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An Overview of the SIGMA Research Project

A European Approach to Seismic Hazard Analysis

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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

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 (**E**nte **N**azionale per l'**E**nergia e**L**ettrica), and the French Atomic Energy Commission (CEA) launched an international research and development program. This program, named SIGMA (**S**e**I**smic **G**round **M**otion **A**ssessment, 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;

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- 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.

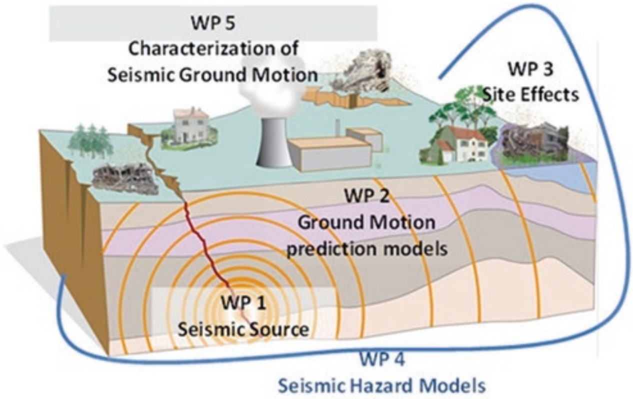

Fig. 1.1 Illustration of relationship between the five technical Work Packages

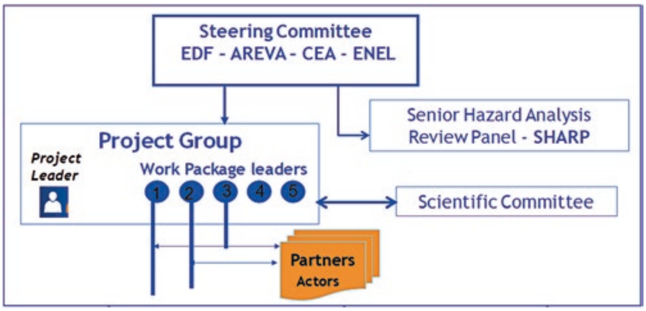

Fig. 1.2 Management flowchart

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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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 site-specific (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.