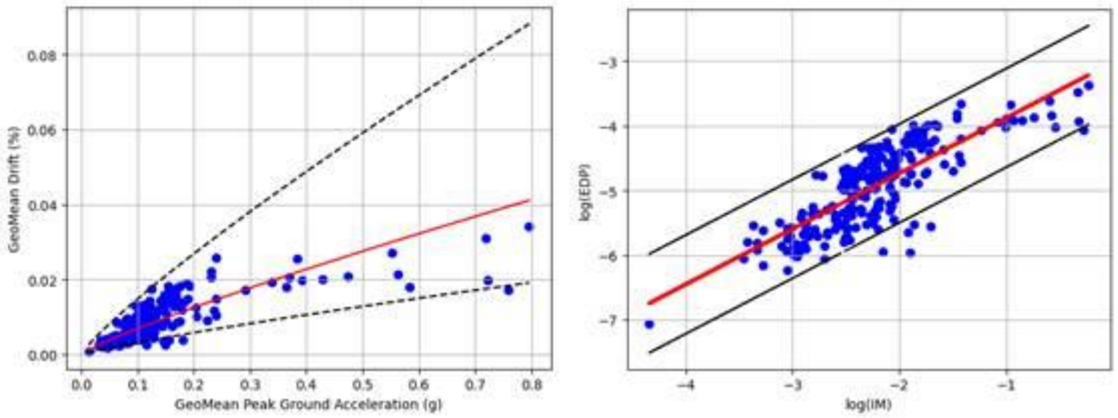


Figure 24. Service Water Pump (EPRI 2013)

4.4. Results and Findings

4.4.1. Reactor Building Fragility

The fragility assessment of the reactor building model highlighted the containment structure as the most critical component under seismic loading. Using pushover analysis results, the limit state was estimated to happen at a drift of 0.08%, this is when the crushing of concrete occurred at the base of the containment. The structural model included uncertainties in material properties and damping, as well as soil-structure interaction modeled through stiffness and damping parameters. A series of nonlinear time history analyses were performed using a set of ground motion records, with geometric mean peak ground acceleration (PGA) selected as the primary intensity measure (IM) and geometric mean drift as the engineering demand parameter (EDP). The relationship between IM and EDP, **Figure 25**, was established using cloud-based regression analysis.



(a) (b)

Figure 25. (a) Reactor Building Response Versus Peak Ground Acceleration (PGA) (b) Logarithmic Relationship Between Engineering Demand Parameter (EDP) and Intensity Measure (IM)

A similar methodology was applied to the remaining case study components. A comprehensive description and the full results can be found in D6.8, titled "Fragility computations for METIS case study".

4.5. Best Practices and Lessons Learnt

The selection of an appropriate seismic intensity measure (IM) can reduce dispersion in fragility curve estimation. Although spectral acceleration at the fundamental period of a component, consistently provides the most accurate results with minimal dispersion, its applicability is limited in multi-component systems due to large range of eigenfrequencies of SSCs. Consequently, in the context of nuclear power plant risk assessment—where multiple components are considered—intensity measures such as average spectral acceleration over a defined period range (AvgSa) or peak ground acceleration (PGA) offer more practical and robust alternatives.

Accurate seismic fragility assessment requires effective uncertainty quantification through appropriate sampling methods. Given the computational complexity of detailed NPP structural models, selecting a time-efficient sampling approach is essential. This study found that Progressive Latin Hypercube Sampling (PLHS) and Sobol sequences significantly reduce computational demands while maintaining precision comparable to traditional Latin Hypercube Sampling (LHS).

Nuclear power plant structures, such as reactor buildings and diesel generator buildings, are primarily designed to remain within the elastic range during seismic hazard events due to their critical nature and the severe consequences that could arise from any permitted damage. Furthermore, accurately capturing the failure behavior of nuclear power plant components requires detailed modeling of both structural and soil aspects. These two considerations significantly influence the selection of an appropriate fragility assessment methodology, particularly when numerical simulations are employed. In this context, it is essential to balance computational efficiency with the objective of thoroughly investigating the seismic intensity levels at which nuclear plant components may fail, while also maintaining hazard consistency regarding the treatment of ground motions. The findings of this study recommend the use of cloud regression as it fulfills these objectives effectively, offering reliable predictions of fragility parameters even in cases where few or no failure instances are observed.

The incoherency effect of seismic ground motions on nuclear power plant structures—a simplified representation within the context of multiple-support excitation—can considerably reduce the inertial forces acting on these structures, particularly at higher frequencies. This reduction becomes notably more significant when extended to components, especially those characterized by frequencies exceeding 10 Hz.

4.6. Dissemination, Other Resources and Impact

- Zouatine, M., Soyluk, K., Sadegh-Azar, H., & Zentner, I. (2024). Investigating the Impact of Spatial Variation of Seismic Ground Motions on Reactor Containment Building Response. In Proceedings of the SMiRT 27 Conference, March 3-8, Yokohama, Japan.
- Soyluk, K., Zouatine, M., & Sadegh-Azar, H. (2024). Effect of Seismic Wave Incoherence Models on the Foundation Responses of NPP. In Proceedings of the SMiRT 27 Conference, March 3-8, Japan.
- Triantafyllou, G., Zentner, I., Kohrangi, M., Alves-Fernandes, V., Khemakem, A., Bazzurro, P. (2024) Fragility modeling of nuclear power plants components. Intensity measures and analysis set-up WCEE Milan, Italy.
- Zentner, I., Triantafyllou, G., Alves-Fernandes, V., Korres, M., Bazzurro, P., Khemakem, A. (2025) INTEGRATED APPROACH TO COMPUTE FLOOR RESPONSE AND FRAGILITY INCLUDING SITE RESPONSE –IMPLEMENTATION AND LESSONS LEARNED FROM METIS CASE STUDY SMirt28, Toronto
- Goldschmidt, K., Progresses in European Earthquake Engineering and Seismology (2022) Long Short-Term Memory Networks for prediction of earthquake demand parameter time series in seismic fragility analysis.
- Goldschmidt, K., Sadegh-Azar, H., Sevbo, O., Richard, B., A. Garcia de Quevedo Iñarritu, P., Bazzurro, P., Vamvatsikos, D. Special Session: Challenges and recent advances from European Research Projects (2022), Innovative approaches for Seismic Fragility Analysis within METIS project.
- Goldschmidt, K., Mohtasham Miavaghi, M., Sadegh-Azar, H. Special Session: Challenges and recent advances from European Research Projects (2022), Relevant intensity measures for seismic damage prediction with artificial neural networks.
- Fathabadi, S., Sadegh-Azar, H. (2024), Evaluation Of Aftershocks Impact On Seismic Safety Of Power Plants Based On Experience Feedback.
- Gerontati, A., Vamvatsikos, D. Progresses in European Earthquake Engineering and Seismology (2022), A comparison of three scalar intensity measures for nonstructural component assessment of nuclear powerplants.
- Karaferis, N., Gerontati, A., Vamvatsikos D. (2024), From PGA To Anything: Fragility Curve Conversions For Nuclear Power Plant Applications.

4.7. Key Contacts

- Mohamed Zouatine, mohamed.zouatine@bauing.rptu.de;
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- Irmela Zentner, irmela.zentner@edf.fr;
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5.PSA tools & methodologies

5.1. Objectives

Open-source tools are available for the hazard and fragility assessment steps, but not yet for PSA computations. The generic objective of this work package (WP7) was to develop and implement new assessment methodologies that allow to deal with hazard and fragility developed in WP3, WP4 and WP6, as well as multi-unit assessment.

The activities were directed to address such challenges in seismic PSA that are not satisfactory treated in the commercial PSA tools used in the nuclear industry. This would entail to achieve the following:

- to push forward an open-source initiative for PSA, based on the open-source tool SCRAM;
- and to address technical issues of seismic PSA by improving the existing tools and technology.

In order to achieve the objectives, technical tasks were planned (see **Figure 26**), and specific activities were scheduled.

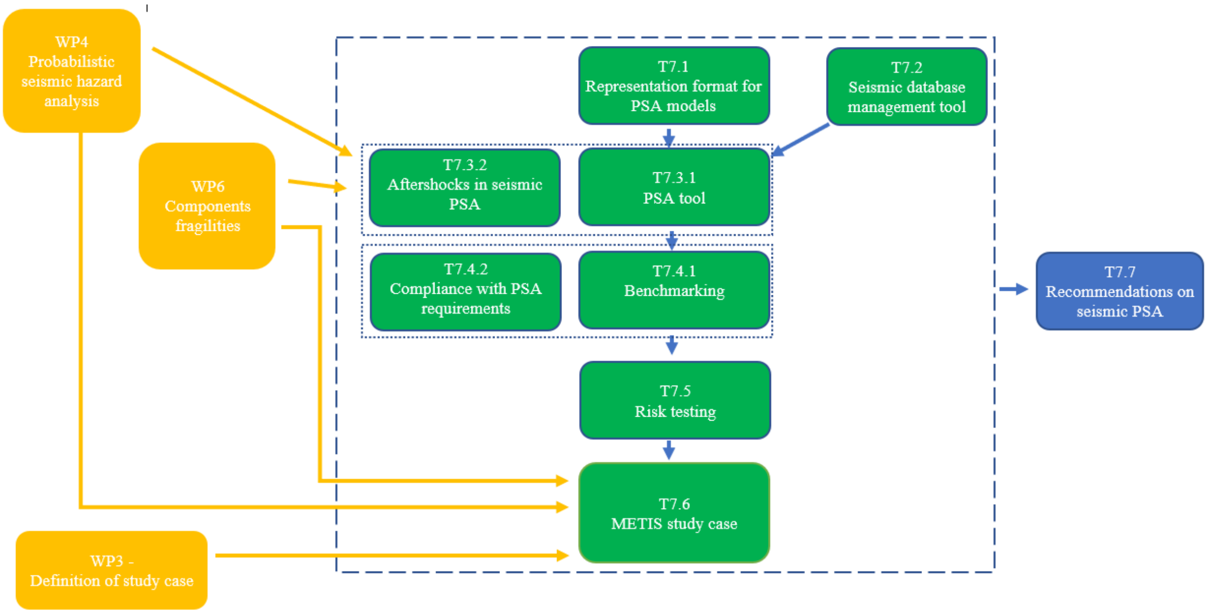


Figure 26. Flow chart of the METIS WP7

As shown at **Figure 26**, these activities include:

- Formulation of requirements and recommendations regarding the seismic PSA models and tools;
- development of various modules of the PSA tool (further called as the METIS tool) that covers important aspects for preparation of seismic PSA models for nuclear facilities and qualification

of the results. Availability of the METIS PSA tool is one of the milestones (Milestone 10) that have been achieved during the project;

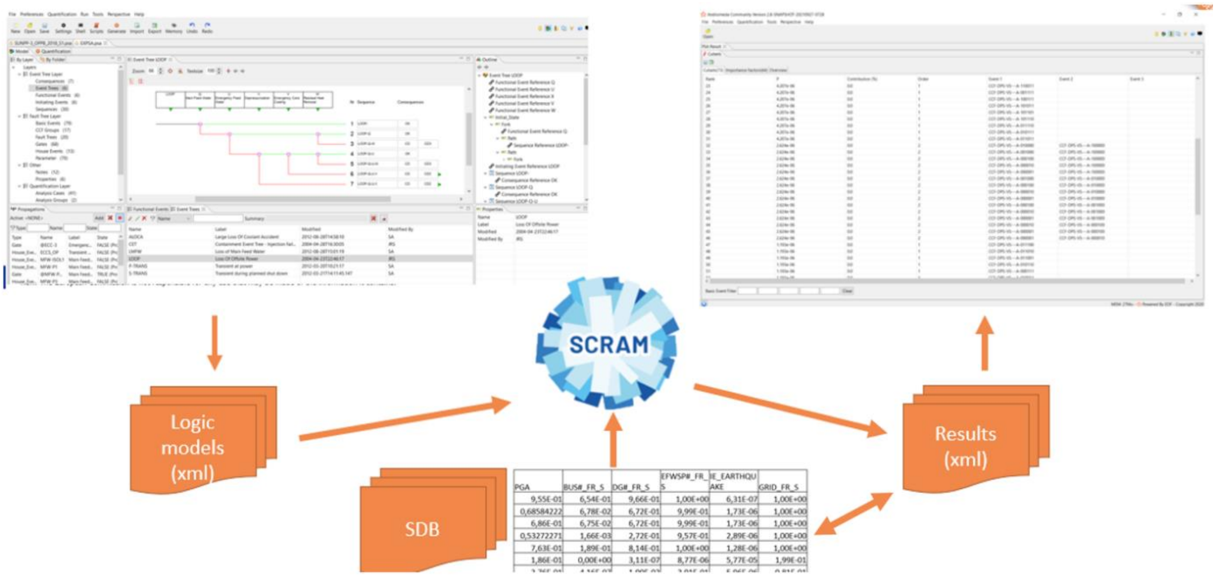
- different testing of methods, as well benchmarking of the METIS tool. Benchmarking of new PSA tool is one of the milestones (Milestone S12) that have been achieved during the project,
- development of improved or new approaches for selected topics of seismic PSA;
- practical application of the METIS tool and approaches for real case study. Associated milestone, Milestone 14 “PSA computations for METIS case study performed” was also successfully achieved; and
- preparation of recommendations based on the results of activities.

5.2. Methodologies

5.2.1. The METIS tool

Commercial PSA tools used in nuclear industry have their own proprietary format to represent models. This situation, inherited from the historical development of tools and market conditions, constitutes a real barrier to the introduction of new tools and methods and more generally to innovation in the domain. The Open-PSA initiative, an informal group of academic and industry experts, proposed an open-source, standard representation format for fault trees and event trees. This format, Open-PSA Model Exchange Format (OPSAMEF), has been extensively tested and adapted in several commercial and non-commercial tools. The expected benefits of this new representation format are: portability of models, validation of models, cross-verification of results, openness to innovation, etc. Within a seismic PSA, it can be an essential tool to exchange models, to incorporate fragility curves and to implement model rewriting techniques.

The METIS tool was prepared as the result of several activities performed as initial part of the work package. The general architecture of the tool is presented in **Figure 27**.



PGA	BUS#_FR_S	DG#_FR_S	EFWSP#_FR_S	IE_EARTHQUAKE	GRID_FR_S
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0,68584222	6,78E-02	6,72E-01	9,99E-01	1,73E-06	1,00E+00
6,86E-01	6,75E-02	6,72E-01	9,99E-01	1,73E-06	1,00E+00
0,53272271	1,66E-03	2,72E-01	9,57E-01	2,89E-06	1,00E+00
7,63E-01	1,89E-01	8,14E-01	1,00E+00	1,28E-06	1,00E+00
1,86E-01	0,00E+00	3,11E-07	8,77E-06	5,77E-05	1,99E-01

Figure 27. The METIS tool

The METIS tool consists of several modules, each of which can be used independently, as a stand-alone tool: coupled Andromeda-SCRAM tool, Seismic Data Base tool, Uncertainty propagation tool. The vital part of the METIS tool is Andromeda, a software tool developed at EDF for probabilistic risk modelling and assessment. Andromeda also can serve as a research environment for testing and evaluating new risk assessment methods and approaches. It utilizes OPSAMEF and follows the modular concept, effectively addressing the challenge of increasing complexity through modularization and instantiation techniques. Modularization breaks down complex models into smaller, manageable modules, enhancing control and clarity. Meanwhile, instantiation enables the adaptation of a generic model to various contexts, ensuring flexibility and applicability. Together, these strategies significantly streamline risk assessment and improve model efficiency.

In this perspective, Andromeda is constructed in a modular fashion with a central core and different modules each providing a different capability, as follows (see **Figure 28**):

- **PSA model editing**: it allows to edit a model by creating and modifying event trees, fault trees, parameters, etc.
- **Model comparison**: it allows to compare two models. For each type of object (basic event, event tree, fault tree, analysis case) Andromeda provides the details of the difference in a graphical as well as in a textual form.
- **Model fusion**: it allows to merge two models after comparing them. Andromeda requires a model A, model B and a base model (that can be one of the two previous models). Andromeda can merge the model A with the model B. In case of conflict (different versions of the same object with respect to the base model), Andromeda asks the user to fix the conflict by selecting the option A or B to be considered into the merged model.
- **Version management**: it allows to use the git platform for the version management of the PSA model. The version management can be done either locally or from/to a remote repository. The version management allows to keep track of all the model modifications, have multiple analysts working simultaneously on the same model (thanks to the branch concept), restore the previous correct version in case of error, *etc*.
- **Scripting**: Andromeda has a Jython API. This means that it provides the user with a set of functions that can be used into a script for model modification. The use of scripts is particularly recommended in case of massive and repetitive modifications.
- **Documentation**: for several elements of the model, Andromeda allows the user to fill up a wiki page. In this way the user can write the documentation at the same time as the model construction. This capability also helps to keep the documentation updated coherently with the model changes.
- **Dependency and Cartography**: this module provides the backward and forward dependency of each model element. For example, for a given basic event, the forward dependency provides the parameters that are associated to the basic event, while the backward dependency provides all the fault trees, function events, event trees, etc. that make use of the considered basic event. A cartography is also provided to show the dependencies in a more visual way and may be used to split large study cases in a coherent manner to perform parallel computation if needed.

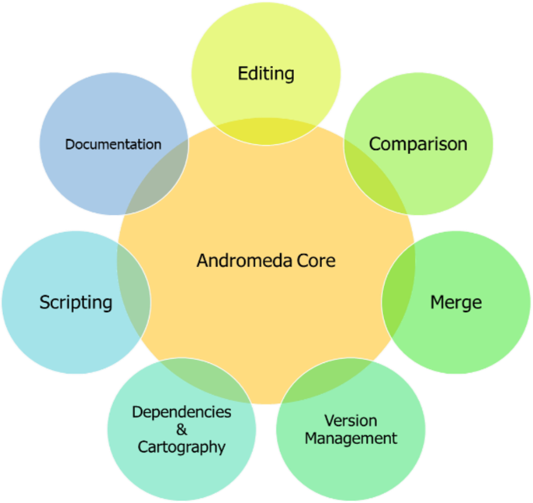


Figure 28. Modules of Andromeda

Screenshots from main graphical user interface (GUI) from Andromeda are included to **Figure 27**.

Within the context of the METIS project, Andromeda is coupled with an open-source quantification software SCRAM. SCRAM is a Command-line Risk Analysis Multi-tool that can perform event tree analysis, static fault tree analysis, analysis with common cause failure models, probability calculations with importance analysis, uncertainty analysis with Monte Carlo simulations. In the METIS tool, SCRAM is dedicated for quantification of PSA results. Under METIS project, initial version of SCRAM was modified to make it usable and compilable (available at https://github.com/SCRAM-NG/scram/releases/download/0.17.0/scram_ng_0.17.0.zip). SCRAM makes it possible to calculate the probability of failure of a safety mission at a time t (of a TOP Event), given the failure probabilities of the basic events depending on time, denoted Q(t). In other words, SCRAM makes it possible to calculate time-dependent unavailability of a safety system. The basic event failure models available in SCRAM are those commonly used:

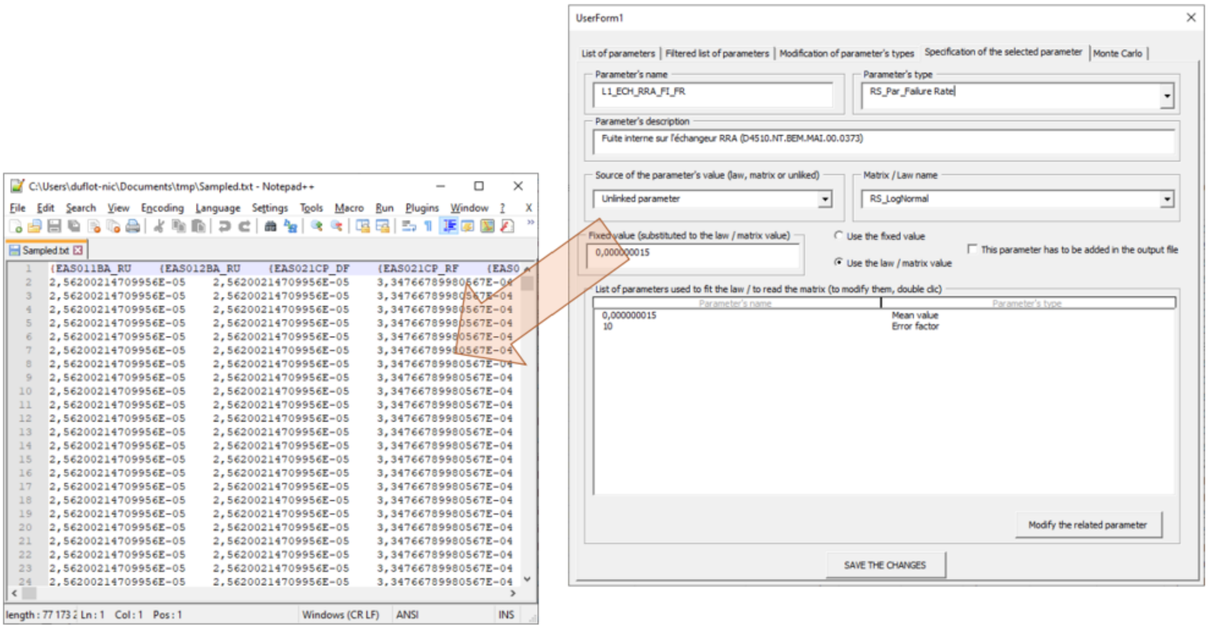
- Repairable component (exponential distributions for failure and repair processes),
- Periodically tested component (exponential distribution for the failure process, constant fixed test interval, constant fixed repair time. Optional time to first test different than test interval),
- Probability – Constant unavailability (Failure probability per demand),
- Fixed mission-time component,
- Non-repairable component (exponential distribution),
- Weibull distribution (exponential distribution with scale and shape factors),
- User defined.

The calculation of the mean unavailability of basic events within PSA model is possible using user-defined probability of unavailability. Under Andromeda, it is possible to use different models for the Basic Events (REPAIRABLE, TESTED, FIXED, MISSION-TIME). For quantification of minimal cut sets (MCS) by SCRAM different algorithms can be used (exact probability calculation with binary decision diagram-based algorithms, rare event approximation, min-cut upper bound).

For calculation of SSC failure probability, a stand-alone tool, the Seismic Data Base (SDB) tool was developed under the METIS project, (see **Figure 29**). SDB tool allows to express the relation through mathematical laws between the SSC failure probability and upstream parameters used in these laws (like PGA level for example). The following features of the SDB tool can be highlighted:

- EPRI method for fragility analysis is implemented;
- Correlation due to common parameters;
- Module for MCS set re-quantification (rare event approximation).

This SDB is designed to be flexible (possibility to define new mathematical laws), simple and robust (internal check of data consistency). It can be used either to generate the probability of failure of each SSC for a given seismic hazard level (in the frame of a seismic PSA approach with several discrete intervals defined by the analyst); or to generate a sampled set of SSC seismic failure probability (Monte Carlo approach) for a given seismic level or for the entire spectrum of seismic levels in a continuous manner. The principle of this tool is to allow the user to declare all the parameters used to fit the different mathematical laws that define the seismically induced probability of each basic event of the seismic PSA. These parameters are named "parent" or "upstream" parameters and can be shared by several basic event probability definitions. Each upstream parameter can be: a fixed value; a random and independent value (defined by a distribution law); a value based on upstream parameters (i.e. defined from "grandparents" parameters through mathematical laws).



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Parameter's type: RS_Par_Failure Rate
Parameter's description: Fuite interne sur l'échangeur RRA (D4510.NT.BEM.MAI.00.0373)
Source of the parameter's value (law, matrix or unliked): Unlinked parameter
Matrix / Law name: RS_LogNormal
Fixed value (substituted to the law / matrix value): 0,000000015
○ Use the fixed value
● Use the law / matrix value
☐ This parameter has to be added in the output file

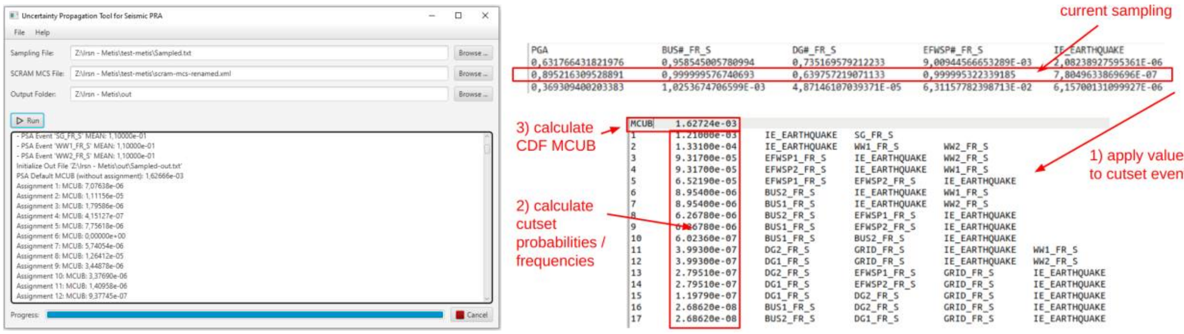
List of parameters used to fit the law / to read the matrix (to modify them, double clic)

Parameter's name	Parameter's type
0,000000015	Mean value
10	Error factor

Figure 29. GUI of the SDB tool

The METIS tool chain works as follows: the user constructs probabilistic model (fault trees, event trees) of nuclear facility to evaluate impact of seismic event, assigns seismic failure probabilities (calculated either by SDB tool, or manually) for basic events; Andromeda builds the Master Fault Tree (MFT), then it transfers it to the calculations tool, SCRAM. SCRAM then generates the list of corresponding cutsets that are further processed by Andromeda.

Finally, a special module that, given the samples of basic events probabilities (resulted of uncertainty propagation) and given the results of the Seismic PSA model in terms of MCSs, is able to provide the value of the Core Damage Frequency (CDF) for each sample has been developed. The user generates: file from Andromeda-SCRAM, containing the cutsets, file from SDB tool containing the sampling values for basic events. Then, the user precises these files as inputs by using the graphical interface of the tool (see **Figure 3030**), together with the path and name of the folder.



Sampling File: Z:\Irsn - Metis\test-metis\Sampled.txt

SCRAM MCS File: Z:\Irsn - Metis\test-metis\scram-mcs-renamed.xml

Output Folder: Z:\Irsn - Metis\out

```
- PSA Event 'SG_FR_S' MEAN: 1,10000e-01
- PSA Event 'WW1_FR_S' MEAN: 1,10000e-01
- PSA Event 'WW2_FR_S' MEAN: 1,10000e-01
Initialize Out File 'Z:\Irsn - Metis\out\Sampled-out.txt'
PSA Default MCUB (without assignment): 1,62666e-03
Assignment 1: MCUB: 7,07638e-06
Assignment 2: MCUB: 1,11156e-05
Assignment 3: MCUB: 1,79586e-06
Assignment 4: MCUB: 4,15127e-07
Assignment 5: MCUB: 7,75618e-06
Assignment 6: MCUB: 0,00000e+00
Assignment 7: MCUB: 5,74054e-06
Assignment 8: MCUB: 1,26412e-05
Assignment 9: MCUB: 3,44878e-06
Assignment 10: MCUB: 3,37690e-06
Assignment 11: MCUB: 1,40958e-06
Assignment 12: MCUB: 9,37745e-07
```

```
PGA                 BUS#_FR_S            DG#_FR_S             EFWSP#_FR_S          IE_EARTHQUAKE
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0,895216309528891   0,999999576740693    0,639757219071133    0,999995322339185    7,80496338696696E-07
0,369309400203383   1,0253674706599E-03  4,87146107039371E-05 6,31157782398713E-02 6,15700131099927E-06
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```
MCUB    1.62724e-03
1       1.21000e-03   IE_EARTHQUAKE   SG_FR_S
2       1.33100e-04   IE_EARTHQUAKE   WW1_FR_S        WW2_FR_S
3       9.31700e-05   EFWSP1_FR_S     IE_EARTHQUAKE   WW2_FR_S
4       9.31700e-05   EFWSP2_FR_S     IE_EARTHQUAKE   WW1_FR_S
5       6.52190e-05   EFWSP1_FR_S     EFWSP2_FR_S     IE_EARTHQUAKE
6       8.95400e-06   BUS2_FR_S       IE_EARTHQUAKE   WW1_FR_S
7       8.95400e-06   BUS1_FR_S       IE_EARTHQUAKE   WW2_FR_S
8       6.26780e-06   BUS2_FR_S       EFWSP1_FR_S     IE_EARTHQUAKE
9       6.26780e-06   BUS1_FR_S       EFWSP2_FR_S     IE_EARTHQUAKE
10      6.02360e-07   BUS1_FR_S       BUS2_FR_S       IE_EARTHQUAKE
11      3.99300e-07   DG2_FR_S        GRID_FR_S       IE_EARTHQUAKE   WW1_FR_S
12      3.99300e-07   DG1_FR_S        GRID_FR_S       IE_EARTHQUAKE   WW2_FR_S
13      2.79510e-07   DG2_FR_S        EFWSP1_FR_S     GRID_FR_S       IE_EARTHQUAKE
14      2.79510e-07   DG1_FR_S        EFWSP2_FR_S     GRID_FR_S       IE_EARTHQUAKE
15      1.19790e-07   DG1_FR_S        DG2_FR_S        GRID_FR_S       IE_EARTHQUAKE
16      2.68620e-08   BUS1_FR_S       DG2_FR_S        GRID_FR_S       IE_EARTHQUAKE
17      2.68620e-08   BUS2_FR_S       DG1_FR_S        GRID_FR_S       IE_EARTHQUAKE
```

Figure 30. GUI of uncertainty propagation tool

The tool generates a file similar to the original sampling file but with an additional MCUB column containing the calculated CDF values. At each iteration, basic event values from the current sample are applied (1) in order to re-calculate cutset values (2) and the final CDF value (3), see **Figure 30**.

The METIS tool for PSA probabilistic modelling has been drafted and benchmarked. The benchmark results showed good agreement between the METIS tool, SAPHIRE and RiskSpectrum, that could conclude, that using of the similar input data and similar approaches for modelling could establish evidenced results of the METIS tool. There were, however, insignificant differences in the results between the METIS tool and SAPHIRE that are explained by sensitivity of SAPHIRE algorithm to roundoff of SSC capacity parameter (Am) during calculation of seismic failure probability.

5.2.2.Strategy for consideration of aftershocks in seismic PSA

Nuclear power plants are complex and critical structures comprised of numerous interdependent structures, systems and components, whose safety must be rigorously evaluated through probabilistic safety assessment. During the time between a reactor's emergency shutdown resulting from a mainshock and its subsequent cold shutdown state, some SSCs may experience nonlinear behavior due to the mainshock, but they do not fail. The importance of aftershocks lies in their potential to compound the effects of the mainshock, potentially leading to the failure of these SSCs. In addition, the core damage sequences that were in progress because of the mainshock can be exacerbated by additional failures (e.g., containment functions) due to aftershocks. Therefore, the occurrence of an aftershock during this time frame may affect the NPP safety based on the cumulative damage of both the mainshock and aftershock, which can result in the failure of these SSCs. Analyzing these failures, understanding the accident sequences that they contribute to, understanding how the associated risks can be reduced, and developing other associated insights are the principal tasks of an aftershock seismic PSA analysis.

Several challenges were identified associated with treatment of aftershocks, like:

- Identification of the post-mainshock plant state, status of each of the critical safety functions, and timeframe of importance for aftershocks consideration;
- Characterization of the damage state of the plant and SSCs important to safety after the mainshock;
- Lack of data to characterize fragilities of SSCs that have suffered partial damage from the mainshock;
- Characterization of the aftershocks hazard (conditional probability and/or probabilistic hazard characterization as a function of the "size" of the mainshock);
- It is necessary to consider both sequences that do not result in a core damage state after the mainshock analysis but have some damage and accident sequences that result in a specified core damage state and are vulnerable to further damage from the aftershocks;

- Understanding the usefulness of modifications made in response to the Fukushima event (e.g., FLEX equipment and offsite resources).

To cope with these challenges, a strategy for consideration of aftershocks in seismic PSA was developed and tested by PSA calculations.

The general method for consideration of aftershocks in Seismic PSA includes the same main stages, as for mainshock PSA:

- Seismic hazard analysis of aftershocks: aftershock activity can be predicted by combining the estimate of the number of aftershocks after the mainshock and the frequency of aftershocks of certain magnitude. Seismic motions caused by the aftershocks are estimated from the attenuation equation or fault model, taking into account the spatial distribution of aftershocks in the source area.
- Seismic fragility assessment: the fragility of SSCs can be estimated by considering seismic vibrations caused by the mainshock and aftershocks that can occur within a short period of time.
- Analysis of systems: reliability analysis of NPP systems taking into account additional impacts (failures) caused by aftershocks while the reactor plant is in cold shutdown state after the emergency shutdown resulting from the mainshock.

Probabilistic part of PSA for aftershocks includes modification of mainshock PSA models (both fault trees and event trees) to account predicted condition of NPP after mainshock (time frame between mainshock and aftershock) and to model additional failures of those SSCs that have survived mainshock. It was recommended to consider in the aftershocks PSA those initiating events that have occurred in the period from the reactor emergency shutdown caused by the mainshock to the transition to cold shutdown state, as shown in **Figure 31**. This duration can vary depending on the design of NPP (PWR, VVER) and on plant-specific operational procedures. Duration of associated Plant Operational States (POS), as well as list of operable SSCs needed to achieve long-term safe shutdown states are determined/modelled at Low power and shutdown modes PSA. That is why for aftershocks PSA a full-scope PSA model that covers all POSs is needed.

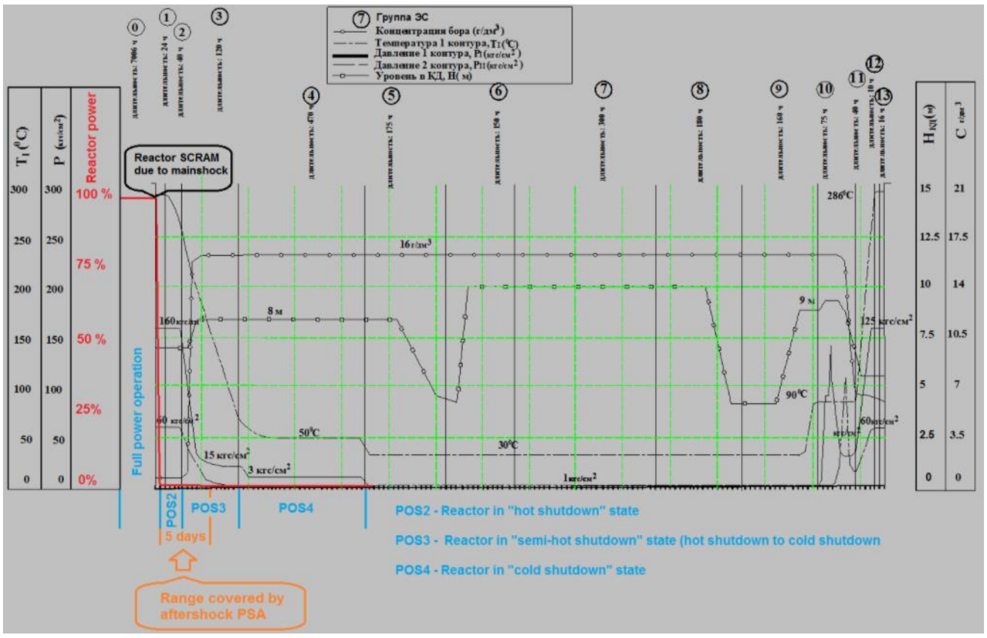


Figure 31. Relation of mainshock and aftershocks with plant operational states (ZNPP example)

In Seimic PSA, for each level of seismic impacts, an event tree is developed to define the hierarchy of initiating events that may be caused by this particular impact, depending on their effect on the NPP. To assess aftershocks in accident sequences, success paths leading to cold shutdown have to be selected, excluding fault paths to be considered as core damage from the mainshock (see **Figure 32**). The event trees for aftershocks are modeled in the same way as for the mainshock, taking into account the POS.

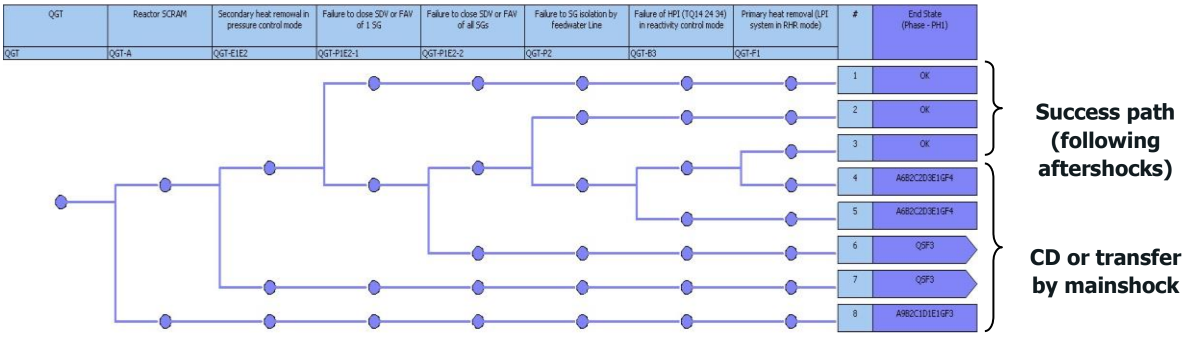


Figure 32. Example of a general transient event tree

The fault trees should be modified: for each SSC that is presented in the model, potential failure caused by a random failure (defined in the component reliability database) and potential equipment failure caused by a seismic impact from the mainshock and aftershocks should be considered. SSC failure caused by an aftershock is modeled explicitly in the fault trees. The probability of failure caused by an aftershock is estimated by multiplying the probability of zero failure (non-failure) of the SSC from the mainshock and the probability of its failure from the aftershocks: Pas=(1-Pms)*Pas.

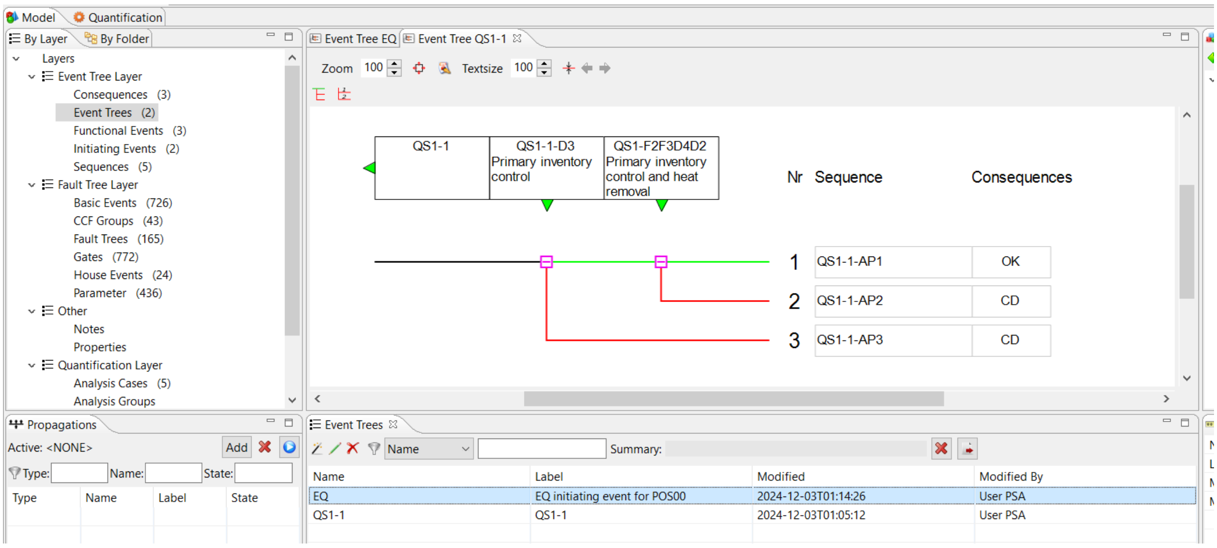
Actually, the total risk contribution is quantified using a simplified formula:

$$CDF = \sum_{i=1}^{n}\left[Hm_i.CDPm_i\right] + \sum_{i=1}^{n}\left\{(1 - CDPm_i)\sum_{j=1}^{k}\left[Ha_j CDPa_j\right]\right\}$$

5.3. Case Study Application

The METIS case study was defined in WP3 and was modeled using the METIS tool in the framework of WP7. The case study is hybrid one. It deals with the combination of the Zaporizhzhia Nuclear Power Plant SSCs virtually placed to selected site in central Italy (for seismic hazard assessments). ZNPP Seismic PSA model including fragility analysis constitutes the reference information to evaluate the impact of all METIS developments and proposed improvements.

One seismically induced initiating event “Loss of coolant accident”, associated safety functions and front-line systems needed to perform the safety functions, as well as supporting and auxilairy SSCs were modelled in detail via the METIS tool. Additional (comparing to the ZNPP Seismic PSA) five seismic bins have been considered. Scope of the PSA model – seven hundred basic events with failures of SSCs including human failure events, dozens of families of common cause failures, hundreds of fault trees with system failures, etc. – is illustrated on the METIS tool screenshot (**Figure 33**).



Nr	Sequence	Consequences
1	QS1-1-AP1	OK
2	QS1-1-AP2	CD
3	QS1-1-AP3	CD

Name	Label	Modified	Modified By
EQ	EQ initiating event for POS00	2024-12-03T01:14:26	User PSA
QS1-1	QS1-1	2024-12-03T01:05:12	User PSA

Figure 33. The METIS case study screenshot

For the METIS case study fragility computations were performed for limited number of risk-significant SSCs. For another SSCs, the appropriate information regarding seismic failure probabilities was taken from ZNPP Seismic PSA. Actually, the case study has been intended to provide basis for comparison of different methodologies, and it does not represent a real PSA for a real NPP due to hybrid nature of the analysis. The METIS case study includes approaches improved under the METIS project regarding:

- treatment of seismic correlations in the PSA model. Approach relies on modelling partial seismic correlations using common cause failure beta-factor technique, which is rather standard option for PSA (see **Figure 34**);
- more precise modelling of seismic impact on human behavior to ensure consistency with seismic fragilities of SSC. Human failure probabilities were adjusted depending on seismic level (PGA) and seismic influence on such performance shaping factors, like location of action, availability of alarm and control systems, time window, etc.

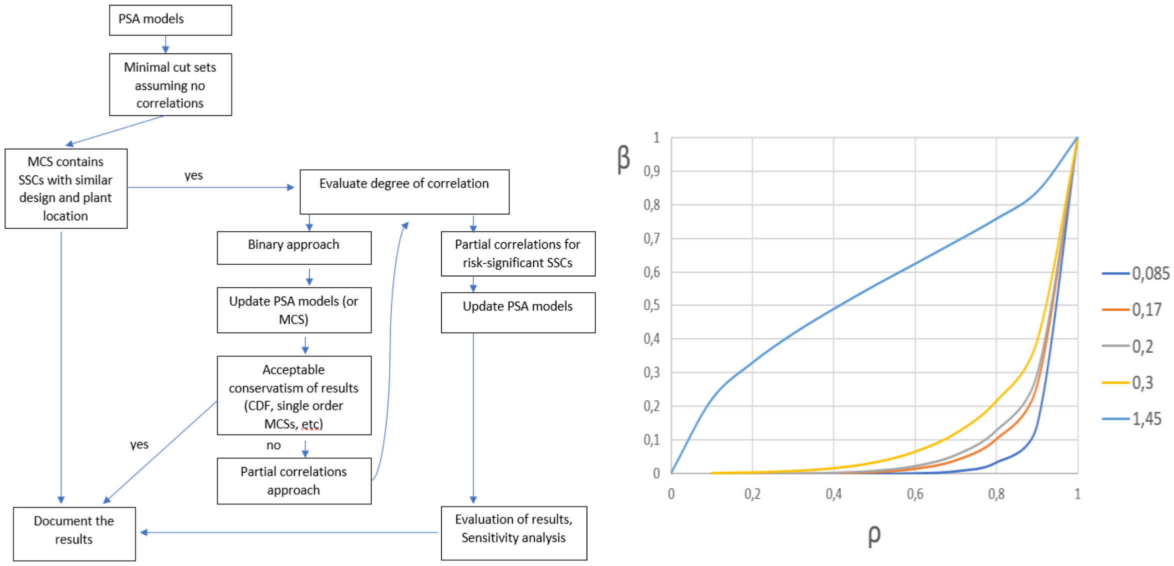


Figure 34. Flowchart for consideration of correlations (left) and illustration of dependency between seismic correlation coefficient vs common cause beta-factor (right)

As part of development of the strategy for consideration of aftershocks in seismic PSA, probabilitic test calculations were fulfilled using the ZNPP base case model. The same seismically induced initiating event

"Loss of coolant accident" occurred after mainshock with aftershock combination was modelled and quantified according to the proposed strategy.

5.4. Results and Findings

5.4.1. The METIS case study

After base case calculations, and definition of reasons for differences in the results, the METIS case study model was updated to account for the approaches and results developed at the METIS project:

- new human error probabilities.
- partial correlations for risk-significant redundant components, instead of full correlations.
- seismic levels that have been omitted in the base case (between 0.3g and 1,47g).

The results – Core Damage Frequency (CDF) and Conditional Core Damage Probability (CCDP) - are presented in **Figure 35**.

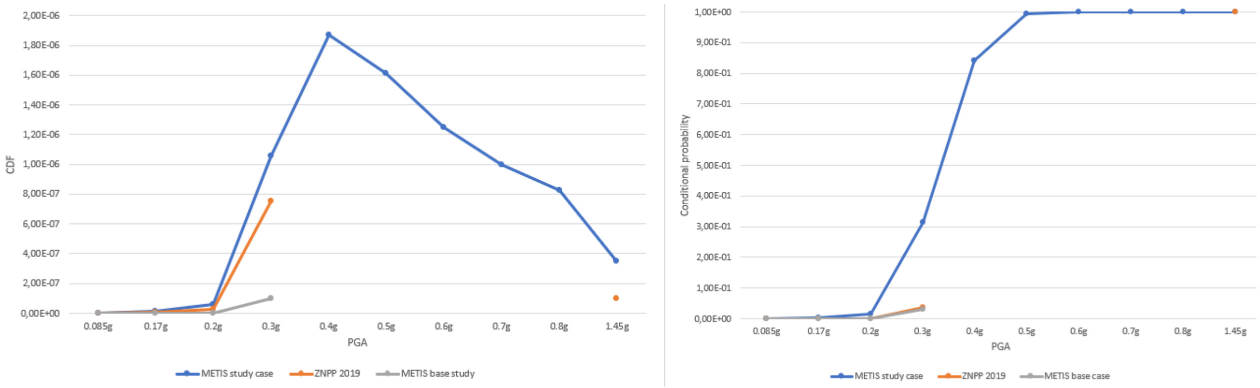


Figure 35. METIS case study CDF and CCDP

Shape of CCDP curve looks like fragility curve for a component, in some extent it can be called as "NPP fragility curve".

The results have shown significant, one order of magnitude increase in total CDF and CCDP. This increase is totally explained by implementation of new approaches. Scope and order of dominant contributors have also completely changed due to new, more justifiable, fragility parameters for risk-significant components. For new risk-significant failures, like essential service water pump, control cabinets, partial correlations have been considered. According to the results of the sensitivity analysis, the CDF is not sensitive to the correlations of the base case dominant contributors (like diesel-generators, power supply components). The METIS case study re-evaluated fragilities have significantly reduced the importance of these components. From other hand, the CDF is more sensitive to the correlations between new dominant contributors, especially for medium range of seismic levels (0.17g, 0.2g, 0.3g). For higher PGA the CDF is not sensitive to any correlations due to dominant contributions of another SSCs like reactor building.

It is, therefore, recommended for seismic PSA to analyze dominant contributors and perform analysis of correlations for each seismic interval separately.

5.4.2. Aftershocks PSA

The test modelling of aftershocks was performed as part of strategy for consideration of aftershocks in seismic PSA, taking into account the following input data and assumptions: POS "Operation at full power" during the mainshock; group of initiating events QS1 "Primary leaks in containment S1, S2, S3";

mainshock Q4 with PGA=0.3g and 2.00E-05 frequency; aftershock AS (A1) with PGA=0.17g and 5.00E-01 postulated probability after the mainshock; accident sequences that lead to damage of the reactor core resulting from the mainshock are not considered in the aftershock analysis. For the test modelling, the model and input data (including the SSC fragility curves) of the Zaporizhzhia NPP Unit 1 SPSA were used.

The test calculation results showed that the aftershock made a small contribution to the CDF for the low intensity area of Zaporizhzhia NPP Unit 1 SPSA (test case performed to support the Strategy): lower than 1% in the SAPHIRE test model and about 2% in the RiskSpectrum PSA test model. For test calculation to determine the influence of aftershock on CDF considering the "intermediate damage state" of the ZNPP Unit 1 reactor compartment building, combinations of seismic effects were addressed. The contribution to the core damage frequency was assessed for the following combination: mainshock with PGA=0.5g and 3.61E-06 frequency and subsequent aftershock with PGA=0.3g and 5.00E-01 postulated probability after the mainshock reached ~ 11%.

5.5. Best Practices and Lessons Learnt

Regarding aftershocks PSA. Before starting the SPSA analysis considering aftershocks, the following caveats are very recommended to be taken into account: the most likely risks arising from aftershock would occur when the NPP is subjected to a mainshock larger than the design basis, but smaller than would cause a core-damage accident; some SSCs might suffer some damage – not enough damage to cause them to fail to perform their safety function ("intermediate damage state"). Then the aftershock occurs later, and that SSC (now weaker than it should be) is more vulnerable, and the aftershock causes it to fail. For a "full scope aftershock SPSA" to provide the usual insights it is expected from a seismic PSA it would be required to analyze accident sequences in which one or more SSCs are in an intermediate damage state arising from the mainshock. The initial condition for the aftershock SPSA is that the SSC still performs its safety function but is weakened. At the beginning of the analysis there is essentially zero information concerning how to characterize those intermediate damage state situations. Many issues would require shake-table testing: shake-table testing that causes some damage but at input levels lower than the "damage threshold" defined as "the SSC cannot perform the safety function" - That would be the intermediate state of the item, after the mainshock but before the intermediate damage state; shake-table testing with that equipment item, partially damaged by the simulated main earthquake, and shake it more (the aftershock simulation) until it truly cannot perform its safety function. Without that data, a realistic full intermediate damage state SPSA is not feasible.

The other way is to perform a "conservative" or "simplified" SPSA using demonstrably conservative PSA-type analyses or simplified PSA evaluations but keeping a target objective of achieving realistic safety significance (or not) of aftershocks consistently with experience feedback and observations. For example, after analyzing the plant design, safe shutdown paths, etc., SSCs that can be potentially damaged in the event of a mainshock of specific level are selected (i.e., the corresponding damage is "assigned" to them). Further, failures in the event of an aftershock are "assigned" to the selected SSCs, which will accordingly influence the change in their fragility curves in relation to those used in the mainshock SPSA. Aftershock SPSA is then performed according to the procedure described in the Strategy. It should be taken into account that the assignment of damage/failure to SSCs strongly depends on the site seismic intensity level (levels of considered mainshocks and aftershocks).

Based on the analyses performed during the development of this Strategy, the following key notes could be recommended for future studies of considering aftershocks in SPSA:

- The goal of an aftershock evaluation would be to identify SSCs necessary to maintain the plant in a safe shutdown state and assess their potential vulnerability to aftershocks or perhaps to guide post-earthquake inspections.

- Significant challenges exist in developing fragilities for SSCs that consider the damage state due to the mainshock. For SSCs not damaged by the mainshock, the fragility should be the same as before the mainshock.
- The systems model should simulate the post-earthquake shutdown state of the plant.
- Future research into these areas would be necessary to optimize aftershock SPSA evaluations and determine the appropriate insights.

This is a challenge for SPSA developers considering aftershocks to choose and substantiate such SSCs and their "intermediate damage state". Some items which are important for analysts are as follows:

- Selection of mainshock and aftershock characteristics for the sensitivity analysis (for example, from a de-aggregation of hazard, selection of a reference earthquake etc.);
- Selection of critical safety functions, in case that the plant has been successfully shutdown (for situations where no core damage has occurred) after an MS and continued cooldown;
- Selection of critical systems and subsystems to fulfil the required safety functions (for example, residual heat removal and supporting systems);
- Identification and evaluation of the post-mainshock status of SSCs associated with the systems that are vulnerable to damage;
- Estimate of the fragility shift (where applicable).

Application of PSHA vector-valued analyses and vector-valued fragility analyses for METIS case study has been discussed in the project. Although vector-valued analyses can provide a higher level of accuracy than scalar analysis, the use of vector intensity measures often entails a cost that, in many cases, may outweigh the benefits of achieving a more precise prediction of engineering demand parameters. For this reason, the scalar analysis was selected to be applied for the case study.

Main results (CDF, CCDP, dominant contributors) changed from original ZNPP PSA to the METIS case study PSA. The reasons for changing conditional core damage probabilities are:

- Implementation of enhanced approaches for fragility analysis, which gives different results (both more optimistic and more pessimistic) regarding the seismic resistance of selected SSCs;
- Different, more precise quantification algorithms used in the METIS tools;
- Best estimate, more justifiable treatment of correlations for risk-significant components;
- Consideration of new seismic intervals that were omitted in the original PSA.

Sensitivity analysis to the seismic event frequencies showed that the most conservative results were obtained using average frequencies for considered seismic interval. The least conservative results were obtained using frequencies for the upper PGA values of the corresponding acceleration ranges. It is recommended for real SPSA to use average frequencies for seismic interval and quantify these frequencies using reasonable number of bins within the seismic interval. Increasing number of bins gives more precise, more accurate calculation of the frequencies. The same recommendation – to use probability, averaged for seismic interval, instead of probability calculated for point value like upper PGA value – can be applied for treatment of SSCs seismic failure probability.

It should be noted that fragility modelling uses lognormal distribution. While lognormal hypothesis holds for the body of the distribution, but it inaccurately represents the fragility tails (as it considers higher probabilities of failure at low accelerations, which is conservative). This may be considered for improvements on low seismicity regions, like Zaporizhzhia site.

Another aspect that should be mentioned is that PSHA results should be produced taking into account real PSA purposes, e.g. the same intensity measure (and terminology) should be used both for seismic hazards, seismic fragilities and risk.

Further improvements may be considered regarding the METIS tool:

- Code debugging to ensure more stable operation of the solver at different platforms;
- Further integration and debugging of software within the METIS tool pack;
- Improvement of the solver to correctly treat initiating event frequencies.

5.6. Dissemination, Other Resources and Impact

The approaches, methods, tools developed and obtained results were discussed and presented at a set of open workshops and training schools:

- Workshop on PSA theory and Andromeda-SCRAM tutorial, 25 February, 2022;
- METIS Summer School on Seismic Fragility, Athens, Greece, 8-9 June 2022;
- Workshop on PSA Tools, EDF PARIS Saclay, France, 21 October 21 2022;
- Aftershock Workshops, online, 09 February, 14 February 2023;
- TUK-SSTC NRS Training School on PSA, online, 11-13 March 2025

5.7. Key Contacts

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6. Outcomes from peer review of case study

6.1. Objectives

As described in section 1.3, the objective of METIS case study was to provide a common framework and datasets to assess project developments, scientific and engineering results. The case study implements the different steps of a seismic PSA for a NPP (seismic hazard, site response, fragility analysis and risk assessment), leveraging from real data at all steps, although it doesn't represent a real seismic PSA for a real NPP.

Following the practice for seismic PSA on real projects, a peer-review of the case study was also conducted to assess the technical quality, discuss on hypothesis and comparisons conducted by different WP about developed and existing methodologies, and finally to assess the feasibility of new and improved approaches implemented in METIS for industrial applications.

6.2. Organization, participants and recommendations

The peer-review group was composed of members from the External Advisory Board (EAB) and some members from the End-Users group (EUG). Several technical meetings were organized between project partners and the peer-review group focusing on Deliverables from different WP linked to the case study (D4.6, D5.4, D6.8 and D7.9). Discussions covered both technical and methodological aspects for the different steps of the case study, but also general remarks and recommendations for the project. These aspects are described in detail in Deliverable D3.2.

From the minutes of these technical meetings emerged a total of 22 main remarks and recommendations from the peer-review group, which are fully discussed in Deliverable D3.3. Among them, the project emphasizes that:

- The difficulty in producing a case study sufficiently simple and yet complex enough to be representative of the different steps of a real seismic PSA. The integrated approach developed in the project aimed enforcing interfaces between different scientific fields (seismic hazard, geotechnical and structural engineering, risk analysis) to avoid inconsistencies.
- The case study hazard model is sufficiently complex and adapted for the project applications. However, active faults are absent in the model, which is not appropriate for all projects. The project tried to follow SSHAC's philosophy, looking to capture seismic hazard center, body and range, although not compliant to SSHAC procedure.
- The joint occurrence probability of mainshock-aftershock events needs to be assessed in seismic hazard assessment to conduct mainshock-aftershock risk studies. The proposed mainshock-aftershock methodology used in the METIS case study, based on obtaining aftershock hazard after the mainshock, is appropriate for PSA studies.
- However, more research is required to assess possible impact of aftershocks on NPP safety. It is expected that the aftershock has not a major impact on risk assessment due to shut down after the main event.
- In cases where substratum depth differs significantly across the site, it is important to assess and integrate differences across the site correctly for site response analysis; or on a simplified manner to define a common substratum depth and a characteristic seismic motion compatible to the different soil columns.
- Conditional spectrum method enforces consistency of hazard spectral shape for the selection of time-histories. Including other characteristics of the ground motions in the methodology is

possible (e.g. Magnitude-Distance, duration…) but there will be a trade-off between enforcing these characteristics and the sufficiency of existing databases to select natural time-histories.

- PGA is generally used as intensity measure (IM) to develop fragility curves. It is not possible to choose one unique optimal intensity measure for all SSC due to the large frequency ranges and variety of phenomena considered for SSCs failure. The project has analysed the consideration of multiple IMs for PSA process. The benefit and feasibility of considering different IMs on a vector approach for PSHA, fragility analysis and risk assessment require more sensitivity studies. Another option is to consider an averaged spectral acceleration instead of PGA covering the (most) frequencies of interest for the different SSC.
- The opportunity provided by datasets produced by the project can serve as benchmark for new developments on specific steps of seismic PSA on future research projects. Also, the opportunity to promote the project results, accomplishments, and limitations, by conference or journal paper targeting the nuclear community.

6.3. Outcomes and Lessons Learned from case study

This section summarizes the main accomplishments and limitations of this case study. The main accomplishments are the following:

- METIS case study successfully constructed a hybrid site relying on real data for different steps of seismic PSA (seismic hazard, site response, structural and fragility estimation, safety assessment). The open datasets produced for the METIS case study and available on OpenMETIS at Zenodo (https://zenodo.org/communities/openmetis) can be a starting point for other research teams to test new methodologies and integrate them in the framework of the METIS case study.
- The methods used in the different work packages (WPs) of the case study are not fully consistent in terms of their potential applicability to real-life PSA studies, as some steps are based on the state of the art and others on the state of the practice. Taking this into account, most of the participating teams managed to use the data provided to test the methods and tools developed within the project and compare them with the established practices for the different steps of the PSA studies.
- Training sessions on PSA methodologies organized by the METIS project benefited from the case study as example of the applicability and expected results from developed methodologies. This educational characteristic of the case study can be enforced after METIS, serving as basis for further training sessions organized by project partners on seismic PSA.
- The case study allowed state-of-the-art methodologies dissemination within project partners and served as a starting point for sharing partners knowledge in their specific scientific discipline within METIS consortium.
- The case study also served as a vector for testing new developments motivated by the project on numerical platforms developed or tested by project partners (OpenQuake, code_aster, Andromeda).

Compared to seismic PSA studies carried out on real projects, the case study shows some limitations due to the partial use of simplified procedures. The main limitations are the following:

- The computed seismic hazard on rock didn't consider possible active faults, as consequence of lack of specific fault characterization data for the region. It would be expected for high return periods to consider rare, low probability events coming from capable faults.
- METIS methodology relies on better estimation of uncertainties in seismic hazard by explicitly characterizing epistemic uncertainties on site response. However, GMMs used for the hazard

model present similar uncertainties for either rock or soil sites, therefore not explicitly rewarding epistemic uncertainty quantification and propagation for site response. This drawback recalls that more research is necessary in constructing specific GMMs for rock sites.

- Although the project investigated state-of-the-art methods for modeling site response and SSI, the datasets generated for the METIS case study relied on simplified methods used in engineering practice. This pragmatic decision was mainly justified by (i) the need to implement the METIS strategy to avoid double counting of uncertainties in the soil at the interface between site response and SSI, and (ii) the capabilities of the numerical tools chosen by the project partners to build and run the numerical models. Further efforts and research would be needed to address this issue.

- The datasets related to site response time histories present a large variability for vertical motions, as (i) the time-histories selection procedure consistent with rock hazard for the horizontal component didn't apply any constraint in the vertical motion, and (ii) vertical motion from 1D site response considered soil elastic properties. Within Linear Equivalent approach, methodologies increasing Poisson ratio exist to calculate Vp properties linked to Vs reduction, however presenting limitations for strong motions. This second point recalls that more research is necessary to establish methodologies for site response to vertical ground motions.

- The PSA calculations relied both on fragility curves estimated from specific datasets from the Italian site and already established fragility curves from ZNNP PSA conduct previously to METIS. This consequence of the hybrid characteristic of the case study enforces that NPP-site combinations are unique and different seismic PSA results can be obtained for identical structures on different sites.

6.4. Key contacts

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- Irmela Zentner, irmela.zentner@edf.fr.

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