COMPARATIVE ANALYSIS OF THE INTERNATIONAL REGULATIONS AND GUIDELINES RELATED TO THE SEISMIC HAZARD ASSESSMENT FOR NUCLEAR FACILITIES

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

COMPARATIVE ANALYSIS OF THE INTERNATIONAL REGULATIONS AND GUIDELINES RELATED TO THE SEISMIC HAZARD ASSESSMENT FOR NUCLEAR FACILITIES

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Turkey intends to build and operate twelve nuclear reactor units in the next ten years; therefore, the regulatory body of Turkey needs a systematic, comprehensive, and up-to-date seismic hazard assessment (SHA) guideline that is applicable for all candidate designs and compatible with the international legislative structures. To facilitate towards this goal, current SHA practice and related regulatory requirements of the leading countries, international organizations, and Turkey are evaluated and compared by focusing on the critical aspects of seismic source and ground motion characterization. Discussions are qualitatively supported by the good practice implemented in the previous nuclear power plant (NPP) projects and the lessons learned from the past experiences. Considerable differences in practical applications and regulatory requirements have been identified in the definition of spatial scales, capable fault terminology, estimation of magnitude recurrence parameters, considered minimum magnitude, assigned maximum magnitude, selection of ground motion models, and truncation of ground motion variability. Quantitative comparisons in terms of the hazard curves are provided to further underline the range and extend of the differences in international approaches for a reference NPP site. Analysis results revealed that the selection and level of truncation for the uncertainty of ground motion models and the possibility of existence for a relatively small capable fault in near region scale have a higher impact (up to 2-fold increase) on the design-basis ground motion, compared to the other parameters. Tangible recommendations are provided for Turkey's and other embarking countries' future SHA guidelines and applications based on the comparison results.

Keywords: Probabilistic Seismic Hazard Assessment, Seismic Source Characterization, Ground Motion Modelling, Nuclear Facilities

ÖZ

NÜKLEER TESİSLER İÇİN SİSMİK TEHLİKE ANALİZLERİ İLE İLGİLİ ULUSLARARASI DÜZENLEME VE KILAVUZLARIN KARŞILAŞTIRMALI ANALİZİ

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Türkiye, önümüzdeki on yıl içinde 12 ünite nükleer reaktör inşa etmeyi ve işletmeyi planlamaktadır, bu sebeple Nükleer Düzenleme Kurumu, tüm aday tasarımlar için uygulanabilir olan ve uluslararası düzenlemelere uygun; sistematik, kapsamlı ve güncel bir sismik tehlike değerlendirme kılavuzuna ihtiyaç duymaktadır. Bu amaca ulaşmak için, mevcut sismik tehlike analizi uygulamaları ile önde gelen ülkelerin, uluslararası kuruluşların ve Türkiye'nin ilgili düzenleyici gerekleri sismik kaynak ve yer hareketi karakterizasyonunun kritik taraflarına odaklanarak değerlendirilmekte ve karşılaştırılmaktadır. Karşılaştırmalar, önceki nükleer santral projelerinde uygulanan iyi pratikler ve geçmiş deneyimlerden alınan öğrenilmiş dersler yoluyla niteliksel olarak desteklenmektedir. Karşılaştırma sonucunda, mekânsal ölçeklerin ve yetkin fayların tanımlanmasında, deprem tekrarlanma parametrelerinin tahmininde, dikkate alınan en küçük deprem büyüklüğü değerinde, en büyük deprem büyüklüğünün belirlenmesinde, yer hareketi tahmin modellerinin seçilmesinde ve yer hareketi değişkenliğinin belirlenmesinde pratik uygulamalarda ve düzenleyici gereklerde dikkate değer farklılıklar tespit edilmiştir. Uluslararası yaklaşımlardaki farklılıkları daha da vurgulamak amacıyla, referans NGS sahası için tehlike eğrileri üzerinden sayısal karşılaştırmalar yapılarak sunulmuştur. Analiz sonuçları, yer hareketi modellerinin ve bunlara ilişkin belirsizlik seviyesinin seçiminin ve yakın bölge ölçeğinde görece küçük yetkin bir fayın bulunması olasılığının tasarıma esas yer hareketi üzerinde diğer parametrelere kıyasla daha büyük bir etkiye (2 kata kadar artış) sahip olduğunu ortaya koymaktadır. Karşılaştırma sonuçları göz önünde bulundurularak, Türkiye'ye ve diğer nükleer alana girmekte olan ülkelere gelecekteki sismik tehlike kılavuzları ve uygulamaları için somut tavsiyeler sunulmaktadır.

Anahtar Kelimeler: Olasılıksal Sismik Tehlike Analizi, Sismik Kaynak Karakterizasyonu, Yer Hareketi Modellenmesi, Nükleer Tesisler

To my son Çınar Ada GÜNER…

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LIST OF ABBREVIATIONS

ABBREVIATIONS

AD	Anno Domini (in the year of the Lord)
AES	One of the design types of the VVER-1200 NPP
AESJ	Standard for Seismic Probabilistic Risk Assessment
AFE	Annual Frequencies of Exceedance
ANPP	Akkuyu Nuclear Power Plant
ASK	Abrahamson Silva Kamai (2014) Ground-Motion Model
ANS	American National Standards
ANSI	American National Standards Institution
APE	Annual Probability of Exceedance
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ATMEA-1	Pressurized Water Reactor (PWR) designed by AREVA NP (AREVA) and Mitsubishi Heavy Industries, Ltd (MHI)
BOO	Build-Own-Operate
BSSA	Bulletin of Seismological Society of America
C14	Carbon14
CAV	Cumulative Absolute Velocity
CB14	Campell and Bozorgnia (2014) Ground-Motion Model
CBK	Presidential Decree (Cumhurbaşkanlığı Kararnamesi)
CEUS	Central and Eastern United States

CFR	Code of Federal Regulation (in USA)
CY	Chiou and Youngs (2008) Ground-Motion Model
C&GS	Name of the Station#117 recording from 18 May 1940 El Centro
DBE	Design Basis Earthquake
DCPP	Diablo Canyon Nuclear Power Plant
D	Distance
DE	Design Earthquake
D_{hyp}	Hypocentral Depth
DOE	U.S. Department of Energy
DRS	Design Response Spectra
DSHA	Deterministic Seismic Hazard Analysis
DSIR	Detailed Site Investigations Report
ECC	Name of the Background Zone of Nuclear Site in South Africa
EERI	Earthquake Engineering Research Institute
EMME	Earthquake Model of the Middle East
EMRA	Energy Marketing Regulatory Authority
EMS	European Macroseismic Scale (EMS-98)
ENVY	Assystem Envy Enerji ve Çevre Yatırımları Anonim Şirketi
ENSI	Regulatory Authority of Switzerland
EPRI	Electric Power Research Institute
ERT	Electrical Resistivity Tomography
EQ	Earthquake
EQRISK	A Computer Program for Finding Uniform Risk Spectra of Strong Earthquake Ground Motion

EQs	Earthquakes
EUAŞ	Elektrik Üretim Anonim Şirketi
EUR	European Union Requirements
ε	Epsilon
ε_{max}	Epsilon max
g	Gravitational Acceleration
GDC	General Design Criteria
GEJE	Great East Japan Earthquake
GM	Ground Motion
GMC	Ground Motion Characterization
GMPE	Ground Motion Prediction Equation
GMPEs	Ground Motion Prediction Equations (ground motion attenuation relationships)
GMRS	Ground Motion Response Spectrum
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GR	Gutenberg-Richter
GSDP	Guide on Specific Design Principles
GSZ	General Seismic Zoning
GSZR	General Seismic Zoning Refinement
HS-RNS	High Seismic Reference Nuclear Site (fictive nuclear site)
HSK	The Swiss Nuclear Safety Inspectorate - predecessor to ENSI
Hz	Hertz
IAEA	International Atomic Energy Agency

IGA	Inter-Governmental Agreement
I_{min}	Minimum Intensity
INSAG	The International Nuclear Safety Group
IRSN	Regulatory Authority of France
IRSS	Integrated Regulatory Review Service
IPE RAS	Institute Physics of the Earth, Russian Academy of Science
ISG	Interim Staff Guidance
ITU	Istanbul Technical University
JMA	Japan Meteorological Agency
JSC	Joint Stock Company
KHK	Degree Law (Kanun Hükmünde Kararname)
km	Kilometer
km^2	Square Kilometer
KOERI	Kandilli Observatory and Earthquake Research Institute
KTA	The Nuclear Safety Standards Commission of Germany
ky	Thousand Year
LLNL	Lawrence Livermore
LSM	Least Square Methodology
LS-RNS	Low Seismic Reference Nuclear Site (fictive nuclear site)
MCE	Maximum Credible Earthquake
MDE	Maximum Design Earthquake
M-D-ε	Magnitude-Distance-Epsilon
MENR	Ministry of Energy and Natural Resources

METU	Middle East Technical University
MFD	Magnitude Frequency Distribution
MFDs	Magnitude Frequency Distributions
MHE	Maximum Hypothetical Earthquake
$M_{(w)}$	(Moment) Magnitude
M_c	Cut-off Magnitude
M_{max}	Maximum Moment Magnitude
$M_{max(cal)}$	Calculated Maximum Moment Magnitude
$M_{max(obs)}$	Observed Maximum Moment Magnitude
$M_{max,back}$	M_{max} Assigned to Background Zone
mi	Mile
M_{min}	Minimum Magnitude
$M_{min(obs)}$	Observed Minimum Magnitude
Mw	Megawatt
MWe	Megawatt Electric
MLM	Maximum Likelihood Methodology
MSK	Medvedev–Sponheuer–Karnik Scale
MTA	Minerals Research and Exploration General Directorate
My	Million Year
NAF	North Anatolian Fault
NBK	Newmark, Blume and Kapoor
NRC	Nuclear Regulatory Commission
NDK	Nuclear Regulatory Authority of Turkey

NEA	Nuclear Energy Agency
NED	National Earthquake Data
NGA	Next Generation Attenuation
NISA	Nuclear and Industrial Safety Agency
NP	Nuclear Power
NPP	Nuclear Power Plant
NPPs	Nuclear Power Plants
NPT	Non-Proliferation Treaty (The Treaty on the Non-Proliferation of Nuclear Weapons)
NRA	Nuclear Regulatory Authority of Japan
NRC	Nuclear Regulatory Commission (or U.S. NRC)
NSC	Nuclear Safety Commission
NS-G	Nuclear Safety Guide
NS-R	Nuclear Safety Requirement
NUREG	Technical Document Set of NRC
NUTED	Internal Technical Support Organization of Turkey
OBE	Operation Based Earthquake
OECD	Organization for Economic Co-operation and Development
ϕ	Total Sigma
ϕ_{SS}	Single-station Sigma
$\phi_{SS\text{-}GLOBAL\text{-}R50}$	Single-station Sigma (Global Data)
$\phi_{SS\text{-}CA}$	Single-station Sigma (California Data)
PDF	Probability Density Function
PEER	Pacific Earthquake Engineering Research Center

PEGASOS	(German acronym for "Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites", original; "Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-StandOrte in der Schweiz"
PFDHA	Probabilistic Fault Displacement Hazard Analysis
PGA	Peak Ground Acceleration
PGD	Peak Ground Displacement
PG&E	Pacific Gas and Electric Company
PGV	Peak Ground Velocity
PHA	Peak Horizontal Acceleration
PHD	Peak Horizontal Displacement
PHV	Peak Horizontal Velocity
PRA	Probabilistic Safety Analysis
PRP	PEGASOS Refinement Project
PSA	Probabilistic Safety Analysis
PSHA	Probabilistic Seismic Hazard Assessment
PSHAs	Probabilistic Seismic Hazard Assessments
PTDHA	Probabilistic Tectonic Deformation Hazard Analysis
PVA	Peak Vertical Acceleration
PVD	Peak Vertical Displacement
PVV	Peak Vertical Velocity
PVNGS	Palo Verde Nuclear Generating Station
PWR	Pressurized Water Reactor
R_{jb}	The Joyner-Boore Distance
R_{hyp}	Hypocentral Distances

R_{max}	Maximum Epicentral Distance
R_{rup}	Shortest Distance to The Fault Rupture Plane
RB	Regulatory Body
rev.	Revision
RG	Regulatory Guide
RGs	Regulatory Guides
RNPPS	Regulation on Nuclear Power Plant Sites
RTN	Rostekhnadzor (Regulatory Authority of Russian Federation)
SAF	San Andreas Fault
S1	OBE according to Regulation on Nuclear Power Plant Sites
S2	SSE according to Regulation on Nuclear Power Plant Sites
SDC	Seismic Design Category
SECY	NRC’s Commission Papers
SEI	Structural Engineering Institute
SEP	Systematic Evaluation Program
SF	Safety Fundamentals
SHA	Seismic Hazard Assessment
SHARE	Seismic Hazard Harmonization in Europe
SPR	Site Parameters Report
SSHAC	Senior Seismic Hazard Committee
SRP	Standard Review Plan (NUREG-0800)
SRS	Safety Report Series
SSC	Seismic Source Characterization

SSCs	Structures, Systems and Components (of Nuclear Facility)
SSE	Safe Shutdown Earthquake (Ground Motion)
SSG	Specific Safety Guide
SSR	Specific Safety Requirement
SSHAC	Senior Seismic Hazard Analysis Committee
SWUS	Southern Western United States
STUK	Radiation and Nuclear Safety Authority of Finland
TAEK	Turkish Atomic Energy Authority (former RB of Turkey)
TECDOCs	IAEA’s Technical Documents
TEIAŞ	Türkiye Elektrik İletim Anonim Şirketi
TETAŞ	Türkiye Elektrik Ticaret Anonim Şirketi
TEK	Türkiye Elektrik Kurumu
TI	Technical Integrator
TSOs	Technical Support Organizations
UAEA	Uluslararası Atom Enerjisi Ajansı (original IAEA)
UHRS	Uniform Hazard Response Spectrum
UHS	Uniform Hazard Spectrum
UBC	Uniform Building Code
UNAM	Universidad Nacional Autonoma de Mexico
U. S.	United States
USA	United States of America
USGS	United States Geological Survey
USNRC / U.S. NRC	United States Nuclear Regulatory Commission

VC	The Virgil C. Summer Nuclear Power Station in USA
VVER	The Water-Water Energetic Reactor
V_{s30}	Averaged Shear-Wave Velocity to 30 m Depth
Vsk	Vs-kappa adjustments
WUS	Western United States
VVER	Water-Water Energetic Reactor (Russian PWR Reactor Design)
YVLs	Regulatory Guide series of STUK (in Finland)
WUS	Western United States
WAACY	Named for authors Wooddell, Abrahamson, Acevedo-Cabrera, and Youngs (model is a recently introduced magnitude PDF that combines concepts of the characteristic earthquake and truncated exponential models)
Z_{TOR}	Depth to Top of Rupture

CHAPTER 1

INTRODUCTION

All nuclear facilities may have the potential of radiation hazard on the environment, public or workers; therefore, these structures shall satisfy conservative requirements for initiating events. Approximately 20% of the currently operating nuclear power plants (NPPs) are located in the regions with significant seismic activity around the world (World Nuclear Association, 2014); hence, the seismic performance requirements of these facilities are expected to be quite high (ASCE/SEI 4-16, 2017). Still, major contributors of the core damage frequency, an important performance parameter for nuclear facilities, are directly related to the seismic hazards (Abrahamson et al., 2004) in some regions such as Turkey. Historical development of the concepts related to seismic hazard analysis for nuclear facilities is briefly summarized in Table 1.1, considering the generally accepted practice in the world from early conventional building codes era to the modern days.

1.1. Seismic Hazard Assessment in Nuclear Codes and Regulations: The Historical Perspective

Seismic hazard analysis has been a fundamental component of seismic codes and standards for the design of conventional structures and critical facilities (e.g. dams, nuclear power plants) for many decades (Atkinson, 2004). During the Long Beach Earthquake in 1933 (M_w=6.4), the Seal Beach Power Plant of the Los Angeles Gas and Electric Corporation was extensively damaged (Aircraft Corporation Lockheed and Holmes & Narver Inc., 1963). After this earthquake, in mid-1940s, the masonry construction practice was revived and this review process implied new provisions on the reinforced concrete design regulations, requiring that the lateral seismic forces should be considered in the earthquake-resistant design of buildings (Chen and Lui, 2005). Seismic design provisions in building codes were tended to be based on the qualitative evaluations of seismic hazard during the 1940s and 1950s. After 1950s, quantitative seismic hazard maps based on probabilistic analysis were slowly introduced.

Table 1.1. Seismic Hazard Eras in Nuclear Industry

Time Interval	Eras	Main characteristics of era
Before 1965	Conventional Building Codes Era	- Only the building code requirements were employed for NPPs, - Minimum lateral seismic forces were assumed, - Design loads were applied pseudo-statically, - Only the life safety of occupants of buildings was considered.
1965 – ~1997	Deterministic Era	- Mostly deterministic analysis was utilized, - Uncertainties were considered[1] up to a certain level, - Maximum Hypothetical Earthquake approach was introduced, - Dynamic response spectra analysis was used, - Probabilistic approaches were slowly evolved.
~ After 1997	Probabilistic Era	- Mostly probabilistic analysis is preferred, - Integration of the seismotectonic database and treatment of uncertainties in all input parameters, - Deterministically designed NPPs was re-assessed using probabilistic methodology, - Performance based design approach has been adopted.

Initial design of NPPs was based on using available national building codes of the late 1950's, which were enforcing the ground motions with 10^{-2}/yr probability of exceedance (100-year return period) on pseudo-static analysis. Completion of the Shippingport reactor in 1957 at Pennsylvania was the beginning of the commercial nuclear power era in the U.S. and the World (Stevenson, 2010). These first-generation

[1] Mean plus one standard deviation design basis response spectra based on a normal probability density function was established and used.

nuclear power facilities in the U.S., which were commissioned in late 1950s and at the beginning of the 1960s, were designed by using the U.S. Uniform Building Code (UBC-64) (Larsson, 2014), without any specific or additional requirements for NPPs (Stevenson, 2003). For example, the Connecticut Yankee NPP was originally designed for PGA=0.03g based on the requirements of UBC-64 and during the detailed re-design of this plant in 1966, the design value was re-evaluated and upgraded to PGA=0.17g (Stevenson, 2003). Five nuclear power plants were designed in U.S. during early to mid-1960's period and none of them had a seismic design requirement specific to nuclear power plants. This approach was continued in Finland, Sweden, Great Britain and East Blok Countries (in Europe) until the mid-1980's (Stevenson, 2003).

In 1960, Housner suggested that different seismic design categories should be considered for structure and components of the NPPs, inspired by the ordinary coal-steam power generators which were classified into two categories (the structure and the equipment) in seismic design. Three different categories were suggested by (G. W. Housner, 1960) for nuclear power reactors. Class I structures, systems and components (SSCs) were supposedly designed with the probability of failure being zero when they are subjected to the "strongest probable earthquake ground motion". The C&GS Station#117 recording from 18 May 1940 El Centro earthquake was considered as the "strongest probable earthquake ground motion" in highly seismic region of U.S. (Zone 3). Ground motion one-half as intense was usually taken as the "strongest probable ground motion" in Zone 2; and the strongest probable ground motion in Zone 1 is taken to be one-half as intense as that in Zone 2.

During the 1960s and 1970s, because of the rapid expansion of the nuclear power industry, seismic design requirements applicable to safety-related nuclear SSCs were swiftly progressed in U.S. (Larsson, 2014). The concept of free-field ground response spectra was developed in 1953 (Housner et al., 1953) but were applied to nuclear power plant facilities after the publication of TID-7024 Report (Aircraft Corporation Lockheed and Holmes & Narver Inc., 1963). Between the years of 1964 and 1967, dynamic structural analysis was usually accomplished by applying the peak of the Housner defined ground response spectra to SSCs. The ground response spectrum proposed by Housner was replaced by the original Newmark and modified Newmark, Blume and Kapoor (NBK) response spectrum after 1967. The NBK spectrum was actually the mean plus one standard deviation of the spectra of 14 different strong motion recordings from California (Stevenson, 2003), which was widely used between 1968 and 1971 (Larsson, 2014). After that, the United States Nuclear Regulatory Commission published the RG 1.60 response spectrum, which officially replaced the NBK spectrum in 1973 (U.S. NRC/RG 1.60, 1973).

In 1966, Maximum Hypothetical Earthquake (MHE) level was introduced, which was usually defined as the largest earthquake recorded in history that had happened within 300 km (200 miles) radius of the site. Definition of MHE level was considered as the first departure from National Building Code requirements to the seismic safety guidelines for NPPs. MHE nomenclature was soon redefined in U.S. as the Safe Shutdown Earthquake (SSE). Also, a smaller (usually taken as one half the SSE in the U.S.) ground motion level was defined as the Operating Basis Earthquake (OBE) (Stevenson, 2003). The procedure for defining the SSE level in RG 1.60 was deterministic (Braverman et al., 2007). Tectonic province approach for selecting the design earthquake that would nowadays be classified as deterministic seismic hazard analysis (DSHA) was so common until and through the 1960s (and till much later in some parts of the world) (Bommer and Abrahamson, 2006). The NPPs that were granted construction permits during the 1960s and 1970s were designed by deterministic approach based on site-specific investigations of local and regional seismology, geology, and geotechnical soil conditions to determine the maximum credible earthquake from a single source (Andrews and Folger, 2012).

In 1979, similar terminology was also adopted by the International Atomic Energy Agency (IAEA/50-SG-S1, 1991) as the S1 and S2 earthquakes, which represent the OBE and SSE levels, respectively. IAEA 50-SG-S1 suggested the deterministic approach for estimating S2 (postulated maximum earthquake), however, probabilistic methods and/or deterministic approach was suggested for S1 (please note that S1 was generally assumed one-half of the S2 according to (IAEA/50-SG-S1, 1979). IAEA/50-SG-S1 suggested that the provided requirements are only applicable for the areas of high and medium seismicity; for areas of low seismicity, the guide may not be entirely applicable. This guide also recommended the use of generic response spectra given in RG 1.60 in design (IAEA/50-SG-S1, 1979).

Probabilistic seismic hazard analysis (PSHA) were first considered in the 1960s and have become the basis for the seismic design of engineered facilities not only for common buildings but also for critical facilities such as nuclear power plants (McGuire, 2007). In 1978, the Systematic Evaluation Program (SEP) was started for the seismic re-evaluation of existing NPPs by the U.S. NRC. Results of this program pointed out that the NPPs in the U.S. that were designed before 1972 (roughly 69 NPPs) should be re-evaluated for the sufficiency of their seismic design (Stevenson, 2003). Large scaled research programs were implemented by Electric Power Research Institute (EPRI) and the U.S. NRC to re-evaluate the seismic hazard assessment and to apply the contemporary PSHA methodologies to get ground motion estimates of existing nuclear power plant sites in the Central and Eastern United States (CEUS) in late 1980s and early 1990s.

In 1991, a new version of IAEA Safety Guide was published (IAEA/50-SG-S1, 1991). In the revised guideline, the minimum of 0.1g requirement for the PGA value become official by the statement of "*regardless of any lower apparent exposure to seismic hazard, it is recommended that every nuclear power plant adopt a minimum value of 0.1g peak ground acceleration corresponding to the safety level SL-2 earthquake*". With the new guidelines developed by IAEA in 2002 (IAEA/NS-G-3.3, 2002) and by U.S.NRC in 2007 (U.S. NRC/RG 1.208, 2007), PSHA completely or partially replaced DSHA in seismic design of NPPs. RG 1.208 is based on the fully utilized PSHA framework and it repealed the previous regulation (RG 1.165). IAEA NS-G-3.3 introduced significant changes over the previous version such as: (1) more guidance on the new topics of data generation (e.g. paleoseismology), (2) guidance on for PSHA components, and (3) decoupling of design response spectra and the hazard based response spectra (Godoy, 2005, Gürpınar, 2004). Most recently, in 2010, IAEA published SSG-9, which is the successor of NS-G-3.3 (2002), and U.S. NRC published RG 1.60 (2014) to satisfy the requirements of Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," to Part 100, "Reactor Site Criteria," of Title 10 of the Code of Federal Regulations (10 CFR Part 100). Today, both procedures (probabilistic and deterministic approaches) are used to define seismic loads for the NPPs all over the world.

1.2. History of NPP Siting and Construction in Turkey

Turkey has been planning to establish nuclear power generation since 1970s. In order to meet the increasing domestic demand for energy and reduce dependency on energy imports, various initiatives were undertaken in the past to build Turkey's first nuclear power plant. First site selection studies were performed in 1974 and 1975, and the Gülnar-Akkuyu (on the eastern Mediterranean coast near the city of Mersin) location was found to be suitable for the construction of the first NPP. In 1976, the Atomic Energy Commission granted the site license for Akkuyu (Ministry of Energy and Natural Resources, 2014). Between early 1970s and 2010, five attempts were made for the construction license, but none of them become a reality because of some technical, economical and/or political issues. After this five attempts, negotiations to build a NPP in Akkuyu were kicked off with the Russian Federation in February 2010 and concluded on May 12th, 2010 with the "*Agreement between the Government of the Russian Federation and the Government of the Republic of Turkey on cooperation in relation to the construction and operation of a nuclear power plant at the Akkuyu site in the Republic of Turkey*" (briefly called Akkuyu Inter Governmental Agreement) based on a Build-Own-Operate (BOO) model. According to the Akkuyu Inter Governmental Agreement, a Project Company named "Akkuyu Nuclear Joint-Stock Company" was established under Turkish jurisdiction on December 13th, 2010. This company is responsible for the construction and operation of 4 units of Water-Water Energetic Reactor (WWER), each with the capacity of 1200 MWe power (Table 1.2).

The Sinop NPP is the second nuclear power plant project of Turkey. Within this context, "*Agreement between the Government of Republic of Turkey and the Government of Japan on Cooperation for Development of Nuclear Power Plants and the Nuclear Power Industry in the Republic of Turkey*" was signed on May 3th, 2013, aiming the construction and operation of an NPP comprising of 4 units of ATMEA-1 design in Sinop site (TAEK/Department of Nuclear Safety, 2013a) (Table 1.2).

Table 1.2. Planned and Proposed Nuclear Power Reactors in Turkey (After World Nuclear Association 2018) & (Ministry of Energy and Natural Resources 2014)

NPP Units	Type	MWe gross	Start construction	Start operation
Akkuyu 1	VVER-1200	1200	April 2018	2023
Akkuyu 2	VVER-1200	1200	2019	2023
Akkuyu 3	VVER-1200	1200	2020	2024
Akkuyu 4	VVER-1200	1200	2021	2025
Sinop 1	Atmea1	1150	uncertain	Before 2030
Sinop 2	Atmea1	1150	uncertain	Before 2030
Sinop 3	Atmea1	1150	uncertain	Before 2030
Sinop 4	Atmea1	1150	uncertain	Before 2030
İğneada 1-4	AP1000x2, CAP1400x2	2x1250 2x1400	uncertain	Before 2030

In 1956, "General Secretariat of Atomic Energy Commission" was established in Ankara after signing of agreement on peaceful use of the atom with the U.S in 1955. In 1982, the Commission was restructured as "Turkish Atomic Energy Authority - TAEK" affiliated to the Prime Ministry (Ülgen et al., 2011). Turkish Atomic Energy Authority was the regulatory body of Turkey in nuclear field between years 1982 and 2018, until the establishment of the Nuclear Regulatory Authority of Turkey (NDK) in 2018. Moreover, Turkey is a party member to various international and bilateral cooperation that regulate the nuclear field, examples of which are as follows; “Treaty on the Non-Proliferation of Nuclear Weapons” (NPT) since 1980 and a member state of the “International Atomic Energy Agency” since 1957. With the new changes in 2018, TAEK (former regulator) is mainly in charge of research and development activities, while the NDK (current regulatory) is performing regulatory functions (authorization, inspection, etc.) in the nuclear field (NDK/Nükleer Düzenleme Kurumu, 2018a; b). Current organizational structure of NDK can be seen at Figure 1.1 and the general organizational structure of Turkish governmental bodies with regulatory functions on nuclear activities is shown in Figure 1.2. References made to TAEK in this study and legislation that continues to be applied shall be deemed to have been made to the NDK.

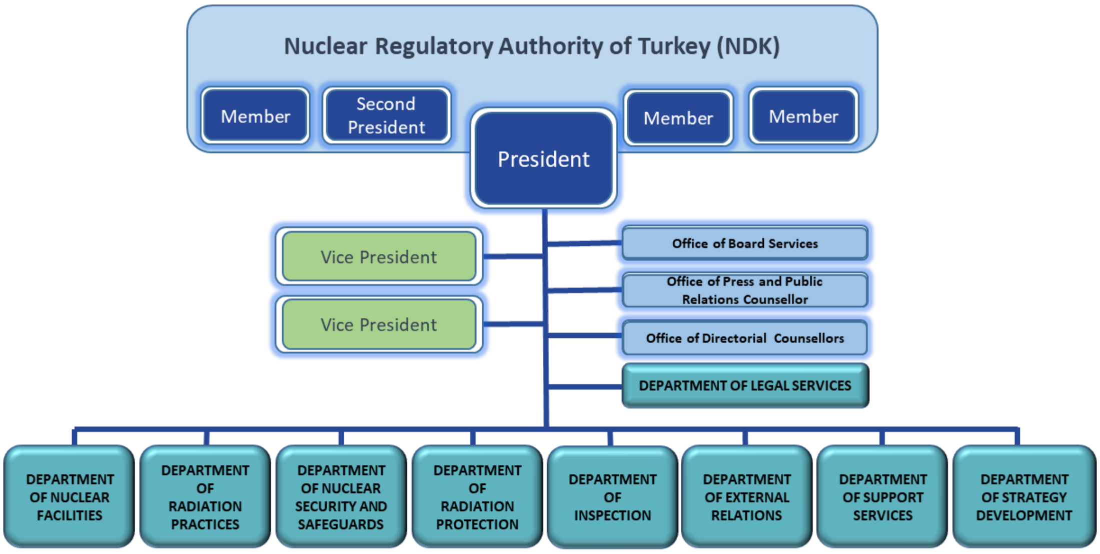

Figure 1.1. Organization chart of Nuclear Regulatory Authority of Turkey - NDK (departmental level)

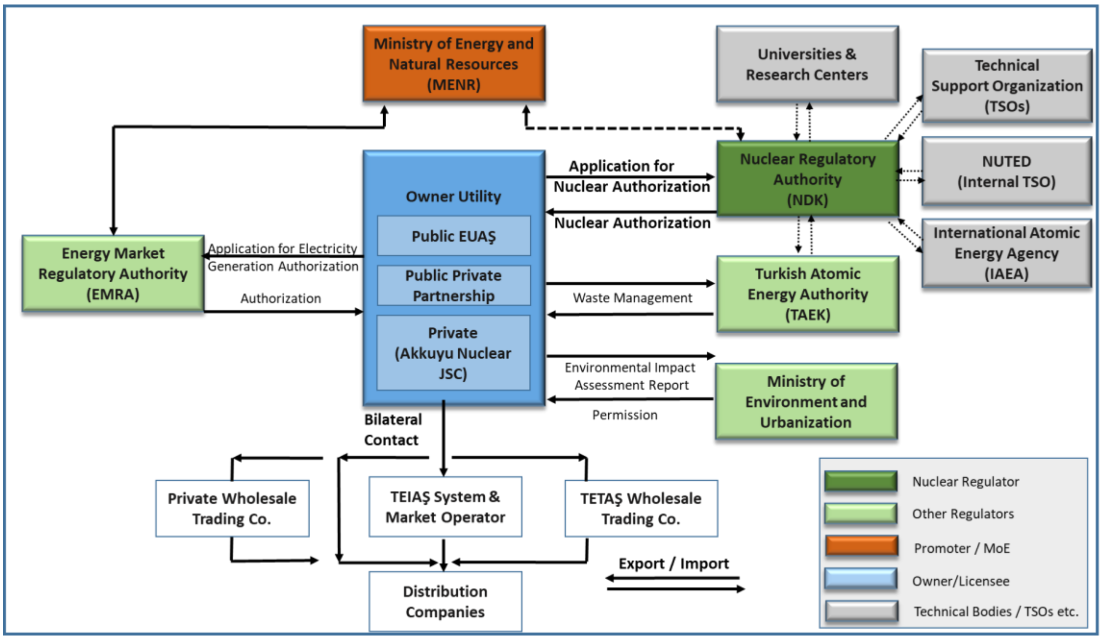

Figure 1.2. General organizational structure of Turkish governmental bodies with regulatory functions on nuclear activities (after TAEK/Department of Nuclear Safety 2013a)

1.3. The Akkuyu NPP Experience

A feasibility study, including site survey for the first NPP in Akkuyu site had been carried out by a consortium, composed of some companies from Switzerland, France, Germany and some national institutions between 1968-70 (Bektur, 2004). TEK issued a report in 1975 (TEK; NED-I-14, Nuclear Power Plant: Site Report, November 1975), stating that no significant faults had been identified along with the results of the regional structural-geological studies including a general regional seismotectonic map of the Akkuyu NPP site (Akkuyu Nuclear JSC, 2013). The detailed seismic safety evaluation was initiated in 1977. Data collection, numerical analysis for seismic parameters, regional geology studies etc. were carried out by some Turkish Institutions and ENG (the consortium of Swiss, French and German firms). Important national institutions involved in this effort were Istanbul Technical University (ITU), Minerals Research and Exploration General Directorate (MTA), and Middle East Technical University (METU). ENG produced the final report on the seismotectonic database of the site in 1980 in collaboration with national institutions (Bektur, 2004). ENG report had considered the regional seismotectonic features and mainly focused on the geological aspects and seismic history of the region (300 km) with the purpose of the areal seismotectonic regionalization. Eight seismotectonic regions (R) and seven seismic source zones (S) were identified in this report. METU/EERI also presented a report for the earthquake resistant design parameters of seismic parameters required for the Akkuyu NPP seismic design in 1979. In parallel with these feasibility studies, ITU had conducted micro-earthquake investigations. Three different (1978, 1983 and 1989) seismotectonic regionalization studies and further micro-earthquake investigations were performed by ITU at three phases between years 1977-1978, 1985-1986 and 1987-1988 (TEAŞ - Hacettepe University - METU, 2000).

TEK submitted a ten volume "Detailed Site Investigations Report" (DSIR) document to TAEK comprising all site related information and evaluations. In the report, geological and seismic issues were given the most prominent consideration. Report of IAEA review team mission performed in 1983 (one staff member and four independent experts) agreed with the information and evaluations of the DSIR but also recommended some further investigations (TEAŞ - Hacettepe University - METU, 2000). The work related to seismic issues was performed during the 1980’s in compliance with the related IAEA and U.S. NRC documents (Bektur, 2004). The seismotectonic zoning was refined and summarized again in the METU report (Doyuran et al., 1989) in 1989. This refined model proposed 11 seismotectonic regions for the Akkuyu region. TEK/KOERI summary report of seismicity and the design ground motion parameters of the Akkuyu NPP was published in 1990 (Akkuyu Nuclear JSC, 2013).

Between years of 1968-2010, more than 200 reports were prepared by eminent universities and private/governmental organizations in Turkey for Akkuyu NPP site. Approximately 30 of these reports are directly related to seismic issues. Majority of these seismic studies were evaluated independently by the IAEA experts. After the Akkuyu Inter Governmental Agreement was signed in 2010, it was decided that

Akkuyu Site License was out of date, which can be remedied by updating the Site Report, accordingly by the authorized committees of TAEK (Turkish Atomic Energy Authority, 2012). Within the framework of the renewed Akkuyu NPP project, the seismic hazard assessment investigations of the site were restarted and four different seismic hazard studies have been performed in 2011-2012 by four different groups: ENVY/KOERI (Kandilli Observatory and Earthquake Research Institute), IPE RAS (Institute Physics of the Earth, Russian Academy of Science) (subsequently excluded), Rizzo (Paul C. Rizzo Associates) and Worley Parsons (TAEK/Department of Nuclear Safety, 2013b).

1.4. Research Statement

Turkey intends to build at least 12 units of nuclear power reactors based on three different designs at three different locations in the next ten years (TAEK/Department of Nuclear Safety, 2016). Because the vendor of each design is (almost certainly) different (Table 1.2), the regulatory body of Turkey has to consider the safety standards and guidelines of different countries in addition to TAEK's regulations and the IAEA's safety standards during the review and licensing processes. Ongoing Akkuyu and Sinop projects underlined the necessities concerning the licensing issues for the safety-related structures at the NPP sites in Turkey, indicating that the main area of concern is the seismic safety of these structures; because the active seismic environment of Turkey results in substantial design basis and beyond design basis ground shaking levels. Following the standards and guidelines of Turkey, IAEA, and the vendor country for seismic hazard assessment, in coordination, may be quite challenging for the practitioners, mainly because of the inconsistencies in the terminology and the differences of applied seismic hazard assessment practice. These inconsistencies result in the loss of effective communication among the earthquake engineers and professionals work for the owner, utility and regulatory bodies and increase the uncertainty levels in design ground motions. In order to perform the regulatory functions properly, the regulatory authority of Turkey needs a systematic, comprehensive and up-to-date comparison of the international standards and guidelines related with the seismic safety and design ground motions.

The fundamental objective of this study is to compare the seismic hazard assessment approaches of leading countries in the nuclear energy field (e.g. USA and Japan) and international organizations (e.g. IAEA) in terms of significant issues related to seismic source and ground motion characterization. For this purpose, main headings of controversial topics; such as estimation of maximum magnitude potential, truncation applied on standard deviation, etc. are defined, and the statements/regulations given in guidelines under each heading are compared. The comparative assessments for each controversial issue are qualitatively supported by the “good practice” implemented in the previous NPP projects and the “lessons learned” from the past experiences. In order to support the qualitative comparisons, sensitivity analysis is performed to understand the effect of observed differences on the hazard outcomes, for a “standard/reference” NPP site designed in seismically active regions. It is expected that the comparisons presented in this study will identify and highlight the differences in international seismic hazard assessment practice for NPP sites. Ultimately, it is intended that the results and recommendations of this study will form the basis of Turkey’s updated regulatory guidelines and/or standards on seismic hazards and vibratory ground motions.

1.5. Scope of Thesis

First chapter of this thesis provides a short summary of the historical evaluation of seismic hazard codes, regulations, and practice from the NPP perspective. Turkey’s involvement in this progress, along with the Akkuyu NPP experience is also briefly explained in Chapter 1. Chapter 2 is dedicated to the explanation of safety terminology for NPPs in global sense: the documents related to safety standards and guidelines in different countries and international organizations are introduced in this chapter. Therefore, Chapter 2 may be apprehended as the “literature survey” of seismic hazard related documents in current NPP practice. These documents are frequently referred to in Chapter 3, where the approaches related to seismic hazard assessment, seismic source and ground motion characterization, hazard input documentation of different countries and international organizations are compared in a systematic manner. A quantitative comparison in terms of hazard curves are provided in Chapter 4 when possible, to further underline the range and extend of differences in international approaches for a “standard” NPP site. Finally, in Chapter 5, main conclusions of this study are provided along with the recommendations for the possible update of Turkey’s regulatory guidelines for seismic issues.

CHAPTER 2

SEISMIC HAZARD RELATED DOCUMENTS OF DIFFERENT COUNTRIES AND INTERNATIONAL ORGANIZATIONS

For a systematic, comprehensive and up-to-date comparison of regulatory guidelines, the seismic hazard assessment applications and related legislations, standards and guidelines of leading countries (USA, Japan, Finland, Russian Federation etc.) and international organizations (IAEA) should be evaluated by considering hierarchy of documents. Although the examples from other countries are mentioned from time to time, this study provides a brief summary of comparison results for 6 "core" countries/organizations that are listed in Table 2.1.

Table 2.1. Selected "core" countries, regulatory authorities and selection reasons

International Organization / Country	**Regulatory Authority (abbreviation)**	**Reason for Selection**
International Atomic Energy Agency (IAEA)	International Atomic Energy Agency (**IAEA**)	- International consensus documents - One of the most prestigious nuclear organizations - Used in practice for Akkuyu NPP project
United States of America (USA)	United States Nuclear Regulatory Commission (**U.S. NRC**)	- Using internationally recognized best practices - Having detailed regulations/standards - Easy access to legislation and practices
Japan	Nuclear Regulatory Authority of Japan (**NRA**)	- Situated in seismically active region - Having different legislation and practices compared to IAEA - Possibility of using for Sinop NPP project
Finland	Radiation and Nuclear Safety Authority of Finland (**STUK**)	- Having a reputable regulatory body - Assumption to reflect general European practice - Recently revised regulatory guideline sets

Table 2.1 (continued)

Russian Federation	Rostekhnadzor (**RTN**)	- Practically applied for Akkuyu NPP project - Relatively detailed legislation and standard sets - Having different legislation and practices compared to IAEA
Turkey	Nuclear Regulatory Authority of Turkey (**NDK**) (after 2018) or (**TAEK**) (before 2018)	- Situated in seismically active region - Having 2-3 ongoing nuclear projects - Need for detailed regulations, guides and standards - History of good/bad practice in seismic hazard

2.1. IAEA Approach

IAEA has the statutory function to "*establish standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes*" (IAEA/NS-G-1.10, 2004). It was indicated that in IAEA safety guides that "*under the terms of Article III of its Statute, the IAEA is authorized to establish standards of safety for protection against ionizing radiation and to provide for the application of these standards to peaceful nuclear activities*" (IAEA/NS-R-1, 2000). IAEA safety standards are structured in 3 categories as shown in Figure 2.1 (Godoy, 2005; IAEA/NS-R-3, 2003; IAEA/SSG-35, 2015):

1. **Safety Fundamentals** presents the general principles of safety. It is the highest-level safety document of the IAEA.
2. **Safety Requirements** are a series of documents detailing the principles of the safety fundamentals. These are establishing the general and some specific requirements (a.k.a. the "*shall statements*").
3. **Safety Guides** recommends more specific actions, procedures, good and best practices for meeting safety requirements (a.k.a. the "*should statements*") (IAEA/SSG-35, 2015).

IAEA also prepares different publications to support the safety standards; e.g. safety and security reports, emergency preparedness and response publications, radiological assessment reports, the international nuclear safety group's (INSAG) reports, technical reports and TECDOCs (IAEA/NS-R-3 rev.1, 2016). It was emphasized that "*the IAEA's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities*" by (IAEA/NS-R-3, 2003). It was clearly stated that IAEA's safety standards are not above the standards of Member States. However, these standards can be used as a reference by member countries (IAEA/SSG-9, 2010).

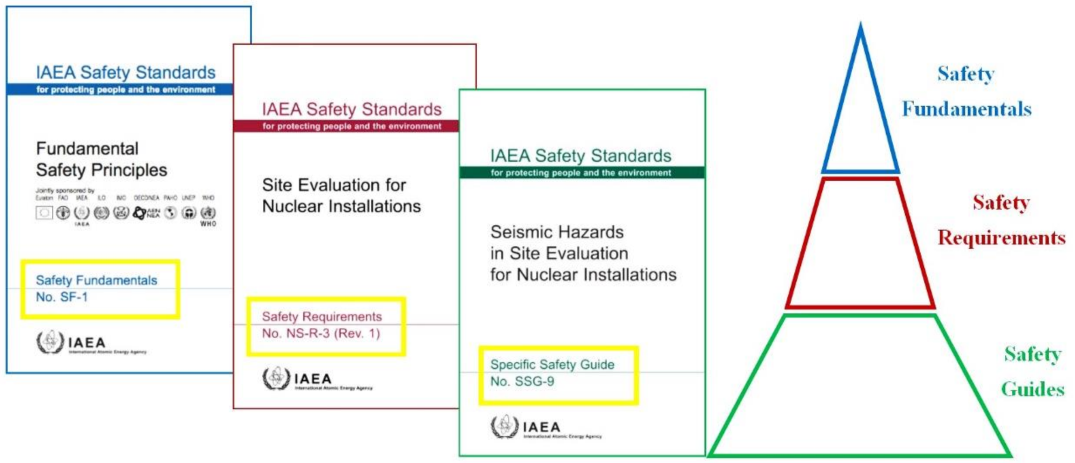

Figure 2.1. Categories and hierarchy of IAEA safety standards

IAEA safety fundamentals, safety requirements and safety guides having requirements and provisions directly related to seismic hazard or bases of them are listed below by their own hierarchy:

- IAEA/SF-1: "Fundamental Safety Principles" (2006)
- IAEA/NS-R-3 (rev.1): "Site Evaluation for Nuclear Installations" (Safety Requirement) (2016)
- IAEA/SSG-9: "Seismic Hazards in Site Evaluation for Nuclear Installations" (Safety Guide) (2010)

2.1.1. IAEA/SF-1: "Fundamental Safety Principles"

The objective of SF-1 is declared as "*to establish the fundamental safety objective, safety principles and concepts that provide the bases for the IAEA's safety standards and its safety related program*" (IAEA/SF-1, 2006) as internationally accepted consensus principles (IAEA/NS-R-3 rev.1, 2016). SF-1 presents the fundamental safety objective and principles of protection and safety, and provides the basis for the safety requirements (IAEA/SSG-18, 2011). This document has ten general safety principles. These principles are very broad and not directly related to seismic hazard; however, they serve as the basis for all other IAEA safety standards and form the basis of all safety considerations.

2.1.2. IAEA/NS-R-3 (rev.1): "Site Evaluation for Nuclear Installations"

(IAEA/NS-R-3 rev.1, 2016) is the safety requirement that regulates main subjects related to site evaluation. The objective of this safety requirement is that "establish the requirements for the elements of a site evaluation for fully characterization of the site-specific conditions pertinent to the safety of a nuclear installation".

This safety requirement (IAEA/NS-R-3 rev.1, 2016) mainly covers; site related external factors, site evaluation and events to be considered in the design; e.g. external natural and human induced events, earthquake and surface faulting, flooding, geotechnical hazards, hazard monitoring, quality assurance subjects.

2003 version of this safety requirement has been updated based on lessons learned from the Fukushima Daiichi accident, occurred at the Fukushima Daiichi NPP in Japan followed the Great East Japan Earthquake and Tsunami of 11 March 2011, and also other experience from research and development. New revision was published in 2016. The revisions to NS-R-3 relate to the following main areas (IAEA/NS-R-3 rev.1, 2016):

- "The potential occurrence of events in combination;

- Establishing levels of hazard for the design basis for the installation and their associated uncertainties;
- Multiple facilities at a single site;
- Monitoring of hazards and periodic review of site-specific hazards”

2.1.3. IAEA/SSG-9: “Seismic Hazards in Site Evaluation for Nuclear Installations”

SSG-9, IAEA’s current safety standards related to seismic hazard assessment that namely “*Seismic Hazards in Site Evaluation for Nuclear Installations*”, was prepared for nuclear installations and published in 2010. It supplements the IAEA safety requirements of NS-R-3. The present publication provides guidance and recommends procedures for the evaluation of seismic hazards for NPPs and it supersedes “*Evaluation of Seismic Hazards for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-3.3 (2002)*” (IAEA/SSG-9, 2010).

This safety guide is based on mainly feedback of information from IAEA reviews over the previous decade and new methodologies. Objective of this safety guide is to provide guidance on evaluating seismic hazards, including determination of the ground motion hazards and fault displacement, for the nuclear facility sites (IAEA/SSG-9, 2010).

Scope of this safety guide (IAEA/SSG-9, 2010) mainly covers; seismotectonic environment, seismic database, graded approach, PSHA, DSHA, fault displacement ground motion evaluation, etc.

Considering seismic hazard analysis related issues, NS-R-3 (rev.1) and SSG-9 are the main requirement and guide, respectively. But IAEA publishes also other safety related publications, e.g. safety guides, safety reports, technical reports and TECDOCs. The most important ones to be reviewed in the subsequent chapters of this study are as follows:

- IAEA/SSR-2/1 rev.1. “Safety of Nuclear Power Plants: Design” (2016)

- IAEA/NS-G-1.6. “Seismic Design and Qualification for Nuclear Power Plants” (2003)
- IAEA/SRS No.85. (2015). “Ground Motion Simulation Based on Fault Rupture Modelling for Seismic Hazard Assessment in Site Evaluation for Nuclear Installations”
- IAEA/SRS No.89. (2016). “Diffuse Seismicity in Seismic Hazard Assessment for Site Evaluation of Nuclear Installations”
- IAEA/TECDOC-724. (1993). “Probabilistic Safety Assessment for Seismic Events”
- IAEA/TECDOC-1333. (2003). “Earthquake Experience and Seismic Qualification by Indirect Methods in Nuclear Installations”
- IAEA/TECDOC-1341. (2003). “Extreme External Events in the Design and Assessment of Nuclear Power Plants”
- IAEA/TECDOC-1722. (2013). “Review of Seismic Evaluation Methodologies for Nuclear Power Plants Based on a Benchmark Exercise”
- IAEA/TECDOC-1767. (2015). “The Contribution of Palaeoseismology to Seismic Hazard Assessment in Site Evaluation for Nuclear Installations”
- IAEA/TECDOC-1796. (2016). “Seismic Hazard Assessment in Site Evaluation for Nuclear Installations: Ground Motion Prediction Equations and Site Response”

2.2. U.S. NRC (USA) Approach

The U.S. Nuclear Regulatory Commission (briefly U.S. NRC) is the federal agency responsible for licensing and regulating nuclear facilities and materials to protect public health, safety and the environment (Nuclear Energy Institute, 2007). Generally, U.S. NRC is the leading organization to develop new standards and guidelines, included seismic design and analysis, in nuclear industry. Then, these standards and guidelines are being adopted for nuclear facilities in other countries (Larsson, 2014).

In the USA, there is a hierarchy of legislation, consisting of acts, federal laws, code of federal regulations, regulatory guides, and standards to regulate the seismic issues of NPPs. These requirements are as follows (Larsson, 2014):

- **Federal Laws:** These are laws passed by the U.S. Congress. These laws provide the highest tier of requirement which are in broadly stated objectives and have the force of law and are mandatory. "The Atomic Energy Act" (1946) and "The Energy Reorganization Act" (1974) is the most important acts. These acts basically describe the legal basis, organizational structures and functions of the NRC (Nuclear Energy Institute, 2007).

- **Code of Federal Regulations (CFR):** These are requirements prepared by the U.S. NRC to provide more guidance how to implement the laws. The requirements also mandatory. NRC regulations are codified in Title 10 of the Code of Federal Regulations (CFR) after they are promulgated (Nuclear Energy Institute, 2007).

- **Regulatory Guide (RG)**, **Standard Review Plan (SRP) and other Staff Interpretations:** RG and SRP are not defining new requirements, they provide detailed guidance to meet the requirements in the regulations. Specifically, NUREG-0800 ("Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants") is applicable for NPPs licensing review process (Nuclear Energy Institute, 2007). These are not mandatory, but if RG or SRP are not used or departed from, the designer must justify the difference to the satisfaction of the U.S. NRC (Larsson, 2014). This category also covers NUREGs[2], Interim Staff Guidance, and so forth.

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[2] The U.S. NRC "NUREG series includes NRC staff and NRC contractor reports on unclassified scientific, technical and administrative information dealing with licensing and regulation of nuclear facilities and materials. These publications present information that may be used to support regulatory decisions, guidance for meeting regulations, results of task force investigations of specific topics or incidents, results of NRC or contractor research programs, resolution of generic safety issues, analyses of certain regulatory programs, proceedings of conferences and workshops, etc."

- **Industry Documents, Codes & Standards:** Industry Documents cover topical reports, industry initiatives and guidelines. Codes and standards are for design and construction. The NRC currently classifies approximately 4,000 codes and standards in regulations, regulatory guides, branch technical positions, the standard review plan, inspection procedures and NUREG documents. Roughly 20 voluntary consensus standards are mandated in NRC regulations according to SECY[3] 99-029 document. Clearly, a vast number of codes and standards are incorporated into plant design and licensing bases without the need for a regulatory mandate (Larsson, 2014; Nuclear Energy Institute, 2007).

Legislative hierarchical structure of U.S. NRC can be seen at Figure 2.2.

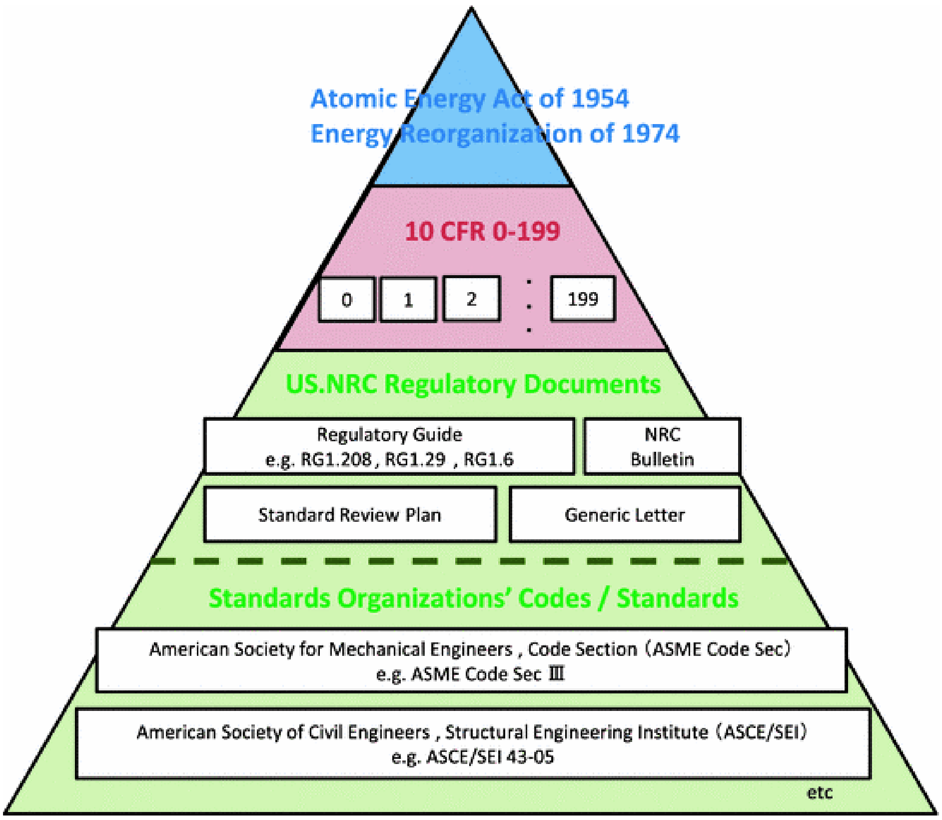


Figure 2.2. Legislative hierarchical structure of U.S. NRC (After Itoi et al. 2017)

[3] "Commission Papers (SECY): Written issues papers the NRC staff submits to the Commission to inform them about policy, rulemaking, and adjudicatory matters."

U.S. NRC’s main documents, studied within the scope of this study, having requirements and provisions directly related to seismic hazard are listed below:

- 10 CFR Part 50, Appendix A, General Design Criteria 2 (GDC 2), “Design Bases for Protection Against Natural Phenomena,”
- 10 CFR Part 100, Appendix A, “Seismic and Geologic Siting Criteria for NPPs” 10 CFR Part 50, Appendix S, “Earthquake Engineering Criteria for Nuclear Power Plants,”
- 10 CFR Part 100.20, “Factors to Be Considered When Evaluating Sites”
- 10 CFR Part 100.23, “Geologic and Seismic Siting Criteria”
- U.S. NRC/RG 4.7, "General Site Suitability Criteria for Nuclear Power Stations,"
- U.S. NRC/RG 1.208, “A Performance-Based Approach to Define Site-Specific Earthquake Ground Motion,”
- U.S. NRC/RG 1.60 (rev.2). “Design Response Spectra for Seismic Design of Nuclear Power Plants”
- U.S. NRC/RG 1.29, “Seismic Design Classification”
- U.S. NRC/NUREG 800 2.5.1. “Geologic Characterization Information”
- U.S. NRC/NUREG 800 2.5.2. “Vibratory Ground Motion”
- U.S. NRC/NUREG 800 2.5.3. “Surface Deformation”
- U.S. NRC/NUREG 800 3.2.1. “Seismic Classification”
- U.S. NRC/NUREG 800 3.7.1. “Seismic Design Parameters”
- U.S. NRC/ISG-001. “Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications”
- U.S. NRC/ISG-017. “Interim Staff Guidance on Ensuring Hazard-Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses”

- U.S. NRC/ISG-020. “Interim Staff Guidance on Implementation of a Probabilistic Risk Assessment-Based Seismic Margin Analysis for New Reactors”
- “Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts” (NUREG/CR-6372)
- “Implementation of the SSHAC Guidelines for Level 3 and 4 PSHAs - Experience Gained from Actual Applications” (USGS/2009-1093)
- “Guidance for Performing Probabilistic Seismic Hazard Analysis for a Nuclear Plant Site: Example Application to the Southeastern United States” (NUREG/CR-6607, UCRL-ID-133494)

In this study, some important regulations and guidelines related to seismic hazard will be explained briefly in the following sections under this subheading.

2.2.1. 10 CFR Part 50, Appendix A, GDC 2 – “Design Bases for Protection against Natural Phenomena”

10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities,” governs the licensing of domestic production and utilization facilities (U.S. NRC/RG 1.60 (rev.2), 2014). Appendix A to 10 CFR Part 50, which is namely “General Design Criteria for Nuclear Power Plants,” contains general design criteria (GDC) for NPPs. Specifically, GDC 2, “Design Bases for Protection Against Natural Phenomena,” requires that nuclear power plant’s “*SSCs important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions*” (U.S. NRC/RG 1.29 (rev.5), 2016). Actually, Appendix A to 10 CFR Part 50 and GDC 2 were established firstly in 1971 by U.S. NRC (Kammerer, 2011) and it has been revised at several times, with the final revision made in 2007 (U.S. NRC/10 CFR Part 50 Appendix A, 1971). This document, which is at the legislative level, emphasizes the importance and necessity of consideration of the earthquake issue, which is only one of the external factors.

2.2.2. 10 CFR Part 100, Appendix A, "Seismic and Geologic Siting Criteria for NPPs"

Actually, Appendix A to 10 CFR Part 100 were established firstly in 1973 by U.S. NRC and it has been revised at several times, with the final revision made in 2013 (U.S. NRC/10 CFR Part 100 Appendix A, 1973). Appendix A provides the seismic and geologic siting criteria for NPPs licensed before January 10, 1997, and it describes the surveys required to obtain the geologic and seismic data required to determine site suitability to minimize health and safety related risk of the public. It give general guidance for determining the vibratory ground motion design basis due to earthquakes and describes information about surface faulting (U.S. NRC/10 CFR, 2016; U.S. NRC/RG 1.60 (rev.2), 2014).

2.2.3. 10 CFR Part 50, Appendix S, "Earthquake Engineering Criteria for NPPs"

Appendix S to Part 50 applies to applicants for a construction permit or operating license under 10 CFR Part 50, or a "design certification, combined license, design approval, or manufacturing license" under 10 CFR Part 52, on or after January 10, 1997 (U.S. NRC/10 CFR Part 50 Appendix S, 1996). Appendix S to 10 CFR Part 50 indicates that "*SSE ground motion is the vibratory ground motion for which certain structures, systems, and components must be designed to remain functional*". This is the performance-based requirement replacing the deterministic DBE (Kammerer, 2011). It also states that "*the nuclear power plant must be designed so that, if the SSE ground motion occurs, certain structures, systems, and components will remain functional and within applicable stress, strain, and deformation limits*" (U.S. NRC/10 CFR Part 50 Appendix S, 1996). This document can be regarded as the first legal step of the US transition from deterministic to probabilistic approach. In this respect, it is a very significant regulation.

2.2.4. 10 CFR Part 100.20, “Factors to Be Considered When Evaluating Sites”

In order to in determine the site’s acceptability for a NPPs, 10 CFR Part 100 addresses the physical characteristics of a site including seismology, geology and as well as guidelines for limiting potential offsite exposure (U.S. NRC/RG 1.29 (rev.5), 2016). In Part 100, “Subpart B - Evaluation Factors for Stationary Power Reactor Site Applications on or After January 10, 1997” covers 10 CFR Part 100.20 “Factors to Be Considered When Evaluating Sites” (U.S. NRC/10 CFR, 2016). 10 CFR Part 100.20 indicates that physical characteristics of the site, including seismology and geology shall be considered when determining the suitability of a site (U.S. NRC/10 CFR Part 100.20, 1996).

2.2.5. 10 CFR Part 100.23, “Geologic and Seismic Siting Criteria”

Section 100.23, describes the criteria and nature of investigations required to obtain the geologic and seismic data necessary to determine the suitability of the proposed site and the plant design bases (U.S. NRC/10 CFR Part 100.20, 1996).

Paragraphs (c) and (d) of 10 CFR 100.23 issue that “geological, seismological, and engineering characteristics” and “geologic and seismic siting factors” respectively. Paragraph (c) requires that “*the geological, seismological, and engineering characteristics of a site and its environs must be investigated in sufficient scope and detail to permit an adequate evaluation of the proposed site, to provide sufficient information to support evaluations performed to arrive at estimates of the SSE Ground Motion, and to permit adequate engineering solutions to actual or potential geologic and seismic effects at the proposed site*” (U.S. NRC/10 CFR Part 100.23, 2007). In addition, paragraph (d)(1) of 10 CFR 100.23 Determination of the SSE Ground Motion requires that uncertainty inherent in estimates of the SSE be addressed through an appropriate analysis, such as a probabilistic seismic hazard analysis (PSHA) (U.S. NRC/NUREG-2117 Rev.1, 2012).

2.2.6. U.S. NRC/RG 4.7, "General Site Suitability Criteria for Nuclear Power Stations"

This guideline debates the public health and safety related major site characteristics which is considered by the reviewer during determining the suitability of sites for NPPs (U.S. NRC/NUREG 800 2.5.3, 2014). This document also discusses environmental issues. According to this guide, site selection involves consideration of the "geology, seismology, geomorphology, nearby facilities & activities, surface and ground water hydrology, climatology, air quality, limnology, water quality, fisheries, wildlife habitat, recreation resources, archeological and historical resources, land use, public health and safety, engineering and design, economics, institutional requirements, environmental impacts", and other related factors (U.S. NRC/RG 4.7 (rev.3), 2014). This document is a guideline-level document addressing site suitability and main topics to be examined.

2.2.7. U.S. NRC/RG 1.208, "A Performance-Based Approach to Define Site-Specific Earthquake Ground Motion"

In 2007, NRC issued PSHA based RG 1.208. This guide has been developed for use with ASCE 43-05 (Kammerer, 2011). This regulatory guide is prepared to provide guidance on the development of the site-specific ground motion response spectrum (GMRS), which represents the first part of the development of the SSE for a site. It provide general guidance on methods for (U.S. NRC/RG 1.208, 2007): (i) geological, geophysical, seismological, and geotechnical investigations, (ii) identifying and characterizing seismic sources, (iii) conducting a PSHA, (iv) determining soil amplification characteristics of soil and rock sites, (v) determining a site-specific, performance based GMRS.

This Regulatory Guide provides regulatory guidance to satisfy the requirement of 10 CFR Part 100.23 and Appendix S to 10 CFR Part 50 (U.S. NRC/NUREG-2117 Rev.1, 2012). This guide is one of the main important documents deals with seismic hazard in a detailed way.

2.2.8. U.S. NRC/RG 1.60 (rev.2), "Design Response Spectra for Seismic Design of NPPs"

This regulatory guide defines response spectra for the seismic design of NPPs to fulfill the requirements of related 10 CFR documents. SSE ground motion for NPPs especially constructed during the 1970s and 1980s is defined by RG 1.60 response spectrum. The Certified Seismic Design Response Spectra for numerous new reactor designs are derived from RG 1.60 spectra, but RG 1.60 is no longer employed to characterize the hazard for the seismic design of NPPs (U.S. NRC/RG 1.60 (rev.2), 2014).

2.2.9. U.S. NRC/ NUREG 800, "Standard Review Plan (SRP) for the Review of Safety Analysis Reports for NPPs"

NUREG-0800, which is namely as "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants", is non-obligatory review and assessment document set applicable for NPPs licensing process in order to provide guidance to U.S. NRC employees during performing safety reviews of license or permit applications (Nuclear Energy Institute, 2007; U.S. NRC/NUREG 800 0 (rev.2), 2007).

Main documents related to seismic hazard subject are:

- U.S. NRC/NUREG 800 2.5.1. "Geologic Characterization Information"
- U.S. NRC/NUREG 800 2.5.2. "Vibratory Ground Motion"
- U.S. NRC/NUREG 800 2.5.3. "Surface Deformation"
- U.S. NRC/NUREG 800 3.7.1. "Seismic Design Parameters"

2.2.10. U.S. Nuclear Standards

ASCE 4-98 & 4-16 "Seismic Analysis of Safety-Related Nuclear Structures"

When this thesis is being written, new version (4-16) of ASCE 4 has been published in 2017, and this is a comprehensive update of ASCE 4-98. ASCE 4 provides mainly requirements for carrying out "*analysis to obtain response information*" and this is applicable for new or existing facilities. This standard is used with ASCE 43-05 (ASCE/SEI 4-16, 2017).

Chapter 2 of this standard are covers seismic hazard related subjects. In Chapter 2 of 4-16 are mainly concern with (ASCE/SEI 4-16, 2017); (i) seismic input, (ii) performance-based design motions (according to ASCE/SEI 43-05), (iii) Probabilistic site response analysis (new section added by 2016 version).

ASCE/SEI 43-05 "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities"

This standard requires the use of PSHA for determining DBE. In order to characterize the site and to determine the ground motion, it also refers ANSI/ANS 2.27 and 2.29. This document mostly covers structural design related issues (linear, nonlinear analysis, evaluation of structural capacity, load combinations etc.) (ASCE/SEI 43-05, 2005).

Probabilistic Analysis of Natural Phenomena Hazards at Nuclear Facilities Sites, ANSI/ANS 2.29 (ANSI/ANS 2008a)

This standard contains provisions for seismic hazard analysis for nuclear structures. Selection of methods, source and ground motion characterization steps, site response, and evaluation of uncertainties are covered by this document (U.S. NRC/NUREG-2117 Rev.1, 2012).

Criteria for Investigations of Nuclear Facility Sites for Seismic Hazard Assessments, ANSI/ANS 2.27

This standard outlines the geological, seismological, and geotechnical studies required for nuclear structures. These studies are intended to provide data to PSHA studies on topics such as seismic source characterization, site response, surface faulting hazard (ANSI/ANS-2.27, 2008).

2.3. NRA (Japan) Approach

To understand current Japanese regulatory system and framework, Fukushima Daiichi nuclear accident initiated by the March 11, 2011, Great East Japan Earthquake (GEJE) should be considered firstly. This nuclear accident has fundamentally changed whole regulatory system and regulations especially related to nuclear power plant design, natural hazards and seismic hazard issues in Japan.

On March 11, 2011, a severe earthquake (Mw=9.0) occurred 180 km off the coast of the Fukushima Daiichi Nuclear Power Station. This was the largest earthquake Japan has ever experienced. This earthquake also generated a series of seven tsunamis (Institute of Nuclear Power Operations, 2011). The Fukushima Daiichi Nuclear Power Plant and also Fukushima Daini, Onagawa, and Tokai Daini NPPs were stricken by the GEJE and series of tsunamis (Kurokawa et al., 2012). In Fukushima Daiichi, situation has become extremely severe nuclear accident (Japan Nuclear Emergency Response Headquarters, 2011) that was the worst accident at a NPP since the Chernobyl disaster in 1986 (IAEA, 2015).

Before the Fukushima accident, there are two main governmental regulatory bodies in nuclear industry, which is namely Nuclear and Industrial Safety Agency (NISA) and Nuclear Safety Commission (NSC). NISA undertook the safety review of NPPs according to the regulatory guidelines that were prescribed by the NSC. NISA authorized the construction permits and the operational safety programs of NPPs with the agreement of the NSC (Yasuhiko, 2013). The Fukushima Daiichi accident occurred because of weaknesses in Japan's regulatory framework that responsibilities were divided among a number of bodies, and it was not clear (IAEA, 2015).

After the Fukushima accident, the government abolished the NSC and founded the NRA that has the power to permit and approve NPPs (Yasuhiko, 2013). Japan has reformed its regulatory system to better meet international standards and they gave regulators clearer responsibilities and greater authority (IAEA, 2015). NRA is an independent commission with decision making power, and it was finally instituted in

September 2012 (Ahn et al., 2015). Japanese government changes some acts (National Diet of Japan, 2013a, 2013b) in order to ensure the availability of a harmonious, independent and single authority in nuclear regulatory area. For this purpose, they integrate NPPs safety regulations including the “Electricity Business Act” (periodic inspections) into the “Act on the Regulation of Nuclear Source Material”, “Nuclear Fuel Material and Reactors (the Reactor Regulation Act)” (Nuclear Regulation Authority of Japan, 2013b).

Accompanied by the change of regulatory system, the NRA projected to revise existing regulatory guidelines or prescribe new regulatory guidelines after the Fukushima Daiichi accident (Ahn et al., 2015; Yasuhiko, 2013). NRA declared that the new regulatory requirements for NPPs is based on lessons learned from the Fukushima accident and in consideration of international requirements (Nuclear Regulation Authority of Japan, 2013a). The new regulatory requirements for commercial NPPs got into force on July 8, 2013. Previous assumptions on the impact of earthquakes, tsunamis and other external events have been re-evaluated, and NRA were decided to be enhanced that countermeasures for nuclear safety against these external events by this new requirements (Nuclear Regulation Authority of Japan, 2013b).

Nuclear and radiation safety related legislative and regulatory framework in Japan is based on a five-level system (IAEA/IRRS Mission, 2016). Japanese five-level hierarchical structure of regulatory legislations (acts, cabinet orders, regulations, regulatory guides and technical documents) can be seen at Figure 2.3.

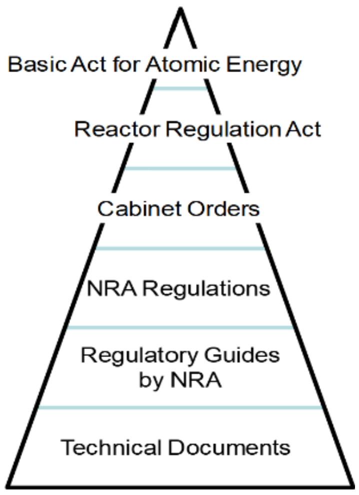


Figure 2.3. Japanese five-level hierarchical structure of regulatory legislations (Nuclear Regulation Authority of Japan, 2015)

Most NRA documents including acts, orders, ordinances, guides and standards are not available in English. Because of this obstacle, within this study, only publicly available English version of these documents are used. A brief information of the most important requirements and guides in seismic hazard field are given below after Fukushima accident era.

2.3.1. "New Regulatory Requirements for Light-Water Nuclear Power Plants – Outline" – (July 2013)

In July 2013, NRA declared enforcement letter with annexes that is namely "New Regulatory Requirements for Commercial Nuclear Power Reactors" (Nuclear Regulation Authority of Japan, 2013b). This document fundamentally based on lessons learned from Fukushima accident.

Considering Fukushima accident, NRA re-evaluated the previous assumptions on the impact of earthquakes, tsunamis and other external events (volcanic eruptions, tornadoes and forest fires) and it was decided that countermeasures for nuclear safety against these external events to be enhanced. Active fault definition and evaluation methodology of sub-surface structure beneath NPPs have been changed and become more conservative (Nuclear Regulation Authority of Japan, 2013b).

2.3.2. "Outline of New Regulatory Requirements for Light Water NPPs (Earthquakes and Tsunamis)" (April 3, 2013)

This document is based on the discussions at the review team meetings and public comments (Nuclear Regulation Authority of Japan, 2013e) after Fukushima accident. Actually, this is not the legally binding regulation, guideline or standard, this is only report. But NRA declare this publication as if it was legislation (regulatory decision). This report basically concerned that basic design policy for earthquakes and tsunamis.

2.3.3. "Outline of New Regulatory Requirements (Design Basis)" (April 3, 2013)

This document provides a holistic overview of the issues to be addressed in design in general. It covers a broad spectrum and regulates some basic requirements related to natural (earthquake, tsunami etc.) and human induced events, test and inspections, reactor core design, control systems, instrumentation & control systems, electrical systems and radiation management etc. (Nuclear Regulation Authority of Japan, 2013d).

2.3.4. "Review Guide for Surveys on Geology and Geological Structure in and around NPP Sites" (June 2013)

This document, like the others, is also revised guide by considering the lessons learned from the Fukushima accident. This guide mainly concerns about site surveys, evaluation of geology, identification of fault activity, NPP near site investigations, and tsunami related investigations (Nuclear Regulation Authority of Japan, 2013f).

2.3.5. "Guide for Review of Standard Seismic Motion and Seismic Design Policy" (June 19, 2013)

This guideline provides a specific guidance about earthquake types, earthquake sources, seismic data collection, source modelling, source characterization, ground motion assessment, determination of standard seismic motion and seismic design policy (seismic classification, seismic force calculations, load combinations) etc. (Nuclear Regulation Authority of Japan, 2013c). This guide is the most detailed guide on seismic hazard among other Japanese legislation and guides.

2.4. STUK (Finland) Approach

In the Finland, there is a hierarchy of legislation, consisting of laws, decrees, regulations, regulatory guides, and international standards to regulate the seismic issues of NPPs. Their hierarchy is very similar to Turkish regulatory hierarchy. After Fukushima accident in Japan, STUK renewed some regulations and Finnish regulatory guides (YVL Guides) series in order to reflect lessons learned from this accident (STUK, 2016). New structure can be seen at Figure 2.4. Requirements for the nuclear facility's protection against external hazards, especially seismic hazard, are given also in the following regulations and guides.

2.4.1. Y-1-2016: "Regulation on Radiation and Nuclear Authority Regulation on the Safety of a Nuclear Power Plant"

This regulation is applicable to NPPs and adjacent nuclear facilities intended for the storage of spent nuclear fuel. It is legally binding compulsory regulation and it regulates general nuclear safety issues, considering external natural hazard included seismic hazards, related to NPPs. It also requires probabilistic risk assessment (PRA) to perform quantitative assessment of hazards (STUK/Y/1, 2016).

2.4.2. YVL A.2: "Site for a Nuclear Facility"

YVL A.2, considers examination of external hazards, and specifically indicates that probabilistic risk assessment methodology should be applied on external events (STUK/YVL A.2, 2013). YVL A.2 suggests using Guide YVL A.7 during consideration of external hazards. This document has so general provisions about external events like IAEA requirements.

Structure of the new YVL Guides

A Safety management of a nuclear facility	**B Plant and system design**
A.1 Regulatory oversight of safety in the use of nuclear energy	B.1 Safety design of a nuclear power plant
A.2 Site for a nuclear facility	B.2 Classification of systems, structures and components of a nuclear facility
A.3 Management system for a nuclear facility	B.3 Deterministic safety analyses for a nuclear power plant
A.4 Organisation and personnel of a nuclear facility	B.4 Nuclear fuel and reactor
A.5 Construction and commissioning of a nuclear facility	B.5 Reactor coolant circuit of a nuclear power plant
A.6 Conduct of operations at a nuclear power plant	B.6 Containment of a nuclear power plant
A.7 Probabilistic risk assessment and risk management of a nuclear power plant	B.7 Provisions for internal and external hazards at a nuclear facility
A.8 Ageing management of a nuclear facility	B.8 Fire protection at a nuclear facility
A.9 Regular reporting on the operation of a nuclear facility	
A.10 Operating experience feedback of a nuclear facility	
A.11 Security of a nuclear facility	
A.12 Control of information security on a nuclear facility	
C Radiation safety of a nuclear facility and environment	**D Nuclear materials and waste**
C.1 Structural radiation safety and radiation monitoring of a nuclear facility	D.1 Regulatory control of nuclear safeguards
C.2 Radiation protection and dose control of the personnel of a nuclear facility	D.2 Transport of nuclear materials and nuclear waste
C.3 Control and measuring of radioactive releases to the environment of a nuclear facility	D.3 Handling and storage of nuclear fuel
C.4 Radiological control of the environment of a nuclear facility	D.4 Predisposal management of low and intermediate level nuclear waste and decommissioning of a nuclear facility
C.5 Emergency arrangements of a nuclear power plant	D.5 Disposal of nuclear waste
C.6 Radiation monitoring at a nuclear facility	D.6 Production of uranium and torium in mining and milling activities
C.7 Radiological monitoring of the environment of a nuclear facility	D.7 Barriers and rock engineering of nuclear waste disposal facility
E Structures and equipment of a nuclear facility	
E.1 Authorised inspection body and the licensee's in-house inspection organisation	E.6 Buildings and structures of a nuclear facility
E.2 Procurement and operation of nuclear fuel	E.7 Electrical and I&C equipment of a nuclear facility
E.3 Pressure vessels and pipings of a nuclear facility	E.8 Valves of a nuclear facility
E.4 Strength analyses of nuclear power plant pressure equipment	E.9 Pumps of a nuclear facility
E.5 In-service inspection of nuclear facility pressure equipment with non-destructive testing methods	E.10 Emergency power supplies of a nuclear facility
	E.11 Hoisting and transfer equipment of a nuclear facility
	E.12 Testing organisations for mechanical components and structures of a nuclear facility

Collected definitions of YVL Guides: same data is shown both as the collection and within the guides.

Figure 2.4. New structure of YVL Safety Guides in Finland (after Fukushima Accident) (taken from STUK, 2016)

2.4.3. YVL A.7: "Probabilistic Risk Assessment and Risk Management of the NPP"

This regulatory guidelines covers seismic PRA and fragilities as well as the PRA of other external events (STUK/YVL A.7, 2013). This guide has very general provisions without details related to seismic hazard.

2.4.4. YVL B.2: "Classification of Systems, Structures and Components of a Nuclear Facility"

YVL B.2 regulates safety classification and seismic classification of structures, systems and components (SSCs). According to this guide, SSCs of nuclear facilities shall be assigned to three categories, S1, S2A and S2B, based on the seismic resistance requirements set for them (STUK/YVL B.2, 2013).

2.4.5. YVL B.7: "Provisions for Internal and External Hazards at a Nuclear Facility"

This regulatory guide contains the most detailed provisions about earthquakes and seismic hazard comparing other Finnish YVL Guides. This guide defines the design basis earthquake that the anticipated frequency of occurrence of stronger ground motions is less than once in a hundred thousand years (1×10^{-5}/y) at a median confidence level. This guide requires the use of only local seismic data from Finland during determining the ground response spectrum. Also this guide addresses the some USA standards (ASCE 43-05 and ASCE 4-98) and U.S. NRC's NUREG (NUREG/CR- 6926, NUREG/CR-6728, NUREG/CR-6919) documents in order to explain applicable methodology to some specific issues (STUK/YVL B.7, 2013).

2.5. Russian Federation Approach

As explained in the first chapter more detailed way, there is an IGA which was signed between Turkey and Russia in 2010 for the construction of nuclear power plant in Turkey. According to this agreement, the first nuclear power plant in Turkey is being built by the Russian Federation. Therefore, the Russian example has been also included in this study. However, the documents of the Russian Federation on seismic hazard are comparatively limited in number and content, and their approaches are not fully compatible with the modern seismic hazard approach in most aspects. Under this sub-section, the hierarchy of legislation and important regulations, guidelines and standards related to seismic hazard be briefly explained. Legislation hierarchy of Russian Federation can be seen at Figure 2.5.

2.5.1. 170-FZ: "Federal Law on the Use of Atomic Energy"

In Russian case, law on the use of atomic energy (Russian Federation, 2007) is the main legal basis that defines the legal basis and the principles of regulating relations arising during the use of atomic energy and is aimed at protecting the lives and health of the people, environment, property. The Russian Federation has many laws governing this area, but these are not discussed here as they are incompatible with the scope of this study.

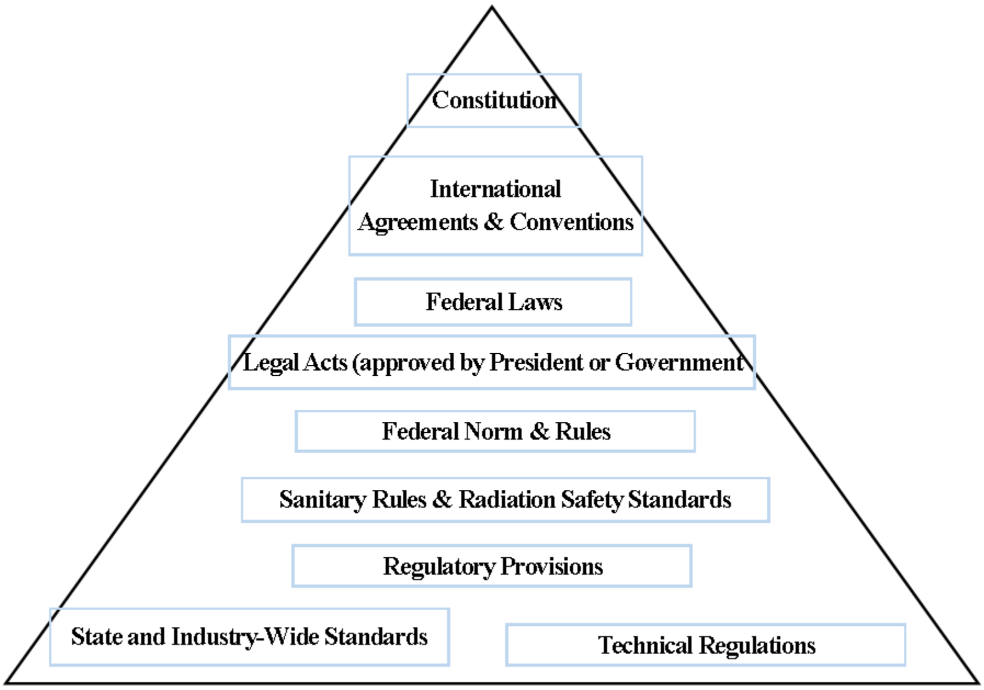


Figure 2.5. Nuclear legislation hierarchy of Russian Federation (after Russian Federation 2014)

Brief information on important legislation, guidelines and standards is provided on the following parts of this sub-section.

2.5.2. NP-032-01: "Nuclear Power Plant Siting Main Criteria and Safety Requirements"

It is a regulatory document at the federal norm and rules level in the Russian Federation. It determines the basic requirements to be taken into consideration in the selection of new nuclear power plants. Within this scope, it defines major requirements related to natural external events (including earthquakes and active faults criteria), human-induced external events (fires, explosions, aircraft crash etc.), and environment and population (RTN/NP-032-01, 2002).

2.5.3. NP-031-01: "Standards for Design of Seismic Resistant Nuclear Power Plant"

This document mainly deals with the following issues; basic principles of design of nuclear power plants against earthquake, identifying requirements for the different stages from feasibility to life extension, seismic classification of structures, systems and components (SSCs), structural performance criteria for SSCs by considering seismic classification level, identification of required site surveys for facilities according to spatial scales, maps and data to be prepared, parameters to be calculated, definition of design and maximum credible earthquake levels, load combinations to be considered in the design (RTN/NP-031-01, 2002).

2.5.4. NP-064-05: "Accounting of External Natural and Man-Induced Impacts on Nuclear Facilities"

This regulation describes in detail the requirements for natural external events and human-induced external events whose general requirements are defined in the documents NP-032-01 and NP-031-01 as explained before. Additionally, it specifically separates requirements by considering the stage of authorization (siting, design, construction, commissioning, decommissioning etc.) and categorize all possible hazards into 3 category (RTN/NP-064-05, 2006).

2.5.5. RB-006-98: "Determination of Initial Seismic Ground Oscillations for Design Basis"

This is safety guide level document aiming that determination of design basis ground motion. This document mainly covers; applicable methods to determine design basis ground motion (standard response spectra, vertical/horizontal component etc.), requirement for accelerogram etc. (RTN/RB-006-98, 1999)

2.5.6. RB-019-01: “Evaluation of Seismic Hazards of Sites Intended for Nuclear and Radiation Hazardous Installations Based on Geodynamic Data”

This is also safety guide level document including that recommendations for site investigations and deformation data (slip rate, fault displacement, GPS data etc.) to meet the requirements of NP-064-05. It also contains categorization of tectonic structures, suggestion on evaluation and calculation of M_{max}, recommended spatial scales for nuclear facilities by considering lessons learned from real NPP examples (e.g. Kalinin NPP, Novovoronezh NPP), fault capability criteria (RTN/RB-019-01, 2002).

2.5.7. RB-123-17: “Basic Recommendations for Elaboration of the NPP Unit Level 1 PSA of Initiating Events Resulted from Seismic Effects”

In 2017, The Federal Environmental, Industrial and Nuclear Supervision Service has been published new safety guide about seismic PSA. This document includes suggestions about seismic PSA studies, recommendations on PSHA and fragility analysis, calculation recommendations of contributions by seismic loads to get aggregate core damage frequency, selection criteria for systems and components to be analyzed, suggestion about uncertainties etc. (RTN/RB-123-17, 2017).

2.6. Turkey Approach

In Turkey, hierarchy of legislations mainly includes constitution, laws, international agreements, presidential decrees, regulations, directives, regulatory guides, and standards (mandatory and nonobligatory) etc. This hierarchy can be seen at Figure 2.6.

Turkey, as an embarking country (newcomer in nuclear) where the nuclear sector is being newly formed, decided to use IAEA safety standards and vendor countries’ regulations, standards and guides, in addition to their national legislations, as a licensing basis documents during authorization and inspection of nuclear power plant projects. In the Akkuyu NPP Project, TAEK considered the IAEA and Russian Federation requirements in addition to the national requirements according to internal directive (TAEK/Turkish Atomic Energy Authority, 2012a) that requires that complete list of regulations, guides and standards forming the licensing basis for the plant shall be determined for each NPP project.

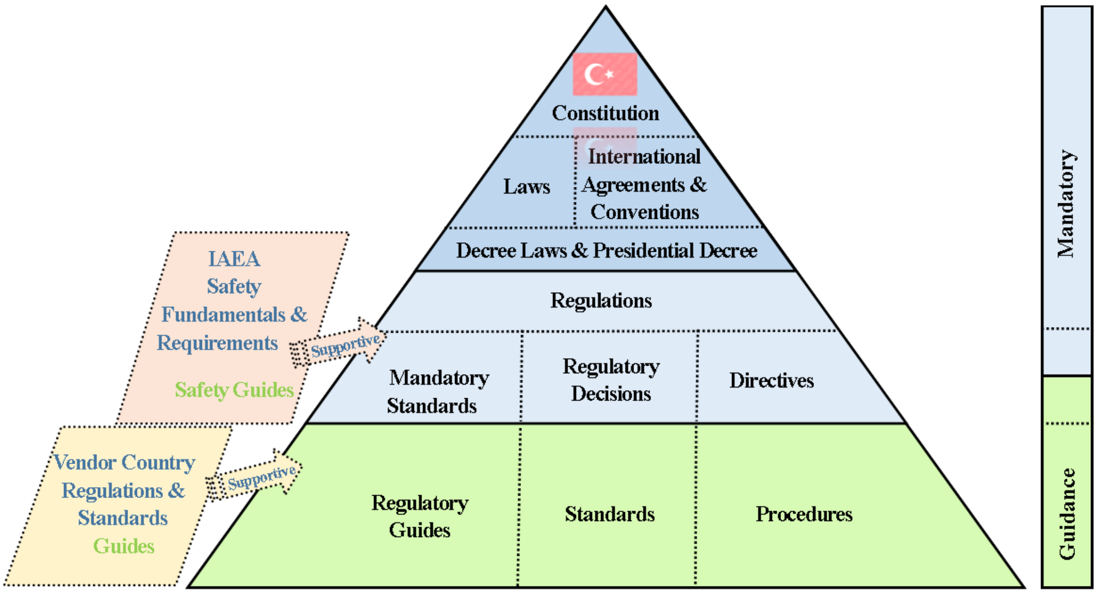


Figure 2.6. Legislation hierarchy of Turkey

Turkey's main legislations, studied within the scope of this study, having requirements and provisions related to seismic hazard or related subjects are briefly explained following pages.

2.6.1. "Decree on Licensing of Nuclear Installations" (1983) (obsolete after 2018)

This Decree is a high level legislation specifying the general requirements for licensing of nuclear facilities and requires that information be provided to evaluate the potential impacts of an earthquake on the facility (TAEK/Turkish Atomic Energy Authority, 1983). This Decree was repealed by the KHK-702 and Presidential Decree

(No-4) published in 2018 and it is still partially implemented for the Akkuyu NPP Project (NDK/Nükleer Düzenleme Kurumu, 2018a, 2018b).

2.6.2. "Regulation on Nuclear Power Plant Sites" (2009)

This Regulation is at the same level as the IAEA's NS-R-3 Requirement or USA's 10 CFR series. It aims to determine the main subjects (seismic issues, population, human induced external events, meteorology etc.) to be considered during site selection for a nuclear facility and the parameters to be determined for the detailed assessment of the site. Considering seismic issues, it deals with geological events, surface faulting, geotechnical hazards, slope stability etc. (TAEK/Turkish Atomic Energy Authority, 2009b)

2.6.3. Other Turkish nuclear regulation and guidelines

Turkey has more than 20 regulations regulating the nuclear business. However, few of these have provisions on seismic hazards or just general design provisions against earthquake ground motion.

"Regulation on Design Principles for Safety of NPPs" (2008) & "Regulation on Specific Principles for Safety of Nuclear Power Plants" (2008)

These two regulations mainly cover design principles from site evaluation to decommissioning of the plant; including design specifications of safety systems, reliability targets, radiation protection, reactor core integrity (especially "*geometric stability of the core during potential earthquakes*"), confinement of radioactive materials, emergency plans etc. Provisions of these documents are quite general and most of them are not directly related to seismic issues.

"Guide on Specific Design Principles" (2012)

This Guide is prepared to elaborate some of the design criteria set out by the two Regulations summarized above. The main provisions of the Guide related to the scope of this study; criterion for not allowing the placement of NPPs in sites directly located on active faults, determination of annual exceedance probability for S2 level earthquake ground motion and determination of minimum ratio of vertical ground acceleration to horizontal ground acceleration. These provisions will be discussed in detail in Chapter 3 of this study under the relevant headings.

CHAPTER 3

INTERNATIONAL SEISMIC HAZARD ASSSESSMENT PRACTICE FOR NUCLEAR FACILITIES

Within this chapter, international safety-related documents introduced in Chapter 2 are elaborated for issues related to seismic hazard assessment, seismic source and ground motion characterization, hazard input documentation, etc. to compare the seismic hazard assessment approaches of different countries and international organizations. Discussions provided here consider the latest versions of the related guidelines/standards and supported by the recent literature; however, the "good practice" implemented in the previous NPP projects such as PEGASOS (Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites), Diablo Canyon and Yucca Mountain and the "lessons learned" from the past experiences (e.g. Kashiwazaki-Kariwa NPP experience after the Niigataken-Chuetsu-Oki earthquake and Fukushima Daiichi accident after the Tohoku earthquake and tsunami) are also frequently referred to improve the discussions. In addition to the international practice, seismic hazard applications in the ongoing nuclear projects in Turkey are presented and discussed in each sub-section. To identify the weaknesses and strengths of different approaches, parameters discussed in this chapter are documented in the comparison chart given as Appendix-A.

3.1. Seismic Hazard Assessment in Nuclear Regulations: PSHA, DSHA and Recipe Approaches

In Deterministic Seismic Hazard Assessment (DSHA), individual earthquake scenarios (with the maximum magnitude and the closest possible location) are determined for each relevant seismic source and the ground motion is computed based on the specified ground motion probability level (typically, either 1 or 0 standard deviation above the median is selected) (Figure 3.1). The frequency of the earthquake occurrence is generally not considered and the DSHA approach does not suggest a formal and clear way of treating the uncertainties (U.S. NRC/NUREG/CR-6372, 1997a). Therefore, DSHA only provides a straightforward structure for the evaluation of worst-case earthquake scenario (Kramer, 1996a) and the hazard is defined as the ground motion at the considered site, originating from that scenario (Bommer, 2002). It is common to set ε=1 (epsilon is the number of standard deviations above or below the median) for the worst-case earthquake scenario in DSHA for critical facilities and this preference disregards 16% probability of which the design ground motions could be surpassed for the selected worst-case earthquake scenario (Bommer and Abrahamson 2006). According to Klügel (2008), DSHA in current regulations still use the state-of-the-art of the early 1980s and the new developments in DSHA practice (e.g. scenario-based deterministic methods, incorporation of local site effects and potential directivity factors) haven't been reflected to the current regulations/guides.

In the Probabilistic Seismic Hazard Assessment (PSHA), all possible and relevant deterministic earthquake scenarios (with all possible magnitude and location combinations) are considered and the ground motions at a range of epsilons are calculated (Figure 3.1). The essential difference between DSHA and PSHA is that the DSHA considers only one or a few M-D-ε (magnitude-distance-epsilon) scenarios, but the PSHA includes all potential combinations of M-D-ε, with rates attached to each scenario (Bommer and Abrahamson 2006). Therefore, PSHA can estimate the probability that various levels of ground motion will be exceeded in a given time period at a given location (Andrews & Folger, 2012).

In the early periods of the nuclear era, especially before 1997, most of the countries employed DSHA approach. DSHA was outlined in national or international regulations for nuclear industry (e.g. NRC RG 1.60 (1973) for USA, KTA rule 2201.1 for Germany or IAEA NS 3.3 (2002), which are not valid guides anymore) (Klügel, 2008). In USA, the DSHA approach was utilized in 1960s and 1970s (Andrews & Folger, 2012): most of the currently existing and operating NPPs (2 Western US sites and 28 Central/eastern US sites) had been designed using DSHA approach (U.S. NRC/NUREG/CR-7230, 2017). However, in the new guidelines (U.S. NRC/RG 1.208, 2007) that was developed by U.S. NRC, DSHA is completely replaced by PSHA: RG 1.208 is based on a fully-utilized PSHA framework and it repealed the previous regulation (RG 1.165). Currently, Germany, France, Japan, Korea and India still enforce the DSHA approach. According to the OECD report; France and Japan use only the deterministic approach; while Canada, Finland, Sweden, Netherlands and United Kingdom use solely the probabilistic approach, and Germany and South Korea enforce both methodologies at the same time (OECD/NEA, 2015).

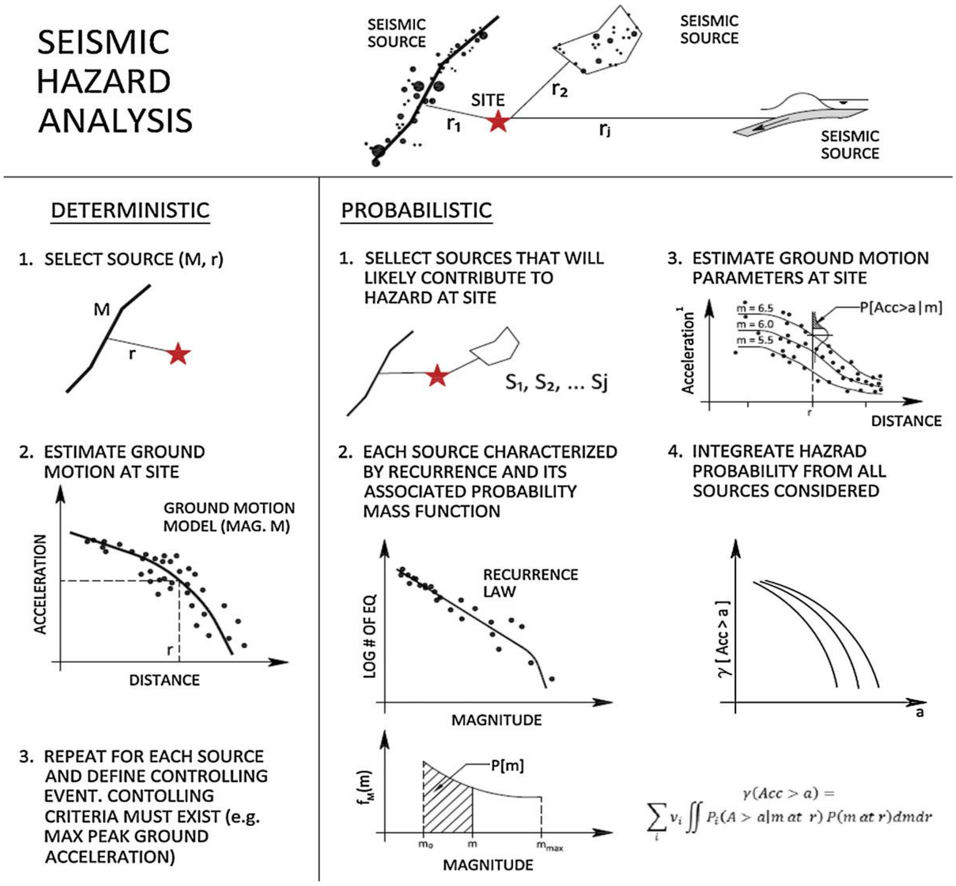


Figure 3.1. Seismic hazard assessment steps for PSHA & DSHA (after Ares & Fatehi, 2013)

IAEA recommends using both DSHA and PSHA methodologies during the evaluation of the ground motion hazard in SSG-9. NS-R-3 requires that the probabilistic methodologies should be considered and underlines the importance of performing probabilistic safety assessments for external events (IAEA/NS-R-3 rev.1, 2016; IAEA/SSG-9, 2010). This guide suggests that the DSHA can be used as a check against PSHA in terms of the rationality of the results, especially when small annual frequencies of exceedance are considered.

The seismic hazard analysis has a deterministic nature in Japan (U.S. NRC, 2013). The L-DS-I.02 guide that provides guidance on the seismic classification, seismic hazard analysis, and seismic design criteria was issued in 1977, revised in 2006, and had been utilized until the Fukushima accident. A DSHA methodology based on ground motion simulations, a.k.a. the “Recipe” approach, was generally employed in the previous nuclear projects in Japan. Recipe is a methodology based on source modelling for individual specific earthquakes to get the ground motion time histories from the waveform inversion (Irikura & Miyake, 2006a). Broadband ground motion time histories at the engineering bedrock are computed by a hybrid approach: for the long periods (>1 s), the 3D finite difference method is utilized while for the short period (<1 s) range, the stochastic Green’s function method that uses a 3D velocity structure model is preferred. After the ground motions at the bedrock is determined, the ground motions on the surface are estimated by using the 1D site response analysis (Iwaki, Maeda, Morikawa, Miyake, & Fujiwara, 2016). Main steps and the overall framework of Recipe approach is summarized in Figure 3.2.

In Recipe approach, seismic sources are defined by using the outer, inner and extra fault parameters (Irikura & Miyake, 2006a). The outer fault parameters are the standard parameters describing the size of an earthquake, such as the size of the rupture area, epicenter location, and the seismic moment (IAEA/SRS No.85, 2015; Iwaki et al., 2016). Area of the asperities and the stress drop on each asperity are considered as the main inner fault parameters (Irikura et al., 2004). Extra fault parameters are related to geomorphology of faults and they define the starting point and the pattern of the rupture propagation. Validation exercises of the Recipe methodology with the empirical earthquake ground motions had been published for 2000 Tottori and the 2004 Chuetsu (mid-Niigata) earthquakes (Iwaki et al., 2016), 1995 Kobe, 2005 Fukuoka, 2007 Noto-Hanto earthquakes (Irikura & Kurahashi, 2010; Morikawa, Senna, Hayakawa, & Fujiwara, 2008) and the 2003 Tokachi-oki subduction-zone earthquake (Irikura & Miyake, 2006b).

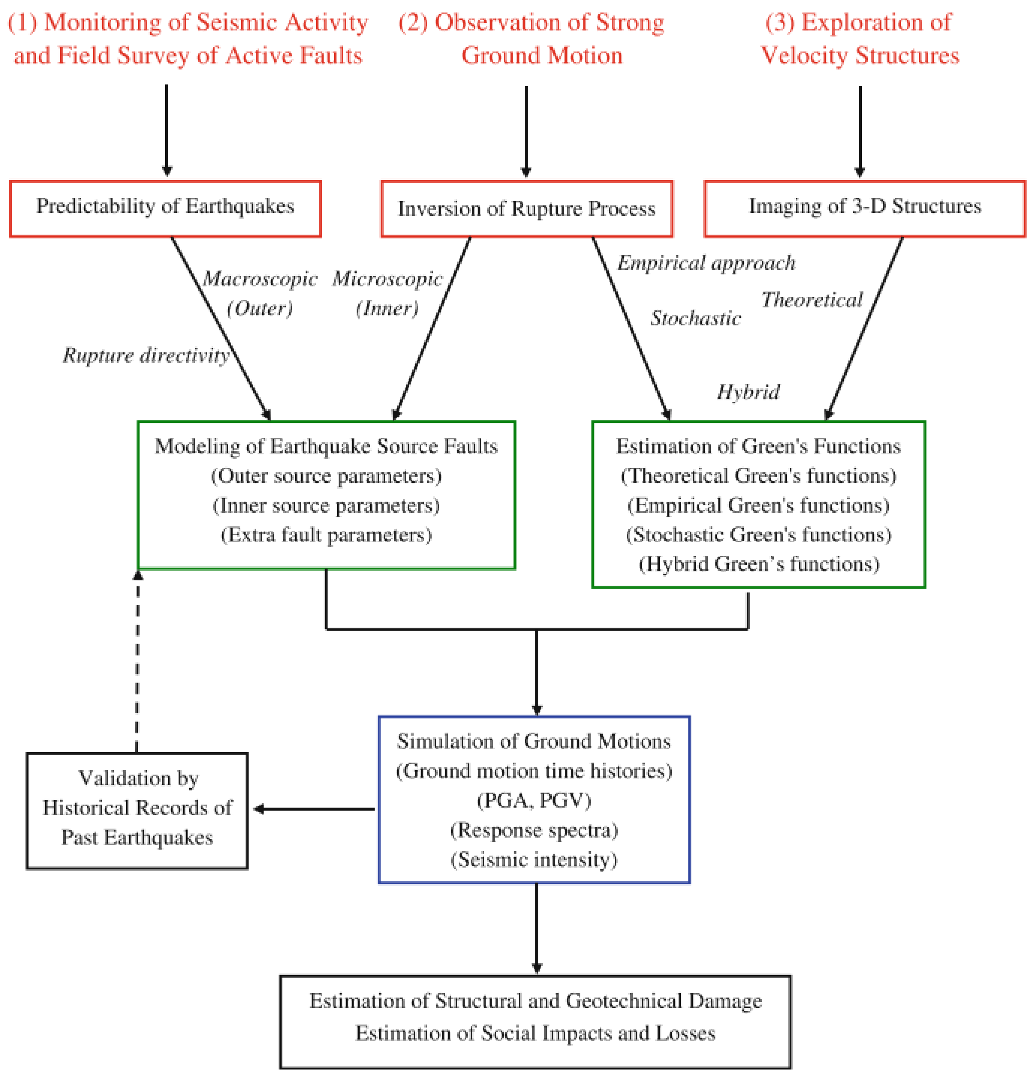


Figure 3.2. Framework of Recipe approach in Japan (after Irikura and Miyake 2011)

These studies showed that the results of Recipe approach are valid for the subduction zone earthquakes with M_w>8 and the crustal earthquakes that extend over 80 km in length (Fujiwara, Morikawa, Okumura, Ishikawa, & Nojima, 2012), except for the short period range (0.01–0.1 s) and for large hypocentral distances (>70 km) (Iwaki et al., 2016).

In 2013, after the foundation of NRA (Nuclear Regulation Authority of Japan, 2015), new regulatory requirements for NPPs in Japan were announced. New guidelines require that the consistent probabilities of exceedance should be referred for earthquake ground motions and their response spectrum that match the level of exceedance probability (Nuclear Regulation Authority of Japan, 2013e). New Japanese standard, namely the AESJ Standard for Seismic Probabilistic Risk Assessment, has been updated after Fukushima accident, and it has three main parts related to seismic hazards (Ebisawa, Kamae, Annaka, Tsutsumi, & Onouchi, 2014): (i) evaluation related to seismic hazard, (ii) seismic motion hazard evaluation, and (iii) fault displacement hazard evaluation. This standard may be considered as an improvement, putting into the practice the lessons learned from Japanese experiences after 2007, including 2011 Great Tohoku EQ.

In Finland, Regulations on the Safety of a Nuclear Power Plant (STUK/Y/1, 2016) and some YVL guides suggest the probabilistic risk assessment (PRA) methodology on external events and hazards (STUK/YVL A.1, 2013; STUK/YVL A.2, 2013; STUK/YVL B.1, 2013; STUK/YVL B.6, 2013; STUK/YVL E.6, 2013). External hazards that are considered possible at the site shall also be processed by means of a PRA in accordance with (STUK/YVL A.7, 2013). According to YVL A.7, PRA covers following subjects as the initiating events: "*the plant's internal failures, disturbances and human errors, loss of off-site power supply, fires, flooding, hoisting of heavy loads, abnormal weather conditions, seismic events and other environmental factors as well as external factors caused by human activities*". Even if STUK (regulatory authority of Finland) emphasize the importance of PRA, there is no specific requirement or suggestion about the seismic hazard methodology (PSHA and/or DSHA). It can be assumed that these guidelines implicitly recommend PSHA, because PRA is an inherently probabilistic approach and seismic PRA uses the outputs of the PSHA study (e.g. the hazard curves and fractiles).

Russian Federation accepted and used mainly the deterministic approach up to 1997. In 1997, the new national seismic hazard maps, GSZ-97 A, B, C, and D which corresponds to the approximate return periods of 500, 1000, 5000, and 10000 years, were prepared based on the probabilistic approach (Ulomov, 2003). Ground motions from GSZ-97 B (1000 years return period) and GSZ-97 D (10000 years return period) are employed as the design ground motions for the Design Earthquake (DE) and Maximum Design Earthquake (MDE) or Maximum Credible Earthquake (MCE) for NPPs, respectively (RTN/NP-031-01, 2002; RTN/PIN AE-5.6, 1999). Currently, some Russian guidelines (e.g. RTN/NP-064-05 2006; RTN/RB-006-98 1999) suggest both deterministic and probabilistic approaches; while some of the guides and standards promotes probabilistic approach instead of deterministic (RTN/NP-031-01, 2002; RTN/RB-019-01, 2002; RTN/RB-123-17, 2017). The most recent guideline about Level 1 seismic PSA clearly states that probabilistic seismic hazard analysis should be employed on new NPPs and NPPs under construction (RTN/RB-123-17, 2017).

In France, deterministic approach had been used for seismic nuclear safety assessment (RFS 2001-01, 2001). However, the official technical support organization of regulatory authority of France (IRSN) claims that both deterministic and probabilistic site-specific seismic hazard studies should be conducted in practice to get more robust evaluations of seismic risk at nuclear sites in France, especially for regions having low to moderate seismicity (Scotti, Clément, & Baumont, 2014).

In Turkey, TAEK’s site regulation and complementary guides require that probabilistic and deterministic methodologies should be employed simultaneously for seismic hazard studies, and methods must be up to date and compatible with the characteristics of the region (TAEK/Turkish Atomic Energy Authority 2009a;b). However, these regulations and complementary guides don’t have any specific provisions about the comparison of deterministic and probabilistic results. Generally, for the low seismicity regions, DSHA tends to predict higher median spectral values compared to PSHA. For the higher seismicity regions, DSHA and PSHA produce comparable results when recurrence period is considered 1000 year. Hence, considering 10.000 year period, PSHA results generally exceed the DSHA results (Scotti et al., 2014).

In Akkuyu NPP project, Licensee's (Akkuyu Nuclear JSC) technical teams performed both DSHA and PSHA in order to meet TAEK's requirements and IAEA safety guide's suggestions (Akkuyu Nuclear JSC, 2013, 2017). Three independent PSHA studies were performed by three different technical teams (Worley Parsons, Rizzo & Associates and KOERI) and DSHA was executed independently by Worley Parsons and KOERI teams. Eventually, all PSHA studies were consolidated into one PSHA report in 2016 and submitted to TAEK (Akkuyu Nuclear JSC, 2017). In the report, it is pointed out that "*a comparison is possible only if both epistemic and aleatory uncertainties have been considered in a similar manner in the PSHA and the DSHA*". For the DSHA, the response spectrum for ε=1 is considered (Akkuyu Nuclear JSC, 2017). For Akkuyu NPP site, the results of the three independent studies for the PSHA and the results of the DSHA were found to be within about 10% of each other (Akkuyu Nuclear JSC, 2017).

Within the scope of the feasibility studies for Sinop NPP, Licensee (EÜAŞ) and some other project sponsors decided to perform SHA to evaluate and demonstrate the suitability of the site and the viability of the project. Senior Seismic Hazard Committee (SSHAC) process, suggested by (U.S. NRC/RG 1.208, 2007) based upon two internationally excepted guidelines (U.S. NRC/NUREG-2117 Rev.1 2012; U.S. NRC/NUREG/CR-6372 1997a;b), has been employed for Sinop NPP. Until 2018, three SSHAC workshops were held and numerous detailed analyses were performed; however, the final report hasn't been finalized and submitted to Regulatory Authority yet.

One of the most important applications of the SSHAC process was performed between the years of 2000 and 2012 in Switzerland. The seismic hazard studies for commercial NPPs in Switzerland dates back to the early 1960's: PSHA methodology was employed at that time; however, the approach was relatively new and still in the early stages of practical application (ENSI, 2015). The seismic ground motions had been identified as an important contributor to the risk at four NPP sites, even if Switzerland is generally assumed to have a low-to-moderate level of seismicity (Grimaz & Slejko, 2014). In 1998, the HSK (the Swiss Nuclear Safety Inspectorate - predecessor to ENSI) requested to update the SHA for four Swiss NPPs (Mühleberg, Beznau, Gösgen and Leibstadt) because of the prominent advancements in the implementation of PSHA and the new systematic SSHAC framework for implementing PSHA. HSK requested the most elaborate form of SSHAC analysis, the Level 4 (ENSI 2015), and the Licensees accepted and performed the well-known 'PEGASOS Project' (Abrahamson et al., 2004). PEGASOS (Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-StandOrte in der Schweiz) (Wiemer, García-Fernández, & Burg, 2009) is one of the largest international seismic hazard studies that evaluates the earthquake-induced ground motion hazards and their uncertainty (Musson et al., 2005). Results of the PEGASOS project and the results from the older studies performed in the past two decades (Basler & Hofmann 1984, 1989, 1991, 1996) have significant differences. It was common practice to conduct PSHA without including the ground motion variability (epsilon), especially in the 1970s and early 1980s. Older PSHA studies for these four NPPs that were conducted between 1984 and 1996 did not include the ground motion variability as well. Therefore, the main inconsistency in the results is originated from the aleatory variability in ground motions. If the aleatory variability in ground motions (calculated within the PEGASOS project) are added to the previous results, findings of all studies would be comparable (Abrahamson et al., 2004).

After the completion of the PEGASOS study, several issues were raised up (Renault, 2012). In order to refine the hazard results based on new data, an updated earthquake catalogue, and updated ground motion models, PEGASOS Refinement Project (PRP) had been carried out between 2008 and 2012 by using again the SSHAC methodology (Grimaz & Slejko, 2014; Renault, 2012; U.S. NRC/NUREG-2117 Rev.1, 2012). Besides, new regulations about PSA (ENSI-A05/e, 2009) has been issued in Switzerland, changing the safety analysis from the deterministic to a fully probabilistic approach in 2009. Currently, the official regulatory guide (ENSI-A05/e, 2009) clearly states that PSHA shall be performed for nuclear facilities in Switzerland by complying with the SSHAC Level 4 methodology.

In summary, many countries including Japan (especially after Fukushima), which are studied in the scope of this study, are currently using the probabilistic approach. For many new nuclear projects in USA (Vogtle NPP, VC Summer NPP, Yucca Mountain, Diablo Canyon NPP), in Switzerland (PEGASOS & PRP), in South Africa (Thyspunt site), in New Mexico (Waste Isolation Pilot Project WIPP) (U.S. NRC/NUREG-2117 Rev.1, 2012), in Brazil (Angra dos Reis NPP) (Almeida et al., 2013), in Turkey (Akkuyu and Sinop NPP projects) (Akkuyu Nuclear JSC, 2013; Tractabel Engineering GDF Suez, 2017) etc., PSHA is used as the norm methodology and even the SSHAC process has gradually become a world standard. Switzerland has made it mandatory to use PSHA and SSHAC Level 4 in the new guidelines (ENSI-A05/e, 2009), and the Russian Federation also has favored the probabilistic methods and PSHA in the recently published guide (RTN/RB-123-17, 2017). Concordantly, the deterministic approach is mostly abandoned in SHA and safety assessments, or it exists as a secondary method for comparison and/or benchmarking of the PSHA results. DSHA maintains its importance for the reason that the presence of nuclear power plants in the world, which are still in operation and most of them were built in the period of 1960-1980 according to DSHA methodology.

3.2. Seismic Source Characterization in Nuclear Regulations

One of the main tasks of PSHA (or DSHA) is the development of seismic source characterization (SSC) model. SSC can be defined as the geographic allocation of seismic source zones and/or active/capable faults (Chen & Scawthorn, 2003) and defining the parameters required in PSHA for these sources. Description of the future spatial and temporal distribution of earthquakes can be considered as the cornerstones of SSC modelling (EPRI - U.S. DOE & U.S. NRC, 2012)

3.2.1. Radius of the region investigated and spatial scales

The initial step for SSC is the selection of the spatial scales (or areas) to be investigated, considering the density of the investigation activities for each scale. At this step, main geological definitions (definition of active fault, capable fault, surface faulting criteria etc.) should be solicited based on the applicable standards and/or regulatory requirements. After that, areal source zones and/or faults sources and their parameters can be defined based on the collected database. SSG-9 (Article 2.4) provides the requirements regarding the size of the region to be investigated, the type of information to be collected, and the scope and details of the investigations in accordance with the nature and complexity of the seismotectonic environment (IAEA/SSG-9, 2010). This guide suggests 4 different spatial scales in terms of radius around the NPP site as *regional scale* (typically 300 km), *near regional* scale (typically not less than 25 km), *site vicinity* (not less than 5 km) and the *site area* (that include the entire area covered by the nuclear power plant layout, which is typically 1 km^2). From regional scale to the site area, the intensity of the site investigations increases, and the type of the investigation shifts from geological surveys towards geotechnical site surveys and field tests.

Similar spatial scales are given by U.S. NRC in terms of radius as the *site region* (320 km / 200 mi), *site vicinity* (40 km / 25 mi), *site area* (8 km / 5 mi) and the *site location* (1 km / 0.6 mi) (U.S. NRC/RG 1.208, 2007). Similar to IAEA regulations, the density of the site investigations increases from the site region to the site location. From the seismic hazard perspective, whenever faults or other tectonic structures are encountered at a site, their capability (capable tectonic sources) shall be investigated (U.S. NRC/RG 1.208, 2007). Levels of requested investigations to characterize faults by considering the seismic environment and seismic design category (SDC) are explained in (ANSI/ANS-2.27, 2008) standard. According to this standard, for SDC-

5 level (e.g. NPPs), sources within 320 km (or more) that contributed more than %5 to total hazard should be identified and characterized for “low seismic environment” (please note that the maximum considered earthquake spectral response acceleration <0.1 g in “low seismic environment” and varies between 0.1 – 0.3 g for “moderate seismic environment”). For “high seismic environment” sites (>0.3 g), more detailed characterization of Quaternary faults within 40 km of the site is requested in addition to the criteria given above. U.S. NRC has another requirement about the minimum length of the fault to be considered versus the distance from site as given in Table 3.1. Applicants/Licensees need to report any significant neotectonic features according to these distance ranges, if they have a potential to impact the site safety (U.S. NRC/NUREG 800 2.5.3, 2014).

Table 3.1. Minimum length of fault to be considered versus distance from site when determining SSE (adapted from U.S. NRC/10 CFR Part 100 Appendix A 1973)

Distance (D) from the facility site (km)	Minimum length (km)
0 < D < 32	1,6
32 < D < 80	8
80 < D < 160	16
160 < D < 240	32
240 < D < 320	64

In Japanese regulations and standards published after the Fukushima Accident, there is no information on site investigation scales. In the pre-Fukushima period, two spatial scales were used (Park & Hofmayer, 1994); *survey of wide region* (within about 30 km of the site) and *survey of the site* (for the site and its vicinity).

In Russian Federation regulation (RTN/NP-031-01 2002, Appendix 2) it is recommended that the general seismic zoning should start with an assessment beyond 320 km and should be concentrated in radius at least 150 to 320 km range from the center of NPP in 1:500000 scale. For this scale, it is requested that identification of alternative sites in this area that are not disturbed by active faults that having a length of 30 km or more and identification of seismotectonic zones with their parameters.

NP-031-01 also requests that the refined seismic zoning should be concentrated in radius at least 25 km from the center of NPP on a scale of 1:50000. For this scale, it is requested that; (i) justification of alternative sites that are not disturbed by active faults with a length of 3 km or more, (ii) identification of seismotectonic zones with their parameters, (iii) identification of fault parameters (type, length, width, slip rate etc.).

Another Russian Federation regulation divides (in terms of radius from the reactor building) the considered region into; *region* (not less than 300 km), *location* (not less than 30 km), *site* (not less than 3 km), *controlled area* and *surveillance zone* (based on the radiation safety analysis results) (RTN/NP-006-98, 2003). On the other hand, the document (RTN/RB-019-01, 2002) proposes the following spatial scales which are wider than all other Russian Federation standard or regulations: *(i) planetary (20000 - 3000 km), (ii) regional (2000 - 300 km), (iii) district (200 - 30 km), (iv) district or local (20 - 10 km), (v) local (6 - 1 km)*. Taking these scales into consideration, it is recommended to conduct studies for "area sources" up to 300 km radius for nuclear facility sites and to investigate the "fault resources" for 30 km radius. For these spatial scales, the data to be collected and the studies to be performed are summarized in sub-chapter 3.2.4. It can be inferred that the dimensions mentioned in the different documents of the Russian Federation dealing with the spatial scales of seismic hazard are not fully consistent with each other.

TAEK defines 4 spatial scales such as *regional scale* (typically with radius of 150 km or more), *near regional* scale (25 km in radius), *site vicinity* (5 km in radius), and *site area* (includes the entire area covered by the NPP layout - typically 1 km^2) (Turkish Atomic Energy Authority 2009a).

Considering the Finland (STUK) approach, there is no provision about spatial scales in regulatory guides (YVLs). But a newly published report (OECD/NEA, 2019) indicates that Finland uses a 500 km radius for regional scale, which is beyond the radius defined by conventional practice. This report also provides some information about maximum spatial scales considered by different OECD countries, for example; France (200 km), Germany (≥200 km), Japan (100 km), Switzerland (300-500 km), Canada (500-800 km), England (5 km for site vicinity, 25 km for near region, 100 km for mid-region and 300 km for region). Considering this information holistically, it is possible to conclude that the countries with low seismicity (Finland, Canada, Russian Federation, Switzerland etc.) generally use relatively larger spatial scales. In contrast, countries located in more seismically active regions (such as Japan and Turkey) are using the narrower spatial scales.

Figure 3.3 compares the spatial scales employed by core countries and organizations considered this study. There is a clear consensus among the countries on the limits of the site area; almost all countries define site area as 1 km^2. Radius of the site vicinity varies between 3-8 km: 3 km is used by RTN (Russian Federation), 5 km is used both in TAEK's and IAEA's regulations, and 8 km is used by U.S.NRC. For the near regional scale, TAEK and IAEA use 25 km, RTN uses 30 km, and U.S.NRC uses 40 km. TAEK's requirement of 150 km radius for the regional scale is the smallest among the others, followed by RTN and IAEA with 300 km radius, and U.S.NRC with the largest radius of 320 km.

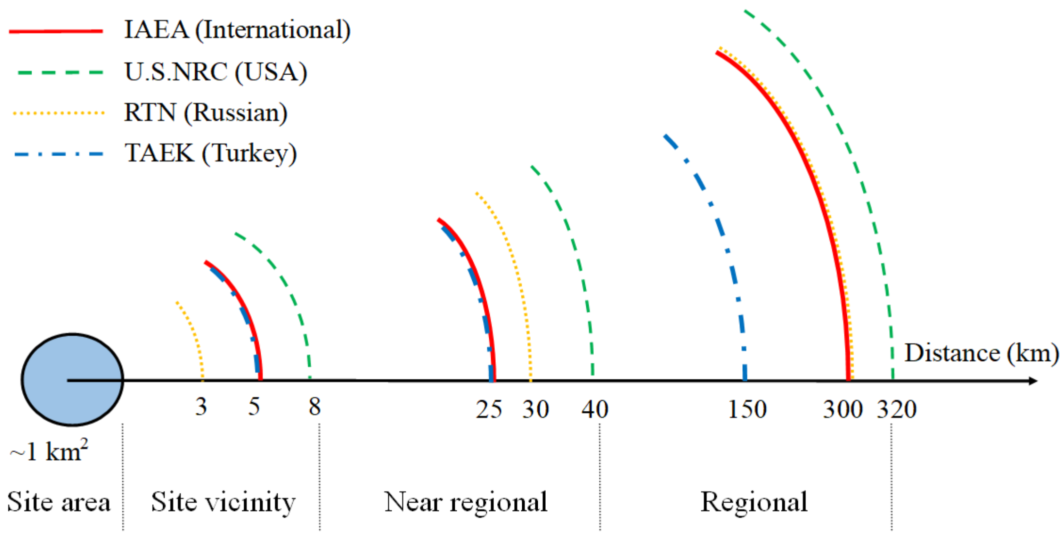


Figure 3.3. Comparison of investigated regional scales (drawn not to scale) (RTN values are based on NP-006-98, 2003)

In the Akkuyu NPP Project, TAEK considered the IAEA and Russian Federation requirements in addition to the national requirements according to "Directive on Determination of Licensing Basis Regulations, Guides and Standards and Reference Plant for Nuclear Power Plants" (TAEK/Turkish Atomic Energy Authority, 2012a) that requires that complete list of regulations, guides and standards forming the licensing basis for the plant shall be determined for each NPP project. IAEA spatial scales are implemented in Akkuyu case due to the fact that the IAEA documents have been agreed upon by all member states including Turkey and Russian Federation. According to site report for Akkuyu NPP site, the Licensee or the sub-contractor used more conservative approaches, for example one sub-contractor (Rizzo team) used the U.S. NRC scale, 320 km instead of 300 km for regional scale. Figure 3.4 demonstrates major tectonic structures in the Akkuyu (black circle is representing the regional scale 320 km). In Akkuyu NPP, 25 km radius are considered as "near regional investigations scale" as defined by IAEA.

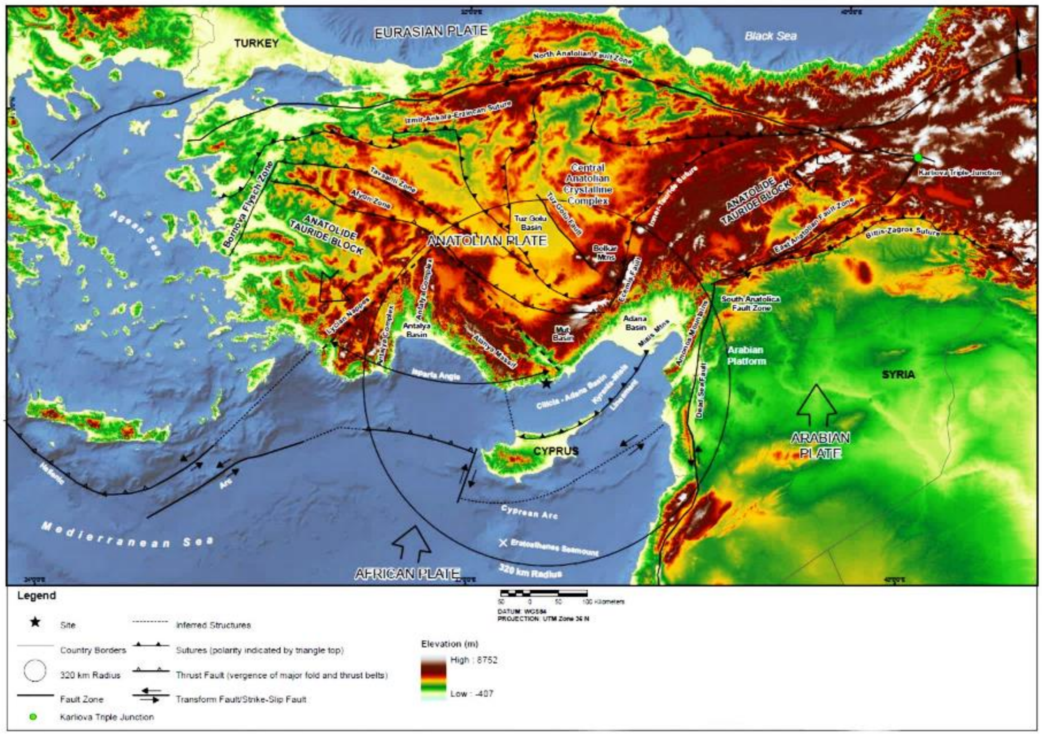


Figure 3.4. Major tectonic structures in the Akkuyu (Regional scale 320 km) (after Akkuyu Nuclear JSC 2017)

3.2.2. Geological definitions in nuclear regulations; active fault, capable fault, surface faulting and paleoseismology

IAEA describes the capable fault as “*seismogenic structures close to the site that has a potential for displacement at or near the ground surface*.” SSG-9 and NS-R-3 also use capable fault and surface faulting terminology interchangeably as stated in Article 8.4 of SSG-9 and (IAEA/SRS No.85, 2015);

- Periods in the order of tens of thousands of years (e.g., Late Pleistocene–Holocene) (1.8 My to present) may be appropriate for the assessment of capable faults for “*highly active areas*” where both earthquake and geological data consistently indicate short earthquake recurrence intervals (e.g., inter-plate regions),
- In “*less active areas*” (e.g., intra-plate cratonic areas), it is likely that much longer periods (e.g., Pliocene–Quaternary) (approximately last 5.3 My to present) are appropriate.

After the Fukushima accident, the IAEA safety requirement related to site evaluation for nuclear installations (IAEA/NS-R-3 rev.1, 2016) is updated and redefined the fault capability based on surface faulting definition consistent with SSG-9 approach.

IAEA suggests an in-depth investigation in the site vicinity (5 km radius) during the site selection process to evaluate fault capability (IAEA/SSG-35, 2015). Exclusionary distance criteria from the capable fault are typically considered as 8.0 km according to SSG-35, but (IAEA/TECDOC-1341, 2003) argues that the deterministic exclusion criterion for the distance to capable faults is a non-consensus value and it can be implemented differently, ranging from 0.5 km to 8.0 km by member states. On the other hand, SSG-9 implicitly recommends that there should be no capable fault at or near the site (within or near the 1 km radius); however, if there is a capable fault in this area, SSG-9 does not set a clear exclusion criterion, stating that its parameters (direction, extent, history, and rate of movements, etc.) should be determined.

SSG-9 defines paleoseismology as the study of the geological record of prehistoric and historical earthquakes. When historical earthquake records are limited, paleoseismological studies may be particularly useful. Purposes of paleoseismic studies are: (i) to identify seismogenic structures by recognition of effects of past earthquakes in the region, (ii) to improve the accuracy of earthquake catalogues for large events, identification, and dating of fossil earthquakes, (iii) to evaluate the maximum potential magnitude of a given seismogenic structure, (iv) to calibrate the PSHA by using the recurrence intervals of large earthquakes (IAEA/TECDOC-1767, 2015).

In the U.S. NRC approach, one fault can be regarded as a capable fault for demonstrating the following characteristics (U.S. NRC/10 CFR Part 100 Appendix A, 1973):

- Movement within the past 35ky at least once (upper limit of C^{14} dating at the time) or recurred movement (more than one) within the past 500ky.
- Direct relationship with a fault and instrumentally recorded macro seismic activity.

Capable fault definition of 10 CFR Part 100 Appendix A and (U.S. NRC/RG 1.208, 2007) is fully compatible with considering a 500ky (recurring) period. But, RG 1.208 declares 50ky instead of 35ky indicated at 10 CFR Part 100 Appendix A for the at-least-once-movement period.

Surface faulting is defined as "*differential ground displacement at or near the surface caused directly by fault movement*" (U.S. NRC/10 CFR Part 100 Appendix A, 1973). Hence, RG 1.208 emphasizes that capable tectonic sources do not always show deformation at the ground surface. Therefore, this guide suggested that detailed investigations need to be performed on the ground surface and in the subsurface to characterize all geological structures. Generally, within a radius of 8 km, candidate sites have minimal likelihood of surface or near-surface deformation and a minimal probability of earthquakes on faults within the boundary. For tectonically active areas, Quaternary or Holocene is particularly critical considering surface or near-surface deformation, whereas, for the stable continental regions, recurrence times may vary between hundreds of thousands of years (ANSI/ANS-2.30, 2015).

U.S. NRC does not specify a precise exclusion criterion for the nearest capable fault distance from the nuclear facility. U.S. NRC does not require that the site is neglected in case of the presence of a capable fault within an 8 km radius, but it recommends selecting another site as an alternative. Otherwise, more detailed geological, geophysical, seismological, and geotechnical studies must be performed in the area (DOE-STD-1022, 1994; U.S. NRC/RG 1.208, 2007; U.S. NRC/RG 4.7 (rev.3), 2014).

In Japan, the term "active fault" is still used instead of the "capable fault." After the Fukushima accident, NRA has decided to tighten their standards and declared that the faults with activities later than the Late Pleistocene (later than 120 ky-130 ky) should be considered for seismic hazard. Additionally, faults with activity in the middle Pleistocene (more than 400ky) have to be evaluated (Ahn et al., 2015; Horino, 2014; Nuclear Regulation Authority of Japan, 2013e, 2013b, 2013f; Tomita, 2014). For the Japanese case, the time frame has increased from 50ky to 120ky-130ky even more than 400ky. This is more conservative than SSG-9 and previous Japanese requirements (50ky). Japan's NRA does not specify an exclusion criterion for the nearest capable fault distance from the nuclear facility. Instead, NRA requires that important structures of a nuclear facility cannot be located on the outcrop of capable fault (Horino, 2014; Nuclear Regulation Authority of Japan, 2013b, 2013e).

Russian regulations (RTN/NP-031-01, 2002) have two definitions: the "*seismically active fault*" is defined as the "*discontinuous disturbance the Earth crust to which the past or recent seismic occurrences are dated (earthquake sources, paleoseismic dislocation, seismic dislocation)*" and the "*tectonically active fault*" is defined as *"tectonic fault within the area whereof the displacement of adjoining blocks by 0,5 m and more took place over the last 1 My*" (approximately since Middle Pleistocene). "*Tectonically active fault*" term defined by NP-031-01 may be considered as "*capable fault*" in terms of internationally excepted terminology. On the other hand, this document considers that the quaternary period dates back to 1My, but this definition is not fully compatible with the formal definition (Cohen, Finney, Gibbard, & Fan, 2014). The Quaternary period comprises 1.6 My, according to Andrews and Folger (2012), 1.8 My, according to Harding et al. (2006), 2-3 My by Bell (2015) and according to formally accepted chronology, it is 2.588±0.005 My (Cohen et al., 2014). Even in the other Russian codes (e.g., RB-019-01) beginning of the Quaternary period is defined as 1.8 My (RTN/RB-019-01, 2002).

RB-019-01 suggests that homogeneous tectonic block near NPPs within the 30-km radius should be selected, and they should be devoid of tectonically active structures. In this regard, it suggests to carry out detailed investigation and exploration within the NPP site and its vicinity in a radius up to 8 km in order to validate the absence of active faults within this radius (RTN/RB-019-01, 2002). Moreover, another Russian Federation guide (RTN/NP-032-01 2002) does not allow NPPs in sites directly situated on an active fault. This guide also prohibits sites when the seismicity is categorized by the maximum credible earthquake (MCE) intensity of more than 9, according to the Medvedev-Sponheuer-Karnik intensity scale (MSK-64) (RTN/NP-032-01, 2002).

In Turkey's NPP guides, geological issues are mainly regulated by two documents: Regulation on Nuclear Power Plant Sites (RNPPS) and Guide on Specific Design Principles (GSDP). RNPPS specifically requires focusing on neotectonic structures and micro-earthquake observations to locate capable faults. A neotectonic period is defined as the latest wholesale tectonic reorganization in an area (Şengör, 1980). Such an improvement around Turkey took place by the end of the Middle Miocene (11.63 My), and it is regarded as the beginning of Neotectonic period in Turkey (Şengör 1980). Capable fault is defined as "*(a) Movement at or near the ground surface at least once within the past 35,000 years or movement of a recurring nature within the past 500,000 years*" and *"(b) Macro-seismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault"* by (TAEK/Turkish Atomic Energy Authority, 2009b). This definition is almost the same as the definition used by U.S. NRC/10 CFR Part 100 Appendix A. According to the

GSDP, NPPs shall not be placed on sites directly located on active faults (TAEK/Turkish Atomic Energy Authority, 2012b). This guide prefers to use “active fault” terminology contrary to the RNPPS. TAEK regulations do not provide any specific screening distance value for the distance from capable fault; however, it enforces IAEA and Russian approach both of which have similar exclusion criterion for the nearest capable fault distance from the nuclear facility and it is typically 8.0 km. It is also compatible with U.S. NRC approach

In Akkuyu NPP site, in addition to the 10 trenches excavated and reported in 1983, 4 additional verification trench studies were conducted in 2011 to confirm that there is no capable fault. As a result of these studies, it is reported that there is no capable fault in Akkuyu NPP site.

Diablo Canyon Nuclear Power Plant (DCPP) is a striking example related with this issue, because a capable fault was discovered after the site selection. For the Western United States (WUS) plants (Diablo Canyon and San Onofre in California, Palo Verde in Arizona, and Columbia in Washington), seismic source characterization is much more site-specific and generally local faults dominate the seismic hazard (Richards, Hamel, & Kassawara, 2012). During the site evaluation process, geological and seismological site investigations for DCPP limited to land area, and the sources beneath the Pacific Ocean was not considered in the 60s. Hence, one of the important capable faults, also known as the Hosgri fault, couldn’t be considered in the original seismic source characterization. Construction began in 1968 at Diablo Canyon, and during the construction period (in 1971), Hosgri fault was discovered just 3.5 miles offshore. Including this fault in DSHA as requested by US NRC regulations at that time would have had a remarkable impact on the design basis of the plant (J.-U. Klügel, 2008). Additionally, in 2008, a new fault (the Shoreline fault) located within 2,000 feet distance of the reactors and 1,000 feet from the water intake structure has been found after the plant had been operating for almost two decades.

In 2012, after the Fukushima accident in Japan, U.S. NRC has requested that all operating NPPs in the U.S. perform a site-specific PSHA and develop a ground motion response spectrum in accordance with Regulatory Guide 1.208 for comparison to the SSE ground motion in the plant license (Lettis et al., 2015). By performing a SSHAC Level 3 study, the site-specific seismic source characterization model was developed for DCPP between June 2011 and March 2015 (Lettis et al., 2015). Former evaluations of the seismic hazard at the DCPP site have presented that the hazard is controlled by the four adjacent (<10 km) faults (Hosgri, Shoreline, Los Osos, and San Luis Bay faults). The DCPP site is also located on the hanging-wall side of the nearby dipping faults. Based on the deaggregation, at low probability levels, the earthquakes with magnitudes between 5.5 and 7.0 at short distances (<10 km) control the hazard at the high frequencies (>5 Hz). For the low frequencies (<1 Hz), the controlling earthquakes are shifted slightly to higher magnitudes (M6.0 - M7.5), but are still at short distances (<10 km) (GeoPentech, 2015). After, as a result of many years of seismic studies and technical discussions, Pacific Gas & Electric Company (PG&E) (operating organization of DCPP) requested withdrawal of its license renewal application that having requested 20 years of additional operation for DCPP. U.S. NRC has accepted this request. Consequently, DCPP Unit 1 will have been closed on November 2, 2024 (U.S. NRC, 2018).

3.2.3. Seismic source modelling in nuclear guidelines

In PSHA terminology, "fault sources" and "area sources" define the two general categories of seismic sources that are implemented in seismic hazard studies. Planar fault sources are preferred when a specific capable fault, e.g. North Anatolian Fault Zone in Turkey, is considered (Abrahamson et al., 2004). By using the geological information and historical seismicity, an active/capable fault can be modelled as a planar seismic source (Atkinson, 2004). Typical parameters of the planar fault sources are the location, geometry, depth extent, slip sense, slip rate, magnitude-frequency distribution shape, and probability of occurrence of an earthquake in a given time period. Area sources are described by their defined location, crustal thickness, rate of earthquakes, maximum magnitude potential (M_{max}), and magnitude-frequency distribution shape (Lettis et al., 2015). Area sources are utilized in cases where the active tectonic structures are not well-defined (e.g. buried faults) and only the seismicity is used to establish the rates of earthquake occurrence for earthquakes of different magnitudes (Atkinson, 2004). Typically, the historical seismicity is assumed to be uniformly distributed over specified source zones (Abrahamson 2006). However, this uniform spatial distribution assumption within a source area can be a poor approximation of the actual spatial distribution (Pavlenko 2016).

SSG-9 defines these two types of seismic sources as the *seismogenic structures* (capable faults) and *zones of diffuse seismicity* (area sources), mentioning that the location and the earthquake potential of seismogenic structures could contribute to both the seismic hazard and fault displacement hazard. Because of this potential, SSG-9 suggests that the main seismogenic structure characteristics to be determined are: the dimensions of the structure (length, down-dip, width), orientation (strike, dip), amount and direction of displacement, rate of deformation, maximum historical intensity and magnitude, paleoseismic data, and geological complexity (segmentation, branching, structural relationships). Additionally, the magnitude–frequency relationship should be derived for each seismogenic structure in order to determine the activity rate, type of magnitude–frequency relationship (exponential, characteristic etc.) and the associated uncertainty for each considered parameter. For diffuse seismicity zones (or areal source), SSG-9 recommends that:

- each seismotectonic province have geographically uniform rate of seismicity (if the opposite can be shown based on the data, geographically non-uniform distribution of seismicity can also be used),
- depth distribution of the diffuse seismicity zones should be incorporated,
- significant differences in activity rates, focal depths, focal mechanism, states of stress, tectonic characteristics, and b-values can be assumed as the indicators of the boundaries of the seismotectonic provinces.

In USA, the regulatory guide (U.S. NRC/RG 1.208, 2007) defines 4 distinct types of seismic sources*: (i) fault sources, (ii) area sources representing concentrated* *historical seismicity that is not associated with known tectonic structures, (iii) area sources representing geographic regions with similar tectonic histories, type of crust, and structural features, and (iv) background sources*. Two geographical regions of USA are defined with respect to the differences of source characteristics in seismic source modelling (Figure 3.5). In CEUS region, background and area sources tend to dominate the hazard results in contrast to the WUS, where the fault systems are significant and control the hazard (U.S. NRC/NUREG/CR-7230, 2017). For CEUS region, the historical and instrumental seismicity is generally not associated with surface faulting, it is difficult to find any evidence of prehistorical earthquakes, and strain-rates are remarkably low (except the New Madrid Seismic Zone and some other few zones in CEUS). Figure 3.6 presents one of the most recent seismotectonic models developed for the NPP sites in CEUS region, indicating that the seismotectonic model is solely composed of areal source zones. On the contrary, having tectonically more active areas than the CEUS region, identification of the active faults permitted fault source modelling (EPRI - U.S. DOE & U.S. NRC, 2012) in WUS and site specific hazard studies were performed according to SSHAC process for four NPP sites in WUS (U.S. NRC/NUREG/CR-7230, 2017). At larger distances, the effect on hazard from fault and area sources is similar. Thus, faults and small area sources at larger distances can usually be generalized as large area sources (U.S. NRC/NUREG/CR-6372 1997a).

For the Diablo Canyon NPP site in WUS (representing the most recent example that have applied the U.S. NRC practice), fault sources and area sources were combined in the PSHA analysis. Faults sources were categorized according to the spatial scales discussed in Section 3.2.1 as: (i) primary fault sources (Hosgri, Los Osos, San Luis Bay, and Shoreline faults) that are located within 12 km of the DCPP and (ii) regional fault sources located between 40 to 320 km radiuses as shown in Figure 3.7 (Lettis et al., 2015). The largest one of the regional fault sources is the San Andreas Fault located roughly 80 km northeast of Diablo Canyon NPPs. This fault contributes a few percent to the total hazard at long periods. Besides the San Andreas Fault source, the other regional fault sources represents less than 1% of the aggregated total hazard (Lettis et al., 2015). Primary fault sources that are expected to have a major contribution to the total hazard were studied and analyzed extensively. At low probability levels (especially for 10^{-3} to 10^{-6} annual frequency of exceedance), the hazard was controlled by the primary fault sources and by the earthquakes to be occurred at a depth between 12 to 15 km (GeoPentech, 2015). Three areal background source zones (Regional, Vicinity, and Local) are considered in the Diablo Canyon seismic source characterization model (Lettis et al., 2015) as shown in Figure 3.8. Geometry of the Regional and Vicinity areal source zones roughly matches with the definitions of "site region" (with areas described by radii of 320 km) and "site vicinity" (40 km) defined by (U.S. NRC/RG 1.208, 2007).

The new NRA Guide of Japan divides the earthquakes into three different classes as: the crustal earthquakes, inter-plate earthquakes and intraplate (subducting or subducted/intra-slab) earthquakes. The guide suggest that during the site investigation process, all three earthquake types should be considered and their parameters (earthquake distribution, details of geometry/fault location, length, width, displacement, kinetics, and interactions etc.) should be collected considering the distinct physical characteristics of each type (Nuclear Regulation Authority of Japan, 2013c). Seismic sources are divided into two classes; "*earthquake ground motion formulated with a hypocenter specified for each site*" and the "e*arthquake ground motion formulated without a hypocenter specified*". First definition is similar to the seismogenic sources/capable faults defined in SSG-9 and the second one might be considered as similar to diffuse seismicity zones/area sources. NRA also suggest that the fault length, seismogenic layer thickness, fault inclination angle, fault displacement, mechanisms, fault fracture process, asperities, scaling rule, fault-to-fault interactions (coupled motions of multiple faults), etc. should be identified for fault sources (Nuclear Regulation Authority of Japan, 2013c).

In Finland, there aren't any specific provisions about the type of seismic sources and related source parameters in STUK Guides.

In Russian Federation guidelines, “area source” and “fault source” are defined as the two main source modelling options (RTN/NP-031-01, 2002; RTN/RB-006-98, 1999). Area source parameters are listed as the maximum magnitude, focus depth, focus mechanism, seismic regime parameters etc. For fault sources; segmentation, length, width, dip angle, amplitude, slip rate etc. are defined as the main source parameters (RTN/NP-031-01, 2002) (RTN/RB-006-98, 1999) without any further details.

In Turkey, the site regulation (TAEK/Turkish Atomic Energy Authority, 2009b) mentions area sources for seismic hazard assessment (without any specifications about the parameters of area sources) and faults are only mentioned in terms of surface faulting phenomena. In the Guide on Site Report Format and Content for NPPs (TAEK/Turkish Atomic Energy Authority, 2009a), area sources are included, however, compilation of some fault parameters (types of faults in seismotectonic zones, their length, depth, dip angle, relations with each other and activity/capability properties) is recommended. In Akkuyu NPP Project, all of the seismic sources are defined as area sources and no planar fault modelling has been included in PSHA (Figure 3.9). Majority of the area sources had crustal characteristics; deeper sources for the subduction interface and intra-slab were only included in the Envy-KOERI (Kandilli Observatory and Earthquake Research Institute) Model#2 and Rizzo models (shaded sources in Figure 3.9 shows the seismic sources that represent the subduction zone). Sources close to the Akkuyu site (or the host zone) was also characterized by diffuse seismicity sources (Akkuyu Nuclear JSC, 2017). In the Sinop NPP Project, both area source and fault source models (drafts) are developed for the official SSHAC workshops, however, the final PSHA report hasn’t been finalized and submitted to the regulatory body yet.

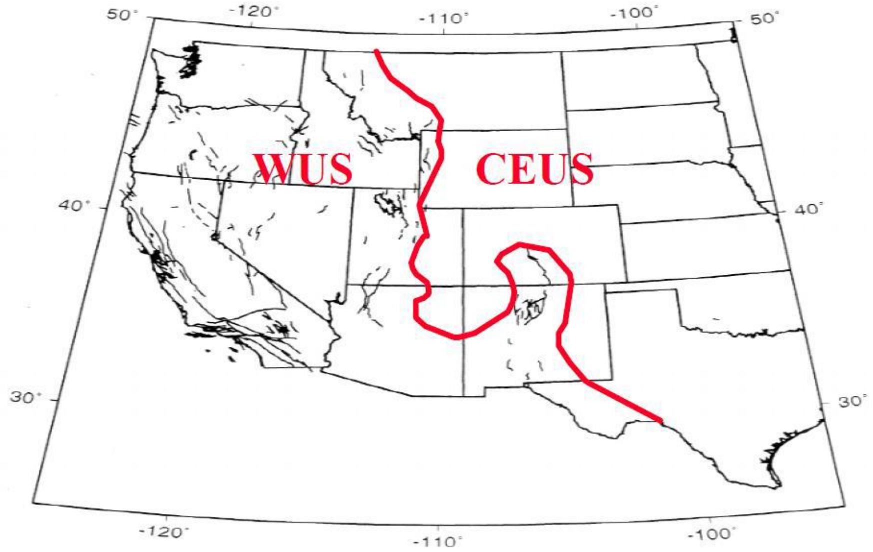


Figure 3.5. WUS and CEUS regions of United States, defined by USGS (after Como 2009)

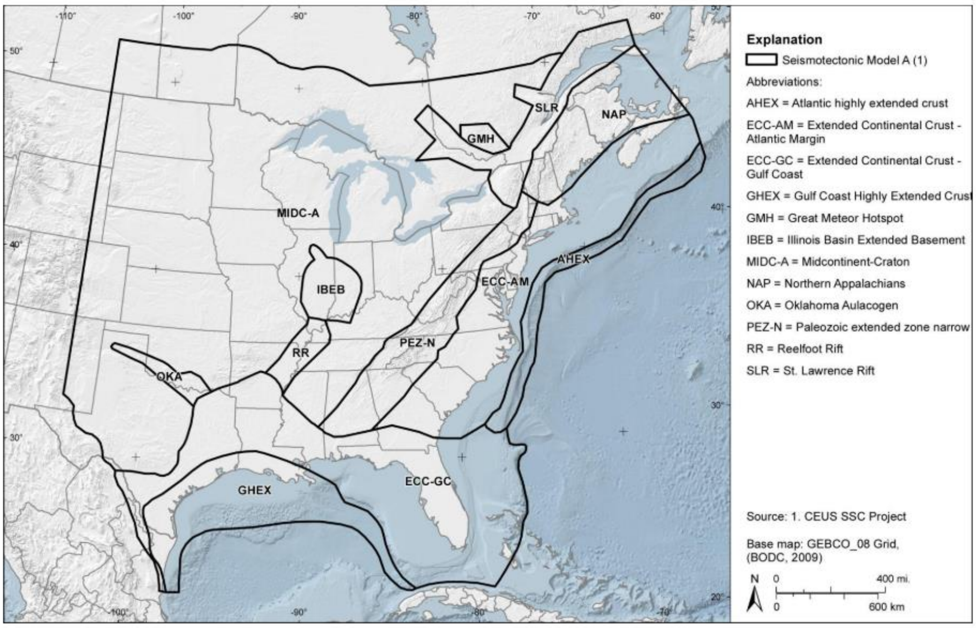


Figure 3.6. An example seismotectonic model used in CEUS seismic source characterization (after EPRI - U.S. DOE & U.S. NRC 2012)

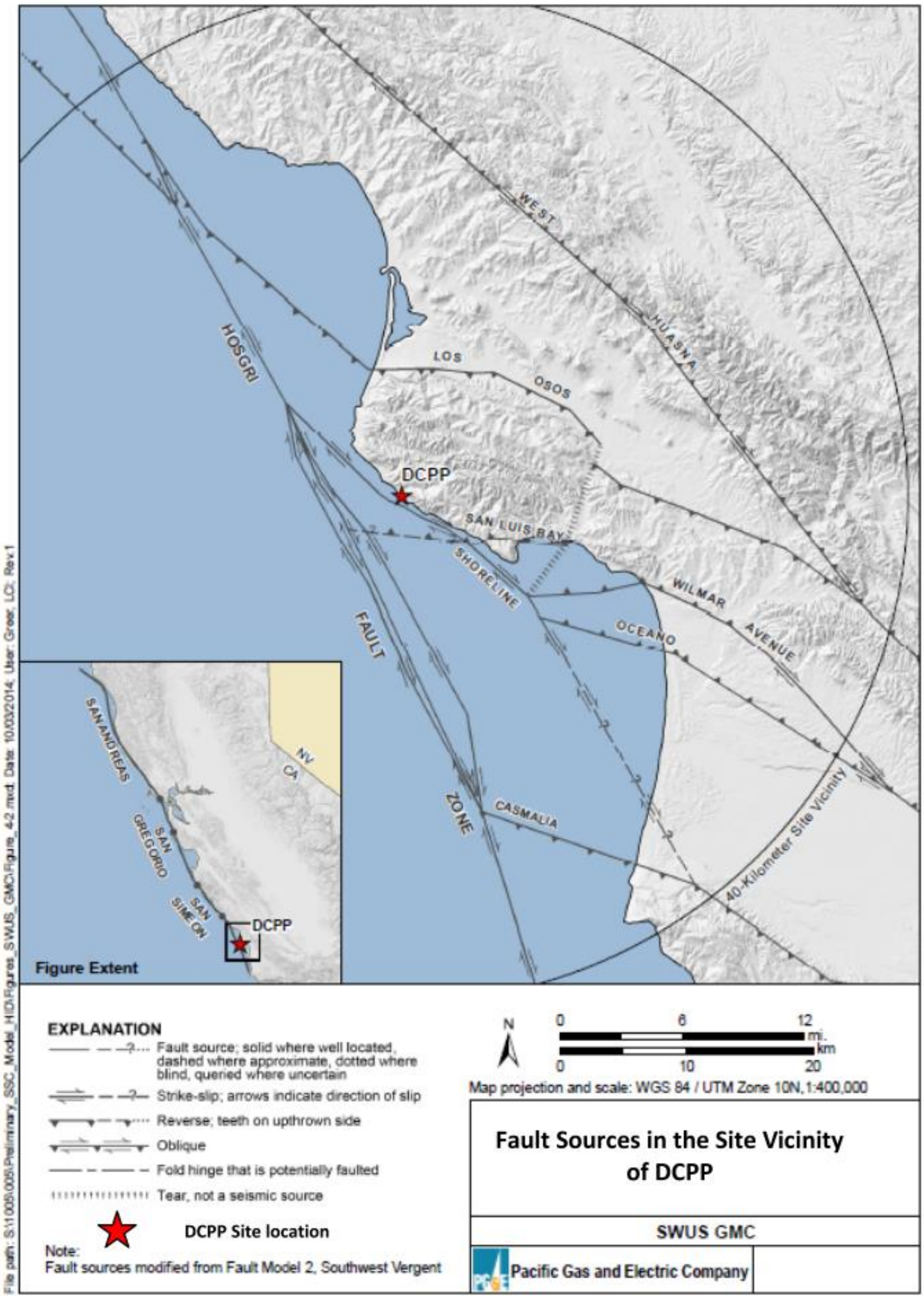


Figure 3.7. Fault sources in the site vicinity (40 km) of Diablo Canyon Power Plant (taken from GeoPentech, 2015)

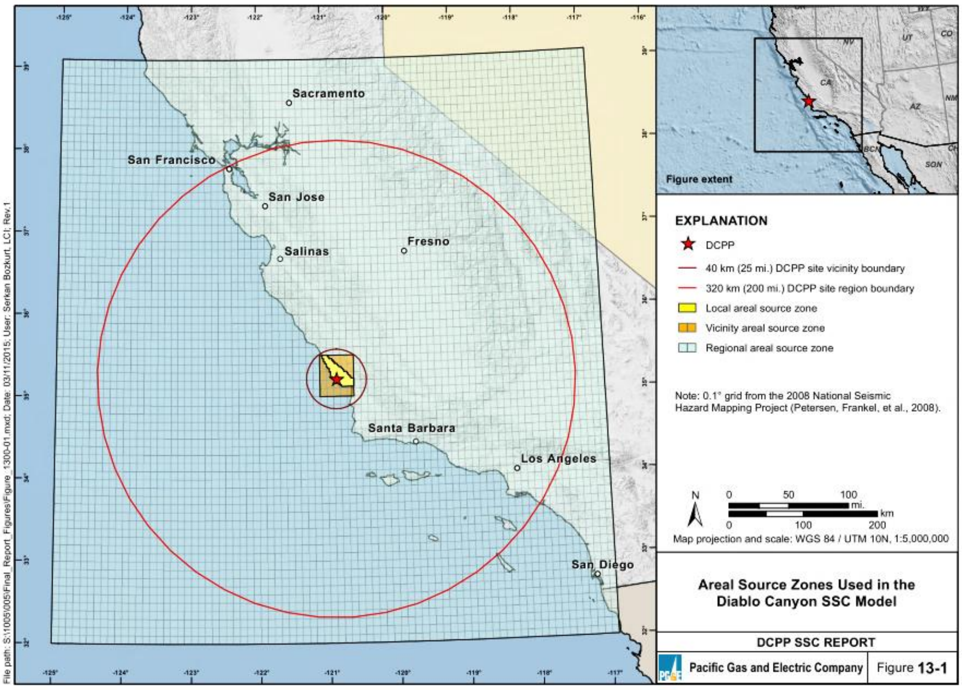


Figure 3.8. Areal source zones used in the Diablo Canyon seismic source characterization model (taken from GeoPentech, 2015)

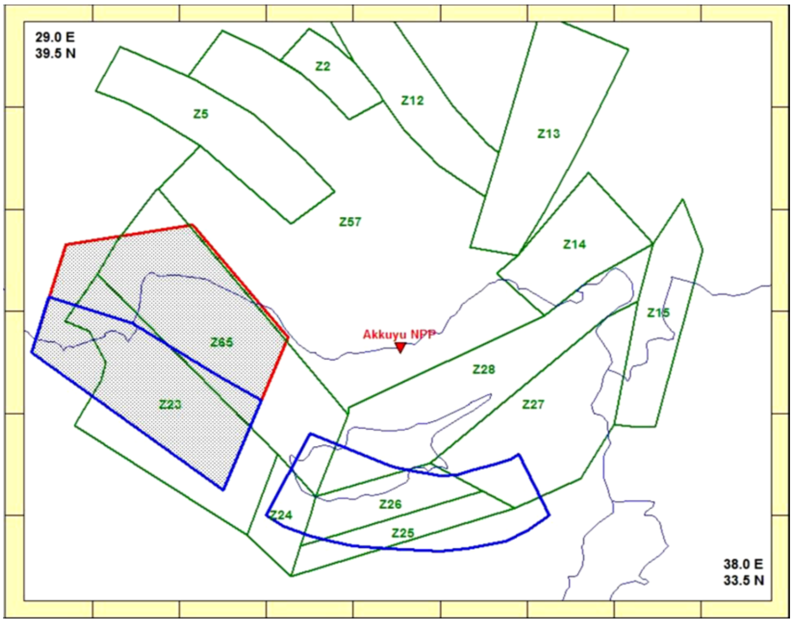


Figure 3.9. Areal Source Zone Model suggested by Kandilli Observatory and Earthquake Research Institute (KOERI) for Akkuyu NPPs (after Akkuyu Nuclear JSC 2017)

3.2.4. Data collection requirements and the earthquake catalogue

In order to support the site characterization and SHA studies with an up-to-date and site-specific database, both SSG-9 and RG 1.208 require that geological, seismological, and geophysical investigations should be performed by increasing the intensity of the investigations and diversifying them according to the requirements, from larger regional scales (~generally 300-320 km) to the relatively smaller site level (~generally 1 km^2). According to SSG-9, IAEA suggested the following investigation methods and data collection activities by considering spatial scales explained at Chapter 3.2.1;

- For **regional scale** [typically 300 km]; broad geological data collection and investigations, identification of current tectonic regime, literature review for geological and geophysical data, paleoseismological investigations, compiled earthquake catalogue etc.,

- For **near regional scale** [≥25 km]; seismotectonic characteristics of the near region, latest movements of faults, rates of activity, segmentation of faults, geometry, extent and rate of deformation for fault sources, interferometry data for deformations, stratigraphy, structural geology, age dating methods for assessment of fault capability, geophysical investigations [seismic reflection, refraction, gravimetric, electric and magnetic techniques etc.], interpretation of aerial and satellite photographs etc.

- For **site vicinity** [≥ 5 km]; geomorphological and geological mapping, geophysical investigations and profiling, boreholes and trenching; age, type, amount and rate of displacement of all the faults in the area etc.

- For **site area** [~ 1 km^2]; detailed geological, geophysical and geotechnical studies, including in situ and laboratory testing, investigations on “potential for permanent ground displacement phenomena” (surface faulting, liquefaction etc.) because of earthquakes, geologic mapping (including stratigraphic and structural mapping, hydrogeological investigations.

NUREG 2117 indicates that geological data collection process can include field studies, remote sensing imagery, geodetic measurements, gravity and magnetic surveys, trenching, dating, etc. (U.S. NRC/NUREG-2117 Rev.1, 2012). Another US Standard (ANSI/ANS-2.27, 2008) provides guidelines for compilation and analysis of seismotectonic database for the region of interest. Required data types and field work for identifying and characterizing fault and area sources are catalogued in this standard as shown in Figure 3.11. Also, in U.S. approach, examples of suggested investigation and data collection activities considering different spatial scales are summarized briefly at Table 3.2.

Table 3.2. Collected data and suggested investigations considering different spatial scales according to US approach

Investigation Area (spatial scales)	**Main Purpose / Characteristics**	**Investigations / Collected Data**
"Site Region" (320 km - 40 km)	- to identify seismic sources and describe the Quaternary tectonic regime - quite broad investigations - comprehensive literature review - onsite ground-truth survey (if necessary)	- regional geologic mapping - aerial photographs - other remote sensing imagery - topographic mapping - earthquake catalogue (including historically and instrumentally recorded data) within a radius of 320 km of the site
"Site Vicinity" (40 km - 8 km)	- to identify and characterize the seismic sources and surface faulting potential - "reconnaissance-level investigations"	- geologic mapping (including stratigraphic and structural mapping) - geophysical surveying (e.g., seismic reflection, seismic refraction, aeromagnetic, gravity, etc.) - borings, and trenching etc.

Table 3.2 (continued)

"Site Area" (8 km - 1 km)	- "to delineate the geology and the potential for tectonic deformation at or near the ground surface" - quite detailed investigations - detailed geological, seismological, geophysical, and geotechnical investigations	**Surface Investigations** - aerial photographs and other remote-sensing imagery - topographic mapping - geomorphic mapping - hydrologic surveys - descriptions of stratigraphy (particularly Quaternary) - descriptions of surface tectonic structures - descriptions of Quaternary geomorphic features - evaluation of vertical crustal movements (geodetic surveys etc.) - fault scarp morphology - etc. <u>For coastal sites (additional surveys)</u>; - geomorphology (particularly mapping marine and fluvial terraces) - bathymetry - submarine landslides - geophysics (e.g. seismic reflection) - hydrographic surveys **Subsurface Investigations** - geophysical investigations (magnetic and gravity surveys, seismic reflection and refraction surveys, bore-hole geophysics, electrical surveys, GPR etc.) - map subsurface geology - trenches - etc.
"Site Location" (~≤ 1 km)	- very detailed geological, geophysical, and geotechnical engineering investigations - to assess specific soil and rock characteristics	- exploratory trenches - the mapping of the excavations for the plant structures (especially seismic class 1) - geological, geophysical, and seismological investigations (indicated above) - detailed geotechnical investigations according to RG 1.132 (not directly related to seismic studies)

A trade-off always exists between the potential for uncertainty reduction in PSHA and the resources required to conduct new data collection activities (U.S. NRC/NUREG-2117 Rev.1, 2012). However, comprehensive data compilation is a crucial primary requirement for SHA studies (U.S. NRC/NUREG-2117 Rev.1, 2012). Actually, the data collection problems faced with in mid-1980s is the driving force of the development of SSHAC process in USA. Results of two important studies, EPRI 1989 and "Lawrence Livermore (LLNL)" (Bernreuter et al. 1989), which were aiming to characterize ground motion in the U.S. East of the Rocky Mountains, presented differences in mean seismic hazard curves for most of the sites that could not be easily explained. The main reason of the establishment of SSHAC was to examine the cause of these alterations and offer methodological guidance. SSHAC process identified that procedural issues were the main reason of the difference between two studies, and technical considerations have only minor impact. SSHAC also pointed out the need for a formalized procedure that could increase the stability of future studies and advised procedural guidance at 4 different 'levels of complexity' (from 1 to 4 degree of sophistication, effort and additional means and resources increases) for a PSHA study (Abrahamson et al., 2004). These 4 different levels can be seen at Figure 3.10.

ISSUE DEGREE	DECISION FACTORS	STUDY LEVEL
A Non-controversial; and/or insignificant to hazard		**1** **TI** evaluates/weights models based on literature review and experience; estimates community distribution
B Significant uncertainty and diversity; controversial; and complex	•Regulatory concern •Resources available •Public perception	**2** **TI** interacts with proponents & resource experts to identify issues and interpretations; estimates community distribution
C Highly contentious; significant to hazard; and highly complex		**3** **TI** brings together proponents & resource experts for debate and interaction; **TI** focuses debate and evaluates alternative interpretations; estimates community distribution
		4 **TFI** organizes panel of experts to interpret and evaluate; focuses discussions; avoids inappropriate behavior on part of evaluators; draws picture of evaluators' estimate of the community's composite distribution; has ultimate responsibility for project

Figure 3.10. SSHAC study levels (taken from U.S. NRC/NUREG/CR-6372, 1997a)

Partly depending on chosen level, data collection and database creation are started from the very beginning of the project, and usually the final database is available before finalization of SSC and GMC in the SSHAC process. The need for new data in the process is evaluated according to the need to reduce uncertainties and the importance / criticality of the data for the seismic hazard study, although it is not an obligation to collect this new data. The need for new data generation should be projected at the early stages (before or during WS#1) of the SSHAC process (U.S. NRC/NUREG/2213, 2018).

Japanese guidelines are in agreement (in general terms) with the internationally excepted approach. It is suggested that the paleo-seismological surveys and collection of historical and instrumental earthquake data are performed. Gathering of existing documents, literature and data, analysis of earthquake records, investigation on the regional structures, geological survey, drilling survey and geophysical survey, etc. are required by NRA (Nuclear Regulation Authority of Japan, 2013f). Another guide (Nuclear Regulation Authority of Japan, 2013c) mentions that the data about active faults and historical data on seismic activities may support the earthquake hazard assessment.

STUK Guidelines require the collection of regional data, such as Finland’s earthquake locations and magnitudes. This guide only mentions instrumental observation data and historic data, but not specifically mentions pre-historical data in terms of earthquake catalogue (STUK/YVL B.7, 2013).

According to Russian Federation's nuclear specific standard (RTN/NP-031-01, 2002), data to be collected and the studies to be performed are detailed substantially similar to the IAEA and NRC’s data collection requirements. Generally, for 150 to 320 km range from the NPP, identification of active faults and identification of seismotectonic zones with their parameters is requested. For radius at least 25 km from the center of NPP, NP-031-01 also requests the detailed identification of seismotectonic zones with their parameters and identification of fault parameters (type, length, width, slip rate etc.). For Russian Federation approach, examples of suggested investigation and data collection activities considering different spatial scales can be summarized briefly as explained:

- **For General Seismic Zoning (GSZ) scale** [≥320 km]; evaluation of distant sources, initial determination of the area seismicity by using the OSR-97-D map for the Maximum Credible Earthquake level and, by using OSR-97-B map for the Design Earthquake level,

- **For General Seismic Zoning Refinement (GSZR) scale** [320≤GSZR≤150 km]; geological mapping, structural tectonic maps, interpretation of aerial and space photographs, field geological-geomorphologic studies and morphometric analysis of the territory; consolidated earthquake catalogue (including historical and instrumentally recorded earthquakes), intensity maps,

- **For refinement zone** [≤25 km]; topographic, geophysical, geodynamic, hydro-geological and engineering-geological maps, combined geological-lithologic sections, instrumental recording of microearthquakes etc.

- **For plant site** [≤5 km]; mostly geotechnical and geophysical investigations and results, underground water parameters etc.

Another Russian standard related to seismic hazard (RTN/RB-019-01, 2002) has a simple requirement that instrumentally recorded, historical, “ancient”, and paleo-earthquakes should be compiled.

Turkish regulation also requires the collection of pre-historical, historical and instrumentally recorded information and records (TAEK/Turkish Atomic Energy Authority, 2009b). Within the scope of the Akkuyu NPP project, firstly, previous studies and reports for the Akkuyu site that was prepared since the 1960s have been compiled. Approximately 30 reports and documents related to SHA were available before the year of 2010. Afterwards, some additional studies (additional geological, surface and borehole geophysical, geodetic, and trenching surveys) have been carried out, considering the spatial scales based on the IAEA approach.

Hazard teams working within the scope of Akkuyu NPP Project, initially collected data from earthquake catalogs (including historical and instrumental periods) independently of each other and carried out their hazard studies based on their own catalogue. However, TAEK requested that these catalogs become a single compiled project catalog as suggested by the IAEA (SSG-9) and Russian Federation (NP-031-01) standards. After the completion of this compilation process, hazard studies were renewed based on the compiled project catalog (Akkuyu Nuclear JSC, 2013, 2017). Historical and instrumental earthquake data from the compiled project catalogue for Akkuyu NPPs (320 km radius) can be seen at Figure 3.12.

In Sinop NPP Project, licensee and designer preferred to use SSHAC methodology to perform SHA according to NUREG/CR-6372 Vol.1 & 2 (U.S. NRC/NUREG/CR-6372, 1997a, 1997b) and (U.S. NRC/NUREG-2117 Rev.1, 2012). Within the scope of SHA studies for Sinop NPP site, first of all, previous studies and reports have been compiled. Considering NUREG 2117 suggestions, some additional studies such as compilation of regional geology map, geological observation trenches and pits boreholes & age dating, on-shore & off-shore seismic reflection, ERT, deep vertical stratigraphic BH, P wave velocity logging, additional archives analyses for some EQs (e.g. 1943), compilation of an earthquake catalogue for the pre-1900 period (1000 AD to 1900) and instrumental catalogue (after 1900) have been performed. The details of the studies carried out under this project are not publicly available.

Data type	Seismic source							
	Individual faults						Area/volume sources	
	Location	Activity	Length	Dip	Depth	Style	Area	Depth
Geological/remote sensing								
Detailed mapping	X	X	X	X		X		
Geomorphic data	X	X	X			X	X	
Quaternary surface rupture	X	X	X			X		
Fault trenching data	X	X		X		X		
Paleoliquefaction data	X	X					X	
Borehole data	X	X		X		X		
Aerial photography	X	X	X					
Low sun-angle photography	X	X	X					
Satellite imagery	X		X				X	
Digital elevation model (DEM)	X	X	X				X	
Regional structure	X			X		X	X	
Balanced cross section	X			X	X		X	
Geophysical/geodetic								
Regional potential field data	X		X				X	X
Local potential field data	X		X	X	X	X		
High-resolution reflection data	X	X		X		X		
Standard reflection data	X			X		X		
Deep crustal reflection data	X			X	X		X	X
Tectonic geodetic/strain data	X	X		X	X	X	X	X
Regional stress data						X	X	
Seismological								
Reflected crustal phase data								X
Preinstrumental earthquake data	X	X			X	X	X	
Teleseismic earthquake data							X	
Regional network seismicity data	X	X	X	X	X		X	X
Local network seismicity data	X	X	X	X	X			X
Focal mechanism data				X		X		
NOTE—Length includes both total fault length and information on segmentation.								

Figure 3.11. General data types during identifying and characterizing seismic sources (after ANSI/ANS-2.27, 2008)

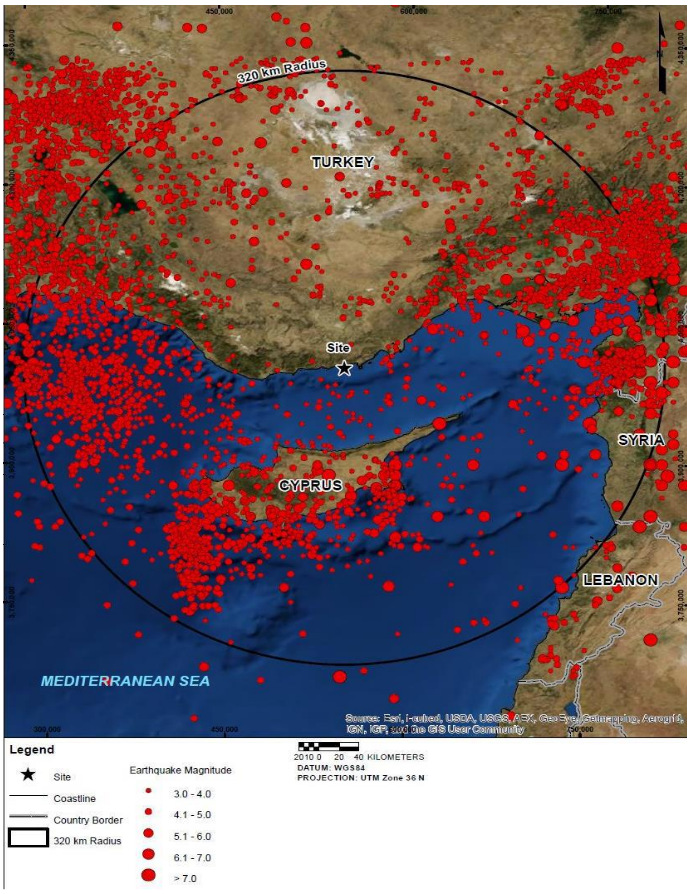


Figure 3.12. Historical and instrumental earthquake data from the compiled catalogue for Akkuyu NPP site (320 km radius) (after Akkuyu Nuclear JSC 2017)

Project earthquake catalogue is one of the most important inputs of the seismic source model, especially when the total hazard is dominated by areal seismic sources. According to the Requirement#3.2 of IAEA (IAEA/NS-R-3 rev.1, 2016), information on prehistorical, historical, and instrumentally recorded earthquakes in the region shall be collected and documented. Site earthquake catalogue should be compiled to cover all spatial scales discussed in Section 3.2.1 (IAEA/SSG-9, 2010). In parallel with Requirement#3.2, Requirement #2.17 (IAEA/NS-R-3 rev.1, 2016) states that "*prehistorical, historical and instrumentally recorded information and records, as applicable, of the occurrences and severity of important natural phenomena shall be collected for the region and shall be carefully analyzed for reliability, accuracy and* *completeness*". In this regard, "prehistorical information" may be defined as the information recorded by nature (fault displacements, age of deposit etc.), "historical information" may be defined as the information recorded by humankind (historical inscriptions, books, chronicles etc.) and, lastly "instrumentally recorded information" may be defined information recorded by instruments (seismograph). This guide also recommends several analyses on the compiled earthquake catalogue:

- The selection of a consistent magnitude scale (it should be consistent with the magnitude scale used in the GMPEs),
- Determination of the uniform magnitude for each event in the catalogue according to selected magnitude scale,
- Declustering of foreshocks and aftershocks (and identification of mainshocks),
- Estimation of the completeness of the catalogue,
- Quality assessment of the derived data (with uncertainty estimates of all parameters).

In parallel with the IAEA approach, U.S. NRC guidelines require that the geological evidences of prehistorical earthquakes, historical and instrumental seismicity data should be considered in addition to geological and geophysical data in seismic source characterization (U.S. NRC/RG 1.208, 2007). U.S. Standard (ANSI/ANS-2.27, 2008) suggests that; (i) the earthquake catalog should have an uniform magnitude measure which is consistent with the GMPEs used for ground motion hazard characterization, (ii) statistical relationships and procedures should be used for the conversion of earthquake size to the uniform magnitude measure, (iii) the catalog completeness time period for each magnitude level included in the catalog should be determined, and (iv) epicentral locations for historical and instrumental earthquake data and earthquake focal depths should be addressed.

Completeness in the catalog as a function of magnitude, location, and time for the observed seismicity should be accounted for the recurrence assessment for faults and areal source zones. SSG-9 briefly explains that the catalogue incompleteness is related to;

- the long recurrence intervals and/or the relatively short period of coverage of the catalogues for large magnitude events and,
- threshold of recording sensitivity for small magnitude events.

Therefore, SSG-9 suggests that the completeness and reliability of the earthquake catalogue should be assessed (particularly in terms of macro seismic intensity, magnitude, date, location and focal depth) after the compilation of data. On the other hand, SSG-9 doesn’t suggest any particular method for taking the catalogue completeness issue into consideration.

A commonly used method for defining the completeness intervals is the Stepp’s approach (Stepp, 1972) that calculates “*the catalog completeness for specific magnitude ranges by starting at the present and moving back in time and counting the total number of earthquakes in the catalog in each magnitude interval. At each point in time when an earthquake in the specified magnitude interval occurred, the rate of earthquakes in the magnitude interval is computed by dividing the sum of the number of earthquakes from that point in time to the end of the catalog by the length in time from that point to the end of the catalog*” (EPRI - U.S. DOE & U.S. NRC, 2012). Accurate estimation of magnitude of completeness is critical, because it can lead to under-sampling when it is too high or may result in incorrect seismicity parameter values when it is too low (Mignan & Woessner, 2012). Recently, the completeness of the PEGASOS project catalogues are determined based on the information from the Stepp-plots as shown in Figure 3.13 (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra), 2004b). Also for the Akkuyu NPP Project, completeness of catalogue was calculated by the hazard teams using the Stepp’s approach (Akkuyu Nuclear JSC, 2013).

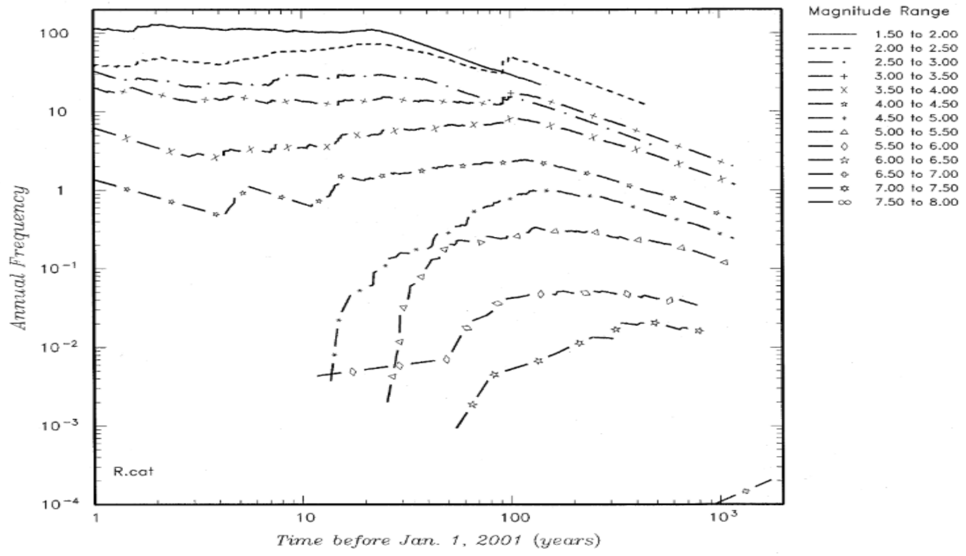


Figure 3.13. Stepp's completeness plots for PEGASOS catalogue that is de-clustered using the Reasenberg approach (after Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra) 2004)

The recurrence rate that is utilized in SHA is the rate of independent main shocks; therefore, dependent events (aftershocks, foreshocks and clusters) have to be removed (declustered) before the calculation of recurrence rate (U.S. NRC/NUREG/CR-6372, 1997a). For declustering, (IAEA/SRS No.89, 2016) mentions the methodologies proposed by Gardner and Knopoff (1974) and Reasenberg (1985) as the two most widely employed methods for eliminating foreshocks and aftershocks from the collected catalogue. These two methodologies can be considered as the industry standard (Güner, Menekşe, Gülerce, & Özacar, 2015). On the other hand, most of the countries don't have clear regulations on this specific issue and almost none of the country-specific regulations reference any declustering methodology mentioned in literature. However, most of the countries and experts use internationally accepted methodologies in current applications. For example, two declustered earthquake catalogs were prepared for the Diablo Canyon NPP in 2015, one of them was declustered by using the Gardner and Knopoff (1974) algorithm and the other one was declustered by Reasenberg (1985) methodology (Lettis et al., 2015). For the PEGASOS project, totally four declustered versions of the project catalog were developed; three of them are based on the original Gardner & Knopoff (1974) approach, Uhrhammer (1986) approach and an updated version of Grünthal (1985) and the fourth one is built by using the Reasenberg algorithm (Abrahamson et al., 2004). Güner et al. (2015) showed that the recurrence parameters (e.g. the b-value) may be changed by 15-20% and if area sources are utilized in PSHA, this range in b-value will affect almost same effect (in percentage) on the estimated ground motions. In CEUS NPP projects, seismic sources consist of areal source zones because of lack of active faulting, low rate of seismic activity and short span of historical records and the recurrence rates are generally depending on incomplete historical earthquakes catalog, unlike WUS. Therefore, considerable care must be taken to correct for incompleteness in catalog and to model the uncertainty (U.S. NRC/RG 1.208, 2007).

3.2.5. Magnitude recurrence parameters and distributions

The next step after the identification and elimination of dependent events (declustering) and evaluation of the catalogue completeness, is the development of the magnitude recurrence models (Abrahamson et al., 2004). The magnitude recurrence model demonstrates the annual frequency of earthquakes having various magnitudes up to the maximum magnitude (M_{max}) that should be developed for each seismic source (U.S. NRC/NUREG/CR-6372, 1997a). The magnitude-frequency distribution (MFD) defines the shape of the recurrence curve as it expresses the annual frequency of various magnitude earthquakes. The traditionally used magnitude distribution models are: (i) truncated exponential (Gutenberg-Richter/GR) distribution, (ii) simplified maximum magnitude distribution, and (iii) characteristic earthquake (Youngs and Coppersmith (1985) distribution (Lettis et al., 2015). Recently, a new MFD is developed by modifying the tail of the characteristic earthquake distribution (a.k.a. the WAACY model). Schematic diagrams of alternative MFD are shown in Figure 3.14.

Even if other distributions could better represent the magnitude–frequency data, truncated exponential GR distribution, derived from Gutenberg & Richter (1954) original recurrence model by (Cornell & Van Marke 1969), is commonly and traditionally used in PSHA (Abrahamson et al., 2004; Atkinson, 2004; Jenny, Goes, Giardini, & Kahle, 2004). Truncated GR distribution is represented by 3 main parameters: a-value, b-value and M_{max} and these parameters are also used by other MFDs with some modifications (Jenny et al., 2004). The a-value specifies the overall rate of earthquakes in a region (Baker, 2013), which is known briefly as the activity rate (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra), 2004b) or, the log of cumulative annual frequency of events larger than magnitude 0 (zero) (U.S. NRC/NUREG/CR-6372, 1997a). The b-value indicates the ratio between the numbers of large and small magnitude earthquakes (IAEA/SRS No.89, 2016), in other words, it describes the relative likelihood of large and small earthquakes (Kramer, 1996b). The a-value can have very different values. Generally, calculation of the a-value is straight-forward regardless of the size of the zones; though, the determination of the b-value can be challenging because of the shortage of data, especially for low seismicity regions (IAEA/SRS No.89, 2016).

SSG-9 provides only generic and basic suggestions about the earthquake recurrence parameters and the MFDs. Before using the earthquake catalogue to estimate MFD for a seismic source, SSG-9 briefly suggests that the catalogue should be subjected to the procedures specified in Chapter 3.2.4 (declustering, compilation, quality assessment etc.). Additionally, it is requested that: (i) selected magnitude scale should be consistent with the moment magnitude (M_w) scale to avoid magnitude saturation effects, (ii) MFD including the maximum potential magnitude should be developed individually for each seismic source, (iii) the rate of earthquake activity (a-value), an appropriate type of MFD (e.g. characteristic or exponential) and the uncertainties should be considered for each seismogenic structure (IAEA/SSG-9, 2010). SSG-9 argues that the b-value varies over a relatively narrow range within a given tectonic setting and uncertainty in the determination of the b-value should be considered and incorporated into the seismic hazard analysis. IAEA have one additional safety report, which provides practical examples and detailed methods that can be used in support of the safety standards (IAEA/SRS No.89, 2016).

This safety report discusses the MFD types (truncated exponential, characteristic and maximum magnitude), indicating that the distributed seismicity is usually modelled using the truncated exponential/GR relation, but the seismically active areas, especially shallow crustal-scale faults and strike-slip faults that form plate boundaries, are often modelled using the characteristic earthquake recurrence model or the maximum earthquake model (IAEA/SRS No.89, 2016). IAEA/SRS No.89 (2016) also provides some details about calculation of the b-value and points out different methodologies to be used in calculations (e.g. Aki 1965, Weichert 1980, Kijko and Smit 2012).

IAEA/SRS No.89 (2016) mention that the truncated exponential model was employed for nuclear installations in USA, in general. USA regulations (RG 1.208) only suggest that the earthquake recurrence for each seismic source (recurrence rate and recurrence model) should be modelled. This guide refers to NUREG/CR-6372 for acceptable methods and details. According to NUREG/CR-6372, fault and area sources should be considered separately in terms of modelling the magnitude recurrence. For fault sources; historical seismicity (as applied to the area source - common practice) and the geological records (it mainly helps the calculation of frequency of large magnitude events) are included in the development of recurrence relationships. Geological data collection mainly covers the compilation of the paleoseismic data (recurrence intervals and the magnitudes of the paleoseismic events should be included) and fault slip rate estimations. This document suggests truncated exponential and the characteristic earthquake model as alternative MFD models for fault sources. For area sources, only truncated exponential distribution is suggested as the proper MFD model (U.S. NRC/NUREG/CR-6372, 1997a).

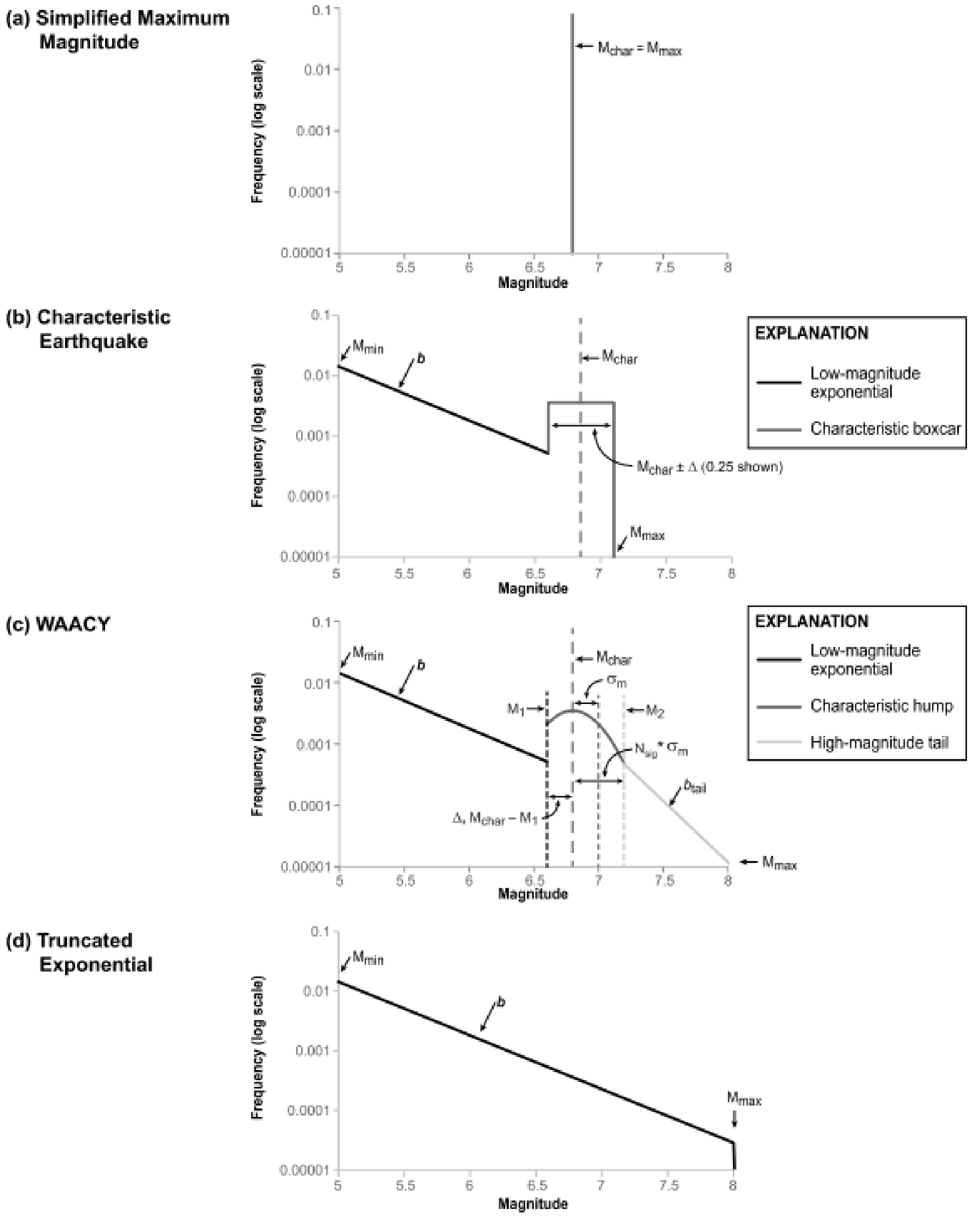


Figure 3.14. Schematic diagrams of commonly used Magnitude Probability Density Functions (PDFs) (taken from Lettis et al. 2015)

In addition to NUREG/CR-6372, NUREG 2117 discusses and elaborates magnitude recurrence models. NUREG 2117 suggests the use of primarily instrumental (approximately covers a century in length) and historical (covers hundreds or even thousands of years) earthquake catalogs and supporting the catalogue by using geological data (that covers thousands or even tens of thousands of years) to calculate earthquake recurrence parameters by considering higher level of uncertainty (U.S. NRC/NUREG-2117 Rev.1, 2012). Three main types of MFD (truncated exponential, characteristic and maximum magnitude models) are mentioned as shown in Figure 3.15. According to NUREG 2117, suitability of truncated exponential or characteristic MFD for fault sources is still debatable.

Four MFDs shown in Figure 3.14 were employed for the Diablo Canyon NPP SSC model (Lettis et al., 2015). In the SSC model of Diablo Canyon NPP, three areal source zones (regional, vicinity, and local) were defined. For the regional which is located at distances greater than roughly 20 km from the DCPP and the vicinity source zones, no modifications to the recurrence rates provided by 2008 US National Seismic Hazard Map were applied. Both for regional and vicinity area sources, the b-value was taken as 0.8. For the local areal source zone, the a- and b-values were calculated by using MLM of Aki (1965) and plot of distribution of b-value (between 0.8 and 1.0) vs M_c values ($1 \leq M_c \leq 2$) for local areal source can be seen at Figure 3.16. The b-value for $M_c \geq 2$ are considered less reliable due to low number of events in the Hardebeck (2014a) catalog which includes 627 events between 1987 and 2013. Also, uncertainty in the b-value is calculated based on Weichert (1980) for different magnitude intervals by considering the 90% confidence interval for $M \geq 2$. All alternatives of b-value fit the data within the 90% confidence interval. Finally, the three b-values of 1.0, 0.9, and 0.8 were given symmetrical weights of 0.3, 0.4 and 0.3 for the local areal source zone (Lettis et al., 2015).

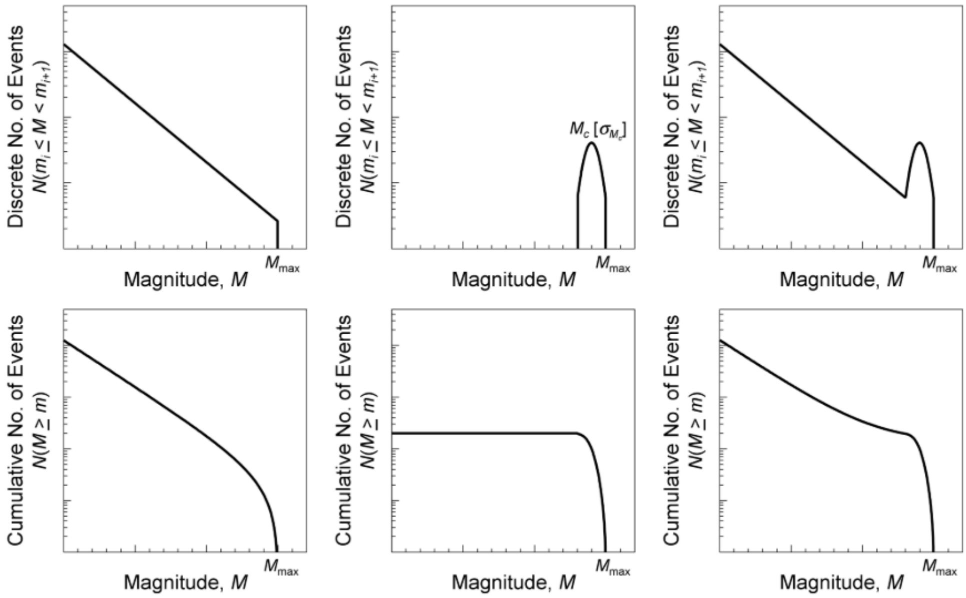


Figure 3.15. Tree type of MFD (from left to right: truncated exponential, maximum magnitude and characteristic models) mentioned in related NUREGs (after U.S. NRC/NUREG-2117 Rev.1, 2012)

For Finland and Japan, related regulatory guidelines don’t have any specific criteria on this subject.

Two Russian Federation regulatory guides suggest the use of truncated exponential (Gutenberg-Richter/GR) model (RTN/RB-019-01, 2002; RTN/RB-123-17, 2017).

Turkey does not have any specific provision about this subject in nuclear regulations and guides. In Akkuyu NPP Project, three different hazard calculation teams performed PSHA and all of them used truncated exponential (Gutenberg-Richter/GR) distribution model because areal source zones were preferred by each team (Akkuyu Nuclear JSC, 2013). Additionally, different statistical techniques, e.g. maximum-likelihood, least squares and modified least squares regression were used by different teams to calculate the recurrence parameters. Each hazard calculation teams has its own completeness analysis and magnitude-frequency distribution fitted to their respective seismotectonic models and for the uncertainty treatment logic tree approach applied to recurrence parameters (Akkuyu Nuclear JSC, 2013) (Akkuyu Nuclear JSC, 2017).

In PEGASOS project, truncated exponential MFD was combined with the areal source zones. The b-value calculations have been performed by using two different statistical approaches; the maximum likelihood (MLM) and the least squares (LSM) methods for each declustered catalogs with M_{min}=1.5 (please see the previous section for details regarding the PEGASOS catalogues). Calculated b-values (varying between 0.66-0.68 with MLM, 0.96-0.99 with LSM) are very similar amongst the catalogues; however, two alternative fitting approaches results in approximately 30% difference in b-value. Considering catalog completeness, calculations were repeated for magnitudes larger than 3.8 events (M_{min}=3.8) and new results (0.93-0.96 for MLM, 1.23-1.25 for LSM) were obtained as shown in Figure 3.18 (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra), 2004b). To cover for the epistemic uncertainty explained above, 5 different a-value & b-value combinations are used: (i) constant b = b_0 (b_0=0.9), variable a-value, (ii) variable b and a, (iii) constant b = b_0 and two variable a-values (a1 and a2): one for the instrumental data (1975 – 2000), one for the historical period 1300 – 1975, (iv) variable b-value and two variable a-values, (v) Bayesian error weighted b-value. The results of the different studies performed, as explained above, were combined by considering the epistemic uncertainties. As a result, the final b-values accepted for the spatial sources have values ranging from 1.0 to 0.88 for the regions (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra), 2004b).

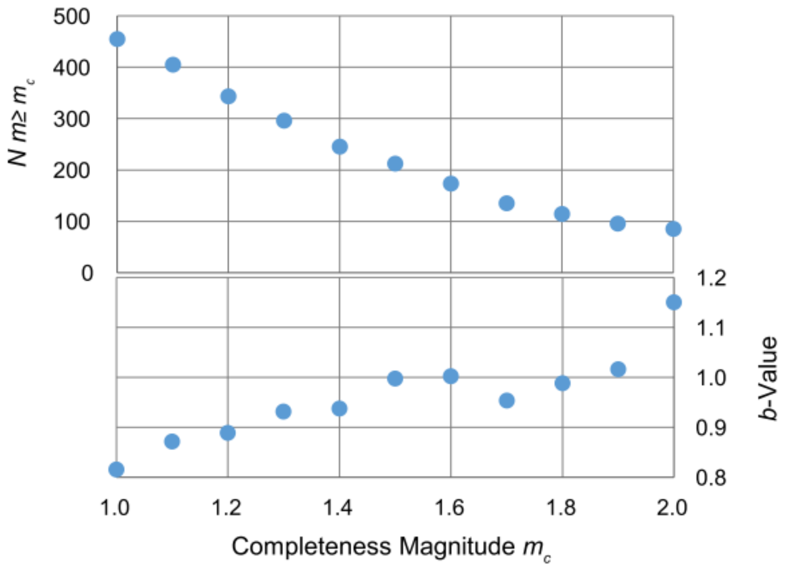


Figure 3.16. b-value calculated from different estimates of completeness magnitude ($1<=M_c<=2$) and number of earthquakes used in the calculations for Diablo Canyon NPP (after Lettis et al. 2015)

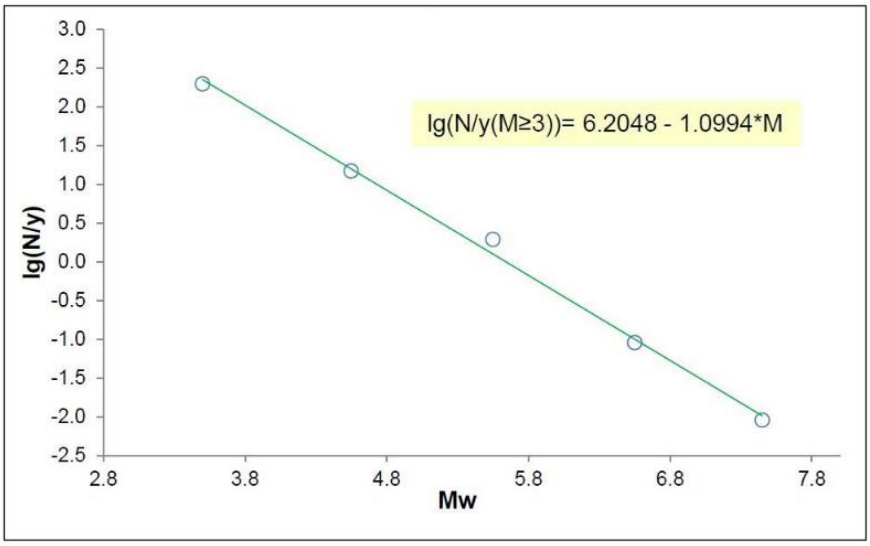


Figure 3.17. Magnitude–frequency distribution (MFD) for the radius of 500 km around Akkuyu NPP Site (example) (after Akkuyu Nuclear JSC 2017)

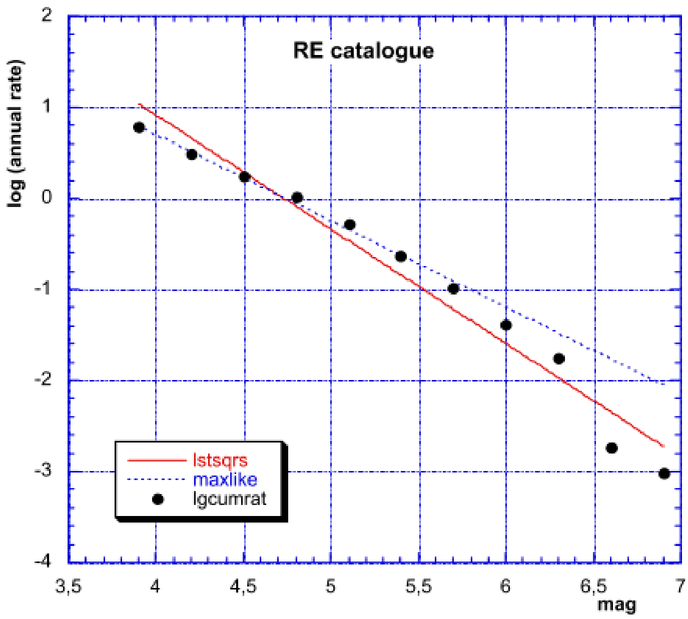


Figure 3.18. Magnitude-frequency distribution and recurrence parameters according to MLM and LSM fits for the de-clustered (Reasenberg method) PEGASOS catalog (M_{min}=3.8) (after Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra) 2004)

3.2.6. Considered minimum magnitude (M_{min})

The selection of the M_{min} (minimum moment magnitude) has a substantial impact on the design ground motions at higher frequencies (Ares & Fatehi, 2013). In PSHA integral, the earthquakes below the lower bound magnitude value (M_{min}) that are assumed to be incapable of damaging the engineering structures are not taken into account. This is typically considered as 5.0 in nuclear projects according to Pecker et al. (2017); nevertheless, (EPRI & US DOE, 2005) claims that the "*lower bound body wave magnitude cut-off value is 5.0 (approximate moment magnitude of 4.6)*". M_{min} was taken as 5.0 in Diablo Canyon Power Plant SSC model (Lettis et al., 2015) and in the PEGASOS project (Klügel, 2005). On the other hand, smaller M_{min} values (4.0 or 4.5) were employed (Abrahamson, 2006) in practice, for example M_{min} was set to 4.3 in some alternative models for PEGASOS (Abrahamson et al., 2004) and M_{min} was equal to 3.5 for Akkuyu NPP.

Choosing a small M_{min} value has a potential drawback: because the hazard curve and the deaggregation is sensitive to the selection of the M_{min}, especially for sites in which an adjacent background source zone has a significant contribution to the hazard, a small M_{min} value may introduce a bias to the low hazard estimates particularly for higher response spectral frequencies. In order to eliminate this drawback, using a cumulative absolute velocity (CAV) filter to identify earthquakes that are not potentially damaging was suggested (Abrahamson, 2006; EPRI & US DOE, 2005). CAV is defined as "*the average value of the absolute value of acceleration during 1 sec time windows that include an acceleration of 0.025g or larger, multiplied by the total duration of the 1-sec time windows*". If the CAV value is less than 0.016g-sec, ground motion is considered as non-damaging for well-engineered structures and the application of the CAV-filter had reduced the contribution of small magnitude events to the hazard curve (Abrahamson, 2006).

The lower magnitude limit for the NPP projects is selected based on the level at which safety related structures, systems and components of the NPPs wouldn't be damaged. Selected lower bound magnitude should not exceed M_w=5.0 (IAEA/SSG-9, 2010). SSG-9 emphasized that setting a low-magnitude threshold value is not the best way of representing the damage potential of earthquakes. As an alternative to the lower magnitude limit, using the CAV parameter is suggested by SSG-9. New draft revision of SSG-9 suggests that "*peak ground velocity and, instrumental seismic intensity*" may be considered in addition to CAV. IAEA/SRS No.89 (2016) suggest that appropriate sensitivity analyses should be performed by consulting the designer or analyst to determine the of lower limit magnitude.

In USA, the EPRI methodology (EPRI & US DOE, 2005) that suggests the CAV-filter is used for defining the lower-bound magnitude cut-off level. RG 1.208 indicates that "*CAV was determined to be the best parameter correlating damage with the Modified Mercalli Intensity Scale*" compared to the others (e.g. PGA, Arias intensity, root mean square acceleration etc.) (U.S. NRC/RG 1.208, 2007). According to NUREG 800, the minimum magnitude of truncation can be taken M_w=5 or can be calculated according to the CAV filter (should be less or equal to M_w=5.5) for SHA process (U.S. NRC/NUREG 800 2.5.2, 2014). A CAV-filter was applied in the PSHA analysis of CEUS NPP sites, showing that the UHS is reduced approximately by 10% to 25% when the CAV filter is applied (Figure 3.19).

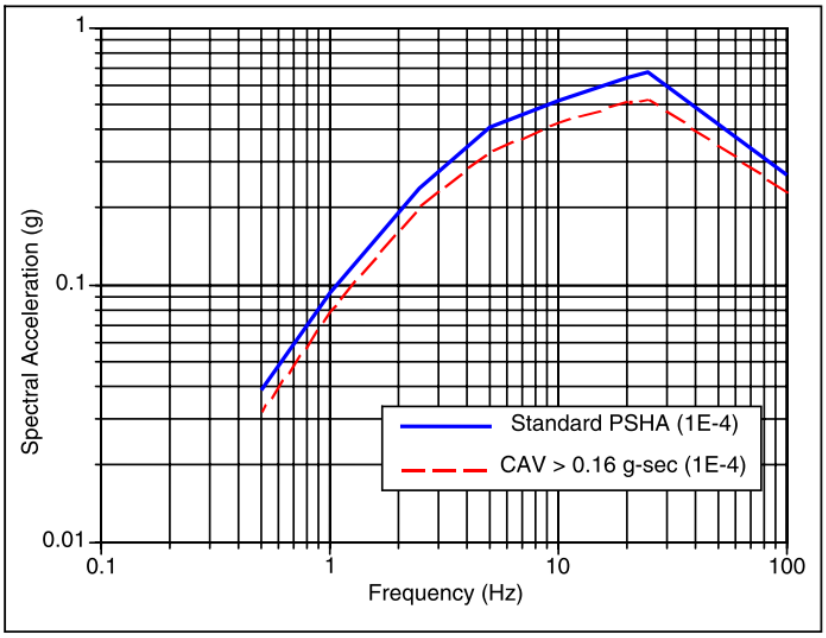


Figure 3.19. Comparison of UHS for CEUS area sources with and without CAV filtering (taken from EPRI & US DOE 2005)

In Japanese (NRA), Finland’s (STUK) and Turkey’s (TAEK) guidelines, there aren’t any specific provision about minimum magnitude cutoff value.

In Russian Federation, M_{min} is usually taken 4.0 and/or the lowest intensity of shaking being I_{min}=5 according to MSK-64 or EMS-98 scales (Ulomov, 2003). It is recommended that M_{min} is taken as 4.5 in RTN/RB-019-01. No additional provision regarding this issue is given in the legislations and standards of the Russian Federation.

M_{min} is taken as 5.0 in the Sinop NPP SSHAC process (Tractabel Engineering GDF Suez, 2017). Second revision of the SPR of Akkuyu NPP covers the sensitivity analysis regarding the selection of M_{min} and M_{max} values for different source zones. These sensitivity analyses were performed because the M_{min} value was reduced to 3.5 from 5.0 during the review process of the SPR. Sensitivity analysis showed that the reduction in M_{min} value results in roughly 2-3% increase between 5 and 10 hz higher frequency band at UHS at a hazard level of 1E-4 (Akkuyu Nuclear JSC, 2017).

3.2.7. Assigned maximum magnitude (M_{max})

M_{max} is the upper magnitude cutoff value of the magnitude–frequency distribution curve (U.S. NRC/NUREG/CR-6372, 1997a) and it is one of the most important parameters of PSHA and DSHA, both for areal and fault sources. IAEA/SRS No.89 (2016) underlined that the selection of M_{max} value will most probably have a significant impact on the hazard results. There are three key approaches to estimate and assign the M_{max} value to a seismic source: (i) using the historical and instrumental catalogue for maximum observed magnitude and adding 0.5 or 1 magnitude units to this value, (ii) using the statistical parameter estimation techniques that considers the maximum observed magnitude and takes into account the global analogues such as EPRI-Bayesian estimation, and (iii) using empirical magnitude-rupture area equations to derive the M_{max} value from controlling and/or significant faults within the source zone.

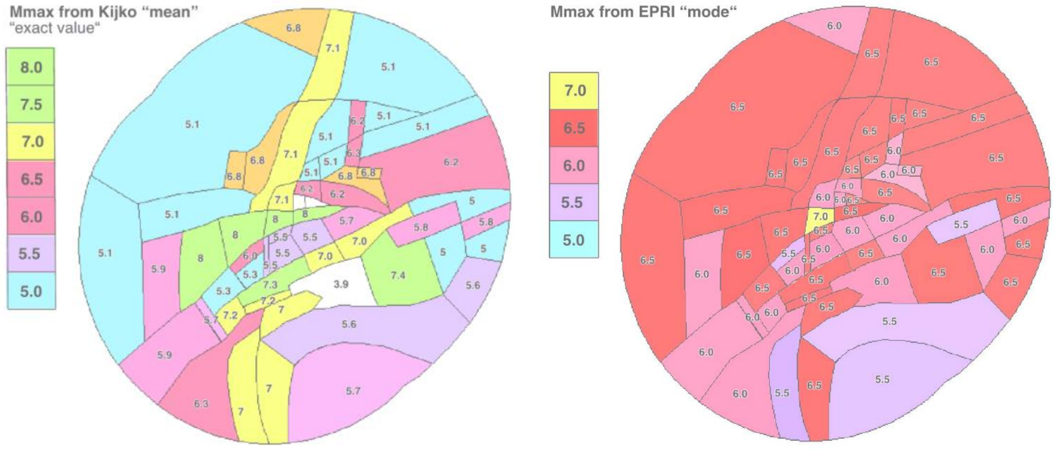
SSG-9 mentions that the largest observed earthquake is “a poor and unconservative” estimate of M_{max}, especially for intraplate regions. Therefore, it is suggested that, when sufficient information about the fault or seismogenic structure (such as segmentation, fault length and width, average stress drop etc.) is available, this information is used to evaluate the maximum potential magnitude by empirical relationships. The maximum potential magnitude can be estimated from the total dimensions of the seismogenic structure, in case of sufficient detailed data are not available. If faults have multiple segments, each segment should be taken into consideration and the possibility of multi-segment ruptures should be analyzed.

Different possible fault rupture length scenarios should be created and used to deal with the uncertainty in the M_{max} parameter. An IAEA document that was published in 2015 (IAEA/TECDOC-1767, 2015) had grouped the empirical rupture area-magnitude relations by their applicability in different tectonic regimes and fault mechanism (slip types) as given in Table 3.3. On the other hand, the methodology to treat the epistemic uncertainty in M_{max} based on these alternative relations was not specified, except that it is stated that the uncertainty in M_{max} should be described and the sensitivity of the resulting hazard to the selection of the M_{max} should be tested.

Table 3.3. M_{max} empirical formulas mentioned at IAEA/TECDOC-1767

Methodology	Mechanism	Tectonic regime
Hanks and Bakun (2008) Wesnousky (2008) Leonard (2010)	Strike-slip dominated	Plate Boundary crustal
Yen and Ma (2011)	All faults	
Hanks and Bakun (2008) Stirling et al. (2008) Wesnousky (2008) Yen and Ma (2011)	Strike-slip	
Wesnousky (2008)	Normal	
Stirling et al. (2008) Wesnousky (2008) Yen and Ma (2011)	Reverse	
Anderson et al. (1996) Nuttli (1983)	Reverse	Stable continental
Anderson et al. (1996) Nuttli (1983)	Strike-slip	
Strasser et al. (2010) [interface events]	Thrust	Subduction
Strasser et al. (2010) [interface events] Blaser et al. (2010) [Oceanic/subduction Reverse]	Thrust	
Ichinose et al. (2006)	Normal	
Villmor et al. (2001)	Normal (<10km)	Volcanic
Wesnousky (2008)	Normal (>10km)	

For area sources, IAEA/SRS No.89 (2016) suggests two alternative approaches for estimating the M_{max}; (1) the EPRI-Bayesian approach, which depend on analogies to tectonically comparable regions (global data) to calculate the M_{max}, and (2) the Kijko (Kijko, 2004) method, which uses only the earthquakes within the source of interest (local data). For the PEGASOS project, research teams initially used the Kijko & Graham (1998) and the EPRI-Bayesian (Johnston, Kanter, Coppersmith, & Cornell, 1994) approaches to calculate M_{max}. However, Kijko's approach was abandoned after the completion of initial calculations, because of producing unrealistic M_{max} values as shown in Figure 3.20, especially for small areal zones (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra), 2004b). Later on, the research teams have evaluated several different techniques such the Regenauer-Lieb & Petit 1997; DeMets et al. 1990 methods, global statistical models (Kagan 1999; Kagan & Jackson 2000), Kijko's numerical approach (Kijko & Graham 1998; Kijko et al. 2001) and 'One step beyond' method (e.g. Slejko et al. 1998). Finally, the EPRI-Bayesian approach shown in Figure 3.21 was considered the best-suited model and the research team had applied two equally weighted logic tree branches for the truncation of M_{max} distribution as 7.5 and 8.0 based on expert judgment (Wiemer et al., 2009).



(a) (b)

Figure 3.20. PEGASOS M_{max} results by EPRI and Kijko approach within small zones (after Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra) 2004)

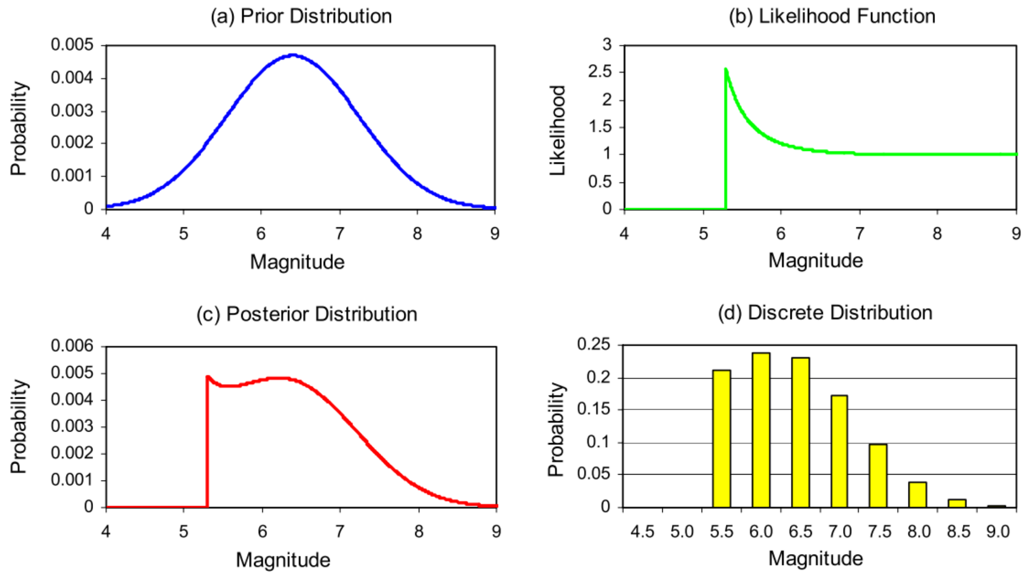


Figure 3.21. EPRI-Bayesian approach for M_{max} (taken from Abrahamson et al. 2004)

USA is divided into three distinct regions in terms of calculating the M_{max} parameter as; CEUS (mostly area sources), WUS, and near subduction zones (mostly fault sources). For area sources, especially in CEUS, M_{max} is defined based on the historical seismicity record, rate of seismic activity, the Quaternary geological record, the current stress regime, paleoseismic data, and analogs to sources in other tectonically similar regions. For acceptable methods of defining M_{max}, RG 1.208 refers to NUREG/CR-6372 (U.S. NRC/RG 1.208, 2007). NUREG/CR-6372 indicates that M_{max} for area sources is particularly based on "the historical seismicity record and analogies to other sources" due to the fact that other parameters (such as fault rupture geometry) are not known. Maximum historical seismicity record could be assessed as a best estimate of the maximum magnitude. Then adding an increment of 0.5 magnitude unit or 1.0 intensity unit to the maximum historical earthquake to get M_{max} for the area source according to (U.S. NRC/NUREG/CR-6372, 1997a), and in parallel with this, (Chen & Scawthorn, 2003) indicates that between 0.5 and 1.0 unit bigger the historically observed maximum earthquake were judged to M_{max} for earthquakes with recurrence intervals of 10,000 years in application to nuclear facility sites.

RG 1.208 indicates that faults located in WUS are known tectonic structures with a "high degree of certainty"; therefore, M_{max} is calculated by using some alternative empirical formulas based on the features of the rupture (total rupture area, the length, or the amount of fault displacement). This guide mentions that there are some alternative empirical formulas for the relation of rupture dimensions and M_{max}, without enforcing any specific ones. In parallel with this, NUREG/CR-6372 suggests that M_{max} should be calculated based on estimated maximum dimensions of rupture, considering maximum surface rupture length, subsurface rupture length, maximum displacement, and average displacement (U.S. NRC/NUREG/CR-6372, 1997a). This document cited the empirical relations proposed by Slemmons (1977), Wyss (1979), Bonilla and others (1984), and Wells and Coppersmith (1994) for calculating the M_{max} for fault sources in shallow crustal regions. Additionally, NUREG-2117 mentions five different empirical equations proposed by Wells and Coppersmith (1994), Hanks and Bakun (2002), Leonard (2010), Blaser et al. (2010) and Strasser et al. (2010). For near subduction zones, especially in the Pacific Northwest and Alaska, RG 1.208 suggests that M_{max} should be assessed by considering the expected dimensions of the rupture or analogies to other subduction zones worldwide. But this guide does not mention any specific empirical relations for subduction zones.

In CEUS SSC, the EPRI-Bayesian (Johnston et al., 1994) and Kijko (2004) methods were utilized to assess the M_{max} potential for area source zones. The EPRI-Bayesian approach was assigned with a higher weight in the logic three than the Kijko approach for all cases, because of its statistical stability. For faults sources, Wells and Coppersmith (1994), Hanks and Bakun (2002), Ellsworth (2003) and Somerville et al. (2001, 2005) empirical equations were utilized. Figure 3.22 shows how M_{max} values were estimated for the Cheraw fault using different options provided by Wells and Coppersmith (1994) and Somerville (2001), underlining that the differences among the methods are roughly between 5% to 15%. In DCPP, M_{max} values were calculated for each area and fault source by using the empirical formulas shown in Figure 3.22 (Lettis et al., 2015). Figure 3.23 shows that the epistemic uncertainty in magnitude-rupture area scaling relations is noteworthy for both for strike-slip and reverse or reverse-oblique faults.

Approach	**Rupture Length**[1]		**Max. Displacement**[2]		**Average Displacement**[3]		**Rupture Area**[4]			**Rupture Area**[5]		
Parameter Value	30 km (18.5 mi.)	46 km (28.5 mi.)	1.6 m (5.2 ft.)	2.6 m (8.5 ft.)	1.1 m (3.6 ft.)	2.1 m (6.9 ft.)	430 km^2 (L = 30 km SD = 13 km Dip = 65°)	1,020 km^2 (L = 46 km SD = 17 km Dip = 50°)	1,321 km^2 (L = 46 km SD = 22 km Dip = 50°)	430 km^2 (30 km × 14.3 km) (assumes 65° dip)	1,020 km^2 (L = 46 km SD = 17 km Dip = 50°)	1,321 km^2 (L = 46 km SD = 22 km Dip = 50°)
Estimated Magnitude (M)	6.6/6.6	6.9/6.9	6.8/6.8	6.9/7.0	6.8/7.0	7.0/7.2	6.6/6.7	7.0/7.0	7.1/7.1	7.0	7.4	7.5

1 Wells and Coppersmith (1994)—Subsurface rupture length (km) to magnitude (M), normal fault/all types
2 Wells and Coppersmith (1994)—Maximum displacement (m) to magnitude (M), normal fault/all types
3 Wells and Coppersmith (1994)—Average displacement (m) to magnitude (M), normal fault/all types
4 Wells and Coppersmith (1994)—Area (km2) to magnitude, normal fault/all types
5 Somerville et al. (2001)—Area (km2) to magnitude

Figure 3.22. M_{max} calculations for the Cheraw fault (CEUS SSC) by the methods Wells and Coppersmith (1994) and Somerville (2001)

In Japanese (NRA), Finland (STUK) and Turkey's (TAEK) regulations, there aren't any specific provisions about how M_{max} should be determined. In Akkuyu NPP project, three independent PSHA studies were performed by three different technical teams (Worley Parsons, Rizzo & Associates and KOERI) and the DSHA was executed by Worley Parsons and KOERI teams independently. Therefore, there are significant differences in the estimation of M_{max} distribution and its uncertainty in each study. A brief summary of the empirical formulas used for Akkuyu NPP project and their application is provided in Table 3.4.

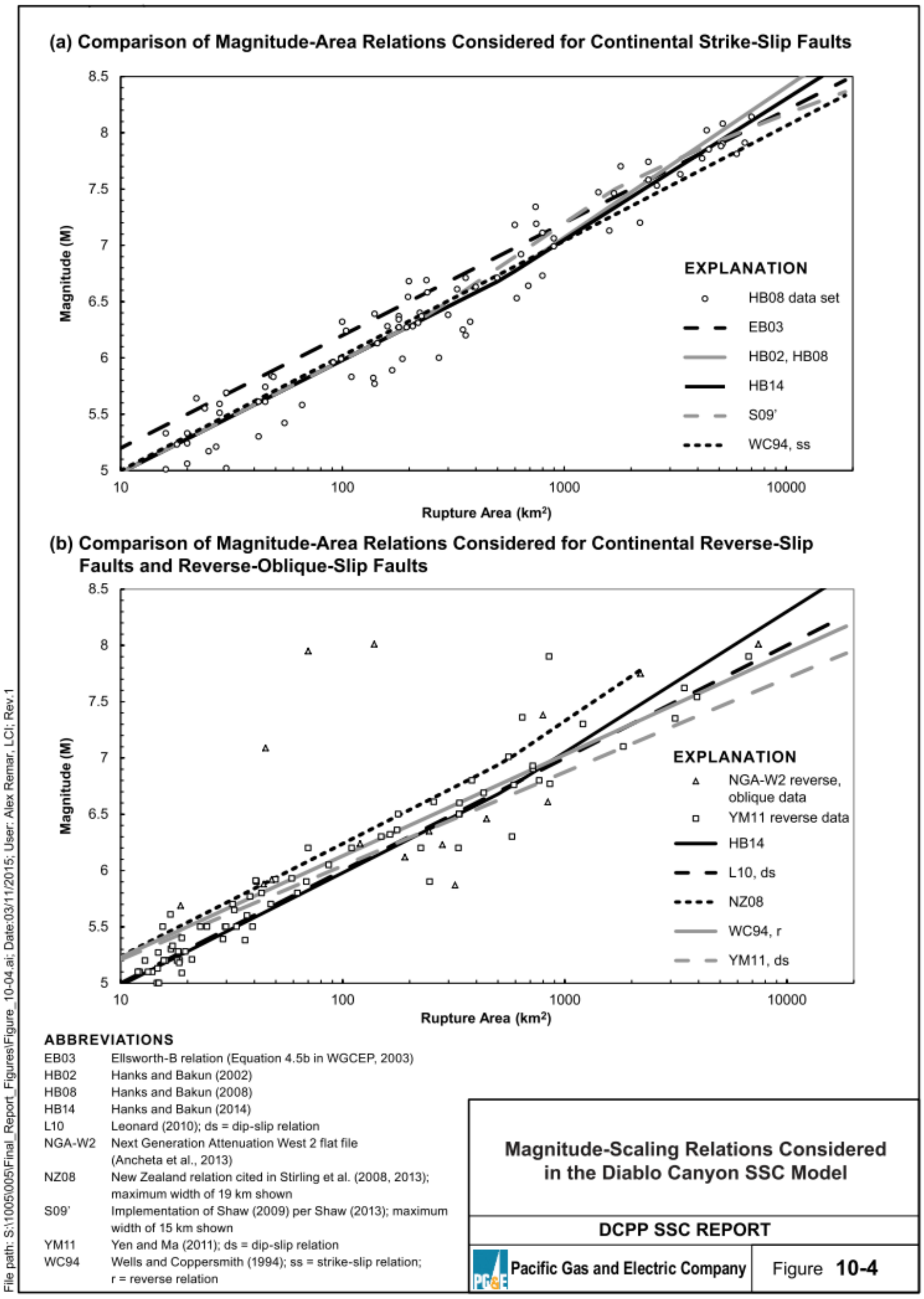


Figure 3.23. Magnitude area scaling relations considered in the DCPP SSC study (taken from Lettis et al. 2015)

Table 3.4. Empirical magnitude-rupture area relations used in Akkuyu NPP project (Akkuyu Nuclear JSC, 2017)

Empirical Formulas	Methodology	Tectonic regime
PA04	Papazachos B.C., Scordilis E.M., Panagiotopoulos D.G., Papazachos C.B., Karakaisis G.F. (2004). Global relations between seismic fault parameters and moment magnitude of earthquakes. Bulletin of the Geological Society of Greece vol. XXXVI, 1482-1489.	Crustal zones
ST10	Strasser, F.O., M.C. Arango, J.J. Bommer (2010). Scaling of the Source Dimensions of Interface and Intraslab Subduction-zone Earthquakes with Moment Magnitude, Seism. Res. Lett. 81 (6), 941-950.	Subduction zones
WE08	Wesnousky, S.G. (2008). Displacement and geometrical characteristics of earthquake surface ruptures: Issues and implications for seismic-hazard analysis and the process of earthquake rupture, Bulletin of the Seismological Society of America, 98 (4), 1609-1632.	Crustal zones
WC94	Wells, D. L., Coppersmith, K. J., 1994, New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974-1002.	Crustal zones
SD86	Slemmons, D.B. and CM. dePolo (1986), Determination of earthquake Size, in Proc. of the Conf. XXIV: A Workshop on "Probabilistic Earthquake Hazard Assessments", USGS Open File Report 86-185, Reston, Virginia.	Crustal zones

Within the Akkuyu NPP project, Worley Parsons team is employed these empirical formulas; PA04, WC94, ST10 (only for subduction zones), WE08 and SD86 (only during updated site report period); while the team of Rizzo, utilized only the WC94 relation for crustal sources except for Source Zone#5, which represents the subduction along the Cyprus Trench. For that particular zone, the empirical relation of Strasser et al. (2010) (ST10) for interface subduction earthquakes was implemented. KOERI team takes M_{max} from SHARE and EMME projects mainly based on WC94 (Akkuyu Nuclear JSC, 2013, 2017). In all independent PSHA reports of Akkuyu NPP, except for the report prepared by Worley Parsons, the uncertainty in M_{max} was considered by including the mean and mean±1 standard deviation value of M_{max} in the logic tree.

Rizzo hazard team considers M_{max} uncertainty and they suggested 3 different M_{max}= $M_{max(cal)}$ - 0.3, $M_{max(cal)}$ and $M_{max(cal)}$ + 0.3 with different weight ratios 0.2, 0.6, 0.2 respectively. Additionally, M_{max} calculation approach based on largest observed magnitude plus an increment is also implemented by Rizzo team for some area sources; M_{max}= $M_{max(obs)}$ + 0.3, $M_{max(obs)}$ + 0.6 and $M_{max(obs)}$ + 0.9 with weight ratios 0.2, 0.6, 0.2 respectively.

KOERI team used three times 0.2-unit increments for consideration of M_{max} uncertainty (M_{max}= $M_{max(cal)}$ - 0.2, $M_{max(cal)}$ and $M_{max(cal)}$ + 0.2) with same weight ratios. Another team (Worley Parsons) used one single estimated M_{max} value for the area sources in general at the logic tree, although more than one M_{max} was calculated by using empirical formulas as stated in the previous paragraphs by considering the largest observed magnitudes and paleoseismic investigations (Akkuyu Nuclear JSC, 2017). Different M_{max} values suggested by the teams in the calculations are integrated into the logic tree for treatment of the epistemic uncertainties. Two seismotectonic model example suggested by Worley Parsons and KOERI, considered in Akkuyu NPP seismic hazard analysis are demonstrated as an example at Figure 3.24.

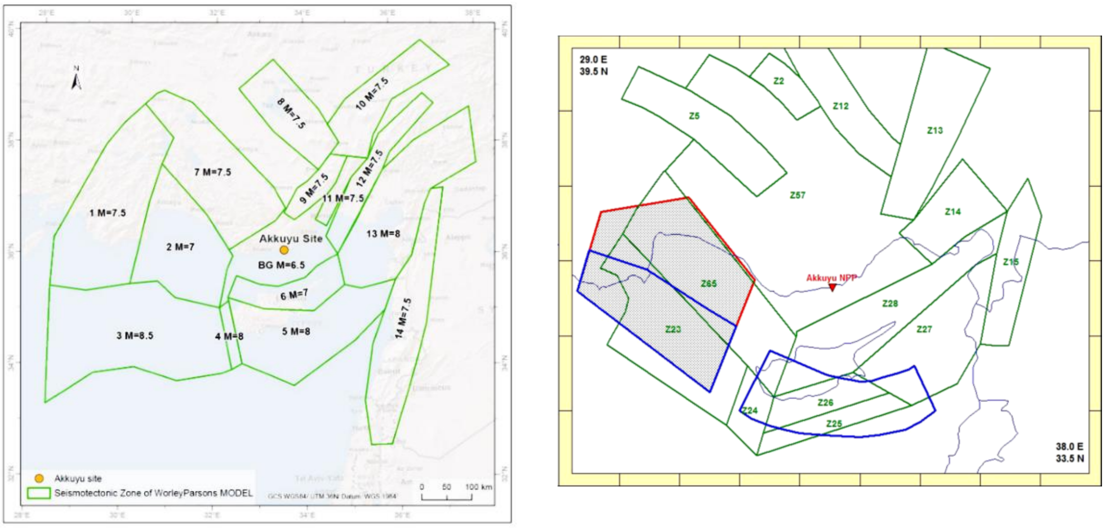
In Russian Federation guidelines, it is suggested that special attention should be paid to source parameters (length, width, motion amplitude etc.) which help to estimate M_{max}. Also, available historical and instrumental data on earthquakes should be considered to calculate M_{max} (RTN/RB-019-01, 2002). RB-019-01 has also been proposed to use statistical methods for the determination of M_{max}, but, only the Gumbel’s type III distribution (Extreme value theory or extreme value analysis) method are specified. This guide also indicates that $M_{max} \geq M_{max(obs)} + 0.5$ of a magnitude unit (RTN/RB-019-01, 2002).

For seismically **active areas**, RB-019-01 recommends empirical formulas to calculate M_{max} based on fault rupture parameters; and **for low-active areas** it suggests empirical formulas based on deformation.

3.2.8. Host zone parameters (magnitude and depth)

Regions with the low seismic activity (also considering other factors for siting) are preferred as possible sites for nuclear facilities. In regions with such characteristics, there is often not enough seismic data to model all possible seismic sources as fault sources. Therefore, in the PSHA studies conducted for these facilities, a background source zone around the facility (as known as the **host zone**) is modelled using the seismotectonic database. The approximate radius of the host zone can vary from tens of kilometers to hundreds of kilometers. Figure 3.24 presents the host zones defined for the Akkuyu NPP project in two independent PSHA reports: the host zone delineated in the KOERI report shown in Figure 3.24 (b) is significantly larger than the host zone defined in the Worley Parsons report as presented in Figure 3.24 (a). In addition to the seismotectonic constraints, dimensions of the host zone are typically defined based on the experts' opinion, bringing in significant subjectivity and uncertainty in PSHA calculations.

Spatial distribution of the activity rate of the host zone is typically characterized by the floating or random earthquakes (DePolo, 1994) and these zones are the dominant contributors of the total hazard, especially within stable continental regions (e.g. CEUS in USA) when area sources are preferred. Figure 3.25 shows the fractional contribution of the seismic sources in the SSC model of Palo Verde Nuclear Generating Station (PVNGS) in Arizona and Figure 3.26 compares the hazard curves for the individual seismic sources to the total hazard curve of Thyspunt NPP in South Africa (J. J. Bommer et al., 2014). Both examples clearly show that the hazard is dominated by the host zones; indicating that the parameters of the host zone such as M_{max}, depth distribution and magnitude PDF have a significant impact on the hazard results.



(a) (b)

Figure 3.24. Areal Source Zone Model including background source suggested for Akkuyu (a) by Worley Parsons (b) by KOERI (taken from Akkuyu Nuclear JSC, 2017)

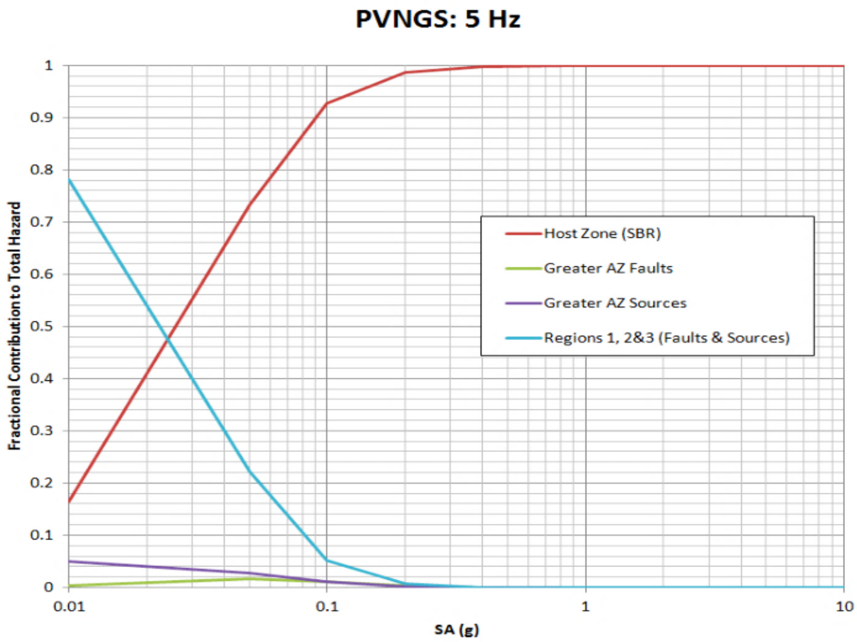


Figure 3.25. Deaggregation by source as a function of ground motions for 5 Hz spectral acceleration for Palo Verde Nuclear Generating Station (PVNGS) (after GeoPentech, 2015)

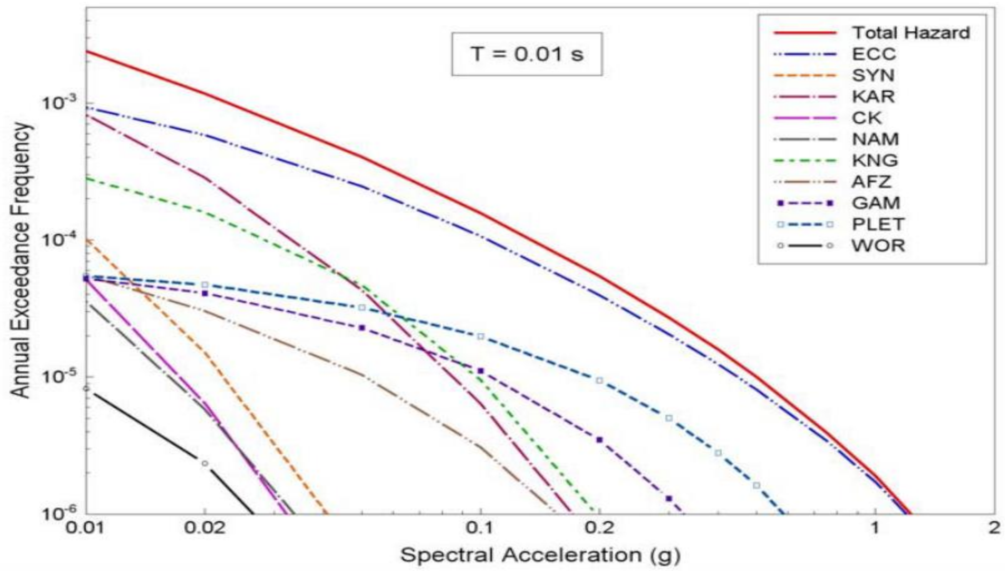
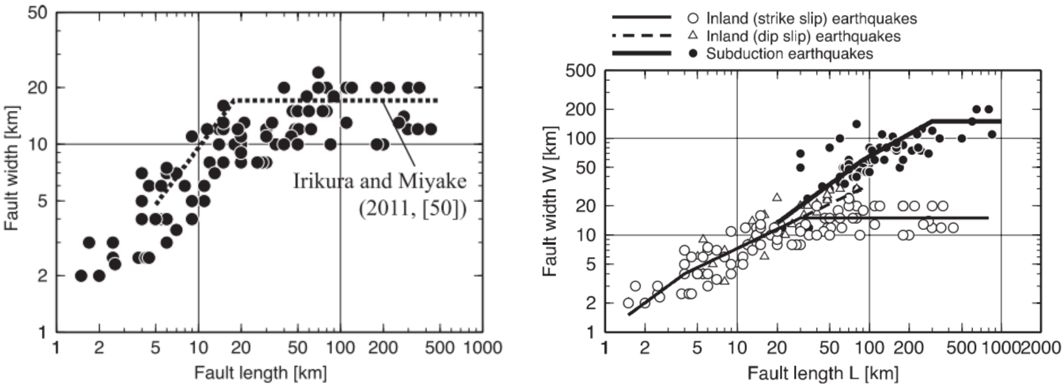


Figure 3.26. Mean hazard curves in bedrock for spectral accelerations at 0.01s and the contributions to the mean hazard from the seismic sources at Nuclear Site in South Africa (ECC: Background zone) (taken from Bommer et al. 2014)

Though it is not physically and geologically realistic, generally during seismic hazard analysis, especially when there is not enough available seismic data to define seismogenic structures for areas, background zone earthquakes concept is employed. It is particularly significant for areas where 5.5-6.0 magnitude or bigger earthquakes are expected (IAEA/TECDOC-1767, 2015).

According to IAEA guide (IAEA/SSG-9, 2010), incorporation of depth distribution of the diffuse seismicity is requested by considering the fact that earthquakes are occurred within or above the brittle to ductile transition of the Earth for crustal source zones. According to IAEA safety report (IAEA/SRS No.85, 2015), relationship between fault length and width (indicator of depth of fault) for different tectonic regimes are demonstrated at Figure 3.27. This figure can be used as an analogy to determine depth at background zone. In IAEA documents there is no other specific provisions about background zone and selection of depth.



(a) (b)

Figure 3.27. Relationship between fault length and width for different tectonic regimes (a) for crustal EQs, (b) for crustal and subduction zones (IAEA/SRS No.85 2015)

Assigned M_{max} to background zone (hereinafter $M_{max,back}$) is one of the most important parameters. $M_{max,back}$ may be taken as 6.5 (Cao, Petersen, & Reichle, 1996; DePolo, 1994; Horino, 2014; Nuclear Regulation Authority of Japan, 2013c; Petersen, Mueller, Frankel, & Zeng, 2008) and this is the general practice. In the WUS, $M_{max,back}$ usually ranges from 6.0 to 6.5 according to (Akkuyu Nuclear JSC, 2017; URS Corporation/Jack R. Benjamin & Associates, 2006).

For both fault and area sources, it is important to make a consistent depth determination (U.S. NRC/NUREG/CR-6372, 1997a). Considering the background zone, assigned $M_{max,back}$ and determination of hypocentral depth (hereinafter D_{hyp}) mutually interrelated and have a potential significant effect on hazard results.

In USA, background source zone are defined as "*a part of the earth's crust, usually of large areal dimension, within which potentially damaging earthquakes could occur that are not associated either with known fault sources or even with the uniform pattern, rate, or style of deformation or seismicity commonly identified with volumetric seismic source zones*" by (ANSI/ANS-2.27, 2008). According to (U.S. NRC/RG 1.208, 2007), background zones are employed to consider uncertainty in general seismic sources in the studied area. RG 1.208 references to (U.S.

NRC/NUREG/CR-6372, 1997a) for acceptable approaches, but NUREG/CR-6372 doesn't have any specific criteria about determination of $M_{max,back}$. These documents categorize seismic sources into four basic source types as; type 1 (faults), type 2 (concentrated seismicity area sources), type 3 (regional area sources) and type 4 (background area sources) (U.S. NRC/NUREG/CR-6372, 1997a) as demonstrated in Figure 3.28.

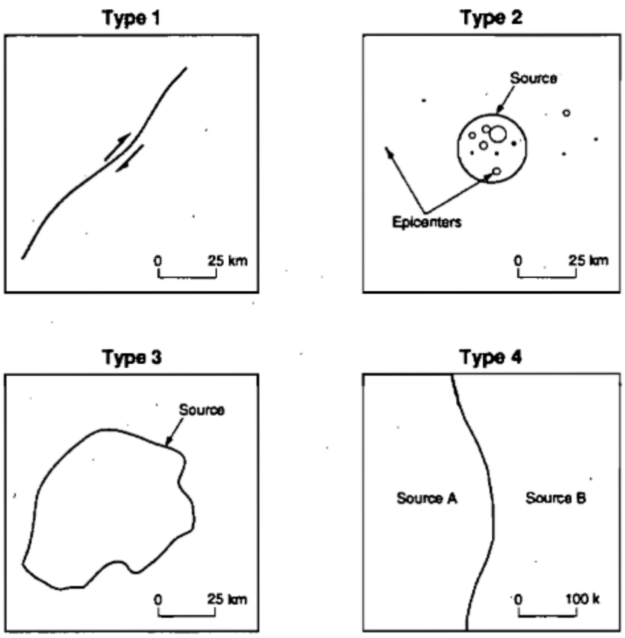


Figure 3.28. Seismic sources types defined by NUREG/CR-6372

For the background sources or for faults situated close to the site, depth consistency is required. For small and moderate, distance from the earthquake to the site are not negligible for background source zone. Appropriate distance (hypocentral distance or epicentral distance) should be used in consistent with depth and selected GMPE model parameters (U.S. NRC/NUREG/CR-6372, 1997a).

In Japan, for the inland crustal earthquakes, although it does not cause any surface faulting, it is assumed that magnitude of 6.5 or smaller earthquakes can happen anywhere in Japan. It is also stated that, although the activity of fault is unknown, magnitude of 6.5 earthquakes or bigger one can be expected because of causative faults. Examples of these earthquakes are given in the related document, the magnitude range being sampled from 5.0 to 6.9 (Horino, 2014; Nuclear Regulation Authority of Japan, 2013c). In Japan, minimum earthquake scenario is generally assumed $M_{max,back}$=6.5 and D_{hyp}=10 km (U.S. NRC/NUREG/CR-7230, 2017) for the inland crustal earthquakes. Hence, upper limit of $M_{max,back}$ (between 7.0 and 7.5) for background earthquakes for the pacific plate near Japan can be seen at Figure 3.29 (Fujiwara et al., 2012).

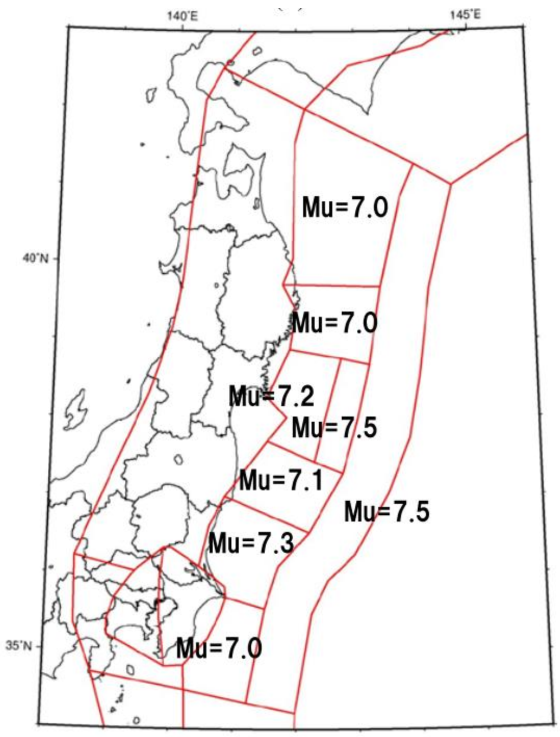


Figure 3.29. Upper limit of Mmax for background earthquakes for the Pacific plate near Japan (before 2011 Tohoku EQs) (Fujiwara et al. 2012)

In Russian Federation, it is assumed that magnitude 4.0 or smaller earthquakes can happen anywhere in studied area (RTN/RB-006-98, 1999). In the other Russian standard and guides, there is not provision about $M_{max,back}$.

Finland and Turkey don’t have any specific requirement or provisions about this topic. But Turkey’s application is explained considering Akkuyu NPP case. In Akkuyu NPP SHA, firstly it is assumed that maximum expected background earthquake magnitude $M_{max,back}$=5.5 may occur in any place within the studied region (Akkuyu Nuclear JSC, 2013). Then Worley Parsons SHA team suggested mean $M_{max,back}$=6.5 for background zone. More specifically, this team suggested $M_{max,back}$= 6.3, 6.5 and 6.7 with 0.2, 0.6, 0.2 logic tree weights, respectively. Rizzo SHA team suggested six alternative seismotectonic models for the background zone with different logic tree weights and, this team suggested three different $M_{max,back}$= 6.6, 6.9 and 7.2 with 0.2, 0.6, 0.2 weights, respectively (Akkuyu Nuclear JSC, 2013, 2017).

Although, there is no evidence of a seismic source creating 6.5 magnitude earthquakes in the Akkuyu site area and/or even in the near regional area, this value is arbitrarily assumed for $M_{max,back}$ in seismic hazard studies by considering internationally accepted practice. According to ENVY/KOERI model, it is suggested that $M_{max,back}$= 6.5, 6.7 and 6.9 with 0.50, 0.25, and 0.25 respectively (Akkuyu Nuclear JSC, 2017). Results of the Worley Parsons SHA team, background source zone and Cyprian Trench zone are the two sources controlling the hazard results. In the DSHA studies of Akkuyu, worst case was assumed that the earthquake occurred right under the site for the background source (Akkuyu Nuclear JSC, 2013). In DSHA studies, Worley Parsons SHA team suggested two alternatives for R_{jb}; 5 and 10 km, and 3 alternative for Z_{TOR}; 11, 13 and 15 km respectively (Akkuyu Nuclear JSC, 2017). Most conservative case R_{jb}; 5 and Z_{TOR}; 11 km for background source options can be seen at Figure 3.30.

In the Akkuyu NPP project, the depth distribution in the 0-35 km range are considered uniform for the active shallow crustal sources, except for the host zone. For host zone, depth distribution between 0-13 km (0.1), 13-22 km (0.6) and 22-35 km (0.3) are assumed different weights indicated in brackets. For the subduction interface sources (located between 20 and 50 km) and inslab sources (between 50 and 130 km) depth distribution are assumed uniform (Akkuyu Nuclear JSC, 2017). Depth distribution histogram of compiled earthquake catalogue of Akkuyu NPP can be seen in Figure 3.31.

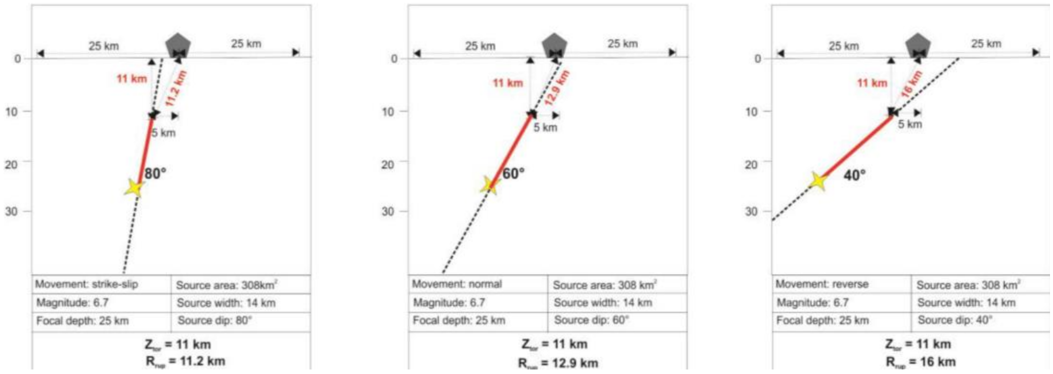


Figure 3.30. Akkuyu NPP Project, Worley Parsons Model, Background source options for Rjb=5 km Z_{TOR}=11 km

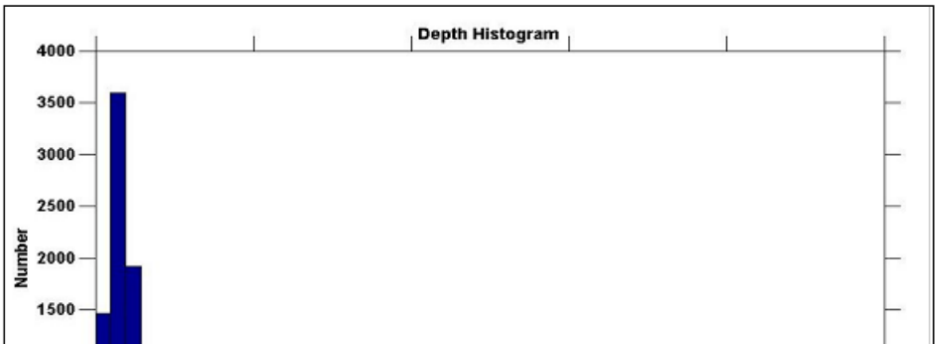


Figure 3.31. Depth distribution histogram of compiled earthquake catalogue of Akkuyu NPP (Akkuyu Nuclear JSC, 2017)

In the Akkuyu NPP project, there are many different background sources with different geometric dimensions according to the suggested seismotectonic models generated by different SHA teams. Two of these are provided as examples, in Figure 3.24, where the order of magnitude of the size of these sources varies from 15 km to hundreds of km.

For the DCPP, totally three type of areal sources namely regional (up to ~320 km), vicinity (up to ~40 km), and local sources are employed. Vicinity source indicated at Figure 3.32 are considered host zone for DCPP SSC. Maximum magnitudes for host zone are chosen as $M_{max,back}$= 6.5, 7.0 and 7.5 with 0.4, 0.5, 0.1 weights, respectively. b-value for this zone chosen as 0.8 by considering past hazard studies (Lettis et al., 2015).

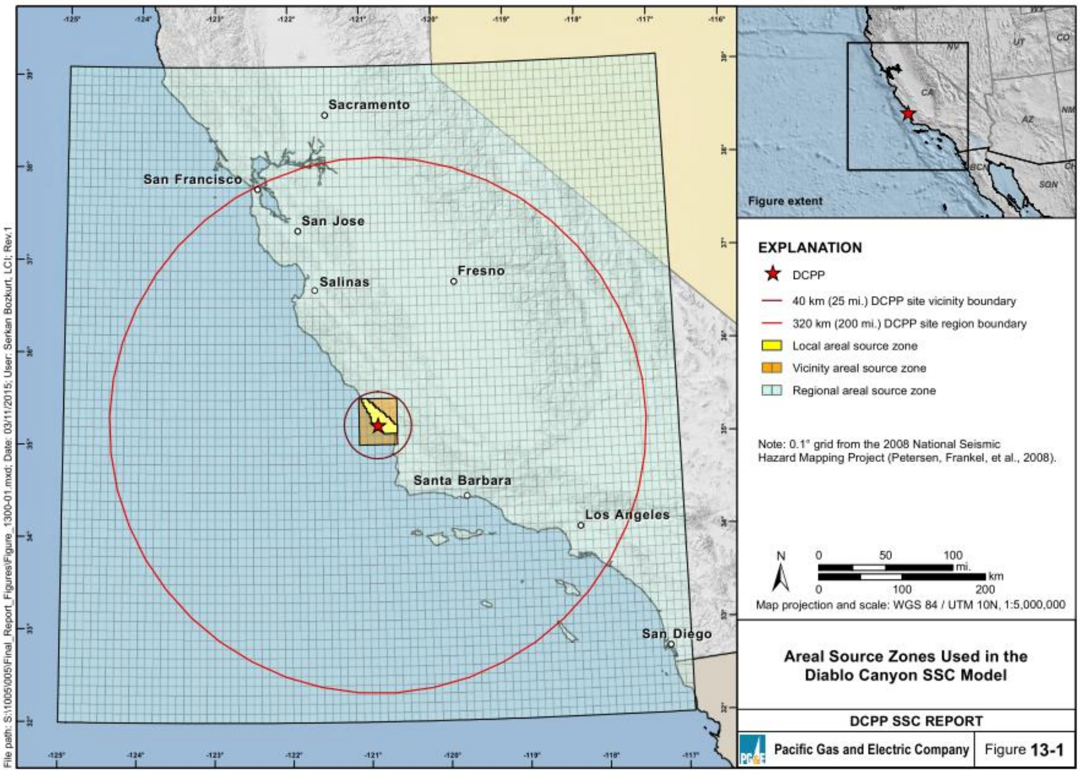
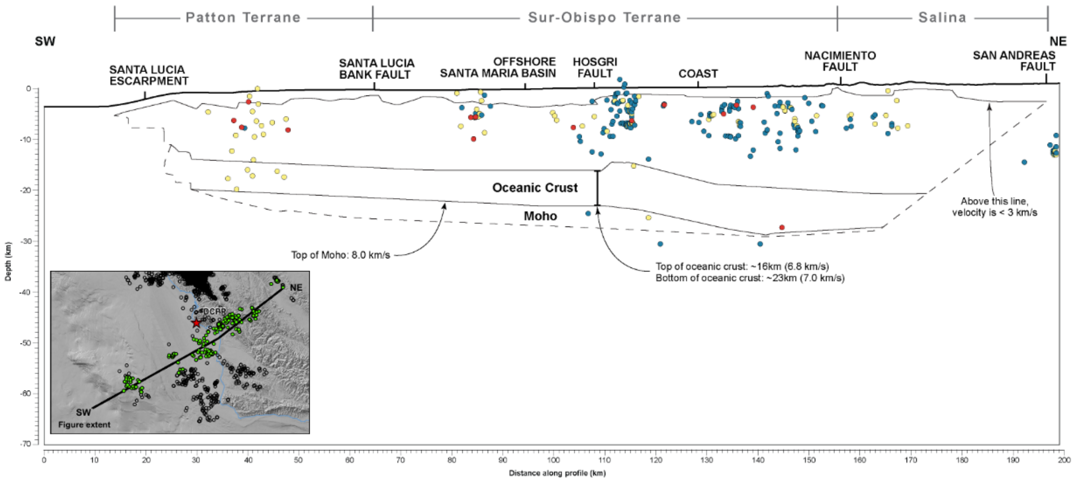
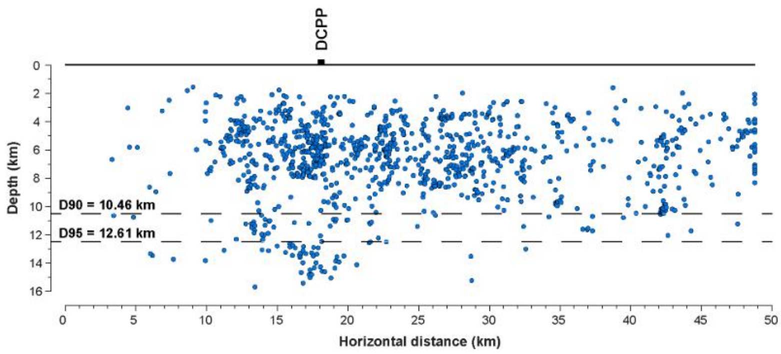


Figure 3.32. Areal source zones (including host zone) for DCPP SSC model (after Lettis et al. 2015)

In Diablo canyon example, depth of the areal sources has been chosen between 12-25 km (GeoPentech, 2015). For regional (up to ~320 km) and vicinity (up to ~40 km) areal source zones, depth distribution is assumed uniform between 0-12 km (Lettis et al., 2015). Preliminary sensitivity analyses presented at Workshop 1 (Wooddell, 2011) showed that variability in the depth of seismogenic faulting has very little effect on hazard at the DCPP. Accordingly, epistemic uncertainty is not characterized for this parameter. The maximum rupture depth is 12 km for all fault sources in the SLPB group, as well as for fault sources in the Hosgri group for events with M < 7.4. For events with M ≥ 7.4, the maximum rupture depth for Hosgri group fault sources is 15 km (Lettis et al., 2015).



(a)



(b)

Figure 3.33. (a) Typical depth distribution cross section example considered in DCPP (b) Cross section showing seismicity distribution with depth with D90 and D95 values (Lettis et al. 2015)

Typical depth distribution cross section example considered in DCPP and seismicity distribution with depth with D90 and D95 values can be seen at Figure 3.33 (a) and (b).

3.3. Ground Motion Characterization in Nuclear Regulations and Applications

In addition to seismic source characterization (SSC) discussed in detail in sub-chapter 3.2, another main task of SHA study is the development of Ground Motion Characterization (GMC). GMC is described as "*the excitation and propagation of earthquake ground motion for all the earthquakes that may affect the site as a function of earthquake magnitude, distance, and frequency content of the radiated field*" according to (Hanks, Abrahamson, Boore, Coppersmith, & Knepprath, 2009).

Ground motion parameters to characterize the ground motion are mainly considered under 3 main groups (Bozorgnia & Bertero, 2004; Chen & Scawthorn, 2003; Gioncu & Mazzolani, 2011; IAEA/SSG-9, 2010; Kramer, 1996b); **(i) amplitude/intensity** (acceleration/PGA or PHA [most popular], velocity/PGV or PHV, displacement/PGD or PHD, and PVA, PVV, PVD, or effective acceleration etc.), **(ii) frequency content** (Fourier spectra, power spectra, response spectra [most popular]) **(iii) duration** (bracketed duration, significant duration, etc). All these parameters and ground motion models also create uncertainty that it is one of the major contributor to total uncertainty in the SHA (Renault, 2012), and this uncertainty has a significant impact on the hazard curves (Julian J. Bommer & Abrahamson, 2006). Ground motion prediction equations (GMPEs) are used to estimate amplitude parameters that are significant in the characterization of ground motion. Because of this, GMPEs are firstly discussed. Frequency content and duration are not deeply studied within this study.

3.3.1. Ground Motion Prediction Equations (GMPEs)

GMPEs are used to estimate intensity parameters (acceleration/PGA or PHA, velocity/PGV or PHV, displacement/PGD or PHD etc.) of ground motion for specific site with their uncertainties by considering the seismic source (magnitude, style-of-faulting etc.), path (source-to-site distance), local site effects (site class, V_{s30}, depth to basement rock) and other factors (hanging wall etc.) (Akkar & Sucuoğlu, 2014; Bozorgnia & Bertero, 2004; Kramer, 1996b; Stewart et al., 2015). GMPEs are often called as "attenuation relationships" (IAEA/SSG-9, 2010) and sometimes "predictive relationship" by (Kramer, 1996b) or "attenuation functions" by (STUK/YVL B.7, 2013).

IAEA guide (IAEA/SSG-9, 2010) suggests that available recordings of regional and local strong ground motion should be collected and used for deriving or selecting appropriate GMPEs and in developing response spectra. During selection of GMPEs, IAEA guide suggests mainly (IAEA/SSG-9, 2010):

- GMPEs should be selected to be consistent with magnitude, distance and the other parameters (style of faulting, hanging wall effects and local site conditions etc.)
- GMPEs should be consistent with the types of earthquake and tectonic environment and attenuation characteristics of the region of interest
- GMPEs should use local ground motion data (if available)
- Validity check for the GMPEs by consistency of range of magnitudes and distance should be performed
- GMPEs should be compatible with the reference site condition, or it can be adjustable by site response factors and their parallel uncertainty
- Current and well established GMPEs should be used
- Multiple suitable GMPEs should be employed in order to capture epistemic uncertainty and range of credible interpretations adequately.

In USA, using attenuation relationships (GMPEs) are suggested for PSHA studies by (U.S. NRC/RG 1.208, 2007) and according to (U.S. NRC/NUREG 800 2.5.2, 2014) GMPEs should be employed in line with the methods described in NUREG/CR-6372, "*Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts*" and NUREG-2117, "*Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies*". NUREG 2117, by considering the interface between SSC, GMC and hazard calculation steps, suggests that all elements (magnitude scale, style of faulting & range of rake angle, R_{max}-maximum distance of sources, M_{max}, M_{min}, R_{hyp}, R_{rup}, R_{JB}, Z_{TOR}, V_{s30} etc.) should be used consistent with each other and should be within the limits of each GMPEs.

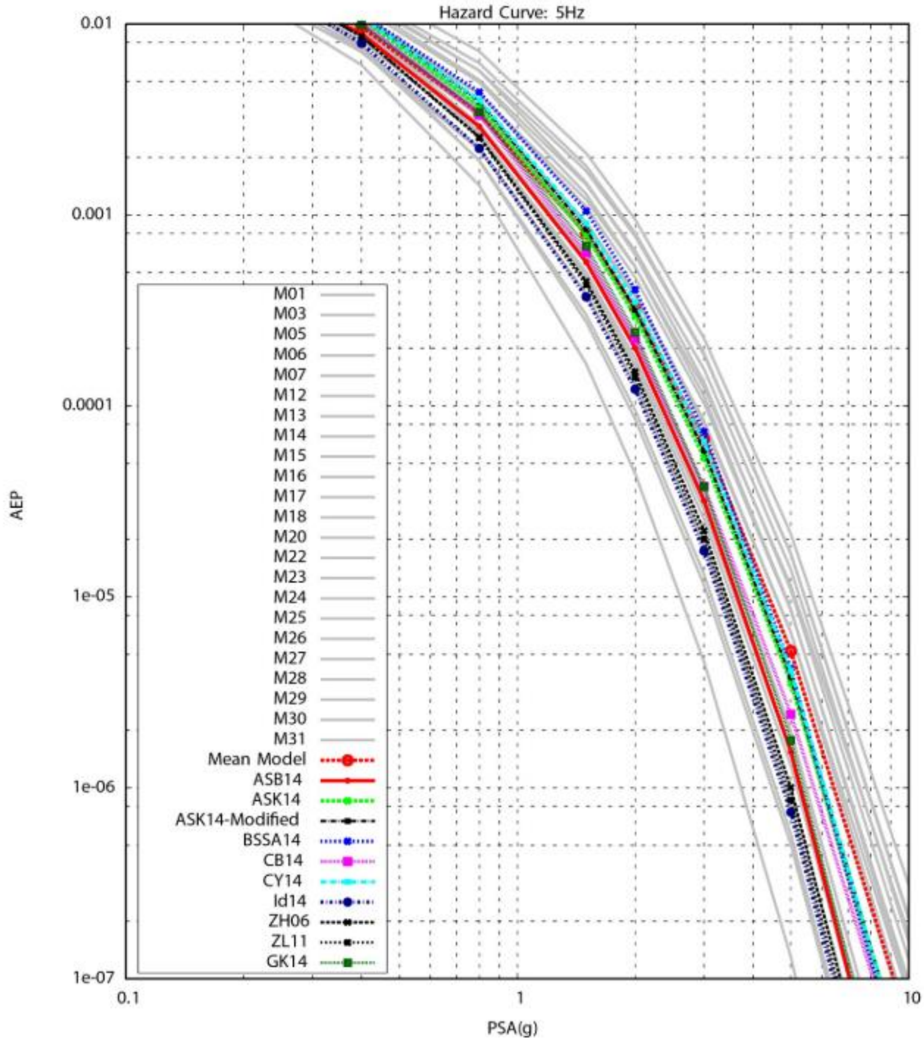


Figure 3.34. Comparison of hazard curves using 31 GMPEs (grey lines) and the selected 8 GMPEs for 5 Hz for DCPP GMC SSHAC project (taken from GeoPentech 2015)

Selected 8 GMPEs for DCPP project is that (GeoPentech, 2015); Abrahamson et al (2014), Boore et al (2014), Campbell and Bozorgnia (2014), Chiou and Youngs

(2014), Idriss (2014), Zhao et al (2014), Zhao and Lu (2011) adjustment to magnitude scaling and Akkar et al (2014a, 2014b) by considering; recent publication (between 2004-2014)/based on updated data, applicability to seismotectonic environment and distance, considering hanging-wall and directivity effects etc. During the selection process, these 8 GMPEs are compared with other 31 models and the comparison results of hazard curves is demonstrated in Figure 3.34.

Considering applications in Japan, "recipe" approach is employed for prediction of ground motion (Irikura, 2006; Irikura & Miyake, 2006a, 2011). According to a recently published study (Pitarka, Graves, Irikura, Miyakoshi, & Rodgers, 2019) which also includes comparison results of recorded data and simulation results with prediction results by using NGA-West 2 GMPEs (ASK14, BSSA14, CB14 and CY14) that can be seen at Figure 3.35. This figure basically demonstrates that recorded data, simulation results and GMPE results are consistent with each other. In Japanese nuclear regulatory requirements and guides, no provision has been found related to GMPEs.

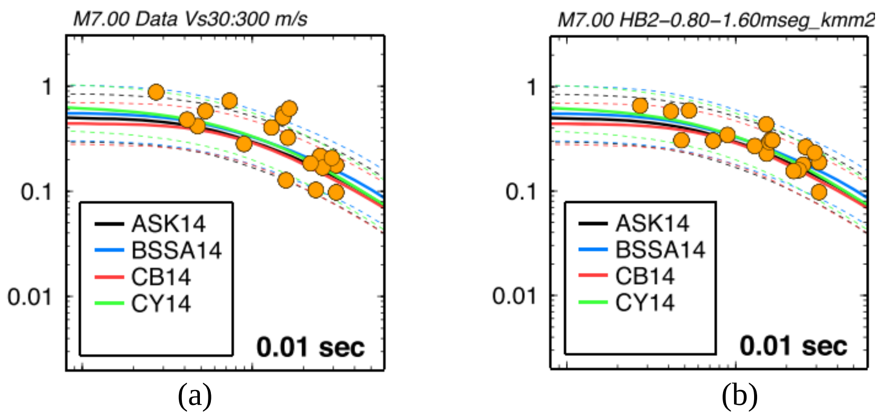


Figure 3.35. Comparison of recorded data (a) and simulated results (b) with GMPEs calculations (taken from Pitarka et al. 2019)

In Finland, STUK has only one provision (provision no 404) about GMPEs (it is originally referred to as "attenuation functions" at that guide). This provision basically suggests that GMPEs should be used for calculation of intensity/amplitude parameters of ground motion by considering magnitude and distance values and it also requires justification of selection reason of GMPEs (STUK/YVL B.7, 2013).

Considering Russian Federation (RTN/RB-123-17, 2017) and Turkish nuclear regulations (TAEK/Turkish Atomic Energy Authority, 2009b) and guides, they only suggest using attenuation relationships (GMPEs) but they don't have any detailed provision about it.

In Akkuyu NPP Project, two types of GMPEs are considered: (i) for "subduction zones"; Atkinson and Boore (2003, 2008), Zhao et al. (2006) and Youngs et al (1997); (ii) for "crustal zones"; NGA Campbell and Bozorgnia (2008), NGA Abrahamson and Silva (2008), NGA Boore and Atkinson (2008), NGA Chiou and Youngs (2008) and Akkar and Bommer (2010) model.

During the PEGASOS PRP, "Next Generation Attenuation" (NGA) and some European and Japan models are employed: (Akkar and Bommer, 2010), (Akkar and Cagnan, 2010), (Abrahamson and Silva, 2008), (Boore and Atkinson, 2008), (Campbell and Bozorgnia, 2008), (Chiou and Youngs, 2008), (Zhao et al., 2006), (Edwards and Fäh, 2013b) (Edwards & Fäh, 2014; Renault, 2012).

Although GMPEs come with their significant uncertainty, these are generally used in SHA process frequently (IAEA/SRS No.89, 2016). But there is no standardized selection process for GMPEs. Hence, after NGA models, most of the SHA application performed in USA, Turkey and some other regions tends to use global models.

3.3.2. Ground motion simulation

IAEA safety guide (IAEA/SSG-9, 2010) also suggests ground motion simulation methodology as an option especially for seismically active regions and areas where contribution of the nearby fault on seismic hazard is significant. In the case of short distance from the fault rupture, the ground motion simulation based on fault rupture modelling is considered more appropriate than using GMPEs (IAEA/SRS No.85, 2015). Especially in Japan seismic hazard is generally performed "by modeling the earthquake rupture at the source and then propagating seismic waves from the source to the site taking into account the physical properties of the medium" (IAEA/TECDOC-1767, 2015).

Lack of comparable provisions in legislations, guides and standards on this subject and since the researcher does not have the ability to make a real comparison analysis on this subject, further researches could not be performed on this topic.

3.3.3. GMC uncertainties & sigma truncation

Main sources of uncertainties in SHA studies are that; (i) limited scientific data about the "*specific fault locations, orientations, slip rates, energy dissipation mechanisms*", etc. (ii) different expert judgements/interpretations (U.S. NRC/NUREG/CR-6372, 1997a) (iii) M_{max}, recurrence rates, median GM scaling factor, standard deviations of GMPEs (sigma / σ) etc. (U.S. NRC/NUREG/2213, 2018). It is claimed that ground motion predictions can be calculated with significant uncertainty according to (U.S. NRC/NUREG/CR-6372, 1997a), and (Renault, 2012) also suggest that epistemic uncertainty is the major source of uncertainty that has a serious impact on seismic hazard results.

One example on relative contribution of different parameters on total uncertainties of hazard calculation can be seen at Figure 3.36. This figure is prepared within the SSHAC level-3 seismic hazard study of Hanford Site located in southeast of Washington State. Considering the sensitivity results for 1 second spectral period (T=1 sec), it is demonstrated that; (i) Vs-kappa adjustments in the crustal ground motions (labeled as **crustal Vsk**) has limited effect for this period; (ii) "***subd anelastic attenuation (theta6)*** *scaling on the anelastic attenuation term for subduction ground motions*" has significant contribution especially for 10^{-3} AFE-level (annual frequencies of exceedance level); (iii) **median scaling** ("*the crustal backbone adjustment model that creating the branches with scaled and adjusted versions of a single backbone model and the epistemic uncertainty on the median subduction model grouped in one histogram bin - labeled as median scaling*") contribute total variance between 20% and 35% for different AFE level; (iv) "**host-to-target** adjustment factors for crustal ground motions" affects the results 7-22%, (v) **sigma** model, for both crustal and subduction ground motion, also effects uncertainty significantly. These Ground Motion Characterization (GMC) model elements has significantly contributed the total uncertainty. On the other hand, Seismic Source Characterization (SSC) elements also contribute the uncertainty; especially $\mathbf{M_{max}}$, **recurrence model**s, and **b-value** have relatively large contribution to uncertainty (Pacific Northwest National Laboratory, 2014).

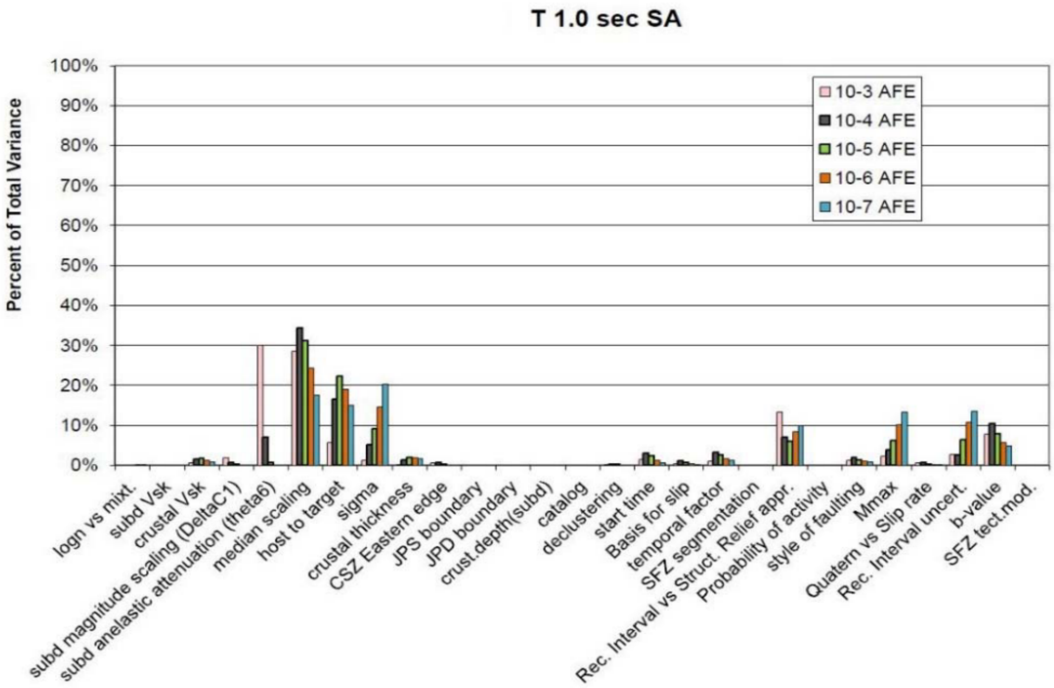


Figure 3.36. Relative contribution of different SSC and GMC elements on total uncertainties of hazard calculations (for T=1.0 sec) (taken from U.S. NRC/NUREG/2213 2018)

Some of these factors contributing to uncertainty, as demonstrated in Figure 3.36 (Vs-kappa adjustments, host-to-target adjustment factors etc.) are not addressed in the relevant nuclear standards. Therefore, the subject of variability of GMPEs (sigma and number of epsilon), which is a controversial issue and discussed in nuclear standards and applications, will be examined comparatively in a detailed way. Before addressing this issue, it is necessary to consider the general structure of modern GMPEs and their uncertainties.

GMPEs can be expressed following form (Julian J. Bommer & Abrahamson, 2006):

$$log\ (Y) = f(magnitude, style - of\ faulting, distance, site) + \varepsilon\sigma \qquad (1)$$

And,

$$\delta = \varepsilon\sigma \qquad (2)$$

where δ: residual (the difference between an observed value and the predicted value from model)

ε: epsilon (number of standard deviations e.g. 1, 2, 3)

σ: sigma (standard deviation of the logarithmic residuals)

In many past studies, sigma has been completely ignored (Atik et al., 2010). In the 2000s, this issue was discussed and some different experts (Reiter, Abrahamson, or Romeo and Pristininzi) proposed the epsilon value between 2.5 and 4 while some hazard codes were used 6 epsilon as an max truncation value (Julina J. Bommer, 2002). Sigma and sigma truncation has become important and indispensable parameter for today's modern GMPEs (Atik et al., 2010).

One of the best and striking examples of this is the PEGASOS project. In the original PSHA study of Swiss NPPs, aleatory variability of the ground motion is not considered (σ=0) (Norman Abrahamson et al., 2004). Figure 3.37 clearly shows the results of the old and new study and the effect of sigma on these results (for 10^{-4} AFE, difference is change between 1.7 to 2.7 times).

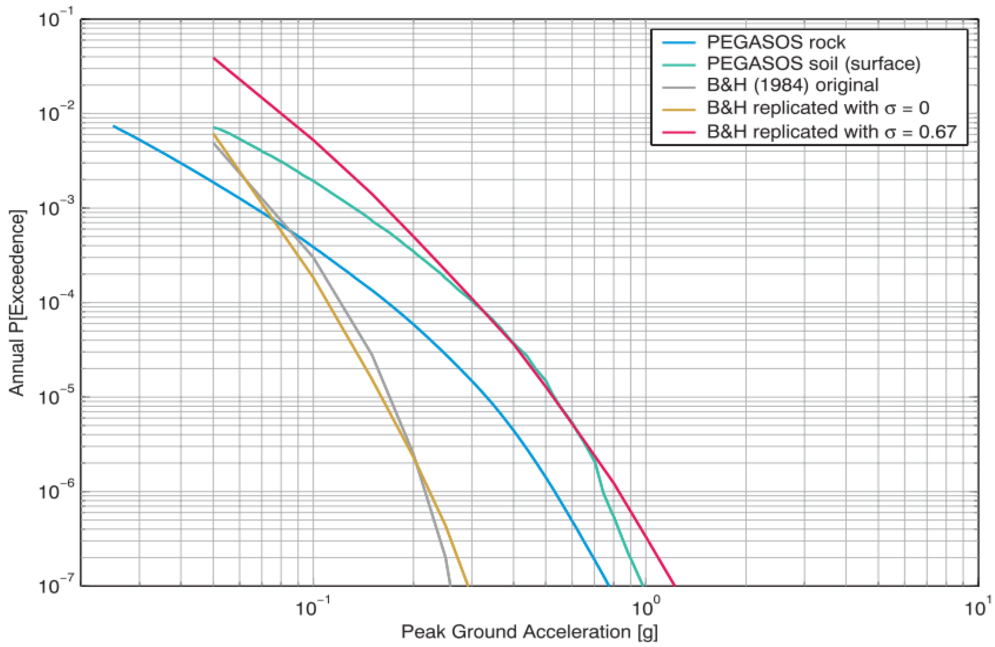


Figure 3.37. Comparison of hazard results of the original (1984) PSHA study on Swiss NPPs with the new PEGASOS study results and the effect of sigma (for median PGA) (Norman Abrahamson et al., 2004)

In most modern PSHA studies, epsilon is typically taken as 2 or 3, but in some projects epsilon is taken only as 1 (N. Abrahamson, 2006). According to the (Fleur O. Strasser, Bommer, & Abrahamson, 2004), epsilon significantly effects the hazard results as demonstrated at Figure 3.38. For 10^{-4} AFE level (it was generally used for nuclear installations in the past), difference between 3 and 6 sigma truncations is almost insignificant, but as AFE values decrease (from 10^{-4} to 10^{-8}; AFE was considered for Yucca Mountain as 10^{-8} and for PEGASOS 10^{-7}), difference tend to significantly grow (Fleur O. Strasser et al., 2004). Because of quite different application examples and approaches on variability in GMPE (sigma and number of epsilon) and its effects on the hazard results, this will be discussed in more detailed way.

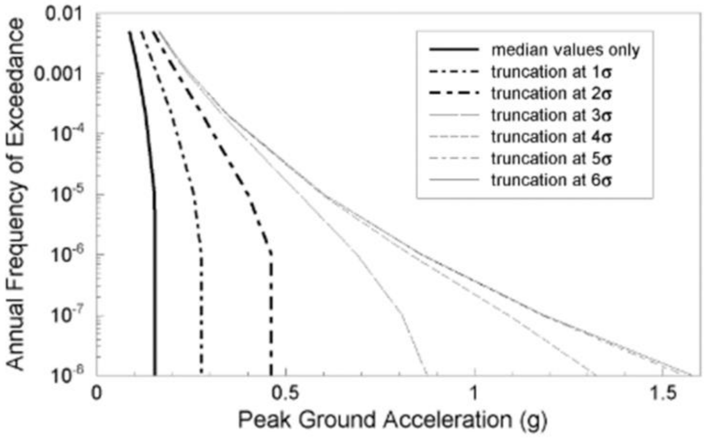


Figure 3.38. Seismic hazard curves derived using the GMPE of Ambraseys (1996) truncated at different σ levels (by assuming source to site distance=25 km, M_{max}=7.5, b-value=0.7, a-value=3.5) (after Strasser et al. 2004)

IAEA requires that uncertainty analysis must be part of SHA (IAEA/NS-R-3 rev.1, 2016). Also, it has been suggested by (IAEA/SSG-9, 2010) as a principle that uncertainties should be reduced to obtain reliable results in seismic hazard studies. Collection of reliable and relevant data is expressed as the most important parameter affecting the uncertainties. In order to reduce uncertainties, SSG-9 suggests; (i) to compile a sufficient amount of reliable and relevant data, (ii) to collect a site-specific data, (iii) to take into consider irreducible uncertainties including aleatory and epistemic uncertainties, (iv) to avoid bias in interpretations of expert's opinion, (v) to consider all viable hypotheses and models, (vi) to conduct sensitivity analysis systematically to find out the significance of the contributions of the various input data in the model, (vii) to develop an integrated evaluation considering both knowledge and uncertainties, (viii) to include multiple attenuation relationships suitable for each tectonic environment in order to reduce epistemic uncertainty. This SSG-9 document does not contain a direct provision for the epsilon value for SHA. According to (IAEA/SRS No.89, 2016), in DSHA practice, epsilon value generally assigned as 0 or 1, but, considering PSHA, this document also does not suggest any specific epsilon value.

In USA, one of the most important reasons for the development of SSHAC process is incorporation of uncertainties (U.S. NRC/NUREG/CR-6372, 1997a). (U.S. NRC/RG 1.208, 2007) also highlights the significant effects of uncertainties on hazard results. Considering specifically epsilon, RG 1.208 and (U.S. NRC/NUREG 800 2.5.2, 2014) refers the EPRI report (1013105) on the determination of the epsilon value, by indicating that "no truncation should be performed for a specific epsilon value”. Main results and suggestions of this EPRI report (EPRI & US DOE, 2006) are given below; (i) variability in ground motion significantly affect the hazard results (ii) selection of 2 or 3 sigma (common practice in PSHA) truncation is not technically defensible assumption, (iii) number of selected epsilon have significant effect on hazard results, (iv) “*there is no basis for truncating the ground motion distribution at an epsilon value of less than 3 and there are observations of epsilon values greater than 3. We conclude that using an untruncated lognormal ground motion distribution in probabilistic seismic hazard analyses is appropriate for ground motion values that are below the physical limits of the underlying rock or soils*”. Similarly (U.S. NRC/NUREG-2117 Rev.1, 2012) states that the small negative values of epsilon have almost no effect on hazard results, whereas the positive values have a significant effect. It also emphasizes that generally epsilon is taken as 2 or 3, but this cannot be technically justified. Comparison of untruncated/unbounded ground motion distribution with +3σ, +4σ and +5σ truncations can be seen at Figure 3.39.

Because of the importance of the PEGASOS project, the practices in this project will be discussed in a more detailed way in terms of number of epsilons. Firstly, when the issues contributing to uncertainty are taken into consideration as a whole, Figure 3.40 demonstrates the relative contributions of considered components. Dominant contributor is the median ground-motion prediction models to overall uncertainty (rock).

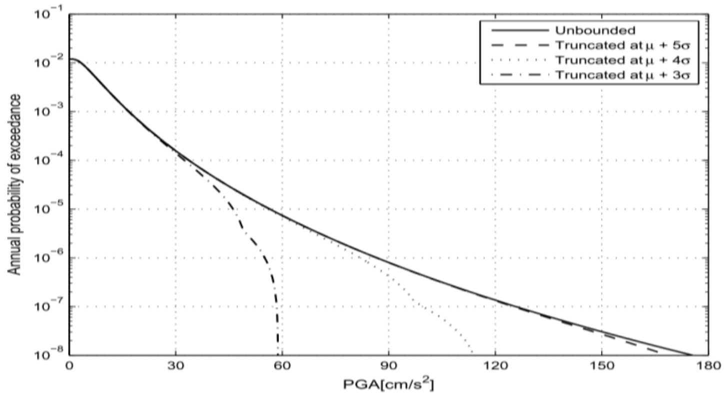


Figure 3.39. Comparison of untruncated ground motion distribution with +3σ, +4σ +5σ truncations (after Pavlenko 2016)

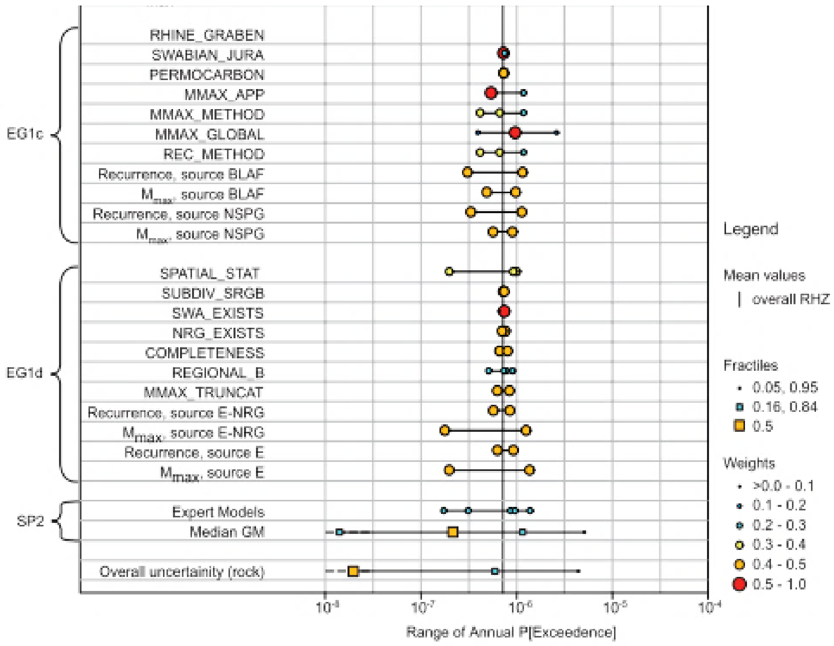


Figure 3.40. Components' contributions to the uncertainty in rock hazard for PGA at PEGASOS project (median ground-motion prediction models are the dominant contributor) (Norman Abrahamson et al., 2004)

Within the scope of the PEGASOS project, (Norman Abrahamson et al., 2004) states that; ε has moderate effects for AFEs generally considered in the design. In contrast, the effect is quite high at low AFE (e.g. 10^{-7}) values. According to (J. Bommer, Bungum, Cotton, Sabetta, & Scherbaum, 2004) there in almost no difference between untruncated and 4 σ case. Considering this, ε value is taken as 3.5, 3.0 and 2.5 with 0.1, 0.6 and 0.3 weights respectively. Also, for sensitivity analysis, sigma truncation alternatives between 2 and 6 are considered (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra), 2004a). Figure 3.41 demonstrates hazard deaggregation by magnitude, distance and epsilon. Contributions of epsilon bins can be clearly seen in this figure.

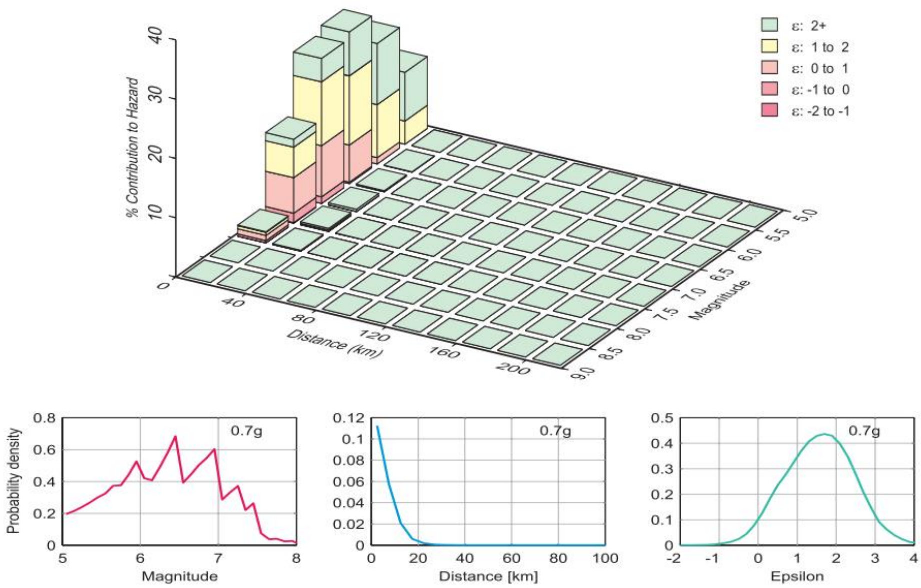
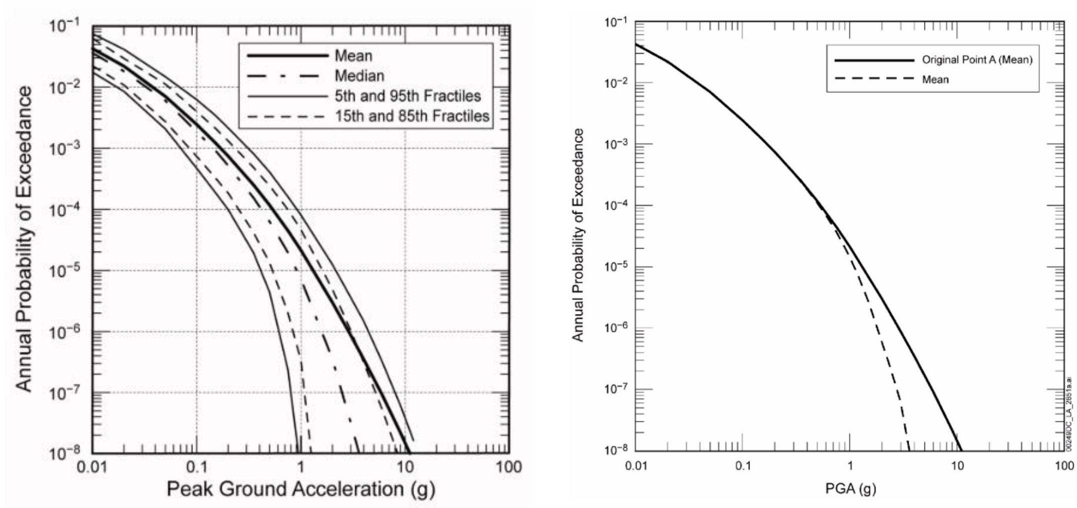


Figure 3.41. Hazard deaggregation by magnitude, distance and epsilon for PEGASOS (PGA) (taken from Abrahamson et al. 2004)

Another pioneering example is the Yucca Mountain project that is high-level radioactive waste repository site in Nevada/USA. As a result of the original SSHAC Level-4 study conducted in 1998 for the Yucca Mountain project, very high amplitude values were obtained especially for low AFE levels (for 10^{-7} AFE level; 6g & 6.5 m/s and for 10^{-8} AFE level; 11g & 13.0 m/s). Amplitudes close to these values have never been recorded or observed, and studies conducted by the USGS and some other institutions have shown that these PGA and PGV amplitudes (upper limit recommended 1.7 to 3.2 m/s for PGV) are not physically possible. Considering these studies, the hazard curve of Yucca Mountain has been modified by DOE; and the original and modified hazard curves are shown in Figure 3.42. After this modification, PGA value decreased from 11g to 3.5g for mean values.



(a) (b)

Figure 3.42. Yucca Mountain hazard curves; (a) original hazard curve suggested by SSHAC Level-4 study by DOE (b) modified hazard curve (dotted line) produced by considering physical limit of soil/crust of Earth (after Stamatakos, 2017)

In Japan, Finland, Russian Federation or Turkey, regulatory guides and standards do not have any specific requirement or provisions about this topic. But according to newly published report that compare the epsilon values employed during PSHA studies (OECD/NEA, 2019), there is no consensus about epsilon value in OECD countries, for example; Belgium and United Kingdom used ε=2; Canada, Czech Republic, Finland, Switzerland are used unbounded/untruncated model but France used ε=3. In Akkuyu NPP SHA studies in Turkey, hazard teams used the untruncated sigma approach (Akkuyu Nuclear JSC, 2017).

In case of such different applications, (Fleur O. Strasser, Bommer, & Abrahamson, 2008) has developed a proposal by considering AFE levels. They suggested that for each AFE level and recommended sigma truncation levels for it [in parenthesis], respectively; 10^{-1} [ε_{max}=1.28], 10^{-2} [ε_{max}=2.32], 10^{-3} [ε_{max}=3.09], 10^{-4} [ε_{max}=3.72], 10^{-5} [ε_{max}=4.26], 10^{-6} [ε_{max}=4.75].

As a general conclusion about sigma truncation (or selection of ε_{max}); (i) Regulatory guides and standards almost entirely ignore this or cover only by general provisions. (ii) In DSHA studies, traditionally 1 sigma level is taken generally, whereas in PSHA studies this value is taken usually as 2-3 or sometimes untruncated. From this point of view, it is debatable that how much DSHA is worst case (iii) Major nuclear projects, particularly the Yucca Mountain and PEGASOS projects, have generated a wide scientific debate on this issue, but there is still no unity in practice. (iv) For APE levels 10^{-4} and larger levels, 3 sigma generally provide approximately the same values as larger epsilon values, but lower APE levels (10^{-6} - 10^{-8}) needed in some nuclear plant projects or seismic PSA/PRA studies 3 sigma levels may be insufficient. (v) In addition, only statistical approach to sigma truncation is not enough, but to determine the sigma truncation level for higher APE levels, the physical limits of the material/soil/crust should be considered.

3.3.4. Sigma reduction (single-station sigma)

Generally, site specific ground-motion observations are not available for a long enough time span (Luzi, Bindi, Puglia, Pacor, & Oth, 2014). Because of this global or regional GMPEs are employed for ground motion predictions. GMPEs are based on ergodic assumption and global data set coming from different regions-countries and events recorded by broad network (N. A. Abrahamson & Hollenback, 2012). Aleatory variability of GMPEs (sigma) and its effects on SHA results have been discussed in 3.3.3. Basically, single-station sigma approach is based on fundamental assumption that aleatory variability based on single-station ground motion data should be less than aleatory variability obtained from broad network ground motion records (Atkinson, 2006; Luzi et al., 2014). Sigma basically consist of uncertainties arising from source, path and site effects. Single-station sigma is aimed to eliminate uncertainties coming from site effects (GeoPentech, 2015).

Using single-station sigma approach, aleatory variability are reduced because of the exclusion of the station-to-station variability term (IAEA/TECDOC-1796, 2016). Single-station sigma may reduce the sigma between 15%-30%, according to (Luzi et al., 2014), %9-14 by (N. A. Abrahamson & Hollenback, 2012), 10 to 40 % by (Ornthammarath, Douglas, Sigbjörnsson, & Lai, 2011).

Single-station sigma is "*potentially highly relevant to nuclear installations, and it could also be used in site selection*" according to (IAEA/SRS No.89, 2016). Because of this possible relative importance, this issue is included in this study.

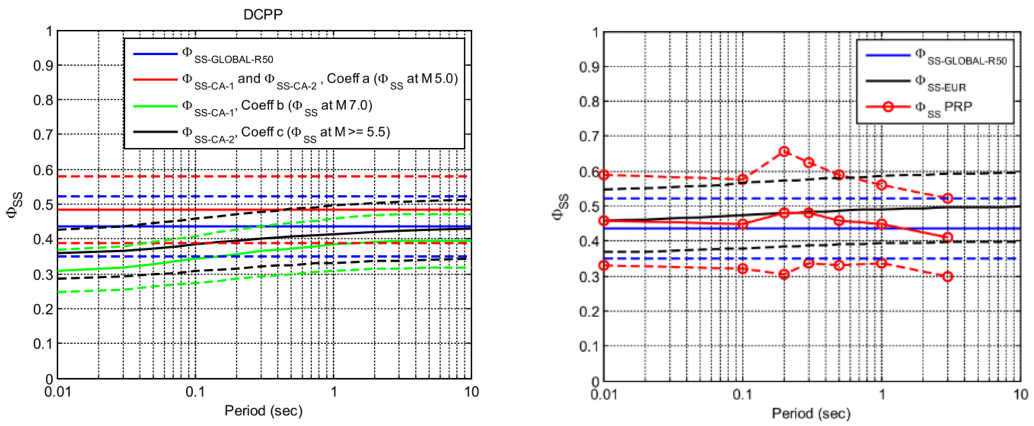
IAEA safety requirements and related safety guide (SSG-9) does not specifically recommend the consideration of the single-station sigma. But, two newly published IAEA documents (IAEA/SRS No.89, 2016; IAEA/TECDOC-1796, 2016) mention the single-station sigma. However, these documents only describe briefly the concept and mention its possible effects on sigma.

Similarly, in the USA, also any regulatory guide does not have any provision about this specific topic. Only two NUREGs mention (U.S. NRC/NUREG-2117 Rev.1, 2012; U.S. NRC/NUREG/2213, 2018) and describe single-station sigma briefly similar to IAEA. Considering Japan, Finland, Russian Federation and Turkey's regulatory guides and standards, there is no specific requirement or provision about single-station sigma.

In Akkuyu NPP case, total sigma was used but within the scope of sensitivity analysis single-station sigma approach was employed in order to demonstrate the conservativeness of the hazard results (Akkuyu Nuclear JSC, 2017).

International practices on this subject will be discussed here. The first application example is the SSHAC Level-3 Southwestern United States Ground Motion Characterization (SWUS GMC) study (GeoPentech, 2015) whose final report was published in 2015. Within the scope of SWUS GMC, for DCPP and PVNGS nuclear power plants, single-station sigma method is used. Sigma models are developed based on European, NGA-West2 and Lin et al. (2011) and California data sets for whole project. Specifically, for DCPP, NGA-West 2 and Lin et al (2011) databases are employed. Figure 3.43 (a) shows that comparison of period-dependent ϕ_{SS} based on global data sets (NGA-West 2 and Lin et al. 2011) (labeled as $\phi_{SS\text{-}GLOBAL\text{-}R50}$) and ϕ_{SS} based on California data (labeled as $\phi_{SS\text{-}CA}$) for DCPP. Generally, ϕ_{SS} models are between 0.35 and 0.45 with an ~0.1epistemic uncertainty.

Figure 3.43 (b) demonstrates that comparison of period-dependent ϕ_{SS} based on global data sets with ϕ_{SS} based on EUR data and ϕ_{SS} PEGASOS Refinement Project (PRP) results.



(a) (b)

Figure 3.43. Comparison of the the ϕ_{SS} models based on different data sets for DCPP (dashed lines represents epistemic uncertainty): (a) ϕ_{SS} based on global ($_{GLOBAL\text{-}R50}$) & California ($_{CA}$) data sets (b) Comparison of the magnitude-independent ϕ_{SS} models to the magnitude-independent PEGASOS Refinement Project ($_{PRP}$) and Europe ($_{EUR}$) ϕ_{SS} model (after GeoPentech, 2015)

Figure 3.44 shows that hazard sensitivity example based on M_w=7 earthquake with 15 km distance by employing 3 different ϕ_{SS} values (0.36, 0.45 and 0.54). For the low AFE level, hazard quite sensitive to ϕ_{SS} values.

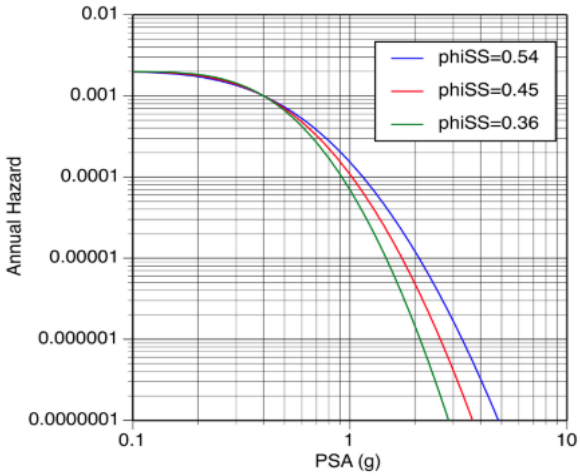


Figure 3.44. Simplified hazard sensitivity example (for M_w=7, distance=15 km, AFE=500 years) considering different ϕ_{SS} (labeled as phiSS) (taken from GeoPentech, 2015)

In addition to the SWUS GMC project, single-station sigma approach has been used in various nuclear projects such as; "*PEGASOS Refinement Project*" (PRP), "*Thyspunt Nuclear Siting Project in South Africa*", "*Hanford PSHA Project*" (GeoPentech, 2015). This approach can be expected to be widely used in nuclear site selection and PSHA studies in the future (Renault, 2012).

Figure 3.45 (a) shows a comparison of ergodic standard deviation (ϕ) and single-station standard deviation (ϕ_{ss}) by countries. ϕ values are between ~0.48-0.72 but, range of ϕ_{ss} is between ~0.38-0.55. This study has been performed within the scope of "PEGASOS Refinement Project" (PRP) by (Rodriguez-Marek et al., 2013)

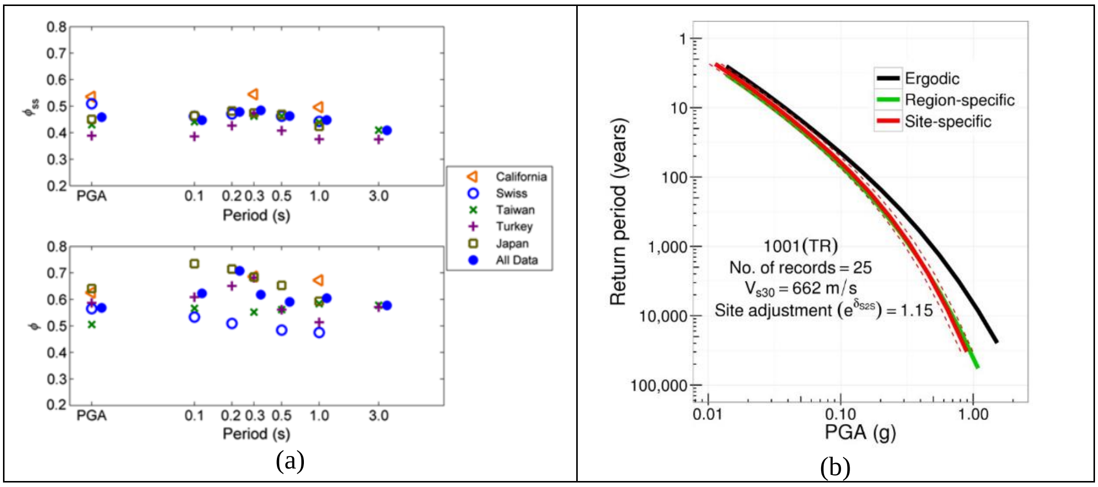


Figure 3.45. (a) Comparison of single-station standard deviation (ϕ_{ss}) (top) and ergodic within-event standard deviations (ϕ) (bottom) (b) Comparison of ergodic hazard curves (black line) and partially ergodic (single-station sigma) hazard curves (red line) based on Turkey data (Kotha, Bindi, & Cotton, 2017; Rodriguez-Marek et al., 2013)

Additionally, Figure 3.45 (b) demonstrates the comparison results of hazard curves based on ergodic sigma (black line) and partially ergodic (single-station sigma) (red line) based on Turkey data.

As a result; single-station sigma is a promising approach for both critical and nuclear projects and has the potential to significantly affect seismic hazard results. However, this issue is fairly new and has not yet been introduced into nuclear regulatory guidelines or standards. In addition, it should be noted that if this method is used in seismic hazard studies, the uncertainty eliminated during seismic hazard calculations should be taken into account when conducting site response analysis.

3.4. Hazard Outputs

Comparison results of hazard outputs (hazard curves, considered annual frequency of exceedances, response spectra, deaggregation etc.) related requirements and different applications have been briefly submitted at Appendix-A.

CHAPTER 4

COMPARISON ANALYSIS

Main purpose of this Chapter is to perform comparison analysis based on results and identified differences at Chapter 3. Also, some sensitivity analyses are designed and performed to show possible effects of required applied practices in nuclear projects on hazard results. The sensitivity analyzes are designed to test all limit values of the relevant parameters as much as possible for “high seismic” and “low seismic” sites.

4.1. Reference Nuclear Sites (Base Cases) & Parameter Assignment

In order to perform comparison analysis, one reference fictive nuclear site is created based on mainly Akkuyu NPP (ANPP) and Diablo Canyon NPP (DCPP) real parameters. These nuclear facilities are located at relatively high seismic areas. Because of this, by using real parameters of this sites, High Seismic Reference Nuclear Site (HS-RNS) parameters are created.

Comparison results of Chapter 3 shows that the hazard is generally dominated by the host zones based on selected host zone parameters such as M_{max}, depth distribution and earthquake recurrence parameters (activity rate and b-value). Based on these results, one 25-km radius host zone suggested by using average real values of ANPP and DCPP. Also, 100 km long fictive far fault is identified arbitrarily. Reference Nuclear Site general layout, reference spatial scales and employed fictive sources can be seen at Figure 4.1. The reason that this far fault is chosen as arbitrary is to represent the faults that are likely to be located within the proximity of approximately 100 km of high seismicity areas. This fault is intended to represent NAF whose nearest distance is 110 km off the Sinop NPP (Yılar, 2014), and SAF whose nearest distance is 77 km off the DCPP example (Lettis et al., 2015). High Seismic Reference Nuclear Site (HS-RNS) parameters (or also referenced as Base Case 1) are defined and suggested at Table 4.1. Then, in order to compare the high seismic site results with low seismic site results, additionally one Low Seismic Reference Nuclear Site (LS-RNS) is also suggested as a Base Case 2. LS-RNS sites are represent the low seismic nuclear sites (e.g. in Europe [Oskarshamn 3 and Forsmark 3 – 0.15g in Sweden, ASCÓ I-II – 0.13g in Spain] and in Eastern USA [Davis-Besse, Three Mile Island 1 NPPs and 19 more NPPS having 0.15 g design SSE level for 10^{-4} AFE level] (OECD/NEA, 2008, 2019).

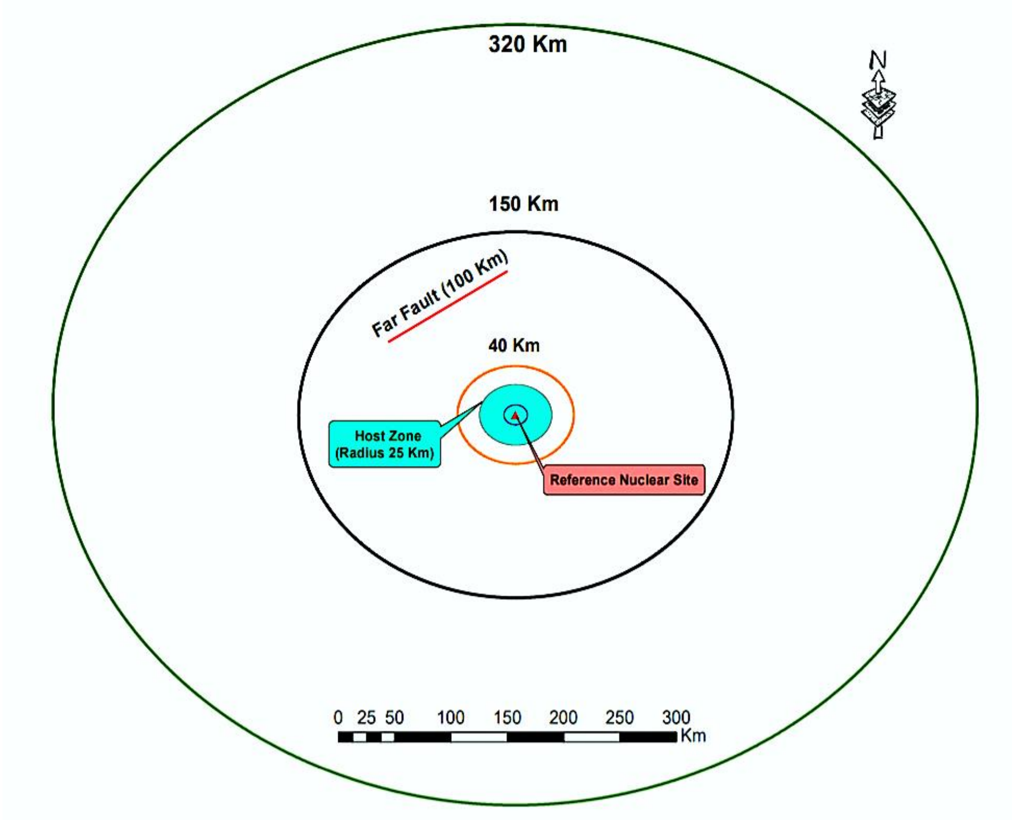


Figure 4.1. Reference Nuclear Site general layout, spatial scales and employed fictive sources (red strait line represents the Far Fault 100 km, blue circle represent the 25-km radius Host Zone, red triangle represent the Reference Nuclear Site)

Base Case 2 (LS-RNS) is identical to Base Case 1 (HS-RNS), except that “activity rate” parameter. Activity rate is utilized as 0.0022 for Base Case 2 (LS-RNS) (one fifth of HS-RNS activity rate) to get relatively low seismic site that roughly represent above mentioned European, Eastern US or other similar sites.

In order to perform seismic hazard analysis for HS-RNS and LS-RNS by using parameters at Table 4.1, additional parameters given at Table 4.2 are assumed by considering ANPP and DCPP applications. Unless otherwise stated in the text or figures, all comparisons are made for PGA (T=0).

Table 4.1. ANPP, DCPP and High Seismic Reference Nuclear Site (HS-RNS) parameters (Base Case 1)

Case	Parameters / Source Name	Activity rates	*weights*	b-value	*weights*	M_{min}	M_{max}	*weights*	Depth distribution	*weights*	Width	MFD model	Z_{TOR}
Approximate Real Applied Values	**5-15 Km Area Host Zone (ANPP)**	0.0035 0.0020 0.0011	*(0.3)* *(0.4)* *(0.3)*	0.90 1.00 1.10	*(0.3)* *(0.4)* *(0.3)*	3.5	6.0-7.2	*1.0*	0-13 km 13-22 km 22-35 km	*(0.1)* *(0.6)* *(0.3)*	~20 km	Truncated exp.	5 km (assumed)
	40 Km Area Host Zone (DCPP)	0.035 0.025 0.020	*(0.3)* *(0.4)* *(0.3)*	0.8	*(1)*	5.0	6.5 7.0 7.5	*(0.4)* *(0.5)* *(0.1)*	uniform	*uniform*	12 km	Truncated exp. + alternatives	5 km (assumed)
Base Case 1 High Seismic Reference Nuclear Site (HS-RNS)	**Parameters / Source Name**	**Activity rates**	***weights***	**b-value**	***weights***	M_{min}	M_{max}	***weights***	**Depth distribution**	***weights***	**Width**	**MFD model**	Z_{TOR}
	25 Km Area Host Zone	0.011	*(1)*	0.9	*(1)*	4.5	6.5	*1.0*	uniform	*uniform*	20 km	Truncated exp.	5 km
	Parameters / Source Name	**Dip angle**	**Fault mech.**	**b-value**	***weights***	M_{min}	M_{max}	***weights***	**Slip rates**	**MFD model**	**Fault width**	**Fault length**	**R**
	Far-Fault (100-km)	90	SS	0.70 0.80 0.90	*(0.3)* *(0.4)* *(0.3)*	4.5	7.35 7.40 7.28	*WC94-(0.34)* *WC94-(0.33)* *HB08-(0.33)*	10 mm/year	Y&C	20 km	100 km	100 km

Table 4.2. Additional Reference Nuclear Site parameters for HS-RNS & LS-RNS

Case	**Parameters / Source Name**	Z_{TOR}	$Z_{1.0}$	$Z_{1.5}$	$Z_{2.5}$	V_{S30}	**GMPEs**	ε_{max}
Real Applied Values	**5-15 Km Area Host Zone (ANPP)**	5 km (assumed)	0.048	0.4	0.607	1138 m/s	CB2008 AS2008 BA2008 CY2008 AB2010	untruncated
	40 Km Area Host Zone (DCPP)	5 km (assumed)	0.048	0.4	0.607	760 m/s	ASK14 BSSA14 CB14 CY14 I14 Zhao14 ASB14	untruncated
Base Case 1 & 2 (for HS-RNS & LS-RNS)	**Parameters / Source Name**	Z_{TOR}	$Z_{1.0}$	$Z_{1.5}$	$Z_{2.5}$	V_{S30}	**GMPEs**	ε_{max}
	25 Km Area Host Zone	5 km	0.048	0.4	0.607	1100 m/s	ASK14, BSSA14, CB14, CY14	3.0

4.2. Host Zone (25-km) Sensitivity Analysis for HS-RNS & LS-RNS

Within this sub-section, sensitivity analysis has been performed based on selected host zone parameters, for example magnitude recurrence parameters (activity rate, b-value), M_{max}, M_{min}, depth distribution, employed GMPEs, sigma truncation and reduction levels. During the sensitivity analysis for Host Zone, all parameters of Far-Fault are held fixed, and all other parameters of Host Zone are held fixed except for the evaluated one.

4.2.1. Magnitude recurrence parameters sensitivity analysis

Recurrence parameters, especially the b-value can be changed by 15-30% just because of employed declustering methodology and/or b-value calculations by MLM or LSM (Güner et al., 2015; Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra), 2004b) if area sources are utilized in PSHA, and this change in b-value affect significantly the hazard results (Gülerce & Vakilinezhad, 2015). Because of this, some sensitivity analyses have been performed to show the effects of “b-value” and “activity rate” changes on hazard results. During analysis all other parameters are held fixed except for the evaluated one. Figure 4.2 illustrates the sensitivity results of magnitude recurrence parameters.

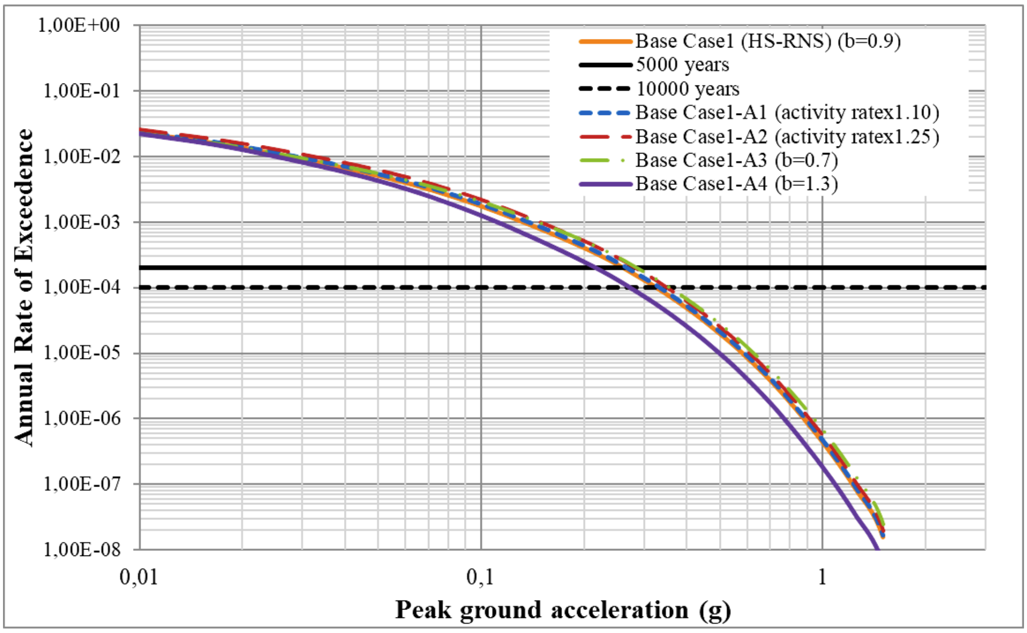


Figure 4.2. Magnitude recurrence parameters (activity rate and b-value) sensitivity analysis for Base Case 1 (for HS-RNS)

According to Figure 4.2, for 10^{-4} AFE level (~10.000 year return period) and lower AFE levels, 10% increase in the activity rate is almost negligible, but %25 increase in the activity rate change hazard results ~6%. For AFE level 10^{-4}, Base Case 1 peak ground acceleration is 0.33 g; Base Case 1-A1 is 0.34 and Base Case 1-A2 is 0.35 respectively.

On the other hand, b-value sensitivity for 10^{-4} AFE level; 22% decrease in the b-value (Base Case1-A3, b=0.7) increases the hazard results by ~12% (0.04g), 44% increase in the b-value (Base Case1-A4, b=1.3) decreases the hazard results by ~18% (0.06g).

Same sensitivity analysis has been performed for Base Case 2 (for LS-RNS) and results are demonstrated at Figure 4.3. PGA value corresponding to Base Case 2 (LS-RNS) (represented by orange curve) is 0.17g for 10^{-4} AFE level. Considering the percentage differences of the parameter variability are examined, it is almost identical to the results obtained from HS-RNS.

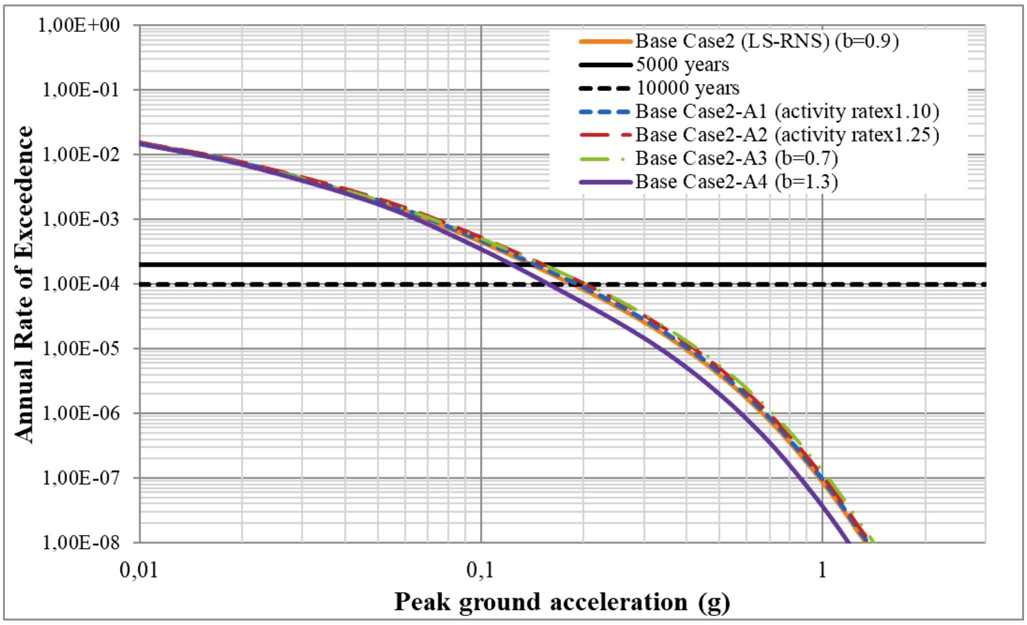


Figure 4.3. Magnitude recurrence parameters (activity rate and b-value) sensitivity analysis for Base Case 2 (for LS-RNS)

4.2.2. M_{max} sensitivity analysis

To demonstrate the sensitivity of hazard results to the M_{max}, base cases are compared to different M_{max} values. M_{max} values for host zone are employed between 5.5 and 7.75, justifications and labels are briefly described at Table 4.3.

Table 4.3. Selected M_{max} values for Host Zone and justifications

Source Name / Cases	**M_{max}**	*weights*	**Justification of selected M_{max}**	**Label**
Host Zone Base Case 1 & 2 (for HS-RNS & LS-RNS)	5.5	*1*	First proposed value for ANPP IAEA - TECDOC 1767	Base Case# (M_{max}=5.5)(ANPP Previous)
	6.0	*1*	Arbitrary	Base Case# (M_{max}=6.0)
	6.5	*1*	General practice (base case value)	Base Case# (M_{max}=6.5) (HS-RNS)(General Practice)
	7.0	*1*	DCPP alternative 1	Base Case# (M_{max}=7.0)(DCPP-1)
	7.2	*1*	ANPP maximum alternative	Base Case# (M_{max}=7.2)(ANPP Max)
	7.5	*1*	DCPP alternative 2	Base Case# (M_{max}=7.5)(DCPP-2)
	6.0 6.25 6.5 6.75 7.0 7.25 7.5 7.75	*0.17* *0.17* *0.17* *0.15* *0.13* *0.10* *0.06* *0.05*	Based on PEGASOS data by using Bayesian M_{max} approach suggested by (Johnston et al., 1994)	Base Case# (Bayesian M_{max})

According to Figure 4.4, Base case 1 (M_{max} = 6.5) and Bayesian M_{max} hazard curves almost exactly match with all AFE levels. For AFE level 10^{-4}, Base case 1 (Mmax = 6.5) peak ground acceleration is 0.33 g, 15% decrease in the M_{max} (Base Case 1 M_{max} = 5.5) decreases the hazard results by 21% (0.26g), 15% increase in the M_{max} (Base Case 1 M_{max} = 7.5) increases the hazard results by 9% (0.36g). The curves obtained for other M_{max} values vary between these ranges.

Same sensitivity analysis considering M_{max} parameter has been performed for Base Case 2 (for LS-RNS) and results are demonstrated at Figure 4.5. PGA value corresponding to Base Case 2 (LS-RNS) (represented by orange curve) is 0.17 for 10^{-4} AFE level. Considering the percent differences of the parameter variability are examined, it is completely parallel to the results obtained from HS-RNS Mmax sensitivity cases.

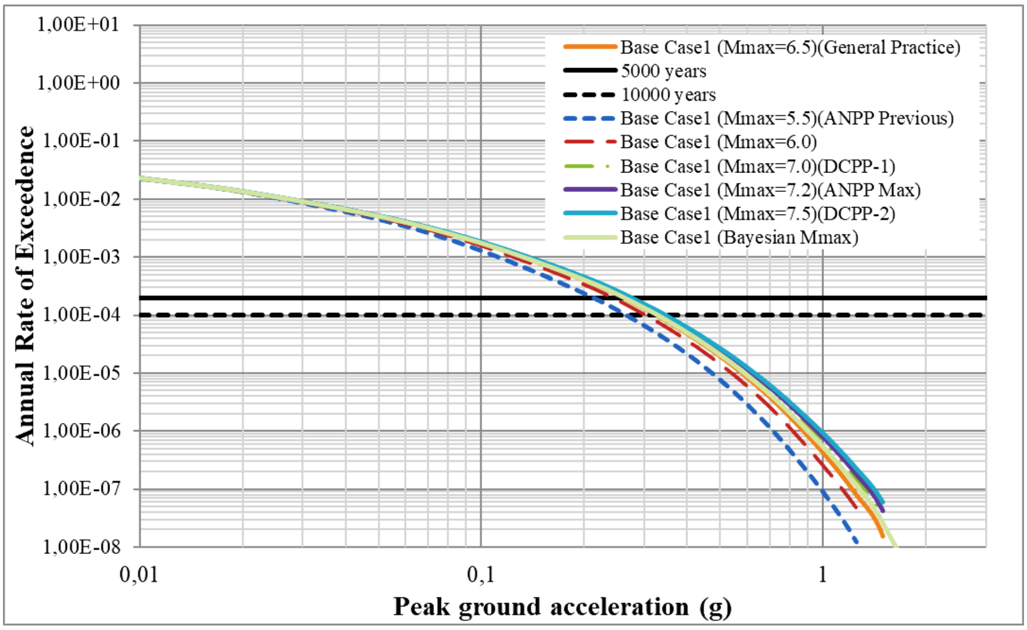


Figure 4.4. M_{max} sensitivity analysis for Base Case 1 (HS-RNS)

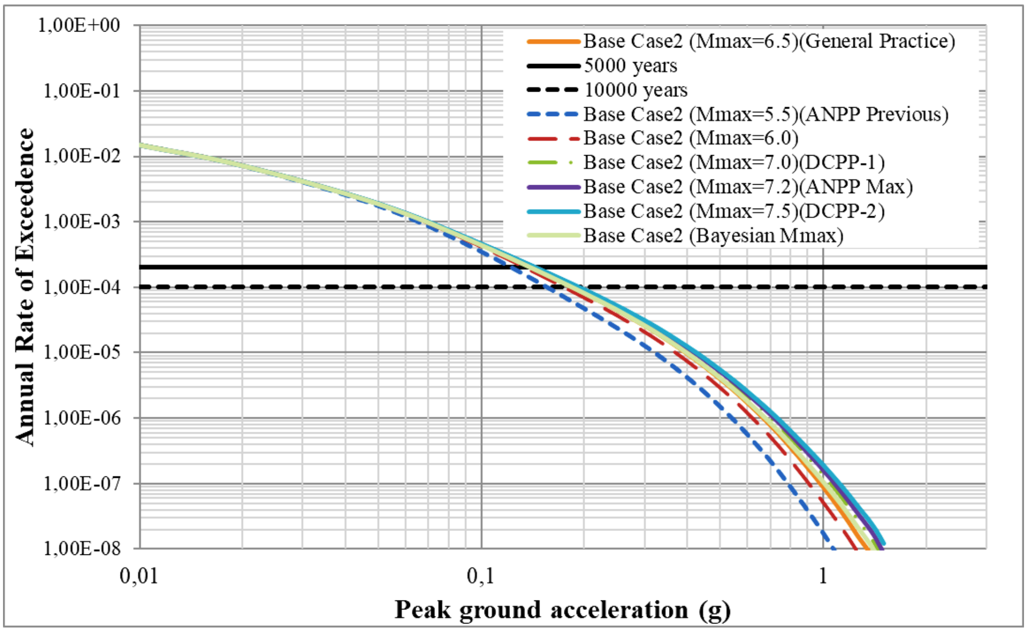


Figure 4.5. M_{max} sensitivity analysis for Base Case 2 (LS-RNS)

4.2.3. M_{min} sensitivity analysis

To demonstrate the sensitivity of hazard results by M_{min}, two base cases are compared to different M_{min} values. Selected M_{min} values for two base cases and justifications are briefly described at Table 4.4.

Table 4.4. Calculated activity rates for each M_{min} alternatives for Host Zone and justifications of selected M_{min}

M_{min}	Activity rates for Base Case 1 (HS-RNS)	Activity rates for Base Case 2 (LS-RNS)	*wt*	Justification of selected M_{min}	Label
2.5	0.700	0.140	*1*	2.5 Finland case	Base Case# (M_{min}=2.5)(Finland)
3.5	0.088	0.0176	*1*	3.5 ANPP case	Base Case# (M_{min}=3.5)(ANPP)
4.0	0.031	0.0063	*1*	4.0 UK case	Base Case# (M_{min}=4.0)(UK)
4.5	**0.011**	**0.0022**	***1***	**4.5 ~EPRI minimum=4.6 & Base Case & RF case**	**Base Case# (M_{min}=4.5)(Base Case,~EPRI, Russian)**
5.0	0.004	0.0008	*1*	5.0 General Practice (IAEA, DCPP, PGSS etc.)	Base Case# (M_{min}=5.0)(General Practice, IAEA, DCPP, PGSS)
5.5	0.0013	0.0003	*1*	5.5 Upper limit (NRC) (not obligatory)	Base Case# (M_{min}=5.5)(Upper Limit NRC)

Considering M_{min} sensitivity analysis results demonstrated at Figure 4.6 and Figure 4.7 together, hazard results for high seismic sites are more sensitive to M_{min} parameter. For AFE level 10^{-4}, except that M_{min}=5.5, all other case alternatives ($M_{min} \leq 5$) correspond to same peak ground acceleration (0.33 g), hence, 22% increases in the M_{min} (for the M_{min}=5.5) decreases the hazard results by 18% (0.27g). For AFE level 10^{-3} that is generally considered as an OBE (Operation Based Earthquake) level, effect of M_{min} is quite significant (7% increase for M_{min}=2.5 and 40% decrease for M_{min}=5.5).

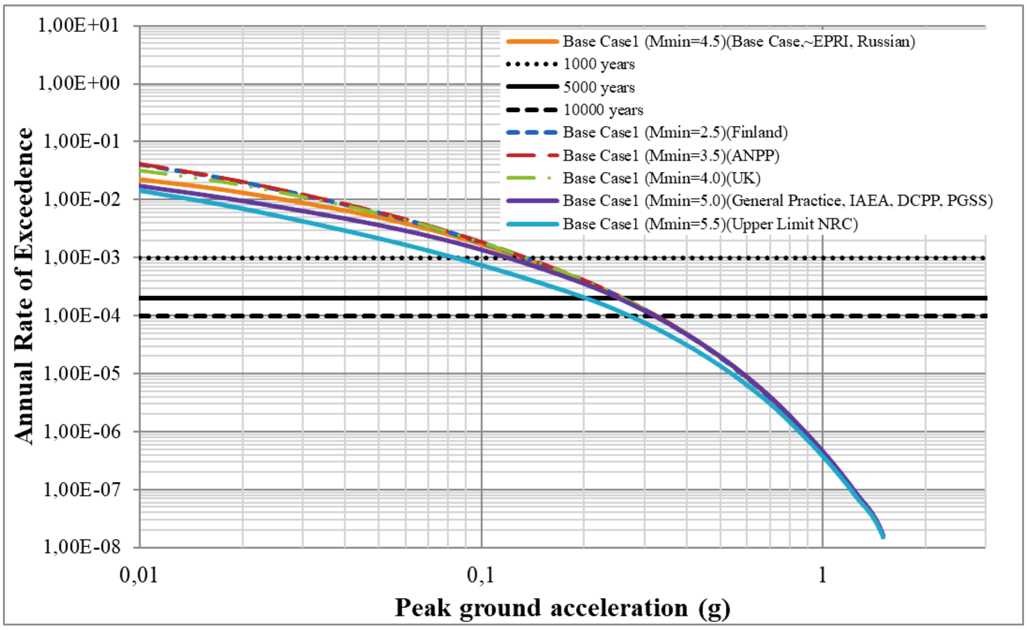


Figure 4.6. M_{min} sensitivity analysis for Base Case 1 (HS-RNS)

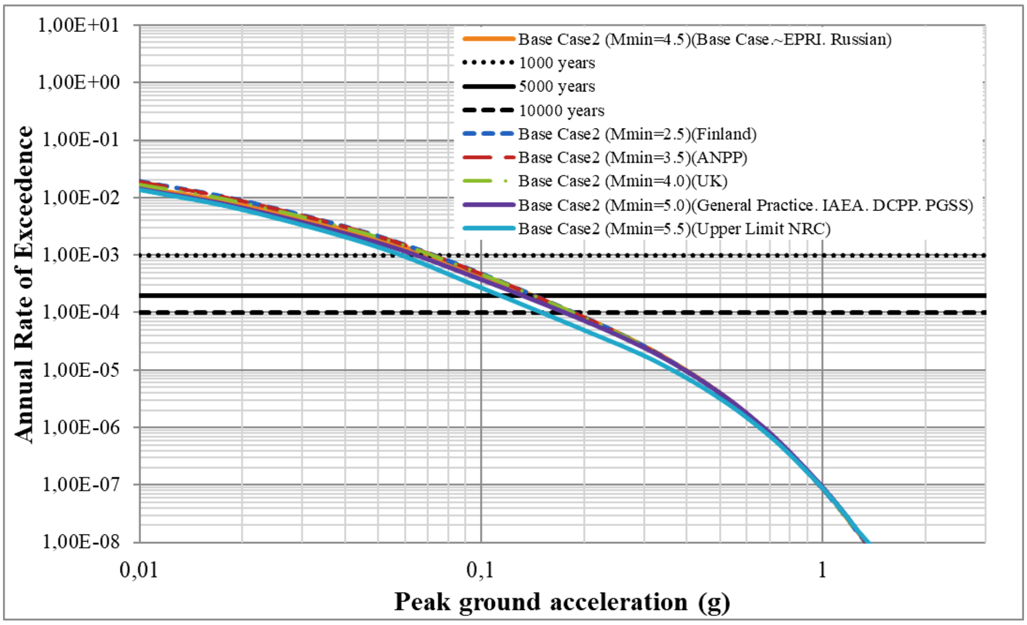


Figure 4.7. M_{min} sensitivity analysis for Base Case 2 (LS-RNS)

4.2.4. Depth distribution sensitivity analysis

To show the sensitivity of hazard results to the depth distribution in Host Zone, base cases are compared to different Z_{TOR} and width alternatives. Z_{TOR} values for host zone are employed between 0 and 13 km, and width value are employed between 15 and 35 km. Employed Z_{TOR} and width alternatives are showed at Table 4.5.

Table 4.5. Employed Z_{TOR} and width alternatives for Host Zone

Source Name / Cases	Width	Z_{TOR}	*weights*	Justification of selection	Label
Host Zone Base Case 1 & 2 (for HS-RNS & LS-RNS)	15 km	0 km	*1*	Based on ANPP, DCPP and other practices	Base Case# (W=Width ZTOR=Z_{TOR}) for each pair
	25 km	0 km	*1*		
	15 km	5 km	*1*		
	20 km	**5 km**	*1*		
	25 km	5 km	*1*		
	20 km	10 km	*1*		
	35 km	10 km	*1*		
	20 km	13 km	*1*		
	35 km	13 km	*1*		

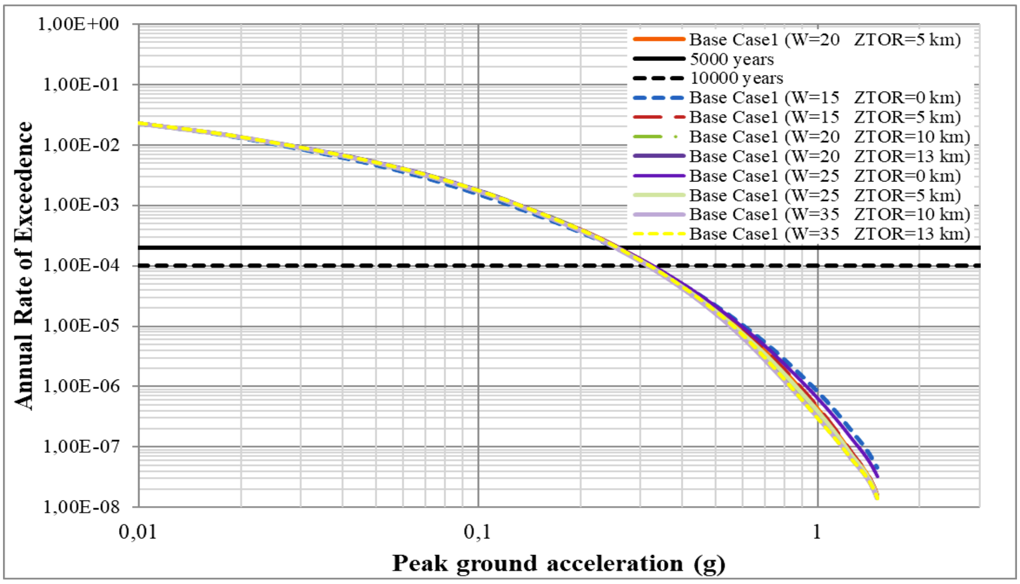


Figure 4.8. Depth distribution sensitivity analysis results based for Base Case 1 (HS-RNS)

Considering depth distribution sensitivity analysis results demonstrated at Figure 4.8 and Figure 4.9 together, for AFE level 10^{-4}, effects of depth distribution on hazard results are negligible for both cases (high and low seismic sites).

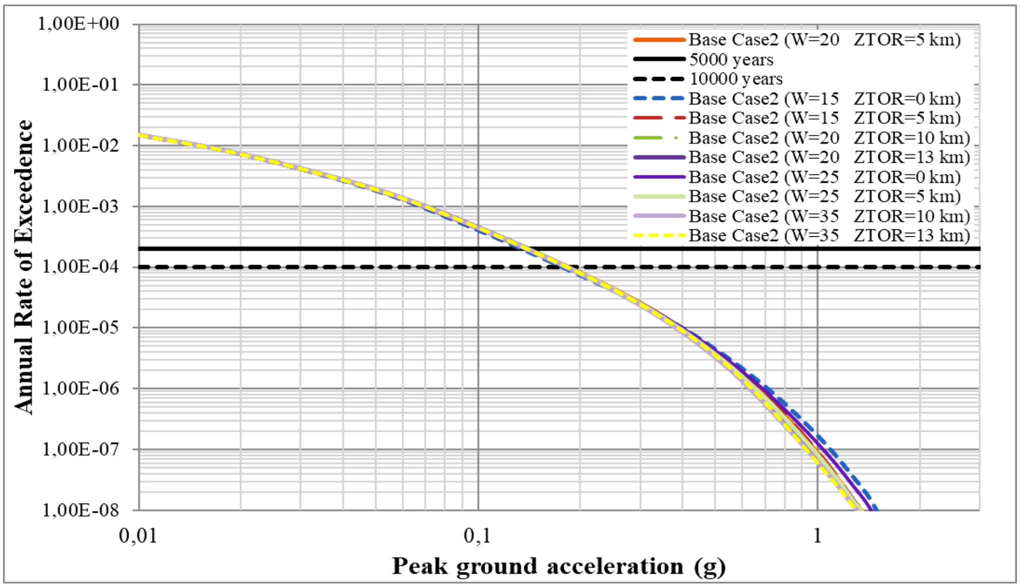


Figure 4.9. Depth distribution sensitivity analysis results based for Base Case 2 (LS-RNS)

4.2.5. GMPEs sensitivity analysis

To demonstrate the effects of selected GMPEs on hazard results, sensitivity analysis performed by employing different GMPEs. During sensitivity analysis these candidate GMPEs are used: the NGA West-1 models proposed by Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008) and local GMPE model proposed by Akkar and Bommer (2010). These 5 models are also employed for Akkuyu NPP project in Turkey (Akkuyu Nuclear JSC, 2013).

Table 4.6. Selected GMPEs for Base Case and sensitivity analysis & justifications

GMPEs	**Group**	*wt*	**Justification of selected GMPEs**	**Label**
Abrahamson and Silva (2008)	NGA-West1	*1*	Used in ANPP	Base Case# (AS08)
Boore and Atkinson (2008)	NGA-West1	*1*	Used in ANPP	Base Case# (BA08)
Campbell and Bozorgnia (2008)	NGA-West1	*1*	Used in ANPP	Base Case# (CB08)
Chiou and Youngs (2008)	NGA-West1	*1*	Used in ANPP	Base Case# (CY08)
TR-Adjusted - Abrahamson and Silva (2008)	TR-Adjusted NGA-West1	*1*	Turkey adjusted version of NGA-West1	Base Case# (AS08-TR)
TR-Adjusted - Boore and Atkinson (2008)	TR-Adjusted NGA-West1	*1*	Turkey adjusted version of NGA-West1	Base Case# (BA08-TR)
TR-Adjusted - Campbell and Bozorgnia (2008)	TR-Adjusted NGA-West1	*1*	Turkey adjusted version of NGA-West1	Base Case# (CB08-TR)
TR-Adjusted - Chiou and Youngs (2008)	TR-Adjusted NGA-West1	*1*	Turkey adjusted version of NGA-West1	Base Case# (CY08-TR)
Abrahamson et al (2014)	NGA-West2	*1*	Used in DCPP GMC SSHAC	Base Case# (ASK14)
Boore et al (2014)	NGA-West2	*1*	Used in DCPP GMC SSHAC	Base Case# (BSSA14)
Campbell and Bozorgnia (2014)	NGA-West2	*1*	Used in DCPP GMC SSHAC	Base Case# (CB14)
Chiou and Youngs (2014)	NGA-West2	*1*	Used in DCPP GMC SSHAC	Base Case# (CY14)
Akkar and Bommer (2010)	Turkey Local	*1*	Used in ANPP & PEGASOS PRP	Base Case# (AB10)
Akkar and Çağnan (2010)	Turkey Local	*1*	Used in PEGASOS PRP	Base Case# (AC10)
Akkar et al (2014)	Turkey Local	*1*	Used in DCPP GMC SSHAC	Base Case# (ASB14)

Turkey adjusted version of NGA West-1 models (TR-Adjusted Abrahamson and Silva (2008), TR-Adjusted Boore and Atkinson (2008), TR-Adjusted Campbell and Bozorgnia (2008), TR-Adjusted Chiou and Youngs (2008) proposed by (Gülerce, Kargıoğlu, & Abrahamson, 2015) are also used. Additionally, NGA West-2 models Abrahamson et al (2014), Boore et al (2014), Campbell and Bozorgnia (2014), Chiou and Youngs (2014) and local GMPE model proposed by Akkar et al (2014) are employed. These models are used for DCPP GMC SSHAC project (GeoPentech, 2015). Additionally, another local GMPE model proposed by Akkar and Çağnan

(2010) that also used within PEGASOS PRP is used. Selected all GMPEs and brief justification summary for each candidate model is provided at Table 4.6.

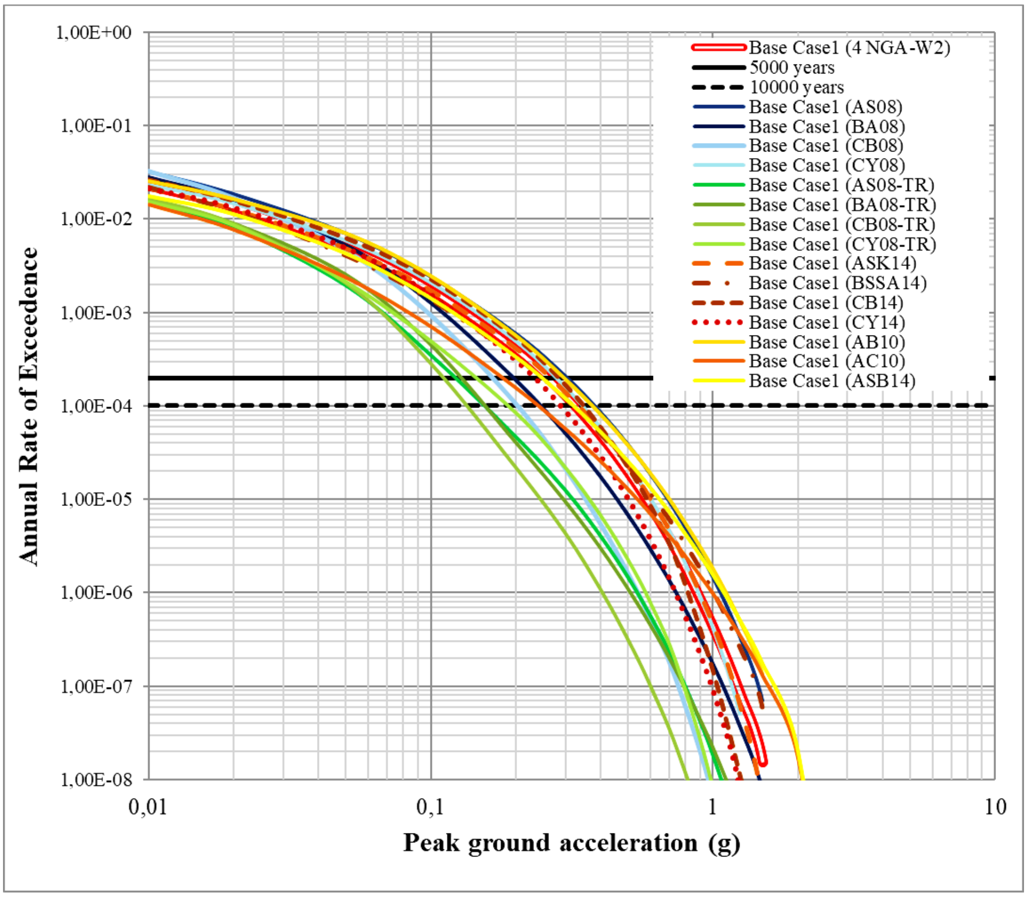


Figure 4.10. GMPEs sensitivity analysis for Base Case 1 (HS-RNS)

GMPEs sensitivity analysis results demonstrated at Figure 4.10 and Figure 4.11 shows that GMPE models introduce one of the biggest uncertainty in the hazard calculations and hazard results are very sensitive to selected GMPEs. Generally, TR-Adjusted NGA-West1 models (green group) result in relatively low hazard estimates, original NGA-West1 models (blue group) predictions are in between TR-Adjusted NGA-West1 and NGA-West2 (red group labeled as dashed lines) predictions. Local models (yellow-orange group) generally predicts compatible results with NGA-West2.

Considering Figure 4.10, for AFE level 10^{-4}, predictions are between 0.13 g to 0.39 g (three-fold difference).

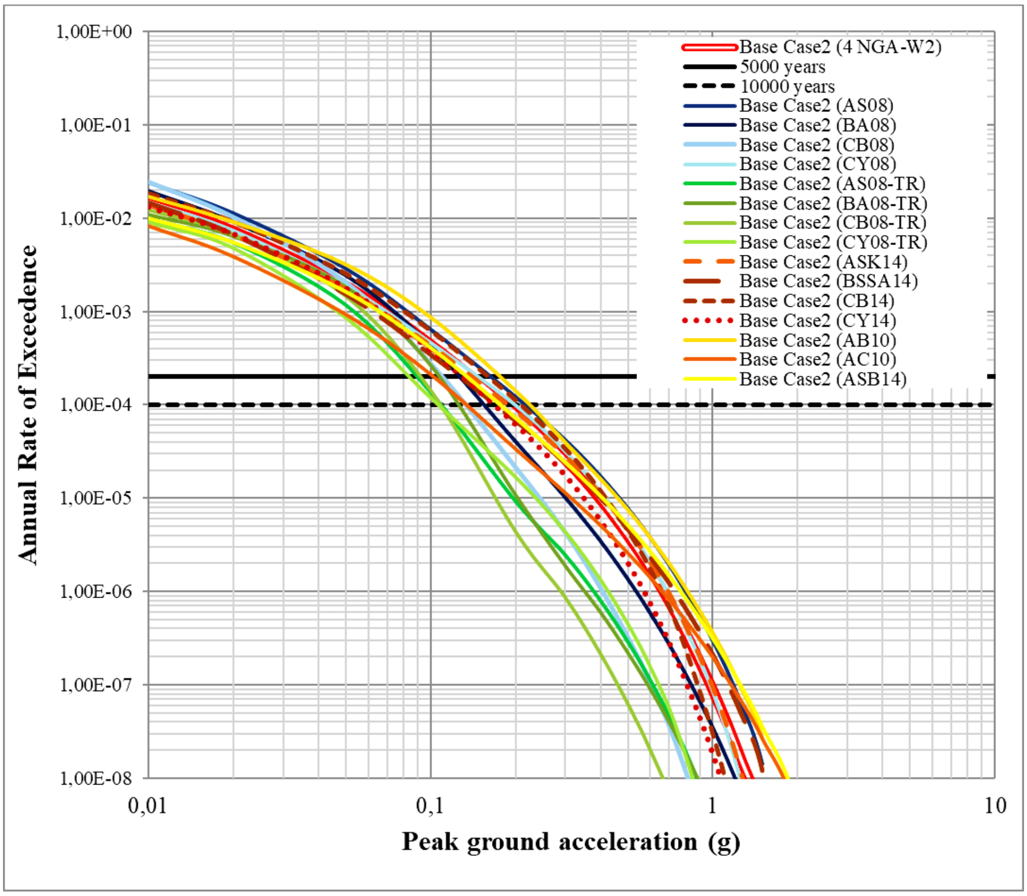


Figure 4.11. GMPEs sensitivity analysis for Base Case 2 (LS-RNS)

Considering Figure 4.11, for AFE level 10^{-4}, predictions are between 0.11 g to 0.24 g (more than two-fold difference).

4.2.6. Sigma truncation sensitivity analysis

To reveal the possible effects of sigma truncation on hazard results, sensitivity analysis is performed by employing different epsilon (ε) values. Different ε values are considered to determine where the epsilon value is saturated and demonstrate the effects of different ε applications on the hazard results. Belgium and United Kingdom used ε=2; Canada, Czech Republic, Finland, Switzerland used unbounded/untruncated model, France employed ε=3 (OECD/NEA, 2019), in Akkuyu NPP SHA studies untruncated sigma approach is utilized (Akkuyu Nuclear JSC, 2017), in PEGASOS sensitivity analysis sigma truncation alternatives between 2 and 6 are considered (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra), 2004a).

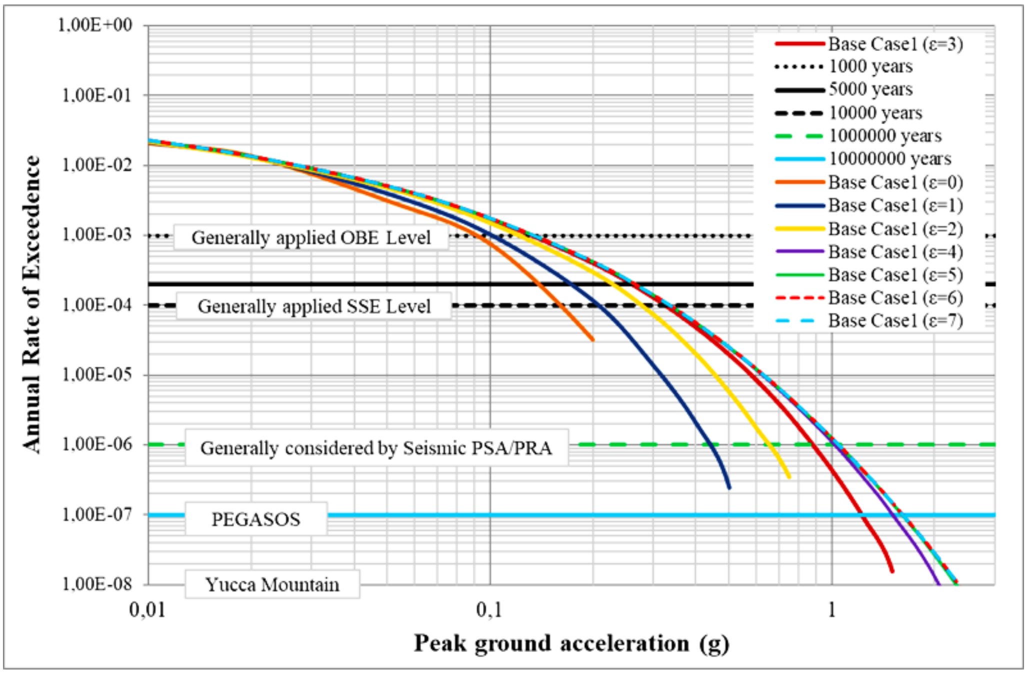


Figure 4.12. Epsilon (ε) sensitivity result by ε =0, 1, 2, 3, 4, 5, 6 and 7 for Base Case 1 (HS-RNS) & important AFE levels

Based on these different applications, taking ε = 0, 1, 2, 3, 4, 5, 6 and 7 respectively and totally eight sensitivity hazard calculations are performed for Base Case 1 and 2. Results are demonstrated at Figure 4.12 for Base Case 1 (HL-RNS). Selected ε value change hazard results significantly up to ε=5 level. ε=5 and bigger levels all hazard curves are almost the same for all AFE level. For AFE level 10^{-4}, PGA value is 0.16 g (~50% of base case) by ε=0, 0.21 g by ε=1, 0.28 g by ε=2, 0.33 g by ε=3 (base case), 0.34 g by ε=4-7.

Same sensitivity analysis has been performed for Base Case 2 and results are demonstrated at Figure 4.13. For AFE level 10^{-4}, PGA value is between 0.11 and 0.20 g (~two-fold difference) for different ε values.

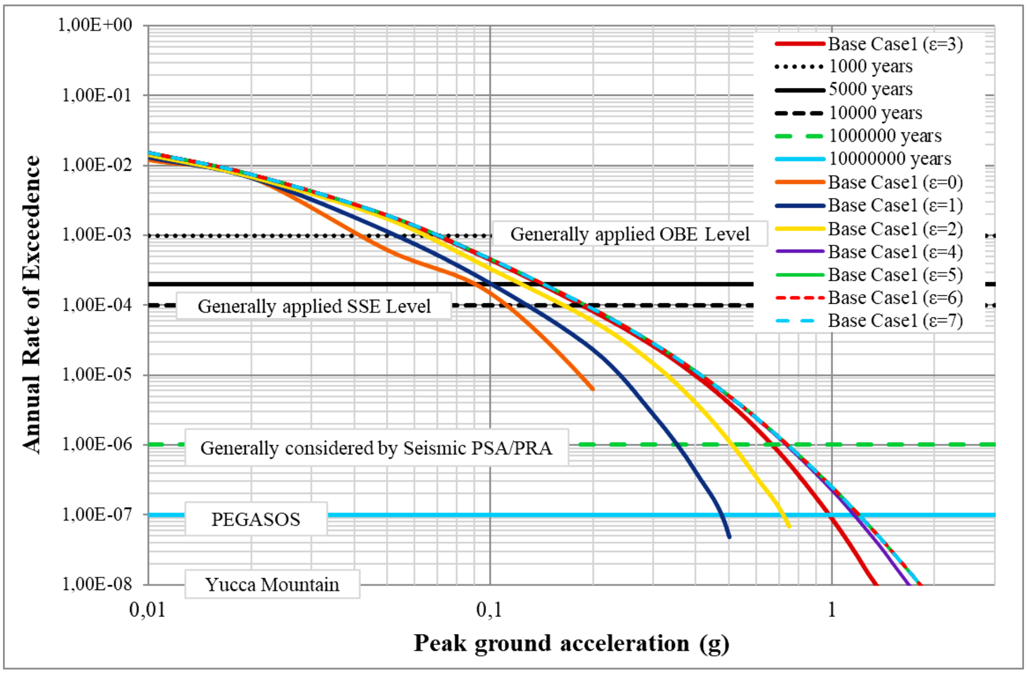


Figure 4.13. Epsilon (ε) sensitivity result by ε =0, 1, 2, 3, 4, 5, 6 and 7 for Base Case 2 (LS-RNS) & important AFE levels

4.2.7. Sigma reduction sensitivity analysis

To demonstrate the effect of sigma reduction (a.k.a. single-station sigma) on hazard estimations, sensitivity analyzes are performed utilizing different sigma reduction percentages between 10% and 30%. These percentages are employed by considering the literature about this subject. It is claimed that single-station sigma may reduce the sigma between 15% - 30% according to (Luzi et al., 2014), 9% - 14% by (N. A. Abrahamson & Hollenback, 2012), 10% - 40 % by (Ornthammarath et al., 2011).

During analysis only one GMM (ASK14 – NGA West-2) is utilized for simplicity. Sigma reduction sensitivity results are presented at Figure 4.14 and Figure 4.15. Analysis results show that %30 reduction in total sigma decreases the PGA for AFE level 10^{-4} from 0.33 g to 0.25 g (24%) for the high seismic base case; besides from 0.17 g to 0.15 g for the low seismic base case.

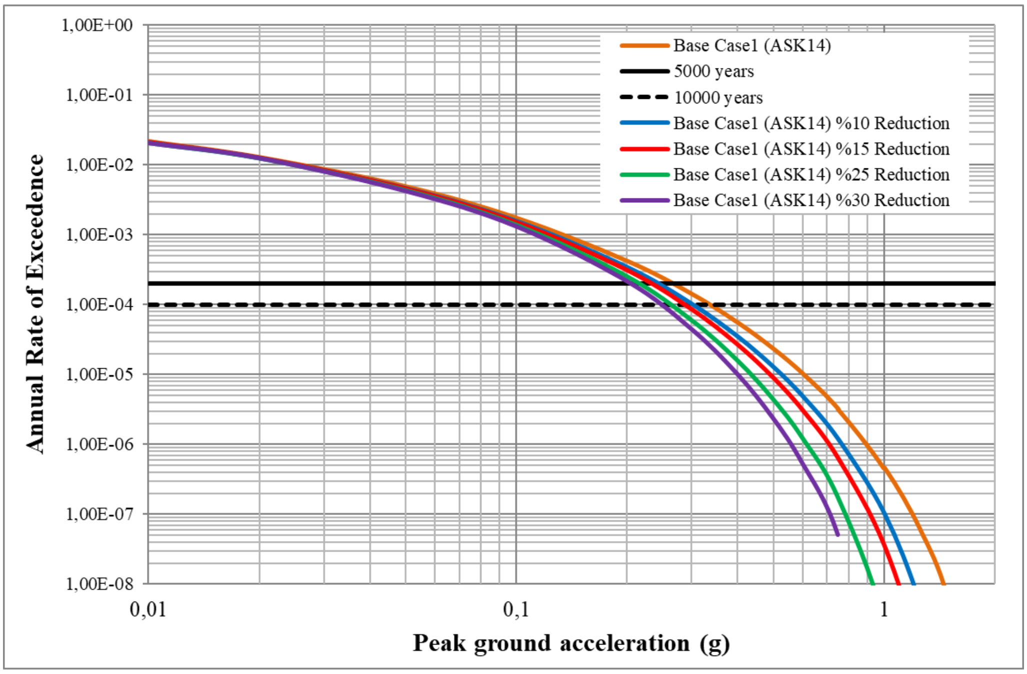


Figure 4.14. Sigma reduction (single-station sigma) sensitivity result by different reduction percentages using ASK14 GMPE for Base Case 1 (HS-RNS)

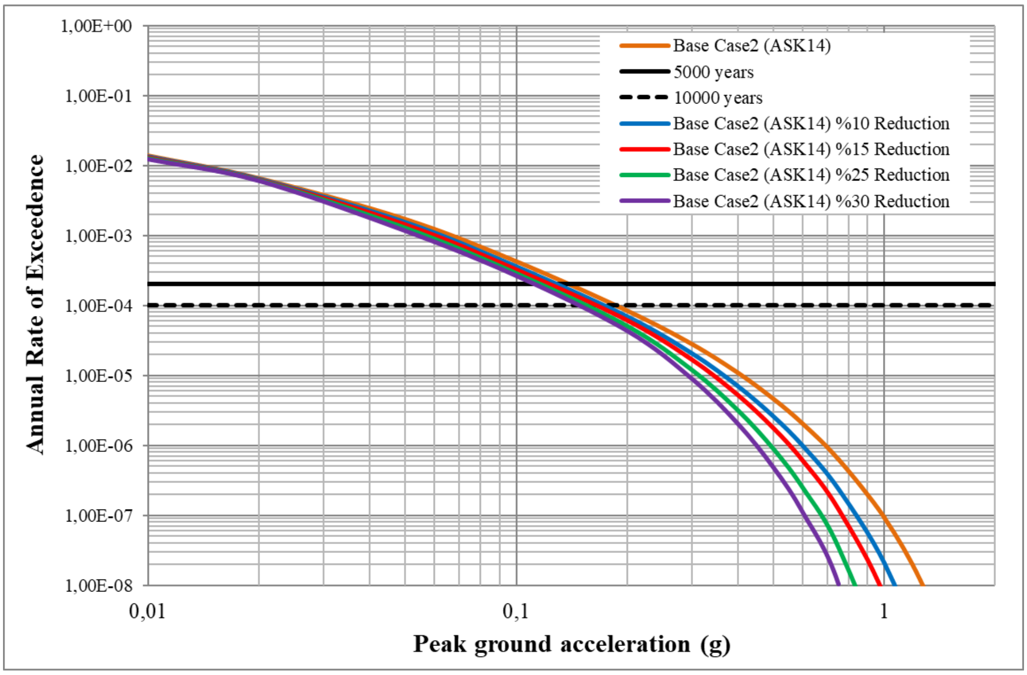


Figure 4.15. Sigma reduction (single-station sigma) sensitivity result by different reduction percentages using ASK14 GMPE for Base Case 2 (LS-RNS)

4.3. Far-Fault (100-km) Sensitivity Analysis for HS-RNS & LS-RNS

Within the scope of this sub-section sensitivity analysis has been performed on Far-Fault. Fault geometry and its parameters have been presented at Table 4.1 and Figure 4.1. Enlarged layout of Reference Nuclear Site, spatial scales and employed fictive sources details demonstrated at Figure 4.16.

During the sensitivity analysis for Far-Fault, all parameters of area Host Zone (25-km) are held fixed, and all other parameters of Far-Fault are held fixed except for the evaluated one.

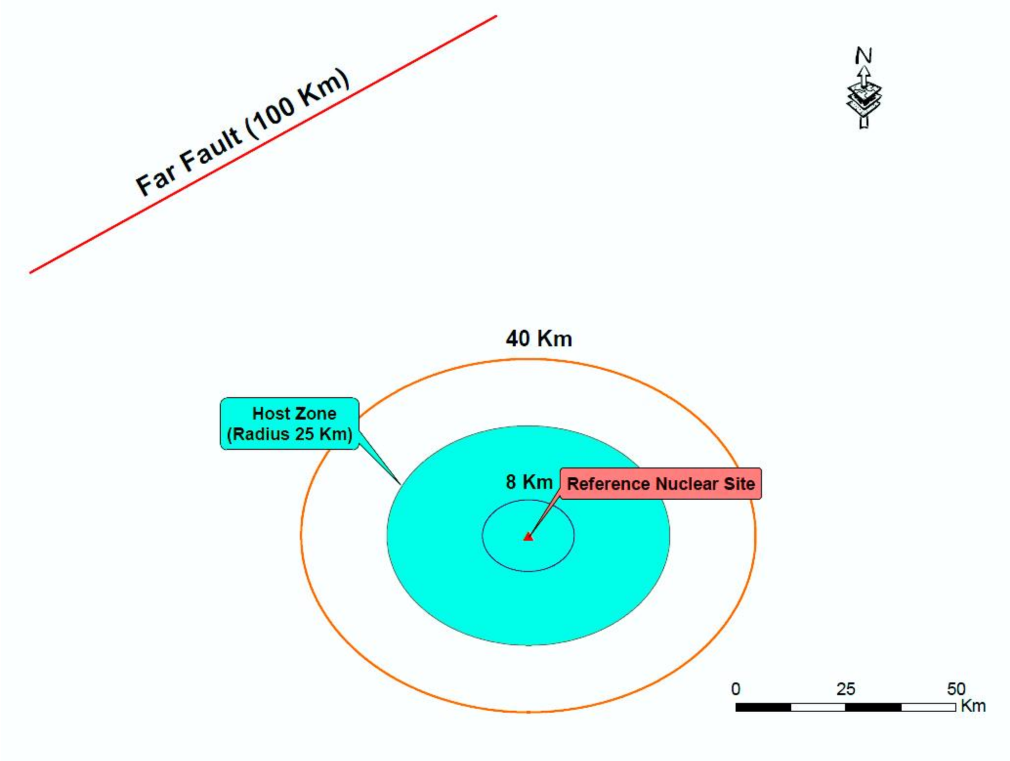


Figure 4.16. Reference Nuclear Site enlarged layout, spatial scales and employed fictive sources (red strait line represents the Far Fault 100 km, light green circle represent the 25-km radius Host Zone, red triangle represent the reference nuclear site)

4.3.1. Far-Fault M_{max} sensitivity analysis

To demonstrate the sensitivity of hazard results to the Far-Fault M_{max}, base cases are compared to different M_{max} values. M_{max} values for Far-Fault are selected as 6.5, 7.0, 7.5 and 8.0 for sensitivity analysis. Considering the 100 km distance between Reference Nuclear Site and Far-Fault, in addition to PGA, hazard curves for spectral accelerations at T = 2 seconds are calculated.

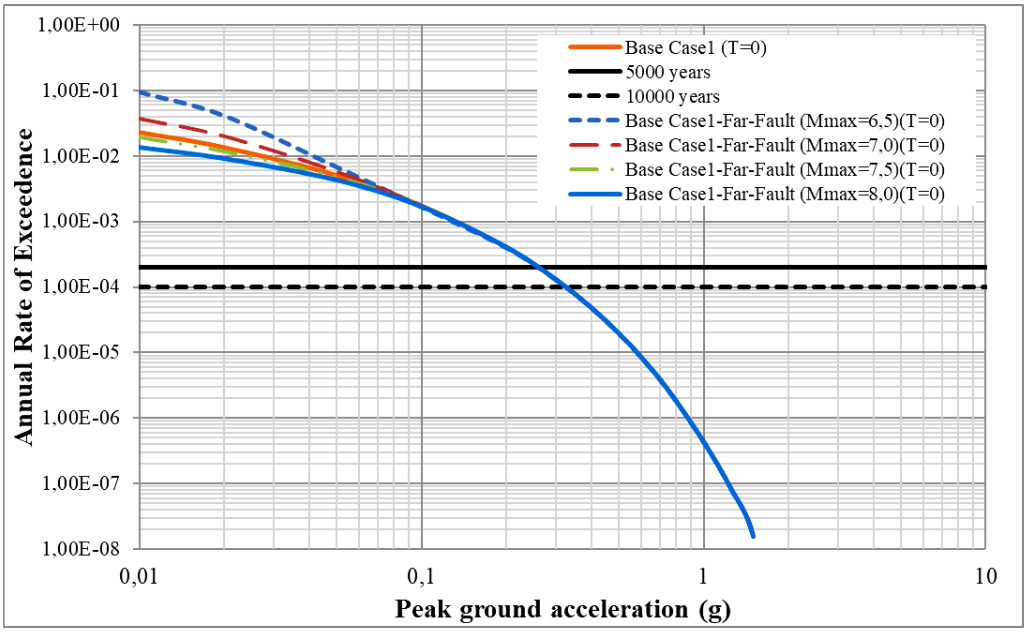


Figure 4.17. Far-Fault M_{max} sensitivity analysis for Base Case 1 (HS-RNS) (PGA)

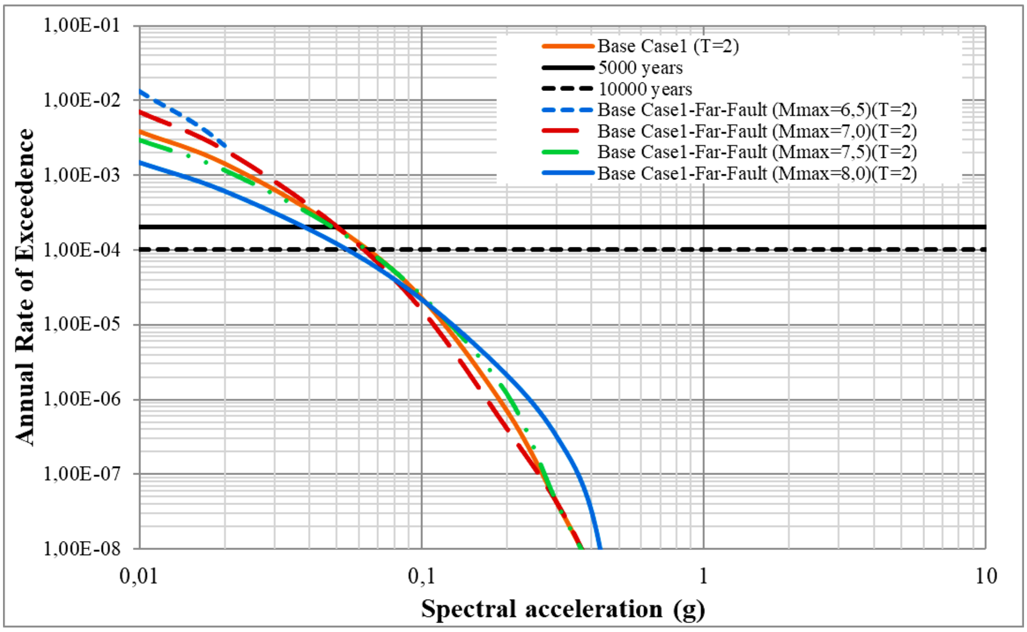


Figure 4.18. Far-Fault M_{max} sensitivity analysis for Base Case 1 (HS-RNS) (T=2)

Far-Fault M_{max} sensitivity results are demonstrated at Figure 4.17 for PGA and Figure 4.18 for T=2 sec by considering HS-RNS. PGA is not sensitive to Far-Fault M_{max} changes, but spectral accelerations are quite sensitive to M_{max} changes. For AFE level 10^{-4} and T=2, minimum and maximum spectral acceleration is between 0.065 g (M_{max} = 6.0, 7.0, 7.5, base case 1) and 0.055 g (M_{max} = 8.0). For M_{max} = 8, although the maximum magnitude value growth, hazard estimation results is reduced due to deterioration of the moment balance.

Far-Fault M_{max} sensitivity results are demonstrated at Figure 4.19 for PGA and Figure 4.20 for T=2 sec by considering Base Case 2 (for LS-RNS). Hazard estimates are compatible with the results obtained from HS-RNS.

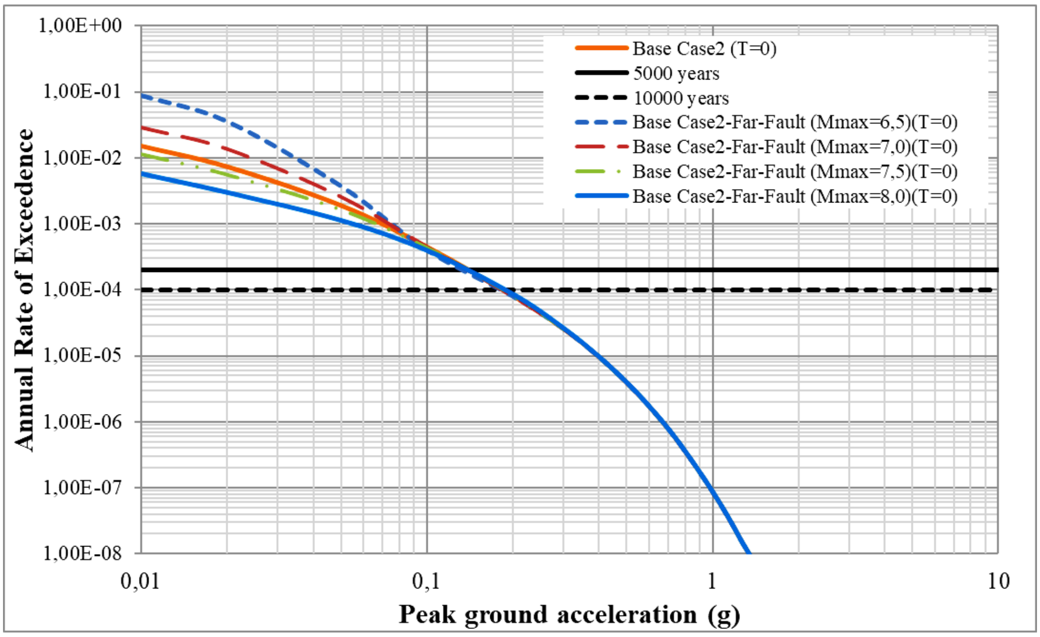


Figure 4.19. Far-Fault M_{max} sensitivity analysis for Base Case 2 (LS-RNS) (PGA)

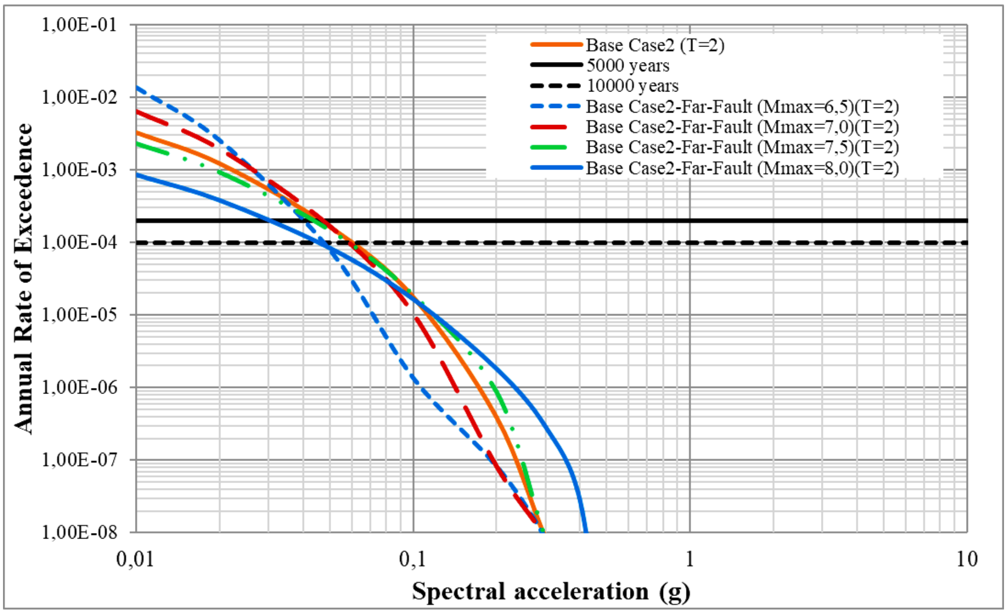


Figure 4.20. Far-Fault M_{max} sensitivity analysis for Base Case 2 (LS-RNS) (T=2)

4.3.2. Far-Fault slip rate sensitivity analysis

To review the sensitivity of hazard results to the Far-Fault slip rate, two base cases are compared by using different slip rates. Slip rates for Far-Fault are selected as 8 mm/year, 10 mm/year (base case value), 13 mm/year, 15 mm/year, 18 mm/year and 20 mm/year for sensitivity analysis. Considering the 100 km distance between Reference Nuclear Site and Far-Fault, in addition to PGA, hazard curves for spectral accelerations at T = 2 seconds are also calculated.

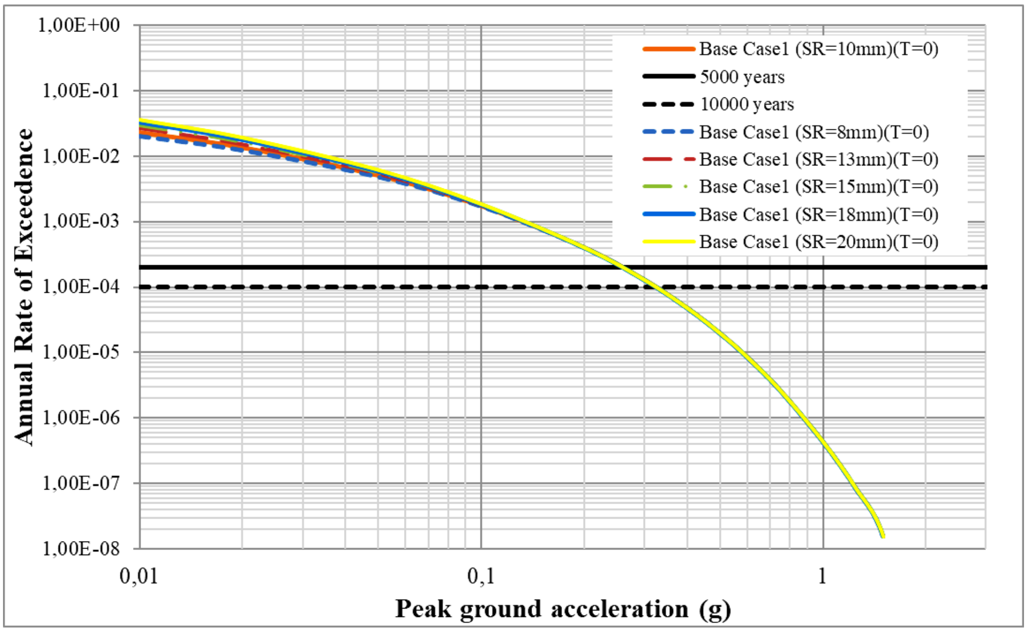


Figure 4.21. Far-Fault slip rate sensitivity analysis for Base Case 1 (HS-RNS) (PGA)

Far-Fault slip rate sensitivity results are demonstrated at Figure 4.21 for PGA and Figure 4.22 for T=2 sec by considering HS-RNS. PGA is not sensitive to Far-Fault slip rate changes, but spectral accelerations are relatively sensitive to slip rate changes. For AFE level 10^{-4} and T=2, minimum and maximum spectral acceleration is between 0.060 g (slip rate = 8 mm) and 0.080 g (slip rate = 20 mm). 20% decrease in the slip rate (from 10 mm to 8 mm) decreases the hazard results by 8% (0.06g), 100% increase in the slip rate increases the hazard results by 23% (0.80g) when base case values are 0.065g.

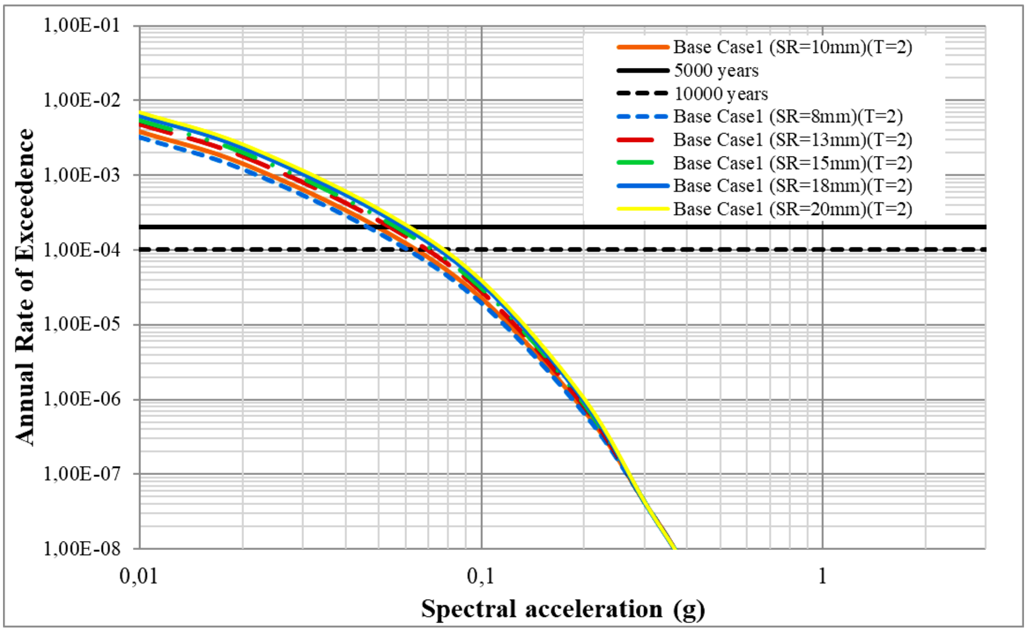


Figure 4.22. Far-Fault slip rate sensitivity analysis for Base Case 1 (HS-RNS) (T=2)

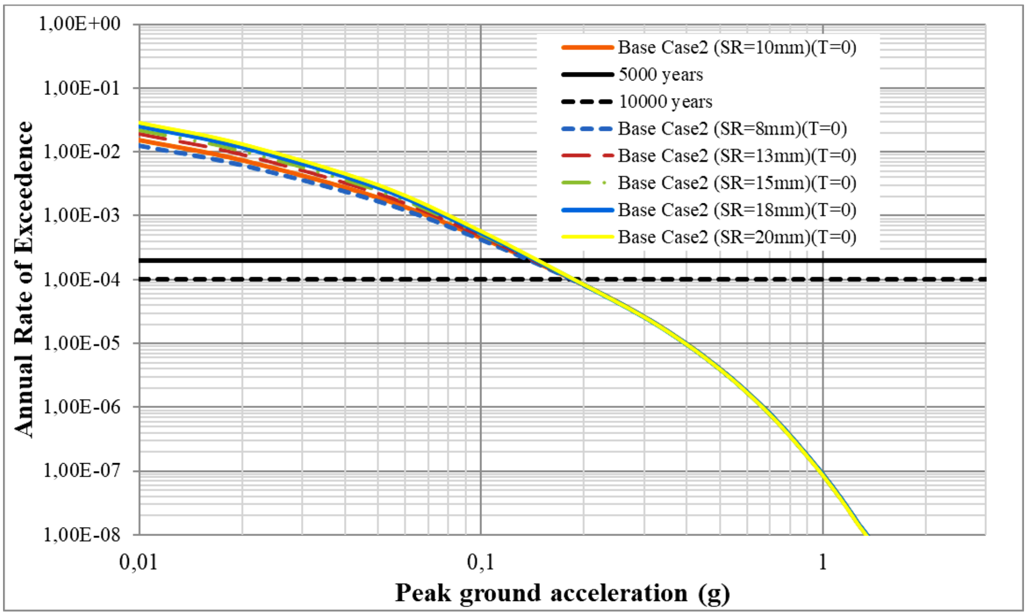


Figure 4.23. Far-Fault slip rate sensitivity analysis for Base Case 2 (LS-RNS) (PGA)

Same sensitivity analysis cases have been performed for Base Case 2 (for LS-RNS) and results are demonstrated at Figure 4.23 and Figure 4.24. Hazard estimates ratios are compatible with the results obtained from Base Case 1 (HS-RNS).

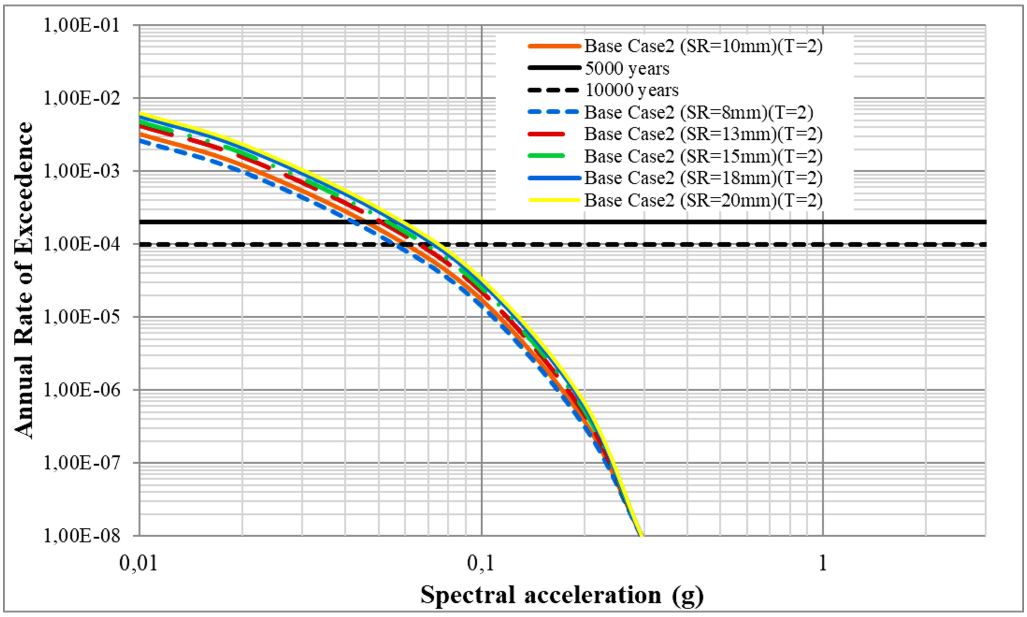


Figure 4.24. Far-Fault slip rate sensitivity analysis for Base Case 2 (LS-RNS) (T=2)

4.4. Near-Fault (within 40-km) Sensitivity Analysis for HS-RNS & LS-RNS

In this sub-section, in addition to the studied seismic sources, namely Host Zone and Far-Fault (100-km) presented as Base Case 1 (HS-RNS) and Base Case 2 (LS-RNS) considering different parameters; the presence of a Near-Fault by four different location alternatives within the site vicinity (40 km radius) and possible effects of its parameters are studied in a detail way.

This Near-Faults are also “fictive fault source” that is intended to represent the near active/capable faults discovered after the building of nuclear facilities. This fault can be represents the faults (F-B Folds from 34 km, Takado-oki fault from 25 km or Katakai Fault from 16 km which causes The Niigataken Chūetsu-Oki (NCO) earthquake (M_w=6.8) in 2007) that locates within the 40 km off the Kashiwazaki-Kariwa Nuclear Power Plants (KKNPP) in the Japan (Irikura & Kurahashi, 2010; World Nuclear Association, 2014) or four adjacent (<10 km) faults (Hosgri, Shoreline, Los Osos, and San Luis Bay faults) of DCPP in USA according to (Lettis et al., 2015)

During the hazard sensitivity analysis for Near-Fault, all parameters of Base Case 1 (HS-RNS) and Base Case 2 (LS-RNS) that is introduced at sub-chapter 4.1 are held fixed, and all other parameters of Near-Fault are held fixed except for the evaluated one.

Fault geometry, location alternatives and its parameters have been presented at Table 4.7. Fault location alternatives have been demonstrated at Figure 4.25.

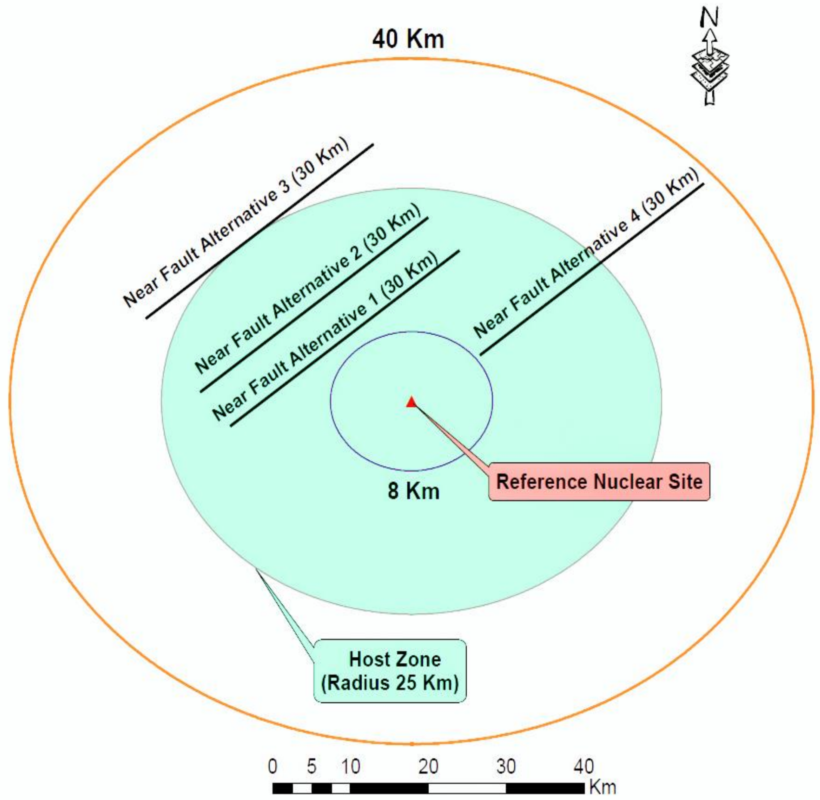


Figure 4.25. Reference Nuclear Site enlarged layout (within 40 km radius), spatial scales and Near-Fault location alternatives (each black strait line represents the Near-Fault 30 km)

It is assumed that this Near-Fault only moves once in the last 70ky and its slip rate does not exceed 5 mm/year. In this case; this fault is assumed capable/active according to criteria of IAEA and Japan; correspondingly, it is assumed not capable/active by USA, Russian Federation, Finland and Turkey's criteria as explained in a detailed way at sub-chapter 3.2.2. In reality, it is a quite complicated geological discussion and it should be discussed in depth through real faults and real practices. In here, the aim is to show how important the evaluations on this issue, fault capability criteria and demonstrate that how the Near-Fault can be affecting the hazard results.

Table 4.7. Near-Fault parameters and alternative case parameters

Parameters / Source Name		**Dip angle**	**Fault mech.**	**b-value**	***w***	$\mathbf{M_{min}}$	$\mathbf{M_{max}}$	***weights***	**Slip rates**	**MFD model**	**Fault width**	**Fault lenght**	**R**
Base Case 1 & 2 +	**30 Km Near-Fault (Alternative 1-4)**	90	SS	0.70 0.80 0.90	*(0.3)* *(0.4)* *(0.3)*	4.5	6.50 6.80 6.45	*WC94-(0.34)* *WC94-(0.33)* *HB08-(0.33)*	0.5 mm/year 1.0 mm/year 2.0 mm/year 3.0 mm/year 5.0 mm/year (for each location alternative)	Y&C	10 km	30 km	10 km (Alternative 1) 15 km (Alternative 2) 25 km (Alternative 3) 10 km-perpendicular (Alternative 4)
	30 Km Near-Fault (Alternative 1-RV)	60	RV	0.70 0.80 0.90	*(0.3)* *(0.4)* *(0.3)*	4.5	6.50 6.80 6.45	*WC94-(0.34)* *WC94-(0.33)* *HB08-(0.33)*	0.5 mm/year 1.0 mm/year 2.0 mm/year 3.0 mm/year 5.0 mm/year (for each location alternative)	Y&C	10 km	30 km	10 km (Alternative 1) (Reverse Faulting)

4.4.1. Near-Fault location alternatives and slip rate sensitivity analysis

To examine the sensitivity of hazard results to the Near-Fault, four different distance and location alternatives (from 10 to 25 km) as indicated Table 4.7 and demonstrated in Figure 4.25 are considered and related analysis are performed for two base case (HS-RNS and LS-RNS) parameters. Five different slip rates (from 0.5 mm/year to 5 mm/year) are also considered for each different location alternatives and results are compared to each other and base cases. This slip rates are employed by considering

DCPP near fault slip rates according to Lettis et. al. (2015) and Russian Federation fault capability criteria by (RTN/RB-019-01, 2002).

Near-Fault Alternative 1 (10 km) (HS-RNS)

According to Figure 4.26, for AFE level 10^{-4}, even for 0.5 mm/year slip rate for Near-Fault alternative increases the total hazard results from 0.33 g (Base Case 1) to 0.42 g. For other slip rate alternatives, PGA values are between 0.48 and 0.68 g. The presence of this fault changes the results from 27% to ~106% (two-fold).

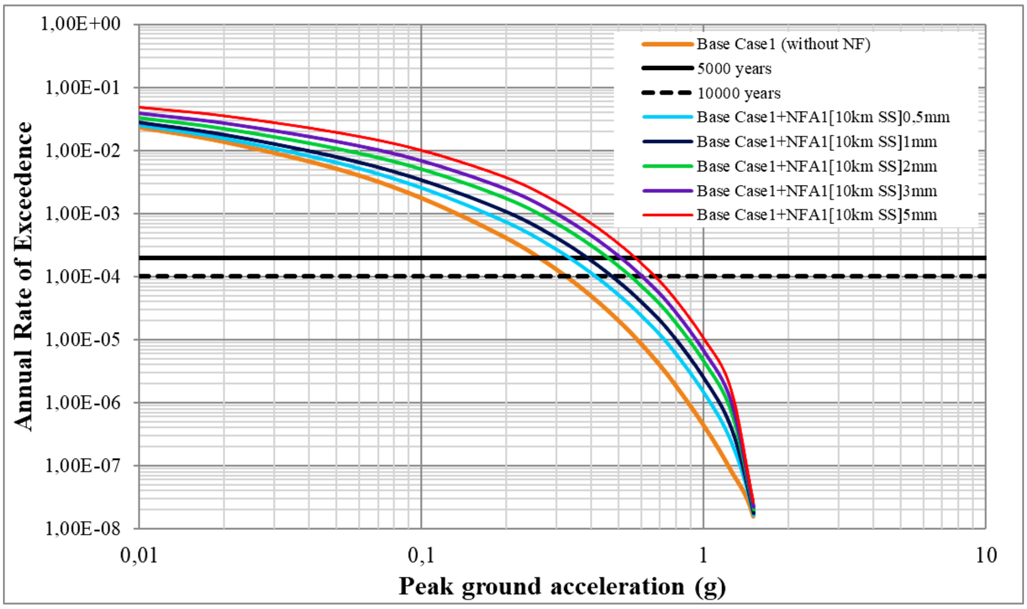


Figure 4.26. Sensitivity analysis results for Near-Fault Alternative 1 labeled as NFA1 (10 km) by considering different slip rates by assuming strike slip faulting style & comparisons to Base Case 1 (without Near-Fault) (for HS-RNS)

Near-Fault Alternative 2 (15 km) (HS-RNS)

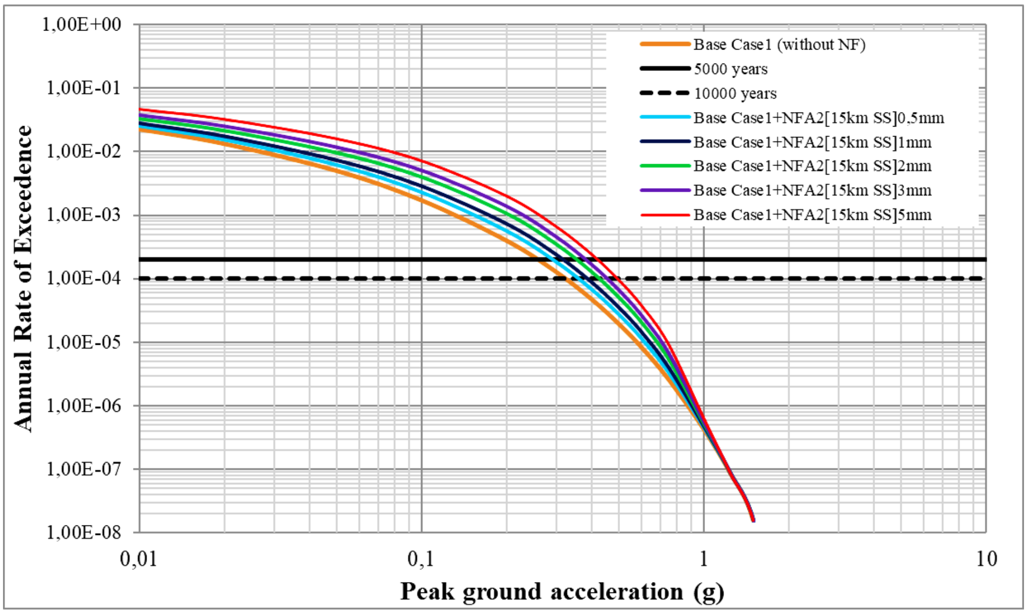


Figure 4.27. Sensitivity analysis results for Near-Fault Alternative 2 labeled as NFA2 (15 km) by considering different slip rates by assuming strike slip faulting style & comparisons to Base Case 1 (without Near-Fault) (for HS-RNS)

According to Figure 4.27, for AFE level 10^{-4}, for 0.5 mm/year slip rate for Near-Fault alternative increases the total hazard results from 0.33 g (Base Case 1) to 0.36 g. For other slip rate alternatives, PGA values are between 0.38 and 0.50 g. The presence of this fault changes the results from 10% to ~52%.

Near-Fault Alternative 3 (25 km) (HS-RNS)

According to Figure 4.28, for AFE level 10^{-4}, PGA values are between 0.33 and 0.37 g by different slip rates for Near-Fault. The presence of this fault changes the results 12% at maximum slip rate.

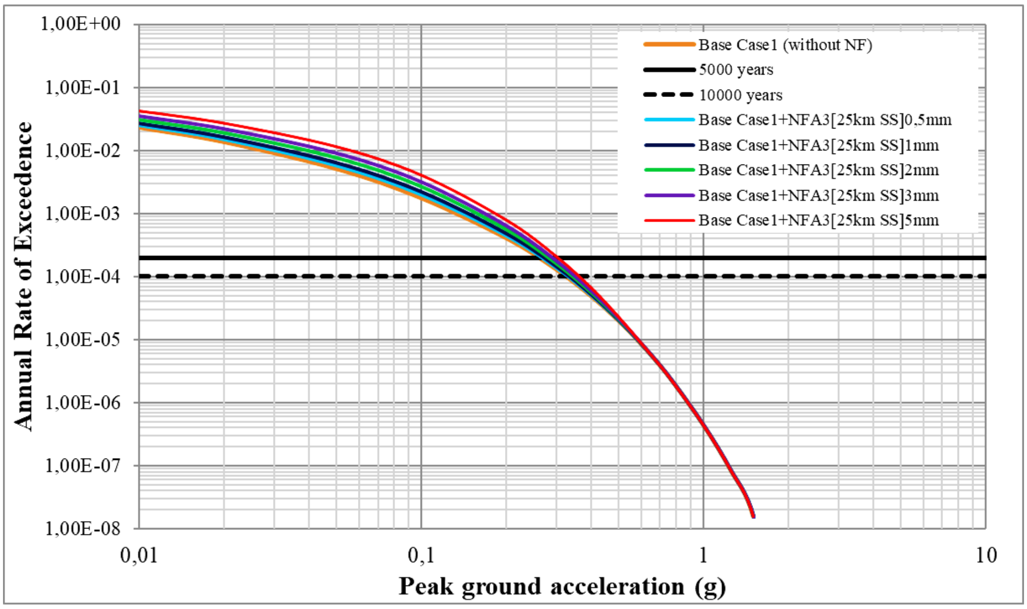


Figure 4.28. Sensitivity analysis results for Near-Fault Alternative 3 labeled as NFA3 (25 km) by considering different slip rates by assuming strike slip faulting style & comparisons to Base Case 1 (without Near-Fault) (for HS-RNS)

Near-Fault Alternative 4 (10 km – perpendicular position) (HS-RNS)

According to Figure 4.29, Alternative 1 demonstrated at Figure 4.26 and Alternative 4 are gives almost identical hazard results.

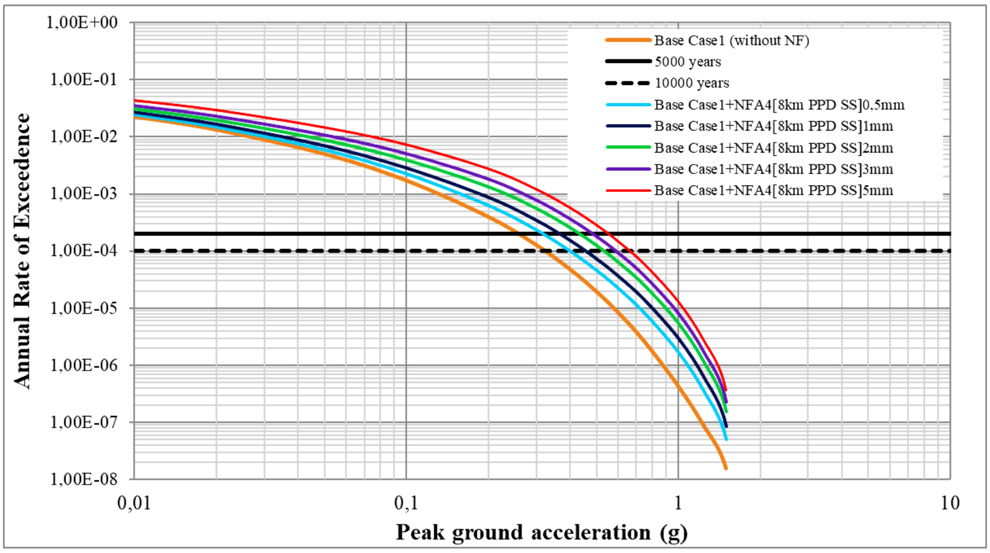


Figure 4.29. Sensitivity analysis results for Near-Fault Alternative 4 labeled as NFA4 (10 km – perpendicular position) by considering different slip rates by assuming strike slip faulting style & comparisons to Base Case 1 (without Near-Fault) (for HS-RNS)

Near-Fault Alternative 1 (10 km) (LS-RNS)

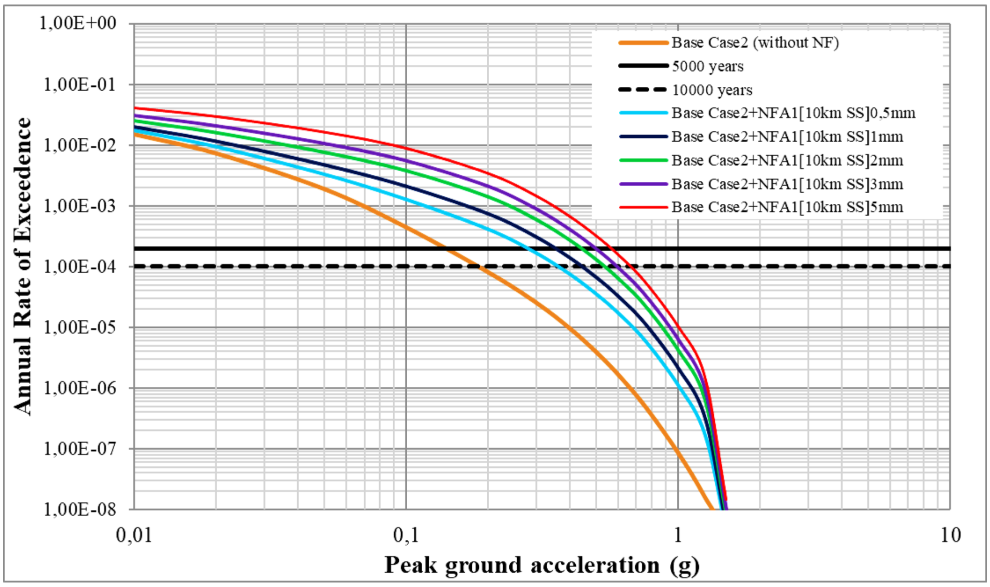


Figure 4.30. Sensitivity analysis results for Near-Fault Alternative 1 labeled as NFA1 (10 km) by considering different slip rates by assuming strike slip faulting style & comparisons to Base Case 2 (without Near-Fault) (for LS-RNS)

Effects of Near-Fault on low seismic base case site (LS-RNS) are also examined for only Alternative 1. According to Figure 4.30, for AFE level 10^{-4}, for 0.5 mm/year slip rate for Near-Fault alternative increases the total hazard results from 0.17 g (Base Case 1) to 0.36 g. For other slip rate alternatives, PGA values are between 0.44 and 0.68 g. The presence of this fault changes the results from 112% to 300% (three-fold).

4.4.2. Near-Fault faulting style sensitivity analysis

In order to show possible effects of faulting style on hazard results by assuming presence of Near-Fault as "reverse fault" with 60-degree dip angle. Under this assumption, hazard calculations repeated, and results are demonstrated at Figure 4.31 for HS-RNS case.

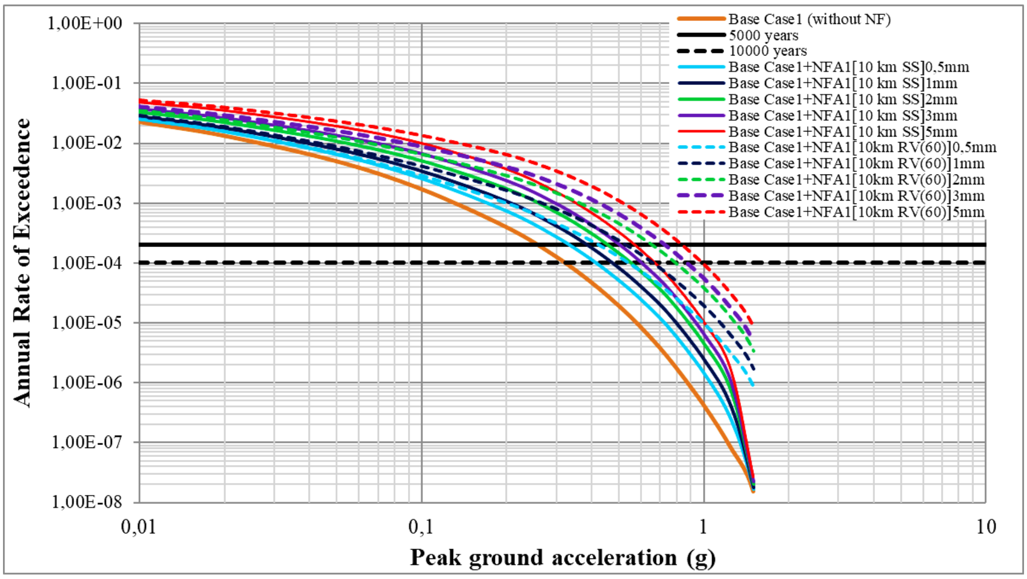


Figure 4.31. Sensitivity analysis results for Near-Fault Alternative 1 labeled as NFA1 (10 km) by considering different slip rates by assuming "reverse faulting" style & comparisons to Base Case 1 (without Near-Fault) and "strike slip faulting" option (for HS-RNS)

According to this figure, reverse fault alternatives give relatively high (~35 - 45%) hazard results comparing to strike slip options. PGA values are between 0.33 (Base

Case 1) and 1 g. The presence of this fault as reverse faulting style changes the results from 67% to ~200% (two-fold).

Figure 4.32 demonstrates the sensitivity results for Base Case 2 (LS-RNS) considering different slip rates by assuming reverse fault. Presence of this fault dramatically changes the results in low seismicity case. PGA values are between 0.17 (Base Case 2) and 1 g (almost five-fold).

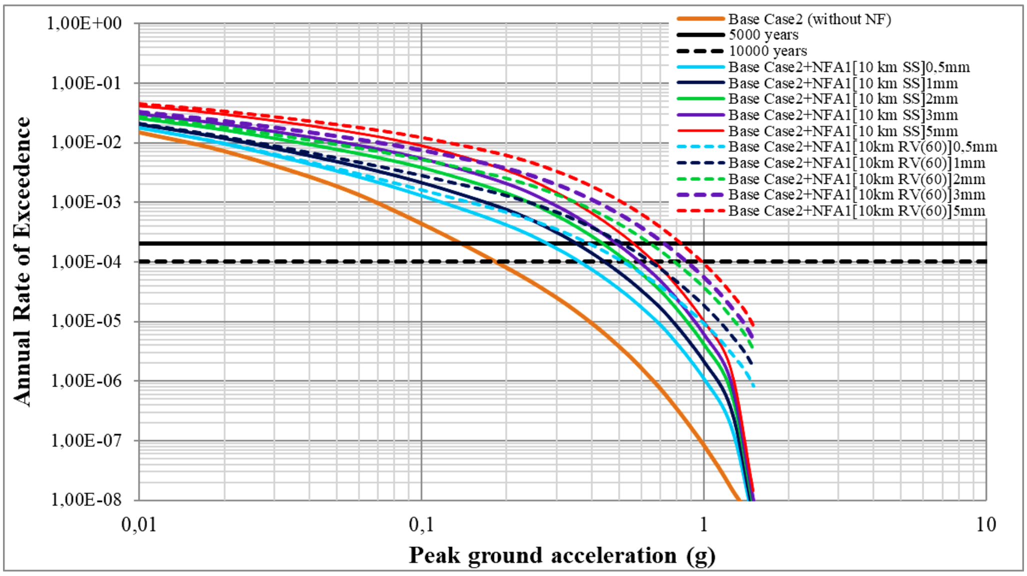


Figure 4.32. Sensitivity analysis results for Near-Fault Alternative 1 labeled as NFA1 (10 km) by considering different slip rates by assuming "reverse faulting" style & comparisons to Base Case 2 (without Near-Fault) and "strike slip faulting" option (for LS-RNS)

CHAPTER 5

SUMMARY AND CONCLUSIONS

Seismic hazard assessment studies to estimate the design ground motions for the nuclear facilities have been performed since early 60s. Comparing different countries' regulations and the practice in the recent NPP projects indicate that the subjects related to seismic hazard assessment are still not "fully standardized" for the nuclear industry. There are several reasons for this non-standardization, most important ones being the rapidly evolving practice in the field of engineering seismology and the reduced interest of the leading countries (especially USA, France, Japan, Russia, etc.) to build new nuclear reactors. Most of the power plants built in these developed countries are more than 30 years old and they were designed according to the generic design values and/or the deterministic approach summarized in Chapter 1. These old standard designs were licensed according to the methods applicable at that time, and even if periodic reviews and stress tests are performed during the lifecycle of the facility, it is not always possible to reflect the new developments in the seismic hazard assessment practice to the evaluation of NPP sites both for legal and economic reasons.

The USA appears to be the country that has made the greatest effort toward achieving the standardization in the seismic hazard practice by publishing open-to-public technical documents with significant contributions provided by the international organizations such as IAEA. Because of the important projects implemented in USA and some other countries in the 2000s (e.g. the Yucca Mountain, PEGASOS, seismic characterization efforts on Diablo Canyon NPP, SSHAC Level-3 CEUS Seismic Source Characterization study etc.) and the Great Tohoku Earthquake occurred in Japan causing Fukushima Nuclear Disaster in 2011, subjects related to seismic hazard had been discussed intensively in the last decade. These important projects revealed the importance of the standardization in seismic hazard assessment for NPP sites.

In the last ten year, U.S. NRC had issued the construction licenses for two reactors after a 30-year-long hiatus, Russian Federation had developed nuclear projects to build power plants in different regions having different seismic characteristics, United Kingdom had started a new project at Hinkley Point C, and many developing/embarking countries including Turkey had considered nuclear energy as an alternative resource. Most important from the national perspective, Turkey intends to build at least 12 nuclear reactors with three different designs at three different sites in the next ten years. In order to regulate the seismic hazard assessment processes of these three designs, Regulatory Body of Turkey needs a systematic, comprehensive and up-to-date seismic hazard guideline that is applicable for all candidate designs and compatible with international legislative structures. Comparison of the legislative structures of the core countries/organizations considered in this study shows that:

- U.S. NRC has the most comprehensive and up-to-date legislations, standards and technical documents (in particular the NUREGs) on seismic hazard assessment. Following U.S. NRC, most comprehensive documents are provided by IAEA. IAEA's main safety guide on seismic hazard (SSG-9) is very general and does not contain specific guidance on SHA details, as it is a consensus document of all member states. However, IAEA has an extensive set of technical documents such as TECDOCs about source and ground motion characterization, site response analysis, etc. On the other hand, it is very difficult to access Japanese regulations and standards, mostly due to the language barrier. Additionally, Japanese NRA address the SHA issue with criteria and methods that are different from the rest of the world (e.g. Recipe methodology). Many of the regulations and standards of the Russian Federation date back to the 80s; therefore, majority of them are not in synch with the current practice. Finland's STUK, that has a respectable place among the regulatory authorities among the world, has some up-to-date guidelines; however, their provisions regarding seismic hazard assessment are very generic and limited.

- After the Fukushima accident (2011) in Japan, some countries/organizations, specifically the IAEA and Japan, have updated their requirements and standards by considering the lessons learned from that experience. STUK has also made an update but has very few concrete rules and criteria specific to the seismic hazard related subjects. In Russian Federation, an extensive update is still underway but not yet finalized. Turkey, as an embarking country in the nuclear field, has only one specific regulation and relatively few general criteria on the subject matter. To support the national legislations, Turkish Regulatory Authority requires that the owner perform detailed seismic investigations, not only in compliance with Turkish regulations but also with the IAEA fundamentals & requirements, owner's legislations and some third-party guides & standards as the form of a licensing basis list.
- Although the licensing basis list temporarily solves the problem of the lack of detailed national legislations and standards to some extent, this approach poses an inherent fundamental problem. Because of the licensing basis list approach, three different NPP sites in Turkey might be licensed by using 3 different sets of rules and standards for seismic hazard assessment. It would be beneficial to update the regulations and prepare detailed guidelines for Turkey by considering the results of this study, at least with the gained experiences through the real applications in Turkey, especially the good practices in the Akkuyu NPP case.

The fundamental objective of this study was to compare the seismic hazard assessment approaches of leading countries and international organizations in the nuclear energy field in terms of significant issues related to seismic source and ground motion characterization. For this purpose, main headings of controversial topics; such as estimation of maximum magnitude potential, truncation applied on standard deviation, etc. were defined, and the statements/regulations given in guidelines under each heading were compared. Appendix-A summarizes comparison results under each heading and the main conclusions related to SSC are given below:

- PSHA is the primary seismic hazard assessment methodology for the countries evaluated within the scope of this study. PSHA is used as the norm methodology for the new nuclear projects in USA (Vogtle NPP, VC Summer NPP, Yucca Mountain, Diablo Canyon NPP SSC), in Switzerland (PEGASOS & PRP), in South Africa (Thyspunt site), in New Mexico (Waste Isolation Pilot Project WIPP), in Brazil (Angra dos Reis NPP), in Turkey (Akkuyu and Sinop NPP projects) etc. Even, the Senior Seismic Hazard Assessment Committee (SSHAC) approach has gradually become a world standard. Switzerland has made it mandatory to combine PSHA with the SSHAC Level 4 methodology in their new guidelines. The Russian Federation also favors the probabilistic methods and PSHA in the recently published guidelines on 2017. Concordantly, the deterministic approach is mostly abandoned in SHA or it exists as a secondary method for comparison and/or benchmarking of the PSHA results.

- There is no consensus about considered "spatial scales" for seismic hazard studies, especially on the extend of regional scale. Radius of the regional scale (the one with the maximum radius among the spatial scales) ranges from 100 km (in Japan) to 800 km (in Canada), but mostly around 300 km. In general, countries located at seismically active regions (Turkey, Japan etc.) use relatively small regional scales (100-150 km); on the other hand countries located at low seismicity regions (Finland, Canada, Russian Federation, Switzerland etc.) prefer relatively large regional scales (300-800 km). Turkey's regional scale's radius is 150 km, which may need an update, considering other countries' applications and IAEA recommendations. The radius of the regional scale should be enlarged to at least 300 km (IAEA recommendations) or 320 km (U.S. NRC approach) since these scales have already been implemented during Akkuyu and Sinop NPP projects.

- There is no consensus among countries on the definition of capable faults (or active faults for some countries) and the rejection criterion or screening distance value in the presence of a capable fault. The IAEA uses a fairly wide time span (from 5.3My to present) for capable fault definition while U.S. NRC's and Turkey's definitions (500ky or 35ky) are almost the same. Japanese approach (120-130ky or 400ky) has been tightened after the Fukushima accident and it is now more conservative than Turkey's approach. Finland does not have any definition or criteria on this issue and the Russian Federation defines the capability based on slip rates.

- Considering the differences in the definition of capable fault among different countries, a set of sensitivity analysis is performed under the assumption that it is possible to discover a capable fault within the near regional scale as experienced in DCPP in western USA or KKNPP in Japan. Analysis results showed that a capable fault in the near regional scale (within 25-40 km) significantly increase the hazard estimates (e.g. 27% - 67% by considering different faulting styles for 10 km distance alternative) even if the fault has a very low slip rate (0.5 mm/year). Therefore, intensive efforts should be made to determine the capability of potential faults within the near regional and site vicinity scales by considering appropriate capability criteria.
- Finland, Turkey and Japan do not have any clear and specific exclusion criteria for nearest capable fault distance. Some IAEA safety guides and TECDOCs mentions 8 km and / or 0.5-8 km, but the limits or the consequences are not clearly expressed. Similarly, the U.S. NRC recommends that the site is rejected if there is a capable fault within 8 km from the site, but it does not set a clear exclusion criterion on screening distance. Russian Federation recommends that there should not be capable faults closer than 30 km (not obligatory), and, also requests the evaluation of alternative sites if there is a capable fault closer than 8 km (semi-obligatory). It should be underlined that all countries have reached a broad consensus that nuclear facilities cannot be built directly on the capable faults and if there is a capable fault in the near region scale, an extensive site investigation program should be designed. Turkey should also

reflect this broad consensus on the regulatory documents by defining a clear exclusion criterion for nearest capable fault distance (e.g. 5 km or 8 km).

- Except for Finland, all other core countries including Turkey distinguish between fault and area sources and define main parameters that needs to be determined for each type of seismic source. Considering the MFD models, IAEA and U.S. NRC mention 3 different models, Japanese NRA and RTN only suggest using truncated exponential model, but Turkey and Finland do not have any specific provision on this subject. The provisions of the Turkish regulation and guides should include further elaborations on these subjects; especially the treatment of uncertainties of the MFD model parameters should be strongly emphasized.

- As a general evaluation on data collection, countries require that the geological, seismological (including earthquake catalogue), geophysical and geotechnical database is compiled by performing different type investigations in each spatial scale. Some countries (such as Finland, Turkey) have generic provisions on this issue and some others (especially USA, IAEA and Russia) have tried to systematize the subject with more detailed requirements. This standardization effort led to the emergence and development of SSHAC methodology in the USA. For Turkey, SSHAC methodology should be directly adopted or a similar formalized method should be developed to ensure that the entire process, inputs and outputs are recorded in a controllable, traceable and reproducible manner. If the SSHAC methodology is directly adopted, the regulatory authority will participate in the process by establishing a "review team" as implemented in the PEGASOS project according to related NUREG rules and best practices.

- The "project earthquake catalogue" is one of the most important inputs of the seismic source characterization model, especially when the total hazard is dominated by area sources. A single project catalog should be compiled covering the prehistorical, historical and instrumental earthquake data and Turkey should update the national provisions to reflect this conclusion.

- Most of the countries don't have any clear requirements on the catalogue completeness and almost none of the country-specific regulations reference any declustering methodology mentioned in literature, except for IAEA and U.S. NRC's technical documents. However, most of the countries and experts use internationally accepted methodologies in practice as shown in Appendix-A. Turkey should require the consideration of catalogue completeness and declustering of catalogue with state-of-the-art methods in the national guidelines.

- Host zones are the dominant contributors of the total hazard, especially for seismically less active regions that are preferred for nuclear facilities, as indicated by the real cases (including Akkuyu NPP, Palo Verde Nuclear Generating Station, Thyspunt NPP in South Africa etc.). Technical justification and uncertainty modelling for the host zone parameters, especially the selection of M_{max} for host zone, recurrence parameters (e.g. b-value) and depth distribution is critical.

- Magnitude recurrence model parameters (especially the b-value) may change by 15-30% due to selected declustering and/or regression methodology. Previous studies showed that when area sources are utilized in PSHA, change in the b-value may affect the hazard results significantly. To understand the extent of this effect, sensitivity analyses have been performed on the b-value of host zone of the reference nuclear site (details of the reference nuclear site is presented at Chapter 4). According to sensitivity analysis results, variation on the b-value by 40% changes the hazard results by 12 - 18 % for the AFE level (10^{-4}). This effect is more significant than the effect of the activity rate, considering that the variability of the activity rate due to the selected declustering and/or regression methodology is less pronounced (Figure 5.1 & Figure 5.2). Turkey should request the employment of proven methodologies and modern scientific methods for treatment of epistemic uncertainties in magnitude recurrence model parameters in the national guidelines.

- There is no consensus on the selection of M_{min} for seismic hazard studies in nuclear applications. IAEA, U.S. NRC and RTN has concrete suggestions (generally varying between 4.5 and 5.5), but other core countries do not have any provision about M_{min}. Considering the past practices in nuclear field, there is large variation in the selection of M_{min} value (between 2.5 and 5.0). In order to identify the potential effect of M_{min}, sensitivity analysis considering the M_{min} value of the host zone are performed. Results of analysis showed that when $M_{min} \leq 5$, hazard results for AFE level (10^{-4}) are almost the same, but setting the $M_{min}=5.5$ decreased hazard results by 18%. Effect of M_{min} is quite significant (between 7% increase and 40% decrease for $M_{min}=5.5$) for AFE level (10^{-3}) that is generally considered as the OBE level. Turkey may specify the M_{min} value as 4.0 (conservatively) or 4.5 (realistically/world standard) in the national regulations or guidelines.

- M_{max} (especially for the host zone) is known to have a significant effect on the hazard results. IAEA and U.S. NRC discuss M_{max} quite extensively, Russian Federation has simple provisions, but other core countries do not have any specific provision on how to estimate M_{max} for seismic sources. Therefore, two sets of sensitivity analysis are performed: one set considers the M_{max} value of the host zone (which is a quite controversial estimate given the lack of tectonic structures), and the other set varies the M_{max} value of the Far-Fault. For high-seismic reference nuclear site, 15% decrease in the M_{max} value of the host zone (from 6.5 to 5.5) decreases the hazard results by 21%, while 15% increase in the M_{max} increases the hazard results by 9% for AFE level (10^{-4}). Bayesian M_{max} logic tree developed for the host zone, that represents global proxies for low hazard zones (referenced by both IAEA and U.S. NRC) corresponds to the median hazard curves among the other M_{max} estimates both for low and high reference nuclear site. For Far-Fault case, PGA for AFE level (10^{-4}) is not sensitive to M_{max} as expected, but for T=2 sec spectral accelerations, a change by roughly 20% is observed.

- Based on the above given observations, it is clear that Turkey should provide detailed regulations for the M_{max} assigned to both area and fault sources. These regulations or guides should identify at least: (i) how to calculate the M_{max} value for fault sources using empirical magnitude - rupture dimension scaling relations, (ii) how to develop a proper logic tree for the M_{max} of the host zone based on global proxies (such as EPRI-Bayesian approach), (iii) how to treat the uncertainty in M_{max} by using logic tree approach for all type of seismic sources.

- Considering seismogenic depth thickness of the crustal regions, a sensitivity analysis is performed for the depth distribution of the seismicity for the host zone. Figure 5.1 and Figure 5.2 shows that, the effect of depth distribution on hazard estimates are less pronounced for both high and low seismic reference nuclear sites because the PSHA methodology is applied. If DSHA was implemented, the effect of the depth distribution would be much more significant.

Main conclusions related to GMC are given below:

- Ground motion models (GMMs) are utilized in seismic hazard assessment frequently because the way of treating the variability in the alternative methods (e.g. simulations) in the logic tree are not yet clearly demonstrated. While IAEA and U.S. NRC's technical documents discuss the selection and suitability of GMMs for nuclear applications, other core countries (Japan, Russian Federation, Finland and Turkey) do not have detailed provisions on this subject. There is no consensus on the selection GMMs among the local and global alternatives; however, most of the PSHA applications performed in USA, Turkey and other shallow crustal and active tectonic regions tends to use global models, especially after the NGA models were published. In order to understand the effect of GMM selection on the hazard estimates, a set of GMMs are selected among NGA West-1, NGA West-2, Pan-European and regional models considering current applications (Chapter 4 for details) and utilized in PSHA individually. Analysis results show that selection of GMMs introduce the biggest uncertainty in the hazard calculations and hazard results are quite sensitive to selected GMM both for the low and high hazard cases. Figure 5.1 shows that PGA for AFE level (10^{-4}) varies between 0.13 g to 0.39 g (three-fold difference) depending on the selected GMMs.

- Turkey should have detailed provisions on GMM selection and at least require that: (i) GMMs should be consistent with the tectonic environment and attenuation characteristics of the region of interest and particular seismic source, (ii) GMMs should be selected by considering the applicability ranges and the other considered parameters (style of faulting, hanging wall effects etc.), (iii) global and local models should be considered for logic tree in a consistent manner, (iv) candidate GMMs (preferably more than 30) should be tested for prediction performance and a representative set should be utilized in the logic tree to properly capture the epistemic uncertainty.

- Sigma truncation (or selection of ε_{max}) is not clearly regulated by any country; only some technical regulatory documents address this issue implicitly by general provisions. In DSHA, traditionally ε is equal to 0 or 1, whereas in PSHA studies ε is usually truncated at 2-3 or sometimes used without truncation (Appendix-A). Major nuclear projects, particularly the Yucca Mountain and PEGASOS projects, have generated a wide scientific debate on this issue. In order to understand the contribution of sigma truncation on the mean hazard curves, a sensitivity analysis is performed by truncating the ε by several values between 1 and 7. Analysis results shows that: (i) for AFE levels with 10^{-4} and larger, ε=3 results in approximately the same PGA values as ε>3, (ii) for lower AFE levels (10^{-6} - 10^{-8}) that is requested by some nuclear projects (e.g. Yucca Mountain and PEGASOS) or requested by seismic PSA/PRA studies, hazard curve with ε=3 may be quite different than the hazard curves for ε>3. Selected ε value changes hazard results significantly up to ε=4 for lower APE levels (10^{-6} - 10^{-8}) (Figure 5.1 & Figure 5.2).

- Turkey should recommend using the untruncated sigma model (as already employed at ANPP) or at least 4 sigma should be considered for the consistency of AFE levels 10^{-4} (SSE level) with AFE level 10^{-6} (for seismic PSA/PRA studies). Recent studies showed that only statistical approach for sigma truncation may not be enough, the physical limits of the soil/crust should be discussed and considered to determine the sigma truncation for higher APE levels.

- Total sigma of GMMs includes the uncertainties arising from source, path and site effects. Single-station sigma is aimed to eliminate uncertainties coming from site effects (GeoPentech, 2015). Single-station sigma concept is quite new, and it is a promising approach for nuclear projects because it has the potential to significantly reduce the hazard estimates. A sensitivity analysis is performed by implementing only one GMM for simplicity and reducing the total sigma by 10% to 30% percent. Analysis results showed that %30 reduction in total sigma decreases the PGA for AFE level 10^{-4} from 0.33 g to 0.25 g for the high seismic case. On the other hand, single-station sigma approach requires that significant amount of seismic data right at the nuclear site is compiled. Therefore, this issue is fairly new and has not yet been introduced into the nuclear regulatory guidelines or standards. It should be noted that if single-station sigma is used in PSHA, the uncertainty related to site that was reduced from the total sigma during PSHA should be taken into account when conducting the site response analysis. Turkey should closely follow the related updates and carefully regulate this subject in the future.

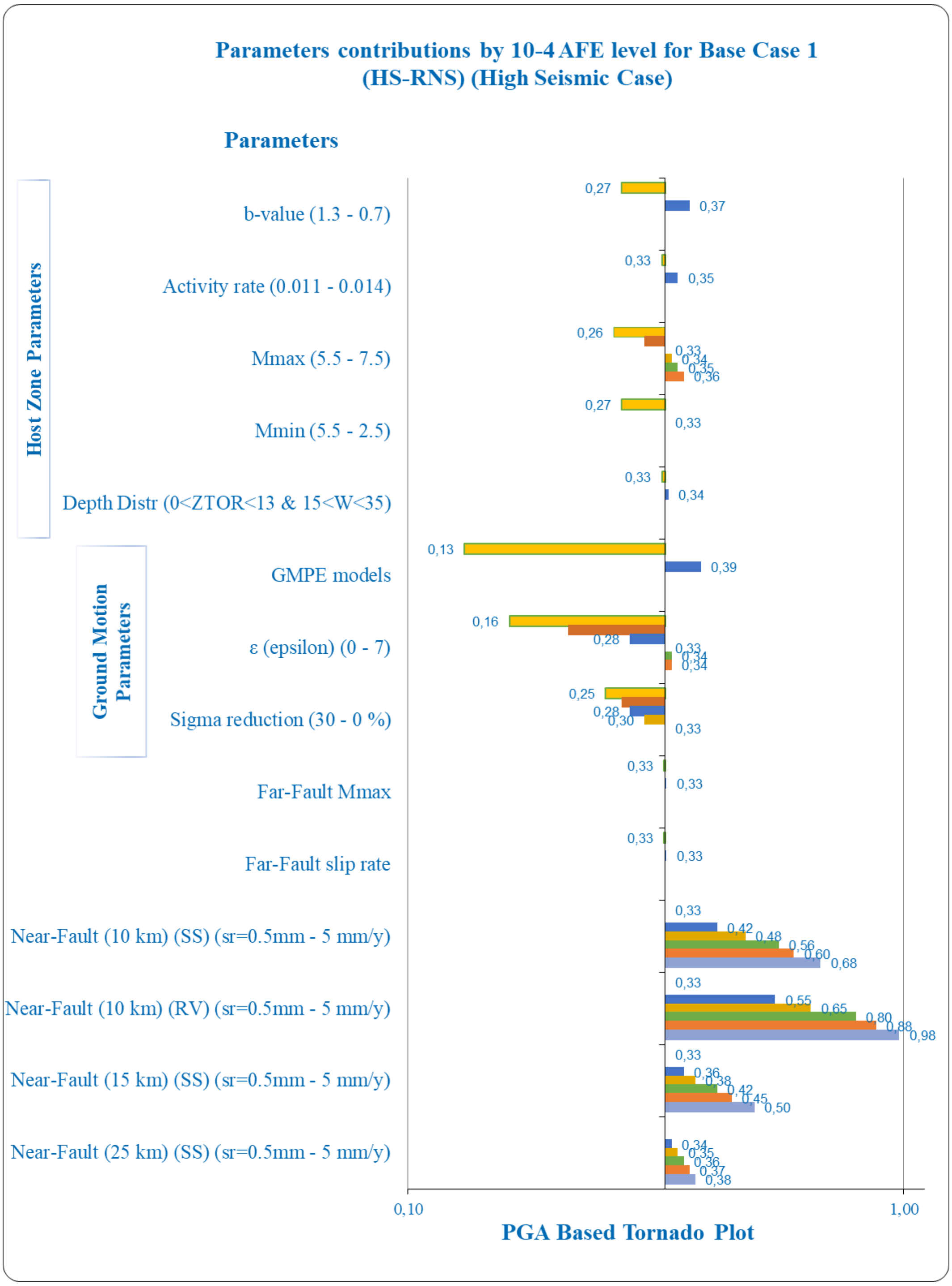


Figure 5.1. Tornado plot for SSC and GMC parameters contributions by 10^{-4} AFE level for Base Case 1 (HS-RNS) (for only PGA)

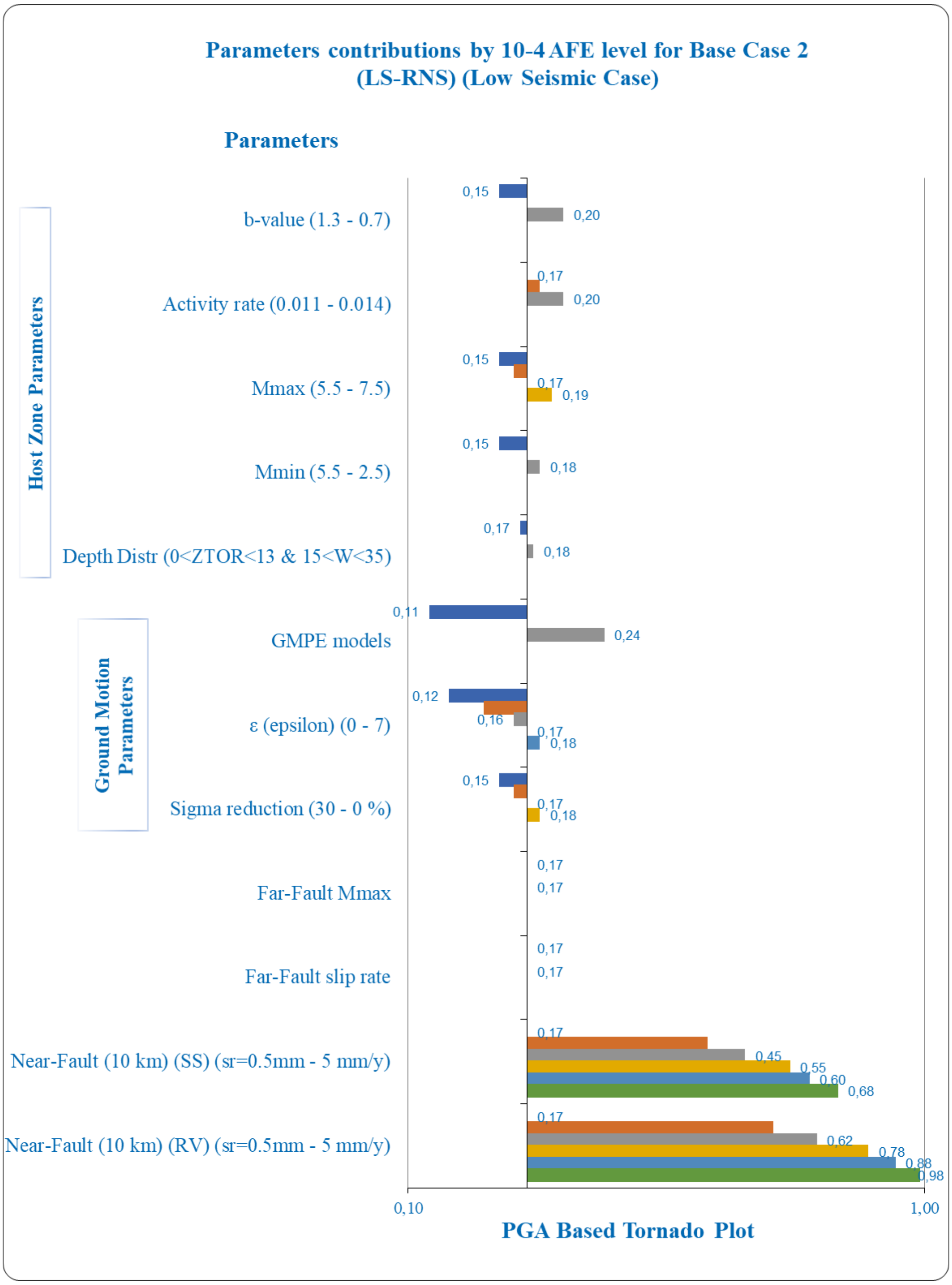


Figure 5.2. Tornado plot for SSC and GMC parameters contributions by 10^{-4} AFE level for Base Case 2 (LS-RNS) (for only PGA)

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APPENDICES

A. Comparison Table on Seismic Hazard Assessment Applications for Nuclear Installations in Terms of Different Countries' Approaches

Related (sub-chapters)	**COUNTRY/ ORGANIZATION** ***Compared Parameters***	**IAEA**	**USA (U.S. NRC)**	**JAPAN (NRA)** Before Fukushima: BF After Fukushima: AF	**FINLAND (STUK)**	**RUSSIAN FEDERATION (RTN)**	**TURKEY (TAEK/NDK)**	**CURRENT PRACTICES** Akkuyu NPP: ANPP Sinop NPP: SNPP PEGASOS: PGSS Diablo Canyon NPP: DCPP Kashiwazaki Kariwa NPP: KNPP
3.1. Seismic Hazard Assessment in Nuclear Regulations	*PSHA, DSHA / Recipe Approaches*	PSHA DSHA	PSHA	Recipe / DSHA (BF, AF) PSHA (partially)(AF)	PSHA	PSHA DSHA	PSHA DSHA	ANPP: PSHA, DSHA (for comparison) SNPP: PSHA, Recipe (for comparison) PGSS: PSHA DCPP: PSHA KNPP: DSHA/Recipe Additional PSHA Examples: USA: Vogtle NPP, VC Summer NPP, Yucca Mountain, Diablo Canyon NPP SSC, CEUS SSC, WUS SSC etc., Switzerland: PEGASOS & PRP, South Africa: Thyspunt site, New Mexico: Waste Isolation Pilot Project WIPP, Brazil: Angra dos Reis NPP
3.2. Seismic Source Characterization in Nuclear Regulations 3.2.1.	*Radius of the region investigated and spatial scales*	4 spatial scales: - Regional (300 km) - Near regional (25 km) - Site vicinity (5 km) - Site area (1 km^2)	4 spatial scales: - Site Region (320 km) - Site Vicinity (40 km) - Site Area (8 km) - Site Location (1 km^2)	2 spatial scales: - Survey of wide region (30 km), - Survey of the site (no specific distance) *Exception: Survey of wide region (100 km) (according to OECD/NEA 2019)*	Not specified in regulatory guides - Regional (500 km) *(according to OECD/NEA 2019)*	4 spatial scales (NP-006-98): - Region (300 km) - Location (30 km) - Site (3 km) - Controlled area and surveillance zone (no specific diameter) 5 spatial scales (RB-019-01): - Planetary (20000-3000 km), - Regional (2000-300 km) - District (200-30 km) - District or local (20-10 km) - Local (6-1 km) *Exception: 150-320 km (according to NP-031-01)*	4 spatial scales: - Regional (150 km or more), - Near regional (25 km) - Site vicinity (5 km) - Site area (1 km^2)	ANPP: IAEA approach SNPP: U.S. NRC approach PGSS: U.S. NRC approach DCPP: U.S. NRC approach Additional Country Examples: France: 200 km, Germany: >=200 km Japan: 100 km Switzerland: 300-500 km, Canada: 500-800 km England: 5 km for site vicinity, 25 km for near region, 100 km for mid region and 300 km for region

Related (sub-chapters)	COUNTRY/ ORGANIZATION *Compared Parameters*	IAEA	USA (U.S. NRC)	JAPAN (NRA) Before Fukushima: BF After Fukushima: AF	FINLAND (STUK)	RUSSIAN FEDERATION (RTN)	TURKEY (TAEK/NDK)	CURRENT PRACTICES Akkuyu NPP: ANPP Sinop NPP: SNPP PEGASOS: PGSS Diablo Canyon NPP: DCPP Kashiwazaki Kariwa NPP: KNPP
3.2.2.	*Geological definitions in nuclear regulations; active fault, capable fault, surface faulting and palaeoseismicity*	Term: “capable fault” - from Late Pleistocene (1.8 My) - Holocene (11k years) to present (highly active areas/interplate) - from Pliocene - Quaternary (5.3 My to present) (for less active areas/intraplate) Exclusion criteria suggestion for nearest capable fault: 8.0 km (IAEA/SSG-35) 0.5-8.0 km (IAEA/TECDOC-1341) (not clear suggestion)	Term: “capable fault” - 35ky (10 CFR Part 100 Appendix A) / 50ky (RG 1.208) (at least once) - 500ky (movement of a recurring nature) OR - proven macro seismic activity determined by instrument Exclusion criteria suggestion for nearest capable fault: 8.0 km (not clear requirement) Minimum length of fault to be considered: 0 < D < 32 1,6 km 32 < D < 80 8 km 80 < D < 160 16 km 160 < D < 240 32 km 240 < D < 320 64 km	Term: “active fault / potential active fault” - Late Pleistocene (later than 120ky-130ky) - Middle Pleistocene epoch (approx. 400ky ago) (50ky) (BF) Exclusion criteria suggestion: no distance / facility cannot be located on outcrop of capable fault	Not specified in regulatory guides	Term: “seismically active fault / tectonically active fault” Total slip >= 0.5 m within the quaternary period (1 My) Or Slip rate >= 5 mm/year (by RTN/RB-019-01) Exclusion criteria suggestion: 30-km (suggested) 8.0 km (semi-obligatory)	Term: “active fault” - 35ky years (at least once) - 500ky years (movement of a recurring nature) OR - proven macro seismic activity determined by instrument	ANPP: Turkey’s approach SNPP: U.S. NRC approach PGSS: U.S. NRC approach DCPP: U.S. NRC approach KNPP: Japanese approach Nearest capable fault examples: DCPP: Hosgry Fault (5.6 km) & Shoreline Fault (300-600 meter) KNPP: Takado-oki fault (25 km) & Katakai Fault (16 km) which causes The Niigataken Chūetsu-Oki Earthquake (M_w=6.8) in 2007
3.2.3.	*Seismic source modelling in nuclear guidelines (Fault Source, Area Source)*	- seismogenic structures (fault sources) - diffuse seismicity (area source)	- fault sources - area sources representing concentrated historical seismicity that is not associated with known tectonic structures - area sources representing geographic regions with similar tectonic histories, type of crust, and structural features, and - background sources Note: Fault sources (especially for WUS) Area sources (especially for CEUS)	- earthquake ground motion formulated with a hypocenter specified for each site (seismogenic sources/ fault source) and - earthquake ground motion formulated without a hypocenter specified (diffuse seismicity zones/area sources)	Not specified	Fault Source Area Source	Area Source Fault Source	ANPP: Area Source SNPP: Area & Fault Source DCPP: Area & Fault Source
3.2.4. (a)	*Catalogue periods (Instrumental, historical, prehistorical, etc.)*	- Prehistorical - Historical - Instrumental	- Prehistorical - Historical - Instrumental	- Paleo-seismologic - Historical - Instrumental	- Historical - Instrumental	- Paleo-earthquakes - Historical - Ancient - Instrumentally recorded	- Prehistorical - Historical - Instrumental	ANPP: Prehistorical, Historical, Instrumental SNPP: Prehistorical, Historical, Instrumental PGSS: Prehistorical, Historical, Instrumental DCPP: Prehistorical, Historical, Instrumental

Related (sub-chapters)	COUNTRY/ ORGANIZATION *Compared Parameters*	IAEA	USA (U.S. NRC)	JAPAN (NRA) Before Fukushima: BF After Fukushima: AF	FINLAND (STUK)	RUSSIAN FEDERATION (RTN)	TURKEY (TAEK/NDK)	CURRENT PRACTICES Akkuyu NPP: ANPP Sinop NPP: SNPP PEGASOS: PGSS Diablo Canyon NPP: DCPP Kashiwazaki Kariwa NPP: KNPP
3.2.4. (b)	*Catalogue completeness & Declustering methodology*	- Gardner and Knopoff (1974) - Reasenberg (1985)	Stepp (1972) (for completeness) & - Gardner and Knopoff (1974) - Reasenberg (1985) (for declustering)	Not specified	Not specified	Not specified	Not specified	ANPP: Stepp (1972) (for completeness) & Reasenberg (1985) and Tibi et.al (2011) (for declustering) PGSS: Gardener & Knopoff (1974), [modified version of GK-1974: Uhrhammer (1986), Grünthal (1985)], Reasenberg (1985) (for declustering) DCPP: Gardner and Knopoff (1974), Reasenberg (1985) (for declustering)
3.2.5. (a)	*b-value calculation*	- Maximum likelihood / Aki (1965) - Weichert (1980) - Kijko and Smit (2012)	- Maximum likelihood / Aki (1965) - Weichert (1980)	Not specified	Not specified	Not specified	Not specified	ANPP: maximum-likelihood, least squares and modified least squares methods PGSS: maximum likelihood method and the least squares method DCPP: maximum likelihood / Aki (1965), Weichert (1980)
3.2.5. (b)	*MFD models*	- truncated exponential - characteristic - maximum magnitude	- truncated exponential - characteristic earthquake model - maximum magnitude model	- truncated exponential	Not specified	- truncated exponential	Not specified	ANPP: truncated exponential PGSS: truncated exponential DCPP: (i) truncated exponential, (ii) simplified maximum magnitude distribution, (iii) characteristic earthquake distribution, (iv) modified characteristic earthquake distribution (WAACY)
3.2.6.	*Considered minimum magnitude (M_{min})*	- M_{min}<=5.0 or - CAV filtering	- M_{min}=5 or - CAV filtering (but M_{min}≤5.5) - M_{min}=4.6 (EPRI approach)	Not specified	Not specified	M_{min}=4.5	Not specified	ANPP: M_{min}=3.5 SNPP: M_{min}=5.0 PGSS: M_{min}=5.0 (and 4.3) DCPP: M_{min}=5.0 Additional Country Examples: Finland: M_{min}=2.5 UK: M_{min}=4.0 France: M_{min}=5.0 Chezh Republic: M_{min}=3.0 Spain: M_{min}=3.5 Korea: M_{min}=5.0

Related (sub-chapters)	COUNTRY/ ORGANIZATION *Compared Parameters*	IAEA	USA (U.S. NRC)	JAPAN (NRA) Before Fukushima: BF After Fukushima: AF	FINLAND (STUK)	RUSSIAN FEDERATION (RTN)	TURKEY (TAEK/NDK)	CURRENT PRACTICES Akkuyu NPP: ANPP Sinop NPP: SNPP PEGASOS: PGSS Diablo Canyon NPP: DCPP Kashiwazaki Kariwa NPP: KNPP
3.2.7.	*Assigned maximum magnitude (M_{max})*	- Bayesian approach (global data) - Kijko (2004) (local data) Hanks and Bakun (2008) Wesnousky (2008) Leonard (2010) Yen and Ma (2011) Stirling et al. (2008) Anderson et al. (1996) Nuttli (1983) Strasser et al. (2010) Blaser et al. (2010) Ichinose et al. (2006) Villmor et al. (2001)	Area Sources (especially for CEUS): $M_{max}= M_{max(historical)} + 0.5$ or 1.0 Fault sources (especially for WUS): - Slemmons (1977), - Wyss (1979), - Bonilla and others (1984), - Wells and Coppersmith (1994), - Hanks and Bakun (2002), - Leonard (2010) - Blaser et al. (2010) - Strasser et al. (2010) Subduction zones: Not specified	Not specified	Not specified	- $M_{max} \geq M_{max(obs)} + 0.5$ - RTN/RB-019-01 (2002) formulas based on rupture and/or deformation parameters	Not specified	ANPP: Papazachos et al. (2004), Strasser et al. (2010), Wesnousky (2008), Wells and Coppersmith (1994), Slemmons (1986) PGSS: EPRI-Bayesian approach CEUS SSC: EPRI-Bayesian (Johnston et al., 1994) and Kijko (2004) methods
3.2.8.	*Host zone parameters (magnitude and depth)*	$M_{max,back}$=5.5.-6.0 D_{hyp}=5-20 km (for crustal) (interpreted / deduced from TECDOC 1767 (2015) & SRS No.85 (2015))	$6.0 \leq M_{max,back} \leq 6.5$ (interpreted / deduced)	$M_{max,back}$=6.5 (crustal) and D_{hyp}=10 km $7.0 \leq M_{max,back} \leq 7.5$ (subduction)	Not specified	$M_{max,back} \geq 4.0$	Not specified	ANPP: (i) $M_{max,back}$= 6.3, 6.5 and 6.7 with 0.2, 0.6, 0.2 logic tree weights (ii) $M_{max,back}$= 6.6, 6.9 and 7.2 with 0.2, 0.6, 0.2 weights (iii) $M_{max,back}$= 6.5, 6.7 and 6.9 with 0.50, 0.25, and 0.25 Background depth distribution: 0-13 km (0.1), 13-22 km (0.6) and 22-35 km (0.3). For ANPP DSHA, considered depth: R_{jb}; 5 and 10 km; alternative Z_{TOR}; 11, 13 and 15 km DCPP: $M_{max,back}$= 6.5, 7.0 and 7.5 with 0.4, 0.5, 0.1 weights. Background depth distribution: uniform between 0-12 km
3.3. Ground Motion Characterization 3.3.1.	*Selection of Ground Motion Prediction Equations (GMPEs)*	Please look at sub-chapter 3.3.1 of thesis	Please look at sub-chapter 3.3.1 of thesis	Not specified	Not specified	Not specified	Not specified	ANPP: (i) for “subduction zones”; Atkinson and Boore (2003, 2008), Zhao et al. (2006) and Youngs et al (1997); (ii) for “crustal zones”; NGA Campbell and Bozorgnia (2008), NGA Abrahamson and Silva (2008), NGA Boore and Atkinson (2008), NGA Chiou and Youngs

Related (sub-chapters)	COUNTRY/ ORGANIZATION *Compared Parameters*	IAEA	USA (U.S. NRC)	JAPAN (NRA) Before Fukushima: BF After Fukushima: AF	FINLAND (STUK)	RUSSIAN FEDERATION (RTN)	TURKEY (TAEK/NDK)	CURRENT PRACTICES Akkuyu NPP: ANPP Sinop NPP: SNPP PEGASOS: PGSS Diablo Canyon NPP: DCPP Kashiwazaki Kariwa NPP: KNPP
3.3.1. (continued)								(2008) and Akkar and Bommer (2010) model. PGSS PRP: (Akkar and Bommer, 2010), (Akkar and Cagnan, 2010), (Abrahamson and Silva, 2008), (Boore and Atkinson, 2008), (Campbell and Bozorgnia, 2008), (Chiou and Youngs, 2008), (Zhao et al., 2006), (Edwards and Fäh, 2013b) DCPP: Abrahamson et al (2014), Boore et al (2014), Campbell and Bozorgnia (2014), Chiou and Youngs (2014), Idriss (2014), Zhao et al (2014), Zhao and Lu (2011) and Akkar et al (2014a, 2014b) (these are compared with other 31 GMPEs)
3.3.3.	*Number of epsilon (ε)*	Not specified	no truncation / untruncated / unbounded	Not specified	Not specified	Not specified	Not specified	ANPP: no truncation (in SPR) & truncated 3.5 – 4.0 for PSA PGSS: ε_{max}= 3.5, 3.0 and 2.5 with 0.1, 0.6 and 0.3 weights For sensitivity analysis: $2 \leq \varepsilon_{max} \leq 6$ Yucca Mountain: no truncation, but truncated by physical limits of soil/crust Additional Country Examples: Belgium and United Kingdom used ε=2; Canada, Czech Republic, Finland, Switzerland are used unbounded/untruncated model France used ε=3
3.3.4.	*Sigma reduction (single-station sigma)*	Not clearly specified	Not clearly specified at regulatory documents, only 2 NUREGs mentions it	Not specified	Not specified	Not specified	Not specified	ANPP: only used for sensitivity SWUS GMC (for DCPP and PVNGS nuclear power plants): ϕ_{SS} models are between 0.35 and 0.45 with an ~0.1epistemic uncertainty PRP: ϕ values are between ~0.48-0.72 but, range of ϕ_{ss} is between ~0.38-0.55

Related (sub-chapters)	COUNTRY/ ORGANIZATION *Compared Parameters*	IAEA	USA (U.S. NRC)	JAPAN (NRA) Before Fukushima: BF After Fukushima: AF	FINLAND (STUK)	RUSSIAN FEDERATION (RTN)	TURKEY (TAEK/NDK)	CURRENT PRACTICES Akkuyu NPP: ANPP Sinop NPP: SNPP PEGASOS: PGSS Diablo Canyon NPP: DCPP Kashiwazaki Kariwa NPP: KNPP
3.4. Hazard Output Parameters 3.4.1.	*Hazard curves*	Mean hazard curves	Mean uniform hazard response spectra (UHRS)	“average hazard curves”	Median hazard curves	Mean hazard curves	Mean hazard curves	-
3.4.2.	*Fractal/Fractile levels*	Fractile levels: 0.05, 0.16, 0.50, 0.84 and 0.95	Fractile levels: 0.05, 0.16, 0.50, 0.84, and 0.95, as well as the mean	Only require fractals but not specified	Not specified	Fractile levels: 0.05, 0.16, 0.50, 0.84 and 0.95	Not specified	-
3.4.3.	*Annual frequencies of exceedance (AFE) (Recurrence periods)*	AFE levels: 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} and 10^{-6}	AFE levels: 10^{-4}, 10^{-5} and 10^{-6}	Not specified	AFE: 10^{-4}, 10^{-5}	AFE: 10^{-4} (10^{-5})	Not specified	-
3.4.4.	*Earthquake Levels*	SL-1 corresponds to a 10^{-2} AFE level (mean value) SL-2 corresponds to a 10^{-3}, 10^{-4} AFE level (mean values) or 10^{-4}, 10^{-5} AFE level (median)	Operating basis earthquake ground motion (OBE) Safe-shutdown earthquake ground motion (SSE)	S1 (design basis historical max.) S2 (margin check upper bound)	Not specified	DE: 10^{-3} AFE level MCE: 10^{-4} AFE level	S1 (OBE) Not specified S2 (SSE): 10^{-4} AFE level	-
3.4.5.	*Deaggregation*	Not specified	Distance range of bin (km): 0-15 15-25 25-50 50-100 100-200 200-300 >300 Magnitude Bins (Mw): 5.0-5.5 5.5-6.0 6.0-6.5 6.5-7.0 >7.0	Not specified	Not specified	Not specified	Not specified	-

Related (sub-chapters)	COUNTRY/ ORGANIZATION ***Compared Parameters***	IAEA	USA (U.S. NRC)	JAPAN (NRA) Before Fukushima: BF After Fukushima: AF	FINLAND (STUK)	RUSSIAN FEDERATION (RTN)	TURKEY (TAEK/NDK)	CURRENT PRACTICES Akkuyu NPP: ANPP Sinop NPP: SNPP PEGASOS: PGSS Diablo Canyon NPP: DCPP Kashiwazaki Kariwa NPP: KNPP
3.4.6.	*Considered minimum ground motion level*	0.1 g	0.1g (for SDC-5)	Not specified	0.1 g	0.1g (for MCE) 0.05 g (DE)	0.1 g	-