Nuclear Safety
NEA/CSNI/R(2019)14
November 2021
www.oecd-nea.org

Assessment of the Safe Shutdown Earthquake Robustness Against On-site Observations

BETTER POLICIES FOR BETTER LIVES

NUCLEAR ENERGY AGENCY

Nuclear Energy Agency

NEA/CSNI/R(2019)14

Unclassified **English text only**

19 novembre 2021

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

Assessment of the safe shutdown earthquake robustness against on-site observations

This document is available in PDF format only.

JT03485844

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 38 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, Colombia, Costa Rica, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

OECD Publishing disseminates widely the results of the Organisation's statistics gathering and research on economic, social and environmental issues, as well as the conventions, guidelines and standards agreed by its members.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 34 countries: Argentina, Australia, Austria, Belgium, Bulgaria, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Romania, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission and the International Atomic Energy Agency also take part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) is responsible for the Nuclear Energy Agency (NEA) programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

Acknowledgments

Gratitude is expressed to: Emmanuel Viallet (EDF, France) for being the main author of this report; to Nebojsa Orbovic (CNSC, Canada), Pekka Valikangas (STUK, Finland), Ludovic Fulop (VTT, Finland), Philippe Renault (Swissnuclear, Switzerland), John Mac Farlane (EDF-Energy, United Kingdom) for their involvement and reviews; to the whole WGIAGE Seismic Engineering subgroup members for their contributions and support; and to Dr Diego Escrig Forano (NEA Secretariat) for continuously supporting the project.

Table of contents

List of tables

List of figures

List of abbreviations and acronyms

CAPS	CSNI activity proposal sheet
CNSC	Canadian Nuclear Safety Commission
CSNI	Committee on the Safety of Nuclear Installations (NEA)
DBE	Design basis earthquake
DEC	Design extension conditions
EDF	Electricité de France
EQ	Earthquake
FCOD	First commercial operating date
IAEA	International Atomic Energy Agency
NEA	Nuclear Energy Agency
PGA	Peak ground acceleration
PSHA	Probabilistic seismic hazard analysis
RLE	Review level earthquake (as used in the US practice)
SHA	Seismic hazard analysis
SSE	Safe shutdown earthquake
STUK	Radiation and Nuclear Safety Authority of Finland
VTT	VTT Technical Research Centre of Finland
WGIAGE	Working Group on Integrity and Ageing of Components and Structures (NEA)

Executive summary

This activity of the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) Working Group on Integrity and Ageing of Components and Structures (WGIAGE) is entitled "Assessment of the safe shutdown earthquake (SSE) robustness against on-site observations" and it was based on medium-term strategies for the WGIAGE seismic engineering subgroup and the lessons learnt from the Fukushima Daiichi Nuclear Power Plant accident. The question of under-estimation or over-estimation of seismic hazard now or during the original design of nuclear power plants was raised in the WGIAGE group and this activity is looking for evidence on this issue. The objective is to collect and analyse any relevant observations that could help to assess seismic hazard results and identify possible evidence of under-estimation of seismic hazards or the opposite, and to provide the international community with a new, generic and efficient procedure that could be widely applied on nuclear power plant sites (especially in countries with low to moderate seismicity).

The main tasks were to collect relevant information on seismic monitoring and all seismic motion records on the nuclear power plant sites (or in their vicinity) and SSE for the sites under consideration (which could include original SSE and any re-evaluated SSE); and analyse the consistency between SSE and available observations.

It should be noted that assessment of the SSE robustness against on-site observations is a necessary task to be regularly performed and updated among all NEA member countries, and it makes consistency checks possible on a much wider range and a more robust scheme compared to the work at a single country scale. So far, 12 NEA member countries have replied to this questionnaire, which represents 73 nuclear power plant sites, corresponding to 2 464 cumulated years of observations during the time period 1967-2017. Because of its special nature and interest to the nuclear community, this work of collecting, comparing and analysing information of on site observations against current SSE is intended to be repeated from time to time within the WGIAGE seismic engineering subgroup.

From the results of the activity, it is possible to draw the following conclusions:

- The status of the survey indicates that more than 90% of nuclear power plants worldwide have instrumentation installed on-site that allows for the recording of any peak ground acceleration (PGA) higher than 0.01 g to 0.02 g.
- The survey includes 97 reported earthquake events, including 45 events with a PGA higher than 0.01 g (maximum observed earthquake PGA is 0.69 g).
- Compared with original design PGA, the maximum observed PGA is approximately 1.5 x original design PGA.
- Compared with current SSE PGA, the maximum observed PGA is approximately the same as the current SSE PGA.
- In terms of consistency checks (task five of this activity), the comparison between observed earthquakes and expected ones, assuming that the SSE is equivalent to a 10 000 years return period (IAEA, 2003; IAEA, 2010), was performed. Its results

should encourage member countries to further consider their design and re-evaluation practices, including the equivalent return period and its margins related to seismic hazard assessment.

- Member countries could assess possibilities to apply the cost-effective design extension condition (DEC) safety approach against rare seismic events in areas of high seismicity.

It is obvious that the results of the comparisons performed through this activity give evidence of over-estimation or under-estimation, depending on national approaches. Consequently, the results of this activity should encourage member countries to analyse in a deeper manner their existing seismic margins.

Further actions could be performed in order to incorporate other member countries' experience feedback. Further assessments of observed earthquakes compared with expected ones, relying on nuclear power plant hazard assessments, could also be performed. For instance, the assess process would be improved if member countries could provide actual hazard curves coming from site specific PSHA (probabilistic seismic hazard assessment), which would allow for reduction of epistemic uncertainties that were propagated in the present study.

One piece of the investigation presented in this report is relying on typical hazard curve equations. This step of the process would be improved if member countries could provide actual hazard curves coming from site-specific PSHA. This more accurate data would be used in place of the analytical formulae used in this report and would reduce epistemic uncertainties that were propagated in the current analysis.

Finally, performing consistency checks of the results of seismic hazard assessments (SHA) against on-site observations appears to be an objective and a necessary task to be performed among all NEA member countries. Regularly updating this survey and corresponding consistency checks would encourage the international community to further improve nuclear safety and would also help to disseminate knowledge and good practices among member countries. The work of collecting on-site observations could be done in co-operation with IAEA.

The method developed and applied in this activity in the above-mentioned perspective can be used in any context or by any member country, which fulfils the initial objective of this activity.

1. Introduction

Considering that the vast majority of nuclear power plants in Nuclear Energy Agency (NEA) member countries are not concerned with the tsunami hazard, the goal of the Working Group on Integrity and Ageing Components and Structures (WGIAGE) seismic engineering subgroup, at least in a first step, is to focus on strong motion. In this regard, the NEA WGIAGE seismic subgroup is intending to address the following issues:

- On the basis of seismic motion records on nuclear power plant sites (or in their vicinity), is there evidence in some countries or regions (other than Japan) that the seismic hazard is at the moment, or was at the moment of the design, likely underestimated?

  If yes,

- Are the current design practices for seismic events appropriate to provide necessary margins as it was the case in Japan on the Kashiwazaki-Kariwa site in 2007 and Onagawa site in 2011?[1]

The main reason that justifies this activity (CAPS) is driven by the lessons learnt and root causes of the Fukushima Daiichi accident, as discussed in the WGIAGE seismic engineering subgroup meetings:

> The experience feedback of recorded seismic motions on Japanese nuclear power plant sites indicates that the seismic hazard was underestimated at the moment of their original design. This underestimation was recognised and addressed by the Japanese authorities in the early 2000s. Consequently a new regulatory guide was issued in 2006 and the hazard re-evaluated accordingly on all the sites.[2]

In addition, the way that is expected to address this issue is based on new approaches that include any kind of observation (instrumental seismicity, historical seismicity, paleoseismicity and any other relevant observation such as precarious rocks, vulnerable stalagmites...) in order to perform consistency checks and/or Bayesian updating of seismic hazard assessments. This means that methods for using the real local evidence on seismicity history are developed for reviewing and validating the probabilistic seismic hazard estimations.

Such approaches were significantly improved in the recent years. They were presented and extensively discussed during the 2015 CSNI workshop held in Pavia, Italy:

> Recommendation 2.1 – A state-of-the-art PSHA should include a testing (or scoring) phase against any available observation (including any kind of observation and any

1. This text is an extract from an NEA WGIAGE internal guidance document not available to the general public (NEA, 2015a).

2. Ibid.

period of observation) and should include testing not only against its median hazard estimates but also against their entire distribution (percentiles).

Recommendation 3.1 – Use of Bayesian techniques in PSHA is strongly encouraged in order to take into consideration any available observation. (NEA, 2015b)

However, because of these recent developments and the lack of communication, such comparisons of approaches are not yet widely implemented in the nuclear industry. The comparisons of PSHA studies between different areas (NEA, 2019) and the comparisons of the results to the available observations were not included in the international post-Fukushima Daiichi assessments.

The objective of this activity is to collect and to analyse any relevant observation that could help to assess seismic hazards results and identify possible evidence of under-estimation of them or the opposite, and to provide international community with a new, generic, and efficient procedure that could be widely applied on nuclear power plant sites (especially in countries with low to moderate seismicity).

The main tasks of the issues mentioned in the objective are:

- Task 1: Ask member countries' representatives in the seismic engineering subgroup to nominate individual(s) who can provide the expected information.
- Task 2: With the support of contact persons, draw the list of nuclear power plant sites that can be covered by this assessment (as many as possible: minimum objective is Western Europe and North America).
- Task 3: Collect relevant information on seismic monitoring and all seismic motion records on the nuclear power plant sites (or in their vicinity), or any other relevant observation.
- Task 4: Collect SSE for the sites under consideration (could include original SSE and any re-evaluated SSE).
- Task 5: Perform consistency checks between SSE and available observation (during the February 2015 NEA workshop in Pavia, several experts presented methods to perform such checks that will be applied in this activity).
- Task 6: Draw conclusions based on previous task results.

2. Survey report: NEA questionnaire

2.1. Overview

The survey was conducted by means of a questionnaire given to the representatives of NEA member countries to complete (see Annex).

A total of five sets of questions were asked:

- The first part of the questionnaire was dedicated to site description, seismic hazard assessment information and earthquake monitoring system information.
- The second part of the questionnaire dealt with earthquake events information (observations)[3].

At the date of issuance of this report, 12 member countries (Canada, Finland, France, Germany, Japan, the Netherlands, the Czech Republic, Korea, Spain, Sweden, Switzerland and the United Kingdom) responded to the survey. Due to the nature of the activities described in this report, it is intended within the Working Group on Integrity and Ageing of Components and Structures (WGIAGE) seismic engineering subgroup to repeat the activity and publish updates of information and/or analysis.

2.2. Status of answers given by member countries

The next section gives the status of the replies to the questionnaire that were received at the date of issuance of this report.

2.2.1. Canada

<u>Replies obtained</u>

Canada has replied to the questionnaire for three sites:

- DARLINGTON
- PICKERING
- POINT LEPREAU

<u>Earthquake events observed</u>

- **one earthquake event observed (one recorded with a PGA > 0.01 g)**

Other sites could possibly reply to the questionnaire

- BRUCE

3. The term "observation" is used in this report as a simplification of "observed earthquake event", as defined in the glossary.

2.2.2. Finland

Finland has replied to the questionnaire for two sites:

- LOVIISA
- OLKILUOTO

Earthquake events observed

- **zero earthquake event observed**

2.2.3. France

Replies obtained

France has replied to the questionnaire for 19 sites:

- BELLEVILLE
- BLAYAIS
- BUGEY
- CATTENOM
- CHINON B
- CHOOZ B
- CIVAUX
- CRUAS
- DAMPIERRE
- FESSENHEIM
- FLAMANVILLE
- GOLFECH
- GRAVELINES
- NOGENT
- PALUEL
- PENLY
- SAINT ALBAN
- SAINT LAURENT B
- TRICASTIN

Earthquake events observed

- **22 earthquake events observed (one recorded with a PGA > 0.01 g)**

2.2.4. Germany

Replies obtained

Germany has replied to the questionnaire for seven sites:

- BROKDORF
- EMSLAND
- GROHNDE
- GUNDREMMINGEN
- ISAR
- NECKARWESTHEIM
- PHILIPPSBURG

Earthquake events observed

- **zero earthquake event observed**

2.2.5. Japan

Replies obtained

Japan has replied to the questionnaire for 17 sites:

- FUKUSHIMA DAIICHI
- FUKUSHIMA DAINI
- GENKAI
- HAMAOKA
- HIGASHIDORI
- IKATA
- KASHIWAZAKI-KARIWA
- MIHAMA
- OHI
- ONAGAWA
- SENDAI
- SHIKA
- SHIMANE
- TAKAHAMA
- TOKAI DAINI
- TOMARI
- TSURUGA

Earthquake events observed

- **30 earthquake events observed (29 recorded with a PGA > 0.01 g)**

N.B. For Japanese sites, most of DBE and SSE PGAs are given at engineering bedrock where observed PGAs are given at free field. Depending on site, this can induce a bias that was not possible to quantify due to missing information. This could be addressed in a future version of this report.

2.2.6. The Czech Republic

Replies obtained

The Czech Republic has replied to the questionnaire for two sites:

- DUKOVANY
- TEMELIN

Earthquake events observed

- zero earthquake event observed

2.2.7. Korea

Replies obtained

Korea has replied to the questionnaire for four sites:

- HANBIT
- HANUL
- KORI
- WOLSUNG

Earthquake events observed

- **12 earthquake events observed (four recorded with a PGA > 0.01 g)**

2.2.8. The Netherlands

Replies obtained

The Netherlands has replied to the questionnaire for one site:

- KERNCENTRALE BORSSELE

Earthquake events observed

- **one earthquake event observed (no record with a PGA > 0.01 g)**

2.2.9. Spain

Replies obtained

Spain has replied to the questionnaire for five sites:

- ALMARAZ
- ASCÓ

- COFRENTES
- TRILLO
- VANDELLÓS II

Earthquake events observed

- **six earthquake events observed (two recorded with a PGA > 0.01 g)**

2.2.10. Sweden

Replies obtained

Sweden has replied to the questionnaire for two sites:

- OSKARSHAMN
- RINGHALS

Earthquake events observed

- **zero earthquake event observed**

Other sites could possibly reply to the questionnaire:

- FORSMARK

2.2.11. Switzerland

Replies obtained

Switzerland has replied to the questionnaire for four sites:

- BEZNAU (KKB)
- GÖSGEN (KKG)
- LEIBSTADT (KKL)
- MÜHLEBERG (KKM)

Earthquake events observed

- **25 earthquake events observed (eight recorded with a PGA > 0.01 g)**

2.2.12. The United Kingdom

Replies obtained

United Kingdom has replied to the questionnaire for seven sites:

- DUNGENESS
- HARTLEPOOL
- HEYSHAM
- HINKLEY POINT
- HUNTERSTON
- SIZEWELL

- TORNESS

Earthquake events observed

- **zero earthquake event observed**

2.2.13. Other member countries that could still reply to the questionnaire

The list of member countries in which nuclear power plants are in operation, and that have not yet replied is given below. Any new reply will be included in the next version of this report.

- BELGIUM
- HUNGARY
- MEXICO
- RUSSIA
- THE SLOVAK REPUBLIC
- SLOVENIA
- THE UNITED STATES

2.2.14. Non-member countries that could reply to the questionnaire

It should be noted that non-NEA member countries can also reply to the questionnaire.

This initiative could help to enlarge the field of investigation of the survey.

Due to the nature of the activities described in this report, it is intended within the WGIAGE seismic engineering subgroup to continue the work of collecting this site-specific observation information and aim to publish revisions of the report when remarkable updates of information of member countries or non-member countries are available for analysis.

3. Tasks 3 and 4: Synthesis of replies

In the current version of this report, the synthesis is based on the assessment of the replies sent by 12 member countries (see Section 2.1):

- one member country from North America (Canada);
- two member countries from Asia;
- nine member countries from Europe.

Following the structure of the questionnaire, the section will be divided into three sub-sections:

- seismic hazard assessment information;
- earthquake monitoring system information;
- earthquake events information.

3.1. Seismic hazard assessment information

In terms of seismic hazard assessment (SHA) information obtained from the survey, the main outcomes are the following.

Deterministic versus probabilistic SHA

The replies indicate that depending on countries, SHA can be based either on probabilistic or deterministic approaches. Canada, Finland and the United Kingdom use mainly probabilistic approaches and Japan, France, the Netherlands, Korea and Sweden mainly use deterministic approaches. Germany, Spain, Switzerland and the Czech Republic use combined deterministic and probabilistic approaches. This is shown in Table 3.1 below.

Table 3.1. Deterministic versus Probabilistic SHA (worldwide)

Continent	Country	Type of SHA
North America	Canada	Probabilistic
Asia	Japan	Deterministic
Asia	Korea	Deterministic
Europe	Czech Republic	Deterministic and probabilistic
Europe	Finland	Probabilistic
Europe	France	Deterministic
Europe	Germany	Deterministic and probabilistic
Europe	Netherlands	Deterministic
Europe	Spain	Deterministic and probabilistic
Europe	Sweden	Deterministic
Europe	Switzerland	Deterministic and probabilistic
Europe	United Kingdom	Probabilistic

Note that the practice may have evolved since the original design of the plant.

Some member countries indicated that the SHA practice was originally based on deterministic approaches and has since evolved towards probabilistic approaches.

Design basis earthquake and original safe shutdown earthquake

The definitions of design basis earthquake (DBE) and original safe shutdown earthquake (SSE), as used in this report, are given in the glossary.

The replies indicate that the DBE or the original SSE (used for the original design of the plant) are distributed as follows (see Table 3.2):

- Worldwide: PGA from 0.05 g - 0.61 g
- North America: PGA from 0.05 g - 0.2 g
- Asia: PGA from 0.2 g - 0.61 g
- Europe: PGA from 0.05 g - 0.3 g

Current safe shutdown earthquake

The definition of current safe shutdown earthquake (SSE), as used in this report, is given in the glossary.

The replies indicate that the current SSE are distributed as follows (see Table 3.2):

- Worldwide: PGA from 0.03 – 2.34 g (2.34 g is engineering bedrock, not free field)
- North America: PGA from 0.08 - 0.57 g

- Asia: PGA from 0.2 – 2.34 g (2.34 g is engineering bedrock, not free field)
- Europe: PGA from 0.03 - 0.41 g

Table 3.2. Design basis earthquake and original safe shutdown earthquake (2.34 g is engineering bedrock, not free field)

	Range of DBE or original SSE	Range of current SSE
Worldwide	0.05 - 0.61 g	0.03 - 2.34 g
North America	0.05 - 0.2 g	0.08 - 0.57 g
Asia	0.2 - 0.61 g	0.2 - 2.34 g
Europe	0.05 - 0.3 g	0.03 - 0.41 g

3.2. Earthquake monitoring system information

In terms of earthquake monitoring system information obtained from the survey, the main outcomes are the following (see Table 3.3).

The replies indicate that most of the sites are equipped with accelerometers that allow recording of any seismic motion on-site, with a peak ground acceleration (PGA) higher than the threshold that may be defined, as summarised below.

Among the 73 sites that replied to the survey:

- 67 have implemented an instrumentation system, based on accelerometers;
- 42 have some sensors implemented on free field and inside buildings (this number becomes 61 including Japanese sites and two Canadian sites, which have not formally confirmed);
- The range of the trigger level is between 0.005 g and 0.02 g.

Table 3.3. Earthquake monitoring system information

	% of sites with instrumentation	% of sites with instrumentation on free filed and in buildings	Type of instrumentation	Range of trigger level
Worldwide	91.8%	83.6%	Accelerometers	0.005 - 0.02 g

3.3. Earthquake events information

In terms of earthquake events information obtained from the survey, the main outcomes are the following.

3.3.1. Synthesis of crude replies

This section gives an overview of the replies directly obtained from member countries.

Number of sites included in the current version of this report

The replies are summarised as follows:

- Worldwide: 73 sites have replied to the survey
- North America: 3 sites have replied to the survey (Canada only)
- Asia: 21 sites have replied to the survey
- Europe: 49 sites have replied to the survey

Cumulated duration of operation included in the current version of this report

The cumulated duration of operation (cumulated experience feedback, expressed in years) given below is the cumulated years of operation of the sites under consideration (considered independent), from the first commercial operating date (FCOD) of the first unit of the site, until the date of the survey.

The replies are summarised as follows:

- Worldwide: 2 464 years of cumulated duration of operation
- North America: 108 years of cumulated duration of operation (Canada only)
- Asia: 745 years of cumulated duration of operation
- Europe: 1 611 years of cumulated duration of operation

In the present version of this report, it is assumed that the operating time of recording (availability of the monitoring system) is equal to the duration of operation of the plant (since FCOD). This confirmation will be required from member countries and if any difference is identified (instrumentation installed after FCOD for instance), it will be taken into consideration.

Total number of reported earthquake events

The total number of reported earthquake events felt or recorded on-site is distributed as follows:

- Worldwide: 97 reported earthquake events
- North America: 1 reported earthquake event (Canada only)
- Asia: 42 reported earthquake events
- Europe: 54 reported earthquake events

This total number of reported observation includes 59 different earthquake events, with some possible multiple observations at different nuclear power plant sites induced by the same earthquake event.

3.3.2. List of reported earthquakes (EQs)

The list of reported earthquakes (including possible observations at different sites) is given in Table 3.4.

Table 3.4. List of reported earthquakes (EQs)

EQ id	**Date of the EQ**	**Name of the EQ**	**No. of reported observations**
1	1980-07-15	Sierentz	2
2	1983-07-02	Fukushima-Ken Oki	1
3	1987-04-23	Fukushima-Ken Oki	1
4	1992-04-13	Limbourg (Roermond)	2
5	1992-12-30	Wutöschingen	1
6	1993-11-27	The northern part of Miyagi-Ken	1
7	1994-12-14	Genevois (Les Villards-sur-Thônes)	2
8	1996-02-18	Perpignan	1
9	1997-03-26	Kagoshima-Ken Satsuma County	1
10	1997-05-13	Kagoshima-Ken Satsuma County	1
11	1999-02-14	Fribourg	1
12	2000-07-21	Ibaraki-Ken Oki	1
13	2000-10-06	2000 Tottori	1
14	2001-03-24	Geiyo	1
15	2001-06-08	Pouzauges	2
16	2003-02-22	St. Die (Rambervilliers)	4
17	2003-05-26	Miyagi-Ken Oki	1
18	2004-02-23	Besançon (Roulans-Baumes-les-Dames)	5
19	2004-06-21	Liestal	2
20	2004-06-28	Frick	1
21	2004-06-29	Frick	1
22	2004-10-23	Niigata-Ken Chuetsu	1
23	2004-12-04	Freiburg	1
24	2004-12-05	Waldkirch	4
25	2005-03-20	West of Fukuoka	1
26	2005-05-12	Balsthal	1
27	2005-08-16	Miyagi-Ken Oki	1
28	2005-09-08	Vallorcine	1
29	2005-11-12	Mönthal (Frick)	3
30	2006-11-05	Chinon	1
31	2007-03-25	Noto Hanto	1
32	2007-07-16	Niigata-Ken Chuetsu Oki	1
33	2007-06-07	Escopete (Guadalajara)	1
34	2007-08-12	Pedro Muñoz (Ciudad Real)	1
35	2009-01-04	Wildhaus	1
36	2009-05-05	Zell/Germany	3
37	2009-08-11	2009 Shizuoka	1
38	2010-03-13	Fukushima-Ken Oki	2
39	2010-03-14	Fukushima-Ken Oki	2
40	2010-06-23	Val-des-Bois	1
41	2011-03-11	The 2011 Earthquake of the Pacific coast of Tohoku	6
42	2011-03-12	The northern part of Nagano-Ken	1
43	2011-04-07	Miyagi-Ken	1
44	2011-05-11	Lorca (Murcia)	2
45	2011-08-03	Sud de Largentière	2
46	2012-02-11	Zug, ZG	1
47	2012-02-24	Zug, ZG	1
48	2013-09-09	(local)	1
49	2013-09-25	(local)	1
50	2013-12-12	Sargans, SG	1

Table 3.4. List of reported earthquakes (EQs) (Continued)

EQ id	**Date of the EQ**	**Name of the EQ**	**No. of reported observations**
51	2014-01-08	Biel, BE	1
52	2015-02-23	Ossa de Montiel (Albacete)	2
53	2015-05-22	Ramsgate (United Kingdom)	1
54	2016-04-14	Kumamoto-Ken	1
55	2016-04-16	Kumamoto-Ken	1
56	2016-07-05	Ulsan	4
57	2016-10-21	2016 Tottori	1
58	2016-09-12	Gyeongju	4
59	2017-11-15	Pohang	4

3.3.3. Distribution of reported earthquakes

Number of recorded earthquake events with PGA > 0.01 g

The total number of recorded earthquake events with a PGA > 0.01 g is distributed as follows:

- Worldwide: 45 recorded earthquake events (with PGA > 0.01 g)
- North America: 1 reported earthquake event (with PGA > 0.01 g) (Canada)
- Asia: 33 reported earthquake events (with PGA > 0.01 g)
- Europe: 11 reported earthquake events (with PGA > 0.01 g)

Number of observed earthquake events or recorded ones with PGA < 0.01g

The total number of reported earthquake events felt on-site or recorded (with a PGA < 0.01 g) is distributed as follows:

- Worldwide: 52 recorded earthquake events (with PGA < 0.01 g)
- North America: 0 reported earthquake events (with PGA < 0.01 g) (Canada)
- Asia: 9 reported earthquake events (with PGA < 0.01 g)
- Europe: 43 reported earthquake events (with PGA < 0.01 g)

The synthesis of these results is given in Table 3.5.

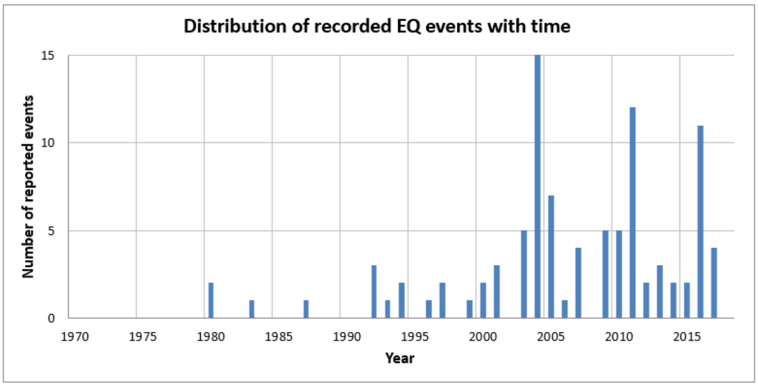
Table 3.5. Earthquake events information: Synthesis of crude replies

	Number of sites	Cumulative duration of observation (years)	Total number of reported earthquake events	Number of reported earthquake events with PGA > 0.01 g	Number of reported earthquake events with PGA < 0.01 g
Worldwide	73	2 464	97	45	52
North America	3	108	1	1	0
Asia	21	745	42	33	9
Europe	49	1 611	54	11	43

Distribution of reported observations with time

The distribution of reported observations with time is shown in Figure 3.1. This figure includes multiple observations (at multiple sites) induced by the same earthquake.

Figure 3.1. Distribution of observation with time (including multiple observations induced by one EQ event)



It should be noted that prior to 1980, only half of the sites covered by this report were in operation. Since 1990, 90% of the sites covered by this report have been in operation (and may consequently report earthquake events).

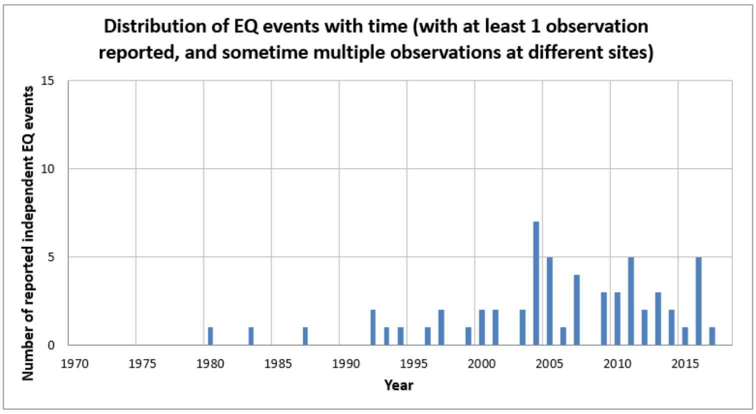
In addition, some earthquake events may have been recorded at different sites. This means that one earthquake may lead to some observations at different sites. One example is the 11 March 2011 Tohoku Earthquake that was recorded on six Japanese sites (there are other examples in Europe, see Table 3.5).

Finally, some reported events can also be identified as aftershocks from previously reported earthquakes. Some examples are observed on Japanese and Swiss nuclear power plants.

These last two points can explain why there can be a high variation in the number of observations from one year to another.

For example, the distribution of reported earthquakes with time, as shown in Figure 3.1, is presented in Figure 3.2, but counting only the number of earthquake events (not the number of observations), and avoiding multiple observations induced by the same earthquake event*.

Figure 3.2. Distribution of recorded earthquakes with time (avoiding multiple observations induced by one EQ event)



From the analysis of Figure 3.1 (97 observations in total including multiple observations induced by one single earthquake event) and Figure 3.2 (59 EQ events in total leading to these 97 observations), it is possible to calculate that the observed correlation coefficient k worldwide is 1.65 (one single earthquake event induces a mean of 1.65 observations at multiple sites).

This process can be developed for each continent. The result obtained (correlation coefficient per continent) is given below.

Observed correlation coefficient:

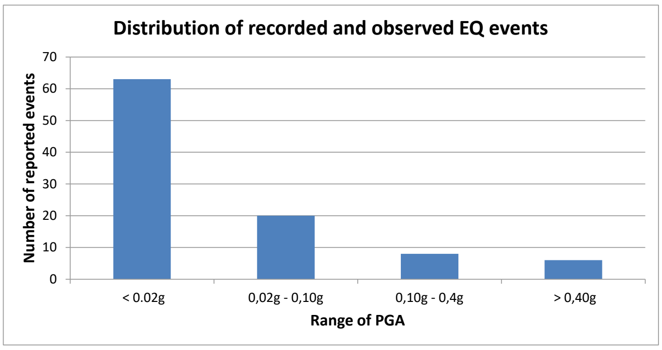
- Worldwide: k = 1.64
- North America: k = 1.00
- Asia: k = 1.62
- Europe: k = 1.69

These correlation coefficients will be used in Section 4.

Distribution of reported earthquakes

An illustration of the distribution of reported earthquakes by range of PGA is given in Figure 3.3.

Figure 3.3. Distribution of recorded earthquakes



4. Task 5: Consistency checks between SSE and available observation

Due to the objective of the activity and the content of the questionnaire, the main parameter that will be used in this section is PGA (peak ground acceleration). This parameter can easily characterise the seismic hazard at a given site (even if it may give a partial indication of it) and it can also directly be compared to the threshold of the monitoring system as well as to the recorded PGA. Then, the comparison between expected events versus observed ones can be made without any bias. In a further development of this study, considerations including spectral acceleration in addition to PGA could be included (if all the necessary information is provided).

4.1. Distribution of recorded earthquake events compared with current SSE level

This section presents the distribution of observed PGA divided by the level of the current SSE of each site under consideration.

Through this process, it is possible to work on dimensionless information (the observed PGA is divided by the current SSE PGA) that allows a comparison of different seismicity context (assuming that the target SSE has the same expected return period, assumed to be 10 000 years) (IAEA, 2003; IAEA, 2010). The expected return period for SSE used in design in NEA member countries is usually 10 000 years; some countries in low seismicity areas are also using a 100 000 year return period for SSE in their design requirements (NEA, 2019). It should also be noted that in some countries in low seismicity areas (e.g. Finland) assessments for Design Extension Conditions (DEC) take into account seismic events with over a one million year return period (STUK, 2013). The cost effective DEC approach could be applicable against rare seismic events of the operating plants in the areas of high seismicity.

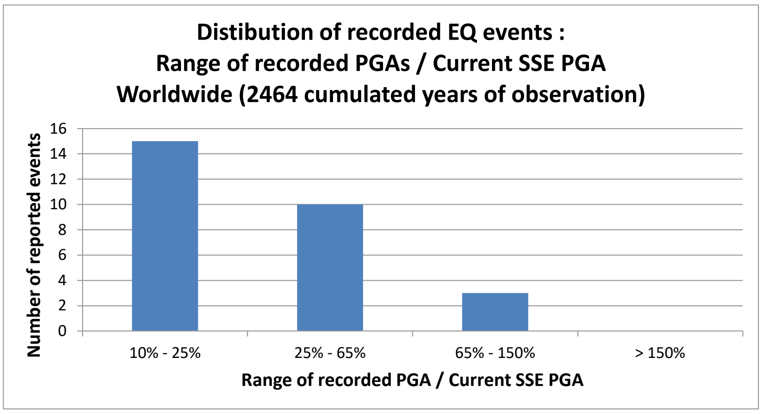
For this comparison, the observations are organised by ranges of PGA in order to develop some statistical considerations, avoiding discussion of any single occurrence of an earthquake event. This means that the total number of observed earthquake events within each range of PGA are counted and presented in the next figures. This will allow for consistency checks to be performed, as described in Section 4.2. Expressed in percentage of the current SSE, the ranges were: [10 - 25%]; [25% - 65%]; [65% - 150%]; [> 150%], which include 28 observations in total. The main reasons for defining such ranges are the following:

- The lowest bound cannot be less than 10% of current SSE because some plants have a SSE PGA of approximately 0.1g and may have recorded less than 10% of this SSE PGA, depending on their earthquake monitoring system's threshold (e.g. 0.01 g, see Section 3.2).
- The ratio between boundaries must be constant (chosen to be close to 2.5 in practice) in order to keep a geometric progression between numbers of earthquake events observed from one range to another (see Section 4.2 and the Annex for details).

- One range is centred on 100% of SSE, which is the dimensionless reference parameter defined in this section.

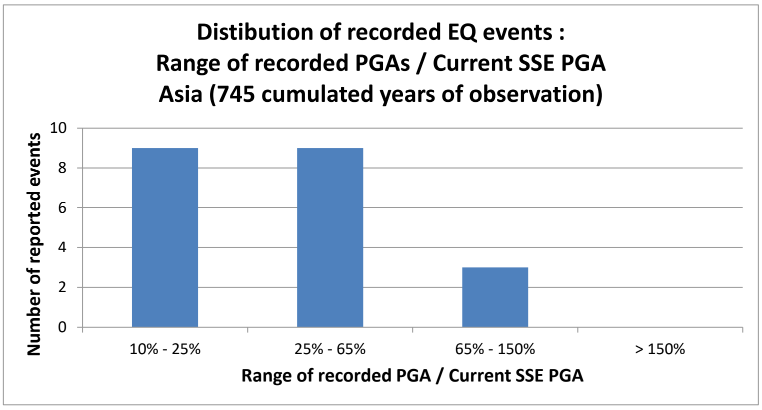
The following figures illustrate the distribution of observations.

Figure 4.1. Distribution of recorded earthquake events compared with current SSE level (dimensionless: recorded PGA / current SSE PGA) - Worldwide



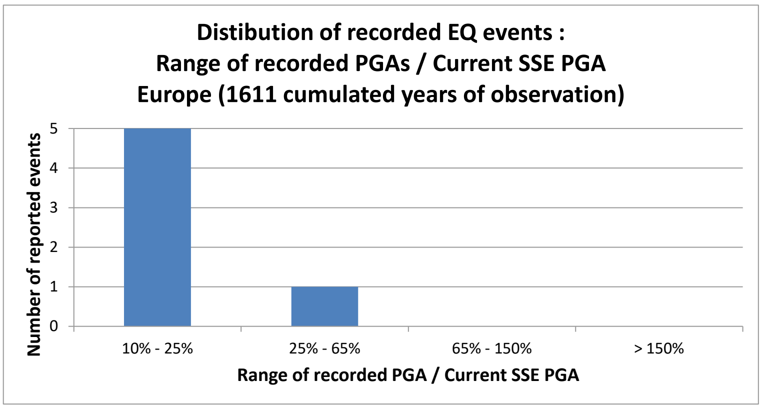
Note: Worldwide – 28 events, 2 464 cumulated years of observation.

Figure 4.2. Distribution of recorded earthquake events compared with current SSE level (dimensionless: recorded PGA / current SSE PGA) – Asia



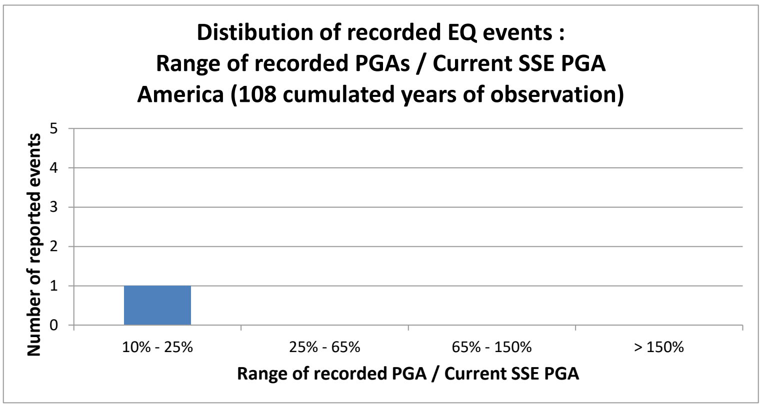
Note: Asia – 21 events, 745 cumulated years of observation.

Figure 4.3. Distribution of recorded earthquake events compared with current SSE level (dimensionless: recorded PGA / current SSE PGA) - Europe



Note: Europe – 6 events, 1 611 cumulated years of observation.

Figure 4.4. Distribution of recorded earthquake events compared with current SSE level (dimensionless: recorded PGA / current SSE PGA) – North America



Note: North America (Canada only) – 1 event, 108 cumulated years of observation.

4.2. Consistency checks between current SSE and recorded earthquakes

4.2.1. Objective and method

The objective of this section is to compare actual observations to the observations that would be expected, relying on the seismic hazard assessment of the nuclear power plant sites. This phase is called “consistency checks in the activity (task five), and is based on some of the methods that were presented and discussed during the February 2015 NEA workshop in Pavia (NEA, 2015b). In practice, the objective is to give an estimation of the number of expected observations within different ranges of PGAs, assuming that the annual exceedance rate of the SSE PGA is 10-4. This means that, theoretically, if the cumulated years of observation would be 10 000, the expected number of observed events with a PGA close to the SSE one would be close to one.

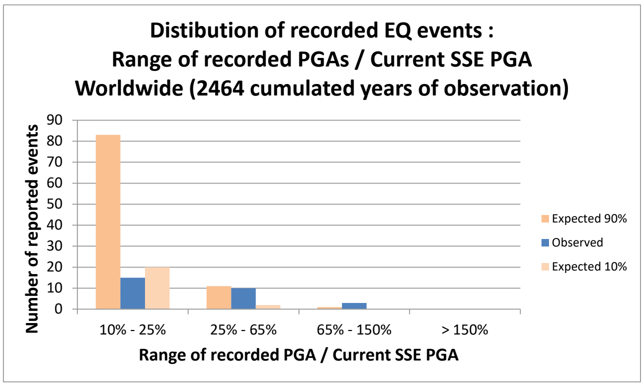
The method that is implemented is detailed in the Annex. The process is synthesised below:

- The first step consists in building a typical hazard curve providing the rate of exceedance of a given PGA. This hazard curve is scaled to 1 for the 10 000 year return period target. The method to build this hazard curve (based on an analytical formula) is described in the Annex.
  - *In order to take into consideration epistemic uncertainties in this process, three different shapes of theoretical hazard curves are used.*
- Based on the previous theoretical hazard curves, the second step consists in calculating the rate of occurrence of earthquakes for each range of PGA (same range as in the previous sections, Figure 4.1 to Figure 4.4, see Annex).
  - *This rate of occurrence is then multiplied by the cumulated duration of observation (which depends on the ensemble of sites under consideration: worldwide, Europe, Asia, North America).*
- The third step consists in calculating a distribution of expected number of observations, taking into consideration the random occurrence of earthquakes during the corresponding period of observation (see Annex).
  - *This is done based on a Poisson's model.*
- The fourth step consists in adjusting the distribution of expected number of observations, taking into consideration the correlation between sites, as given in Section 3.3.1 (see Annex).
  - *This is done based on a negative binomial model.*
- Finally, the range of expected (theoretical) observations is given in terms of confidence level [10% - 90%], including random and epistemic uncertainties as described in steps one to four (see Annex).

4.2.2. Results

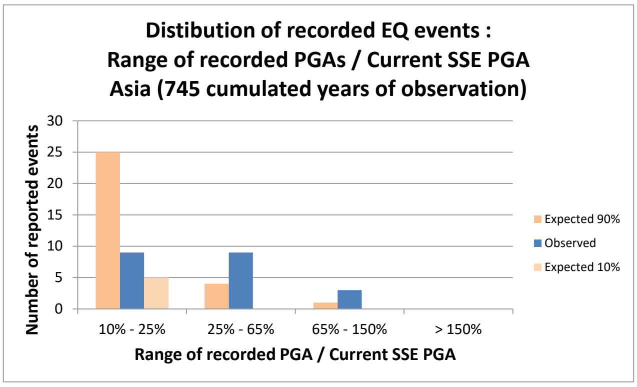
The results obtained are given in the figures below.

Figure 4.5: Distribution of recorded earthquake events compared with expected distribution (dimensionless: recorded PGA / current SSE PGA) – Worldwide



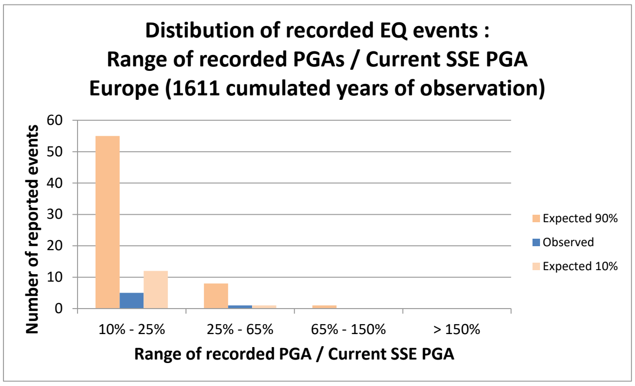
Note: Worldwide – 28 events, 2 464 cumulated years of observation.

Figure 4.6. Distribution of recorded earthquake events compared with expected distribution (dimensionless: recorded PGA / current SSE PGA) – Asia



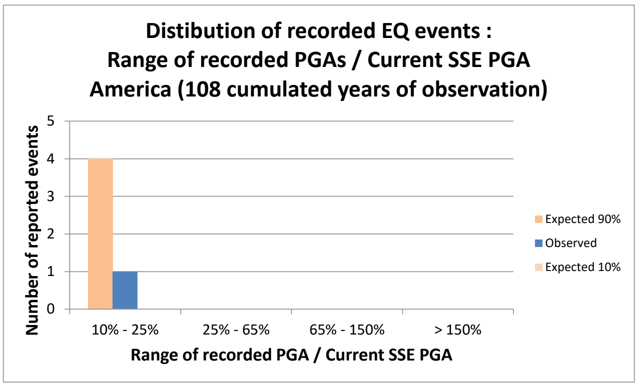
Note: Asia – 21 events, 745 cumulated years of observation.

Figure 4.7. Distribution of recorded earthquake events compared with expected distribution (dimensionless: recorded PGA / current SSE PGA) – Europe



Note: Europe – 6 events, 1 611 cumulated years of observation.

Figure 4.8. Distribution of recorded earthquake events compared with expected distribution (dimensionless: recorded PGA / current SSE PGA) – North America (Canada only)



Note: North America (Canada only) – 1 event, 108 cumulated years of observation.

4.2.3. Analysis of the previous results

Comparing observed events and expected ones relying on seismic hazard assessment of nuclear power plants is not an easy task. The results presented in the previous section of this report must be carefully analysed before making any definitive conclusions.

Thus far, the following observations have been made:

- Worldwide:
  The number of observed low-level earthquakes should be significantly higher than the number of observed earthquakes for higher PGA levels, which is not the case (see Figure 4.1). This can come from the fact that these low-level earthquakes may not be reported in an exhaustive way in the survey. This result seems to be mainly driven by the Asian cases and must be investigated further.

  In addition, the number of observed earthquakes with a PGA close to the SSE PGA (assumed to be 10-4 rate of exceedance) is higher than the 90% confidence level expected, see Figure 4.5 (also mainly driven by Asian case), which should encourage member countries to further investigate this situation.

- Asia:
  Asian sites observed the same tendency as for worldwide sites (number of observed low-level earthquakes should be significantly higher than for higher levels, see Figure 4.2). This may come from the fact that Asian countries (especially Japan) are less interested in low-level earthquakes and corresponding databases are not complete for the low-level earthquake range.

  In addition, the number of observed earthquakes with a PGA close to the SSE PGA (25% to 65% and 65% to 150%) is significantly higher than the 90% confidence level expected (see Figure 4.6), which should enable member countries to further understand the root causes of this.

- Europe:
  In Europe, the results show a good balance among the distribution of observations, see Figure 4.3, but also indicate that the observed earthquake rates are lower than the 10% confidence level expected (see Figure 4.4). This seems to be a safe situation (that could come from margins in the assessment of the SSE level), but should nevertheless encourage member countries to further investigate their SHA practices.

- North America (Canada only):
  Due to the low amount of data collected thus far, no particular observation can be made (see Figure 4.4 and Figure 4.7), which highlights the importance of gathering multiple sites' experience feedback in order to perform consistency checks.

- General consideration:
  One piece of the investigation presented in this report is relying on typical hazard curve equations (see Annex). This step of the process would be improved if member countries could provide actual hazard curves coming from site specific PSHA. This more accurate data would be used in place of the analytical formulae used in this report and would allow reduction of the epistemic uncertainties that were propagated in the current analysis.

4.2.4. Possible ways to process the results and to perform additional consistency checks

Based on the data collected and the method proposed in this report (see Annex), it could be possible to provide the answer to both of the two questions listed below:

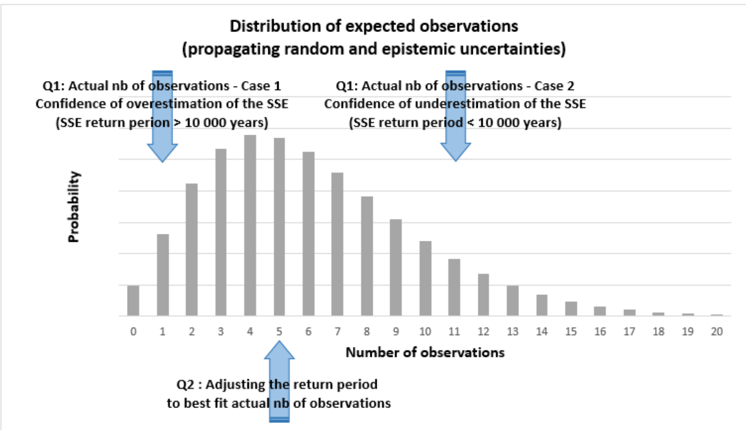
- Q1: What is the confidence of over or under-estimation of SSE at nuclear power plant sites relying on observation?
- Q2: What would be the SSE “best estimate” return period in order to best fit observations?

Concerning Q1, the Annex allows for a comparison of the actual number of observations to the expected (theoretical one) assuming that the SSE return period is 10 000 years. Then, instead of calculating the confidence interval [10% - 90%] as used in Figure 4.5 to Figure 4.8, it would also be possible to directly use the whole probability distribution of the expected number of observations and compare it to the actual one. This would allow for calculation of the confidence of having observed the actual number of events, assuming that the return period of the SSE is 10 000 years. Figure 4.9 illustrates two possible cases.

Case one (top left) highlights an evidence of over-estimation of the SSE (meaning that if the return period of the SSE was 10 000 years, it is highly likely that the number of observations would have been higher than the actually observed one). Case two (top right) highlights an evidence of under-estimation of the SSE (meaning that if the return period of the SSE was 10 000 years, it is highly likely that the number of observations would have been lower that the actually observed one).

Concerning Q2, the approach described in Annex A can also be used to adjust the return period of the SSE (currently defined as 10 000 years, but could be increased or decreased) in order to get the prediction centred on observations (the actual observation would then be located at the median part of the distribution as illustrated in Figure 4.9, bottom part). Applied this way to the results presented in Figure 4.5 to Figure 4.8, the approach would give a “best estimate” SSE return period higher than 10 000 years for European sites and lower than 10 000 years for Asian sites.

Figure 4.9. Illustration of the way to reply to Q1 (What is the confidence of over or under-estimation of SSE at nuclear power plant sites relying on observation?) and Q2 (What would be the SSE “best estimate” return period in order to best fit observations?)



5. Main conclusions and further actions

Based on the results of this Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) activity, it is possible to draw the following conclusions:

- Assessment of the SSE robustness against on-site observations is a necessary task to be regularly performed and updated among all NEA member countries.
- Sharing observed earthquake information among NEA member countries allows for the dissemination of knowledge and performance of consistency checks on a much wider range and a much more robust scheme than those that could be done at a single country scale.
- So far, 12 NEA member countries have replied to the NEA/CSNI questionnaire, representing 73 nuclear power plant sites and corresponding to 2 464 cumulated years of observations in the time period 1967-2017.
- The current status of the survey indicates that more than 90% of the nuclear power plants worldwide have instrumentation installed on-site that allows for the recording of any PGA (peak ground acceleration) higher than 0.01 g to 0.02 g.
- The survey includes 97 reported earthquake events, including 45 events with a PGA higher than 0.01 g (maximum observed earthquake PGA is 0.69 g).
- Compared with original design PGA, the maximum observed PGA is approximately 1.5 x original design PGA.
- Compared with current SSE PGA, the maximum observed PGA is approximately the same as the current SSE (safe shutdown earthquake) PGA.
- In terms of consistency checks (task five of this activity), the comparison between observed earthquakes and expected ones, assuming that the SSE is equivalent to a 10 000 years return period (IAEA, 2003; IAEA, 2010) was performed. The results obtained should encourage member countries to further consider their design and re-evaluation practices, including the equivalent return period and its margins related to seismic hazard assessment in order to improve the confidence of such assessments (the results of the comparisons performed through this activity give evidence of over-estimation or under-estimation, depending on national approaches).
- NEA member countries could assess possibilities to apply the cost effective DEC safety approach against rare seismic events of new and operating plants in areas of high seismicity.

Further actions could be performed in order to incorporate other member countries' experience feedback. Further assessments of observed earthquakes compared with expected ones, relying on nuclear power plant hazard assessments, could also be performed. For instance, the assessing process would be improved if member countries could provide actual hazard curves coming from site specific PSHA, which would allow for the reduction of epistemic uncertainties that were propagated in the present study.

Finally, performing consistency checks of the results of seismic hazard assessments against on-site observations appears to be an objective and necessary task to be performed among all NEA member countries. Regularly updating this survey and corresponding consistency checks would encourage the international community to further improve nuclear safety and would also help to disseminate knowledge and good practices among member countries.

Of course, the method developed and applied in the above-mentioned perspective can be used in any context or by any member country, which fulfils the initial objective of this activity, being aware that the larger the number of sites under consideration, the more valuable the assessment.

6. References

IAEA (2016), "Diffuse Seismicity in Seismic Hazard Assessment for Site Evaluation of Nuclear Installations", IAEA Safety Report Series No. 8, International Atomic Energy Agency, Vienna.

IAEA (2010), "Seismic Hazards in Site Evaluation for Nuclear Installations", IAEA Safety Standards Series No. SSG-9, International Atomic Energy Agency, Vienna.

IAEA (2003), "Seismic Design and Qualification for Nuclear Power Plants", IAEA Safety Standards Series No. NS-G-1.6, International Atomic Energy Agency, Vienna.

NEA (2019), "Comparison of Probabilistic Seismic Hazard Analysis of Nuclear Power Plants in Areas with Different Levels of Seismic Activity", OECD Publishing, Paris, www.oecd-nea.org/upload/docs/application/pdf/2020-01/dir1/csni-r2019-1.pdf.

NEA (2015a), "Medium-Term Strategies for the WGIAGE Seismic Engineering Sub-group for 2015-2020", OECD Publishing, Paris, www.oecd-nea.org/WGIAGE.

NEA (2015b), *Workshop on Testing Probabilistic Seismic Hazard Analysis Results and the Benefits of Bayesian Techniques*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19662/csni-workshop-ontesting-psha-results-and-benefit-of-bayesian-techniques-for-seismic-hazard-assessmentpavia-italy4-6-february-2015.

STUK (2013), "Provisions for internal and external hazards at a nuclear facility", STUK GUIDE YVL B.7, November 2013, Finland.

Glossary

Observation

In this report, the word “observation” is used as a simplification of “observed earthquake event” that could be felt and/or recorded at a given nuclear power plant site, and reported by a member state.

This means that observations can be counted from zero to any natural number.

In the current version of this report, 97 observations are reported in total, including 45 with a recorded PGA higher than 0.01 g.

Design basis earthquake (DBE)

The definition of the design basis earthquake used in the report is the seismic level used for the original design of the nuclear power plant. This can be either a standard design ground motion or a site specific ground motion.

This seismic level must be expressed in terms of PGA at the free field (ground motion). If not available, it should be expressed in term of acceleration at the main buildings foundation level.

Original safe shutdown earthquake (SSE)

The definition of the original safe shutdown earthquake used in the report is the site specific seismic level defined at the time of the original design of the nuclear power plant. This can be the ground motion used for the design itself (i.e. equivalent to the DBE) or it can be covered by the DBE (in case of standard design for instance).

This seismic level must be expressed in terms of PGA at the free field (ground motion). If not available, it should be expressed in term of acceleration at the main buildings foundation level.

Current safe shutdown earthquake (called review level earthquake in North America)

The definition of the current safe shutdown earthquake used in the report is the site specific seismic level defined most recently, either due to regular process (periodic safety review) or a specific context.

This earthquake level is called review level earthquake (RLE) in North America.

This seismic level must be expressed in terms of PGA at the free field (ground motion). If not available, it should be expressed in term of acceleration at the main buildings foundation level.

Annex A

NEA questionnaire sent to member countries

OECD
BETTER POLICIES FOR BETTER LIVES

NEA
Nuclear Energy Agency

OECD/NEA Questionnaire (1/2)

Methodology development for improved assessment of the SSE robustness against on-site observations

National delegate: **Name:** ... **Organization:** ...
E-mail : ... **Date:** ...

Site description (please fill one sheet per site)				
Country	...			
Name of the site	...			
Location (lat. / Long.)	...			
Name of the operator	...			
First Commercial Operating Date (COD)	...			
Number of units on the site	...			
Type of units (PWR, BWR, FBR ...)	...			
On site contact person (name + E-mail)	*Not necessary*			
Seismic Hazard Assessment information				
	PGA (in g)	Type of SHA (deterministic / probabilistic)		
Design Basis Earthquake	...			
Original Safe Shutdown Earthquake	...	...		
Current Safe Shutdown Earthquake	...	...		
Comments (if any) :	...			
Earthquake monitoring system information				
	Type of sensor	Supplier	Location	Trigger level (if any)
Instrument 1	...	...	...	...
Instrument 2	...	...	...	...
Instrument 3	...	...	...	...
More?	...	...	...	...
Date of installation (if different from FCOD)	...			
Comments (if any) :	...			
Earthquake events information				
On site observed seismic event status				
Any seismic event observed on site since COD ?	**YES or NO**			
	NO means "no seismic event observed on site"			
	If YES, please answer to the next questions			

Methodology development for improved assessment of the SSE robustness against on-site observations - Questionnaire 1 / 2

OECD BETTER POLICIES FOR BETTER LIVES

NEA Nuclear Energy Agency

OECD/NEA Questionnaire (2/2)

Methodology development for improved assessment of the SSE robustness against on-site observations

Earthquake events information

Nb of seismic events recorded on site: ...

	Date	Name of the event (or nearest city)	Magnitude (including type of magnitude)	Epicentral Intensity (includ. Int. scale)	Epicentral distance to the site	Maximum recorded horizontal PGA (g)	Type of observation on site (if any)
Event 1	...	...	...	...	...	...	...
Event 2	...	...	...	...	...	...	...
Event 3	...	...	...	...	...	...	...
Event 4	...	...	...	...	...	...	...
Event 5	...	...	...	...	...	...	...
More?	...	...	...	...	...	...	...

Comments (if any) : ...

Nb of seismic events felt on site without any record: ...

	Date	Name of the event (or nearest city)	Magnitude (including type of magnitude)	Epicentral Intensity (includ. Int. scale)	Epicentral distance to the site	Site Intensity if known (includ. Int. scale)	Type of observation on site (if any)
Event 1	...	...	...	...	...	...	...
Event 2	...	...	...	...	...	...	...
Event 3	...	...	...	...	...	...	...
Event 4	...	...	...	...	...	...	...
Event 5	...	...	...	...	...	...	...
More?	...	...	...	...	...	...	...

Comments (if any) : ...

Methodology development for improved assessment of the SSE robustness against on-site observations - Questionnaire 2 / 2

Description of the method used to calculate the expected number of observations

This section describes the method that is used in this report in order to evaluate the expected number of observations (number of expected earthquakes from a given range of PGA that should be observed within a given period of observation).

According to the present CAPS objectives, the consistency checks between observations and expected earthquake occurrences is based on methods that were presented and discussed during the February 2015 NEA workshop in Pavia (NEA, 2015b).

In order to make such consistency checks, some assumptions must be made, and some mathematical tools are used, which are presented and discussed in the present Annex.

Objective

The main objective is to give an estimation of the expected number of observations, within different ranges of PGAs, which should be felt on a given number of sites and during a given period of time.

This expected number of observations will be compared to the actual one, as observed.

Main assumption

The main assumption that is made is that the annual exceedance rate of the SSE PGA is 10^{-4}.

This target is the usual target that is required for assessing nuclear power plant safety, even if some member countries could define a different target.

This means that, theoretically, if the cumulated years of observation is 10 000, the expected number of observed events with a PGA close to the SSE one would be close to 1.

All the assessments performed in this section are based on this assumption, although it is possible to make a reassessment based on a different target.

Method

The method that is implemented follows the process described below:

- The first step consists in building a typical hazard curve that will provide the annual rate of exceedance of a given PGA. This hazard curve is scaled to 1 for the 10 000 year return period target.
- Based on the typical hazard curves defined is step 1, the second step consists in calculating the expected rate of occurrence of earthquakes for each range of PGA under consideration.
- The third step consists in calculating a distribution of expected number of observations related to each range of PGA, taking into consideration the random occurrence of earthquakes during the corresponding period of observation.
- The fourth step consists in adjusting the previous distribution of expected number of observations, taking into consideration the correlation between sites.
- Finally, the range of expected observations related to each range of PGA is given in terms of confidence level (10% - 90%), including random and epistemic uncertainties, as described in steps 1 to 4.

First step: Typical hazard curve definition

The shape of a hazard curve depends on many assumptions and input data that are usually site specific. However, it is possible to estimate the shape of such a hazard curve using mathematical formulae.

One formula used by Labbé in the Pavia Workshop (NEA, 2015b) is the following:

$$\frac{T}{T_{ref}} = \left(\frac{a}{a_{ref}}\right)^n \qquad (1)$$

Where: T_{ref} and a_{ref} are respectively the reference return period and PGA used to "scale" the hazard curve (PGA = 1 for 10 000 return period in the present study)

- T is the return period of the considered PGA "a"
- n is a real number that is usually between 2 and 3

After comparison with some actual hazard curves, and in order not to overestimate the occurrence rate of low return period events, it was decided in this report to use an "acceleration dependent" value of n, with lower values for low return periods and higher values for high return periods, as given in equation (2):

$$\frac{T}{T_{ref}} = \left(\frac{a}{a_{ref}}\right)^{n(a)} \tag{2}$$

Based on equation (2), hazard curves are defined from a range of PGA including 5% to 150% of the 10 000 return period PGA.

However, some other studies propose different shapes of typical hazard curves, such as the formula used by Vaseux and Thiry in the Pavia Workshop (NEA, 2015b), based on a Weibull law, as given in, equation (3):

$$\frac{1}{T} = exp\left(-\left(\frac{a}{\eta}\right)^{k}\right) \tag{3}$$

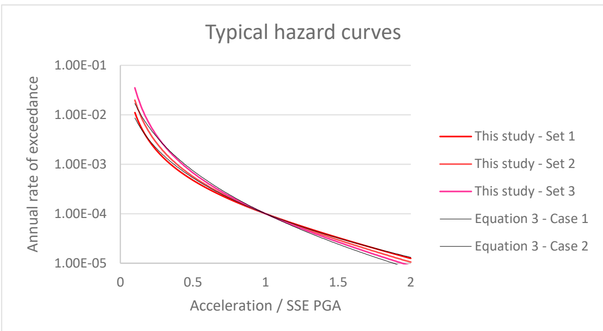
Where: k and η are two parameters that can be defined to best fit actual hazard curves.

In this context, it was decided to use equation (2) with 3 different sets of input data in the present study, in order to account for epistemic uncertainties:

Set 1: $2.0 < n(a) < 3.0$	low rate of exceedance
Set 2: $2.25 < n(a) < 3.25$	medium rate of exceedance
Set 3: $2.5 < n(a) < 3.5$	high rate of exceedance

In Figure A.1., the three corresponding hazard curves used in the present study (eq. 2) are compared with two typical hazard curves that were proposed by Vaseux and Thiry in the Pavia Workshop (NEA, 2015b), (eq. 3).

Figure A.1. Comparison of the shape of hazard curves used in the present study with other references



Second step: Rate of occurrence estimation

Based on typical hazard curves defined in step 1, the rate of occurrence of earthquakes is calculated for each PGA range under consideration.

For a given range of PGA [PGAi ; PGAi+1], its annual rate of occurrence R[PGAi] is the difference between the annual rates of exceedance of the 2 PGA bounds, as given by equation (2):

$$R_{[PGA_i]} = \frac{1}{T_{PGA_i}} - \frac{1}{T_{PGA_{i+1}}} \quad (4)$$

As an illustration, the rate of occurrence obtained from equations (2) and (4) is given in Table A.1.

Table A.1. Expected annual rates of occurrence of ranges of PGA assuming that SSE return period is 10 000 years

	Range of acceleration / SSE PGA			
Hazard curve	10% to 25%	25% to 65%	65% to 150%	> 150%
Set 1 (low)	9.21E-03	1.62E-03	2.39E-04	3.28E-05
Set 2 (medium)	1.71E-02	2.37E-03	2.73E-04	2.96E-05
Set 3 (high)	3.13E-02	3.45E-03	3.11E-04	2.67E-05

Third step: Distribution of expected number of observations including the random occurrence of earthquakes

The distribution of expected number of observation occurrence for a given range of PGA [PGAi; PGAi+1], during the period of observation under consideration, is obtained using Poisson's occurrence, (NEA, 2015b; IAEA, 2016) considering that all the sites under consideration are independent.

$$P(n,t) = \frac{e^{R.t}.(R.t)^n}{n!} \quad (5)$$

Where:

- R is $R_{[PGA_i]}$ calculated with eq. (4);
- t is the period of time under consideration (sum of the periods of observation of all the sites under consideration, assuming that they are independent);
- n is the number of expected observations.

The values of R.t used in the application of eq. (5) is given in Table A.2.

Table A.2. Expected number of observations used in eq. (5), based on eq. (2)

	Expected number of observations			
Worldwide (2 464 years)	10% to 25%	25% to 65%	65% to 150%	> 150%
Set 1 (low)	23	4	1	0
Set 2 (medium)	42	6	1	0
Set 3 (high)	77	8	1	0
Asia (745 years)	10% to 25%	25% to 65%	65% to 150%	> 150%
Set 1 (low)	7	1	0	0
Set 2 (medium)	13	2	0	0
Set 3 (high)	23	3	0	0
Europe (1 611 years)	10% to 25%	25% to 65%	65% to 150%	> 150%
Set 1 (low)	15	3	0	0
Set 2 (medium)	27	4	0	0
Set 3 (high)	50	6	1	0
North America (only Canada) (108 years)	10% to 25%	25% to 65%	65% to 150%	> 150%
Set 1 (low)	1	0	0	0
Set 2 (medium)	2	0	0	0
Set 3 (high)	3	0	0	0

Fourth step: Distribution of expected number of observations taking into consideration the correlation between sites

In order to take into consideration the possible correlation between sites, as observed (see Section 3.3.1), the method used in this report is the one described by Humbert in the Pavia Workshop (NEA, 2015b). The correlation between sites is taken into consideration through the use of a natural logarithm of the gamma function distribution, as given below:

$$f(n,t) = exp\left[ln\Gamma\left(\frac{R.t}{k-1}+n\right) - ln\Gamma\left(\frac{R.t}{k-1}\right) - ln\Gamma(1+n)\right].\left(\frac{1}{k}\right)^{\frac{R.t}{k-1}}.\left(1-\frac{1}{k}\right)^{n} \quad (6)$$

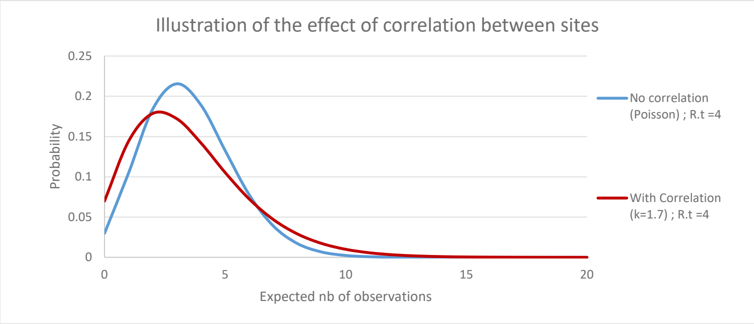
Where:

- R is $R_{[PGA_i]}$ calculated with eq. (4);
- t is the period of time under consideration (sum of the period of observation of all the sites under consideration);
- n is the number of expected observations;
- k is the correlation coefficient under consideration (see Section 3.3.1);

- and $ln\Gamma(x) = ln\left(\int_0^\infty e^{-u}.u^{x-1}du\right)$ is the natural logarithm of the gamma function.

The result of this is illustrated in Figure A.2.

Figure A.2. Illustration of the effect of taking into consideration the correlation between sites (R.t=4 ; k=1.7)



As given in Section 3.3.1, observed correlation coefficients used are the following:

- Worldwide: k = 1.65
- North America: k = 1.0
- Asia: k = 1.6
- Europe: k = 1.7

Fifth step: Quantification of the range of expected observations including random and epistemic uncertainties, and associated with a target confidence level

Based on the process described in the previous steps, the quantification of the range of expected observations, including random and epistemic uncertainties, is defined as the 10% - 90% confidence level taking into consideration the 3 typical hazard curves as epistemic uncertainties (equally weighted) and observed correlation between sites through equation (6), as aleatory uncertainties.

The results of this process are illustrated in Figure A.3 and Figure A.4.

Figure A.3. Quantification of the range of expected observations (Worldwide 2 464 years – PGA = 25% to 65% of the SSE) – Range is 2 to 11 observations (10% - 90% confidence level) – Contribution of the 3 sets of rate of occurrence

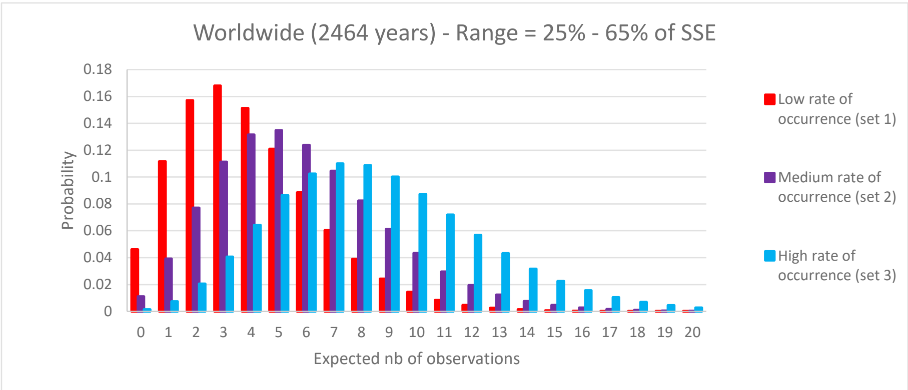
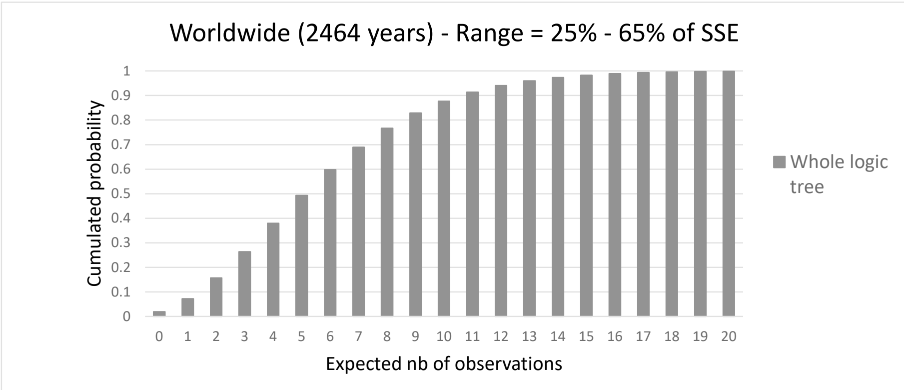


Figure A.4. Quantification of the range of expected observations (Worldwide 2 464 years – PGA = 25% to 65% of the SSE) –Range is 2 to 11 observations (respectively 10% to 90% confidence level) – Whole logic tree (3 sets combined)



All the results obtained through this approach are presented in this report in Section 4.2.