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Safety of Existing Nuclear Installations

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Guidance document on practices to model and implement EARTHQUAKE hazards in extended PSA (final version)
Volume 1

Reference ASAMPSA_E

Technical report ASAMPSA_E / WP21 / D50.15/ 2017-33 volume 1

Reference IRSN PSN/RES/SAG/2017-00004

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Summary :

The current report provides guidance for the assessment of seismotectonic hazards in level 1&2 PSA. The objective is to review existing guidance, identify methodological challenges, and to propose novel guidance on key issues. Guidance for the assessment of vibratory ground motion and fault capability comprises the following :

- listings of data required for the hazard assessment and methods to estimate data quality and completeness;
- in-depth discussion of key input parameters required for hazard models;
- discussions on commonly applied hazard assessment methodologies;
- references to recent advances of science and technology.

Guidance on the assessment of correlated or coincident hazards comprises of chapters on :

- screening of correlated hazards;
- assessment of correlated hazards (natural and man-made);
- assessment of coincident hazards.

Visa grid			
	Main author(s) :	**Verification**	**Approval (Coordinator)**
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EXECUTIVE SUMMARY

The report provides guidance on how to derive quantitative values for seismotectonic hazards (vibratory ground motion and fault capability) for the implementation and use in level 1&2 PSA. The objective is to review existing guidance, identify good practices and challenges in hazard assessment, and provide links to relevant regulatory, technical, and scientific literature. References to recent advances of science and technology are included in all chapters. In addition, novel guidance is proposed for (1) the treatment of some key issues which have large impacts on the hazard results, and (2) the identification and assessment of hazard combinations (correlated and coincident hazards).

(1) Guidance on seismic hazard assessment focuses on:

- a detailed description of the data required as inputs for seismic hazard assessment including site-specific information from geosciences and methods for estimating data quality and completeness; the report particularly identifies the need to critically review earthquake data and to develop reliable data to characterize faults in the surrounding of NPPs; these needs derive from fact that most parts of Europe are intraplate areas with slow to very slow faults, which typically produce earthquakes at recurrence intervals of thousands to ten thousands of years while earthquake catalogues only span few hundred years;
- guidance and in-depth discussion is further provided on how to obtain the key input parameters such as seismic sources, ground motion prediction equations, maximum magnitude, and lower bound magnitude;
- the report finally provides references to guidance on commonly applied hazard assessment methodologies (Probabilistic and Deterministic Seismic Hazard Assessment, Probabilistic Fault Displacement Analysis) and discussions of the associated uncertainties and methodological limits; the most important limitation to probabilistic hazard assessments is seen in the fact that traditional PSHA heavily relies on the extrapolation of short records of earthquake data to the very low occurrence probabilities required as input parameters for PSA (10-4 to 10-7 per year).

(2) Novel guidance on hazards combinations considers both, correlated and coincident hazards. The report provides guidance on the screening of correlated natural and man-made hazards, the assessment of the most important correlated hazards, and the assessment of coincident (contemporaneous) hazards.

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7	Universität Wien	UNIVIE	Austria
8	Cazzoli Consulting	CCA	Switzerland
9	Italian National Agency for New Technologies, Energy and the Sustainable Economic Development	ENEA	Italy
10	Nuclear Research and consultancy Group	NRG	Nederland
11	IBERDROLA Ingeniería y Construcción S.A.U	IEC	Spain
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14	NUBIKI	NUBIKI	Hungary
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CONTENT

GLOSSARY

AEP	Annual Exceedance Probability
AHEAD	European Archive of Historical Earthquake Data
ARP	Alarm Response Procedure
CCF	Common Cause Failure
CDF	Core Damage Frequency
CTM	Centroid-Moment-Tensor (Earthquake)
DBE	Design Basis Earthquake
DEC	Design Extension Conditions
DEC-A	DEC without fuel damage
DEC-B	DEC with postulated fuel damage
DEM	Digital Elevation Model
DG	Diesel Generator
DPD	Discrete Probability Distributions
DSG	Design Safety Guide
DSHA	Deterministic Seismic Hazard Assessment
EMSC	European-Mediterranean Seismological Centre
ENSREG	European Nuclear Safety Regulators Group
EOP	Emergency Operating Procedure
EPRI	Electric Power Research Institute
EPRI	Electric Power Research Institute (U.S.)
EPZ	Emergency Planning Zones
ETL	Event Tree Linking
FDF	Fuel Damage Frequency
FDSN	International Federation of Digital Seismograph Networks
FTL	Fault Tree Linking
GIS	Geographical Information System
GMPE	Ground Motion Prediction Equation
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GR	Gutenberg-Richter-Relation (Earthquake)
HCLPF	High Confidence of Low Probability of Failure
HEP	Human Error Probability
HFE	Human Failure Events
HRA	Human Reliability Analysis
IAEA	International Atomic Energy Agency
IEMS-98	Earthquake intensity measured by the European Macroseismic Scale 1998
IESI-2007	Earthquake intensity measured by the Environmental Intensity Scale ESI-2007
IPEEE	Individual Plant Examination of External Events
ISRS	In Structure Response Spectra
ITC	Informed Technical Community

KTA	Kerntechnischer Ausschuss (Germany)
LBM	Lower Bound Magnitude (=m0)
LERF	Large Early Release Frequency
LIDAR	Light Detection And Ranging (producing DEM data)
LOCA	Loss of Coolant Accidents
LOOP	Loss of Off-Site Power
MCS	Monte Carlo Simulation
Mmax	Maximum Magnitude
Mw	Moment Magnitude (Earthquake)
NDC	NPH Design Category
NPH	Natural Phenomena Hazards
NPP	Nuclear Power Plant
NPP	Nuclear Power Plant
NR	Near-region (25 km radius from NPP site)
NRC	(US) Nuclear Regulatory Commission
NSC	Nuclear Safety Commission, Japan
NUREG	NUREG-Series Publications (U.S.NRC)
OBE	Operational Base Earthquake
OECD	Organisation for Economic Co-operation and Development
OECD/NEA	Nuclear Energy Agency of OECD
PDF	Probability Density Functions
PFDHA	Probabilistic Fault Displacement Hazard Analysis
PFDHA	Probabilistic Fault Displacement Hazard Analysis
PGA	Peak Ground Acceleration
PGAH	Peak Ground Acceleration in horizontal direction
PGAV	Peak Ground Acceleration in vertical direction
POS	Plant Operational State
PSA	Probabilistic Safety Assessment
PSF	Performance Shaping Factor
PSHA	Probabilistic Seismic Hazard Analysis
PSR	Periodic Safety Review
PTDHA	Probabilistic Tectonic Deformation Hazard Analysis
PTDHA	Probabilistic Tectonic Deformation Hazard Analysis
RE	Region (50 km radius from NPP site)
RHWG	Reactor Harmonization Working Group
RS	Remote Sensing (satellite imagery)
SAM	Severe Accident Management
SAR	Safety Analysis Report
SBO	Station Black Out
SFP	Spent fuel Pool
SHA	Seismic Hazard Analysis
SHARE	Seismic Hazard Harmonization in Europe
SI	NPP site (area under control of the licensee)

SMA	Seismic Margin Assessment
SPSA	Seismic Probabilistic Safety Assessment
SSC	Structure System and Component
SSHAC	Senior Seismic Hazard Analysis Committee
SV	Site vicinity (5 km radius from NPP site)
TC	Technical (or Scientific) Community
TCEF	Temporal Course of Earthquake Frequency
TFI	Technical Facilitator / Integrator (SSHAC)
TI	Technical Integrator (SSHAC)
UHRS	Uniform Hazard Response Spectrum
U.S.NRC	U.S. Nuclear Regulatory Commission
USGS	U.S. Geological Survey
VS30	Average shear wave velocity between 0 to 30 m depth of soil/rock
WENRA	Western European Regulator's Association
WSM	World Stress Map

DEFINITIONS

Accident Sequence Analysis	The process to determine the combinations of initiating events, safety functions, and system failures and successes that may lead to core damage or large early release.
Aleatory Uncertainty	Uncertainty inherent in a random (stochastic) phenomenon reflected by modelling the phenomenon by a probabilistic approach. Aleatory uncertainty cannot be reduced by additional information or data.
Bounding Analysis	Analysis that uses assumptions such that assessed outcome will meet or exceed the maximum severity of all credible outcomes.
Cliff Edge Effect	In a nuclear power plant, an instance of severely abnormal plant behavior caused by an abrupt transition from one plant status to another following a small *deviation* in a plant parameter, and thus a sudden large variation in plant conditions in response to a small variation in an input.
Dangerous Occurrence, Incident	A dangerous occurrence is an unplanned and undesired occurrence (incident) which has the potential to cause injury and which may or may not cause damage to property, equipment or the environment.
Design Basis	The range of conditions and *events* taken explicitly into account in the *design* of a *facility*, according to established criteria, such that the *facility* can withstand them without exceeding *authorized limits* by the planned *operation* of *safety systems*. Design basis requirements for existing European plants are prescribed by WENRA (2014a). Requirements include that that *"The design basis shall be reviewed and updated during the lifetime of the plant"*.
Design Basis External Events	The *external event(s)* or combination(s) of *external events* considered in the *design basis* of all or any part of a *facility*. According to WENRA (2014a, Issue T5.1) *"A common target value of frequency, not higher than 10^{-4} per annum, shall be used for each design basis event."*
Epistemic uncertainty	Uncertainty that is attributed to incomplete knowledge about a process or phenomenon which effects the ability to model it. Epistemic uncertainty is due to a variety of variable models to describe a phenomenon, diverging expert opinion, etc. It may be reduced by the acquisition of additional information and data.
Event Tree Analysis	An inductive technique that starts by hypothesizing the occurrence of basic initiating events and proceeds through their logical propagation to system failure events. • The event tree is the diagrammatic illustration of alternative outcomes of specified initiating events. • Fault tree analysis considers similar chains of events, but starts at the other end (i.e. with the 'results' rather than the 'causes'). The completed event trees and fault trees for a given set of events would be similar to one another.
External Event	An event originated outside a nuclear power plant that directly or indirectly causes an initiating event and may cause safety system failures or operator errors that may lead to core damage or large early release. Events such as earthquakes, tornadoes, and floods from sources outside the plant and fires from sources inside or outside the plant are considered external events. By historical convention, LOOP not caused by another external event is considered to be an internal event. According to NUREG 2122, the term external event is no longer used and has been replaced by the term external hazard.
Fault Tree Analysis	A deductive technique that starts by hypothesizing and defining *failure events* and systematically deduces the *events* or combinations of *events* that caused the *failure events* to occur. • The fault tree is the diagrammatic illustration of the *events*. • *Event tree analysis* considers similar chains of *events*, but starts at the other end (i.e. with the 'causes' rather than the 'results'). The completed *event* trees and fault trees for a given set of *events* would be similar to one another.
External Hazard Analysis	The objective is to evaluate the frequency of occurrence of different severities or intensities of external events or natural phenomena (e.g., external floods or high winds).
Probabilistic Seismic Hazard Analysis (PSHA)	PSHA determines the probability of a seismic event that exceeds a certain ground motion (defined as horizontal / vertical acceleration and / or spectral accelerations) is determined through a probabilistic assessment.
Fragility	The fragility of a structure, system or component (SSC) is the conditional probability

	of its failure at a given hazard input level. In seismic hazard analysis the input is the severity of ground shaking induced by an earthquake.
Fragility Analysis	Estimation of the likelihood that a given component, system, or structure will cease to function at the occurrence of a dangerous occurrence of a certain severity. • In a PRA, fragility analysis identifies the components, systems, and structures susceptible to the effects of an external hazard and estimates their fragility parameters. Those parameters are then used to calculate fragility (conditional probability of failure) of the component, system, or structure at a certain intensity level of the hazard event. • Fragility analysis considers all failure mechanisms due to the occurrence of an external hazard event and calculates fragility parameters for each mechanism. This is true whether the fragility analysis is used for an external flood hazard, fire hazard, high wind hazard, seismic hazard, or other external hazards. For example, for seismic events, anchor failure, structural failure, and systems interactions are some of the failure mechanisms that would be considered.
Fragility Curve	A graph that plots the likelihood that a component, system, or structure will fail versus the increasing intensity of a hazard event. • In a PRA, fragility curves generally are used in seismic analyses and provide the conditional frequency of failure for structures, systems, or components as a function of an earthquake-intensity parameter, such as peak ground acceleration. • Fragility curves also can be used in PRAs examining other hazards, such as high winds or external floods.
Hazard	In the current context hazard is referred to as a situation that poses a threat to nuclear installations, life or health of humans in the installation, or the environment. • Internal hazards include equipment failures, human failures, flooding and fires internal to the plant. • External hazards include events such as flooding and fires external to the plant, tornadoes, earthquakes, and aircraft crashes."
Hazard Analysis	The process to determine an estimate of the expected frequency of exceedance (over some specified time interval) of various levels of some characteristic measure of the intensity of a hazard (e.g., peak ground acceleration to characterize ground shaking from an earthquake). The time period of interest is often taken as 1 year, in which case the estimate is called the annual frequency of exceedance.
Hazard Curve	See seismic hazard curve
Human Reliability Analysis	A structured approach used to identify potential human failure events and to systematically estimate the probability of those events using data, models, or expert judgment.
Individual plant examination for external events (IPEEE)	While the "individual plant examination" takes into account events that could challenge the design from things that could go awry internally (in the sense that equipment might fail because components do not work as expected), the "individual plant examination for external events" considers challenges such as earthquakes, internal fires, and high winds.
Initiating Event	An identified *event* that leads to *anticipated operational occurrences* or *accident conditions*. • This term (often shortened to ***initiator***) is used in relation to *event* reporting and *analysis*, i.e. when such *events* have occurred. For the consideration of hypothetical *events* considered at the *design* stage, the term *postulated initiating event* is used.
Large early release	The rapid, unmitigated release of air-borne fission products from the containment to the environment occurring before the effective implementation of off-site emergency response and protective actions such that there is a potential for early health effects.
Large early release frequency (LERF)	Expected number of large early releases per unit of time.
Loss of coolant accident (LOCA)	Those postulated accidents that result in a loss of reactor coolant at a rate in excess of the capability of the reactor makeup system from breaks in the reactor coolant pressure boundary, up to and including a break equivalent in size to the double-ended rupture of the largest pipe of the reactor coolant system.
Loss of Offsite Power (LOOP)	The loss of all power from the electrical grid to the plant. In a PSA/PRA, loss of offsite power (LOOP) is referred to as both an initiating event and an accident sequence class. As an initiating event, LOOP to the plant can be a result of a weather-related fault, a grid-centered fault, or a plant-centered fault. During an accident sequence, LOOP can be a random failure. Generally, LOOP is considered to be a transient initiating event.

Postulated Initiating Event (PIE)	An *event* identified during *design* as capable of leading to *anticipated operational occurrences* or *accident conditions*. • The primary causes of *postulated initiating events* may be credible equipment *failures* and *operator* errors (both within and external to the *facility*) or human induced or natural *events*.
Screening	A process that distinguishes items that should be included or excluded from an analysis based on defined criteria.
Screening criteria	The values and conditions used to determine whether an item is a negligible contributor to the probability of an accident sequence or its consequences.
Seismic Hazard Analysis (SHA)	A process used to assess the hazards of seismic events. Assessments may use deterministic methods, probabilistic methods, or combinations of both. Probabilistic assessments determine the probability of occurrence of different ground shaking severities. These probabilities are used as input parameters to the model used to assess the potential effects on the plant. Deterministic seismic hazard assessment determines the strongest possible ground shaking parameters at a site from the largest earthquake that is regarded possible to occur at a certain fault or in a seismic zone.
Seismic Hazard Curve	A plot of the exceedance frequency (annual probability of exceedance) versus the level of vibratory ground motion denoted by peak ground acceleration, spectral acceleration or other values.
Sensitivity Analysis	A quantitative examination of how the behavior of a *system* varies with change, usually in the values of the governing parameters. • A common approach is parameter variation, in which the variation of results is investigated for changes in the value of one or more input parameters within a reasonable range around selected reference or mean values, and perturbation *analysis*, in which the variations of results with respect to changes in the values of all the input
Severe accident	A type of accident that may challenge safety systems at a level much higher than expected.
Structures, Systems And Components (SSCs)	A general term encompassing all of the elements (items) of a *facility* or *activity* which contribute to *protection and safety*, except *human factors*. • ***Structures*** are the passive elements: buildings, vessels, shielding, etc. • A ***system*** comprises several *components*, assembled in such a way as to perform a specific (active) function. • A ***component*** is a discrete element of a *system*. Examples of components are wires, transistors, integrated circuits, motors, relays, solenoids, pipes, fittings, pumps, tanks and valves.
Uncertainty	See Aleatory Uncertainty and Epistemic Uncertainty
Uncertainty Analysis	An *analysis* to estimate the uncertainties and error bounds of the quantities involved in, and the results from, the solution of a problem.

EXISTING GUIDANCE : KEY DOCUMENTS

Reference	**Remarks**
WENRA-RHWG, 2014a (Reference Levels Issue T: Natural Hazards)	Requirements for hazard assessment, protection, design basis, and design extension conditions
WENRA-RHWG, 2015 (Guidance Document Issue T: Natural Hazards Head Document)	Generic guidance on natural hazards
WENRA-RHWG, 2016 (Guidance Document Issue T: Natural Hazards. Guidance on Seismic Events)	Specific guidance on seismic hazards
WENRA-RHWG, 2014a (Reference Levels Issue F: Design Extension for Existing Reactors)	Requirements for assessment of initiating events exceeding the severity of design basis events, protection and safety goals
WENRA-RHWG, 2015 (F: Guidance Document Issue F: Design Extension of Eexisting Reactors)	Guidance on safety analysis with respect to design extension conditions
WENRA-RHWG, 2013 (Position paper on PSR)	Periodic reviews of natural hazards
KTA, 2011	Design of Nuclear Power Plants against Seismic Events; Part 1: Principles
IAEA, 2003 (NS-G-1.6)	Seismic Design and Qualification for Nuclear Power Plants
IAEA, 2010 (SSG-9)	Hazard assessment: vibratory ground motion, fault capabilty
IAEA, 2015 (TECDOC 1767)	Paleoseismological methods to support seismic hazard assessment
IAEA, 2009 (NS-G-2.13)	Evaluation of seismic safety for extisting nuclear installations
IAEA, 2004 (NS-G-3.6)	Hazard assessment: site conditions, liquefaction
NUREG/CR-6372	Senior Seismic Hazard Analysis Committee (SSHAC), 1997. Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts.
NUREG 2117	Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies
WENRA, 2014a (Reference Levels Issue O: PSA)	Requirements for Probabilistic Safety Analyses
EPRI, 2013 (Seismic Probabilistic Risk Assessment)	Guidelines to seismic probabilistic risk assessments (SPRAs)
IAEA, 1995 (50-P-7) Superseeded	External hazards in PSA
IAEA, 2011 (A Methodology to Assess the Safety Vulnerabilities of Nuclear Power Plants against Site Specific Extreme Natural Hazards)	Seismic PSA, Seismic Margin Assessment (SMA)

1 INTRODUCTION

1.1 SCOPE AND OBJECTIVES

The recent experience of the severe accidents at the Fukushima Dai-ichi NPPs has shown how significant the impact of a strong earthquake and causally connected hazards (in this case tsunami and seismically triggered local landsliding) can be for a nuclear site. It has particularly shown that, in spite of the fact that in the design basis of each NPP natural hazards should have been appropriately taken into account and efficient protection should be in place, hazard assessments for defining the design basis may have underestimated hazards. The occurrence of events with severities exceeding the design basis can therefore not be generally excluded.

In the aftermath of the Fukushima accidents the ENSREG Stress Tests have addressed these issues for European NPPs. The Stress Tests specifically explored the adequacy of the seismic design bases and whether protection against earthquakes is in place which is sufficient to exclude potential severe damage to SSCs important to safety in cases of seismic loads that exceed the design basis values. It was further attempted to quantify these “safety margins”. Although ENSREG did not explicitly identify the need for updates of hazard assessments and revisions of design basis values, ENSREG (2012 a) issued the following European level recommendations for natural hazards as a conclusion of the Stress Tests:

- *“The peer review Board recommends that WENRA … develop guidance on natural hazards assessments, including earthquake, flooding and extreme weather conditions, as well as corresponding guidance on the assessment of margins beyond the design basis and cliff-edge effects.”*
- *“The peer review Board recommends that ENSREG underline the importance of periodic safety review. In particular, ENSREG should highlight the necessity to re-evaluate natural hazards and relevant plant provisions as often as appropriate but at least every 10 years.”* (ENSREG, 2012a, p. 2)

With respect to seismic hazards, ENSREG further stressed the following (ENSREG, 2012 b):

- *“With regard to hazards, particularly seismic, it would appear that techniques and available data are still developing. It is recommended that regulators should consider co-operation with other agencies in order to develop a consistent approach across Europe, taking account of updates in methodology, new findings and any relevant information from continuous research on active and capable faults in the vicinity of NPPs.” (p. 20)*
- *“PSRs including re-assessment of the seismic hazard were found to be particularly strong safety features since such repeated periodic updates make it possible to take advantage of advances in science and technology.” (p. 17)*

WENRA has consequently published Safety Reference Levels defining the requirements for natural hazard assessments and protection against natural hazards (WENRA, 2014a, Reference Levels, Issue T) and corresponding Guidance Documents for assessing natural hazards in general (WENRA, 2015), and seismic hazards in particular (WENRA, 2016). One of the main advances in the requirements published by WENRA (2014a) is that the design bases for protecting existing plants against external hazards shall be reviewed as often as necessary (the design basis may consequently change during the lifetime of a plant; WENRA. 2014a, p. 19 etc.; WENRA, 2015). This review process involves regular reviews and re-assessments of external hazards, e.g., during Periodic Safety Reviews (WENRA, 2013).

The requirements and expectations that are expressed in the cited WENRA documents are formulated in concise forms which refrain from detailed technical guidance and from detailed explanations of how to achieve the expectations. Such guidance is also not fully covered by documents on seismic hazard assessment published by IAEA, U.S.NRC, and other organisations (see table “Existing guidance : key documents”, page 16). The ASAMPSA_E consortium therefore decided to develop specific guidance on seismic hazards taking into account existing documents but identifying and closing “gaps” in the available literature and identifying needs to supplement or update existing guidance to meet the current state of the science.

Developing guidance on seismic hazard assessment in ASAMPSA_E should further address the needs of “End Users” expressed during the ASAMPSA_E End-User Workshop held in Uppsala, 2014 (Guigueno et al., 2014). Accordingly, ASAMPSA_E should:

- address earthquake as one of the most important external hazards (Recommendation No.3[1]),
- provide practices and methods to model combinations/correlations/dependencies of hazards (No. 7),
- provide guidance on how to assess coincident hazards in cases of long-lasting accidents (No. 8),
- develop a glossary, common for all PSAs (No. 16),
- present and compare existing methods for external hazards modelling including uncertainties (No. 27),
- examine how experts judgement shall be used for external hazards characterisation and how uncertainties can be considered (No. 28),
- PSHA assesses hazards for very low occurrence probabilities by extrapolating earthquake observations covering only few 100 years of records. Guidance should be provided on how to assess earthquake catalogue completeness and reliability, on how to assess the maximum possible earthquake (M_{max}), identify, analyse and assess (potentially) active faults relevant to the safety of the site (No. 32),
- a fact: in a region with low seismicity like Sweden, an earthquake M 8 is “possible” (and observed in paleo history) with a return period 1 million years examine how can such information be presented in a PSA (33),
- insist on the need to update periodically the design-basis hazards curve (No. 34).

The current document consequently focuses on providing guidance for seismic hazard assessments for extended PSA particularly considering the listed end-user requests. Development of a seismic PSA or extended PSA including seismic should be able to verify or demonstrate that that the protection against seismic design basis events is sufficient. It should further be able to demonstrate a minimum of protection against events with severities exceeding the design basis values leading to design extension conditions (DEC). For DEC events without fuel damage (DEC-A), it should be demonstrated that protection is sufficient to ensure the fundamental safety functions. For

[1] Numbers refer to End User Recommendations listed in Guigeno et al., 2014, p. 20 – 28.

design extension conditions with postulated fuel damage (DEC-B), it should be demonstrated that the plant is able to fulfil confinement of the radioactive material (WENRA, 2014a, Issue F).

The current document provides guidance on the assessment of seismotectonic hazards listed in Table 1 with priority given to the evaluation of vibratory ground motion.

Code	Hazard	Dur.	P&P	Hazard definition and hazard impact
N1	Vibratory ground motion (including long period ground motion)	s-m	U/R	The hazard is defined by the contemporaneous impact of vibratory ground motion on all civil structures and SSCs of the plant and its surrounding.
N2	Vibratory ground motion induced or triggered by human activity (oil, gas or groundwater extraction, quarrying, mine collapse)	s-m	U/R	The hazard is defined by the contemporaneous impact of vibratory ground motion on all civil structures and SSCs of the plant and its surrounding.
N3	Surface faulting (fault capability)	s-m	U/R	The hazard is defined in terms of impact on the plant of coseismic fault rupture and surface displacement. It includes surface rupture at secondary faults.
N4	Liquefaction, lateral spreading	s-m	U/R	The hazard is defined by the loss of shear strength of foundation soil and its effects on civil structures and underground installations such as pipes or cable trays.
N5	Dynamic compaction (seismically induced soil settlement)	s-m	U/R	The hazard is defined by the effects of soil settlement on civil structures and underground installations such as pipes or cable trays. It includes effects of seismically induced surface cracks.
N6	Permanent ground displacement subsequent to earthquake	d-l	U/R	The hazard is defined in terms of impact on the plant of permanent ground subsidence or ground heave due to strain release after an earthquake.

Table 1. List of seismotectonic hazards covered in the current document (from ASAMPSA_E D21.2). Explanation to columns: Dur.: duration of hazard phenomena classified as s-m (seconds to minutes), m-h (minutes to hours), h-d (hours to days), d-l (days and longer). P&P: Hazard predictability and hazard progression: predictable (P), unpredictable (U), progressing rapidly (R) or gradually (G). Ref: references to international standards introducing the hazard type.

1.2 POTENTIAL IMPACTS ON THE PLANT

Unlike the effects of other external hazards seismic events and vibratory ground motion simultaneously challenge all parts of the site of an NPP, all civil structures, SSCs (both safety and non-safety related), and personnel. The simultaneous impact and the following characteristics distinguish vibratory ground motion from all other external hazards and internal hazards:

1. Seismic events are not predictable and have no precursors (except for foreshocks of earthquake; these, however, cannot be identified as such at the time of their occurrence).
2. Hazard progresses very rapidly in seconds and lasts up to minutes.
3. Potential of aftershocks may aggravate damage due to the higher vulnerability of pre-damaged civil structures and SSCs as compared to intact ones.
4. Vibratory ground motion impacts on non-safety classified civil structures and equipment at the site such as the fire brigades[2] which are important for defense-in-depth.
5. Seismic ground shaking at multi-unit sites affects all units contemporaneously stressing the resources for accident management. The effects and damage to the individual plants at the site may, however, be different due to different site effects (soil type below basemat), basemat depths, and construction details.
6. Vibratory ground motion simultaneously affects the whole region around the site including traffic connections, support routes, and electrical grid.
7. Earthquake effects have a potential impact on regional communication networks.
8. Earthquakes challenge the availability of human resources from outside plant having an impact on human reliability (HRA)[3]. Seismic events therefore are different from other external hazard which progress slowly (as most types of flooding) or affect only very limited areas (such as airplane crash, lightning), but may be similar to some meteorological effects. NPP personnel may be distracted from nuclear safety due to private concerns (rescue, securing homes) reducing their reliability. HRA is thought to decrease with increasing impact (intensity) of the earthquake.
9. Unclear priorities for overall emergency response by local authorities may be in conflict with the priorities for SAMG. The availability of rescue and support from outside the plant (e.g., fire brigades, medical aid, and heavy machines for clean-up operations) may be limited due to the simultaneous needs of civil protection outside the plant.
10. Vibratory ground motion is correlated/associated with a large number of hazards including man-made hazards.

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[2] The importance such effects have been highlighted by the ENSREG Stress Tests finding that some fire brigade buildings are not capable to withstand design basis seismic events althought the action of fire brigades is credited in the defence-in-depth concept (e.g., the support of core cooling by feed and bleed) (ENSREG, 2012 c).

[3] Guidance on the verification and improvement SAM strategies in the context of PSA are included in the ASAMPSA_E Report by Rahni et al. (2017).

11. Issues related to (6) to (9) may arise from events with ground motion values below the design basis of the NPP which by themselves are not challenging the nuclear installation. However, they may cause severe damage to other structures due to the fact that these are not designed for equally high safety standards and have higher vulnerabilities than the NPP.

1.3 LESSONS LEARNED FROM PAST EVENTS

Deliverable D10.3 of the ASAMPSA_E Project (Nitoi et al., 2015) includes a detailed list of earthquakes that affected nuclear power plants. Among them, the following deserve special attention.

1.3.1 KOZLODUY NPP (BULGARIA)

Vrancea earthquake 04.03.1977, Mw 7.2 (Radu et al., 1979)

The earthquake with its epicenter in Romania (region of Vrancea, c. 270 km from the site) was felt with an intensity of MSK~6 at the site. The event had no impact on safety.

"Lessons learned" includes the re-evaluation of site seismicity and upgrading of SSCs. An overview on the most important activities on the Kozloduy NPP site till 1997 can be found in IAEA (2001). Issues concerning the site seismicity are also described and discussed in BNRA (2011) and BNRA (2012) stating that according to the design of Kozloduy NPP Units 1 and 2 (of 1973), the seismic activity in the region had been evaluated as below I_{MSK}=VI degree of the Medvedev-Sponheuer-Karnik seismic intensity scale (MSK-64). Following the March 1977 earthquake, a site seismic re-evaluation had been per-formed. The Operational Base Earthquake (OBE) was set to I_{MSK}=VI degree with Peak Ground Acceleration (PGA) of 0.05g and Design Basis Earthquake (DBE) to I_{MSK}=VII degree with PGA of 0.1g.

The lessons learned from this strongest earthquake were taken into consideration in the design on the next units built on the Kozloduy NPP site. According to the BNRA (2012), the following site maximum seismic impact had been adopted in the design of Kozloduy NPP Units 3 and 4:

- OBE - I_{MSK}=VI (MSK-64 scale);
- DBE - I_{MSK}=VII (MSK-64 scale);
- Surface response spectrum – the spectrum of Vrancea earthquake accelerogram dated 04.03.1977, recorded in Bucuresti and aligned to PGA of 0.1 g.
- The design of Units 5 and 6 had been developed based on the following seismic characteristics:
- OBE - VI degree by MSK-64 scale with PGA of 0.05g for recurrence period of 100 years; and
- DBE - VII degree by MSK 64 scale with PGA of 0.1g for recurrence period of 10,000 years.

A further reassessment of seismic design basis was performed during the period 1990-1992 under a joint IAEA project BUL 9/012 "Site and Seismic Safety of Kozloduy and Belene NPPs" (BNRA, 2011; 2012). New site seismic characteristics were defined accordingly. Seismic levels for recurrence period of 100 and 10,000 years respectively were determined using probabilistic and deterministic methods. Thus, for Kozloduy NPP site, were defined:

- for recurrence period of 100 years - PGA of 0.10g;
- for recurrence period of 10,000 years - PGA of 0.20g; and
- resultant floor design response spectra and respective three-component accelerograms for duration of 61 seconds.

Moreover, following an IAEA recommendation, floor design response spectra and respective three component accelerograms (for duration of 20 s) were additionally defined for local earthquakes.

The seismic characteristics – seismic levels, resultant design floor response spectra and respective three-component accelerograms were reviewed and confirmed by IAEA experts in the period from 1992 till 2008. The so called Review Level Earthquake (RLE) was also defined. This is the level, for which all SSCs of 1st seismic category of plants already designed and commissioned should be reviewed in respect of seismic resistance (BNRA, 2012).

Current seismic characteristics of the Kozloduy NPP site were defined in the period 1990-1992 and are valid for all facilities located on the site (BNRA, 2011; 2012). It should be noted that only two units - Unit 5 and Unit 6, commissioned respectively in 1987 and 1991, are in operation. In pursuance of the Bulgarian commitments made for the country's accession to the European Union, the first four reactors on the Kozloduy NPP site were shut down before the end of their design lifetime.

1.3.2 HUMBOLT BAY NPP (CALIFORNIA, USA)

Eureka earthquake 08.11.1980, M 7.2

The earthquake epicenter was located at a distance of 120 km from the site. The peak ground acceleration associated with the event (free flied) was 0.2 – 0.25 g while the plant was originally designed for 0.25 g and upgraded to 0.5 g. The event did not cause visible damage (IAEA, 2003a).

IAEA (2003) lists the following "Lessons learned":

- *"Upgraded structures can withstand events higher than the original design basis."*

1.3.3 PERRY NPP (OHIO, USA)

Leroy earthquake 31.01.1986, M 5

The earthquake epicenter was located 18 km from the NPP. The event caused strong motion duration of 1 second and a total earthquake duration of 2.7 seconds at the site. Peak ground acceleration of 0.19 g exceeded the design basis of 0.15 g. All SSCs operated properly during and after the earthquake. Post-event inspections and walkdowns by a large group of technicians did not find damage to any SSC (IAEA, 2003a).

IAEA (2003) lists the following "Lesions learned":

- *"PGA as damage indicator is not a suitable choice, while CAV or relative displacement confirmed their validity"*
- *"Low energy earthquakes, even if very close to the site, induce low damage because of their short duration and high frequency content"*
- *"65 people for a walkdown is too large a number and technical outcomes could be confused and contradictory"*

1.3.4 METZAMOR NPP (ARMENIA)

Spitak earthquake 07.12.1988, Ms 6.8

The Armenian (former USSR) NPP Metzamor is located about 70 km SSW of the epicenter of the 1988 Spitak earthquake. After the earthquake the USSR Ministers Council decided to shut down the existing two units of the NPP. Detailed descriptions of the impact of the earthquake on the NPP and of damage to SSCs are not available. In 1995 the Unit 2 of the NPP was re-commissioned after retrofitting of the reactor building, DG buildings and seismic qualification of the primary circuit equipment. Since 1995 several additional seismic upgrading programs were implemented. Actions further include novel PSHA studies for the site (Armenian Nuclear Regulatory Authority, 2015).

1.3.5 KASHIWAZAKI KARIWA (JAPAN)

Niigataken Chuetsu-Oki (NCO) earthquake 16.07.2007, Mw 6.6
The epicenter of the earthquake was about 16 km north of the site of the Kashiwazaki-Kariwa NPP.
There are seven units in Kashiwazaki-Kariwa NPP site.

Design basis: The design basis earthquake ground motion was specified at the free surface of the base stratum at the level of about -150m to -300m (different for each unit) from the ground surface. At the time of design, the vertical component of the earthquake was taken into account by static seismic force and vertical ground motion was not specified. The maximum acceleration of design basis earthquake ground motion is:
PGA_H 450cm/s^2 (in horizontal direction)

Ground motion at the site during the earthquake: the maximum horizontal accelerations (A_{Hmax}) observed on the base mat of the reactor building are as follows (IAEA, 2007b; numbers in the parentheses are the maximum acceleration from the response analysis at the design stage using design basis earthquake ground motion):

Unit 1 A_{Hmax} 680 cm/s2 (273 cm/s2)
Unit 2 A_{Hmax} 606 cm/s2 (167 cm/s2)
Unit 3 A_{Hmax} 384 cm/s^2 (193 cm/s^2)
Unit 4 A_{Hmax} 492 cm/s^2 (194 cm/s^2)
Unit 5 A_{Hmax} 442 cm/s^2 (254 cm/s^2)
Unit 6 A_{Hmax} 322 cm/^{s2} (263 cm/s^2)
Unit 7 A_{Hmax} 356 cm/s^2 (263 cm/s^2)

Estimated PGA (Peak Ground Acceleration) in horizontal direction PGA_H at the free surface of the base stratum about -150m to -300m (different for each rector) underground, where design earthquake ground motion is specified, was estimated by deconvolution analysis:

Unit 1 PGA_H 1699 cm/s^2
Unit 2 PGA_H 1011 cm/s^2
Unit 3 PGA_H 1113 cm/s^2
Unit 4 PGA_H 1478 cm/s^2
Unit 5 PGA_H 766 cm/s^2
Unit 6 PGA_H 539 cm/s^2
Unit 7 PGA_H 613 cm/s^2

Damage: No significant damages to safety related structures, systems and components were found by the plant walkdowns which were confirmed by thorough and detailed inspection and investigation later conducted (IAEA, 2007a).

Large soil deformations: Many of the problems on the Kashiwazaki-Kariwa nuclear power plant site were induced by large soil deformations.

Fire: Unit 3 in-house electrical transformer fire, which was not directly related to nuclear safety, Anchorage Failures: there were a limited number of anchorage failures mainly on transformers and water tanks that are not safety related equipment.

Design basis review: in September 2006, i.e., before the NCO earthquake occurred, guidelines were revised by the regulator (NSC: Nuclear Safety Commission, Japan) concerning the review of the seismic design of nuclear power plants in Japan. The guidelines address that both horizontal and vertical design earthquake ground motions are to be considered. Reflecting the guidelines as well as knowledge obtained from the NCO earthquake, TEPCO newly proposed the design basis earthquake ground motion specified at the free surface of the base stratum about -150 m to -300 m underground. Maximum acceleration of the design earthquake ground motion PGA_H (horizontal) and PGA_V (vertical) are as follows. Numbers in the parentheses are the maximum acceleration on the base mat of the reactor building from the response analysis using the revised design basis earthquake ground motion:

Unit 1	PGA_H	2300 cm/s^2	(845 cm/s^2)	PGA_V	1050 cm/s^2
Unit 2	PGA_H	2300 cm/s^2	(809 cm/s^2)	PGA_V	1050 cm/s^2
Unit 3	PGA_H	2300 cm/s^2	(761 cm/s^2)	PGA_V	1050 cm/s^2
Unit 4	PGA_H	2300 cm/s^2	(704 cm/s^2)	PGA_V	1050 cm/s^2
Unit 5	PGA_H	1050 cm/s^2	(606 cm/s^2)	PGA_V	650 cm/s^2
Unit 6	PGA_H	1050 cm/s^2	(724 cm/s^2)	PGA_V	650 cm/s^2
Unit 7	PGA_H	1050 cm/s^2	(738 cm/s^2)	PGA_V	650 cm/s^2

Upgrades: After NCO earthquake, upgrading to the site and the plant structures, systems and components were conducted such as: soil stabilization works on the site, modifications to structures including the reactor building roof structure, crane rail supports and exhaust stack, addition of new pipe supports and modifications to existing pipe supports (IAEA, 2008).

After Fukushima-Daiichi accident which occurred in 2011 new regulatory guides were issued and the design basis earthquake ground motions are to be re-evaluated. Upgrading works for SSCs against these newly specified earthquake ground motions are (will be) conducted.

1.3.6 FUKISHIMA-DAIICHI (JAPAN)

Great East Japan Earthquake (GEJE) or Tohoku earthquake 11.03.2011, Mw 9.0
The hypocentre was located at 24 km depth and the epicenter at a distance of about 180 km from Fukushima Daiichi NPP site.

Design basis: design basis earthquake ground motion is specified at the free surface of the base stratum at the level of about -200 m from the ground surface. The maximum horizontal and vertical accelerations of the design basis earthquake ground motion in accordance with the guidelines revised in 2006 concerning reviewing seismic design of nuclear power plants in Japan are:
PGA_H 600 cm/s^2
PGA_V 400 cm/s^2

Ground motion at the site: maximum horizontal and vertical accelerations observed on the base mat of the reactor building are as follows (IAEA, 2011; numbers in the parentheses are the maximum acceleration from the response analysis using design basis earthquake ground motion):

Unit 1 A_{Hmax} 460 cm/s^2 (487 cm/s^2) A_{Vmax} 258 cm/s^2 (412 cm/s^2)
Unit 2 A_{Hmax} 550 cm/s^2 (438 cm/s^2) A_{Vmax} 302 cm/s^2 (420 cm/s^2)
Unit 3 A_{Hmax} 507 cm/s^2 (441 cm/s^2) A_{Vmax} 231 cm/s^2 (429 cm/s^2)
Unit 4 A_{Hmax} 319 cm/s^2 (445 cm/s^2) A_{Vmax} 200 cm/s^2 (422 cm/s^2)
Unit 5 A_{Hmax} 548 cm/s^2 (452 cm/s^2) A_{Vmax} 256 cm/s^2 (427 cm/s^2)
Unit 6 A_{Hmax} 444 cm/s^2 (448 cm/s^2) A_{Vmax} 244 cm/s^2 (415 cm/s^2)

Damage (IAEA, 2011): Operating plants were automatically shut down and all plants behaved in a safe manner, during and immediately after the earthquake. Although all off-site power was lost when the earthquake occurred (LOOP occurred due to break of power line caused by failure of a transmission tower due to an earthquake-triggered landslide; Y. Fukushima, IAEA Seismic Safety Center, per. Comm.), the automatic systems at Fukushima Daiichi successfully inserted all the control rods into its three operational reactors upon detection of the earthquake, and all available emergency diesel generator power systems were in operation, as designed. Fundamental safety functions of (a) reactivity control, (b) removal of heat from the core and (c) confinement of radioactive materials were available.

Accident analysis therefore shows that fundamental safety functions were in place until the tsunami reached the sites. Damage by the tsunami was due to insufficient design provisions against tsunami.

1.3.7 FUKISHIMA-DAINI NPPS (JAPAN)

Great East Japan Earthquake (GEJE) or Tohoku earthquake 11.03.2011, Mw 9.0
Fukushima Daini site, located 12km south of Fukushima Daiichi site, has four reactors. At the time of the earthquake, all four units were operating.

Design basis: The design basis earthquake ground motion parameters are specified at the free surface of the base stratum -180m from the ground surface. Maximum horizontal and vertical accelerations of the design basis earthquake ground motion are:

PGA_H 600 cm/s^2
PGA_V 400 cm/s^2

Ground motion at the site: Maximum horizontal and vertical accelerations observed on the base mat of the reactor building are as follows (IAEA, 2011; TEPCO, 2012; numbers in the parentheses are the maximum acceleration from the response analysis using design basis earthquake ground motion):

Unit 1 A_{Hmax} 254 cm/s^2 (434 cm/s^2) A_{Vmax} 305 cm/s^2 (512 cm/s^2)
Unit 2 A_{Hmax} 243 cm/s^2 (428 cm/s^2) A_{Vmax} 232 cm/s^2 (504 cm/s^2)
Unit 3 A_{Hmax} 277 cm/s^2 (428 cm/s^2) A_{Vmax} 208 cm/s^2 (504 cm/s^2)
Unit 4 A_{Hmax} 210 cm/s^2 (415 cm/s^2) A_{Vmax} 288 cm/s^2 (504 cm/s^2)

By deconvolution analysis using the seismic observation records, the seismic motion of the free surface of the base stratum at -180m underground was evaluated and compared to the design basis seismic ground motion, showing that both motions are roughly equivalent.

Damage: The plants achieved cold shutdown safely with no core damage. Also, subsequent facility checks found no damage to functions of safety-critical equipment except for damage by the tsunami. Thus, it is considered that the earthquake had no impact on the functionality of safety-critical equipment.

1.3.8 ONAGAWA NPP (JAPAN)

Great East Japan Earthquake (GEJE) or Tohoku earthquake 11.03.2011, Mw 9.0
Situated on the eastern coast of Japan facing the Pacific Ocean, the Onagawa NPP was the closest nuclear power plant to the epicenter of the Mw 9.0 GEJE. The plant experienced very high levels of ground motion the strongest shaking that any nuclear power plant has ever experienced from an earthquake. The ground subsided about 1 m during the earthquake, from 14.8 m above sea level to 13.8m. There are three units in Onagawa NPP site.

Design basis: design basis earthquake ground motion is specified at the free rock surface -16m to -30m (different for each unit) from the ground surface. Maximum horizontal and vertical accelerations of the design basis earthquake ground motion:
PGA_H 580 cm/s^2
PGA_V 387 cm/s^2

Ground motion at the site: estimated horizontal and vertical PGAs at the free rock surface by the deconvolution analysis were comparable with the design ones.
PGA_H 636 cm/s^2
PGA_V 312 cm/s^2

Response spectrum of the deconvoluted wave is roughly equivalent to that of the design earthquake ground motion. Maximum horizontal and vertical acceleration observed on the base mat of the reactor building are as follows (numbers in the parentheses are the maximum acceleration from the response analysis using design basis earthquake ground motion):
Unit 1 A_{Hmax} 587 cm/s^2 (529 cm/s^2) A_{Vmax} 439 cm/s^2 (451 cm/s2)
Unit 2 A_{Hmax} 607 cm/s^2 (594 cm/s^2) A_{Vmax} 389 cm/s^2 (490 cm/s2)
Unit 3 A_{Hmax} 573 cm/s^2 (512 cm/s^2) A_{Vmax} 321 cm/s^2 (476 cm/s2)

Damage: IAEA (2012b) reports that there were no identified system failures affecting safety functions due to the earthquake. The most significant damage to equipment due to the earthquake shaking was the failure in the 6.9 kV switchgear. A vertically-racked circuit breaker in the non-safety-related turbine building switchgear caused a short circuit and a subsequent arc due to rocking of the breaker and fracture of the insulation around the bus clamps at top. The short circuit arc burnt the switchgear, consuming three or four adjacent cabinets.

Design basis review: after Fukushima-Daiichi accident which occurred in 2011, new regulatory requirements were issued and the design basis earthquake ground motion is to be re-evaluated

Upgrades: upgrading works for seismic capacity of the SSCs are (will be) conducted, e.g., for equipment and piping support, exhaust stack frame and foundation.

1.3.9 TOKAI NPP (JAPAN)

Great East Japan Earthquake (GEJE) or Tohoku earthquake 11.03.2011, Mw 9.0
The Tokai Daini site has a single reactor. At the time of the earthquake, Tokai Daini (unit 2) was operating.

Design basis: the design basis earthquake ground motion is specified at the free surface of the base stratum about -370m from the ground surface. Maximum horizontal and vertical accelerations of the design basis earthquake ground motion:
PGA_H 600 cm/s^2
PGH_V 370 cm/s^2

Ground motion at the site: Maximum horizontal and vertical acceleration observed on the base mat of the reactor building are as follows (numbers in the parentheses are the maximum acceleration from the response analysis using design basis earthquake ground motion):
Unit 2 A_{Hmax} 225 cm/s^2 (400 cm/s^2) A_{Vmax} 189 cm/s^2 (456 cm/s^2)

Damage: In response to the earthquake, the reactor automatically scrammed (shutdown). All three off-site power sources were lost and all three emergency diesel generators started automatically.

Design basis review: After Fukushima-Daiichi accident which occurred in 2011, new regulatory guides were issued and design earthquake ground motion is to be re-evaluated

Upgrades: Upgrading works for SSCs against these newly specified earthquake ground motions are (will be) conducted.

1.3.10 NPP NORTH ANNA (VIRGINIA, USA)

Earthquake of Mineral, Virginia, 23.08.2011, Mw 5.8
The earthquake with an epicenter located some 18 km from the North Anna Nuclear Station led to a loss of offsite power (LOOP) and caused the reactors to automatically shut down. Four emergency diesel generators started up to supply electricity to safety systems. Due to a coolant leak, one of the diesel generators stopped working and was replaced by a fifth EDG. Offsite power was restored during August 23.

1.3.11 MÜHLHEIM-KÄRLICH (GERMANY)

Identification of a fault at the site

The NPP Mühlheim-Kärlich was situated in the Neuwieder Basin in vicinity of the Rhine Graben Fault system. During the construction a fault was discovered at the site where the reactor building should be constructed. This lead to the decision to move the location of the reactor building for about 70 m to a location off the fault. The decision had severe legal consequences which finally resulted in the final shutdown of the NPP only two years after its commercial start. The legal decision to shut down was not related to any questions of fault capability. It was solely based on the invalidity of the planning and building permission resulting from the fact that the reactor building was not constructed at the location planned.

1.3.12 TSURUGA NPP (JAPAN)

Identification of a capable fault at the site

The NPP is located at the so-called Urasoko fault, which extends over a total length of about 10 km and forms a morphological scarp at the site. The foundations of both reactor units are located only 200 m from the fault. The fault was not considered to be active at the time of the siting of the plant. Paleoseismological trenching, however, proofed that the fault has moved repeatedly in the Late Pleistocene, and it is shown as an “active” or “possibly active” fault on Japan’s active fault map. The Urasoko fault is apparently connected to a fault which extends below the basemat of the reactors and therefore should be defined as active as well.

According Japanese national regulations by NRA, critical facilities which are situated on active faults should not be operated. Although this criterion was originally applied for the siting of NPPs (compare IAEA, 2009), NRA extended it to existing facilities. This regulatory approach required to clarify the definition of the term “active fault” and to assess the youngest slip history of the faults using extensive paleoseismological trenching (Chapman et al., 2013).

1.3.13 DIABLO CANYON (U.S.)

Identification of a capable fault in the site vicinity

Relocated microearthquakes led to the identification of an active fault (Shoreline or Hosgri Fault) in the site vicinity offshore of the Diablo Canyon NPP, California. The identification of the active fault in 2008 triggered a series of reviews of the seismic ground shaking hazards using PSHA and deterministic hazard assessment methods (see review by USNRC, 2012). Due to the fact that the seismic hazard at the NPP is controlled by faults located within 10 km, finite fault simulations were conducted for assessing ground motion (Abrahamson, 2015).

The identification of the fault led to the implementation of a license condition for operating the plant requiring the licensee to implement a “Long-Term Seismic Program” to perform regular hazard re-evaluations with the latest techniques and data (Chapman et al., 2013).

1.3.14 KRSKO NPP (SLOVENIA)

Identification of a capable fault in the site vicinity

The NPP Krsko is located close to the high-seismicity plate boundary between the Adriatic and the Pannonian plate in a tectonically complex region of moderate to high seismicity where seismicity is distributed over a large number of (partly unknown) active faults. In the course of geological investigations for the siting of a new NPP close to the existing one at least one active fault has recently been described in the site vicinity/near-region. To assess the resulting ground displacement hazard at the Krsko site a Probabilistic Fault Displacement Hazard Analysis (PFDHA) was initiated which accounts for as many as 10 potentially capable faults in the near-region (Cline et al., 2015).

Besides the capable fault issue the correct assessment of these faults is of vital importance for the derivation of reliable seismic hazard values for vibratory ground motion. The update of the seismic hazard assessment for Krsko is part of the Slovenian National Action Plan in the aftermath of the European Post-Fukushima Stress Test (*"Revision of the 2004 SPSA*"; SNSA, 2014, p. 13). The action follows ENSREG's Stress Tests recommendation which suggested that *"the regulator should consider requesting to update the seismic design basis*" (ENSREG, 2012). The fact that the hazard update has not been completed by now highlights the complexity and duration of a process to revise the seismic design basis. The time between deciding for a hazard update and implementation of protection measures at the plant may be very significant.

2 SCREENING OF SEISMOTECTONIC HAZARDS

Vibratory ground motion (including long period ground motion) (N1) : Seismic ground motion hazards have to be analyzed for all nuclear power plants and cannot be screened out for any site (WENRA, 2015: Issue T, Guidance on Seismic Events).

Vibratory ground motion induced or triggered by human activity (oil, gas or groundwater extraction, quarrying, mine collapse) (N2): Triggered or induced seismic ground motion can be screened out by the absence of man-made facilities which might cause such events (screening out by physical impossibility). Screening needs to consider the following potential sources:

- water, oil, or gas extraction wells,
- hydrothermal plants for thermal water extraction or re-injection,
- liquid waste disposal wells,
- mines and other large open volumes in the subsurface,
- quarries which, by their topography, may produce large volume rock falls.

The screening area around the site should be chosen in accordance with the potential maximum magnitude of the earthquake that may be produced by such facilities, and appropriate ground motion prediction equations (GMPEs)[4] which are applicable to model such events.

For induced earthquakes (i.e., events which are entirely controlled by human intervention) magnitudes up to Mw 5.6 have been observed. Examples include sites in Switzerland (Basel Deep Heat Mining : recorded M_{max}=3.4, Deichmann, 2010; maximum magnitude estimated from seismological data Mw 4.5, Baisch et al., 2009), Germany (Geothermianlage Landau : Imax=5, Ritter et al., 2014), and the USA (Rocky Mountain Arsenal, Denver, M_{max}=5.6, Folger & Tiemann, 2015; Paradox Valley, Colorado, M=4.3, Ake et al., 2005; The Geysers Field, California, M_{max}=4.6, US Department of Energy, 2015).

Although these magnitudes appear low compared to the possible magnitudes of natural earthquakes it must be considered that induced events occur at much shallower depth (typically 2-4 km) than natural earthquakes. The small hypocenter depths lead to large ground motion values at the epicenter. The shallow nature of the events, however, implies that the area affected by ground shaking will be significantly smaller than the area shaken by deeper natural quakes.

Maximum magnitude estimates for triggered seismicity, where human intervention initiates the seismic rupture process of a fault while the subsequent rupture propagation is controlled by natural stress, are more difficult to assess. Estimates should be based on the size of the largest fault that may rupture accounting for the orientation of the fault and the orientation of natural stresses. Maxiumum magnitude estimates can be obtained from scaling laws (Wells and Coppersmith, 1994; see also chapter 4.2.1, page 70).

[4] GMPEs provide relations between earthquake magnitude, distance from the hypocentre, and ground shaking parameters.

Surface faulting (fault capability) (N3): The hazard of surface faulting at the site may be screened out by geological analyses at the site and in the site-vicinity. Past examples of the identification of capable faults at the sites of existing nuclear facilities have shown that capable faults may have not been identified during the siting process (e.g., Kashiwazaki Kariwa NPP; Tsuruga NPP, Chapman et al., 2014; Diablo Canion NPP, U.S.NRC, 2012; Tsuruga NPP, Chapman et al., 2013; Krsko, SNSA, 2013). Screening out surface faulting hazards solely by referring to the results of the siting process should therefore be done with care. Screening must consider master and splay faults, which are related to the earthquake source, and secondary faults which are not related to the seismogenic source but may be triggered by the earthquake (Figure 1).

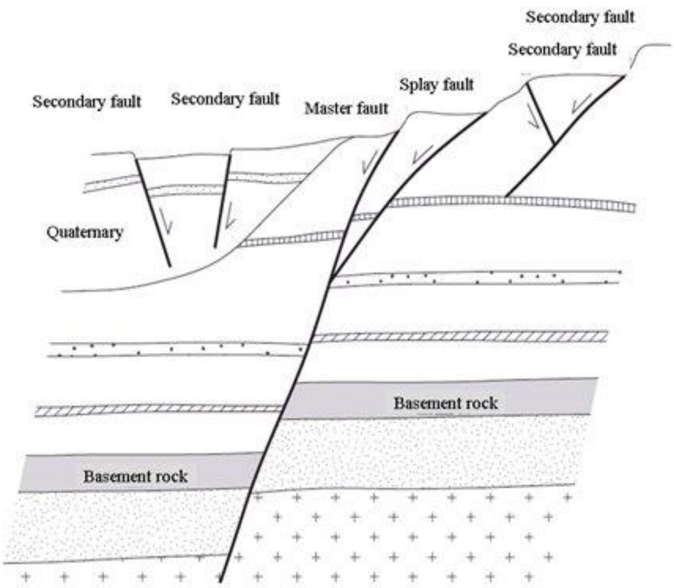

Figure 1: Terminology of capable faults: master fault, secondary fault, splay fault. Note that different terminologies exist in the U.S. *[Fig_Secondary_Faults.JPG]*

Liquefaction, lateral spreading (N4): The phenomena can be screened out by the physical impossibility of liquefaction to occur because a facility is founded on rock, consolidated sediments, or stiff soil which is not susceptible to liquefaction. For other sites more detailed analyses and data are required. These include detailed data of the soil properties below the site, and ground motion parameters and occurrence frequencies of expected earthquakes (ground acceleration, duration of shaking and number of loading cycles). The probability of events with ground motion parameters exceeding the liquefaction threshold may be derived from conventional seismic hazard analysis.

Dynamic compaction (seismically induced soil settlement) (N5) : see paragraph above (N4).

Permanent ground displacement subsequent to earthquake (N6) : The hazard can be screened out by physical impossibility in cases where no faults are present which may lead to significant permanent uplift / subsidence of the site. The hazard cannot be screened out for sites which are located in the vicinity of faults which may accumulate significant vertical displacement during a seismic event. These are sites in the hangingwall of subduction zones or large thrust faults, and locations in the hangingwall / footwall of large normal faults.

3 DATABASE

3.1 DATA FOR THE ASSESSMENT OF SEISMOTECTONIC HAZARDS

3.1.1 DATA FOR ASSESSING VIBRATORY GROUND MOTION HAZARDS

The kinds of data and the detailedness required for data collection in preparation for seismic hazard evaluations should generally follow the graded approach proposed by IAEA (2010). In this paper IAEA suggests to increase detailedness and efforts for data collection with decreasing distance from the utility. IAEA discerns between regional (RE, typically 300 km radius from the site), near-regional (NR, typically 25 km), site-vicinity (SV, 5 km) and site (SI) investigations. Data collection should be as complete as possible and include the acquisition of new data. It should be noted from the beginning of a hazard assessment program that the acquisition of new data will be a suitable and in many cases the only tool to narrow down the uncertainties of the outcome of the assessment.

The collected and newly acquired data should constrain as tightly as possible the following inputs for seismic hazard assessment:

- ***Construction of a regional seismotectonic model***. The aim of a seismotectonic model is to integrate all available data which describe the deformation of the Earth's crust under the current[5] geological conditions into a coherent and self-consistent model. Such a model must not be exclusively based on seismological data. Instead, a reasonable model will integrate earthquake data, geological data, geophysical data, geomorphological data, paleoseismolgoical data, geodetic data, stress data, tectonic data describing the deformation history, etc. (see below). One of the basic inputs is a tectonic map encompassing all relevant tectonic faults (both active and inactive). The seismotectonic model may be regarded as a theory of the current tectonic evolution of the region under consideration.

  In the construction of a seismotectonic model all relevant and scientifically supportable interpretations should be taken into account. This process may result in more than one model without being able to decide about the correctness of the different results. It such cases it should be decided whether the acquisition of new data may reduce the number of possible models (thereby decreasing uncertainty) or it is necessary to propagate the uncertainty of different models in a probabilistic approach, e.g., by adopting a logic tree. In the latter case all reasonable models should be weighted and considered in the final hazard evaluation.

  The construction of a plausible and well supported seismotectonic model is regarded as a key step because many important decisions in the subsequent seismic hazard assessment procedure will depend on it such as the selection of seismic sources / seismic source zones, the characterization of potentially active faults, fault activity rates etc.

  In most if not all parts of Europe the construction of seismotectonic models will be able to benefit from recent scientific studies on seismotectonic and active tectonics, which exploded in numbers during the last two decades.

[5] "Current" in this context refers to the youngest geological history, e.g., the Pliocene to Quaternary.

It should also be noted that a well-defined seismotectonic model which is in agreement with current scientific standards will serve as a strong argument to defend the final results of a hazard assessment.

- ***Seismogenic structures (active faults)***. Earthquakes occur on geological faults. Most parts of Europe are intra-plate areas with slow (< 1 mm/year) or very slow (< 0.1 mm/year) fault displacement rates producing strong earthquakes (M ~ 5 and larger) at recurrence intervals of 10^3 to 10^5 years, which are significantly longer than the time span covered by earthquake records (generally <10^3 years; see below). It is therefore very unlikely that all the active faults, which pose a potential threat in a certain region, have produced earthquakes in historical times, i.e., in the last 500 years or so. It is equally unlikely that all active faults can be recognized from analyzing the earthquake record. The hazard contribution of active faults therefore cannot be assessed from earthquake data alone as active faults which have not produced historical or instrumental seismicity are invisible in the earthquake record. Seismic hazard assessments which are exclusively based on earthquake data disregarding active faults may lead to severely underestimated hazard values.

  The epistemic uncertainties resulting from the inadequate time coverage of earthquake catalogues shall be reduced by systematic fault mapping and the collection of data to locate and characterize active faults (IAEA, 2010; WENRA, 2016). Systematic geologic surveys for identifying seismogenic faults significant for hazard results shall extend to a sufficient distance from the site. The choice of the distance to perform dedicated investigations may depend on the site seismicity. Larger distances may be adequate for sites with apparent low hazard as strong earthquakes occurring on remote faults may produce ground motion on the site, which exceeds the assumed low values. Systematic efforts should at least be made in the near-region of the site (25 km radius according to IAEA 2010).

  General guidance for the identification and characterization of active faults is given by IAEA (2010) and more detailed by IAEA (2015c). Modern geosciences provide reliable tools for the identification and characterization of active faults which are applicable within a reasonable time frame. Among these methods quantitative tectonic geomorphology and paleoseismological techniques are regarded as key methods. The tectonic geomorphology approach identifies landforms which result from the deformation of the Earth's surface by active faulting and deformation. It is capable of applying a time-saving graded approach including: screening of relatively large areas (several 100 km²) to identify potentially active faults, fault mapping, initial fault characterization and selection of faults requiring further analysis by paleoseismological methods. Guidance for the implementation of the method is given below.

  Paleoseismological trenching techniques allow to identify and to characterize prehistorical earthquakes that occurred on surface-breaking faults in terms of the timing of earthquake occurrence, magnitude, and recurrence intervals. These parameters shall be used to update the seismological database (see below).

- ***Seismological (earthquake) database***. The requirements of a seismological database for seismic hazard assessment are described in detail by IAEA (2010). IAEA discriminates between prehistoric, historical and instrumental earthquakes due to the fact that these types of data are characterized by different reliability and accuracy. The main data characteristics are summarized as follows:

Prehistorical earthquake data typically derive from paleoseismological trenching of active faults. The data are precise with respect to the location of the earthquake because they occurred on the trenched seismogenic source. Magnitudes are estimated from empirical relationships between faulting parameters (e.g., surface displacement) and magnitude (compare IAEA, 2015c, pages 95-107). Magnitudes therefore have error bars which can be quantified by statistical methods (Hintersberer & Decker, 2016). The accuracy of timing of the events is limited by the applied dating techniques (compare IAEA, 2015c, pages 82-91) and may therefore be subjected to errors up to a range of few thousand years. Data completeness depends on the effort and depth of research, and the local geological situation which may be favorable or unfavorable to conserve the effects of prehistorical earthquakes. Data quality and completeness can be increased by additional investigations in reasonable time. In some exceptional cases attention needs to be paid to the stationarity of data. Such a case is the deglaciation of Northern Europe during the last late Pleistocene to Holocene.

Historical earthquake data are compiled from historical documents which include descriptions of the earthquake effects at different locations. These descriptions are interpreted in terms of macroseismic intensity resulting in a set of intensity data points, which in turn are used to estimate the location of the epicenter and the maximum (epicentral) intensity. Earthquake magnitudes are derived from empirical intensity-magnitude correlations for the maximum (epicentral) intensity or from modeling approaches using all intensity datapoints of a single earthquake (Gasperini et al., 1999; Álvarez-Rubio & Fäh, 2009). The workflow therefore includes a number of steps that may introduce substantial errors: interpretation of historical sources; intensity assessment for intensity datapoints; assessment of epicenter location; assessment of epicentral intensity; intensity-magnitude conversion. Earthquake location, intensity, and magnitude will therefore be subjected to significant uncertainties, which frequently are not mentioned or quantified in earthquake catalogues. Due to the uncertainties of earthquake locations which may reach up to several tens of kilometers it will only in exceptional cases be possible to associate historical events to a certain seismic source. The data completeness and quality of historical earthquake data can be increased by targeted historical research but will finally be limited by availability of historical documents.

The quality and accuracy of instrumental earthquake data is strongly dependent on the density and quality of the seismic station network which has substantially changed since the beginning of instrumental records in the late 19th century. Location accuracy, reliability of magnitude values, and record thresholds will generally increase in quality through the 20th century but need to be assessed separately for different locations.

As suggested by IAEA (2010) the seismological database data should also include all types of data that help identifying seismogenic structures and support the seismotectonic model. Such data may particularly be obtained from local seismic networks around nuclear installations and include focal mechanisms, fore- and aftershock sequences, and precise relocations of earthquakes. IAEA (2015) further clearly states that *“seismic hazard assessments based on historical data are not sufficient to capture low frequency seismic events. Investigations to collect prehistoric data are needed”*.

- ***Site conditions***. Site-specific seismic hazard assessments require to determine the geotechnical and dynamic characteristics of the site considering site topography, the crustal and soil structure below the reactor basemat, and seismic velocity profiles of seismic and geotechnic bedrocks. Guidance on this issue is provided by IAEA (2004).

IAEA (2009 SSG-9) provides an incomprehensive compilation of data which is required for the assessment at the regional (RE; 300 km), near-regional (NR; 25 km), site-vicinity (SV; 5 km) and site (SI) scale. In addition to the data listed there the following data should be collected and acquired to support hazard assessment:

Database of scientific and technical literature:

- ***Data:*** Geological and geophysical research papers on seismicity, seismotectonics, and active faulting. The number of topical papers has tremendously increased in the past years due to a recent shift of the focus of academic research to active seismotectonic phenomena and processes. It is therefore indispensable to collect a database of relevant scientific papers (RE, NR, SV)
  Purpose: Support the construction of a seismotectonic model

Seismological data:

- ***Data:*** Earthquake catalogues with instrumental / historical / paleoseismological data (RE, NR, SV) Earthquake data from local observation networks (NR, SV) and data listed in by IAEA (2010)
  Purpose: Definition of seismicity; construction of a seismotectonic model; identification of active faults
- ***Data:*** Compilations of focal mechanism (fault plane solution) data and seismic moment tensors (RE)
  Purpose: Assess the orientation and kinematics of seismogenic faults; support the construction of a seismotectonic model
- ***Data:*** Strong motion data and/or intensity data points of individual events, isoseismal maps, ground motion prediction equations published in scientific and technical literature data (RE)
  Purpose: Selection of appropriate ground motion prediction equations

Geological and tectonic data:

- ***Data:*** Tectonic maps showing all relevant faults (both inactive and active) with adequate scales; compilation of the tectonic history of the area under consideration as derived from structural geology techniques and tectonic analyses (literature compilation); list of significant[6] tectonic faults (both active and inactive) with fault names, orientation, slip characteristics, geological evidence for youngest slip events (RE, NR, SV); recent stress data preferably from deep industrial boreholes (RE)

[6] Significant faults are > 10 km long (RE), > 5 km (NR), and > 1 km (SV)

Purpose: Support the construction of a seismotectonic model; locate and characterize faults (orientation, slip characteristics); identify faults which could move in current stress field (RE, NR, SV)

- ***Data:*** List of proved / disputed active faults from published data or fault databases (RE, NR)

  Purpose: Support the construction of a seismotectonic model; locate and characterize active faults

Geophysical data:

- ***Data:*** Reflection / refraction seismic, seismic tomography, heat flow, gravity (RE)

  Purpose: Define the thickness of the seismogenic crust and sources of seismicity in the mantle[7]
- ***Data:*** Reflection seismic, gravity, magnetic (RE, NR)

  Purpose: Map tectonic faults
- ***Data:*** High-resolution near-surface geophysical data (reflection seismic, resistivity, gravity, ground penetrating radar) (NR, SV, SI)

  Purpose: Map and locate potentially active faults precisely for paleoseismological investigations

Topographic and remote sensing data:

- ***Data:*** Satellite imagery, aerial photographs, Digital Elevation Models (DEM) and high-resolution LIDAR elevation data with resolution adequate to the scale (RE, NR, SV)

  Purpose: Support tectonic geomorphology and mapping of potentially active faults
- ***Data:*** GPS data and conventional geodetic data (repeated precise levelling) (RE, NR)

  Purpose: Asses horizontal / vertical crustal movements to support the identification of active faults

Site-specific data:

- ***Data:*** Rock and soil profiles below facility, geotechnical bedrock and soil properties, seismic velocities of bedrock and soil (Vs 30), topographic data obtained from boreholes and geophysical investigations (SI), cross-hole seismic tests

  Purpose: Assess site conditions in terms of dynamic elastic properties to characterize soil-structure interaction

Human activities

- ***Data:*** Location and type of facilities that may induce / trigger seismicity (deep oil, gas or water extraction wells; deep injection wells; mines; quarries etc.) (NR)

  Purpose: Assess induced and triggered seismicity

Numerical simulation data

- ***Data:*** earthquake ground motion models, (e.g., modeling of ground motion from fault parameters),

  Purpose: constrain ground motion characteristics.

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[7] E.g., the subducting slab in the Vrancea region, Romania.

3.1.2 DATA FOR ASSESSING SURFACE FAULTING AT THE SITE (FAULT CAPABILITY)

Guidance on the assessment of fault capability is provided by IAEA (2010, paragraphs 8.1 to 8.13). The cited document provides a definition of the term “capable fault”. Accordingly, *“a fault should be considered capable if it shows evidence of past movement or movements … of a recurring nature within such a period that it is reasonable to conclude that further movements at or near the surface may occur. In highly active areas … periods of the order of tens of thousands of years (e.g. Upper Pleistocene-Holocene, i.e., present) may be appropriate for the assessment of capable faults. In less active areas, it is likely that much longer periods (e.g. Pliocene-Quaternary, i.e. present) are appropriate.”* (IAEA, 2010).

Most parts of Europe are intra-plate areas with low to moderate seismicity produced by slow to very slow faults. Such regions cannot be regarded as “highly active”. According to IAEA’s definition the assessment of fault capability therefore shall address a geological time period that at least includes the entire Quaternary (< 2.6 mio. years before present) or extends back into the Pliocene (5.3 to 2.6 mio. years b.p.). The assessment of whether a fault moved repeatedly through that period of time, or not, requires an in-depth geological and paleoseismological approach as partly outlined by IAEA (2015c).

Although the assessment of fault capability focuses on the site it may be necessary to acquire data reaching out beyond this geographical area. This is due to the fact that faults in the near region (25 km) or site vicinity (5 km from the site) may extend into the site and that fault assessment at the site is hindered or impossible due to geological, technical, or logistical reasons.

The following data are required for the assessment:

Seismological data:

- ***Data:*** earthquake data from local observation networks with precise hypocenter locations; focal mechanism data (fault plane solutions, moment tensor solutions) from events that occurred in the region around the site,

  Purpose: check the coincidence of earthquake hypocenters with known tectonic faults; assess the location, orientation, and kinematics of the faults which produce earthquakes close to or at the site.

Geological data:

- ***Data:*** geological and tectonic maps showing all types of faults (both inactive and active) at adequate resolution (1:5.000 or higher); borehole data; lithology, stratigraphy, and age data of sediments which are offset by faults or seal faults; data on the fault rock (mylonite, cataclasite etc.),

  Purpose: locate and characterize faults (orientation, dip); date the youngest fault movements by offset/non-offset sediments; check consistency of fault rock with near-surface faulting (nature of fault gouge with respect to P/T conditions and deformation mechanisms).

Geophysical data:

- ***Data:*** reflection seismic, airborne geophysical data (resistivity, magnetics), gravity data to locate faults on the RE and NR scale; reflection seismic as the state-of-the-art method providing images of the layering and structures of the underground should be preferred,

  Purpose: map and locate faults for further investigations.

Topographic and remote sensing data

- ***Data:*** high-resolution aerial photographs, high-resolution LIDAR elevation data,

  Purpose: support tectonic geomorphology and map surface expressions of capable faults.

Geodetic data:

- ***Data:*** GPS derived and conventional geodetic data (repeated precise levelling),

  Purpose: assess horizontal and vertical movements to support the identification of active faults.

Geophysical data for precise fault location:

- ***Data:*** high-resolution reflection seismic, resistivity, gravity, ground penetrating radar data (GPR) to locate near-surface faults; methods providing images of the layering and structures of the underground such as reflection seismic and GPR should be preferred,

  Purpose: map and locate potentially active faults precisely for paleoseismological investigations.

Paleoseismological data:

- ***Data:*** evidence for past fault movements derived from paleoseismological trenching (age of the youngest fault displacement; magnitude and timing of repeated slip events; evidence for paleoearthquakes; recurrence intervals of slip events) and offset,

  Data: evidence for the sealing of the fault by undisplaced sediments (age of the youngest fault displacement),

  Purpose: asses the possibility, magnitude, timing, and recurrence rate of surface faulting.

3.1.3 DATA FOR ASSESSING LIQUEFACTION AND DYNAMIC COMPACTION

The data requirements for assessments of the liquefaction and dynamic compaction potential are summarized by IAEA (2004). Data collection should include the following:

Site-specific geological and geomechanical data:

Data: high-resolution geological maps; drilling profiles; boring logs and test pit logs; lithology, stratigraphy, and age data of sediments; grain size; soil properties from in-situ (e.g., standard or cone penetration tests) and laboratory soil mechanic testing (geomechanical soil parameters); seismic wave velocities (Vs30),

Purpose: constrain the thickness and 3D geometry of sediment layers and soil; characterize lithological and geotechnical properties of the layers.

Geophysical data:

Data: high-resolution reflection seismic, resistivity, ground penetrating radar data (GPR); methods providing images of the layering and structures of the underground such as reflection seismic and GPR should be preferred,

Purpose: constrain the 3D geometry of sediment layers and soil.

Site-specific hydrological and hydrogeological data:

Data: groundwater level and ground water level fluctuations; hydrological data of fore-flood river, lake or sea; climate and rainfall records; porosity, permeability, and water saturation of sediments and soil,

Purpose: constrain the thickness and 3D geometry of sediment layers; characterize variations of the hydrogeological properties of layers.

Paleoseismological data:

Data: evidence for past liquefaction of sediments at the site or at locations which are similar to the site (e.g., evidence of clastic dykes or intrusions, paleo-sand volcanoes, lateral spreading etc.,

Purpose: confirm or reject the occurrence of past liquefaction at the site.

3.1.4 DATA FOR ASSESSING PERMANENT GROUND DISPLACEMENT

The assessment of the potential of permanent ground displacement by earthquakes requires the assessment of major active faults which have the potential to cause significant vertical ground displacement of the site. Large co-seismic and post-seismic vertical displacements in the order of several meters have been recorded from numerous earthquakes at oceanic subduction zones which are not present in Europe. In intra-plate Europe vertical displacement may occur in the vicinity of normal faults (e.g., the Rhine Graben) and thrust faults (e.g., in Europe's active orogenic mountain belts). Vertical displacement may also occur above blind faults and related folds.

Data: all kinds of data required for the identification and characterization of active faults in the near-region of the site (see above); fault dimensions,

Purpose: assess the maximum credible vertical displacement.

3.2 DATA SOURCES

3.2.1 EARTHQUAKE CATALOGUES

Earthquake catalogues with continent-wide coverage have been compiled by several European projects including the projects SHARE (Seismic Hazard Harmonization in Europe) and AHEAD (European Archive of Historical Earthquake Data). The compiled catalogues (Table 2) are homogeneous with respect to the magnitude (Mw, moment magnitude; see discussion by Grünthal et al. [2009] and Grünthal & Walström [2013]). The catalogues do not consider earthquakes with magnitudes / intensities below a certain threshold (see references in Table 2 for details).

European earthquake catalogues			
Region	**Link**	**Reference**	**Time coverage**
Europe	http://www.emidius.eu/SHEEC/	Stucchi et al., 2013	1000-1999
Europe	http://www.gfz-potsdam.de/emec/	Grünthal & Walström, 2013	1000-2006
Europe	http://www.gfz-potsdam.de/en/section/seismic-hazard-and-stress-field/products-and-services/cenec-earthquake-catalogue/	Grünthal et al., 2009	1000-2009
Europe	http://www.bgr.bund.de/EN/Themen/Seismologie/Erdbebenauswertung_en/Kataloge_en/historisch/EU_Oe_Schw_en.html	Van Gils & Leydecker, 1991	479 BC-1983
Europe	http://emidius.eu/GEH/info/popup_pdf_complete.php?id=5801	Shebalin et al., 1998	342 BC-1990

Table 2. List of European earthquake catalogues with continent-wide coverage.

National earthquake catalogues **are commonly being maintained and updated by the national seismological, geophysical or geological surveys. Table 3 provides a non-exhaustive list of online links and references to such catalogues.**

National earthquake catalogues			
Country	**Link**	**Reference**	**Time coverage**
Austria	Not online	AEC, 2015	1201-2015
Belgium	http://seismologie.be/index.php?LANG=EN&CNT=BE&LEVEL=0		1900-2015
Bulgaria	Not online	Bayliss & Burton, 2007 Grigorova et al., 1978	
Croatia	Not online ftp://hazards.cr.usgs.gov/LAHR/iaspei/data/croatia/zag_eq.txt	Herak, 1995 Herak et al., 1996	 1908-1992
Czech Republic	http://www.czechgeo.cz/en/gfu-catalog/ Not online	 ACORN, 2004	1976-2015 1267-2004
Denmark			
Finland	http://www.helsinki.fi/geo/seismo/maanjaristykset/suomi.html http://www.seismo.helsinki.fi/english/bulletins/	FENCAT Catalog of earth-quakes in Finland since 2000 FENCAT Catalog of earth-quakes in Finland 1610 - 1999	2000-2015 1910-1999
France	Not online Not online	LDG, 2011 Baumont & Scotti, 2011	1962-2011
Germany	http://www.bgr.bund.de/DE/Themen/Erdbeben-Gefaehrdungsanaly-sen/Seismologie/Seismologie/Erdbebenauswertung/Erdbebenkataloge/historische_Kataloge/germany.html;jsessionid=65EFBFA658A59A61C9D528A2B1D33014.1_cid284?nn=1544984 Not online	Leydecker, 2011 Grünthal, 1988	800-2008 823-1984
Hungary	Not online http://www.seismology.hu/index.php/en/seismicity/earthquake-bulletins	Hungarian Nastional Seismological Bulletin	2002-2013 456-1986
Italy	http://emidius.mi.ingv.it/CPTI/	CPTI Working Group, 2004.	
Lithuania	http://www.lmaleidykla.lt/ojs/index.php/geologija/article/view/1894/800	Pačėsa & Šliaupa, 2011	1375-2006
Nether-lands	http://www.knmi.nl/nederland-nu/seismologie/aardbevingen		Recent earthqua-kes
Norway	http://www.norsardata.no/NDC/recenteq/lastweek.html	NORSAR - Research Coun-cil of Norway	
Poland		Guterch & Lewandowska-Marciniak, 2002	
Portugal Portugal	http://www.emidius.eu/ahead/main/info/?en=62712 Not online	LNC, 1986 Solares & Rodriguez, 2002	
Romania	http://www.seismo.ethz.ch/static/gshap/neurasia/nordasiacat.txt http://www1.infp.ro/seismic-catalogue/events?page=1 Not online	Kondorskaya & Ulomov, 1999 National Institute for Earth Physics Oncescu et al., 1999	 984-1997

Slovakia	http://www.emidius.eu/AHEAD/main/info/?en=16940 **Not online**	**Labak & Broucek, 1995.** **ACORN, 2004**	**1267-2004**
Slovenia	**Not online** **Not online**	**Poljak, Živčić & Zupančič, 2002** **Ribaric, 1988**	
Spain	http://www.ign.es/ign/resources/sismologia/publicaciones/Catalogohasta1900.pdf **New Atles Sísmic de Catalunya Vol.1 - Seismicity Catalogue**	**Solares & Rodriguez, 2002**	**800-1900** **880-1996**
Sweden	**Not online** http://snsn.geofys.uu.se/	**Walström, 1990**	
Switzer-land	http://www.seismo.ethz.ch/prod/catalog/index	**ECOS-09 (Earthquake Catalog of Switzerland 2009**	**250-2009**
United Kingdom	http://quakes.bgs.ac.uk/earthquakes/dataSearch.html	**Musson, 1994** **Musson & Sargeant, 2007**	
Ukraina	http://wdc.org.ua/en/data		

Table 3. List of national earthquake catalogues of European countries.

In addition to the national earthquake catalogues a number of catalogues exist which focus on ***historical earthquakes*** (Table 4). The most comprehensive database is accessible via the AHEAD online portal (Locati et al., 2014). It comprises extensive information on major historical events including macroseismic datapoints, estimates of epicentral uncertainties, epicentral intensity with uncertainties, estimated magnitude (Mw) with uncertainties, and references. The coverage of the database is shown in Figure 2.

A non-exhaustive list of catalogues of historical earthquakes that cover individual countries or regions is included in Table 4.

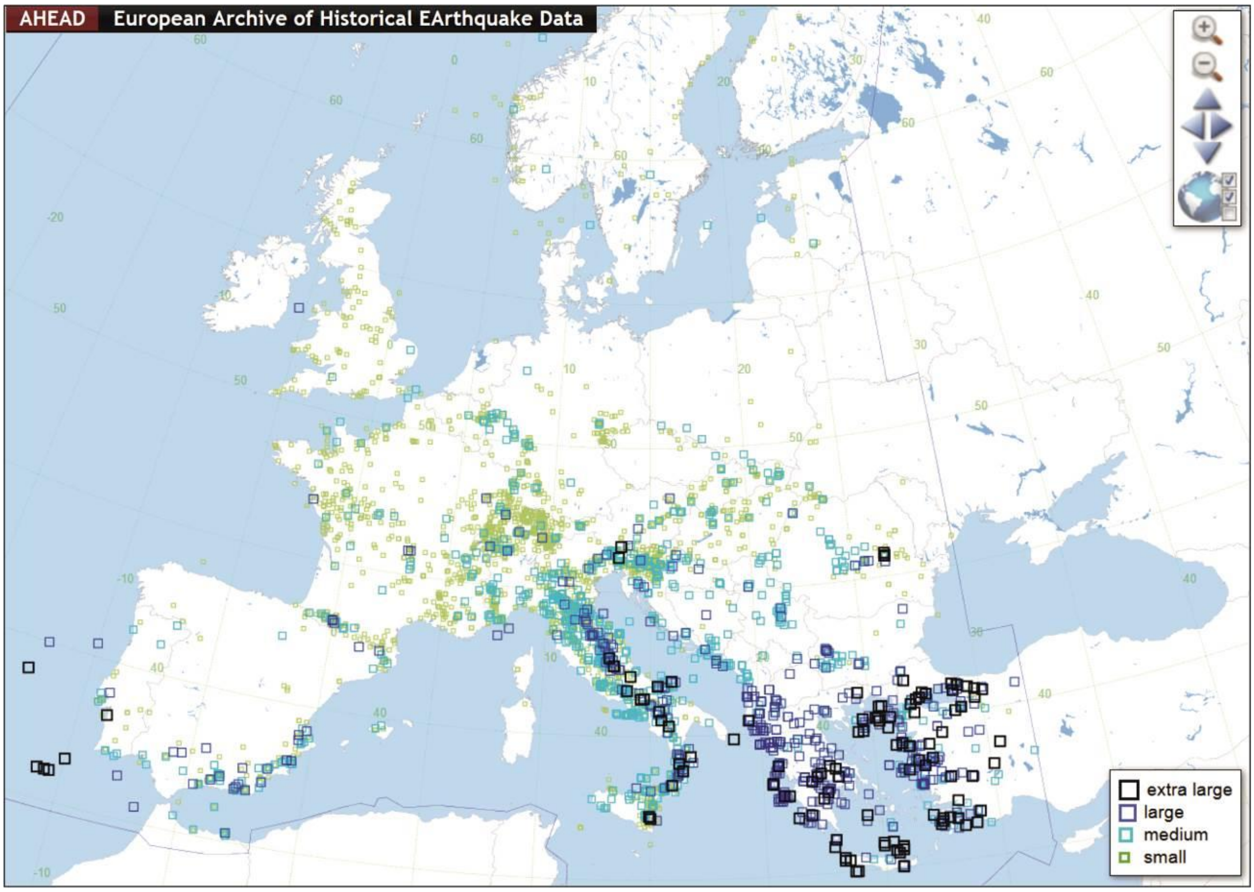


Figure 2. Coverage of the database of historical earthquakes AHEAD (2015)
[Fig_AHEAD_historical_earthquake_data.JPG]

Catalogues focused on historical earthquake data		
Region / Country	**Link**	**Reference / database**
Europe	http://www.emidius.eu/ahead/main/	Locati et al., 2014
Austria	https://www.zamg.ac.at/cms/de/geophysik/erdbeben/historische-erdbeben	
Austria	http://opac.geologie.ac.at/wwwopacx/wwwopac.ashx?command=getcontent&server=images&value=Abhandlungen_67.pdf	Hammerl & Lenhardt, 2013
Belgium	http://seismologie.be/index.php?LANG=NL&CNT=BE&LEVEL=230	Royal Observatory of Belgium
Bulgaria		
Czech Republic	http://www.ipe.muni.cz/newweb/english/temelin_en/hluboka_fault.php	Spacek et al., 2011, p. 19 ff
France	http://www.sisfrance.net/	Sismicité historique de la France Métropolitaine
Germany	http://www.bgr.bund.de/EN/Themen/Seismologie/Erdbebenauswertung_en/Kataloge_en/historisch/historische_erdbeben_inhalt_en.html	Bundesanstalt für Geowissenschaften und Rohstoffe
Spain	http://www.ign.es/ign/layoutIn/bdmacrosismica.do http://www.igc.cat/web/ca/sismologia_bdmacrosis.html Not online	Base de datos de intensidad macrosismicita (IGN) Base de Dades Macrosísmica de Catalunya Mezcua et al., 2004
Finland	Not online	Mäntyniemi et al., 2007
France	http://www.sisfrance.net/	Sismicité historique de la France Métropole
Greece	http://macroseismology.geol.uoa.gr/ Not online	Hellenic Macroseismic Database (UoA) Kouskouna & Sakkas, 2013
Italy	http://emidius.mi.ingv.it/ASMI/	ASMI Archivio Storico Macrosismico
Lithuania	Not online	Mäntyniemi et al., 2007.
Norway	http://www.norsar.no/seismology/Earthquakes/SeismicityNorway/ELOCS/	Historical seismicity on the norwegian continental shelf (ELCOS)
Poland	http://private.igf.edu.pl/~pwiejacz/p/	Pagaczewski, 1972
Slovakia	Slovak macroseismic earthquake catalogue (SLOVMEC)	Kysel et al., 2016
Slovenia		Cecić, 2016
Spain	http://www.igc.cat/web/files/IGC_2006_sismologia_segles.pdf	Olivera et al., 2006
Sweden	Not online	Mäntyniemi et al., 2007
Switzerland		Fäh et al., 2016
United Kingdom	http://www.earthquakes.bgs.ac.uk/historical/data/studies/MUSS008/MUSS008.pdf	UK Historical Earthquake Database

Table 4. List of earthquake catalogues focused on historical earthquake data.

Seismological data in excess of data recorded in earthquake catalogues may exist from ***local seismic monitoring networks***. Such networks may not be connected with the national observation grid and the recorded data may therefore not be included in national or regional earthquake catalogues.

Seismic networks may be installed or have been operational for some periods of time for research purposes, e.g., the observation of aftershock sequences subsequent to major earthquakes or to monitor teleseismic events for seismic tomography. Such data may be accessible via the operating scientific organizations. A list of digital seismograph networks, both permanent and temporary, is provided and updated by the International Federation of Digital Seismograph Networks (FDSN; http://www.fdsn.org/networks/?). The list includes deployment countries / regions, network names, links to network operators, and data access.

Data recorded by such temporary networks may significantly contribute to identify seismogenic faults by accurately localized earthquake hypocenters, understand fault kinematics using first arrival studies or seismic moment tensor solutions, etc. An example for the benefit of analyzing microearthquakes recorded by dense local seismological networks is the identification of the Shoreline Fault close to the Diablo Canyon NPP which led to an update of the seismic hazard assessment (USNRC, 2012).

Local seismic monitoring networks around nuclear power plants are dealt with in chapter 3.2.5 on page 54.

3.2.2 EARTHQUAKE FOCAL MECHANISMS AND RECENT STRESS DATABASES

Earthquake focal mechanisms (fault plane solution) data and seismic moment tensors provide evidence on the orientation and slip direction of the fault which created a specific earthquake and are therefore an important basis for the construction of seismotectonic models. For strong earthquakes such data are routinely produced and collected in a number of databases, which all allow data queries and downloads (Table 5).

Recent stress data (orientation of the maximum horizontal compressive stresses) are equally important to constrain seismotectonic models and assess the probability of slip at pre-existing faults. Data are collected in the World Stress Map (WSM) database (

Figure 3, Table 5). The WSM includes tools for data query, download, and visualization.

The databases listed in (Table 5) are not comprehensive and numerous additional data may exist in scientific literature or at the local geophysical / seismological / geological surveys. Focal mechanisms may particularly be available from site-specific observation networks. Stress data which are not included in the WSM may be available from deep drilling (e.g., for hydrocarbon or thermal water exploration) and mining activities.

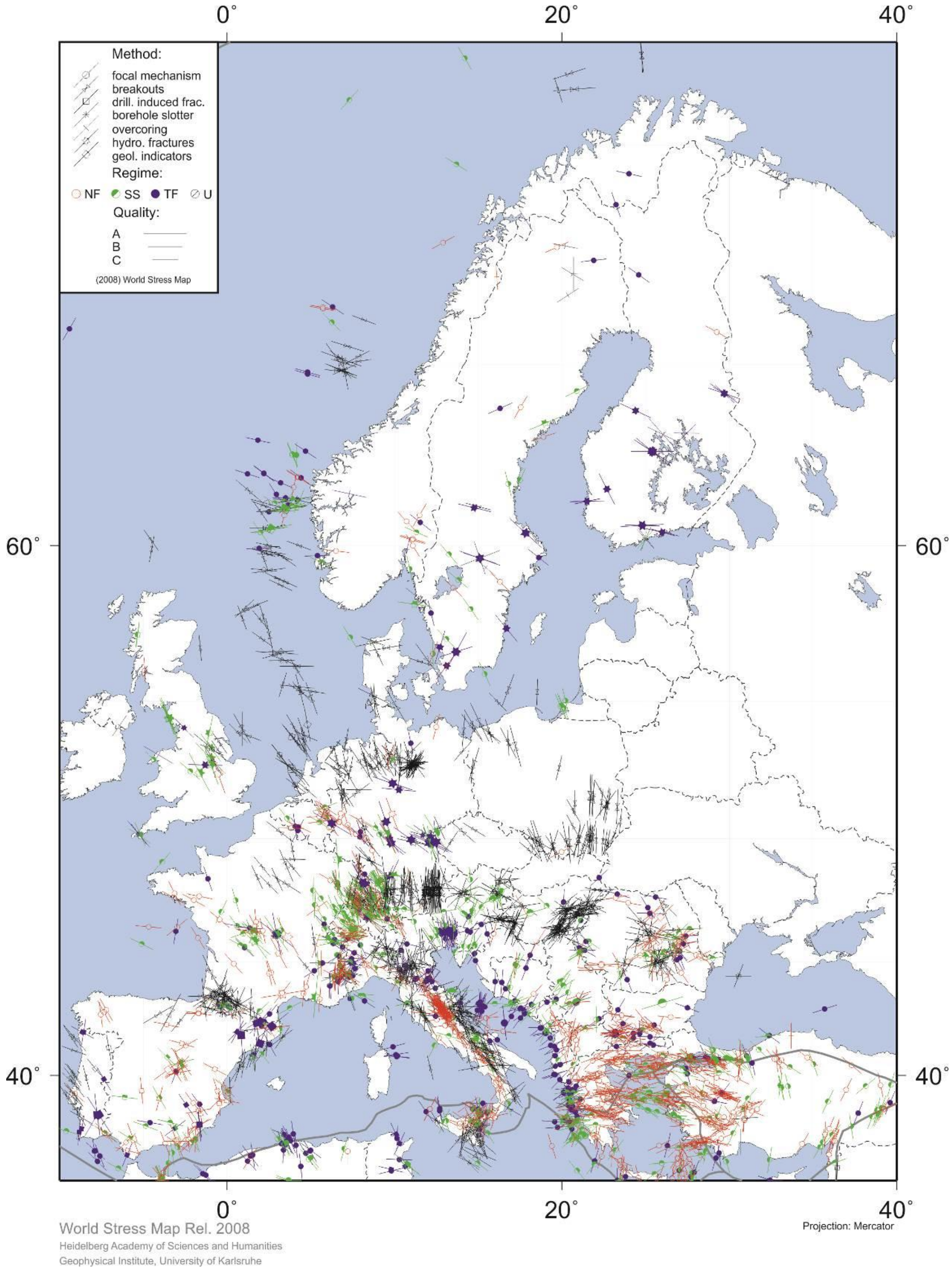


Figure 3. European stress data of the World Stress Map (WSM) database (release 2008)
[Fig_WSM_Database.JPG]

Moment tensor, earthquake mechanisms and recent stress orientation databases		
Name	**Link**	**Reference**
Global Centroid-Moment-Tensor (CMT) Database	http://www.globalcmt.org/	Dziewonski et al., 1981
Global Centroid-Moment-Tensor (CMT) Database	http://www.globalcmt.org/	Ekström et al., 2012
EMSC quick Moment Tensor Solutions	http://www.emsc-csem.org/Earthquake/index_tensors.php	
USGS Moment Tensor and Broadband Source Parameter Search	http://earthquake.usgs.gov/earthquakes/eqarchives/sopar/	
Moment Tensor Product Query - IRIS	http://ds.iris.edu/spud/momenttensor	
European-Mediterranean RCMT Catalogue	http://www.bo.ingv.it/RCMT/searchRCMT.html	
EMMA Database of Earthquake Mechanisms for European Area	http://www.emsc-csem.org/Earthquake/emma.php	Vanucci & Gasperini, 2003
EMMA Database of Earthquake Mechanisms for European Area	http://www.emsc-csem.org/Earthquake/emma.php	Vanucci & Gasperini, 2004
WSM World Stress Map database	http://dc-app3-14.gfz-potsdam.de/pub/stress_data/stress_data_frame.html	Heidbach et al., 2008

Table 5. List of moment tensor, earthquake mechanism and stress databases.

3.2.3 SEISMOGENIC SOURCE AND ACTIVE FAULT DATABASES

Active and capable fault databases which are maintained by geological surveys or academic research groups only exist for a small number of European countries. References and links to these databases are included in Table 6. A comprehensive database of active and capable faults in Europe does currently not exist. The only available European scale dataset is the European Database of Seismogenic Faults (EDSF) established by the SHARE project (SHARE, 2012), which collected information of faults that are regarded to be capable of generating earthquakes with M ≥ 5.5 as input for vibratory ground motion hazard assessment. The database is not comprehensive and almost exclusively contains information from those European countries which participated in SHARE (Figure 4, Table 6). The EDSF has not been updated since May 2012 (http://diss.rm.ingv.it/share-edsf/index.html).

Figure 4. Active and capable fault data: coverage of the SHARE database (SHARE, 2012)
[Fig_SHARE_overview_map.JPG]

Active and capable fault databases			
Country	**SHARE** [1]	**National Database**	
Austria	Yes		In preparation (Austrian Geological Survey & University Vienna)
Belgium	No [2]		Lower Rhine Graben (Vanneste et al., 2013) [2]
Bulgaria	Yes		
Croatia	Yes		
Czech Republic	No [2]		
Denmark	No		
Finland	No	[2]	Kiuvamäki et al., 1998
France	No [2]	NEOPAL [3]	French Database of Recent Deformation and Paleoseismicity http://www.neopal.net/
Germany	No [2]		In preperation (BGR & Aachen University) (Hürtgen et al., 2014)
Greece	Yes	GreDaSS [4]	Greek Database of Seismogenic Sources http://gredass.unife.it/
Hungary	No		Atlas of present-day geodynamics of the Pannonian Basin: neotectonic (actdive) structures (Horváth & Bada) http://geophysics.elte.hu/atlas/geodin_atlas.htm
Italy	Yes	ITHACA DISS [4] CEDIT	Italian Database of Capable Faults (Michetti et al., 2000) http://sgi1.isprambiente.it/GeoMapViewer/index.html Italian Database of Individual Seismogenic Sources (Basili et al., 2007) http://diss.rm.ingv.it/diss/ Italian Catalogue of Earthquake-Induced Groudn-Failures (Fortunato et al. 2012) http://www.ceri.uniroma1.it/
Lithuania	No		
Netherlands	Yes		Lower Rhine Graben (Vanneste et al., 2013) [2]
Portugal	Yes		Active Fault Databsae of Portugal (included in Spanish database QAFI) (Nemsa et al., 2012)
Romania	No		
Slovakia	No [2]		
Slovenia	Yes		In preperation (Geological Survey of Slovenia) (Jamsek-Rupnik et al., 2015)
Spain	Yes	QAFI	Quaternary Active Faults Database of Iberia (Garcia-Mayordomo et al., 2012) http://www.igme.es/infoigme/aplicaciones/qafi/
Sweden	No		
Switzerland	No [2]		
Ukraine	No		
United Kingdom	No		

1 SHARE 2013: http://diss.rm.ingv.it/share-edsf/SHARE_WP3.2_Database.html
2 Only single faults included in database
3 Database of geomorphic evidence for active tectonics; no fault data
4 Seismogenic sources, no fault data

Table 6. List of active and capable fault databases available for European countries.

Comparison of the active fault databases in the U.S. and Japan with the available databases in Europe shows that the U.S. and Japanese databases fulfill significantly higher quality standards with respect to completeness and data quality.

The main reasons for these differences appear to result from the different scientific approaches to seismic hazard. The high quality and detailedness of the Japanese fault database clearly reflects the high level of seismic hazard and the need to develop adequate hazard levels.

In the U.S. seismic hazard assessment is a common target of seismological and geological sciences, probably stimulated by shortness of historical earthquake records which led to the study of active faults and implementation of paleoseismological techniques already during the early 1970s. In contrast, seismic hazard assessments in Europe were traditionally almost exclusively performed by seismologists who relied heavily (or exclusively) on earthquake records. The first paleoseismological studies in Europe were consequently only made in the late 1990ies (e.g., Camelbeek & Meghraoui, 1998) and sporadic collections of fault data only commenced in the last years. Also, and different from the U.S., no national or Europe-wide research programs exist for a systematic effort to identify, map, and parameterize active fault. Such dedicated efforts, however, would be required to develop a European fault database which is comparable to the U.S. or Japanese ones.

3.2.4 GEOLOGICAL, TOPOGRAPHICAL AND GEOPHYSICAL DATA OTHER THAN EARTHQUAKES

Geological, topographical and geophysical data are generally available from:

- national geological surveys, geological departments of local governments and districts or municipal administration: geological maps, tectonic maps, geological cross-sections, thematic geophysical maps, borehole data etc.,
- national geodetic surveys, geodetic departments of local governments and districts or municipal administration : topographic data, digital elevation data, digital topographic contour lines (to be used for gridding to produce digital elevation data), LIDAR digital elevation data,
- national geophysical surveys: various types of geophysical data, maps and cross-sections etc.
- industry data from hydrocarbon, mining, or geothermal exploration : borehole data, geophysical data (e.g., reflection seismic),
- universities and other research institutes doing active geological / geophysical research in the area of interest : scientific and technical papers and data.

3.2.5 SITE-SPECIFIC DATA INCLUDING DATA FROM SITE-SPECIFIC OBSERVATION NETWORKS

Earthquake data. At many nuclear sites site-specific monitoring networks have been established to monitor the seismic activity region around nuclear power plants. Although the recording length of these networks may be short (two decades or less) the data is of particular importance due to its high resolution with respect to both, the record threshold and accuracy. Data are of specific interest for the seismotectonic characterization of the near-region and region of NPPs, the construction of a seismotectonic model, the identification of potential seismogenic faults, and their assessment. Data are mostly proprietary to the nuclear operators.

Site-specific geological and geophysical data. Detailed data on the site are expected to be available from the siting process and construction period of the facilities. Data should be used to assess site conditions with respect to the geological and soil profile below the facilities for the assessment of vibratory ground motion, fault capability, liquefaction, and dynamic compaction hazards.

3.2.6 OPERATIONAL EVENT DATABASE OF PLANTS

Information on observed earthquake effects on NPPs is collected in the ASAMPSA_E Report D10.3. The report provides references to detailed assessments. Additional information on selected occurrences of earthquakes at 10 NPPs is included in chapter 1.3 of this report.

Comprehensive information on incidents related to earthquakes can be found in the international Incident Reporting System (IRS) Database of IAEA (http://www-ns.iaea.org/reviews/op-safety-reviews.asp?s=7&l=49#irs). The IRS is an international system jointly operated by IAEA and the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development (OECD/NEA). The database contains reports on unusual events considered important for safety submitted by thirty-one participating countries. Access to the database is restricted to IAEA Staff, IRS National Coordinators, NPPs, Utilities, and TSOs. Its contents (or parts of its contents) can therefore not be reproduced or cited in ASAMPSA_E Reports.

Further information external hazards related events at NPPs can be obtained from the European Clearinghouse Topical Operational Report (Ramos & Zerger, 2012). The report, however, is not open to use in ASAMPSA_E.

3.3 DATA COMPLETENESS AND QUALITY ASSESSMENT

3.3.1 COMPLETENESS OF EARTHQUAKE DATA

Earthquake catalogues are key data used for estimating the mean annual rate of seismic activity and magnitude-frequency relations using the Gutenberg-Richter relation. A thorough assessment of data completeness is therefore a prime prerequisite for SHA.

Both, historical and instrumental earthquake records are incomplete by their nature. The main sources for incompleteness of historical data are:

- Lack of historical records (e.g., due to low past population density; absence of chronologists; lack of interest; intensities not reaching a record threshold [Gutdeutsch and Hammerl, 1999]; other events distracting from earthquakes [e.g., war, social and political circumstances, other natural disasters]);
- Ambiguity of descriptions that do not allow parameterizing earthquakes (time, intensity, location);
- Lack or insufficient historical earthquake research.

The completeness of instrumental data depends on:

- The timing of the implementation of seismic networks (in Europe generally starting during at the beginning of the 20^{th} century);
- The geometry, density, and coverage of the seismic network;
- Sensitivity of the instrumentation;
- Malfunction of seismic stations over longer periods of time (e.g., due to war action; Hammerl et al., 2001).

Assessments of earthquake catalogue completeness determine the time intervals in which a certain intensity or magnitude class can be considered to be completely reported. Different approaches for such assessments have been proposed (Stepp, 1972; Mulargia and Tinti, 1987; Grünthal et al., 1998; Stucchi et al., 2004; Wössner & Wiemer, 2005). Among these the approaches which are based on Stepp's (1972) method and on the analysis of time-frequency plots are most commonly used (Nasir et al., 2013; USNRC, 2012a, vol. 1). Both approaches require the declustering of earthquake catalogues.

- Time-frequency plots: TCEF (Temporal Course of Earthquake Frequency, Figure 5) estimates the completeness of records for single intensity or magnitude classes by plotting the cumulative number of events of a class versus time. The basic assumption is that earthquakes occur at constant average frequencies through history, and that apparent frequency increases are due to more complete records (Gasperini and Ferrari, 2000). The method is commonly used in Central Europe (e.g. Lenhardt, 1996; Decker et al., 2011; Nasir et al., 2013). Recurrence intervals are computed for the time for which data are considered complete.
- Stepp-type analysis (Stepp Test, Figure 5; Stepp, 1972; Bollinger, 1973; Cuthbertson, 2006; Bus et al., 2009): *"The test relies on the statistical property of the Poisson distribution highlighting time intervals during which the recorded earthquake occurrence rate is uniform. Supposing that earthquake occurrenc-*

es follow a Poisson distribution, the test evaluates the stability of the mean rate of occurrences (λ) of events which fall in a predefined intensity range in a series of time windows (T). If λ is constant, then the standard deviation (σ) varies as 1/√T. On the contrary, if λ is not stable, σ deviates from the straight line of the 1/√T slope. The length of the time interval at which no deviation from that straight line occurs defines the completeness time interval for the given intensity range (Stepp, 1972). This interval is visually determined from the plots. The test further evaluates the minimum observations length needed for establishing reliable average recurrence intervals for events of a certain intensity class." (modified from Nasir et al., 2013).

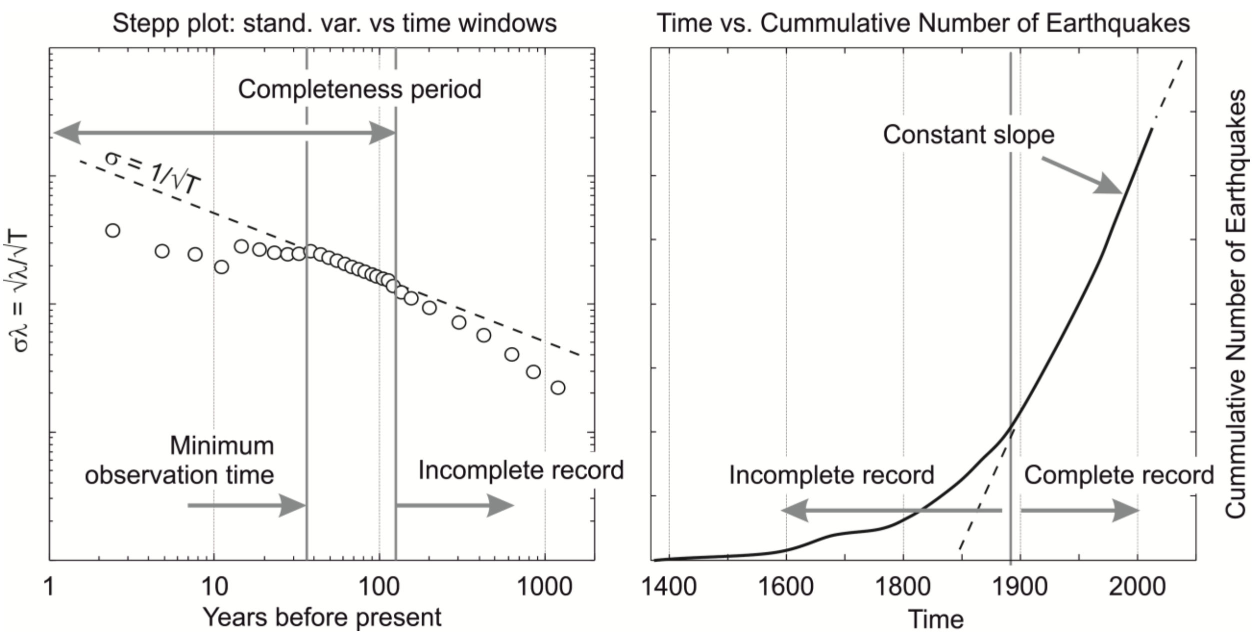


Figure 5. Explanation of completeness assessments of earthquake catalogues using the Stepp Test and the TCEF method for a single magnitude or intensity class. "Minimum observation period" in the Step Plot designates the time required for establishing reliable average recurrence intervals. *[Stepp_TCEF_explanation.JPG]*

An alternative approach to determine magnitude completeness thresholds and/or the year of beginning of complete reporting of earthquakes of a certain magnitude of mainly instrumental data is described by Herak et al. (2008).

Figure 6 to Figure 10 show the results of completeness assessments of typical European earthquake catalogues that were performed with the Stepp Test and the TCEF method. The assessments are performed for a regional European catalogue (CENEC, 2009; Grünthal et al., 2009) and four countries which were selected as examples for low seismicity (Finland), moderate seismicity (Germany), moderate seismicity with extensive historical earthquake research performed (France), and increased seismicity (Spain). The assessments generally show that:

- the time windows of reasonably complete records increase with increasing earthquake magnitude / intensity,
- the number of earthquake records increases sharply at about 1900 AD due to the implementation of seismographs,
- records for “strong” to “heavily damaging” earthquakes (intensity class $5 < I_0 \leq 8$; approximately corresponding to magnitude $M < 6$) are only complete for the last 200 - 300 years,
- records for “destructive” earthquakes (intensity class 9 and higher; approximately corresponding to magnitude $M \sim 6$ to 7) are only complete for the last 300 - 500 years,
- reliable recurrence interval for the strongest events can mostly not be established due to the rareness of these events in the analyzed catalogues (i.e., the minimum observations periods needed for establishing reliable average recurrence intervals for events is longer than the period of historical observations).

An interpretative summary of the completeness intervals is shown in Table 7.

Magnitude class		1.1≤M≤2		2.1≤M≤3		3.1≤M≤4		4.1≤M≤5		5.1≤M≤6		6.1≤M≤7		7.1≤M≤8		8.1≤M	
Country / Method		(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
EU	Stepp		(-)		(-)		1970	25	1960	40	1900	50	1750	100	1500		(-)
EU	TCEF		(-)		(-)		1950		1950		1900		1700		n.d.		(-)
FI	Stepp	5	1990	30	1900	50	1900	>400	n.d.		(-)		(-)		(-)		(-)
FI	TCEF		2000		1950		1900		1800		(-)		(-)		(-)		(-)
ES	Stepp		n.d.		n.d.	15	1980	15	1980	30	1900	90	1750	150	1650	>1000	n.d.
ES	TCEF		n.d.		n.d.		1980		1980		1900		1800		1700		n.d.

Intensity class		5<I0≤6		6<I0≤7		7<I0≤8		8<I0≤9		9<I0	
Country / Method		(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
FR	Stepp	20	1800	60	1800	60	1750	100	1750		(-)
FR	TCEF		1870		1850		1800		1700		(-)
DE	Stepp	30	1870	50	1850	80	1800	300	1500	>1000	n.d.
DE	TCEF		1900		1900		1850		n.d.		n.d.

(1) Minimum observation period to derive reliable recurrence intervals

(2) Complete records since [year] AD

(-) No such magnitude / intensity in catalogue

n.d. Not determined

Table 7. Completeness intervals estimated from European earthquake catalogues using the Step Test and the TCEF method. Data sources: EU: Grünthal et al., 2009; FI: and ES: see Table 3 and Table 4 for reference (magnitude-intensity conversion after Mezcua et al., 2011); FR: Baumont & Scotti, 2011; DE: Leydecker, 2011.

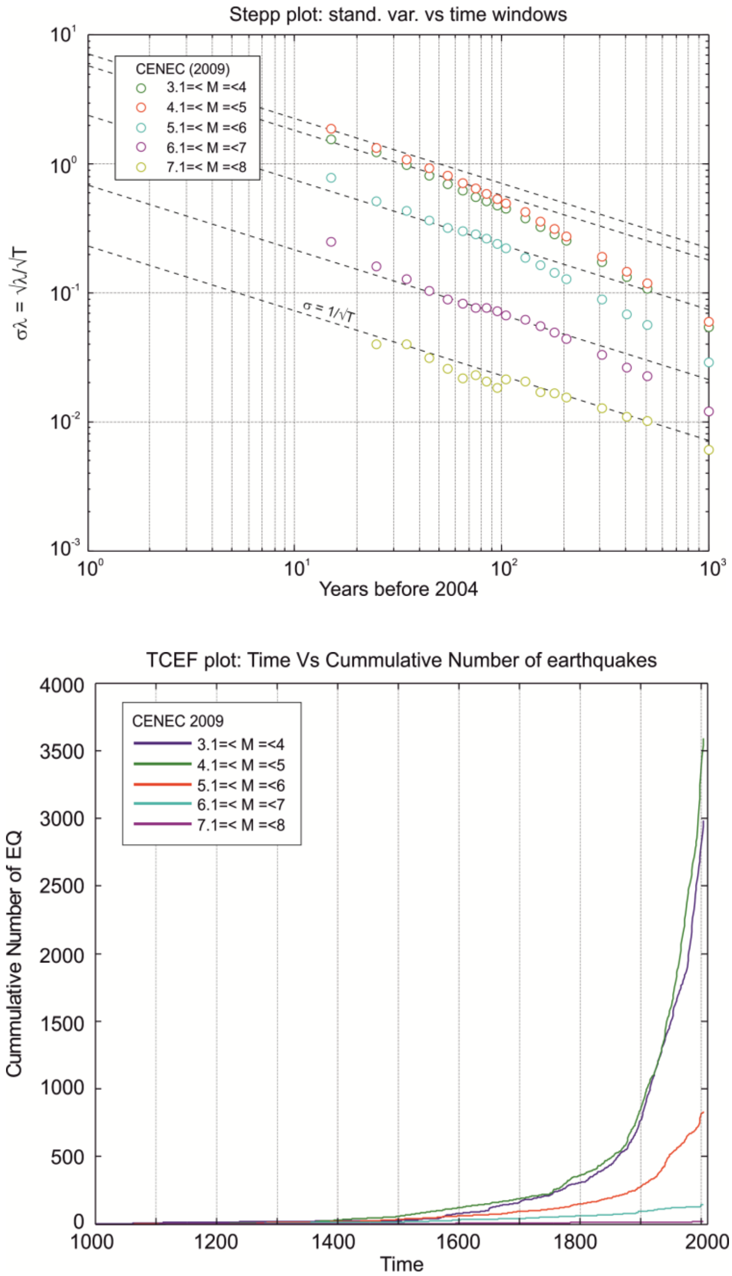
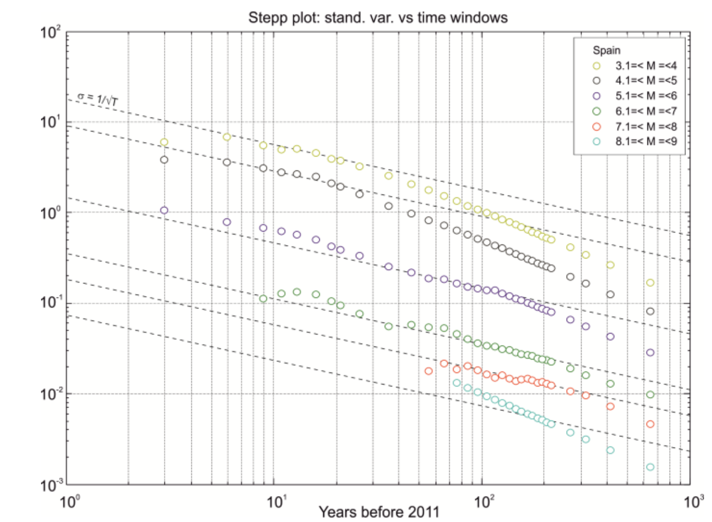


Figure 6. Completeness assessment of the earthquake catalogue for Central, Western and North-Western Europe (CENEC, 2009; Grünthal et al., 2009) using the Stepp Test and the TCEF method.*[CENEC_Stepp.JPG CENEC_Tcef.JPG]*



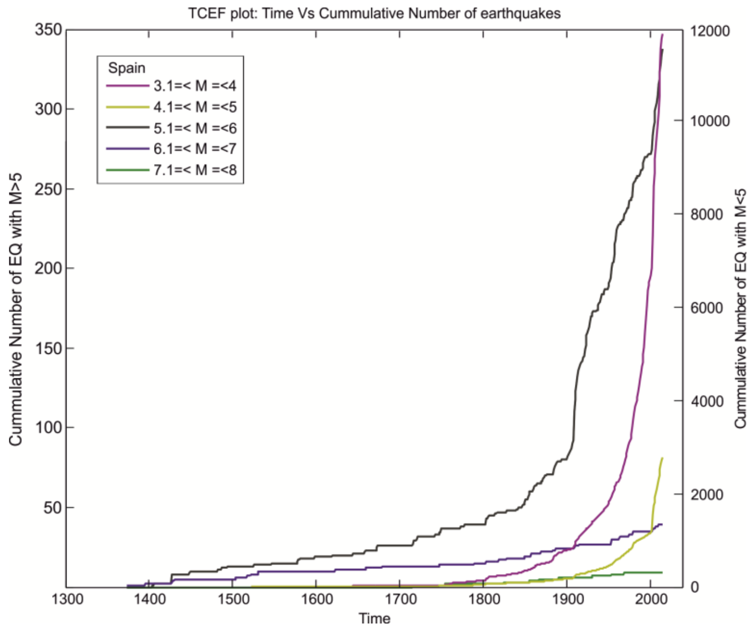


Figure 7. Completeness assessment of the Spanish earthquake catalogue (see Table 3 and Table 4 for reference) using the Stepp Test and TCEF method. ***[ES_Stepp.JPG ES_Tcef.JPG]***

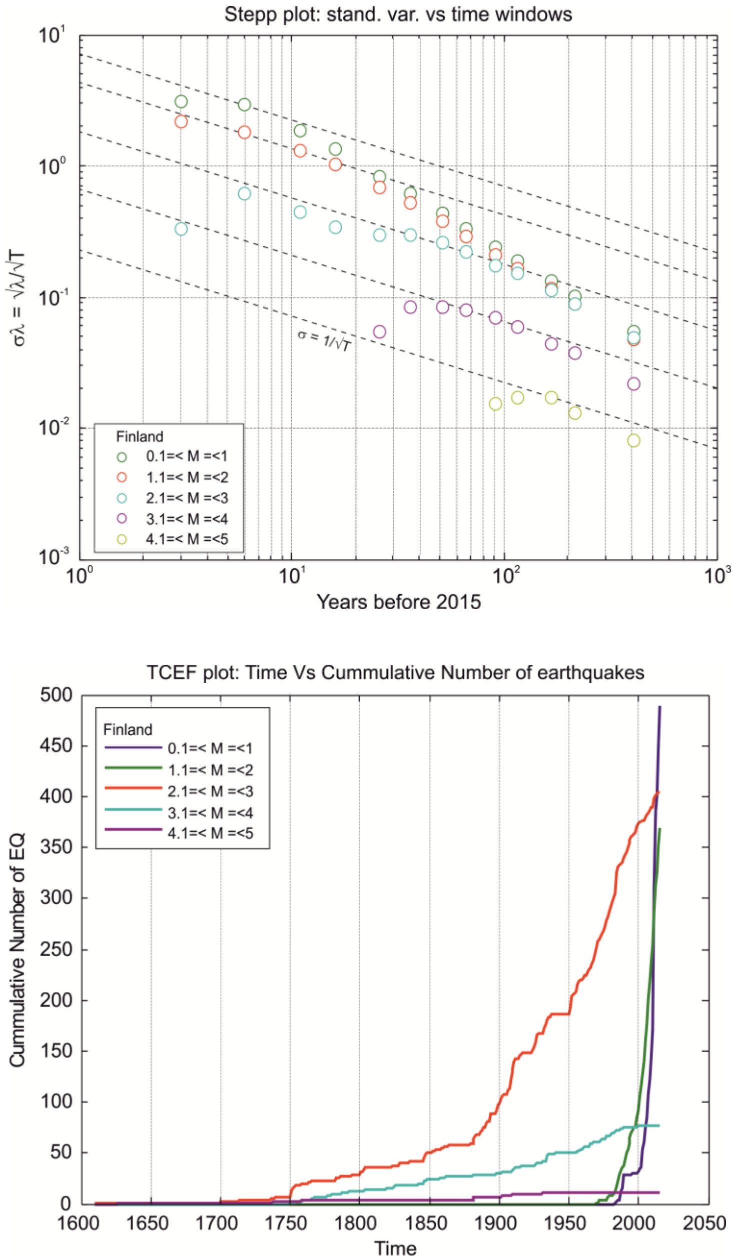
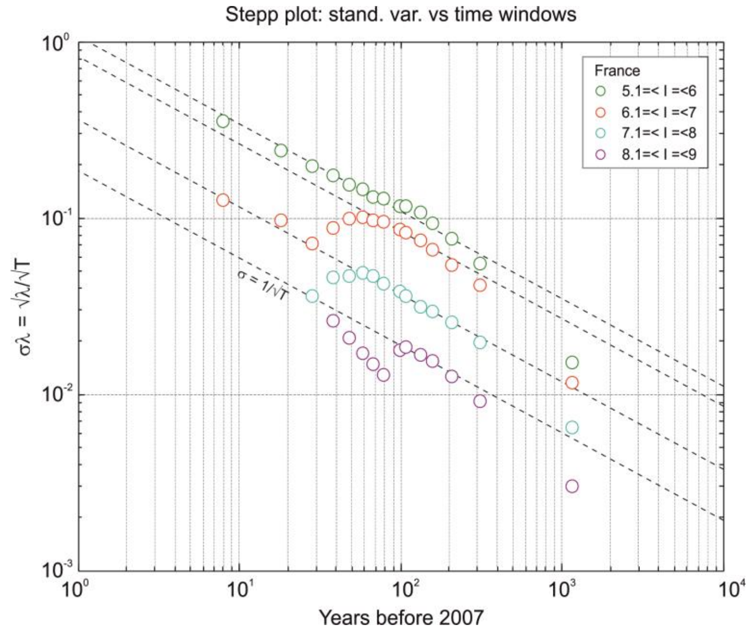


Figure 8. Completeness assessment of the Finnish earthquake catalogues (see Table 3 and Table 4 for reference) using the Stepp Test and TCEF method. ***[FI_Stepp.JPG FI_Tcef.JPG]***



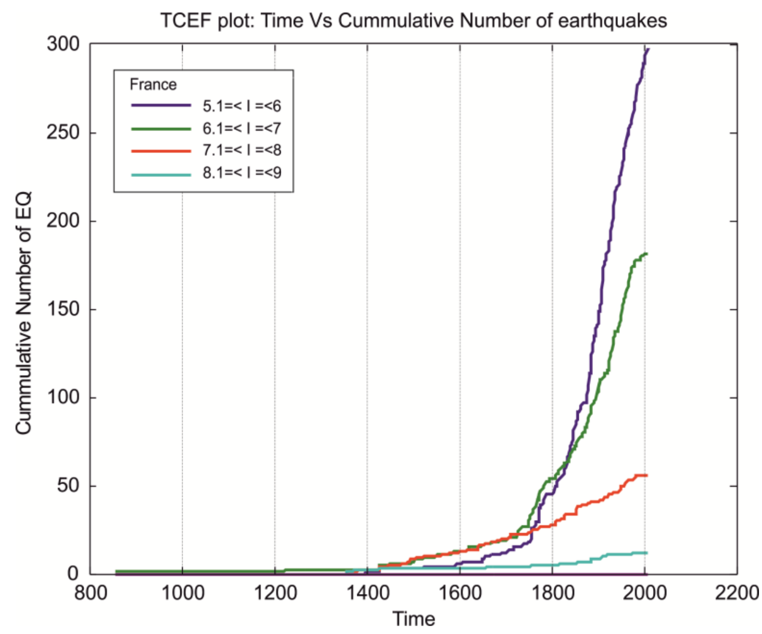
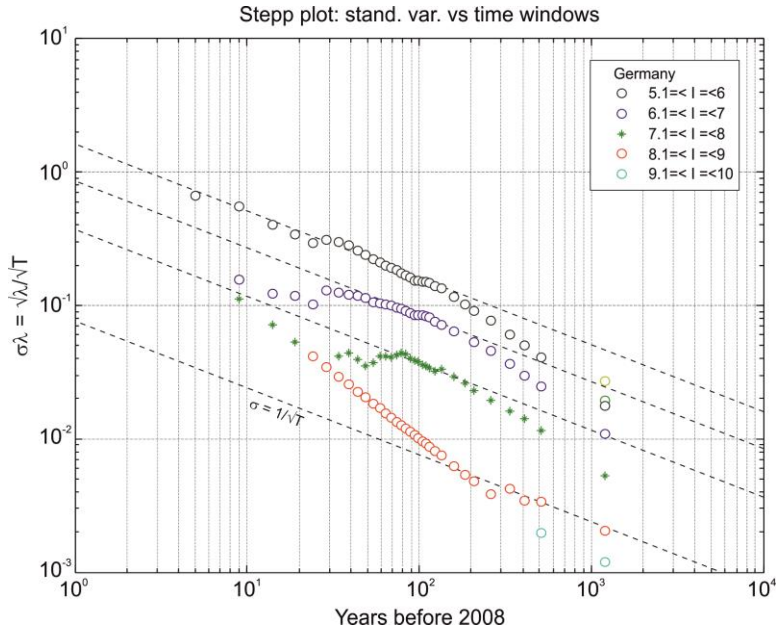


Figure 9. Completeness assessment of the French earthquake catalogues (see Table 3 and Table 4 for reference) using the Stepp Test and TCEF method. ***[FR_Stepp.JPG FR_Tcef.JPG]***



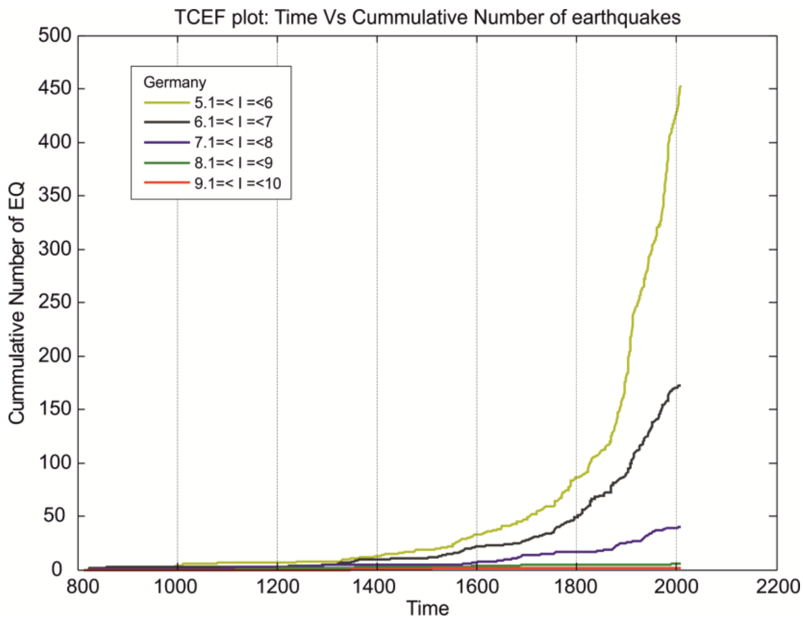


Figure 10. Completeness assessment of the German earthquake catalogues (see Table 3 and Table 4 for reference) using the Stepp Test and TCEF method. ***[DE_Stepp.JPG DE_Tcef.JPG]***

3.3.2 COMPLETENESS OF ACTIVE AND CAPABLE FAULT DATA

Databases or catalogues of active and capable faults in European countries can by their nature not be compared to earthquake catalogues which are systematically compiled and updated by the national geophysical or geological surveys.

The buildup of fault databases in Europe only started in the last decade due to the increased interest of academic research on topics such as earthquake geology, seismotectonic and active fault processes. So far only few European countries committed their geological surveys or other academic institutions to the systematic establishment and maintenance of active fault databases.

The content, quality, and completeness of European databases therefore can currently not be compared to the databases which exist for Japan (Active Fault Database of Japan; AIST, 2015) or the United States (Quaternary Fault and Fold Database for the United States; USGS, 2015). The latter may be regarded as a best-practice example with respect to detailedness, data content, and depth of research. Both, the U.S. and Japanese database are continuously updated and include detailed information on fault location, kinematics, fault dimensions, slip rate, earthquake recurrence intervals, paleoseismological data, and references to original studies.

Such detailedness is mostly not provided by the databases listed in Table 6 (e.g., the SHARE [2012] database only provides part of the listed fault-specific data and only few and incomplete references to original studies). Also, the databases are mostly not kept up to date.

The databases listed in Table 6 must therefore not be regarded as complete. Incompleteness results from:

- limited and non-systematic basic research on active faults;
- possibly incomplete collection of data during the establishment of the database;
- the time elapsed since the compilation of the database.

The databases therefore can only serve as starting points for the assessment of active faults in site-specific hazard assessments. Data needs to be supplemented by thorough literature reviews and site-specific geological investigations.

4 HAZARD ASSESSMENT METHODOLOGIES

4.1 OUTPUT OF THE HAZARD ASSESSMENT

4.1.1 PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)

Probabilistic seismic hazard assessment (PSHA) provides site-specific hazard results and their uncertainties for PGA and different spectral accelerations. Hazard values are typically represented by hazard curves and hazard spectra for a specified range of annual frequencies of exceedance and for different confidence values. These data are required as an input for PSA.

The severity of vibratory ground motion should be expressed in terms of (WENRA, 2016):

- peak ground acceleration (PGA);
- spectral accelerations for all plant-significant vibration frequencies;
- peak ground velocity;
- strong motion duration.

Hazard curves and hazard spectra relate the severity of ground shaking with its annual frequency of exceedance. The severity of ground shaking may be expressed by peak ground accelerations (PGA, PGA_H or PGA_V; Figure 11) or the spectral acceleration. In the latter case exceedance probabilities are calculated for different oscillation frequencies (Figure 12). Hazard curves and hazard spectra should include mean hazard values, median, and percentiles of confidence (0.05, 0.16, 0.84 and 0.95) to quantify the uncertainties of the assessment. Hazard assessment should be based on the mean value of hazard curves as it accounts best for the epistemic uncertainty expressed by the long tail of the hazard distribution (O. Scotti / N. Abrahamsen, pers. comm.)

Hazard results can further be represented by uniform hazard response spectra (UHRS) which provide quantitative values of ground acceleration for different frequencies for a certain annual probability of exceedance (Figure 13). UHRS should be prepared for different annual probabilities of exceedance such as 10^{-4} (corresponding to the minimum design basis requirements) and lower probabilities of exceedance such as 10^{-5} and 10^{-6} required as input for PSA and DEC analysis (WENRA, 2014a, b; 2015). All hazard results should be obtained for both, horizontal and vertical free field motions, and for rock and soil hazard (WENRA, 2016).

Hazard values are required for defining the ground motion values for the design basis earthquake (DBE; 10^{-4}/year; WENRA, 2014a, Issue T), and ground motion values for lower frequencies of exceedance which are required for the assessment of Design Extension Conditions.

Outputs of hazard assessments should further include deaggregation plots to allow assessing the contribution of different sources and assumptions to the overall hazard. A list with a typical output of probabilistic seismic hazard assessment is provided by IAEA (2010, p. 49-50).

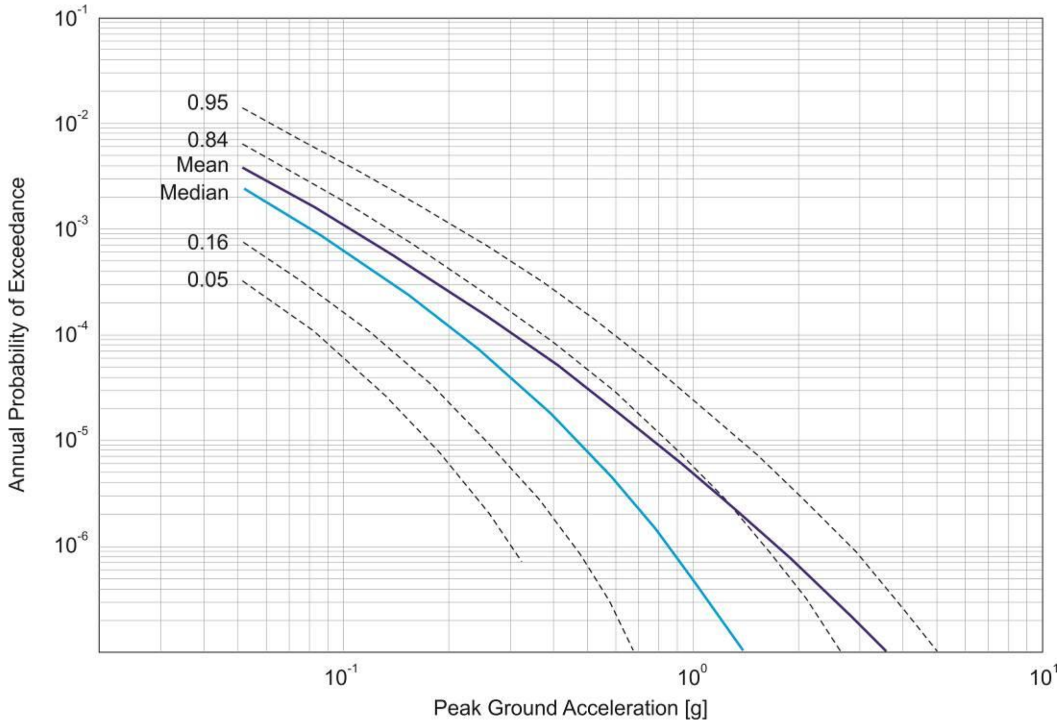


Figure 11. Examples of hazard curves: annual probability of exceedance of peak ground acceleration. Curves are plotted for mean hazard value, median, and the 0.05, 0.16, 0.84 and 0.95 percentiles of confidence. ***[Hazard_curve_examples.JPG]***

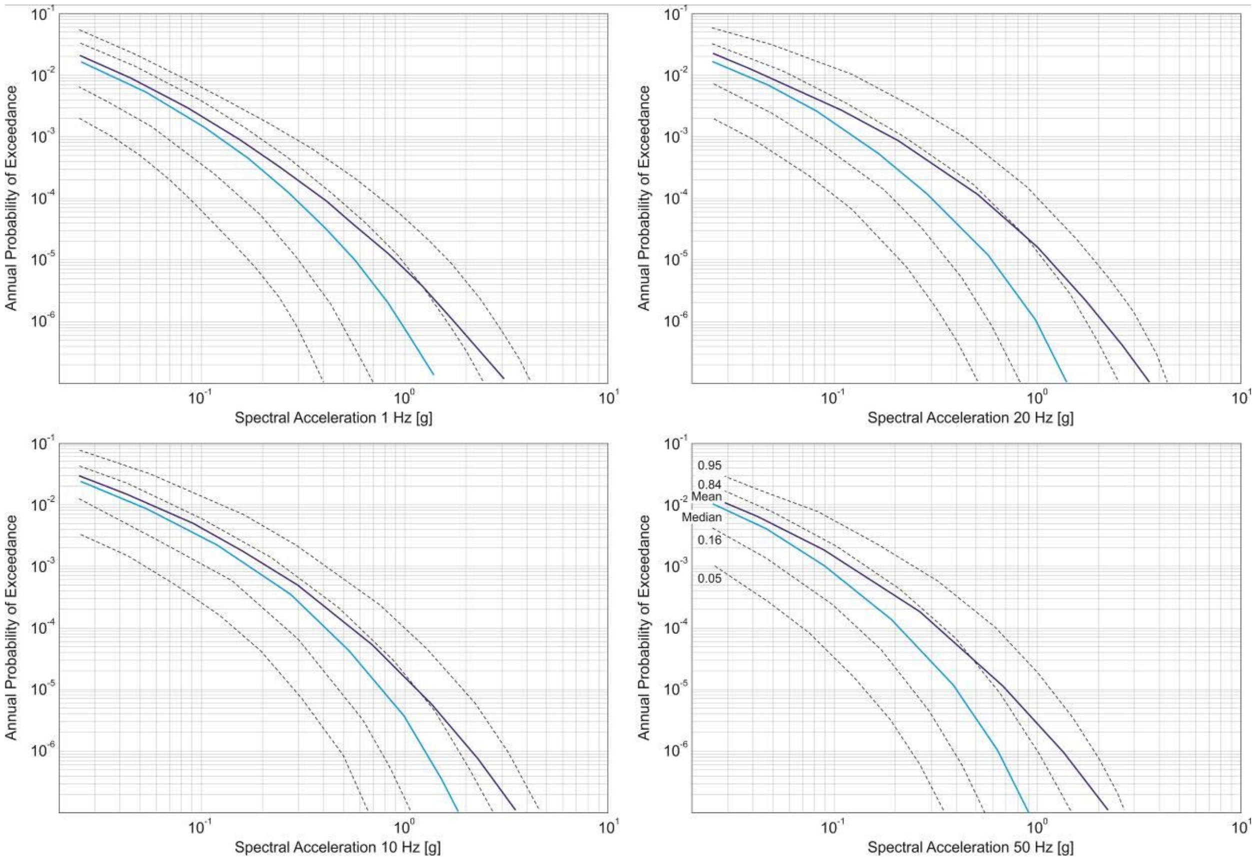


Figure 12. Examples of hazard curves: probability of exceedance of spectral acceleration for different oscillation frequencies (1 Hz, 10 Hz, 20 Hz, 50 Hz) and a selected degree of damping (commonly 5%). Curves are plotted for mean hazard value, median, and the 0.05, 0.16, 0.84 and 0.95 percentiles of confidence. ***[Spectral_acceleration_examples.JPG]***

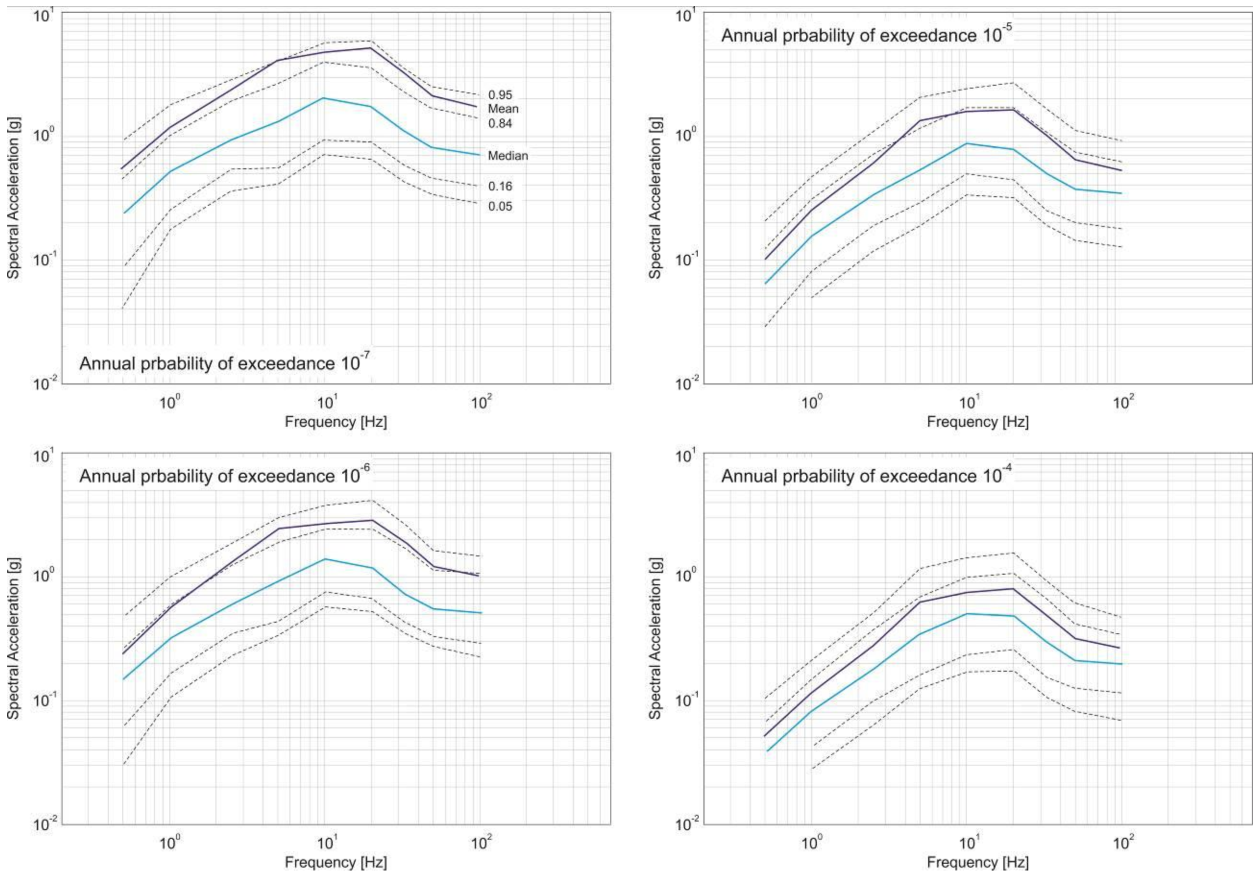


Figure 13. Uniform Hazard Spectra (UHRS) plotted for different annual probabilities of exceedance (10^{-4} to 10^{-7} per year) and a selected degree of damping (commonly 5%). Curves are plotted for mean hazard value, median, and the 0.05, 0.16, 0.84 and 0.95 percentiles of confidence. ***[Uniform_hazard_response_spectra_example.JPG]***

4.1.2 DETERMINISTIC SEISMIC HAZARD ANALYSIS (DSHA)

DSHA determines the maximum credible amplitude of ground motion which may be expected at a site. The method does not account for the probability of this ground motion to occur and it does not assess the recurrence intervals of earthquakes leading to the estimated ground motion. As in PSHA, ground motion may be expressed by peak ground acceleration (PGA), spectral accelerations for different vibration frequencies, peak ground velocity, or strong motion duration.

By not providing probabilities for the occurrence of certain ground motion amplitudes, the method is typically not used to determine input parameters for PSA. However, DSHA can provide an estimate of the largest amplitude of vibratory ground motion to be expected at a site as an upper cutoff value for PSA or for the assessment of Design Extension Conditions (DEC) as required by WENRA (2014a; reference levels F and T).

4.1.3 FAULT CAPABILTIY

The severity of fault capability hazard is expressed by the total amount of surface rupture displacement (horizontal and vertical displacement) for both, primary on-fault and distributed off-fault surface ruptures. IAEA (2010) discerns between primary displacement (*"typically in the form of direct seismogenic fault rupture"*) and secondary displacement (*"typically associated with induced movement along pre-existing seismogenic slip planes (e.g. a triggered slip on an existing fault or a bedding plane from an earthquake on another fault) and non-seismogenic slip planes (e.g. localized fractures and weak clay seams)"*).

Probabilistic Fault Displacement Hazard Analysis (PFDHA) determines the mean annual frequency of exceedance of different amounts of surface fault displacement. Hazard results are expressed as fault displacement hazard curves plotting the mean annual frequency of exceedance versus surface displacement. Assessments should also comprise sensitivity analyses to show the influence of the various PFDHA input data and the sensitivity of results to the range of uncertainty. Unlike for ground motion hazard PFDHA is typically not applied during the planning and constructional stage of a nuclear installation as IAEA recommends that *"an alternative site should be considered"* in cases *"where reliable evidence shows that there may be a capable fault with the potential to affect the safety of a plant"* (IAEA, 2010, para. 8.8). PFDHA is therefore generally applied to existing plants where capable faults were identified during the lifetime of the plant[8]. As a consequence plants are originally not designed against any surface displacement. A pending problem of PFDHA is that only a small number of assessments has been performed so far and that assessments are based on very limited numbers of observations of displacements along primary faults and distributed off-fault surface ruptures (see chapter 4.3.3, page 87).

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[8] A current exception is the planning of the Slovenian NPP Krsko II, where PFDHA was also applied during the siting process after the detection of a number of capable faults in the site vicinity (Cline et al., 2015).

4.2 IDENTIFICATION OF KEY INPUT PARAMETERS

The following chapters provide short discussions of selected input parameters for seismic hazard evaluation, which have significant impact on the outcome of the assessment. It is a common property of all discussed parameters that their assessment is not straight forward and includes significant degrees of epistemic uncertainty. In PSHA these uncertainties are commonly modelled by logic tree approaches which take into account different assessments of the parameters.

4.2.1 FAULT SOURCES (ACTIVE FAULTS)

The identification and correct assessment of active faults in the surrounding of NPPs is regarded as a key issue in seismic hazard assessment. The importance of identifying and characterizing active faults is stressed by IAEA (2010), WENRA (2016), and IAEA (2015c).

As discussed in more detail in the chapter 3.1.1 (page 34), seismically active faults cannot be recognized from analyzing the earthquake record alone. This is due to the fact that the active faults in intra-plate Europe are slow to very slow moving structures which produce earthquakes at recurrence times of thousands to ten thousands of years, which exceed the time coverage of earthquake records by factors between 10 and 100. Not identifying active faults (because they have not produced recorded earthquakes) may result in significantly underestimated hazard values.

The identification and assessment of active faults should use a graded approach as the one proposed in Figure 14 in order to allow for the screening of sufficiently large areas around the site (i.e., the near-region or region as defined by IAEA, 2010). The approach may be structured into the following steps, which require increasing efforts:

- regional assessment using tectonic geomorphology techniques;
- detailed fault analysis and assessment;
- active fault characterization.

The described workflow focuses on the identification of emergent active faults which reach up to the Earth's surface. Although some indications of buried (or "blind") active faults which do not reach up to the surface may be derived from geomorphological studies, these techniques are not sufficient to identify and characterize such faults. Blind faults are particularly important in fold-thrust belts and their forelands (e.g., Molasse unit in the Alpine foreland of Switzerland; Po Plain in the foreland of the Southern Alps / Apennines). Their assessment requires targeted geophysical (reflection seismic) and seismological investigations (assignment of earthquakes to buried faults).

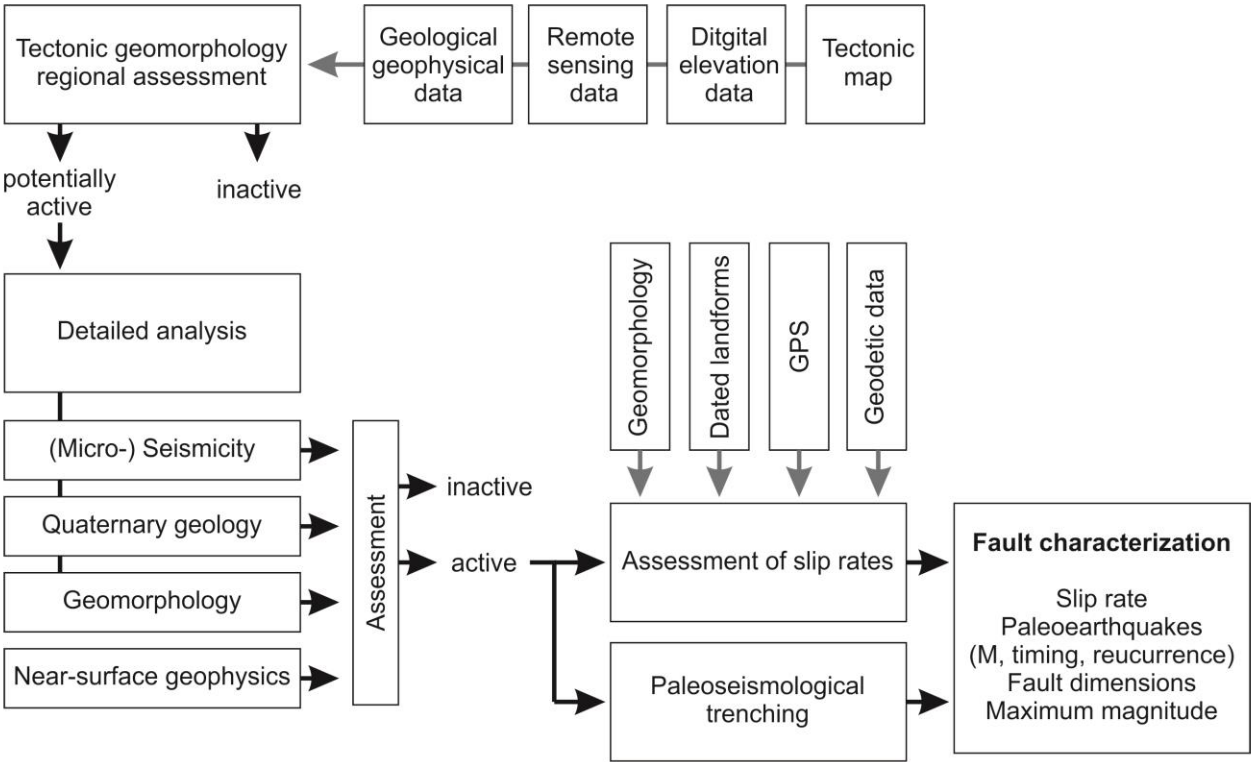

Figure 14. Flow chart of the suggested graded approach for the identification and assessment of active / capable faults in the near-region and region of a site.
[Fig_Fault_Identification_Flow_Chart.JPG]

Regional assessment using tectonic geomorphology techniques. A graded approach for active fault identification and assessment may start from applying tectonic geomorphology techniques (e.g., Burbank & Anderson, 2011; Schumm et al., 2000). The methods are capable to screen relatively large areas for potentially active faults which impact recent morphology within a reasonable time and with sensible effort. Numerous case studies from low seismicity regions with slow to very slow moving faults show that tectonic geomorphology techniques can identify active faults with slip rates below 0.1 mm/year (see Table 8 for references). A recent case study form the near-region of a European NPP has been published by Popotnig et al. (2013).

Many tectonic geomorphology methods are based on quantitative measurements of geomorphic features and on the calculation of quantitative geomorphologic parameters supporting objective decisions about the activity or inactivity of faults and reducing the uncertainties arising from purely experience-based expert opinion. The analysis of landforms and calculation of geomorphologic parameters requires digital elevation data (DEM and/or LIDAR data). The parameters are usually assessed in combination with all available geological and tectonic data in a GIS environment. Analyzed morphological features include: mountain front morphology, drainage basin geometry, river valley morphology, and river planform patterns. Table 8 provides an overview of commonly used quantitative geomorphic indices and references of key studies from non-arid regions which are comparable to European conditions.

Restrictions to the methods may arise in regions which were glaciated during the Würmian. In such areas landforms are overprinted by young glacial erosion that may have erased the morphologic record of slow active faults. Applicability to blind faults is restricted to cases where blind faulting leads to topographic changes at the surface (e.g., fold growth above a buried thrust ramp).

Tectonic geomorphology studies using quantitative geomorphic parameters													
Reference	**Vf**	**SL**	**Smf**	**Be**	**C**	**Re**	**Rf**	**Hi**	**AF**	**T**	**Bs**	**LSP**	**FA**
Ahmad & Bath, 2012		x	x	x				x	x			x	
Azor et al. 2002	x	x	x					x					
Bhatt et al. 2007	x	x	x					x					
Biswas & Grasemann 2005	x	x	x							x			
Bull & McFadden 1977	x		x			x							
Cuong & Zuchiewicz 2001	x		x										
El Hamdouni et al. 2008	x	x	x					x	x		x		
Ezati & Agh-Atabai 2013	x	x						x	x	x			
Font et al. 2010		x						x					
Garcia-Tortosa et al. 2008	x	x											
Garrote et al. 2006					x					x			
Giaconia et al. 2012	x	x	x					x	x			x	
Gürbüz & Gürer 2008			x								x		x
Khavari et al. 2009	x								x	x	x		
Pedrera et al. 2009	x	x						x					
Pérez-Peña et al. 2010	x		x					x	x			x	
Peters & van Balen 2007	x	x	x										
Pinter 2005		x								x			
Popotnig et al. 2013	x	x	x	x	x	x	x				x	x	
Rachna 2012	x					x			x	x			
Shtober-Zisu et al. 2008			x					x			x	x	
Troiani & Della Seta 2008		x										x	
Tsodoulos et al. 2008	x	x	x	x					x	x	x		
Verrios et al. 2004	x	x	x							x			

Vf: Ratio of valley floor-width (Bull & McFadden, 1977)
SL: Stream length-gradient (Hack, 1973)
Smf: Mountain sinuosity (Bull & McFadden, 1977)
Be: Basin elongation
C: Circularity index (Bell, 2004)
Re: Drainage elongation ratio (Schumm, 1956)
Rf: Basin shape (Talling et al., 1997)
Hi: Hypsometric integral (Walcott & Summerfield, 2008)
AF: Drainage basin asymmetry factor (Keller & Pinter, 2002)
T: Transverse topographic symmetry factor (Keller & Pinter, 2002)
Bs: Elongation ratio (Ramirez-Herrera, 1998)
LSP: Longitudional stream profiles (thalweg sections)
FA: Alluvial fan morphology

Table 8. Examples of tectonic geomorphology studies using quantitative geomorphic indices to identify active and capable faults in non-arid regions.

Detailed fault analysis and assessment. The goal of the analysis is to decide whether a potentially active fault (as identified during the regional assessment) is capable / active or not according to IAEA's following definitions:

Capable fault (IAEA, 2010, 8.4., p. 30; compare also IAEA, 2003b, 3.6, p. 10-11):

"On the basis of geological, geophysical, geodetic or seismological data, a ***fault should be considered capable*** *if the following conditions apply:*

(a) If it shows evidence of past movement or movements (such as significant deformations and/or dislocations) of a recurring nature within such a period that it is reasonable to conclude that further movements at or near the surface may occur. In highly active areas, where both earthquake data and geological data consistently reveal short earthquake recurrence intervals, periods of the order of tens of thousands of years (e.g. Upper Pleistocene-Holocene, i.e. the present) may be appropriate for the assessment of capable faults. In less active areas, it is likely that much longer periods (e.g. Pliocene-Quaternary, i.e. the present) are appropriate.

(b) If a structural relationship with a known capable fault has been demonstrated such that movement of the one fault may cause movement of the other at or near the surface.

(c) If the maximum potential magnitude associated with a seismogenic structure, as determined in Section 4, is sufficiently large and at such a depth that it is reasonable to conclude that, in the current tectonic setting of the plant, movement at or near the surface may occur."

Active fault (IAEA, 2015, p. 157):

"A tectonic structure that moved in the recent geologic past and that is expected to move within a future time span of concern for the safety of a nuclear installation. In highly active (e.g., interplate) areas with short earthquake recurrence intervals, periods of the order of tens of thousands of years (e.g., Upper Pleistocene to present) may be appropriate for defining a fault as active. In less active areas (e.g., intraplate) much longer periods (e.g., Pliocene -Quaternary to present) may be appropriate. In the conservative perspective of NPP siting, any fault within the Earth's crust might need to be reassessed for potential re-activation. In fact, it is impossible to exclude that an earthquake of low magnitude may occur along any fault (Modified from IAEA SSG-9, 8.4)."

The definitions differ by the fact that the term "active fault" includes blind faults, which are not capable to cause surface fault rupture (a blind fault is a *"Buried fault not reaching up to the ground surface when it was last active. Usually applied to buried reverse or thrust faults*. [IAEA, 2015c, p. 158]). It should be noted that earthquakes on blind faults, however, may induce ruptures on secondary faults at the Earth's surface.

STATE	EVIDENCE
Extinct	Fault does not displace Pliocene-Quaternary sediments or structures The mineralogy of **mechanically continuous** fault rock is incompatible with the current stress/temperature regime Fault is a small secondary feature
Unproven	Fault does not displace late Quaternary sediments or structures Fault style and orientation makes a displacement unlikely in the current tectonic regime Fault shows geographical association with small macroseismic earthquake or instrumental earthquake located by regional network Fault has undergone multiple post-variscan reactivation Fault influences current morphology as shown by quantitative tectonic geomorphology parameters Fault has a close analogue proved active
Active	Fault has appropriate dimensions and is **uniquely** implicated by well-located earthquake(s) Fault coincides with accurately located hypocentre(s) from local network **and** is consistent with parameters from well-constrained focal mechanism(s) Fault displaces ground surface or Quaternary deposits and/or structures

Table 9. Criteria for assessing faults as “active” or “extinct” (Mallard, 1991)

Table 9 summarizes possible criteria to assess faults as “active”, “extinct” (inactive), or “unproven”.

Guidance on the detailed analysis of potentially active faults is provided by IAEA (2010, 2015c) and references therein. The assessment generally relies on appropriate combinations of geological, geophysical, paleoseismological, seismological, geomorphological, and geodetic methods. Among these, the following methods are regarded to be of crucial importance:

- analysis of seismicity from local networks to find coincidences between faults, accurately located hypocenters, and focal mechanisms,
- analysis (including dating) of Quaternary and Pliocene sediments and their relation to the fault (offset or sealing the fault),
- high-resolution geophysical surveys to map and accurately locate near-surface faults (reflection seismic, resistivity, ground penetrating radar). Preference should be given to methods providing accurate images of subcrop structures.

Active fault characterization. For the modeling of ground motion hazard in PSHA and fault capability in PFDHA active fault sources should be represented by their 3D location (outcrop trace, dip direction, dip), fault length, depth and area, fault kinematics (slip vector and slip direction), slip rate, seismogenic depth (minimum/maximum depth of earthquakes). These geological data allow estimating:

- the maximum magnitude of earthquakes produced by the fault using empirical relationships between faulting parameters and magnitude (e.g., Wells & Coppersmith, 1994; Vakov, 1996; Mohammadioun & Serva, 2001; Hanks & Bakun, 2002; Leonard, 2010; Striling et al., 2002; 2013). An in-depth discussion of the application of these methods and their uncertainties is provided by Stirling & Godet (2012) and IAEA (2015c, page 95 ff),
- the recurrence intervals of earthquakes from geologically determined slip rates and fault dimensions.

Both, the estimates of maximum magnitudes and recurrence intervals of strong earthquakes should be compared to and validated by paleoseismological trenching (see IAEA, 2015c and McCalpin, 2009 for additional guidance).
Probabilistic Fault Displacement Hazard Analyses (PFDHA) require very detailed data to characterize the faults under consideration. Data need to characterize faults in terms of slip rate, event recurrence intervals, magnitude and direction of slip events (fault displacements), existence of secondary faults and fractures etc. (compare IAEA, 2010, chapter 8).

4.2.2 SEISMIC SOURCE ZONES (ZONES OF DIFFUSE SEISMICITY)

Seismic source zones (also referred to as zones of diffuse seismicity, IAEA, 2010; area sources, NAGRA, 2004) are defined as a region (or volume) of the Earth that is assumed to have uniform seismological characteristics with respect to the rate of seismicity, the depth distribution of earthquakes, and maximum magnitude (M_{max}, see below). Source zones are defined as an area delimited by a polygon in a geographical coordinate space. Source zone boundaries consequently delimit areas with different sets of seismicity parameters.
Due to the fact that source zones are regarded homogeneous with respect to the seismicity rates[9], their geometries have a very large potential effect on hazard evaluations. An extreme example is shown in Figure 15 where in one case a site is “fenced” from a higher seismicity by a source zone boundary preventing higher seismicity rates to apply to the site, and a second case where high seismicity is unduly spread over a large area.

[9] Seismicity is considered spatially homogeneous within a single zone. The probability of an earthquake of a certain magnitude to occur is therefore the same throughout the source zone.

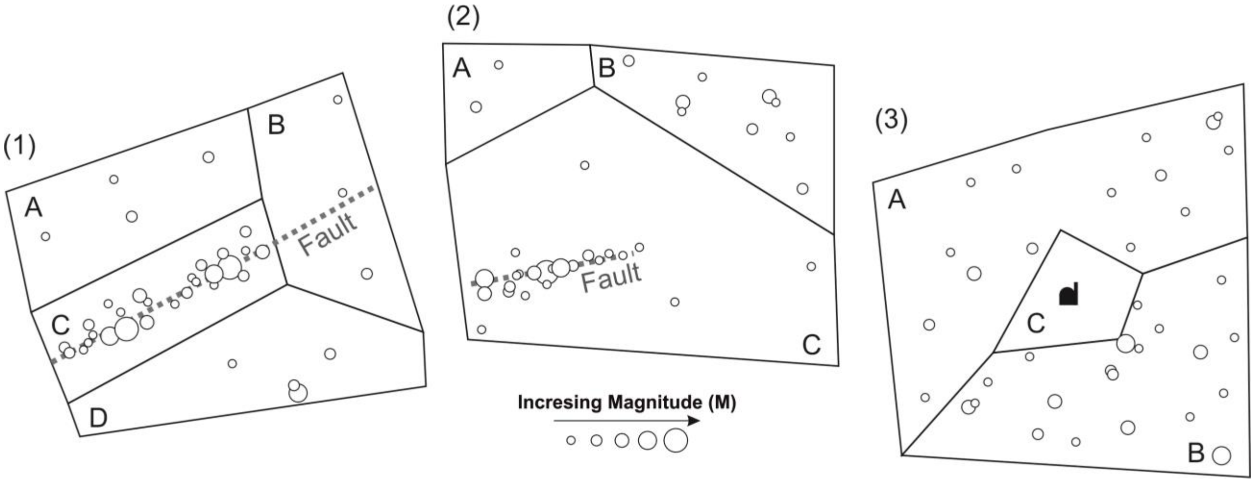

Figure 15. Examples of unreasonable seismic source zone definitions. (1) Source zones B and C divide a continuos fault zone. (2) High seismicity in source zone C related to an unidentified active fault is unduly spread over the entire source zone. (3) Source zone C "fences" a facility from other source zones with higher seismicity. ***[Fig_Source_Zones.JPG]***

The definition of source zones and their boundaries is based on the seismotectonic model (or several alternative models) developed for the region of interest. The delineation of source zone boundaries should account for the following:

1. Lithospheric and /or crustal structure (including crustal thickness / MOHO depth, subducting slabs) delineating large-scale geological and rheological units;
2. Tectonic evolution and long-term deformation history;
3. Tectonic structures (fault orientation, style of faulting);
4. Current tectonic regime and states of stress;
5. Kinematics of seismic ruptures determined from focal mechanisms;
6. Depth of the brittle-ductile transition. The brittle-ductile transition governs the depth distribution of earthquake hypocenters. It is in turn controlled by the crustal structure and the thermal state (heat flow) of the crust;
7. Depth distribution of earthquake hypocenters;
8. Significant differences of the rate of occurrence of earthquakes which may be indicative for distinct tectonic conditions.

Building seismic source zones exclusively on seismicity rates is not recommended and may be grossly misleading as the rate of earthquake recurrence obtained from historical / instrumental data may not be stationary over long (geological) time intervals[10]. Extrapolating the seismicity rate derived from observations through a geologically insignificant time window may therefore lead to wrong estimates of the long-term seismicity rates which are addressed by seismic hazard evaluation for NPPs which aims at providing data for very low occurrence probabilities / very long recurrence intervals.

[10] The Vienna Basin Transfer Fault (Austria, Slovakia) may serves as an example of non-stationarity. Only few segments of the faults moved in historical times producing earthquakes, while several other segments have not caused earthquakes throughout the historical observation period (c. 300-500 years; Hinsch & Decker, 2003; 2010). Defining seismic source zone polygons based on observed seismicity (as for example shown in Figure 15/1) therefore would separate the historically active fault segments (source zones with high seismicity rate) from the inactive ones (zones with low seismicity rate). This would to lead significantly underestimated hazard for the historically inactive fault strands.

4.2.3 GROUND MOTION PREDICTION EQUATIONS

Ground motion prediction equations (GMPEs) and attenuation models are used to relate seismic ground motion parameters (such as ground acceleration, spectral acceleration, peak velocity, shaking duration) to magnitude and distance from the seismic source (Figure 20). GMPEs should include algorithms for predicting the median amplitude, an algorithm describing the variability (standard deviation) of the scatter of observations for the same magnitude and distance, and the maximum ground motion that can occur (NAGRA, 2004).

A large variety of such models which are either based on empirical attenuation relations or numerical simulations is available in seismological literature (see, for example, references in Delavaud et al., 2012).

Empirical relations derive from instrumental records of significant earthquakes and establish relations between ground motion, magnitude, and distance to the source (measured either as hypocentral distance or as Joyner-Boore distance). Due to the sparsity of strong instrumental earthquakes in Europe apart from the Mediterranean region virtually no ground motion records exist which can be used to derive empirical attenuation relations for large parts of Europe. It is therefore necessary to rely on empirical ground motion prediction equations established in different parts of the world or on numerical simulation. Candidate GMPEs need to be adequate with respect to:

- the geological environment (stable continental regions, active shallow crustal regions, subduction zones);
- magnitude range;
- distance range (including minimum distance from fault sources, if applicable);
- hypocenter depth distribution;
- tectonic style (strike-slip, reverse and normal faulting).

Selection further needs to account for the fact that GMPEs relate distance to different ground motion parameters such as peak ground acceleration (PGA, PGA_H, PGA_V) and/or wave periods (most available models not applicable for periods greater than 3 s; Delavaud et al., 2012). Equations account for site conditions in different ways such as site classification (rock, shallow soil, deep soil) or site characteristics expressed by the seismic s-wave velocity V_{S30} using classes or continuous functions for V_{S30}. Advanced GMPEs may further account for point sources as well as extended sources, and nonlinear site response (Akkar et al., 2013).

The results of SHA are very sensitive to the choice of GMPEs / attenuation models, and the difficulties in selecting appropriate sets of GMPEs introduce large uncertainties into the hazard assessment. It is therefore common praxis in PSHA not to base the hazard evaluation on a single GMPE but to select a group of suitable GMPEs to model the related uncertainty using a logic tree approach.

Criteria for selecting GMPEs for a logic tree are discussed in detail by Cotton et al. (2006). Accordingly, GMPEs should be selected in order to *"obtain the smallest possible suite of equations that can capture the expected range of possible ground motions in the target region"* (Cotton et al., 2006). The selection of GMPEs may be justified by comparing model predictions to existing European records of moderate earthquakes (e.g., Hintersberger et al., 2007) or mathematical approaches (Scherbaum et al., 2009). Evaluation of the selected GMPEs should further lead to assign weights to their use in ground motion logic trees, e.g., by expert judgement as described by Delavaud et al. (2012). A comprehensive discussion of various aspects of selecting and adapting ground motion models to a specific SHA is given in by NAGRA (2004, page 183 ff; e.g., magnitude conversion, conversion of hypocenter to Joyner-Boore distances, adjustment for fault styles, site-conditions conversion accounting for V_{S30}).

A comprehensive annotated collection of GMPEs published between 1968 and 2010 is provided by Douglas (2011).

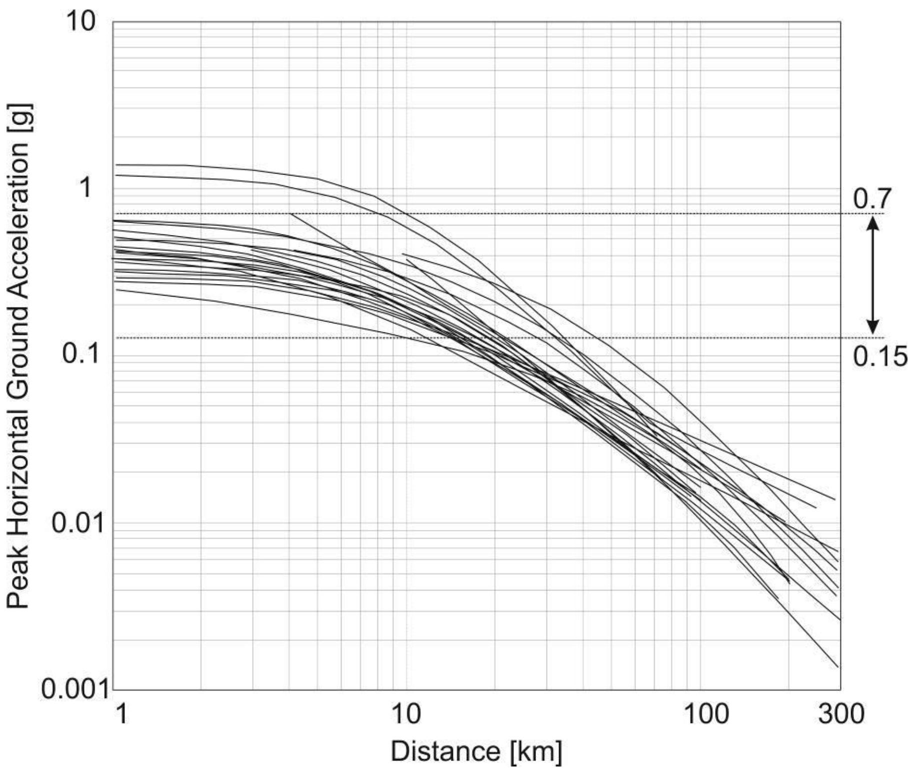

Figure 16. Example of different GMPEs relating PGA_H with distance for an earthquake with M = 6. Note the large spread of predicted ground motion at, e.g., 10 km distance. GMPEs from: Abrahamson & Silva (1997, 2008); Akkar & Bommer (2007); Ambraseys & Douglas (2003); Ambraseys et al. (1996; 2005); Atkinson & Boore (2006); Berge-Thierry et asl. (2003); Boore & Atkinson (2007); Boore et al. (1993; 1997); Campbell & Bozorgnia (2008); Campbell (1997); Kalkan & Gülkan (2004); Sabetta & Pugliese (1996); Sadigh et al. (1993; 1997); Tavakoli & Pezeshk (2005); Toro & Silva (2001). ***[GMPEs_examples.JPG]***

4.2.4 MAXIMUM MAGNITUDE (M_{MAX})

The maximum magnitude (M_{max}) refers to the conceivably largest earthquake that can be generated by a seismic source irrespective of its probability of occurrence. The parameter has to be determined for both, fault sources and zones of diffused seismicity. The concept is based on the assumption that a physical limit exists to the magnitude of an earthquake that can be produced by a seismic source.

The selection of M_{max} (sometimes also referred to as “maximum credible earthquake” or MCE) has a significant impact on the results of seismic hazard assessment. M_{max} is used in all earthquake recurrence relationships which rely on Gutenberg-Richter (or modified Gutenberg-Richter) relations describing seismic sources (Figure 17).

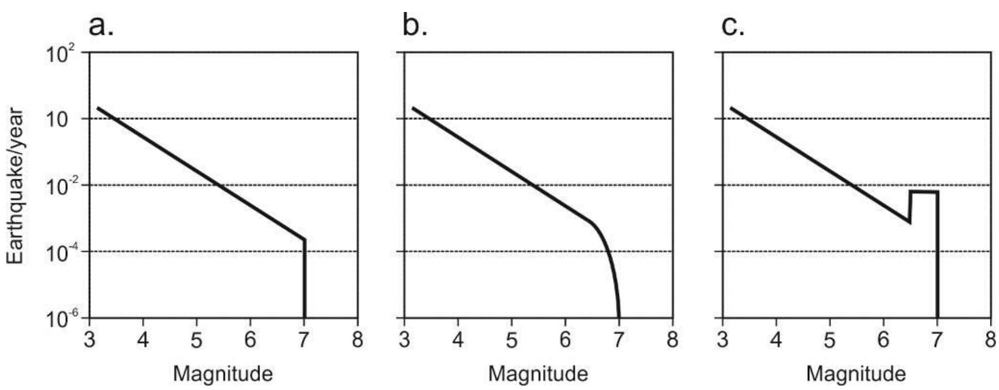

Figure 17. Maximum magnitude: (a) cuttoff Gutenberg-Richter exponential distribution (Cornell & Van Marke, 1969), (b) truncated exponential distribution, and (c) characteristic earthquake model (Youngs & Coppersmith, 1985). Modified from NAGRA (2004)
[Fig_Mmax_truncated_G-R.JPG]

Seismic sources defined as areas. Approaches to assess M_{max} for seismic source zones include both, statistical and deterministic methods:

- in the “EPRI-Approach” (described by NAGRA 2004, p. 107-109) M_{max} is statistically determined from the strongest earthquake which is included in the earthquake catalogue (providing a minimum value for M_{max}) using a statistical approach,
- extrapolation from current earthquake catalogues (Kijko & Graham, 1998; Kijko, 2004); the approach estimates M_{max} by statistical methods solely from the seismicity recorded in a region,
- Gumbel extreme value statistics (e.g., Kijko & Ahjos, 1985); the approach is regarded highly problematic as extrapolations of extreme values to times exceeding the length of catalogue coverage are not reliable (Kijko & Dessokey, 1987; Peruzza & Slejko, 1993); in some cases M_{max} derived from Gumbel statistics even fail to reproduce the maximum observed magnitude (Lenhardt, 1996; Musson, 2003),
- adding a margin or increment to the magnitude of the strongest observed earthquake,
- larger samples earthquake data can be obtained from combining geologically similar areas (e.g., stable continental interiors, rifted margins, subduction zones etc.) in order to obtain a larger number of strong

earthquakes and a database which is more robust for statistical analysis (Kagan & Jackson, 2013; USNRC, 2012a); statistical analysis of the larger sample proved more effective in estimating M_{max} (Kagan & Jackson, 2013; Vanneste et al., 2016),

- deterministic assessment; for source areas where faults, fault characteristics (fault orientation and dimensions), and the current tectonic regime (kinematics, recent stress directions) can be readily described M_{max} can be determined by a deterministic assessment using empirical fault dimension – magnitude relations (see below); the assessment should account for the dimensions of the largest faults which may be regarded to be activated in the current tectonic regime. M_{max} is derived from the maximum rupture dimensions of these faults.

In the absence of any theoretical basis for deriving maximum magnitudes values, estimates using the various statistical approaches cited above often prove to be too low, as in the case of the 2011 Tohoku earthquake causing the Fukushima accident (Stein et al., 2015). Estimating M_{max} is particularly challenging in intra-plate regions such as in Europe, where large earthquakes are infrequent compared to the length of earthquake catalogues, and earthquakes often occur on previously unrecognized active faults. The difficulties of assessing maximum magnitudes from historical / instrumental earthquake information have recently been described by Merino et al. (2013) using Monte Carlo simulations of earthquake catalogues. The authors show that the probability of a maximum magnitude event with an assumed recurrence time of 5000 years to be included in an earthquake catalogue covering 500 years is as low as 5%. As a result, M_{max} cannot be reliably estimated from earthquake catalogs. High probabilities of capturing a maximum magnitude event only exists for earthquake records which cover at least twice the average recurrence time of the maximum event (i.e., 10.000 years in the example). Such times can only be covered geological and paleoseismological observations.

Holschneider et al. (2011) have further shown on a statistical theoretical basis that it is probabilistically / mathematically impossible to derive M_{max} from a Gutenberg-Richter relation without further boundary conditions or assumptions. They conclude that *“From a statistical point of view, a limited data set does not allow us to estimate a magnitude that is maximum for all times,”* and that *“From a physical point of view, numerical models of the earthquake process adjusted to specific fault regions may be a powerful alternative to overcome the shortcomings of purely statistical inference”* (Holschneider et al., 2011). Such numerical models are based on fault dimensions and displacement rates.

Due to the discussed shortcomings of statistical approaches and the shortness of earthquake records, deterministic assessment to estimate M_{max} for area sources should be preferred. The assessment should start from selecting all faults in a source zone which, by their orientation, may potentially be activated in the current stress field, or which are oriented parallel to known active faults. M_{max} can be derived from the dimensions of the largest suitably oriented faults using scaling relations (see paragraph on fault sources below). Due to the fact that source zones in practically all parts of Europe will contain significant numbers of faults with lengths of more than 10 km estimates of M_{max} < 6 to 6.5 are regarded unreasonable (Mw = 6 and Mw = 6.5 correspond to ruptures of faults with 10 km and 30 km length, respectively [Wells & Coppersmith, 1994]).

It should be noted that estimates of M_{max} are made independently of the annual frequency of such events. The recurrence intervals of M_{max} for different regions or source zones will differ significantly depending on the level of seismicity (highly active regions will be characterized with shorter recurrence intervals of M_{max} events while much longer recurrence intervals are expected in low seismicity and stable tectonic environments).

Fault sources. Approaches to assess M_{max} for fault sources are based on empirical relations between the maximum rupture area of a fault and M_{max} accounting for the fault kinematics (e.g., Wells & Coppersmith, 1994; Vakov, 1996; Mohammadioun & Serva, 2001; Leonard, 2010; Striling et al., 2002; 2013). Summaries and discussions of the method and its uncertainties are included in Stirling & Godet (2012) and IAEA (2015c, page 95 ff).

The maximum rupture area of a fault that is used as an input to the assessment may be equal to the total dimension of a fault, or to a segment of a fault which is believed to rupture during a seismic event. The concept of fault segmentation derived from the common observation that especially long faults do not rupture along their entire length during one single earthquake (e.g., King & Nabelek, 1984; Schwartz & Coppersmith 1984; Tsutsumi & Okada, 1996; Zhang et al., 1991). Dynamic fault rupture may be impeded at geometric fault segment boundaries such as changes in fault strike, increase of the number of faults or the width of the fault zone, increased fault complexity, stepover of fault segments, or branch lines of splay faults (Zhang et al., 1991). Among these, significant fault bends are regarded to act as the strongest impediments during dynamic rupture propagation. Further discussion on the effectivity of fault steps in arresting dynamic rupture is provided by Wenousky (2006, 2008). The author particularly showed that dynamic rupture may continue over fault steps smaller than a certain size indicating that attempts *"to place limits on the probable length of future earthquakes on mapped active faults"* by the evaluation of fault steps may be not be straight forward (Wenousky, 2006).

In cases where it is possible to precisely define the 3D geometry of a fault, fault segment dimensions may consequently be used for constraining the maximum fault surface, which is expected to break during single earthquakes, and to assess M_{max} (e.g., Beidinger & Decker, 2011). It must, however, be noted that in many cases such detailed fault analyses will not be available.

Erroneous assumptions of fault segmentation may lead to underestimating M_{max} as it has been the case in the 2011, Tohoku earthquake. In cases where reliable and detailed studies on the subsurface geometry are not available the total fault area should consequently be used to estimate M_{max}. Estimates of M_{max} based on fault size should as far as possible be compared to by paleoseismological data and modelling results.

4.2.5 LOWER BOUND MAGNITUDE

The lower bound magnitude (LBM) or minimum magnitude (m_0) refers to the lowest earthquake magnitude which is considered in deriving ground shaking hazard curves for a site.

The lower bound magnitude (LBM) is significant parameter influencing the results of PSHA in the way that higher values for m_0 commonly result in lower apparent ground motion hazards. The minimum magnitude is a lower cut-off value for the analysis, applied because small-magnitude earthquakes can generate high PGA values in impulsive spikes. It is commonly assumed that these high accelerations do not have the capacity to cause damage to engineered structures as they have insufficient energy or duration. They are consequently filtered out of the hazard calculations. The definition of m_0 is to some extent arbitrary. For ordinary masonry structures, it is common to use M = 4 as the LBM, but engineered structures of good design should not be damaged by earthquakes smaller than M = 5, so this higher value is generally used for major engineering projects. Seismic hazard evaluations for nuclear installations therefore frequently consider only earthquakes with magnitudes greater than Mw = 5 (e.g., NAGRA, 2004). This value corresponds to IAEA's recommended maximum value for m_0 (*"a selected lower bound magnitude* [LBM] *should not exceed Mw = 5.0."* IAEA, 2010, p. 44).

The selection of LBM as Mw = 5 apparently is stimulated by operating experience from the USA where two earthquake occurrences (NPP North Anna, Earthquake of Mineral, Virginia, 23.08.2011, Mw = 5.8; Perry NPP, Leroy earthquake 31.01.1986, M = 5) were found to induce no or only low damage because of their short duration and high frequency content (IAEA, 2003a).

No operating experience about the effects of earthquakes with M ~ 5 exists from European NPPs. In Europe the design base earthquakes for a number of NPPs were originally defined by macroseismic intensities. In some cases hazard assessments performed during the siting process resulting in DBEs with intensity I = 7 to 8. In intraplate Europe intensities of I_0 = 7 correlate with earthquake magnitudes Mw ~ 5 (Grünthal et al., 2009) indicating that the design basis of some NPPs is close to the maximum value of LBM (Mw = 5) proposed by IAEA. It appears therefore not straight forward to apply LBM = 5 to such sites. In addition, WENRA (2016) addresses high-frequency vibratory movement with a frequency higher than 15 Hz as such waves are important for sensitive components, e.g. relays. In the selection process for m_0 it should therefore be clarified whether or not the concept of the lower bound magnitude and the same level of m_0 can be applied to all SSCs of an NPP which are subjected to seismic qualification, an all civil structures which are credited in a protection and defense in depth concept[11]. When applying a specific level of the LBM it should be ruled out that some critical components can be damaged by ground motion resulting from earthquakes with M < LBM.

It is further suggested to base the selection of minimum magnitude a sensitivity study to determine how much influence it has on the hazard results (Reiter, 1990).

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[11] The ENSREG Stress Tests have revealed cases where civil structures such as the fire brigade buildings, which are credited as functional in defense in depth concpets, would suffer severe damage at very low PGA values (ENSREG, 2012c).

4.3 METHODS COMMONLY APPLIED.

4.3.1 PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)

PSHA assesses the probability that a given vibratory ground motion (characterized by ground motion parameters expressed by PGA, spectral acceleration etc.; see chapter 4.1, page 65) happens at least once in a given place and during a given time period. The method is originally based on Cornell (1968). The calculation of probabilities is based on a Poisson model which assumes that all events are independent in both time and space[12]. The model is therefore “stationary” meaning that the likeliness of an earthquake does not change with the time elapsed from the last event. It therefore does not account for the buildup of stress.

The PSHA methodology for calculating the probability of occurrence of vibratory ground motion at a specific site is well established since the 1970s (Cornell, 1971; Der Kiureghian & Ang, 1975; McGuire, 1976; 1978; 1995).

Comprehensive descriptions of the PSHA approach are, for example, included in Green & Hall (1994) and NAGRA (2004, volume 1). PSHA hazard calculation is based on specifications of the following inputs and steps:

1. Identification of sources and establishment of source geometry. PSHA requires to specify the geometry and geographical location of fault (or line) sources (chapter 4.2.1, page 70) and seismic source zones (area sources; chapter 4.2.2, page 75).
2. Earthquake recurrence relationships: For each source the mean annual rate of earthquake occurrence and the magnitude distribution needs to be defined. In most cases, the recurrence is expressed by a Gutenberg-Richter relation with appropriate a- and b-values (Gutenberg & Richter, 1956). The step includes the selection of a maximum magnitude for each source zone (chapter 4.2.4, page 80).
3. Ground motion prediction equation (attenuation function): Algorithms for the estimation of ground motion at a site (e.g., expressed as PGA or spectral acceleration) need to be defined (chapter 4.2.3, page 78).

Green & Hall (1994) and NAGRA (2004, Volume 1) provide detailed descriptions of both, the general PSHA approach and its mathematical formulations. Seismic source characterization, earthquake recurrence models, and ground motion characterization are discussed in detail on the background of relevant literature. Additional discussion on some specific aspects of the methodology (minimum magnitude, site effects) is provided by McGuire (2009).

PSHA includes formalized ways to treat both, aleatory and epistemic uncertainties. Epistemic uncertainty resulting from the limited knowledge of key input parameters (seismic source zones, earthquake recurrence, maximum magnitude, GMPEs, etc.) are incorporated via logic trees (chapter 4.4.1, page 91). The weighting of alternative input parameters or models of the logic tree is based on expert opinion, which may be formalized by an SSHAC approach (Hanks et al., 2009; U.S.NRC, 2012; chapter 4.7, page 98). The type PSHA is therefore sometimes referred to as the Cornell-McGuire-SSHAC model of PSHA.

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[12] Fore- and aftershocks of major events need to be removed from the database (“declustering” of the earthquake catalogue).

Recent advances of PSHA, e.g., driven by the Global Earthquake Model programme (GEM) and the development of the OpenQuake risk calculation software allow for a realistic representation of active faults in the hazard assessment both in terms of fault geometry and earthquake behavior. Advanced seismic hazard calculations can take into account complexities such as geometrical irregularity of faults in the prediction of ground motion, and near-fault effects such as fault directivity (Weatherill et al., 2016). The corresponding methods and computer codes are currently developing and are not yet standard approaches.

Although several critical opinions on the PSHA approach were published in the past (Klügel, 2008[13]; Krinitzsky, 1995[14]; 2003) the method is widely used for the assessment of vibratory ground motion hazards. The application of probabilistic hazard assessment techniques for NPPs is implicitly required for the definition of design basis events by WENRA (2014a, Issue T) stating that *"The exceedance frequencies of design basis events shall be low enough to ensure a high degree of protection with respect to natural hazards. A common target value of frequency, not higher than* 10^{-4} *per annum, shall be used for each design basis event."*

PSHA is further the only method providing ground motion amplitudes for different occurrence probabilities together with the associated uncertainties which are required as input parameters for PSA.

[13] The applicability of the model of a stationary homogeneous Poisson process is questioned.

[14] Points out that experts opinions cannot be averaged meaningfully because the criteria for different models are nonequivalent.

4.3.2 DETERMINISTIC SEISMIC HAZARD ANALYSIS (DSHA)

The deterministic seismic hazard analysis approach typically determines the maximum credible vibratory ground motion at a site. The process includes the following principle steps:

1. Definition of the nearby seismic source zones (zones of distributed seismicity) and fault sources (chapters 4.2.1and 4.2.2, page 70 ff).
2. Evaluation of the maximum magnitude for each source zone and fault source (e.g., using scaling relations between rupture area and magnitude; see chapter 4.2.4, page 80).
3. Identification of the distance between the site and the location of the possible maximum magnitude earthquakes for each source considering the following:
    a. For each fault source the potential maximum magnitude event (M_{max}) should be assumed to occur at the point closest to the site. *"In cases where the site is located within the boundaries of a seismic source* [e.g., on top of a thrust or normal fault] *the maximum potential magnitude should be assumed to occur beneath the site."* (IAEA, 2010).
    b. For seismic source zones not containing the site the potential maximum magnitude event should be assumed to occur at the point closest to the site.
    c. The distance of the maximum potential magnitude in the zone of diffuse seismicity containing the site should be constrained by geological and tectonic data with the aim to demonstrate that either (i) faults are absent from the site and its surrounding, or (ii) the probability of the faults identified at the site and its surrounding to produce earthquakes is *"negligibly low"* (IAEA, 2010). This can be done by showing that faults near the site are extinct (Table 9) or not able to produce earthquakes due to their size, or due to their orientation with respect to the current stress field. The demonstration requires detailed investigations which are typically restricted to some 10 km around the site. The distance of the site to the location of the maximum potential earthquake is then constrained by (i) the distance of an area where faulting cannot be excluded or (ii) the radius around the site for which detailed analyses excluded seismogenic faulting.
4. Selection of appropriate GMPEs (attenuation relations) for the site region to assess the ground motion at the site as a function of earthquake magnitude and source to site distance. Assessments should not exclusively rely on a single GMPE.
5. Calculation of the ground motions resulting at the site from the possible maximum magnitude earthquake in each source or source zone. The earthquake associated with the largest ground motion value is typically used to describe the ground motion hazard.

DSHA calculations should account for the uncertainties related to each step of the evaluation *"with the consideration that the conservative procedure described* [in bullet 3 above] *has already been introduced to cover uncertainties, and double counting should be avoided"* (IAEA. 2010). Statistics can be incorporated into the procedure by taking one standard deviation above median for all parameters determined in each step (e.g., M_{max} estimates from fault dimensions, ground motion derived from GMPEs).

DSHA does not account for the probability of an earthquake occurring in a source zone or on a fault. DSHA is usually considered to be conservative particularly when it is based on tectonic features as it assumes M_{max} to occur at the location on the fault closest to the site, or at the closest fault within the source zone containing the site which cannot be proved to be incapable of producing earthquakes. DSHA is therefore not applicable for defining design basis requirements as required by WENRA (2014a) and occurrence probabilities of ground motion amplitude as required for PSA. The method, however, may provide an estimate of the largest amplitude of vibratory ground motion at a site which can be used for DEC considerations or as an upper cutoff value for PSA.
Guidelines for DSHA are provided by IAEA (2010). McGuire (2001) and Krinitzsky (2003) provide discussions on the combined application of DSHA and PHSHA.

4.3.3 PROBABILISTIC FAULT DISPLACEMENT ANALYSIS (PFDHA)

As outlined in chapter 4.1 PFDHA is typically applied in cases where faults were identified at the site or in the site vicinity during the lifetime of a nuclear installation. According to IAEA (2010) PFDHA should be applied in cases where *"no sufficient basis is provided to decide conclusively that the fault is **not** capable"*. For such cases IAEA (2010) recommends *"to use probabilistic methods analogous to and consistent with those used for the ground motion hazard assessment should be used to obtain an estimate of the annual frequency of exceedance of various amounts of displacement at or near the surface"*. Analyses should consider both, primary displacement (surface rupture) of the seismogenic fault, and secondary displacements such as induced movements along pre-existing slip planes.
Probabilistic Fault Displacement Hazard Analysis (PFDHA) is a method to estimate the frequency of the fault displacement exceeding a certain value for certain period (e.g., frequency of exceedance per year). The result is expressed as a fault displacement hazard curve. A methodology to estimate fault displacement the ground surface associated with earthquakes probabilistically was proposed by Youngs et al. (2003). Youngs et al. (2003) showed evaluation procedures based on diverse data on normal faults in the U.S. Cases for strike-slip faults and reverse faults have been analyzed by Petersen et al. (2011), Robb et al (2011) and Moss & Ross (2011). Takao et al. (2013) showed evaluation formulas based on Japanese earthquakes associated with strike-slip faults and reverse faults.
Detailed requirements for the assessment of tectonic surface fault rupture and surface deformation have recently been formulated by ANSI/ANS (2015). The standard also includes a detailed methodological description to assess surface rupture hazards by PFDHA, and the analysis of permanent ground motion caused by slip on a buried fault by a method referred to as PTDHA (Probabilistic Tectonic Deformation Hazard Analysis).
There are two approaches, the earthquake approach and the displacement approach. The earthquake approach is similar to the probabilistic seismic hazard analysis proposed for areal source (diffusive earthquakes) by Cornell (1968). The displacement approach uses the characteristics of the fault displacement observed at the target point (location) for the analysis. In the displacement approach, characteristics of the fault are used directly with which displacement probability is evaluated. The rate (e.g. annual frequency) of exceedance of displacement is given as (Youngs et al., 2003):

$$\mathbf{v(d) = \lambda_{DE}\ P(D>d)}$$

d: displacement

v(d) : the rate of fault displacement exceeding d

λ_{DE}: the rate of displacement events on the fault

P(D>d): conditional probability that displacement D exceeds d in an event

The displacement approach requires a sound knowledge of the fault history (e.g., determined from paleoseismological records). The annual frequency of exceedance of the fault displacement is estimated for master faults (principal faults) and secondary faults (distributed faults). A master fault is defined as the fault closely related to earthquake source. For seismogenic faults the probability of surface rupture increases with the magnitude of the event (Figure 18). Secondary faults are defined as fault whose displacement occurs at the ground surface and not closely related to earthquake source fault, or those faults whose displacement occur secondarily or subordinately over a wide zone associated with the activity of the master fault. In the earthquake approach, annual frequency of exceedance of the displacement is expressed as below (Takao et al., 2013; JANSI, 2013):

As for Master fault,

$$v(d)_{p1} = P_0 \times P_{1p} \times P_{2p} \times P_{3p}$$

$v(d)_{p1}$: annual frequency of master fault displacement exceeding d

P_0: activity rate of the earthquake source fault (per year)

P_{1p}: probability that the fault displacement due to the master fault occurs at the ground surface when the earthquake source fault becomes active

P_{2p}: probability that the fault displacement occurs at the analysis point when fault displacement due to the master fault occurs at the ground surface

P_{3p}: probability that the fault displacement exceeds a certain value “d” when fault displacement due to the master fault occurs at the analysis point

As for secondary fault,

$$v(d)_{d1} = P_0 \times P_{1p} \times P_{2d} \times P_{3d}$$

$v(d)_{d1}$: annual frequency of secondary fault displacement exceeding d

P_0: activity rate of the earthquake source fault (per year)

P_{1p}: probability that the fault displacement due to the master fault occurs at the ground surface when the earthquake source fault becomes active

P_{2d}: probability that the fault displacement due to the secondary fault occurs at the ground surface at the analysis point when the earthquake source fault becomes active

P_{3d}: probability that the fault displacement exceeds a certain value "d" when fault displacement due to the secondary fault occurs at the analysis point.

Details of the calculation method are described in JANSI (2013), ANS (2015), IAEA (2015), Suziki & Annaka (2015) and Takao et al. (2015).

In the probabilistic analysis, two types of uncertainties can basically be taken into account, i.e., aleatory uncertainties and epistemic uncertainties. Aleatory uncertainties are due to the inherently random and unpredictable nature of future events, and cannot be reduced. Aleatory uncertainties can be evaluated by assuming the probability distribution. Epistemic uncertainties are those resulting from inadequate knowledge or data, which are generally modeled using logic tree branches and the weight given to them (Youngs et al., 2003). Examples of fault displacement hazard curve for secondary fault are shown below (Figure 19, Figure 20).

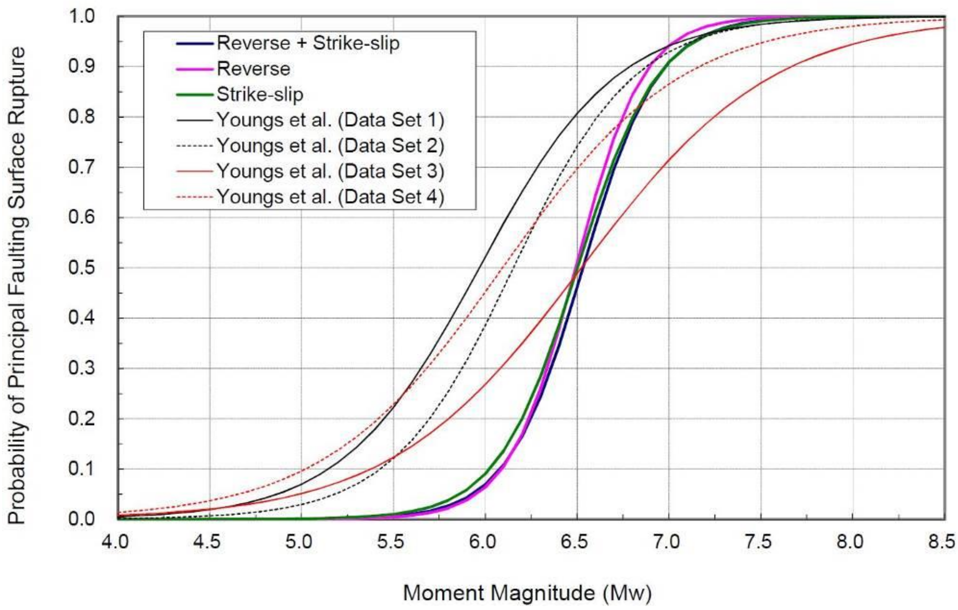

Figure 18. Probability of surface rupture as a function of earthquake magnitude (Takao et al., 2015) *[Takao_probability_surface_rupture.JPG]*

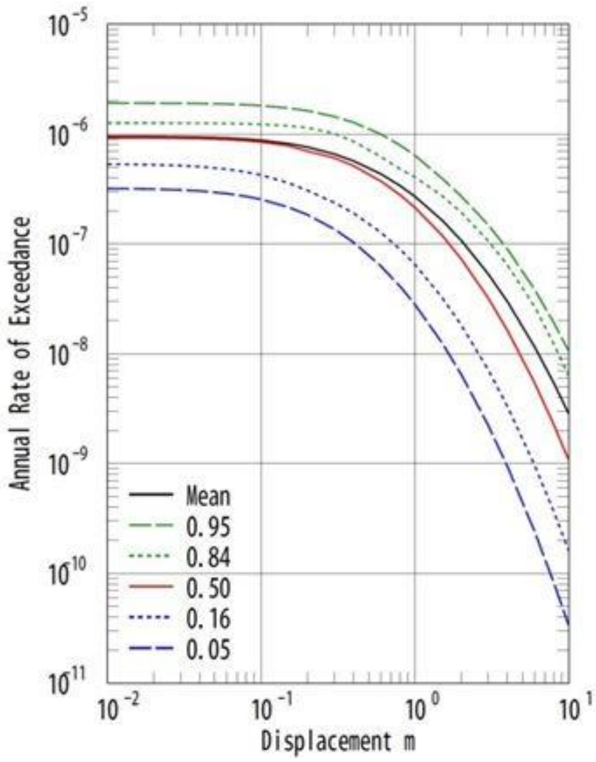

Figure 19. Example of fault displacement hazard curves of secondary fault with fractile values (epistemic uncertainty considered). By courtesy of Y. Suzuki (2015). ***[PFDHA_example_1.JPG]***

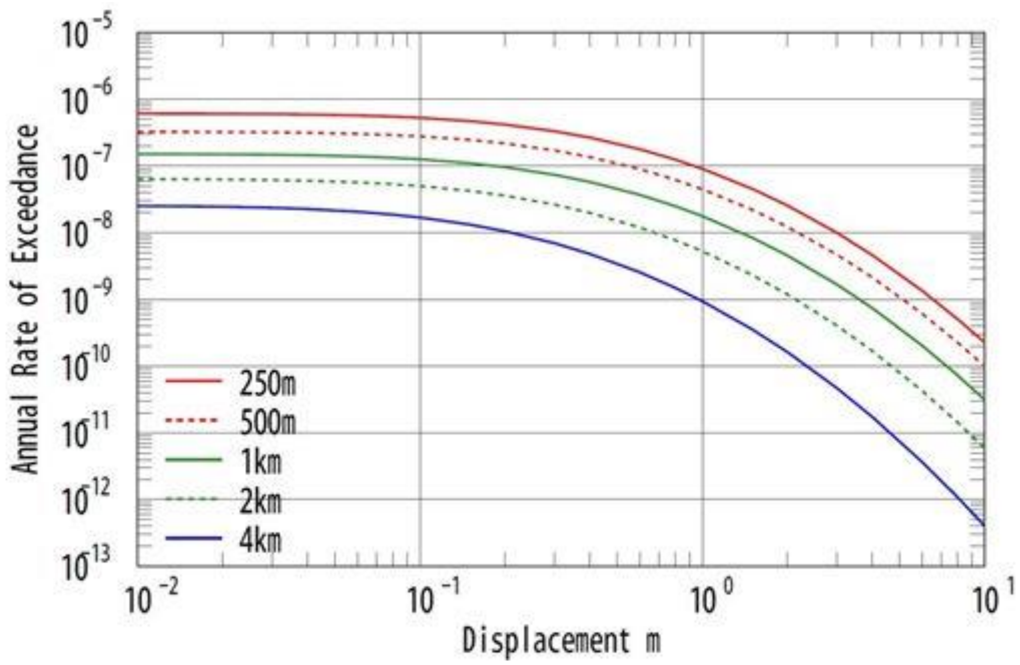

Figure 20. Example of fault displacement hazard curves of secondary fault. Annual rate of exceedence is plotted against distance from master fault as parameter assuming an earthquake with Mw = 6.5 at the master fault. By courtesy of Y. Suzuki (2015). ***[PFDHA_example_2.JPG]***

Issues concerning the application and the Improvement of PFDHA:

- epistemic uncertainties in the fault displacement hazards are estimated using logic tree branches and the weight given to them; uncertainties are expressed as the band of fault displacement hazard curves (fractal hazard curves); it is considered important in the application of PFDHA that options are provided to allow for appropriate setting of logic tree branches and that these options cover almost all future possibilities;
- accumulating field survey data, and utilizing the results of experiments and numerical simulations to complement the data in case of their inadequacy will work to reduce uncertainties in PFDHA;
- in the earthquake approach hazard values depend on the cell size used for analysis; the smaller the cell gets, the smaller the probability of occurrence of secondary fault becomes, decreasing the estimated displacement hazard (Petersen et al., 2011; Takao et al., 2014); therefore appropriate computational cell sizes need to be selected taking account of the size of the target facilities in a specific application;
- the observational database for PFDHA is still very small meaning that the empirical relations used for hazard assessments are based on very limited numbers of observations (e.g., Takao et al., 2013, 2015; Petersen et al., 2015); this applies to correlations between (a) annual rates of exceedance of displacement and magnitude; (b) distance of distributed surface rupture from the primary fault and magnitude; (c) the influence of the fault type (strike-slip, reverse, normal) on these relations;
- displacement records on surface earthquake faults include those occurred both in overlying strata and bedrock; in general, it is difficult to discuss the quantitative relationship between fault displacements on bedrock and those in overlying strata; thus, it is necessary to accumulate survey data, evaluations based on experiments and numerical simulations;
- studies on the probabilistic fault displacement hazard analysis started only recently; although the IAEA safety standards address PFDHA regarding the problems posed by capable faults for existing nuclear power plant facilities, PFDHA has only been applied to a limited number of cases; an example of PFDHA applied to existing NPP (Diablo Canyon NPP) can be found in USNRC (2012).
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4.4 UNCERTAINTY ASSESSMENT

4.4.1 PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)

PSHA commonly distinguishes between aleatory and epistemic uncertainty:

Aleatory uncertainty (or: statistical uncertainty, randomness) *"is the physical variability present in the system being analysed or its environment. It is not strictly due to a lack of knowledge and cannot be reduced. The determination of material properties or operating conditions of a physical system typically leads to aleatory uncertainties; additional experimental characterization might provide more conclusive description of the variability* *but cannot eliminate it completely. Aleatory uncertainty is normally characterized using probabilistic approaches[15]".*

In seismic hazard assessment the location, time and magnitude of an earthquake occurring on an active fault (or within a seismic source zone) and the resulting ground motion are considered aleatory (NAGRA, 2004). *"Even with a perfect knowledge of the state of stress of the earth's crust, future earthquakes could still be occurring at a variety of unknown locations with some probability distribution. In current practice, this probability distribution expresses the irreducible aleatory uncertainty"* (ANS, 2015). The uncertainty about where or when an earthquake occurs on an active fault cannot be reduced by acquiring additional data but could only be reduced with fundamentally new insights into the physical processes of seismic rupture processes. Aleatory uncertainty is assessed by integration over randomly distributed variables to calculate the exceedance probability of a hazard parameter. In PSHA aleatory uncertainty is thereby integrated into a single hazard curve.

Epistemic uncertainty (or: systematic uncertainty) refers to parameters which could in principle be known, but in practice are not. It therefore refers to a lack of knowledge which can, for example, be reduced by the acquisition of new data. *"Epistemic uncertainty is not well characterized by probabilistic approaches because it might be difficult to infer any statistical information due to the nominal lack of knowledge[16]".*

In PSHA uncertainties about the characteristics of seismic source zones, active tectonic structures etc. are treated as epistemic leading to uncertainties in the data used as input into seismic hazard calculations. Uncertainties exist for all basic inputs of the SHA, i.e., active fault sources, seismic source zones, earthquake recurrence intervals expressed by Gutenberg-Richter parameters (a- and b-values), maximum magnitude, ground motion prediction equations (GMPEs), and site effects (local soil conditions).

The epistemic uncertainty is represented in the PSHA by the development of a weighted set of alternative models in a logic tree framework (see below; NAGRA, 2004). In a full-scope PSHA these uncertainties are propagated through the entire hazard analysis resulting in a series of alternative hazard curves. Each of the results derived from a certain set of input parameters therefore results in a distinct hazard curve. In PSHA uncertainties are handled by giving a weight to each individual hazard curve, which represents the credibility of the input dataset. The spread of the results, accordingly, quantify seismic hazard and its uncertainties.

The resulting set of individual hazard curves can further be used to assess the dependence of the results on individual input parameters and identify those input parameters, which contribute most to the observed uncertainty. Such sensitivity assessment may lead to the conclusion that uncertainty of a certain input parameter (e.g., a near-regional fault source) may contribute significantly to the total uncertainty while other parameters do not (e.g., local soil conditions). Such analyses can therefore be used to decide about the acquisition of new data and concentrate resources on the most relevant topics (e.g., fault investigation) in order to reduce the uncertainty of the PSHA result.

[15] https://web.stanford.edu/group/uq/uq_youq.html

[16] https://web.stanford.edu/group/uq/uq_youq.html

A logic tree methodology (Coppersmith & Youngs, 1986) is commonly used to represent epistemic uncertainty in PSHA as suggested by SSHAC (1997). In a logic tree each node represents a key input parameter affecting seismic hazard. Branches emanating from the nodes represent different interpretations of the input parameter under consideration. Each branch is given a probability by experts or expert teams which denotes the assumed likelihood that the branch is "true". The sum of all probabilities of branches emending from a node is 1, and the weight of each branch is conditional on the values of the preceding branches of the logic tree (Figure 21). Further detailed information on uncertainty assessment can be found in NAGRA (2004) and SSHAC (1997).

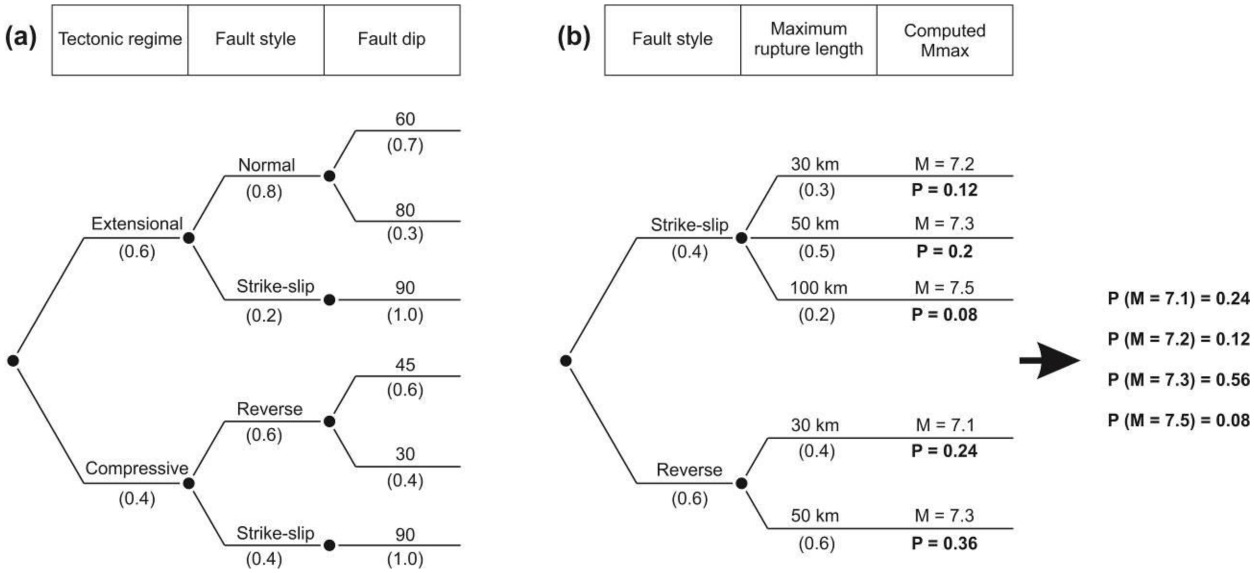

Figure 21. (a) Example of a logic tree for assessing fault geometry as a characteristic of seismic sources. (b) Example of a logic tree to assess maximum magnitude for a seismic source with uncertain kinematics (strike-slip, reverse) and fault length. The probability of the magnitude on the right of the tree is the product of the probabilities of the branches leading to the result. The final result is a distribution of M_{max} to be used as input for PSHA (redrawn from USNRG, 1997).
[Logic_tree_example.JPG]

4.4.2 DETERMINISTIC SEISMIC HAZARD ANALYSIS (DSHA)

DSHA calculations can account for some epistemic uncertainties by introducing simple statistics into the procedure of selecting input parameters, e.g., by taking the standard deviation into account for empirically derived parameters (e.g., M_{max} from fault dimensions, GMPEs). Uncertainties related to different source zone models could, in principle, be handled by logic tree approaches similar to the ones applied in PSHA. The authors, however, are not aware of studies applying such approaches.

4.4.3 PROBABILISTIC FAULT DISPLACEMENT ANALYSIS (PFDHA)

The development of probabilistic methods for analyzing surface ruptures started only recently and PDFHA exercises were only performed for a very limited number of sites (e.g., Diablo Canyon NPP, USNRC, 2012; Krsko NPP, Cline et al., 2015). An elaborated and widely used treatment of uncertainties is therefore not available. Recent studies, however, applied logic tree approaches to model the uncertainties of input parameters (Cline et al., 2015). Input parameters modelled by different branches are the probability of fault activity, fault length and the derived maximum magnitude, slip rate, maximum magnitude, and principle / distributed faulting.

It currently appears that most of the uncertainty of the results is due to the very small database which is available for secondary displacements such as induced movements along pre-existing slip planes (Takao et al., 2015).

4.5 METHODOLOGICAL LIMITS

Outputs of seismic hazard assessments for low and very low exceedance probabilities down to 10^{-5} or 10^{-6} per year are required as numerical input for quantifying accident sequences in PSA. Extrapolations down to very low exceedance probabilities are further implicitly required by the WENRA Reference Levels (WENRA, 2014a) and supporting Guidance Documents for the assessment of design extension conditions (WENRA, 2014b; 2015;; 2016). WENRA (2014a) does not define numerical target values for the non-exceedance probability of events which must be considered in DEC analysis but it requires *"considering those events and combinations of events, which cannot be considered with a high degree of confidence to be extremely unlikely to occur"* (WENRA, 2014a, Reference Levels Issue F).

The commonly used probabilistic methods allow for a straight-forward calculation of hazard curves down to extremely low exceedance probabilities. Examples include the PEGASOS PSHA results (NAGRA, 2004; hazard curves for non-exceedance probabilities of 10^{-7} per year) and PFDHA assessments calculating hazard curves down to 10^{-10} (Cline et al., 205; Takao et al., 2003) or even lower (10^{-13}, Suzuki et al., 2015; Takao et al., 2015). A critical scientific discussion of the reliability of such hazard results which goes beyond the assessment of probabilistic (aleatory and epistemic) uncertainty is, however, commonly not provided.

The interpretation of calculated hazard values and the assessment of their reliability for extremely low exceedance probabilities needs to consider the following issues:

- ***Earthquake data coverage and completeness:*** each hazard assessment is based on a limited number of data which covers a limited time period. As discussed in chapter 3.1.3 (page 41) European earthquake data typically cover time periods of few hundred years only and may be incomplete even for this time interval. Hazard assessments which are exclusively based on such data therefore essentially extrapolate the seismicity of the observation period to extremely long recurrence intervals (10.000 years and longer; Figure 22). The resulting limitations to the reliability of SHA are particularly relevant for regions with low seismicity such as the stable European continental interiors. This is due to the prevalence of active faults with very slow slip rates, long recurrence intervals for large earthquakes, and the general paucity of seismological data.

- ***Availability of paleo-earthquake data and integration of active fault data:*** the time coverage of earthquake data can be significantly expanded by paleoseismological investigations and the assessment of active faults. Interpreting the reliability of an SHA therefore should critically review the availability, completeness and quality of paleoseismological data as well as the depth of research addressing the assessment of active and inactive faults in the area of consideration. In-depth research is expected to increase the reliability of hazard results.
- ***The validation of seismic hazard results is generally not possible.*** Comparisons of hazard predictions of the GSHAP Global Seismic Hazard Map (GSHAP, 1999) which were made significant times ago with the seismicity recorded after 1999, however, show that abundant and severe pitfalls can occur in hazard prediction[17] (Wyss & Rosset, 2013). Similar underpredictions of seismic hazard were proved for the hazard maps of Japan[18] (Geller, 2011) and the USGS (Stein et al., 2012). Some reasons for the observed failure of SHA to correctly predict hazard levels in addition to the ones listed above are discussed by Stein et al. (2012).

Limits to the assessment of seismic ground motion hazards are evident from examples of diverging results of PSHA which were performed for the same site and revealed different results (e.g., USNRC, 2010).

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[17] *"Instrumentally measured accelerations due to 6 earthquakes were about three times larger, on average, than the maximum likely accelerations shown on the map (GSHAP, Giardini, 1999). On average, the accelerations were underestimated by a factor of approximately 3. … Intensities reported for the last 60 earthquakes with M ≥ 7.5 were all significantly larger than expected, based on the hazard map (by 2.3 intensity units for the 12 deadliest earthquakes)."* Wyss & Rosset, 2013.

[18] *"Since 1979, earthquakes that have caused 10 or more fatalities in Japan have occurred in places designated as low risk"*. Geller, 2011.

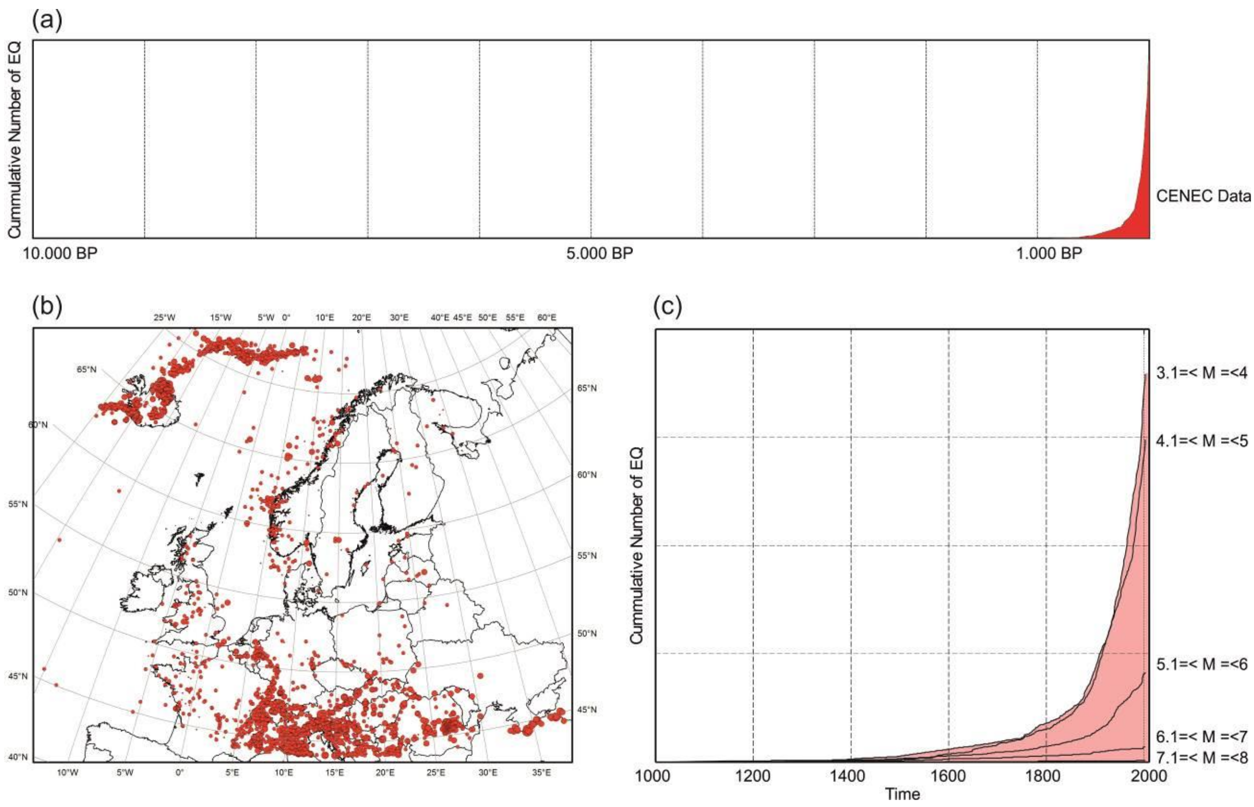

Figure 22. (a) Comparison of the time coverage of the European CENEC earthquake catalogue with a 10.000 years time interval illustrating the extent of extrapolation required to assess events with an average recurrence interval of 10.000 years. This average recurrence time corresponds to the occurrence probability of 10^{-4} per year as defined for design basis requirements (WENRA, 2014a). (b) Regional coverage of the CENEC catalogue. (c) Cumulative number of earthquakes for single magnitude classes of the CENEC Earthquake Catalogue (Grünthal et al., 2009) plotting versus time. See chapter 3.3.1 for detailed explanation. ***[CENEC_vs_10000_years.JPG]***

4.6 EVENT MODELLING

Ground motion simulation. Due to the understanding of physical fault rupture processes ground motion simulation techniques for ground motion hazard assessment gained significant importance during the last years. Modelling techniques address the simulation of ground motion based on the modelling of fault rupture processes to make predictions of the ground motion at a given site. Doing this strong motion simulation complements or substitutes empirical GMPEs, which relate ground motion parameters to earthquake magnitude and epicentral distances.

In contrast to empirically derived GMPE models, ground motion simulations use *"the elastodynamic representation theorem … to compute the total ground motion at a site from time functions of slip on the fault that represent faulting and Green's functions that represent seismic wave propagation"* (IAEA, 2015, SR-85). Simulation accounts for fault geometry parameters, fault slip parameters, crustal structure parameters such as seismic wave velocity, density, damping, and soil parameters. Simulations therefore are, in principle, capable to overcome drawbacks of GMPEs which are related to the common lack of data from locations close to the ruptured fault (i.e., GMPEs are not readily applicable to near-site faults), lack of data for larger earthquake magnitudes, and the scarcity of strong-motion data from low-seismicity stable continental regions which prevent the development of reliable GMPEs for such regions.

It should be noted, however, that ground motion simulation is only applicable for identifiable fault and requires detailed input data. IAEA (2010) lists the following data requirements for simulation:

> *(a) "Fault geometry parameters (location, length, width, depth, dip, strike);*
>
> *(b) Macroparameters (seismic moment, average dislocation, rupture velocity, average stress drop);*
>
> *(c) Microparameters (rise time, dislocation, stress parameters for finite fault elements);*
>
> *(d) Crustal structure parameters, such as shear wave velocity, density and damping of wave propagation (i.e. the wave attenuation Q value)."* (IAEA, 2010, 5.14)

Ground motion simulation approaches therefore require a very detailed geological and seismological understanding of faults.

IAEA (2015 SR-85) provides detailed information on the methodology along with examples of ground motion predictions based on simulation approaches. Due to the advances in modelling, IAEA started revising IAEA SSG-9 (IAEA, 2010) to incorporate modelling techniques. A recent study applying simulation techniques to complement ground motion data has been published for Fennoskandia where ground motion observations for moderate and large eartqhuakes (M > 3) are not available due to the low seismicity of the region (NSK, 2015). In this study modelling techniques were developed to generate synthetic accelerograms starting from fault rupture processes.

4.7 USE OF EXPERT JUDGMENT

A formalized approach for the use of expert judgement and the role of different experts in PSHA has initially been proposed by the "Senior Seismic Hazard Analysis Committee (SSHAC)" in the U.S. through the U.S. NRC (SSHAC, 1997, referred to as "SSHAC Guidelines"). *"The paper addresses why and how multiple expert opinions and the intrinsic uncertainties that attend them should be used in Probabilistic Seismic Hazard Analyses (PSHA) for critical facilities such as commercial nuclear power plants."* (Hanks et al., 2009).

The principal concern of formalizing the contribution of different experts and expert judgement are the epistemic uncertainties in the inputs to PSHA, which drive the uncertainties of the output of the hazard assessments (e.g., uncertainties of the key input parameters discussed in chapter 4.2, page 70 ff). The SSHAC approach to PSHA has been developed to account for these uncertainties as fully as possible. Accordingly, USNRC (2012) summarizes the purpose of the approach as follows:

> *"The fundamental goal of a SSHAC process is to carry out properly and document completely the activities of evaluation and integration, defined as:*
>
> *Evaluation: The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis.*
>
> *Integration: Representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods)."*
> (USNRC, 2012, p. XVI-XVII)

The process of a PSHA using a SSHAC approach is summarized in Hanks et al. (2009) : *"SSHAC Guidelines [SSHAC,1997] are concerned with how to capture, quantify, and communicate both the implicit and explicit uncertainties expressed by multiple experts. … SSHAC (1997) proposed a process for obtaining and aggregating expert interpretations, judgments, and models … . This process begins with diverse inputs, such as differing models and interpretations obtained from multiple experts, which are then evaluated through an interactive process overseen by a technical integrator*[19] *(TI) or technical facilitator/integrator*[19] *(TFI). This process results in a model representing not only the experts from whom it was derived but, ideally, also the larger informed technical community*[19] *(ITC) that the experts in principle represent. … The goal of all this interaction is "to represent the center, body, and range of technical interpretations that the larger informed technical community would have if they were to conduct the [seismic hazard] study.""* (Hanks et al., 2009).

SSHAC consequently established formalized processes to perform a PSHA with different roles attributed to the contributing technical experts (SSHAC, 1997). The interaction between experts which is required in some levels of the SSHAC approach is regarded as the major difference between SSHAC and conventional expert elicitation which

[19] See Table 10 for definition of terms.

involve independent experts as well but do not support their interaction. Another important difference between the SSHAC approach and expert elicitation is that SSHAC-based studies integrate rather than aggregate the assessments of individual experts by stimulating discussions between the experts and the revision of models (USNRC, 2012).

SSHAC (1997) defines four levels of PSHA studies referred to as Level 1 to Level 4. Among these Level 4 studies are regarded to capture and quantify the uncertainties in SHA to the best extent. The levels differ by their complexity and required resources. Both increase from Level 1 to Level 4. A short summary of the main elements of each of these levels and the most important differences between them is provided in Table 11. Detailed descriptions of the four approaches are provided by SSHAC (1997), Hanks et al. (2009), and USNRC (2012).

Detailed guidelines for the implementation of SSHAC Level 3 and Level 4 seismic hazard studies are provided by USNRC (2012). Guidance includes definitions of the roles of involved experts, explanation of the SSHAC concept, structure and process, and implementation guidelines. Hanks et al. (2009) include reports on the experience gathered during past SSHAC Level 3 and 4 studies along with further references.

For existing European NPPs a full-scope SSHAC Level 4 approach has so far only been applied to the Swiss plants in the framework of the PEGASOS Project and the Pegasos Refinement Project (PRP). The hazard assessment process is described in detail in NAGRA (2004). The procedure turned out to be extremely complex and time consuming. Although already started at the end of the 1990s the process of determining hazard levels for regulatory decision has only been finished in 2016. On the other hand there are successful examples of SSHAC Level 3 projects that could be finished in about three years (Brazil; South Africa; Bommer et al., 2015).

Roles of exerts in PSHA according to the SSHAC approach		
Peer Reviewers	*"Review both the soundness of the technical input and the final hazard results and, for SSHAC Levels 3 and 4, the procedural aspects of the expert interaction. Peer review at Levels 3 and 4 is formalized with Participatory Peer Review Panels (PPRP) that provides commentary throughout the course of the project."*	Hanks et al., 2009, p. 9
Technical Facilitator / Integrator (TFI)	*"A SSHAC Level 4 individual or team who compiles the community distributions constructed by each evaluator team into a single community distribution representing the views of the informed technical community."*	SSHAC, 1997, p. 29
Technical Integrator (TI)	*"A SSHAC Level 3 individual or team responsible for capturing the views of the informed technical community in the form of a community distribution."*	SSHAC, 1997, p. 30
Hazard Analyst	*"PSHA cognoscenti who actually perform the PSHA calculations."*	Hanks et al., 2009, p. 9
Normative Expert	*"An expert with sound theoretical and conceptual understanding of probability, logic trees, and model building in probabilistic frameworks."*	Hanks et al., 2009, p. 49
Proponent Expert	*"A technical expert who advocates a particular hypothesis or technical position and has developed and evaluated a particular hypothesis to explain the data."*	SSHAC, 1997, p. 24
Evaluator Expert:	*"A technical expert who provides his/her representation of the community distribution by examining the available data and assessing the technical basis for proponent models; the expert then is expected to represent the community distribution of the ITC in light of the other evaluators distributions."*	Hanks et al., 2009, p. 49
Resource Expert	*"A technical expert who has either site-specific knowledge or expertise with a particular methodology or procedure useful to the evaluator experts in developing the community distribution."*	Hanks et al., 2009, p. 50
Technical Community (TC)	*"The cadre of scientists and engineers known for their experience with and knowledge of SSC [seismic source characterization] or GMC [ground motion characterization] issues."*	Hanks et al., 2009, p. 8
Informed Technical Community (ITC)	A member of the ITC (who is also part of the TC) is described as *"an expert who has full access to the complete database developed for a project and has fully participated in the interactive SSHAC process. … Experts who participate in the PSHA study must endeavour to represent "the larger informed technical community" by assuming the hypothetical case where the others in the larger technical community become "informed" through participation in the same process."*	U.S.NRC, 2012, p. 10

Table 10. Definitions of the roles of experts in a PSHA project according to SSHAC Guidelines.

	SSHAC Level 1
Structure	TI is a single hazard analyst TI reviews literature, datasets, and models; TI quantifies uncertainties and expresses his view on all models and parameters
Peer review	Peer review (late stage) to determine if opinions of ITC are captured and documentation is complete
Application	PSHA for conventional facilities, sensitivity studies to evaluate new information
	SSHAC Level 2
Structure	In addition to Level 1: TI is a evaluator team including the hazard analyst TI contacts members of ITC regarding databases and directly communicates with proponents of alternative viewpoints Topical meetings to resolve questions of key topics
Peer review	Participatory or late stage
Application	PSHA for critical infrastructure
	SSHAC Level 3
Structure	In addition to Level 2: TI team, proponents and resource experts are brought together in workshops to discuss different methods, models and databases TI team questions proponents and resource experts to understand applicability of alternative models Revision to the models in the light of feedback
Peer review	Participatory peer review of technical decisions made by TI team
Documentation	Includes discussion of all models, parameters, and their technical basis; final hazard with sensitivity analyses to understand important contributors to hazard and uncertainties
Application	PSHA for nuclear installations, National Seismic Hazard Map Programme for U.S.
	SSHAC Level 4
Structure	In addition to Level 3: TFI team added; Each TFI is responsible for a single technical topic (e.g., source zone characterization, ground motion characterization, site characterization) Multiple evaluators or evaluator teams perform work of the TI team as defined for Level 3 Evaluators / evaluator teams are limited to a single technical topic (e.g., source zone characterization, ground motion characterization, site characterization)
Peer review	Participatory, including both technical and process review
Documentation	Documentation includes all information required for Level 3 plus individual summaries by each evaluator expert to express his interpretations, technical bases, and estimates of uncertainty
Application	PSHA for nuclear installations (Switzerland: NAGRA, 2004; Yucca Mountain: CRWMS M&O, 1996; 1998)

Table 11. Summaries of the structure and content of SSHAC Level 1 to Level 4 PSHAs

4.8 ADVANCE OF SCIENCE AND TECHNOLOGY

The assessment of seismotectonic hazards currently benefits from dramatic progresses in science which is mainly driven by pure research. The focused interest of a large part of the Earth sciences community in active deformation processes has led to an explosion of the number of scientific articles dealing with seismic rupture processes, the rheology of seismogenic deformation, earthquake geology, and the youngest tectonic and geologic evolution of many European regions. This concerted research efforts led to:

- collection of a large amount of novel and precise data for the assessment of seismotectonic processes (e.g., data from dense and sensitive seismological networks; GPS geodesy; LIDAR digital elevation data);
- updated and novel methodologies to identify active faults including tectonic geomorphology and paleoseismology;
- identification of a still increasing number of active faults driven by basic research and scientific curiosity;
- a better understanding of seismotectonic processes of large parts of Europe.

These new findings can lead to better characterizations of source zones (both fault and area sources) and more accurate assessments of long-term seismicity rates thereby increasing the reliability of the input data for SHA. Most of these new findings are currently not included in the routines of seismic hazard assessment, although the SHARE project made an attempt to include active faults as sources its European seismic hazard map[20] and the GEM project[21] is continuing these efforts.

Significant progress is currently being made in the integration of fault models in PSHA. Current efforts include the implementation of codes into computer programs and software such as OpenQuake[22] which allow to implement 3D fault data both in terms of their geometry and earthquake behavior (Siva et al., 2013; Weatherill et al., 2016). To date seismic hazard calculations can take into account complexities such as geometrical irregularity of faults in the prediction of ground motion.

The outlined continuous progress of science and technology and its significance for nuclear safety has been underlined by ENSREG (2012 a,b) who highlighted the importance to reevaluate natural hazards at least every 10 years (see also chapter 1.1, page 17). Periodic hazard reviews are consequently also addressed by the WENRA Safety Reference Levels (WENRA, 2014a, Issue P, Periodic Safety Reviews) and by WENRA (2013).

For seismic hazards WENRA (2016) further suggests the following: *"The seismic hazard assessment should be reviewed thoroughly and periodically. The reviewers should consider conducting independent hazard assessments involving different groups of experts and considering all relevant interpretations. … New evidence or concerns may arise, e.g. related to seismic sources, newly discovered active or capable faults, new data on ground motion attenuation, or local site effects."*

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[20] http://diss.rm.ingv.it/share-edsf/index.html; http://www.efehr.org:8080/jetspeed/portal/HazardMaps.psml

[21] https://www.globalquakemodel.org/openquake/about/

[22] https://www.globalquakemodel.org/openquake/about/

5 HAZARD COMBINATIONS

According to ASAMPSA_E Report D21.1 the following hazard combinations are distinguished:

1. ***Correlated hazards***. These are linked by a cause-effect relation, where an incident of hazard A triggers or may trigger hazard B (NIER, 2013; “common cause event”, Kuramoto et al., 2014). Hazards may be causally connected in two ways: (a) hazard A may cause hazard B (indicating that A is not a prerequisite to B) or (b) hazard A is a prerequisite for hazard B (Figure 24). Correlations of seismic and other hazards include both types. An example for (a) is vibratory ground motion / liquefaction (seismic shaking is a pre-requisite of liquefaction); an example for (b) is seismically triggered mass movements (landsliding may be triggered by vibratory ground shaking, but may also occur as an independent event).
2. ***Associated hazards***. These refer to events which are probable to occur at the same time due to a common root cause (“contemporary relation”, NIER, 2013). The common root cause (e.g., a meteorological situation) may not necessarily be regarded as a hazard by itself.
   ASAMPSA_E’s Report D21.2 (Decker & Brinkman, 2014) did not identify hazards which are associated to seismotectonic hazards via a common root cause.
3. ***Temporal coincidence***. Such hazard combinations refer to not causally connected independent incidents associated with different hazards (see chapter 5.6, page 115).

5.1 CORRELATED HAZARDS

Seismic hazards are correlated with a large number of natural and man-made hazards (Figure 23). This is due to the fact that vibratory ground motion during an earthquake is not restricted to the site but affects a wide area around the epicenter of the earthquake. Seismic ground shaking consequently impacts on all man-made structures and the entire natural environment in the vicinity of an NPP.

Fault capability, liquefaction, dynamic compaction, and ground displacement potentially have a similar wide-spread impact, but correlate with a smaller number of hazards than vibratory ground motion. A comprehensive list of hazards which are correlated with seismic hazards is provided in the ASAMPSA_E Report D21.2 and shown in Figure 24.

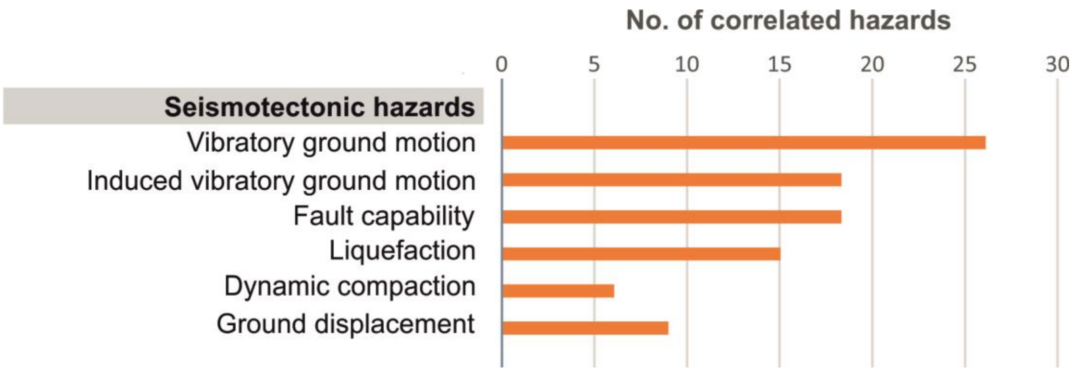

Figure 23. Number of hazards correlated with seismotectonic hazards
[Seismotectonic_hazard_correlation_statistics.JPG]

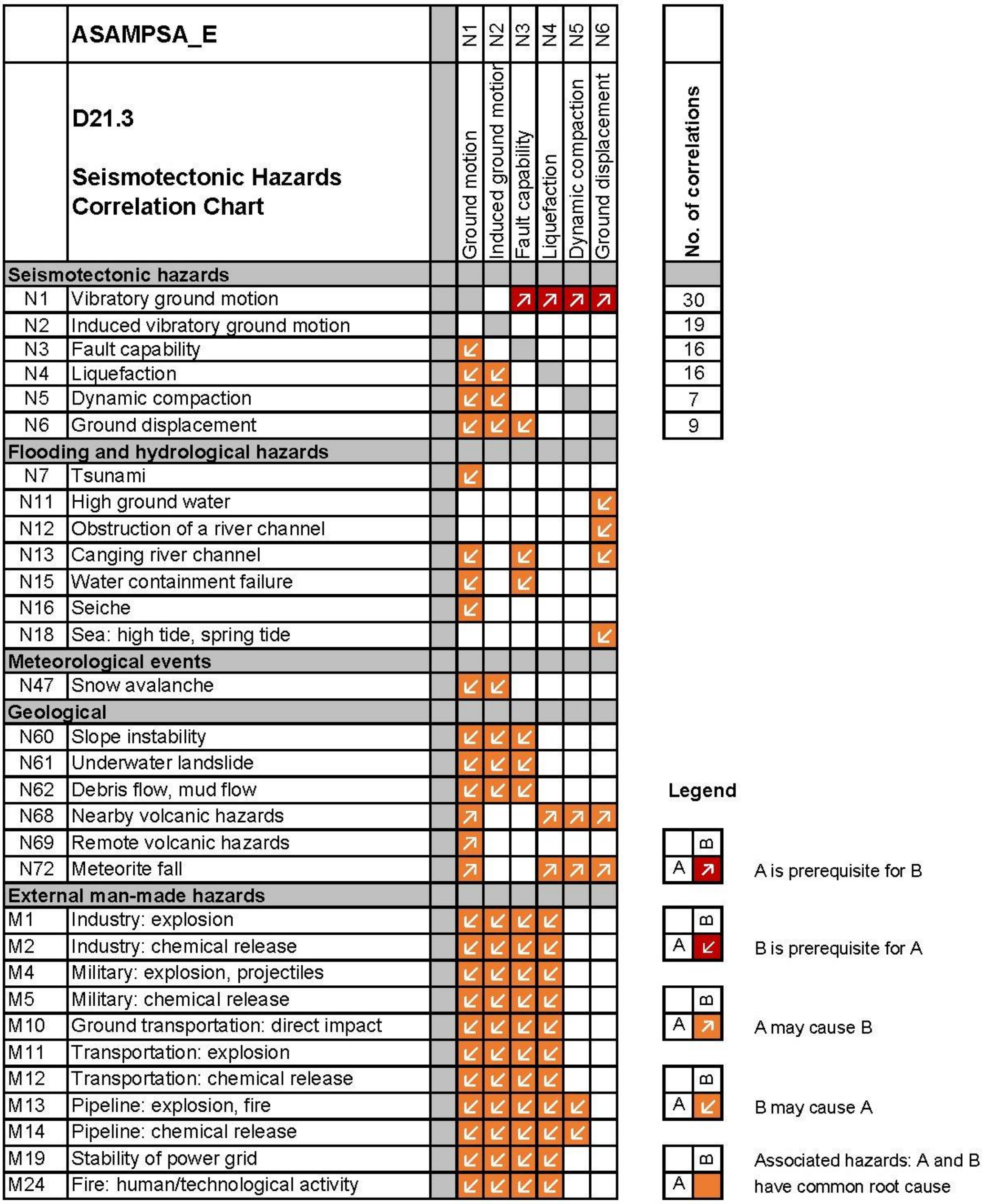

Figure 24. List of hazards correlated with seismotectonic hazards. Only direct consequences of individual hazards are listed. Causal chains are not considered. Combinations of independent phenomena with low severity which cause potential hazards by their contemporaneous occurrence are not identified. ***[Seismic_hazard_correlation_list_2015_07_08.JPG]***

5.2 ASSOCIATED HAZARDS

Associated hazards refer to events which are probable to occur at the same time due to a common root cause ("contemporary relation", NIER, 2013).

Seismic hazards have no common root causes with other external hazards such as external flooding extreme weather conditions, or man-made hazards. D21.2 therefore did not identify hazards which are associated to seismotectonic hazards via a common root cause.

5.3 SCREENING OF CORRELATED HAZARDS

The screening process of correlated hazards should start from the list of hazards and possible hazard correlations shown in Figure 24. In accordance with WENRA (2014a) hazards *"can be screened out on the basis of being incapable of posing a physical threat or being extremely unlikely with a high degree of confidence. Care shall be taken not to exclude hazards which in combination with other hazards have the potential to pose a threat to the facility*. (WENRA, 2014a, Safety Reference Level T3.1)*"*

Screening out of correlated hazards can therefore be based on demonstrating that:

- incidents of the type of hazard are physically impossible at the site (e.g., occurrence of liquefaction on a rock site; the occurrence of a tsunami in the continental interior),
- the impacts of all possible events caused by the incident are incapable of posing a physical threat to the safety of the plant. In this case the screening process requires that (1) a *"maximum possible severity"* of the incident can be defined and (2) a demonstration that an event of that severity does not pose a physical threat to the plant,
- incidents of the type of hazard with severities that pose a physical threat to the safety of the plant are *"extremely unlikely with a high degree of confidence"* (WENRA, 2014a); unfortunately a common understanding does currently neither exist for a probabilistic value for extreme unlikeliness, nor for the degree of statistical confidence required (e.g. use of higher percentiles of the hazard curve rather than median or mean).

Due to the impact of earthquakes and correlated hazards on both, the site and the region around the site the screening processes has to include assessments of the actual NPP site and all sites from which correlated hazards may arise. Examples of the latter include water dams (when dam failure [N15] may pose a threat to the NPP), industrial sites in the site vicinity (industry explosion [M1], chemical release [M2]), transportation routes etc. It should be noted that correlated hazards, which are not applicable to the actual NPP site, nevertheless may pose threats to nearby facilities (e.g., liquefaction of soil may damage an industrial plant while the NPP is funded on non-liquefiable ground; seismically triggered slope instability [N60] may be a threat to water containment structures although the NPP site is located in a topographically flat area).

Screening must take into account that the robustness of structures and utilities that pose a potential threat to the NPP (e.g., dams, industrial facilities) may be significantly lower than the robustness of the NPP itself. Threats by incidents caused by the failure of such structures and utilities may consequently arise from seismotectonic events with severities, which would not pose a threat to the NPP itself.

A screening process for correlated hazards may be structured in the following way:

1. Screening of correlated hazards based on physical impossibility starting from analyzing the location of the NPP site:
    - Site location at seaside, lake, or river. One or several of the following hazards may as an example be screened out : Tsunami [N7], Obstruction of river channel [N12], Changing river channel [N13], Seiche [N16], Underwater landslide [N61]
    - Topography : Snow avalanche [N47], Slope instability [N60], Debris flow, mudflow [N62]
    - Distance to volcanic structures : Nearby and remote volcanic hazards [N68, N69]
2. The screening process should further identify the absence / presence of facilities which, upon their failure due to a seismotectonic event, pose potential threats to the NPP :
    - Water containments [N15]
    - Industrial facilities [M1, M2]
    - Military facilities [M3, M4]
    - Transportation routes and transportation facilities [M10 to M12]
    - Pipelines [M13, M14]
3. For facilities not screened out in (2) vulnerability assessments are required to estimate the hazard severity which leads to incidents or failures which pose threats to the NPP site. Assessments must take note of the fact that events with ground motion values well below the design basis of the NPP may cause severe damage to other structures due to the fact that these are not designed for equally high safety standards and have higher vulnerabilities than the NPP.
4. For the sites of facilities posing potential threats to the NPP step (1) should be repeated to identify correlated hazards relevant for these sites.
5. Correlation with meteorite fall (vibratory ground motion caused by meteorite impact) can possibly be screened out by extreme unlikeliness using statistics quantifying the flux of meteorites to the Earth and providing empirical relations between meteorite size and fall frequency. The latter is defined by a power law quantifying the number of meteorites with a certain diameter colliding with the Earth per year (Brown et al., 2002).
6. Stability of external power grid cannot be screened out even for low levels of seismic ground shaking. The ENSREG Stress Tests identified that the external power grids may be highly vulnerable and may not sustain even small earthquakes with intensities $I_{MSK} > 6$ and $PGA_{hor} > 0.05$ g (SÚJB, 2011, p.76).

For further detailed guidance for screening initiating events and hazards for consideration in extended PSA we refer to the Wielenberg and al. (2017; ASAMPSA_E Report D30.7 vol2).

5.4 METHODS FOR THE ASSESSMENT OF HAZARD COMBINATIONS

The following chapter includes guidance to the assessment of selected hazards which are causally dependent on vibratory ground motion. It should be noted that each of the correlations shown in the hazard correlation chart (Figure 24) may require a specific assessment method. A comprehensive discussion of methods for all hazard correlations, however, is beyond the scope of the current document.

Vibratory ground motion [N1] – Fault capability [N3]:

Ground displacement hazard should be analyzed by PFDHA (Probabilistic Fault Displacement Hazard Analysis) as described in the chapters 4.3.3 and 4.4.3.

Vibratory ground motion [N1] – Liquefaction [N4]:

Vibratory ground motion [N1] – dynamic compaction [5]:

Liquefaction of soil and unconsolidated fine-grained sediments occurs by the expulsion of pore water due to seismic shaking. Liquefaction phenomena typically occur at local intensities of $I_{ESI\text{-}2007}$ = VIII or higher (Michetti et al., 2007). Assessments of the probability of liquefaction are commonly based on the following criteria:

- ***Seismic criteria:*** liquefaction only occurs upon the exceedance of a threshold magnitude within a given epicentral distance (Figure 25). The exceedance of a local level of ground shaking and minimum number of loading cycles (earthquake duration) is a prerequisite for the phenomenon. The probability of ground motion exceeding the threshold (ground acceleration, earthquake duration) derives from seismic hazard assessment.
- ***Geological criteria:*** the susceptibility to liquefaction decreases significantly with the age of sediments (susceptibility of Holocene sediments > Pleistocene > Pre-Pleistocene) and depends on the sediment facies (fluvial, alluvial, lacustrine and aeolian sediments may be highly susceptible; Youd & Perkins, 1978). Other important parameters include grain size (sand is most susceptible, silt under certain conditions, gravely sand rarely susceptible to liquefaction), sorting and angularity of grains.
- ***State criteria:*** The initial "state" of sediment is defined by its density and effective stress at the time it is subjected to loading. At a given effective stress level, looser sediments are more susceptible to liquefaction than denser ones. For a given density, soils at high effective stresses are generally more susceptible to liquefaction than soils at low effective stresses.

Input data required for the assessment of liquefaction hazards are listed in chapter 3.1.3 of this report. Recent examples of soil liquefaction analyses for nuclear power plants include the studies for Paks NPP (Bán et al., 2015; Tóth et al., 2015).

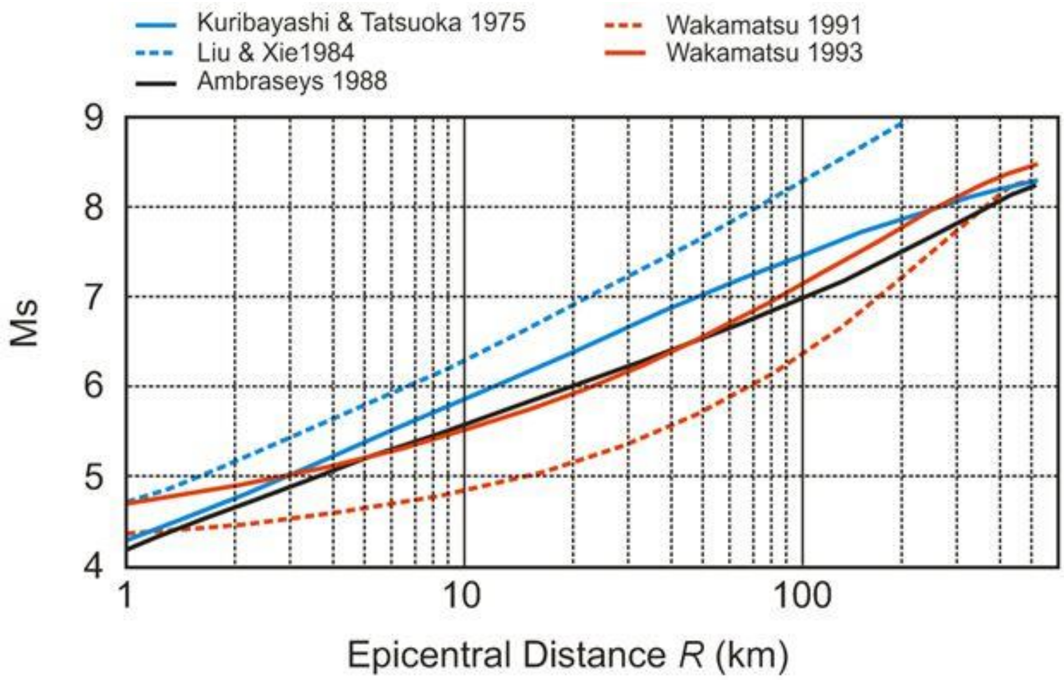

Figure 25. Graph showing surface wave magnitude (Ms) – distance relations for liquefaction phenomena based on empirical data. ***[Liquefaction_seismic_criteria.JPG]***

Vibratory ground motion [N1] – Ground displacement [N6]:

The hazard is only relevant for sites which are located in the vicinity of faults which may accumulate significant vertical displacement during a seismic event, e.g., in the hangingwall of thrust faults or in the hangingwall / footwall of large normal faults, or releasing/restraining bends of strike-slip faults. According to the ESI Intensity Scale (Michetti et al., 2007) permanent vertical ground displacements of < 0.1 m may be induced by earthquakes with local intensity $I_{ESI\text{-}2007}$ = VII. Permanent ground dislocation with amplitudes of about 1 m and more are possible for local intensities $I_{ESI\text{-}2007}$ > IX.

The occurrence probabilities of large displacements at normal or thrust faults may be assessed by methods comparable to PFDHA. Chapter 3.1.4 provides a list of data required for the assessment of ground displacement hazards.

Vibratory ground motion [N1] – Tsunami [N7]:

The perception of the Fukushima Daiichi accident may suggest that vibratory ground motion – tsunami as a typical hazard combination. Although tsunami is a relevant hazard for European costal sites, the combination of tsunami flooding with strong vibratory ground motion is not regarded typical for European coasts. Previous and potential future sources of tsunamis affecting the European Atlantic coast include submarine landslides (e.g., the Storega Landslide; Bondevik et al., 2005; Smith et al., 2004; Weninger et al., 2008), possible volcanic collapse (Canary Islands; Ward & Day, 2001), and offshore earthquakes in the Gibraltar seismic arc (1755 Lisbon earthquake; the earthquake offshore Portugal caused a tsunami with catastrophic effects; e.g., Gutscher et al., 2006). Tsunamigenic seismic sources in the Atlantic, however, are remote from current nuclear sites. The probability for a costal

site to be affected by vibratory ground motion and tsunami is therefore equal to the probability of a tsunamigenic earthquake, e.g., in the Gibraltar seismic arc.
For the Tsunami hazard assessment we refer to the ASAMPSA_E Guidance for External Flooding.

Vibratory ground motion [1] – Water containment failure [15]:
Assessment of the hazard by earthquake induced water containment failure requires a site-specific seismic hazard assessment for the dam sites under consideration. SHA may rely on the same dataset and methodology as the SHA performed for the nuclear installation, but needs to account for the different location and site conditions of the water containment structures. The assessment of the probability of hazards resulting from containment failure further needs to take account of the vulnerability of the structures. Examples from the Swiss NPP Mühleberg and the upstream Wohlensee dam show that fragility analysis is challenging. There, the seismic fragility of the Wohlensee was established by a nonlinear analysis revealing HCLPF values for its seismic resistance (Ghanaat et al., 2011).
Apart from direct coseismic effects on water dams vibratory ground motion may also lead to increased post-seismic vulnerability of water control structures and dykes which persist for long time periods. Such weakening of protection systems may be relevant for the assessment of flooding hazards.

Vibratory ground motion [N1] – Slope instability [N60]:
Slope instability caused by seismic ground shaking is a common and frequent effect of earthquakes on the natural environment for earthquakes with local environmental intensity $I_{ESI-2007}$ = VIII or higher (Michetti et al., 2007). Assessments of the probability of slope instability should account for the following criteria:

- ***Magnitude – distance criteria:*** Empirical data show positive correlations between the earthquake magnitude and the distance from the epicenter or the ruptured fault where slope instabilities may occur (Figure 26, Figure 27). The probabilities of ground motion exceeding the threshold for triggering landslides therefore can be derived from SHA. Assessment may reveal the probability of earthquakes which cause ground motion at the site with $I_{ESI-2007} \geq$ VIII, or the probability of earthquakes with magnitudes exceeding the threshold, which occur within a certain distance from the site. When magnitude-distance criteria are used for hazard assessment care must be taken to apply relations which derived from datasets of climatically similar regions. Several published relations distinguish between “wet” and “dry” countries due to the fact that water saturated soils and rocks are more susceptible to landsliding (e.g., Japanese Geotechnical Society, 1999).
- ***Susceptibility criteria:*** The Japanese Geotechnical Society (1999) proposed a number of factors to assess the susceptibility of slopes to earthquake-induced slope instability. Factors include morphological and geological criteria such as the elevation difference and length of slopes, slope morphology expressed by the shape of contour lines (convex, concave, curved or linear), length of artificial slopes, rock type and fracture patterns. Factors are used for a categorization of the vulnerability of slopes with respect to slope instability.

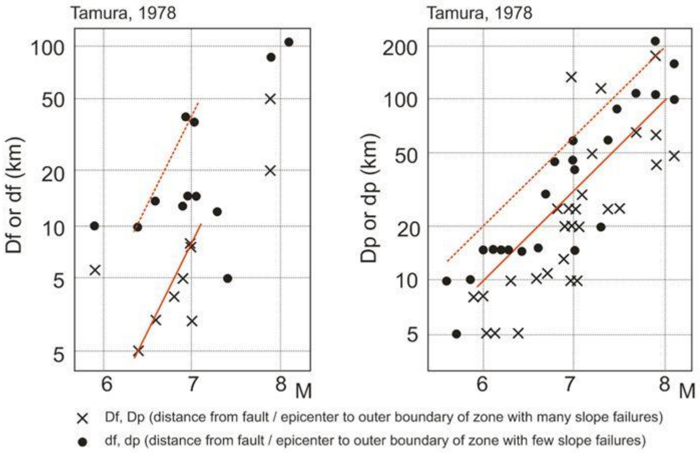

Figure 26. Empirical magnitude-distance criteria for earthquake-induced slope instability for Japan (redrawn from Tamura, 1978). Graphs show the distance from fault or epicenter to the outer boundaries of the zone where many (red line) or few (broken line) slope failures occur *[Slope_instability_Japan.JPG]*

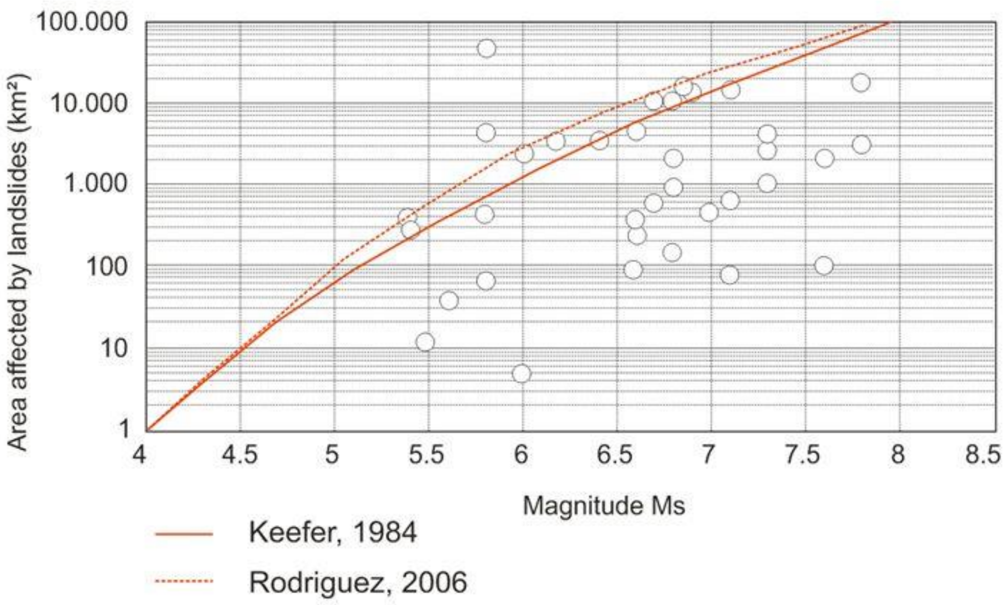

Figure 27. Empirical correlations between the area affected by landslides and magnitude (redrawn from Keefer, 1984; Rodriguez, 2006). *[Slope_instability_Keefer_Rodriguez.JPG]*

Vibratory ground motion [1] – Obstruction of river channel [12]:

Vibratory ground motion [1] – Changing river channel [13]:

Obstructions of river channels may result from the damming of a river or valley by earthquake-induced slope failure or debris flows. The listed phenomena may similarly force river channels to change their course. The assessment of the probabilities of events leading to such changes may use approaches as outlined above (Vibratory ground motion [N1] – Slope instability [N60]) and below (Vibratory ground motion [N1] – Debris flow – mud flow [N62]).

Vibratory ground motion [1] – Debris flow – mud flow [N62]

Earthquake triggered debris flows and mud flows may result from the effect of vibratory ground motion on water-saturated soil. “Wet” soil conditions are a prerequisite for the phenomenon. The probability of occurrence can be estimated as the product of the probability of an earthquake causing ground motion in excess of a threshold value at which debris flows/mud flows can be triggered, and the probability that “wet” soil conditions exist during the time of the earthquake. The temporal and spatial variation debris-flow susceptibility can be estimated from rainfall infiltration and slope stability based on high-resolution topographic data (DEM), data on initial groundwater conditions, physical properties of near-surface earth materials, and depth to bedrock (e.g., Baum et al., 2011).
Although debris flow hazard assessment is well established, assessments of the probabilities of earthquake-triggered debris flows were so far only rarely performed (e.g., Junnan et al., 2015). Debris flow hazard assessments account for the earthquake magnitude, topography (slope), lithology, fault density, land use, and total antecedent rainfall (or rainfall intensity) in the water shed under consideration.
Lesions learned from the 2008 Wenchuan Mw 7.9 earthquake and earthquakes in Taiwan indicate that strong earthquakes do not only trigger coseismic landslides but also lead to increased post-seismic slope instability which persists for a long period of time. The effect is due to the abundance of loose debris derived from landslide numerous small landslides and the formation of co-seismic extension cracks on hill slopes reducing both soil stability and increasing infiltration. In Wenchuan, debris flows further led to the formation debris-dams, dammed lakes, and flooding of the area upstream of the dams. The Wenchuan earthquake may consequently be considered as an event leading to cascading natural disaster chain (Junnan, 2015).

Vibratory ground motion [1] – Man-made hazards [M]

Assessments of combinations of vibratory ground motion with man-made hazards require data on the seismic vulnerabilities of man-made structures outside the site and the identification of accident sequences in off-site facilities which may pose threats to the NPP. As outlined in chapter 5.3 it must be taken into account that the robustness of structures and utilities that pose potential threats to the NPP may be significantly lower than the robustness of the NPP itself. Although higher safety requirements usually exist for non-nuclear high-risk facilities such as water dams or chemical plants, other facilities may only be engineered to fulfill common building codes (i.e., these facilities will only be engineered to withstand ground shaking levels with non-exceedance probabilities of 95% in 50 years; EUROCODE 8). Due to the outlined engineering differences between common structures and NPPs two earthquake scenarios may be distinguished:

- ***man-made hazards induced by earthquake severities below the design basis of an NPP:*** vibratory ground motion at levels below the NPP design base are not expected to challenge the safety of the NPP and should therefore not lead to accident conditions; external man-made events triggered by such earthquakes may therefore be modeled as a single hazard rather than an additional challenge combined with the impact of seismic ground motion on the NPP;
- ***man-made hazards induced by earthquake severities equal to or higher than the design basis of the NPP:*** for such cases failure of the potentially hazardous structures may be reasonably postulated; it may therefore be necessary to consider the resulting adverse effects as coincident with earthquake damage to the NPP.

In both cases the effects of the earthquake-triggered man-made phenomena on the NPP may be conditional on parameters other than vibratory ground motion. Examples are the impact of chemical release or fire which may depend on wind direction, and the amount of emissions which may depend on the type and amount of chemicals available at the plant at the time of the earthquake.

5.5 EXAMPLES OF HAZARD COMBINATIONS

A non-comprehensive list of hazard combinations for seismotectonic hazards which is regarded most likely is shown in Table 12.

Typical and abundant combinations of seismotectonic hazards				
N1*	Vibratory ground motion	N4*	Liquefaction	(1)
N1	Vibratory ground motion	N5	Dynamic compaction	(2)
N1	Vibratory ground motion	N15	Water containment failure	(3)
N1	Vibratory ground motion	N60	Slope instability	(4)
N1	Vibratory ground motion	M1, M2	Industry accidents	(5)
N1	Vibratory ground motion	M19	Stability of power grid	(6)
N3	Fault capability	N15	Vibratory ground motion	
N3	Fault capability	N4	Liquefaction	
N3	Fault capability	N5	Dynamic compaction	

* Numbers refer to hazard list defined in ASAMPSA_E Report D21.2 (Decker & Brinkman, 2014)
(1) Sites on liquefyable soft soil
(2) Sites on soft soil
(3) Up- or donwstram dams, water protection systems, dykes
(4) Including effects of landslide on surrounding infrastructure, rivers etc.
(5) Lower level of seismic design of ordinary facilities as compared to NPPs to be considered
(6) LOOP; high vulnerability of power grid to be considered

Table 12. Non-comprehensive list of typical and abundant combinations of seismotectonic hazards to be considered in extended PSA

Observed and seriously investigated hazard combinations include the following:

- NPP Fukushima Dai-Ichi : combination of vibratory ground motion [N1] and slope instability [N60] where the latter effect leading to loss of offsite power [M19] due to the destruction of energy transmission lines;
- NPP Paks : liquefaction caused by vibratory ground motion which slightly exceeds the seismic design basis value was identified as a serious hazard challenging the stability of underground connections (piping, cables etc.; HAEA, 2014) and led to dedicated hazard assessment (Bán et al., 2ß15; Tóth et al., 2015);
- NPP Mühleberg : Fragility analyses showed that the seismic robustness of one of the safety trains for core cooling is limited by the seismic resistance of the Wohlensee dam wall upstream of the plant because the cooling water intake of the special emergency system is endangered in case of a seismically induced failure of the dam wall (ENSI, 2011).

5.6 ASSESSMENT OF COINCIDENT HAZARDS

Coincident hazards refer to the temporal concurrence of causally not connected independent events which are associated with different hazards. Guidance for the assessment of coincident hazards is provided by WENRA (2015):

"It is possible for more than one independent natural event to apply simultaneously to a site. Such combinations of events should be considered carefully where frequent natural phenomena are involved which pose similar demands to the plants. The analysis of the probability of such event combinations should consider the duration of the events." (WENRA, 2015). It is further stated that *"The simultaneous application of two independent low frequency hazards is considered as unreasonable."*

Based on this guidance two types of coincident hazards may be discerned:

- ***Frequent phenomena which pose similar demands to the plant:*** in this context vibratory ground motion and other seismotectonic hazards are not regarded as "frequent[23]"; the only "frequent" natural phenomenon posing loads similar to those of vibratory ground motion is wind (High wind, storm [N40]); wind loads are similar to horizontal ground acceleration induced by vibratory ground motion; combined effects of both phenomena, however, only apply to buildings and SSCs outside of buildings; due to the short duration of earthquakes (seconds to minutes) and the limited duration of high winds the hazard combination will likely be screened out by its low probability;
- ***Event combinations leading to different demands to the plant:*** earthquakes are short; however, the consequences of vibratory ground shaking and other seismotectonic incidents on the plant and the SSCs relevant to safety may be long lasting; the occurrence of independent natural events during the accident management or repair time subsequent to an earthquake is therefore significantly higher than the probability of a temporal coincidence with the earthquake; assessment of the probability of hazard coincidences should consider the time required until full plant resilience is regained again after an earthquake; special care should be taken to consider earthquake damage to SSCs which protect against other hazards and which are not designed to withstand seismic loads; examples could be the damage or blocking of parts of the sewer system leading to a loss of protection against flash flooding [N8] or the unavailability of mobile equipment (e.g., for flood protection) due to damage of storage buildings;

  similar considerations may be appropriate for the assessment of other hazards which cause long-lasting consequences for the plants; examples are High wind, storm [N40] or icing [N34] leading to the damage of the electrical grid (LOOP); in such cases the event duration should be defined by the repair time instead of the event duration.

[23] Compared to, e.g., combinations of high tide, storm surge and wind-driven waves, whith increase flood hazards.

6 CONCLUSION AND RECOMMENDATIONS

This report summarizes the collective experience of the partners involved in developing guidance on seismic hazard assessment. In order to stimulate progress in the reliability of hazard assessments the following recommendations are highlighted:

Database and key input parameters for hazard assessment	
Seismotectonic model	The construction of a well-supported seismotectonic model is regarded as a key step in the seismic hazard assessment procedure. Decisions such as the selection of seismic sources, characterization of active faults, and assessment of seismicity rates depend on this model. **It is recommended to regard the seismotectonic model as a theory of the Pliocene to Quaternary tectonic evolution of the region under consideration. Seismotectonic models solely derived from seismological data are regarded as outdated. Instead, models should be based on all geoscience data available in the region of interest noting that research activities on active tectonics, earthquake geology, space geodesy, and seismology increased exponentially in the last decade.**
Earthquake data	Completeness assessments of typical European earthquake catalogues performed with the Stepp Test and the TCEF method show that records for earthquakes (including strong ones) are only complete for the last 300 - 500 years. This limitation will remain in spite of extended efforts of historical earthquake research. The data row is too short to establish reliable recurrence interval for the strongest earthquakes due to the rareness of these events. **It is recommended to mitigate the outlined shortcoming of earthquake catalogues by systematic paleoseismological investigations to constrain the magnitudes and recurrence intervals of strong prehistorical earthquakes.**
Active faults	Earthquakes occur on faults. Most parts of Europe are intra-plate areas with slow or very slow faults producing earthquakes at recurrence times of 10^3 to 10^5 years, which are significantly longer than the time covered by earthquake records. It is therefore very unlikely that all faults, which pose a potential threat, are recognized from analyzing earthquake records. **The epistemic uncertainties resulting from the inadequate time coverage of earthquake catalogues should be reduced by systematic fault mapping and the collection of data to locate and characterize active faults. A work flow of a graded approach for the identification and assessment of active / capable faults in the near-region and region of a site is introduced in the current report.**

Active fault catalogues	Comprehensive active fault catalogues are currently neither available at a European scale nor for many EU member states. The available catalogues do not share common quality standards. Comparison of the few available European datasets with active fault databases in the U.S. and Japan shows that the latter fulfill significantly higher quality standards with respect to completeness and reliability. **The development of active fault data is a long-term perspective. The required time and research efforts can hardly be reconciled with the schedules of a PSA or PSR. It is recommended to implement research activities on international or European level to establish a comprehensive uniform active fault database for regions around NPPs to be used for seismic hazard assessment in the framework of PSA and periodic safety reviews (PSR) as required by WENRA (2014a).**
Ground motion prediction equations	Ground motion prediction equations (GMPEs) are a very sensitive issue in seismic hazard assessment. Due to the sparsity of strong instrumental earthquakes in large parts of Europe virtually no ground motion records exist which can be used to derive empirical attenuation relations. These limitations may be overcome by the simulation of ground motion based on the modelling of fault rupture processes, seismic wave propagation, and site effects in the near future. Methods are currently developing.
Maximum magnitude M_{max}	Assessments of M_{max} are highly sensitive for ground motion hazard assessments. Recent research shows that it is not possible to derive reliable estimates of M_{max} from earthquake catalogues. **It is recommended to derive estimates of M_{max} from geological data such as fault dimensions and paleoseismological evidence.**

Methods commonly applied and key input parameters for hazard assessment	
PSHA **(Probabilistic Seismic Hazard Assessment)**	PSHA is the most common method to assess vibratory ground motion hazards in Europe. It is well established and provides all inputs for PSA (i.e., ground acceleration or spectral acceleration values for different annual probabilities and their uncertainties). Formalized procedures exist for the treatment of epistemic uncertainties (logic trees) and the use of expert judgement ("SSHAC levels"). For PSA some annual probabilities at 10^{-4} to 10^{-6} are needed (these values are consistent with LERF for internal events). Hazard estimates for such low exceedance probabilities are

	associated with large uncertainties, which is due to the fact that (a) the time coverage of earthquake records is short (few 10^2 years) and data need to be extrapolated over 2 to 4 orders of magnitude (10^4 to 10^6 years), and (b) complete and reliable data of active faults and paleoseismicity are only locally available and incomplete. **With respect to the reliability of the assessment the following is recommended:** • **assessments should not be based on single expert opinions (SSHAC Level 1); independence of experts (i.e., the ability of an expert to provide his/her own views and not those of their peers, sponsors, or agency) is a key issue;** • **PSHA should be subjected to rigorous participatory peer review by independent experts, including the period of data collection;** • **the preferred approach should correspond to SSHAC Level 3 (application of SSHAC Level 4 in Swiss project PEGASOS turned out to be unduly time consuming).** **The reliability of PSHA can only be increased by increasing the quality of input data (see recommendations above). SHA is therefore a long-term perspective requiring sufficient time for data collection.**
DSHA **(Probabilistic Seismic Hazard Assessment)**	DSHA typically determines the maximum credible vibratory ground motion at a site. It does not provide annual probabilities of occurrences of ground motion amplitudes and the related uncertainties. However, DSHA can provide an estimate of the largest amplitude of vibratory ground motion to be expected at a site as an upper cutoff value for PSA and the assessment of DEC.

Hazard combinations	
Screening of correlated hazards	Vibratory ground motion and fault capability are correlated with a large number of natural and man-made external hazards. The number of correlations can be significantly reduced by screening with screening-out criteria preferably based on demonstrating that incidents of certain types of hazards are physically impossible at the site.

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