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Seismic hazard for critical facilities

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ABSTRACT Critical facilities are man-made equipments, plants, constructions, and structures that, if affected by a strong earthquake, can produce serious impacts on people, environment, and economy. Therefore, for these facilities specific provisions in terms of seismic design are required and detailed seismic hazard evaluations have to be developed. In this paper, firstly the concept and meaning of "critical facilities" is argued. Then, a focus on the seismic hazard of nuclear power plants is presented since this type of critical facilities could be considered the facilities that more than others have contributed to define the most advanced knowledge in the field of seismic hazard assessment.

Key words: seismic hazard, critical facilities, nuclear power plants.

1. Introduction

"Earthquakes don't kill people, buildings do" is the standard mantra of seismologists. In other words: the seismic response of built environment is central in the determination of consequences. When an earthquake affects an area where not only buildings but also critical facilities are present, the impact could be heavily aggravated (Grimaz and Maiolo, 2010). Among the critical facilities, a special role is played by the nuclear power plants (NPPs) due to the terrible disasters they may produce (Slejko, 2011). But NPPs are not the only infrastructures that can determine a serious damage to people and environment, especially if located in highly seismic regions (Grimaz, 2014).

The hazard induced by the presence of critical facilities in the shaken region (e.g., the collapse or failure of dams, toxic-chemical storage facilities, etc.), the disruption of certain services (e.g., medical, fire, police, etc.), and infrastructure disruption (e.g., electricity, damage to roads and highways, etc.) can all bring additional negative impact on the community. Therefore, nowadays earthquakes can produce not only the collapse of buildings but can also trigger technological accidents. This aspect was emphasized in the occasion of several recent earthquakes that hit industrial areas and, specially, in Japan in 2011, when the Fukushima nuclear accident was caused by an unexpected earthquake and the earthquake generated tsunami. For these reasons, protection of critical facilities against earthquakes is one of the main concerns in civilized areas of the world. This means that a specific attention has to be addressed to seismic hazard assessment and standard buildings, but especially critical facilities, must be properly designed against the earthquake threat.

In the following chapters, an overview of existing critical facilities is presented and specific focus is given on the seismic hazard definition for NPPs.

2. Critical facilities

With the term "critical facilities" we refer to all man-made structures or other constructions and systems which have the potential to cause serious bodily harm, extensive property damage, or disruption of vital socio-economic activities if they are destroyed, damaged, or if their services are interrupted, because of their function, size, service area, or uniqueness. Table 1 shows a non-exhaustive list of critical facilities.

Table 1 - List (non-exhaustive) of critical facilities (from DRDE, 1991, modified).

TYPE/SECTOR	CRITICAL FACILITY
PUBLIC SAFETY AND SECURITY	Civil defense installations Communications centres Emergency management centres Fire stations Hospitals and other medical facilities Mass emergency shelters Police stations and other installations for public security
TRANSPORTATION	Airways (airports, heliports) Highways (bridges, tunnels, roadbeds, overpasses, etc.) Railways (track age, tunnels, bridges, yards, depots, etc.) Waterways (canals, locks, seaports, ferries, harbours, docks, etc.)
UTILITIES	Communications systems and apparatus Electric power (production and distribution) Potable water systems Waste water systems Gas installations and distribution system
INDUSTRIAL	Major risk establishments (manufacture, transfer, storage, disposal dangerous substances) Nuclear power plants Petrochemical installations
AGRICULTURAL	Food storage Irrigation systems Water containment (dams, reservoirs, levees, dikes, etc)
HIGH-DENSITY OCCUPANCY	Auditoriums, theatres, stadiums Churches Educational facilities Hotels Office buildings Penal institutions

Terms like "lifelines" and "emergency infrastructure" refer more specifically to transportation and utilities. These two categories are of particular importance for locating and serving new economic activities, supporting existing economic activities, providing the connections to, and support of, emergency facilities, contributing to any disaster preparedness, response, recovery, and reconstruction activity, and receiving a high priority for strengthening before a disaster, for emergency operations, and for rerouting or rapid repair after damage or interruption. Other man-made constructions as for instance, embankments of rivers, have a great importance where, as a consequence of earthquake, a collapse of even only a single part of an embankment could flood large urbanized areas. NPPs could be considered the more representative critical facilities. They have also been the most deeply studied and those that have contributed to produce the most advanced studies in the field of seismic hazard. For these reasons, in the following chapter an overview on the state-of-the-art of seismic hazard for NPPs is illustrated.

3. Nuclear power plants

There are currently 435 operable civil NPPs around the world, producing about 15% of the world electricity (Fig. 1). A further 71 NPPs are under construction (source: World Nuclear Association). Among those in operation, 100 are located in the U.S.A. and 58 in France. Only 7 nuclear accidents are reported since the beginning of the activity in the early 1950s (the first

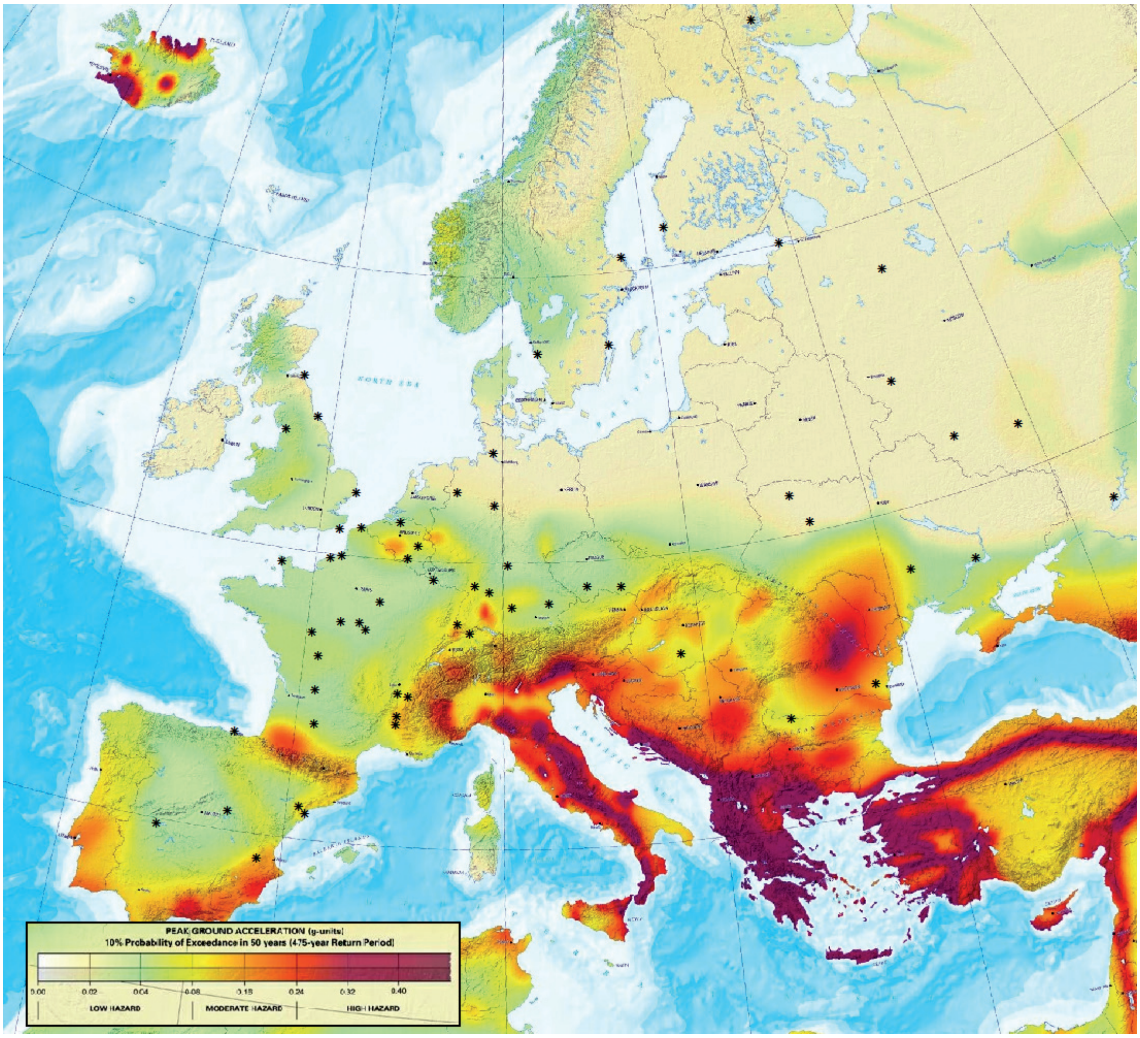

Fig. 1 - NPPs operating in Europe and producing more than 1000 MW. The base shows the *PGA* with a 475-year return period (Jiménez *et al.*, 2001, 2003; http://wija.ija.csic.es/gt/earthquakes/).

NPP was switched on in December 1951 in Idaho, U.S.A) and only the Fukushima catastrophe was caused by a seismic event: the March 11, 2011 Tohoku earthquake. Nevertheless, for the unpredictable possibility of an unexpected earthquake occurrence and the related dramatic impact that a nuclear accident has on the human life, the seismic threat is a fundamental information in NPP designing.

In several countries the exploitation of nuclear energy has been already abandoned; in Italy four NPPs (Latina, Garigliano, Trino, and Caorso) operated between 1963 and 1990 and were shut down on grounds of age, or following the 1987 referendum, notwithstanding, in 1966, Italy was included as the third largest producer in the world of electricity from nuclear power after the U.S.A. and England. A fifth plant, an experimental self-breeding plutonium reactor near Brasimone Lake, was never ignited.

Specific regulations, different from one country to another and generally not mandatory but simple recommendations, were defined for the NPPs because of the high risk represented by these infrastructures.

Already in the late 1960s Caputo *et al.* (1969) performed a seismological study for comparing the earthquake risk at three sites proposed for a nuclear installation in Italy. The analysis followed the Gumbel statistical approach to identify the recurrence interval of the expected strongest earthquake influencing the sites and a rough estimation of the expected shaking at the site itself.

An analysis of the world major regulatory guides for NPP seismic design was done by Serva (1992) and the author identified that, at that time, there was no exclusion criterion associated with the level of ground motion, however there was a minimum design basis peak ground acceleration (*PGA*) requirement of 0.1 g associated with a site specific spectrum in most guides. Moreover, the design earthquake generally was related to the return period of 10,000 years. Conversely, the sites having potential for surface faulting (i.e., presence of capable faults in the site vicinity) were excluded. Design basis earthquakes in the various guides were, and still are, specified in different manners among which it is worth mentioning the safe shutdown earthquake (SSE) of the U.S. guides and the seismic level 2 (SL2) event of the International Atomic Energy Agency (IAEA). The methodology and conceptual approach for the definition of the reference earthquake for the site of a critical facility was outlined by Serva (1990) according to the study performed by the Italian Company for Alternative Energies (ENEA) for a site candidate for the installation of a NPP. The dominant faults in the investigated region were outlined in that study on the basis of a seismotectonic analysis, and the related maximum possible earthquake was identified by a macroseismic – neotectonic method.

Today, the Nuclear Regulatory Commission (NRC: www.nrc.gov) uses a risk-informed regulatory approach, including insights from probabilistic assessments and traditional deterministic engineering methods to make regulatory decisions about existing plants (e.g., licensing amendment decisions). Any new NPP the NRC licenses will use a probabilistic, performance-based approach to establish the plant’s seismic hazard and the seismic load for plant’s design basis.

The milestone about the way a seismic hazard study should be conducted is given by the report prepared by the Senior Seismic Hazard Analysis Committee (SSHAC) in 1997 (SSHAC, 1997), after four years of deliberations, and summarized in Budnitz *et al.* (2006). The SSHAC report addresses why and how multiple expert judgments, and the intrinsic uncertainties that attend them, should be used in probabilistic seismic hazard analysis (PSHA) for critical facilities such as NPPs. More specifically, the SSHAC guidelines are concerned with how to capture, quantify, and communicate the uncertainties expressed by multiple experts. SSHAC was originally convened to review and understand the differing PSHA results obtained by two teams of experts for the same nuclear facilities in the eastern United States.

The SSHAC methodology represents an up-to-date procedure for obtaining reproducible results from the application of PSHA principles established in past practice, not to advance the foundations of PSHA or develop a new methodology. This focus led to an emphasis on procedures for eliciting and aggregating data and models for performing a hazard analysis, rather than an examination of the Earth science foundations of PSHA. A second major theme in the SSHAC methodology is the treatment of aleatory and epistemic uncertainties in data and models to get stable estimates of seismic hazard at a selected site (McGuire, 1977; McGuire and Shedlock, 1981; Toro *et al.*, 1997). The aleatory uncertainty, representing the physical variability of the earthquake process, is taken into account in the PSHA by considering the standard deviation of the physical quantities considered. The epistemic uncertainty, representing the ignorance about the earthquake process because of limited data or unverified models, is taken into account by the use of logic trees, where all the alternative hypotheses of the informed scientific community are considered and properly weighted (Kulkarni *et al.*, 1984; Coppersmith and Youngs, 1986). The SSHAC methodology for PSHA is an example of aggregating expert opinion on a scientific issue. In fact, due to large uncertainties in the geosciences data and in their modelling, multiple model interpretations are often possible, leading to disagreements among the experts. The objective of aggregation is to represent the scientific community's composite state of knowledge on a particular issue. The process should seek to capture the diversity of interpretations, as opposed to the judgment of any particular expert. What should be sought in a properly executed PSHA project are: a) a representation of the legitimate range of technically supportable interpretations among the entire informed technical community, and b) the relative importance or credibility (weight) that should be assigned to the various hypotheses across that range. The type of consensus being sought, therefore, is that all experts agree that a particular composite probability distribution represents, first, them as a panel, and secondly, perhaps modified, the informed community as a whole. In outlining its four levels of complexity (Table 2), the SSHAC methodology visualizes the distinct roles that experts should play at various stages of the process. The SSHAC procedure at the highest (4th) level, recommended for NPPs and other critical facilities, requests the presence of the technical facilitator/integrator (TFI), who is essential to obtain a high degree of agreement among experts with many diverse viewpoints. The TFI approach is not recommended by SSHAC for every PSHA study: the first three levels rely on a single entity called the technical integrator (TI), who is responsible for all aspects of the PSHA, including specifying the input (see Table 2).

If the year 1997 can be considered a milestone for the studies on seismic hazard of NPPs, some notable studies were produced even before in the U.S.A. (Kammerer and Ake, 2012). The first U.S. probabilistic risk assessment (PRA) for a NPP, the Reactor Safety Study, was completed in 1975. Subsequent peer review of the study generally endorsed the PRA methodology but suggested that the uncertainties associated with many of the key inputs were quite significant.

In the years 1988 and 1989, two large PSHAs were conducted to assess the hazard at 69 NPP sites in the central and eastern United States (CEUS) by the Electric Power Research Institute

Table 2 - Degrees of PSHA issues and levels of study (modified from McGuire, 2001).

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

(EPRI) and the Lawrence Livermore National Laboratory (LLNL). Both studies used multiple experts to capture the uncertainties associated with earthquake hazards, although the two teams independently developed seismic source zones and associated seismicity parameters for the study area, explicitly accounting for uncertainties in the evaluations using alternative, weighted interpretations for individual zones or features. The endorsement of the two studies encountered the significant differences in the results obtained by the two teams and motivated the work of the SSHAC.

The nuclear waste repository of the Yucca Mountains was interested by several studies as the probabilistic volcanic hazard analysis (PVHA) in 1996 (updated in 2008), the viability assessment in 1996-1998, and the PSHA of 1998 (Hanks *et al.*, 2009). Both the PSHA and the updated PVHA were consistent with the Level 4 SSHAC recommendations.

Although Switzerland is generally considered to have a low to moderate level of seismicity, seismic hazard was identified as a potentially significant contributor to the risk at the four NPP sites existing in that country. A PSHA was conducted following SSHAC Level 4 methodologies and the study has since become known under the name of the PEGASOS Project (Abrahamson *et al.*, 2002; Sabetta and Slejko, 2003; Coppersmith *et al.*, 2009). A full-scope formal expert assessment process was used, including dissemination of a comprehensive database, multiple workshops for identification and discussion of alternative models and interpretations, feedback to provide the experts with the implications of their preliminary assessments, and full documentation of the assessments.

Because of the large uncertainties associated with the site response and, to a lesser extent, the ground motion aspects of the study, a PEGASOS Refinement Project was conducted between 2008 and 2013 with the aim of incorporating new data mainly regarding the site conditions at the four NPP sites and incorporating new ground motion models (Renault, 2014).

A SSHAC Level 3 ground motion characterization study for CEUS was conducted by EPRI during a one-year period and was the first avowed application of a Level 3 process. The product of the study was a ground motion attenuation model and related aleatory variability as a function of earthquake magnitude and source-to-site distance. Shortly after completion of the EPRI study, a SSHAC Level 2 study was conducted that initially was intended to deal with upper truncation of the ground motion residual distribution, and later focused on the value of the standard deviation for the ground motion variability for the CEUS.

The CEUS Seismic Source Characterization for Nuclear Facilities (CEUS SSC) Project was aimed at developing a comprehensive seismic-source model for the entire CEUS. This SSHAC Level 3 study began in September 2008 and finished in December 2011. The goal of the CEUS SSC Project was to develop a stable and long-lived CEUS SSC that includes: 1) full assessment and incorporation of uncertainties, 2) the range of diverse technical interpretation, 3) consideration of an up-to-date database, 4) proper and appropriate documentation, and 5) peer review.

At present, the SSHAC methodology at the highest level (Level 4) was applied only in two studies: that for the Yucca Mountains waste depository (Stepp *et al.*, 2001) and that for the Swiss NPPs (Musson *et al.*, 2005). A nice review of the seismological studies upon which the NPPs were designed can be found in Musson (2014) for the U.K., Renault (2014) for Switzerland, and Scotti *et al.* (2014) for France. Presently, the main focus is on the re-evaluation of PSHA for existing NPPs, following the concerns after the Fukushima accident. Recent studies are mostly aimed at the comprehension and reduction of uncertainties of hazard estimates (see, e.g., the SIGMA Project, http://projet-sigma.com/).

4. Return periods for seismic design

One of the main aspects that a public officer has to face is the definition of the acceptable seismic risk for the different facilities (standard buildings, strategic facilities, critical infrastructures) disseminated in a country, considering that the level of acceptable seismic risk varies from one country to another according to many natural and economic factors. One way to identify the level of acceptable seismic risk is to compare it to other types of risk inevitable to the human condition (Grandori and Benedetti, 1973): the level of protection can be, then, calibrated according to the economic possibilities of the country. This latter aspect, already introduced by Terroja and Paez (1952) for standard buildings with the concept of minimum cost of building construction plus expected damage (human lives included), was afterwards developed by Grandori (1991, 2012), who computed the marginal cost for a saved life as function of the seismic coefficient applied in building design. A cost/benefit balance drives, thus, the choice of the acceptable seismic risk for a country.

All the previous considerations should have entered in the definition of the return period considered as standard in the national seismic hazard maps, although it is reasonable to find some differences from country to country. The European countries chose to develop some common European guidelines, to which all countries are suggested to conform. The European seismic code EC8 (CEN, 2002) identifies the *PGA* with a 475-year return period as reference ground motion in building design. The return period of 475 years, corresponding to a 10%

exceedance probability in 50 years had a rather peculiar genesis (David Perkins, personal written communication). In the 1960s and 1970s, seismic design in the U.S.A. referred to the recurrence interval of the design earthquake, i.e., 100 or 200 years. Algermissen and Perkins (1976) considered the average life of ordinary buildings, i.e., 50 years, in their first hazard maps of the United States, and chose to show the map referring to the exceedance probability of 10%, among the many maps prepared, computed for different return periods. Therefore, the choice of the 475-year return period was, initially, rather arbitrary, but it seemed to be justified on the basis of considerations of safety of structures using this return period as a basis for design in the U.S. model building code. These first seismic hazard maps, as well as those that followed in the United States, were computed by some shareware software designed at the U.S.G.S. based on the Cornell (1968) approach. As that software was later applied worldwide, it was normal to select the 475-year return period as a standard in PSHA, again because this choice was supported in several countries also by structural motivations.

The most active countries in seismic hazard mitigation, the United States, Japan and Canada, developed national seismic hazard maps referring to longer return periods, indicating the non satisfactory performance of the standard 475-year return period of the previous maps. More precisely, the most recent maps for the United States (Frankel *et al*., 2002) show the expected ground shaking with 2% exceedance probability in 50 years (i.e., the return period of 2475 years), those of Japan (Fujiwara *et al*., 2006) refer to 3% exceedance probability in 30 years (i.e., the return period of 985 years), and those of Canada (Adams, 2011) to 2% exceedance probability in 30 years (i.e., the return period of 1485 years). The abandon in the U.S.A. of the value 10% in 50-year was motivated but the fact that this level seemed to provide values too low for seismic design in the CEUS, where damaging earthquakes occur rarely, while the 2/3 of 2% in 50-year ground motion resulted adequate in design to assure a similar risk level in the whole U.S. (Leyendecker *et al*., 2000; Nordenson and Bell, 2000).

When considering highly populated buildings, as schools, churches, hospitals, etc., return periods longer than 475 years are considered in the seismic codes of all countries and even more severe restrictions are applied for strategic buildings, as chemical factories, NPPs, etc.

One interesting point in the PSHA for the NPPs is the safety level (annual exceedance probability) at which the study should be conducted. This aspect was considered in the U.S.A. by NRC and, for the siting of an NPP, the NRC regulatory guide of 1997 (U.S.NRC, 1997) recommended the reference probability of 1×10^{-5}, as the median annual probability of exceeding the Safe Shutdown Earthquake (SSE). After considerations on median and mean annual probabilities of exceedance in CEUS and western U.S., it was decided (U.S.NRC, 2003) that the mean annual probability of exceedance of 1×10^{-4} would be appropriate for the whole U.S. Additionally, the annual exceedance probability of the design earthquake for spent nuclear fuel waste storage installations was fixed at 5×10^{-4} (U.S.NRC, 2003).

More recently, the same aspect was considered also by IAEA in its guidelines. In fact, IAEA (2010) reports that the smallest annual frequency of exceedance of interest will depend on the eventual use of the probabilistic seismic hazard analysis (i.e. whether for design purposes or for input to a seismic probabilistic safety assessment). This value can be extremely low (e.g. 10^{-8}) when it is associated with seismic probabilistic safety assessment studies in which the NPP has a very low core damage frequency in relation to non-seismic initiators (e.g., for innovative reactors). In such cases, care should be taken to assess the suitability and validity of the database, the seismotectonic model and the basis for the expert opinion, since uncertainties associated with these can significantly bias the hazard results.

In a previous report (IAEA, 2002), IAEA defined two seismic levels (SLs), in agreement of those considered by several building codes. The SL-2 corresponds directly to ultimate safety requirements. This level of ground motion shall have a very low probability (in some states, mean annual frequency of 1×10^{-3} to 1×10^{-4}) of being exceeded during the lifetime of the NPP and represents the maximum level of ground motion to be assumed for design purposes. The SL-1 corresponds to a less severe, more likely (in some states, mean annual frequency of 1×10^{-2}) earthquake which has different safety implications from those of SL-2.

5. Protection levels and ground motion values

Taking into account the great importance of critical facilities, specific protection levels in case of an earthquake must be adopted. Provisions are defined in order to obtain an adequate response for a specific seismic demand.

Generally specific limit states, both operating and final, are identified by referring to the performances of the constructions and facilities. For instance, the limit state defined by the European codes are the following:

- Operating Limit State (OLS): following an earthquake, the overall building, including structural elements, non-structural elements and the installations required for its correct functioning, have not undergone significant damage or interruptions;
- Damage Limit State (DLS): following an earthquake, the overall building, including its structural elements, non-structural elements and installations required for its functioning, has been damaged, but not to the point where users have been put at risk or where the resistance capabilities and stiffness in relation to vertical and horizontal actions have been significantly compromised. It thus remains usable despite interruptions some of its apparatuses.

For the case of critical facilities, where serious secondary hazards could be triggered, for instance for the case of installations and equipment for liquefied natural gas or large dams, the European codes (BS, 2007) defines specific levels of seismic action:

- OBE (Operating Basis Earthquake): it is defined as the maximum earthquake intensity for which no damage is predicted and in which functioning and restart can take place in full safety. The reference period for this analysis is 475 years.
- SSE (Safe Shutdown Earthquake): it is defined as the maximum earthquake intensity for which the essential safety functions and mechanisms are designed. Damage is possible, but the overall integrity is guaranteed. The reference period for this analysis is 5,000 years.

In both cases, the levels of seismic action are generally expressed in terms of *PGA* calculated through a PSHA.

Beside the intensity and magnitude characterization of an earthquake, a detailed representation of the expected ground motion of interest for a facility is given by the horizontal and vertical acceleration time histories at a site or, more easily, by the related uniform hazard response spectrum. As *PGA* has been considered for a long time an unsatisfactory indicator of damage to structures, some seismologists are proposing to replace it with the Cumulative Average Velocity

(CAV) as a more useful measure, since it brings also in duration, or with some spectral integral parameter, like Housner or Arias intensities.

In the case of strategic and special facilities, such as, for example, NPPs, the greatest attention must be paid in considering all reasonable possibilities, including the very remote ones, because the hazard calculations refer to very low levels of annual exceedance probability [i.e., to very long return periods, see Slejko *et al.* (2011) for the comparison of PSHA of standard buildings and critical facilities]. Fig. 2 illustrates the logic tree suggested by an expert group of the PEGASOS project to calculate the seismic hazard at the sites of the existing Swiss NPPs (Coppersmith *et al.*, 2009). The level of annual exceedance probability requested in that study was 10^{-7} and, therefore, both extreme seismogenic situations (Fig. 2a) and possible variability of seismicity (Fig. 2b) were taken into account. More precisely, the possible activity of some seismic sources (e.g., the Permo – Carboniferous trough, the Reinach and the Fribourg faults) and alternative geometries for some others (e.g., Basel, Alps) were taken into account (see Fig. 2a for the details). These considerations determined a logic tree with 21 branches for the seismic sources. Moreover, the seismicity inside each source was modelled by a Gutenberg - Richter distribution with 3 alternative estimates for the *b*-value and for the earthquake rate. In addition, the maximum magnitude for each source was estimated considering 2 statistical approaches controlled by geological considerations (see Fig. 2b for details). The logic tree characterizing the seismicity of each source consisted, then, of 18 branches. In such a way, the total logic tree consisted of 21 branches referring to different possible geometries of the seismic sources and 18 branches for the characterization of their seismicity, for a total of 378 branches (Schmid and Slejko, 2009). Moreover, recently probabilistic estimates of the possible fault displacement are also evaluated as main cause for structural damage (e.g., Stepp *et al.*, 2001).

6. Conclusions

In case of an earthquake, critical facilities could produce domino effects in term of damage, increasing significantly the severity of impact, especially in urbanized areas. Nowadays, critical facilities are relatively diffuse on civilized countries, therefore, accidents triggered by earthquakes could produce serious consequences for people, strategic services, and environment. In some cases, earthquakes can provoke NaTech disasters as consequence of seismic-triggered hazardous substance releases and other types of technological accidents. Among the critical facilities, NPPs have been the most studied for an adequate definition of seismic hazard and seismic design.

In the 1960s and 1970s NPPs were designed according to the results of a deterministic seismic hazard analysis (DSHA), i.e., considering the ground motion generated by the most severe possible event (controlling earthquake). Since then, engineers have adopted in design a more comprehensive approach, i.e., PSHA [for the different applications of PSHA and DSHA see McGuire (2001) and Slejko (2012)]. In addition of the possibility of selecting the probability level at which the facility shall be protected, one of the reasons why PSHA has nowadays a worldwide application is represented by the difficulty of quantifying the occurrence frequency of the controlling earthquake in DSHA. Over the years there have been many terms used to describe earthquake potential; among them, in addition to the already cited OBE and SSE, the Maximum Credible Earthquake (MCE), Design Basis Earthquake (DBE), Maximum Probable Earthquake

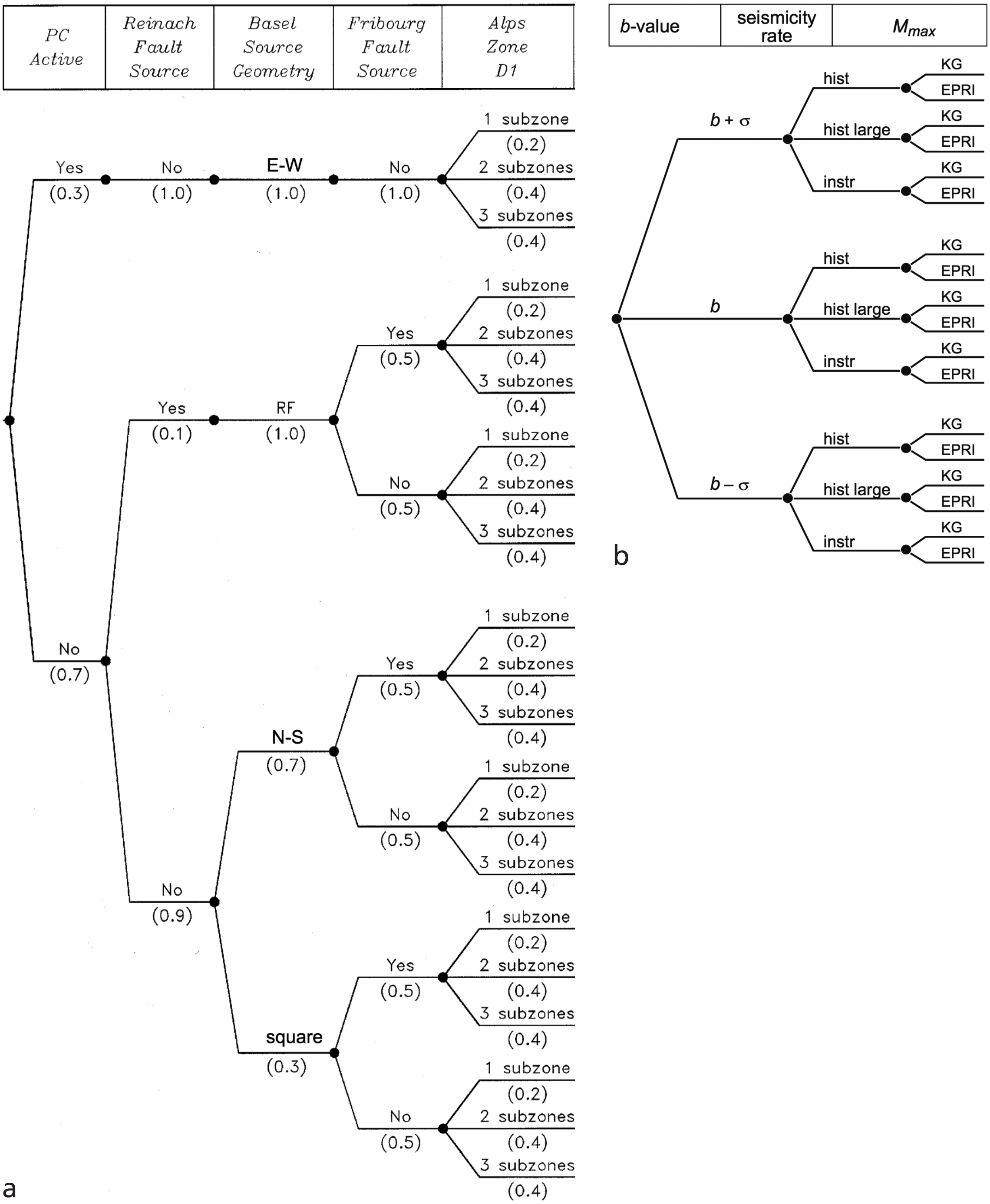

Fig. 2 - Logic trees and weights used by Schmid and Slejko (2009) in the frame of the PEGASOS project: a) for the selection of seismic sources around the site (node PC: Permo-Carboniferous trought activated or not; node Reinach fault: source for the 1356 earthquake or not; Basel geometry: main orientation of the source of the 1356 earthquake; node Fribourg fault: active or not; node Alps zone: number of subzones considered in the Alpine domain); b) for the characterization of their seismicity (node b-value: mean b-value minus one σ, mean b-value, mean b-value plus one σ; node seismicity rate: branch "hist" includes all events, branch "hist large" excludes pre-1975 events with low magnitudes, "instr" includes post 1975 events only; for seismogenic zones outside Switzerland and Germany the rate node was simplified into 2 options: all data and all data with larger magnitudes; node M_{max}: KG= Kijko and Graham (1998) method, EPRI = Johnston *et al.* (1994) method).

(MPE), and Seismic Safety Evaluation Earthquake. The MCE, for example, is usually defined as the maximum earthquake that appears capable of occurring under the known tectonic framework. The DBE and SSE are usually defined in essentially the same way. The MPE has been defined as the maximum historical earthquake and also as the maximum earthquake likely to occur in a 100-year interval. Many DSHAs have used the two-pronged approach of evaluating hazards for both the MCE and MPE (or SSE and OBE). Disagreements over the definition and use of these terms have forced the delay, and even cancellation, of a number of large construction projects. The Committee on Seismic Risk of the EERI has stated that terms such as MCE and MPE "are misleading ... and their use is discouraged" (EERI Committee on Seismic Risk, 1984).

In summary, PSHA estimates the likelihood that various levels of ground motion will be exceeded at a given location in a given future time period and for the design of the new NPPs is, then, worldwide applied. Nowadays, this approach is adopted also for other critical facilities, considering different return periods for defining the seismic action. Experience has shown that, in order to design adequately a critical facility, the seismic action must be adequately taken into account not only considering the seismic hazard at a regional scale but also taking into account the local seismic response and near-field effects. Furthermore, the design has to be addressed to verify specific limit states in terms of scenarios of consequences.

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