RECENT DEVELOPMENTS IN EARTHQUAKE RESISTANT DESIGN OF NUCLEAR POWER PLANTS

NÜKLEER SANTRALLARIN DEPREME DAYANIKLI TASARIMLARINDA YENİ GELİŞMELER

Aybars Gürpinar[1]

ABSTRACT

The following paper outlines the new developments in the assessment of seismic hazard, as well as earthquake resistant design and requalification of nuclear facilities. The activities of the International Atomic Energy Agency are described in order to provide a framework for discussion.

Special emphasis is given to topics related to capable faults, historical earthquakes, levels of design basis ground motion, loading combinations, probabilistic considerations, use of experience data and plant walkdowns in seismic safety reviews.

While most of the data and methods have been developed for and by the nuclear industry, they are equally applicable to conventional engineering structures, such as power plants, industrial and transportation facilities.

INTRODUCTION

There has always been a very significant impact of the extremely high level of nuclear safety standards to the amount and quality of research and development for databases and methodologies in the area of seismic hazard analysis and earthquake resistant design. In particular, in the 1960's and 1970's when many nuclear power plants were designed and constructed worldwide, the development of seismic safety methods used in the nuclear

[1] Scientific Secretary for Nuclear Safety Series on Siting and External Hazards, Division of Nuclear Safety, International Atomic Energy Agency, Vienna

industry was greatly accelerated. These databases, methodologies and criteria have always filtered into other sectors of civil engineering and eventually became part of conventional codes and guides followed by the technical community at large.

The main reason for having a very high target for the seismic safety level in nuclear power plants is due to the requirement that in the siting/design process of nuclear installations external events should contribute to the overall risk no more than events initiated internally, i.e. system failures, human errors, etc.

Today, construction of new nuclear power plants is much slower and the emphasis in seismic safety has shifted to problems related to existing nuclear power plants (either under construction or in operation). New data, new methods and new criteria are being used in the seismic re-evaluation and upgrading of nuclear power plants.

The IAEA has been very active in incorporating new advances in neotectonics, engineering seismology and earthquake engineering in their codes and guides for new nuclear installations as well as developing guidelines for the re-evaluation of the seismic safety and seismic upgrading criteria for existing nuclear power plants.

In this paper, recent documents developed by the IAEA related to seismic safety will be discussed highlighting the areas where new concepts have been introduced. Specific cases where these guides have been implemented will also be briefly outlined.

IAEA DOCUMENTS ON SEISMIC SAFETY

Within the scope of the Nuclear Safety Standards (NUSS) programme, the IAEA has developed five codes in the areas of Governmental Organization, Siting, Design, Operation and Quality Assurance. In the areas of Siting and Design, there are twelve and fifteen safety guides respectively. Two of these safety guides related to seismic safety were recently revised and published.

The first one is the safety guide 50-SG-S1 titled Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting. This was originally published in 1979 and revised in 1991. This is the basic document related to derivation of design basis ground motion and capable faulting.

The second one was numbered 50-SG-S2 and titled Seismic Analysis and Testing of Nuclear Power Plants. It was originally published in 1979.

Both the number (i.e. the series)[2] as well as the title was changed. Now this guide is 50-SG-D15 Seismic Design and Qualification of Nuclear Power Plants (1992).

Since the time of the development of the ideas incorporated in these safety guides, about a decade had elapsed and a review of some of these concepts was necessary, taking into account the information collected and new methods developed within this duration.

In this perspective, several issues emerged as dominant subjects of discussion. Within the scope of 50-SG-S1, collection of more and more strong motion data had permitted tentative results in development of attenuation relationships for various epicentral distances, geological conditions and earthquake magnitude. In particular, near field effects had been studied more closely and carefully. the same data base also enabled several attempts in reconstructing response spectral ordinates (instead of only peak acceleration values) using magnitude (or epicentral intensity), distance, geological conditions, etc. for specified levels of confidence. This constituted a step towards generation of site specific response spectra as opposed to a standard response spectrum anchored to a prescribed peak acceleration.

Also within the scope of 50-SG-S1, several European countries have launched programs of compilation and cataloging of historical seismicity. This has been considered as a viable alternative to the assessment of maximum earthquake potential based on 'fault dimensions' particularly in countries where surface faulting is very rare. Instead, a comprehensive earthquake data base with spatial and temporal homogeneity and extending back about 500 years, is considered to give a sufficiently reliable indication of the maximum potential problem.

Surpassing historical seismicity in time, are the topics of seismicity documented by archeological evidence and paleo-seismicity. Even though the research in these are still rudimentary, through such research, the gap between the information on seismicity and tectonics as two separate entities is certainly narrowing.

Concerning the safety guide 50-SG-D15, four major subjects can be cited; (i) loading combinations which include seismic loads, (ii) two vs one level of design earthquake, (iii) Probabilistic Safety Analysis including earthquake effects, (iv) incorporation of experience data, plant walkdowns, etc. within the scope of seismic safety evaluations. The first two are related and there is a current tendency, particularly in Western Europe, to adopt criteria favoring a single level of design basis. Recently, the PSA studies

---

[2] In the number, S refers to Series in Siting and D refers to Series in Design.

are being considered as very useful in checking various designs and identifying critical areas. Some studies have shown that, in fact, external loads and especially seismic effects may be very important as a PSA input.

DEVELOPMENTS RELATED TO ASSESSMENT OF GROUND MOTION

Estimation of Maximum Earthquake Potential

The IAEA Safety Guide 50-SG-S1 (Rev. 1) requires that, within the scope of the seismotectonic approach the maximum magnitude (or maximum intensity) associated with seismotectonic provinces or seismogenic structures is estimated. This is done in order to have an appreciation for the maximum earthquake potential of the site. therefore it is important to estimate the maximum earthquake potential of each of the seismotectonic provinces and the active faults (i.e. seismogenic structures) within the region under consideration.

Estimates related to maximum magnitudes (or intensities) may be based either on the observed seismicity related to the seismotectonic provinces or active faults, or physical parameters of these structures such as the length of the fault, area of the fault plane, etc.

It should be pointed out that the problem of estimating the maximum magnitude is still controversial due to the lack of data either in historical seismicity or physical fault parameters which can be associated with earthquake magnitude, depending on the region of the world. In California, for example, fault rupture - magnitude relationships yield fairly consistent results, and earthquakes in this area are generally caused by dominant and well established seismogenic tectonic structures. In contrast, historical seismicity data in all of the Americas is constrained only to very recent times. The need, therefore, arises to establish maximum magnitude based on recent seismicity and properties of the faults.

The situation in Europe, on the other hand, is very different. Generally, it is not easy to establish a definitive relationship between earthquakes and tectonic structures even for many events in southern Europe where the seismicity is high. This is mainly due to the lack of observation of surface faulting associated with earthquakes. However, for many parts of Europe there is generally a well documented history of earthquakes.

Recognizing the importance of historical earthquake data in the assessment of seismic hazard and therefore to nuclear safety, the IAEA has been co-ordinating research in this topic with the participation of Member States from the Mediterranean region. This is a region of high seismicity and other earthquake associated hazards, as well as volcanism. Furthermore, the history of the Mediterranean basin is one of the longest and best recorded in the world, making it particularly convenient and attractive for historical research.

Several case histories have been studied because of their significance to nuclear safety in the Western and Eastern part of the Mediterranean which illustrates the importance and benefits of co-operation in the effort to study these events.

Five Workshops hosted by the Atomic Energy Authorities of Spain, Italy, Portugal, Turkey and Syria have proved very beneficial for the joint study of such major earthquakes.

These Workshops, held in April 1987, October 1988, November 1989, October 1990 and November 1992 in Madrid, Rome, Lisbon, Istanbul and Damascus, respectively, brought together specialists from all the Mediterranean countries. Historians, archaeologists, geologists, seismologists, engineers and nuclear safety specialists were all represented strongly in these meetings. Workshops such as these have contributed greatly to the enhancement of the awareness of professionals to the multi-disciplinary nature of their research.

Increasing awareness on historical seismicity, through library research, field evidence from archeological sites as well as paleoseismicity will help in narrowing the gap which still exists between the "seismicity" and "tectonics" approaches to solve the problem of seismic hazard. A truly seismo-tectonic approach may only then emerge.

Documentation of historical and pre-historical earthquakes can eventually lead to a much better understanding of long-term seismological concepts such as earthquake migration, quiescent periods, clustering re-activation, etc.

In the domain of nuclear safety, a sound knowledge of historical seismicity will put the problem of "maximum potential" of seismogénic structures in a more realistic perspective.

Table 1 presents a schematic representation for the data used in the assessment of seismic hazard along with the approximate limiting time frame for which the information may be applicable.

Table 1. Database for Seismic Hazard Assessment

Type of Data	Approximate Limiting Time Frame in Years
Microearthquake	10 E1
Instrumental Seismicity	10 E2
Historical Seismicity	10 E3
Archeological Evidence	10 E4
Paleoseismicity	10 E5
Neotectonics	10 E6

Low Seismicity

The IAEA Safety Guide 50-SG-S1 (1979 Version) made an exception in its scope for nuclear power plants to be constructed in areas of low seismicity. Exactly this problem has been given a great deal of attention in the past decade. Countries in Northwestern Europe have tried to model both the occurrence of earthquakes and the strong ground motion due to earthquakes to be used in their siting and design of nuclear power plants. In France, the United Kingdom and Germany, the nuclear industry have tried to adopt criteria compatible with the seismotectonic setting of these countries.

Although a clear definition of "low seismicity" is not available, the term generally refers to sites for which the majority of the hazard contribution originates from zones of diffuse seismicity and not active faults.

It should be noted that, excepting nuclear power plants sites in Japan, an overwhelming majority of sites in the world fall into low to medium seismicity, i.e. SL2 acceleration less than 0.3g.

One of the major revisions to 50-SG-S1 has been the removal of the exception made for these sites and introduction of a consistent seismotectonic methodology to all nuclear power plant sites.

Response Spectra

The response spectrum which was recommended in the IAEA Safety Guide 50-SG-S1 (1979 Version) had been widely used in the aseismic design of nuclear power plants and other industrial facilities worldwide. This spectrum was originally derived for the USNRC by Newmark et al, 1973. At the time of the derivation of this response spectrum, the number of strong motion recordings was only about 10% of the number which today exists in data banks.

Several authors have attempted a site specific statistical approach using this data base, i.e. deriving empirical relationships between spectral ordinates defined at a number of frequencies and magnitude, distance, soil conditions, etc. as a function of the confidence level.

Studies also exist to correlate intensities and response spectrum ordinates. In particular, the French nuclear power plant siting program uses site specific response spectra based on intensities, magnitudes and hypocentral distance.

In the new revised version of 50-SG-S1, standard response spectra, site specific response spectra and uniform confidence response spectra are all presented as viable alternatives. The specific reference to the USNRC R.G. 1.60 response spectrum has been taken out.

DEVELOPMENTS RELATED TO CAPABLE FAULTING

Significant revision was made to the definition of a capable fault in order to include different tectonic regimes into the scope as well as to give proper weight to historical information. The present definition is given below.

On the basis of geological, geophysical, geodetic or seismological data, a fault shall be considered capable if:

(1) It shows evidence of past movement or movements of a recurring nature within such a period that it is reasonable to infer that further movement at or near the surface can occur. (In highly active areas, where both earthquake and geological data consistently reveal short earthquake recurrence intervals, periods of the order of tens of thousands of years may be appropriate for the assessment of capable faults. In less active areas, it is likely that much longer periods may be required.)

(2) A structural relationship has been demonstrated to a known capable fault such that movement of the one may cause movement of the other at or near the surface.

(3) The maximum potential earthquake associated with a seismogenic structure is sufficiently large and at such a depth that it is reasonable to infer that movement at or near the surface can occur.

DEVELOPMENTS RELATED TO EARTHQUAKE RESISTANT DESIGN

One Level vs Two Level Earthquake Design

The Safety Guide 50-SG-S1 (Rev. 1, 1991) reflects the current thinking related to the two levels of design basis ground motion (SL-1 and SL-2). While the two levels SL-1 and SL-2 are recommended their purposes are different and no interdependence is indicated. The USNRC guides are also being revised in a similar manner.

The two levels of design basis ground motion are defined as follows: The SL-2 level corresponds directly to ultimate safety requirements. This level of extreme ground motion shall have a very low probability of being exceeded during the lifetime of the plant and represents the maximum level of ground motion to be used for design purposes. Its evaluation shall be based on the seismotectonic model and a detailed knowledge of the geology and engineering parameters of the strata beneath the site area.

The SL-1 level corresponds to a less severe, more likely earthquake load condition which has different safety implications than SL-2. The factors which may influence decisions on the level of ground motion chosen to represent SL-1 are:

Seismotectonic setting: the relative exposure of the site to multiple sources of seismicity; the frequency of earthquakes from each such source with respect to the lifetime of the plant;

Design considerations: the safety implications of the required loading combinations and stress limits; the plant type;

Post-earthquake situation: the implications of the agreed required action following SL-1; the need for the plant to continue to operate safely;

Plant inspection considerations: the cost and safety implications of design/construction of the plant to a higher level of SL-1 versus the possibility of more frequent inspections for a lower level.

A minimum value of 0.1g is recommended for SL-2 regardless of where the site is located. The annual probability of exceedance values corresponding to SL-1 and SL-2 are suggested as 10^{-2} and 10^{-4}, respectively.

Loading Combinations

Extreme external loads such as earthquakes are generally not combined with other external loads due to very low probabilities associated with simultaneous occurrence of two rare independent events. However, such considerations with due regard to time delays may be given to extreme events which have a causal relationship. An example of this could be an earthquake followed by a flood due to the seismic failure of an upstream dam.

Combinations of seismic loads with plant process loads are much more significant.

Plant process loads are grouped as follows:

L1: loads due to normal operation
L2: additional loads due to anticipated operational occurrences
L3: additional loads due to accident conditions.

One of the most common scenarios of L3 is a major Loss of Cooling Accident (LOCA).

50-SG-D15 recommends the following loading combinations:

(1) For category 1 items, L1 be combined with SL-2 loads;
(2) For category 2 and uncategorized items, L1 be combined with the loads from the respective earthquakes;
(3) For all items, L2 or L3 be combined with the respective earthquake loads if the L2 or L3 loads are caused by the earthquake and have

a high probability of coinciding with the earthquake loads or if the L2 loads occur sufficiently frequently, independently of the earthquake;

(4) For category 1 items, relevant L3 loads should be combined with SL-2 loads, unless L3 is not correlated with SL-2 loads.

It should be noted that an L3 load for one group of items (e.g. the reactor coolant system) can be an L1 load for another group of items (e.g. containment system or safety injection system).

This clarifies the problem of whether or not LOCA loads should be combined with SL-2 loads; recommending that it is necessary to design only the containment structure for the combined effects of these two extreme loads.

Seismic PSA and PRA Studies

Within the last decade PSA and PRA (probabilistic safety assessment and probabilistic risk analysis) studies have contributed to the basic understanding of safety priorities in nuclear power plants. As earthquake loads are major contributors to the overall risk, it is necessary to pose the question of whether or not it is possible to include these as initiating events into PRA studies. The first requirement for this is to define the earthquakes SL-1 and SL-2 on a probabilistic basis. The present version of 50-SG-S1 (Rev. 1) allows for this definition.

Once these probabilities are assigned to SL-1 and SL-2, then a combination of these with other loads and accident scenarios may be accomplished to be used in PSA and PRA type studies. This requires a reliability analysis where the resistance parameters of the buildings or other systems are also expressed in terms of probabilistic functions.

More commonly these are identified using fragility curves derived from experiments or field observations.

Two IAEA documents will be published this year related to the incorporation of seismic effects into PSA/PRA studies (IAEA, 1992).

Aside from the fact that seismic effects may be significant contributors to the overall risk, other considerations also necessitate including these effects into the framework of a PSA.

The first one is the consideration for events which may exceed the design basis earthquake (i.e. SL-2). This may be necessary for assessing the "what if" situation which arises in safety evaluations based on the defence in-depth concept.

Many PSA studies consider events up till core damage. Seismic effects typically contribute to the final risk even after this point. Some of these are listed below:

increased probability of leakage from the containment structure,

- increased probability of human error subsequent to the occurrence of a destructive earthquake,
- significant probability of damage to lifelines and other infrastructures which may have been planned for use in the context of emergency planning and evacuation,
- increased probability of delayed response to the nuclear accident (by authorities and the public) due to the interference of another catastrophic event.

EXPERIENCE DATA AND PLANT WALKDOWNS

Data related to the performance of structures, components and piping have been gathered and evaluated from many earthquakes affecting mainly conventional power plants or other industrial facilities. This kind of data is being utilized more and more in the seismic requalification of items in existing nuclear power plants. This data have demonstrated certain critical areas such as:

- anchorage of equipment and piping,
- interaction of non-safety items with safety items.

The latter generally involves falling of masonry walls or false ceilings, etc. on seismic category 1 equipment or piping, resulting in an acceptable condition.

In order to assess the potential for anchorage, interaction or other problems, plant walkdowns by experienced specialists have proved to be very effective.

The IAEA has been invited to many nuclear power plants, either under construction or in operation, to review the seismic safety including a walkdown of the plant. Recent activity of the IAEA in this area is summarized in Table 2.

CONCLUDING REMARKS

Despite the general lack of new orders for nuclear power plants within the past decade, nuclear industry still provides new data and methods in engineering seismology and earthquake engineering which can effectively be used particularly for the siting and design of other critical facilities. One of the major areas of activity at the present is the seismic safety review and seismic upgrading of existing nuclear power plants.

REFERENCES

IAEA, NUSS Safety Guide 50-SG-S1 (Rev. 1) "Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting", Vienna, 1991.

IAEA, NUSS Safety Guide 50-SG-D15 "Seismic Design and Qualification for Nuclear Power Plants", Vienna, 1992.

IAEA, Safety Practice "Treatment of External Hazards in PSA", (in publication).

IAEA, Technical Document, "Probabilistic Safety Assessment for Seismic Events", (in publication).

NÜKLEER SANTRALLERİN DEPREME DAYANIKLI TASARIMLARINDA YENİ GELİŞMELER

Aybars Gürpınar

ÖZET

Bu makale, depreme dayanıklı tasarım ve nükleer tesislerin tekrar gözden geçirilmesinin yanısıra sismik tehlikenin değerlendirilmesindeki yeni gelişmeleri özetlemektedir. Tartışmada bir çerçeve belirlemek için Uluslararası Atom Enerji Kurumu'nun faaliyetleri anlatılmıştır.

Sismik emniyet bakımından aktif faylar, geçmiş depremler, tasarım esaslı yer hareketi seviyesi, yükleme bileşimleri, olasılıksal varsayımlar, tecrübeden kazanılan bilgilerin kullanımı ve tesislerin kaldırılması ile ilişkili konulara özel önem verilmiştir.

Nükleer endüstri için bir çok veri ve metodlar geliştirilirken bunlar enerji istasyonları, endüstriyel ve ulaşım binaları gibi klasik mühendislik yapılarına eşit olarak uygulanabilirler.

Table 2. IAEA Seismic Design Reviews and Plant Walkdowns (1990-1993)

Plant	Unit	Country	Reactor Type-Power	Status	Type of Review
Kozloduy	1-4	Bulgaria	WWER-440/230	Operating	Design Input, Seismic Design, Plant Walkdown
Kozloduy	5-6	Bulgaria	WWER-1000	Operating	Design Input
Belene	1-2	Bulgaria	WWER-1000	Construction Stopped	Design Input
Temelin	1-2	Czech Republic	WWER-1000	Under Construction	Design Input, Seismic Design
Bohunice	1-4	Slovakia	WWER-440/230-213	Operating	Seismic Design, Plant Walkdown
Paks	1-4	Hungary	WWER-440/213	Operating	Design Input, Seismic Design, Plant Walkdown
Zarnowiecz	1-2	Poland	WWER-440/213	Construction Stopped	Design Input
Krsko	1	Slovenia	PWR-600 Westinghouse	Operating	Seismic PSA
Cernavoda	1-2	Romania	CANDU-600	Under Construction	Construction Unconformities
Oktemberian	1-2	Armenia	WWER-440/230	Operation Stopped	Design Input, Seismic Design, Plant Walkdown
Gorky	1-2	Russia	District Heating	Construction Stopped	Design Input, Seismic Design, Plant Walkdown
Smolensk	1-2	Russia	RBMK-1000	Operating	Design Input, Seismic Design, Plant Walkdown
Crimea	1-2	Ukraine	WWER-1000	Construction Stopped	Design Input
Karachi	1	Pakistan	CANDU-137	Operating	Design Input, Seismic Design, Plant Walkdown
Chashma	1	Pakistan	PWR-300 (Chinese)	Design	Design Input, Seismic Design