Seismic probabilistic safety assessment (PSA): An update

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Earthquakes are without doubt one of the most devastating events of nature that any society may encounter. The significance of their inclusion in risk assessment of nuclear installations has consequently been self-evident from the very beginning of the development of probabilistic safety assessment (PSA). The methodology of seismic probabilistic safety assessment (SPSA) for nuclear installations was first developed in the late 1970s in the United States but, over time, applications and refinements have been made throughout the world.

Given international interest and the importance of the issue, the NEA sponsored several activities in the field. A Workshop on Seismic Risk was organised in Tokyo in August 1999 to discuss SPSA and seismic margin assessment (SMA) methodologies for nuclear installations.[1] The workshop itself benefited from a state-of-the-art report on the same topic.[2] In 2002, the NEA Committee on the Safety of Nuclear Installations (CSNI) issued a brief technical opinion paper on seismic PSA.[3]

Since the 1999 workshop, SPSA has been applied widely at many nuclear power plants around the world. There have also been technical advances in several aspects of the overall methodology. Today, SPSA is judged to be a mature technology for assessing the risk to nuclear installations from earthquakes. Related methodologies, notably the probabilistic seismic hazard analysis (PSHA) assessing the seismicity hazard and its uncertainties, and the SMA assessing the safety margin against seismic events, are also in widespread use.

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The IAEA is currently updating its guidance in the field. Two other important recent developments are the American Nuclear Society's 2003 standard for SPSA and SMA, and the new methodology standard by the Atomic Energy Society of Japan in 2006.

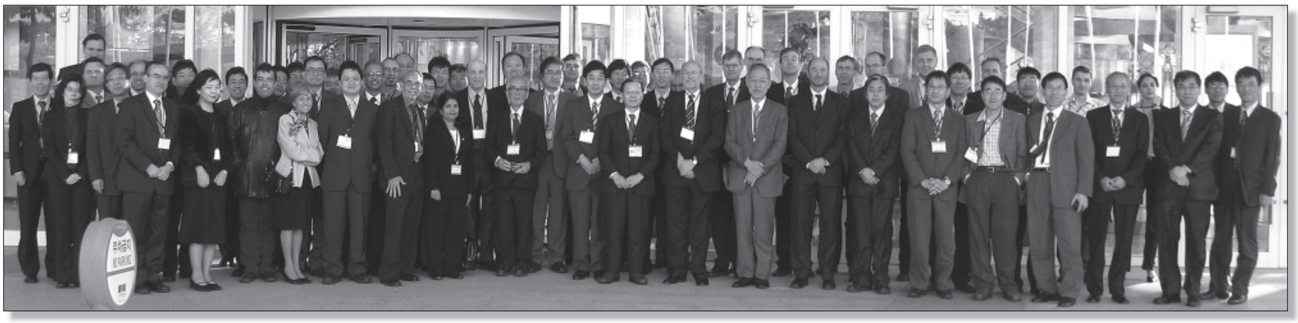
2006 specialists' meeting

In light of these developments, the NEA Committee on the Safety of Nuclear Installations (CSNI) decided to organise a Specialists' Meeting on Seismic Probabilistic Safety Assessment of Nuclear Facilities. The Korea Atomic Energy Research Institute (KAERI) and the Korea Institute of Nuclear Safety (KINS) kindly agreed to host the meeting, which took place on Jeju Island, Republic of Korea on 6-8 November 2006. The meeting was held in co-operation with the International Atomic Energy Agency (IAEA).

The main objectives of the meeting were to review recent advances in SPSA methodology, to discuss practical applications, to review the current state of the art, and to identify methodology issues on which further research would be beneficial. One specific objective was to compare the situation today with the situation in 1999, and to develop a set of findings and recommendations that would update the previous ones. Ample time was allotted to discussing the current situation and developments in SPSA, PSHA and SMA. About 75 specialists from 15 countries participated, providing a large amount of technical material and information that form the basis for this article.

Where do we stand now with SPSA?

SPSA is now in widespread use throughout the nuclear power industry: nuclear power plant (NPP) operators, national regulatory agencies and the designers of new NPPs use it. There is also



75 specialists from 15 countries attended the specialists' meeting in Korea.

broad agreement that SPSA can systematically accomplish several very important objectives, for example to aid in understanding the seismic risk to NPPs, in understanding the safety significance of seismic design shortfalls, in prioritising seismic safety improvements, in evaluating and improving seismic regulations, and in modifying the seismic regulatory/licensing basis of an individual NPP. Compared to the situation in 1999, there has been a significant expansion in the use of SPSA. The most important of the new uses are related to designing advanced NPPs, revising regulations, studying the risk at multiple-unit sites, post-earthquake evacuation and emergency planning issues, and the impact of aftershocks.

The expansion in applications has led to guidance documents to assist the designers, plant owners and regulatory bodies that use SPSA. In almost all cases, information obtained from SPSAs on sequences leading to core damage is used for identifying weaknesses and for evaluating the effectiveness of proposed plant improvements. In several countries, the regulatory requirements concerning seismic design include probabilistic requirements for determining design basis earthquakes, or requirements based on annual frequencies of ground motions that exceed the design basis. In at least two countries (the US and Switzerland), SPSA is now being used in many areas of rule making, risk-informed decisions and guidance for seismic siting and design of NPPs. Several design certifications for standard NPPs have been issued by the US Nuclear Regulatory Commission (NRC) which have used the seismic margin assessment methodology to demonstrate acceptable seismic margin and to identify system-level seismic vulnerabilities. The Finnish regulatory agency STUK has required SPSAs at the design and construction phases of the new Olkiluoto EPR reactor under construction. In addition, a full-scale probabilistic seismic hazard analysis (PSHA) of nuclear power plant sites in Switzerland, sponsored by the Swiss utilities and called the PEGASOS Project, has been conducted.

What still needs to be done?

During the Jeju meeting, a small number of important methodology issues regarding SPSA and its uncertainties were identified. None of these are new, all having been widely recognised for many years by SPSA practitioners. However, for some of the issues, extensive discussions during the meeting provided insights into how to improve matters. The most important questions have to do with PSHA, human action modelling and correlations.

PSHA: Results of properly conducted PSHA studies for regions with low to moderate seismicity, such as Switzerland and Scandinavia, typically exhibit large uncertainty. One source of large uncertainty is that there are very few strong-motion earthquakes in such regions, so that attenuation relationships must start with those taken from other regions with available strong motions (e.g. Japan and coastal California in the United States). Analysts typically seek to select regions with analogous tectonics and structure, and may also rely on simulations using seismological models based on regional geophysical features. This can lead to inconsistencies or to large uncertainties, depending on experts' choices. A proper PSHA in such cases should reflect the uncertainty due to insufficient knowledge of the regional ground motions and attenuation, and it requires expert judgement to a significant extent. Much discussion took place on this topic during the meeting. Naturally, PSHA must be performed as realistically as possible, in order to include all of the uncertainties and all of the variability observed in nature. Adequate consideration of dependencies and factors governing them is also necessary.

Human action modelling: One major area of continuing uncertainty is in quantifying the response of the NPP operating crew and emergency organisations after earthquakes. The problem is partly generic, as with all human reliability analysis where uncertainties remain and there is a lack of data on human and organisational behaviour. However, there are also specific characteristics of earthquakes that make post-earthquake actions more difficult to analyse and to quantify. Among these characteristics are the physical and mental consequences of a seismic shock. Such consequences are due in part to the damage and accessibility to equipment, consequential events such as fires likely to increase the workload, problems with multiple units potentially experiencing different consequences, conflicting goals of the government authorities, accessibility to the site and personnel worrying about their families.

Correlations: Finally, starting with the very first SPSAs in the early 1980s, analysts have struggled with the problem of how to quantify the correlations in the failures of similar equipment or similar structures due to earthquakes. Correlations certainly exist, for example in the response of two identical pumps located near each other, or arising from the identical design and construction of two identical shear walls. Yet the analysis is complex. Testing has produced ambiguous insights at best, and the experience database from real earthquakes is difficult to interpret. The analysts have usually used sensitivity studies to identify where the numerical results are sensitive, but they have also usually assigned large uncertainties to the numbers. On the other hand, the experience with existing plants in the US is that the seismic core damage risk is usually dominated by one or a very few vulnerabilities. In these cases, therefore, the impact of correlations is judged small. The situation may be different for more advanced plant designs in situations where the design basis against earthquakes will lead to even fewer failures. Assuming high dependence between co-located components may be too conservative in such cases.

Where to go from here?

Participants at the Jeju meeting concluded that there are some areas in which follow-up work would be highly desirable on an international level. One of them would be a comparison of seismic hazard studies from countries with high, medium and low seismicity. The PSHA results should be compared to all available observations, especially for return periods where records are available, in order to improve the confidence in the results. Any PSHA activity would benefit from review by all stakeholders: plant owners, regulators, PSA managers, systems analysts and fragility analysts, since bias in the seismic hazard values may have significant effect on cost, risk and licensing effort.

Moreover, because of the rapid progress in using SPSA, it may be necessary to revisit the ten-year-old NEA/CSNI state-of-the-art report on SPSA. Collecting information from conventional industrial sites after large earthquakes may be a good way to increase current knowledge about operator and emergency organisation responses after seismic events, and it provides a means for cross-industry co-operation.

The general consensus of the meeting participants, based on the discussion during the closing session, was that this meeting fully met its objectives and was extremely useful in providing them with new information in the field. The participants also suggested that the NEA should organise similar events in this field more frequently.

To date, no nuclear power plant has ever been challenged by an earthquake large enough to cause damage. Therefore, confidence in NPP safety against earthquake hazards arises from using very robust designs and performing analyses like SPSAs to confirm the adequacy of the designs, in addition to using test data and real-world earthquake data from non-nuclear facilities. Indeed, it is worth noting that other types of infrastructure in society have suffered from earthquakes, but not the NPPs. At the same time, it has been found that not even countries with rather stable bedrock may exclude the possibility of a tremor. A robust seismic design and realistic SPSA are thus beneficial everywhere for preventing the potentially grave consequences of an earthquake. ■

References

1. NEA (2001), "Proceedings of the OECD/NEA Workshop on Seismic Risk", CSNI Report No. NEA/CSNI/R(99)28, www.nea.fr/html/nsd/docs/1999/csni-r99-28.pdf, OECD/NEA, Paris.
2. NEA (1998), "State-of-the-Art Report on the Current Status of Methodologies for Seismic PSA (Probabilistic Safety Assessment)", CSNI Report No. NEA/CSNI/R(97)22, www.nea.fr/html/nsd/docs/1997/csni-r1997-22.pdf, OECD/NEA, Paris.
3. NEA (2002), *CSNI Technical Opinion Papers – Nos. 1-2: Fire Probabilistic Safety Assessment for Nuclear Power Plants and Seismic Probabilistic Safety Assessment for Nuclear Facilities,* ISBN 92-64-18490-2, www.nea.fr/html/nsd/reports/nea3948-fire-seismic.pdf, OECD/NEA, Paris.