Chapter 8
Research on Hazards associated to Natural Events

Taking natural events into account in the design of nuclear installations and during their operation is essential for their safety. The general objective is that the safety functions associated with their structures, systems and components are not harmed by such events. Scientific knowledge in the earth sciences field (such as geology, hydrogeology, seismology, etc.) forms the basis for assessing the risks associated with natural events, i.e. the characteristics to be taken into account in the design or testing of installations (seismic movements of the ground, water level, etc.). Improving installation safety particularly involves working to improve the reliability of our ability to grasp the mechanisms at work in natural phenomena and their effects. This is the general objective of the research initiatives run in the last forty years or so by IPSN (then IRSN), particularly as regards seismic risks.

Natural events, the subject of research and development by IPSN (then IRSN) either on its own or in the context of collaborations, are mainly earthquakes, floods, and climate-related hazards. This work aims to develop, improve and validate the tools (including databases) and methods used so that the hazards and their consequences can be determined more accurately. Field studies, one-off experiments and ongoing instrumental measurements (seismographic network and GPS[86]) complement the theoretical research and modeling.

As the flood at the Le Blayais nuclear power plant site in December 1999 and the accident at the Fukushima Daiichi nuclear power plant in March 2011 showed, nuclear

86. Global Positioning System.

safety can only be guaranteed at the cost of adequate protection of facilities against all types of natural events, which means that the natural events that could strike them need to be evaluated correctly, particularly those associated with seismic events and the occurrence of floods. In Japan, the Tohoku earthquake and the resulting tsunami, and also the earthquake in July 2007 at Chūetsu-oki not far from the Kashiwasaki-Kariwa nuclear power plant[87], and to a lesser extent the earthquake in Virginia (USA) in August 2011, around 18 km from the North Anna nuclear power plant[88], highlighted the importance of the knowledge and methods on which the design of nuclear installations is based and but also their limits. There is a broad international consensus on the need to extend the knowledge and assessment of natural events that can seriously affect nuclear sites – as evidenced by the conclusions of an international conference held by the International Atomic Energy Agency (IAEA) in March 2012. This is particularly true in France, where improving the way seismic risks and flood risks are taken into account is one of the priorities set by IRSN, ASN and the public authorities as a result of feedback from the Fukushima accident, reflected in the call for RSNR projects issued by the French National Research Agency (ANR) with funding from the Investment in the Future Program (PIA). In this new context, there are two issues for research and development when it comes to defining extreme hazards. One is obtaining knowledge of the phenomena (including historical indices), and the other is finding methods for taking account of the associated uncertainties and reaching a definition of the maximum risks to be taken into account when designing nuclear installations.

8.1. Earthquakes

Seismic hazard assessment practice in France for installations at special risk (nuclear and chemical installations, dams, etc.) has historically been based on a deterministic approach. This approach estimates the acceleration that would be produced by the strongest historical earthquake as close as possible to the site, with an added safety margin[89]. This margin is defined by increasing the magnitude[90] of the earthquake in question by a half-degree.

In general, seismic hazard is assessed by identifying possible aggressive earthquake "sources" and characterizing their potentiality. In low-seismicity areas where little is known about faults, the deterministic approach considers regions as possible sources of earthquakes. These regions are defined according to their geological or seismic homogeneity. In regions with slightly higher seismicity (e.g. Provence, Alsace, Pyrénées), more is usually known about faults and, most importantly, significant earthquakes can be

---

87. This nuclear power plant was not damaged.
88. Shallow (6 km deep) earthquake of moderate magnitude (5.8), which was unexpected given the historical seismicity of the part of Virginia concerned.
89. The strongest historical earthquake is known as the MPE (Maximum Probable Earthquake); with the margin added it is known as the SME (Seismic Margin Earthquake).
90. The magnitude of an earthquake is a measurement of the amount of energy released at the hypocenter of the earthquake. The magnitudes usually used these days are expressed as moment magnitudes (denoted M_w).

associated with these source faults (by their cartographic position). Nevertheless, seismic hazard assessment is part of a larger process requiring answers to the following questions:

- how big are the faults capable of producing earthquakes? The magnitude of an earthquake and, therefore, the danger it represents, is directly related to this parameter. The size and extent of an active fault can be determined by surface mapping, locating microseismic events, and depth imaging. This parameter can also be assessed by characterizing major "prehistoric" earthquakes;
- what is the deformation rate of the region affected by the faults considered? This is an important point for determining the periodicity of major earthquakes. In addition to dating geological markers, spatial geodesics measurements (GPS, InSar[91]) also provide useful data for assessing the deformation rate.

The seismic hazard associated with a system of active faults can be assessed by conducting research and development to find answers to the above questions.

IPSN, and later IRSN, pioneered many aspects of seismic risk research, such as studying historical seismicity with the SisFrance database, analyzing deep geophysical data, paleoseismology, and seismic mapping and monitoring of active faults, in particular with studies of the Moyenne Durance fault system, characterized by regular seismic activity (reference document [1], 2007). The results obtained by these studies have been used to characterize the microseismicity of the fault system and to produce a more precise assessment of seismic risk (particularly in terms of magnitude). This will be particularly useful for assessing or reassessing the seismic risk of the nuclear installations at CEA's center in Cadarache.

Over the years, the research programs run have enabled IPSN (then IRSN) to develop a network of scientific partnerships both in France and abroad. In the last few years, IRSN's accumulated expertise has enabled it to benefit ANR funding and has led to requests for assistance with site studies from a number of countries wishing to develop a nuclear power generation fleet (or strengthen the fleet they already have). Its activities have also gradually contributed to the definition of methods applicable to basic nuclear installations, notably those laid down in the French Basic Safety Rule 2001-01. The knowledge and data produced also feed into the expert appraisals performed by IRSN in the frame of safety reviews led by the operators. They have also been widely used in the complementary safety evaluation (ECS) carried out in the wake of the Fukushima Daiichi accident, in the presentation of the French report during the European peer review process, and in reports on the "hard core" being introduced particularly at French nuclear power plants (equipment that must withstand more severe hazards than the ones for which the installations were designed). As a result of the ENSREG[92] recommendations, a probabilistic approach to assessing risks with a low probability of occurrence has been introduced in addition to the deterministic method.

IRSN has also used the knowledge obtained on seismic risk in its role as expert supporting the French Ministry of the Environment during preparation of the seismic risk

91. Interferometric Synthetic aperture radar.
92. European Nuclear Safety Regulators Group.

mapping of metropolitan France, which came into force on May 1, 2011. This new "zoning", which covers conventional buildings and "special risk" installations (apart from nuclear installations and dams), is based not only on historic seismicity, which was essentially the case with the previous zoning in 1991, but also on a probabilistic assessment of seismic risk (estimation of the seismic movement likely to happen or be exceeded according to a fixed probability, typically 10%, over a time period of 50 years). However, to comply with the recommendations of French basic safety rules 2001-01, for nuclear installations IRSN regularly updates a "seismotectonic zoning", mainly to incorporate knowledge acquired through research in general. Also in relation to the recommendations in French basic seafety rules 2001-01, IRSN was involved in the creation of a national database[93] of indices of strong earthquakes that occurred in France a very long time ago (several thousands to several tens of thousands of years), known as paleoearthquakes. In the context of a memorandum of understanding with French General Directorate for Risk Prevention (DGPR[94]), IRSN also recently developed a database of active faults in a 50 km perimeter around any nuclear installations.

IRSN's research on seismic risk is also looking at:

- identifying and understanding how faults function (in France and abroad). The work aims to identify faults likely to cause earthquakes (active faults) and to characterize them (location, geometry, deformation rate). It is based on the analysis of records and on the study of historical seismicity and paleoseismic indices. Characterization of the activity of a fault (i.e. its ability to cause an earthquake) and the discovery of new active faults in France are necessary to form the basis, confirm or improve assessments of seismic risk. This research combines various different approaches (study of morphological anomalies using digital terrain models, Spot images, spatial imaging methods, geological studies of terrain, and trenching studies to find traces of paleoearthquakes). Since the study of the Moyenne Durance fault system mentioned above, IRSN's research has continued in France on the Vuache fault (Jura), which in particular was responsible for the earthquake that caused damage in Annecy in 1996, and on other faults in the Alpine Foreland, the Rhine Graben and the Channel and abroad (Ecuador, India, Spain);
- predicting potential seismic movements: this work is done using empirical approaches (based on observations) and numerical simulations;
- estimating the seismic response of the ground specific to a site (which comes under the term "site effects" [Figure 8.1]). The research has revealed the particular importance of "site effects", which can significantly amplify seismic movements in the frequency range of interest for concrete structures[95]. The research done in this field in particular requires the acquisition of geotechnical and geological data at the sites and the use of complex modeling that takes account in particular of

93. See the website www.neopal.net.
94. French civil service department for risk prevention.
95. A few Hertz. "Site effects" can reduce ground movements at the highest frequencies and amplify them at lower frequencies.

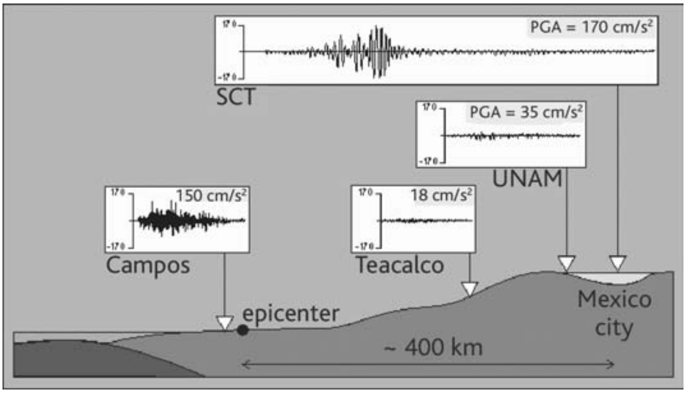

Figure 8.1 Example of site effects in the lakes area of Mexico. © Jean-François Semblat.

non-linear behavior. "Site effects" refers to effects due to the type of ground on which an installation is built (rock, sediment) and effects due to the particular configuration of the site (also known as "site-specific effects", which refer for example to sites in a sedimentary basin set into a rocky environment). The Grenoble Basin has historically been France's test site for observing "site effects" in deep valleys, following the drilling of a deep borehole in 1999 at IPSN's instigation. IRSN has also worked, in collaboration with foreign institutes, in other areas of active seismicity (Gulf of Corinth in Greece, Santiago Basin in Chile). The current sites are in France, in the sedimentary basin of Cadarache, and in Greece, near the town of Argostoli.

IRSN is actively represented within the main bodies involved in seismological research, such as the French Earthquake Engineering Association (AFPS) and the French Seismographic & Geodesic Network (RESIF).

IRSN is also a partner in the SINAPS@[96] project on seismicity and nuclear installations, with CEA (project coordinator), IFSTTAR[97], École Centrale Paris, EDF, ENS[98] Cachan, etc. SINAPS@ is a research project in which seismic risk is assessed as a whole, from the fault to concrete structures and to equipment. It aims to explore the inherent uncertainties in assessing seismic risk and the vulnerability of structures and equipment. The main ultimate objective is to identify, and indeed quantify, the seismic margins resulting from the hypotheses used either when making design choices or when devising the design strategy (conservative hypotheses, choice of materials, etc.). The main themes of the SINAPS@ project to which IRSN is contributing are:

1. Quantification of the uncertainties associated with knowledge of the input data and parameter hierarchy controlling the variability of seismic risk assessments in the deterministic and probabilistic approaches.

96. Earthquakes and Nuclear Facilities, Improving and Protecting Safety.
97. French Institute of Science and Technology for Transport, Development and Networks.
98. French higher education institution.

2. The international benchmark exercise (code and data comparisons) known as PRENOLIN[99]. The PRENOLIN project (2013-2015), reincorporated into SINAPS@ as a result of a request by ANR, aims to produce an approach that takes account of ground non-linearity phenomena in the "site effects" dimension of seismic risk, an approach validated by comparison with field observations. It should eventually be possible to apply this approach to contexts of low and moderate seismicity, which means using simulations, while making use of empirical data (recordings of small earthquakes) for the areas concerned.

3. Numerical simulation of seismic movement close to faults. The aim of this part of the project is to complement the empirical prediction of seismic movement, for which there is a paucity of data close to faults. Numerical simulation is used to explore the physical origins of the variability of seismic movement, which could reduce the uncertainties due to the current lack of knowledge. Quantifying and reducing the uncertainty associated with near-field seismic movement predictions is a major challenge in estimating site-specific seismic risk.

4. Selection of pertinent seismic signals for assessing the earthquake resistance of buildings. This theme lies at the interface between seismology and civil engineering. The multiplicity of selection procedures appropriate to the risk on the one hand, and the evolution of the methods for non-linear modeling of the behavior of buildings on the other, mean that the studies straddle both disciplines. The aim is to provide information for the existing guides to be updated.

There is another research program too: the SIGMA program (Seismic Ground Motion Assessment, 2011–2015) brought together by EDF to meet its own needs and those of other licensees and designers (AREVA, CEA, ENEL[100], etc.). The SIGMA program covers the areas mentioned above: characterization of seismic sources, prediction of ground motion, "site effects" and probabilistic methods. The findings and recommendations for designers and licensees are expected in around 2016–2017.

Lastly, one particular topic of investigation has been chosen for the seismic reviews of France's nuclear power plant reactors: the identification of active faults that could cause ground surface or near-surface movements, commonly known as capable faults[101]. EDF was asked[102] to present a survey of current knowledge concerning the identification of capable faults within a 25 km radius of sites[103] and, where necessary, a methodology for taking account of them when reviewing the seismic risk of sites. The treatment of this

99. Better Prediction of Non-Linear Effects Induced by Strong Seismic Motion.

100. Ente Nazionale per l'Energia Elettrica.

101. On capable faults, see the IAEA guide SSG-1 from 2010.

102. Request made by ASN as part of the safety review associated with the third ten-yearly outage program (VD3) of the 1300 MWe reactors, extended to VD4 900 MWe and VD2 “N4” (letter CODEP-DCN 2014-051797 of December 18, 2014).

103. Investigation radius proposed in IAEA guide SSG-9 (near regional investigations). This guide gives four spatial scales for progressively more detailed investigations: regional, near regional, site vicinity and site area. The guide recommends finding evidence of capable faults going back to very early periods, at least 10,000 years ago.

subject prompted IRSN to launch some new research and development work within international groups (IAEA and INQUA[104]).

8.2. External flooding

As far as other natural events are concerned, the most work has been done on external flooding, with studies of the suitability of statistical methods for explaining outlier events, extreme rainfall, the handling of heterogeneity in the statistical treatment of data (particularly for river floods), the historical analysis of exceptional events (tsunamis on the Atlantic coast, etc.) and assessing the risk of percolation through dikes. The knowledge acquired recently *via* research in this area is set out in the work in reference [2], the outcome of research by a group run by IRSN which brought together representatives from many organizations (ANDRA[105], AREVA, CEA, EDF, the French Technical Maritime and River Study Center (CETMEF), the French National Company of the Rhone river (CNR), the French Naval Hydrographic and Oceanographic Service (SHOM), France's national meteorological service (Météo-France), and the French Technical and Inspection Office for Large Dams (BETCGB). Specialists from the French Geological Research Mining Bureau (BRGM) and the French National Center for Agricultural Machinery, Rural Engineering, Water and Forestry (CEMAGREF) also participated in the group's activities, along with academics.

For each phenomenon (high sea levels including due to tsunamis, river floods, rainwater and runoff, rising groundwater, dam breaches), the following were examined:

- the basic data,
- the physical parameters to be quantified (intensity, volume, water level, etc.),
- the existing characterization methods (deterministic or statistical), identifying the limitations of these methods,
- the identification and incorporation of uncertainties,
- the influence of climate change,
- the dependency between the different phenomena/events.

This report on the state of the art has served notably as the basis for a guide by ASN for nuclear licensees, setting out recommendations for assessing and quantifying external flooding risks, and for defining suitable protection measures[106]. The preparation of this guide reflects the lessons learned from the partial flooding of the Le Blayais nuclear power plant during the December 1999 storm, prompting nuclear licensees to review the safety of installations in view of flood risks under stricter conditions than before and to increase protection for their installations. Aside from these improvements, the report on the state of the art [2] has allowed a detailed reflection process to take place based on

104. International Union for Quaternary Research.
105. French National Radioactive Waste Management Agency.
106. ASN Guide No 13, *Protection of Basic Nuclear Installations against external flooding* - Version of January 8, 2013.

increased knowledge, ensuring external flooding risks are taken into account more comprehensively and more robustly. ASN's guide constitutes a reference text in France not only for new nuclear installation projects but also for the ten-yearly safety reviews for those in operation.

IRSN's ongoing work, especially in the post-Fukushima context, concerns methodological aspects such as:

- statistical methods for determining extreme hydrometeorological events, paleo-sedimentary approaches;
- modeling of flows and runoff phenomena, with application to actual cases.

In addition, concerning the tsunami risk, IRSN is a partner in the TANDEM[107] project (2014–2018) funded by ANR as part of RSNR research, with partners CEA, EDF, BRGM, Ifremer[108], Inria[109] and Pau University. This research project aims to assess the effects of a tsunami on the French coast, focusing particularly on the Atlantic and Channel coasts where there are nuclear installations in operation. This project will deploy new numerical analysis methods, which will be adapted and tested on the databases concerning the March 11, 2011 tsunami off Tohoku in Japan. Once these methods have been validated, they will be applied to the French coast in order to determine the impact of a tsunami on a similar scale. In the long-term, the conclusions should make it possible to produce new guidance for assessing risks to nuclear installations.

References

[1] *Étude du potentiel sismique et de l'enracinement de la faille de la Moyenne Durance*, 2007 scientific and technical report, IRSN, 2007.

[2] *L'aléa inondation – État de l'art préalable à l'élaboration du guide inondation pour les installations nucléaires*, IRSN, Notices and reports/assessment reports/nuclear safety series, 2013.

107. Tsunami in the Atlantic and the English ChaNnel: Definition of the Effects through numerical Modeling.

108. French Research Institute for Exploitation of the Sea.

109. French National Research Institute for the Computational Sciences.