Geotechnical, Geological and Earthquake Engineering

Alain Pecker Ezio Faccioli Aybars Gurpinar Christophe Martin Philippe Renault

An Overview of the SIGMA Research Project

A European Approach to Seismic Hazard Analysis



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This Springer imprint is published by Springer Nature The registered company is Springer International Publishing AG The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland Le doute est un état mental désagréable mais la certitude est ridicule. Doubt is an unpleasant mental state but certainty is ridiculous.

> Voltaire (François-Marie Arouet, 1694–1778)

Contents

1	Introduction		
	1.1	Overview of the Project Organisation	1
	1.2	Object of the Document	4
	Refe	erences	4
2	Gen	eral Concepts and PSHA Background	5
	2.1	Development of a Seismotectonic Framework for PSHA	5
	2.2	Development of Seismic Sources and Logic Trees for Source	
		Definition	6
	2.3	Site Specific vs. Regional Study	6
	2.4	PSHA – A Framework for Seismic Source & Ground	
		Motion & Site Response Characterization	8
	2.5	Logic Tree Approach and Treatment of Uncertainties	12
		2.5.1 Epistemic Uncertainty vs. Aleatory Variability	12
		2.5.2 Logic Tree Methodology	13
		2.5.3 Site Response	14
		2.5.4 Use of Experts	16
	2.6	Interface Issues Between Work Packages	
	2.7	Common Required Outputs for Seismic Hazard Results	18
		2.7.1 Basic Definitions and Requirements	19
		2.7.2 Common Hazard Results	20
		2.7.3 Additional Parameters	22
	Refe	erences	23
3	Seis	mic Source Characterization	25
	3.1	Pre-requisites to Develop the SSC Models	26
	3.2	Database, Earthquake Catalogue, Magnitude Conversions,	
		Uncertainties on Metadata	28

	3.3	Seismic Source Models			
		3.3.1	Diffuse Seismicity Versus Identified		
			Seismogenic Structures	32	
		3.3.2	Seismic Source Characterization Framework	33	
		3.3.3	Area Source, Fault Sources, Gridded Seismicity	34	
		3.3.4	Lessons Learned Related to Seismic Source Models	40	
	3.4	Occur	rence Processes	41	
		3.4.1	Poisson Model	41	
		3.4.2	Characteristic Model	42	
		3.4.3	Time-Dependent Seismicity Models	42	
	3.5	Maxin	num Magnitude and Recurrence Parameters	42	
		3.5.1	Maximum Magnitude	42	
		3.5.2	Recurrence Parameters	44	
		3.5.3	Lessons Learned	45	
	3.6	Logic-	-Tree Implications	47	
	0.0	3.6.1	Logic Tree Approaches	47	
		3.6.2	Efficient Tools for the Logic Tree Conception	.,	
		5.0.2	and Weights Assignment	49	
		363	Verification and Quality Assurance (OA)	53	
	Refe	rences	vormeation and Quanty Assurance (QA)	53	
	1010	renees.		55	
4	Roc	Rock Motion Characterization			
	4.1	Empir	ical Models and Point Source Stochastic Models	57	
		4.1.1	Empirical Ground Motion Attenuation Models	57	
		4.1.2	Point Source Stochastic Models	62	
	4.2	Model	Selection and Criteria	63	
		4.2.1	Modelling Criteria	63	
		4.2.2	Tectonic Consistency	64	
		4.2.3	Site-Conditions Consistency	66	
	4.3	Correc	ctions or Modifications of Published Models	66	
		4.3.1	<i>κ</i> - <i>V</i> _{S30} (Simulation-Based) Correction	67	
		4.3.2	Data-Based Predictions for Hard Rock	71	
	4.4	Standa	ard Deviation of Model Predictions; Truncation	73	
		4.4.1	Sigma Truncation	76	
	4.5	Appro	aches for the Vertical Ground Motion Component	78	
	4.6	Logic	Tree Implications	79	
	4.7	Lesso	ns Learned from the SIGMA Project	80	
	Refe	rences.	~	81	
5	C:to	Deener	and Characterization	05	
5	5 1	Soil C	herecterization	0J 85	
	5.1	5 1 1	Determination of the Drofile Natural Fragmanay f	0J 96	
		512	Determination of the Shear Waya Valacity Profile	00	
		5.1.2	and Site Class	06	
		512	and one Class	00 01	
		J.1.3	Characterization of Nonlinean Cail Descertion	91	
		5.1.4	Characterization of Nonlinear Soil Properties	92	

	5.2	Hazard Assessment at the Ground Surface	93
		5.2.1 Direct Evaluation from Ground Motion Prediction	
		Equations (FpG)	96
		5.2.2 Generic Site Specific Approaches (HyG)	97
	5.3	Completely Site Specific Approaches (HyS)	101
		5.3.1 Linear Numerical Analyses	103
		5.3.2 Equivalent Linear Numerical Analyses	104
		5.3.3 Nonlinear Numerical Analyses	107
	5.4	Treatment of Uncertainties	111
		5.4.1 Fully Probabilistic Generic Site Approach (FpG)	111
		5.4.2 Hybrid Site Specific Approach (HyS)	112
	5.5	Lessons Learned from the SIGMA Project	114
	5.6	Additional Topics in Ground Surface Hazard Assessment	115
		5.6.1 Vertical Ground Motion	115
		5.6.2 Maximum Ground Motion: Truncation	116
	Refe	rences	117
6	Seis	nic Hazard Computation	119
	6.1	Basic Requirements	119
	6.2	Interfaces and Boundary Conditions	120
	6.3	Software Packages	120
		6.3.1 PSHA Software	120
		6.3.2 Site Response Analysis Codes	122
	6.4	Sensitivity Analysis	123
	6.5	Hazard Disaggregation	126
	6.6	Additional Engineering Output Parameters	127
	6.7	Selection of Time Histories	128
		6.7.1 Selection Based on UHS	128
		6.7.2 Selection Based on Conditional Spectra	129
	Refe	rences	130
7	Inte	rfaces Between Subprojects	133
	7.1	SSC and GMC Interfaces	133
	7.2	GMC and SRC Interfaces	135
	7.3	Single-Station Sigma	137
	7.4	V/H Models for Rock and Soil	138
	Refe	rences	139
8	Prot	pabilistic Seismic Testing and Undating of Seismic	
0	Haz	ard Results	141
	8.1	PSHA Testing Using Acceleration and Macroseismic	1 7 1
	0.1	Intensity Data	142
	8.2	Bayesian Update of PSHA	145
	Refe	rences	145

9	Summary and Way Forward		147
	9.1	Seismic Source Characterization	147
	9.2	Ground Motion Characterization	148
	9.3	Site Response Characterization	148
	9.4	Hazard Calculation	149
	9.5	Risk Assessment	149
Ar	inexe	s	151
Bi	bliog	raphy	165
In	dex		169

Acronyms

ASCR	Active shallow crustal region
BPT	Brownian passage time
CAV	Cumulative absolute velocity
COV	Coefficient of variation
EMS	European Macroseismic Scale
EPRI	Electric Power Research Institute
FFS	Finite fault simulation
IAEA	International Atomic Energy Agency
IDP	Intensity data point
GIS	Geographic information system
GMC	Ground motion characterization
GMPE	Ground motion prediction equation
GR parameters	Gutenberg-Richter parameters
NRC	Nuclear Regulatory Commission (USA)
PDF	Probability density function
PGA	Peak ground acceleration
PGV	Peak ground velocity
PSA	Probabilistic safety assessment
PSHA	Probabilistic seismic hazard assessment
QA	Quality assurance
RP	Return period
RVT	Random vibration theory
SCR	Stable continental region
SHA	Seismic hazard assessment
SSHAC	Senior Seismic Hazard Analysis Committee
SOF	Style of faulting
SRC	Site response characterization
SSC	Seismic source characterization
US-DOE	Department of Energy (USA)

Chapter 1 Introduction

In recent years, attempts have been made to identify and quantify uncertainties in seismic hazard estimations for regions with moderate seismicity. These studies have highlighted the lack of representative data, thereby resulting in predictions of seismic ground motion with large uncertainties. These uncertainties, for which no estimation standards exist, create major difficulties and can lead to different interpretations and divergent opinions among experts. There is a wide consensus among the scientific and technical community for the need to improve knowledge so as to better characterize and, ideally, reduce the uncertainties entering in the calculation of seismic ground motion hazard.

To address this situation, in January 2011, an industrial consortium composed of the French electric power utility (EDF), the French company AREVA, the Italian electricity company ENEL (Ente Nazionale per l'Energia eLettrica), and the French Atomic Energy Commission (CEA) launched an international research and development program. This program, named SIGMA (SeIsmic Ground Motion Assessment, http://www.projet-sigma.com), lasted for 5 years and involved a large number of international institutions.

1.1 Overview of the Project Organisation

The main objective of the research programme was to establish a framework to be used in the future to produce stable and robust hazard estimates. Better characterization and more stable uncertainty estimation could provide input for the updating of regulations. It was expected that total uncertainties will be reduced by significantly lowering epistemic uncertainty, and subsequently, this research programme would significantly contribute to the following efforts:

• Validate, homogenize and stabilize input databases for seismic hazard calculations;

- Produce accepted and validated methods and calculation tools;
- Reduce total uncertainties;
- · Improve confidence in seismic hazard assessments; and
- Foster technical and scientific exchanges among French and other European organizations.

The programme was organised around five Work Packages, as follows:

• WP 1: Improve knowledge of seismic sources

The main goal was to produce a French catalogue of earthquakes that covers both the historical and instrumental periods.

• WP 2: Improve seismic ground motion prediction

The goal was to develop methodologies and analysis tools for predicting seismic ground motion that are adapted to the French context and contiguous countries, and which adopt a realistic representation of aleatory and epistemic uncertainties.

• WP 3: Improve local site conditions representation (Site response)

The goal was to develop methods to determine which sites are potentially subject to local site effects, and to develop appropriate tools to be used in seismic hazard calculations.

• WP 4: Improve seismic hazard models

The intention was to better identify and quantify uncertainties with the goal to reduce them, particularly the epistemic uncertainties. It was intended to validate existing methods, and to explore new directions, for testing probabilistic hazard curves against observations.

• WP 5: Improve on characterization and utilization of seismic ground motion The studies in this work package were aimed to ensure that results of the overall project fulfil the engineers and designers' needs for the design and operation of various types of facilities. Its goal was to produce methods and tools for the development of the needed engineering parameter(s) for the earthquake ground motion.

Figure 1.1 summarizes the general framework of study in the five main Work Packages.

To help achieve these ambitious objectives, the project management was organized around four entities (Fig. 1.2):

- A Steering Committee (COSS) composed of the industrial financial sponsors, which is charged with identifying strategic orientations and approval of the technical and scientific choices;
- A management committee (COPIL) composed of the Work Package leaders and the Project Manager;
- A international Scientific Committee (CS) to guarantee high quality scientific research and development; and
- An external committee (SHARP) composed of internationally recognized experts to give the COSS a highly credible scientific assessment.



Fig. 1.1 Illustration of relationship between the five technical Work Packages



Fig. 1.2 Management flowchart

As mentioned previously, a large number (30) of worldwide academic, research and professional institutions contributed to the project and their contributions resulted in the publication of 75 technical reports reviewed by the Scientific Committee, 40 publications in peer-reviewed journals and numerous communications in international conferences, workshops and symposia.

A list of all institutions and members of the different committees can be found in Annex 1. The most important technical reports (deliverables) mentioned in the present document are listed in Annex 2 with the published papers.

The total cost of the programme amounted to 7.5 million Euro over a period of 5 years.

1.2 Object of the Document

The main objective of this document is to present, based on the outcomes of the SIGMA project, lessons learned from conducting a Probabilistic Seismic Hazard Assessment (PSHA), including site response, for selected areas in France and Italy. After a general overview of the elements of a PSHA, the document is organized in chapters closely related to the work packages: Chap. 3 presents the seismic source characterization (WP1), Chap. 4 the rock motion characterization (WP2), Chap. 5 the site effects (WP3) and Chap. 6 the seismic hazard computations (WP4). Two important chapters have been added related to interface issues to be faced in PSHA between the work packages (Chap. 7) and to the testing of PSHA results (Chap. 8). The final chapter attempts to summarize the lessons learned and to identify the areas where additional research is needed.

It must be stressed that not all the topics related to PSHA were covered in the SIGMA project; nevertheless, they will be mentioned in the document for the sake of completeness.

It is assumed that the reader is familiar with PSHA and, therefore, the basic concepts are not covered in detail in the present document. The interested reader is referred to general documents for further details, e.g.: IAEA Safety Standard SSG-9 (2010), USNRC Regulatory Guide RG 1.208 (2007) and the EERI monograph by McGuire (2004).

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- McGuire RK (2004) Seismic hazard and risk analysis, EERI monograph. Earthquake Engineering Research Institute, Oakland
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Chapter 2 General Concepts and PSHA Background

2.1 Development of a Seismotectonic Framework for PSHA

The first step in building the PSHA model is the collection of geological, geophysical, geotechnical and seismological data from published and unpublished documents, theses, and field investigations. These data are integrated to develop a coherent interpretation of a seismotectonic framework for the study region. Its size can vary depending on the purpose. The international practice for a site-specific study is to distinguish between the investigations at a regional, near regional and site vicinity level (e.g. 300 km, 25 km and 5 km radius in IAEA SSG-9, IAEA (2010)). In order to include all features and areas with significant potential contribution to the hazard, it may also be necessary to include information in a radius up to 500 km (e.g. for subduction zones). This framework provides the guiding philosophy for the identification of seismic sources. Furthermore, the framework should address the important issues that each expert expects to influence the identification and characterisation of seismic sources in the region. The main topics to be addressed in the seismotectonic framework include:

- Use of pre-existing geological structures to provide a basis for defining the present and future seismicity.
- Tectonic models that are applicable to contemporary processes, the observed seismicity, and are compatible with seismic sources.
- Spatial distribution of the seismicity in three dimensions, and associated focal mechanisms and their relation to potential seismic sources.
- Implications of contemporary stresses and strains (e.g. earthquake focal mechanisms, geodetics, other kinematic constraints) for defining sources.
- Use of historical and instrumental seismicity and seismic source delineation to provide a basis for defining the locations of future earthquake activity.

The following categories of seismotectonic configurations can be distinguished:

• Stable continental region (SCR);

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- Active shallow crustal region (ASCR); and
- Subduction region.

In Europe two regimes are usually considered and discussed: Active shallow crustal region (ASCR, southern part) and stable continental region (SCR, northern part). Within the SIGMA project the study regions were the South-East of France and Northern Italy. The former region and regime can be considered as being part of the extended crust (SCR) and weighted accordingly, while the seismically active zones of Northern Italy can be predominantly classified as ASCR (see Fig. 4.3). The subduction regime should also be mentioned in this context, but is applicable only for some special regions in Europe, as e.g. Southern Italy, Greece, Turkey and Cyprus. Also, the Vrancea seismic zone in Romania can be treated better with a subduction-related database, although its tectonics are not clear.

The definition of the appropriate seismotectonic model is very important and has implications on many aspects of the PSHA. Especially the source parameters such as the maximum magnitude are closely related with the seismotectonic environment and depend mostly on tectonic metrics (strain rate, etc.). Models for the magnitude scaling and associated uncertainties are also dependent on the defined environment and, thus, have an impact on the hazard.

2.2 Development of Seismic Sources and Logic Trees for Source Definition

Using the seismotectonic framework as a basis, the expert team in charge of seismic source characterization develops its interpretation for the study region (see Sect. 2.5.4). Alternative interpretations of seismic sources (e.g. large regional sources with spatial smoothing of seismicity versus localised source zones) and alternative source zone geometries are usually incorporated in the seismic source models as weighted alternatives using the logic tree methodology. The logic tree framework allows, especially for the seismic source characterization, to capture the epistemic uncertainty lying within the various interpretations. The seismic source zone maps and the supporting calculations of spatial density functions of seismicity, using kernel density estimation, are a part of the seismic source characterization assessment.

2.3 Site Specific vs. Regional Study

PSHA for critical infrastructures (such as dams, power supply structures, e.g. nuclear power plants) is usually done on a site-specific basis and cannot directly be compared to regional studies (such as national seismic hazard maps as used in design codes). The goal of regional studies is to provide seismic hazard results at a

regional or national scale based on a uniform approach. Such a result can of course only be achieved if a common seismological rock layer is defined and simplified models are defined in order to keep the computation effort manageable. Usually, the site response cannot be accurately captured in a regional study and, due to the lack of appropriate soil data, cannot be measured in an adequate and accurate way. The seismic source characterization models for regional or site-specific studies can be compared, as the underlying historical and measured seismic data should theoretically be the same. Nevertheless, seismic sources are not always defined through seismicity data. In a site-specific study, the detail of investigation increases as we approach the site, i.e. regional, near regional and site vicinity scales as defined in IAEA SSG-9. Therefore, the sources can also be different from a regional study in which only regional scale tectonic data are considered. On the other hand, the ground motion characterization can also be quite different, since usually no sitespecific (or even regional) attenuation model exists. Therefore, the choices for adequate models to be used for the PSHA can be different depending on the targets of the study and the resources allocated to deriving adequate models. For example, in modern PSHA published ground motion prediction models are adjusted to make them more site-specific. Furthermore, recent site-specific studies make use of the single-station sigma concept, which requires some local data and very good knowledge of the investigated site. This is usually not the case for a large scale regional study.

A site-specific study should not primarily rely on the scarce regional data but should undertake the effort to collect adequate near regional, site vicinity and site data at appropriate scales. Such data collection is required by nuclear safety standards (IAEA SSG-9). They are also cost effective and can scale over time depending on the available resources. Without more knowledge and data, the penalty to pay for a site-specific study is the acceptance of large uncertainties. Only site specific data collection to constrain the model space can lead to a reduction of uncertainties.

There is usually a difference in the approach and possibilities for existing versus new sites. At a new site the collection of data for the ground can usually be carried out easily, while at an existing site there are constraints to respect. At a regional level the available data for an existing site might be richer, as equipment has been deployed and measurements have been carried out since then. At a new site in a remote location there might be, in the extreme case, no data at all available, as no infrastructure is nearby. Of course, it depends on the scope of the study and the available resources, but the approach should be chosen according to specific safety objectives and implemented in the context of a long-term perspective. Detailed and extensive data collection can appear costly at the beginning, but will be valuable for reduction of uncertainties and updates at a later stage.