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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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SUMMARY REPORT ON OECD/NEA SEISMIC WORKSHOPS

1 - Engineering Characterisation of Seismic Input
2 - The Relation between Seismological Data and Seismic Engineering
3 - Seismic Input Motions Incorporating Recent Geological Studies

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The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of senior scientists and engineers, with broad responsibilities for safety technology and research programmes, and representatives from regulatory authorities. It was set up in 1973 to develop and co-ordinate the activities of the NEA concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations.

The committee's purpose is to foster international co-operation in nuclear safety amongst the OECD member countries. The CSNI's main tasks are to exchange technical information and to promote collaboration between research, development, engineering and regulatory organisations; to review operating experience and the state of knowledge on selected topics of nuclear safety technology and safety assessment; to initiate and conduct programmes to overcome discrepancies, develop improvements and research consensus on technical issues; to promote the coordination of work that serve maintaining competence in the nuclear safety matters, including the establishment of joint undertakings.

The committee shall focus primarily on existing power reactors and other nuclear installations; it shall also consider the safety implications of scientific and technical developments of new reactor designs.

In implementing its programme, the CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA) responsible for the program of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health (CRPPH), NEA's Radioactive Waste Management Committee (RWMC) and NEA's Nuclear Science Committee (NSC) on matters of common interest.

FOREWORD

The Committee on the Safety of Nuclear Installations (CSNI) Working Group on Integrity and Ageing of Components and Structures (IAGE) has as a general mandate to advance the current understanding of those aspects relevant to ensuring the integrity of structures, systems and components, to provide for guidance in choosing the optimal ways of dealing with challenges to the integrity of operating as well as new nuclear power plants, and to make use of an integrated approach to design, safety and plant life management.

The Working Group has three subgroups dealing with (a) integrity and ageing of metal structures and components, (b) integrity and ageing of concrete structures, and (c) seismic behaviour of components and structures.

The Seismic sub-group was set up in 1996, and that time the first task was to propose an action plan to the CSNI detailing key seismic issues considered important. The plan recommended the topics and content of the three ground motion related workshops. In addition to reviewing and documenting the state of knowledge of seismic ground motion, the Seismic sub-group was concerned about the intellectual gap that existed between earth scientists and engineers. Thus, a second primary objective of the workshops, in particular, and the subgroup activities, in general, was to improve the synergy between the two groups.

The three OCED/NEA workshops were conducted between November 1999 and November 2004. This report summarises the main findings and conclusions of the workshops and extracts the seismic information most relevant to current nuclear practice.

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EXECUTIVE SUMMARY

This report summarises the findings of the three OECD/NEA workshops, developed by the Seismic Subgroup of the Working Group of the Integrity and Ageing of Components and Structures. The workshops were conducted between November 1999 and November 2004 and focused on the progress in the fields of: (a) seismic input characterisation, (b) the relation between recent seismological data and seismic engineering, and (c) the enhancement of seismic motions used in nuclear design by the findings of most recent geological studies. The primary goal of this Summary Report is to extract from the wealth of information presented and discussed during the three workshops the seismic information most relevant to current nuclear practice and, thus, the positions/recommended to a national regulatory body such as the U. S. Nuclear Regulatory Commission (USNRC). This information will be viewed on the bases of: (a) it's potential in challenging the current practice and understanding of the earthquake input side of the safety equation, and (b) its contribution towards the ever refined nuclear codes and practices from a regulatory standpoint.

The first of three workshops, hosted by the USNRC and held in 1999 at Brookhaven National Laboratory (BNL) focused its attention on the engineering characterisation of the seismic input and in particular on the aspects that influence the establishment of an appropriate input at a given site. These included: (a) understanding of the seismological parameters associated with a site or a region including elements of probabilistic hazard analysis as well as applicability and maturity of numerical techniques that help bridge the gap in regions of limited data or low seismicity, (b) the dominant effect of the local site conditions on the determination of the seismic input and in particular the correlation between the site effects from rock sites or regions to those of soil sites, and (c) characterisation of the seismic input at a site both from deterministic and probabilistic standpoints including attempts to validate the assumptions used to characterise seismic inputs through simulation of observations on actual structures. A key element of the proceedings of the first workshop was the regulatory view on the enhanced understanding in the above three areas and the way this will, or should, influence the revision of standards.

The second workshop hosted by the Turkiye Atom Enerjisi Kurumu, TAEK (Turkish Atomic Energy Agency) and held in Istanbul, Turkey in 2002, focused attention on the link between seismic data and earthquake engineering and analysis procedures used to evaluate the response of nuclear structures. The delineation of recorded data with the help of seismologists and the extraction of the dominant features that will feed/support the engineering analysis of a local site that includes a nuclear structure of interest were key elements of the proceedings. Special attention was given to a class of earthquakes, Near-Field Earthquakes (NFEs) that continue to puzzle the earthquake community for its wide variability in damage effects on structures. The understanding of the underlying mechanisms for these earthquakes that have generally been excluded from rigorous analysis or even consideration by the regulatory codes on the basis of low magnitude was considered important and recommendations for further study on this topic were made. Emphasis was also placed on the applicability or direct use of seismic motions generated by the seismological side of the equation in estimating structural damage and on the potential for incorporating such approach into regulatory safety guides.

The third workshop, hosted by the Japanese National Research Institute for Earth Sciences and Disaster Prevention (NIED), was held at NIED in Tsukuba, Japan in 2004. While the different aspects and focus areas of the two previous workshops were still discussed, at this workshop attention was placed on the most recent deep geological studies of source characterisation, fault structure and fault capability, and the way the recent findings influence the definition of seismic input. Particular attention was paid to the characterisation of asperities and especially to ways of establishing the link between asperities and strong motions. The need for deep borehole research, including technical guidelines for optimisation of such undertaking, was emphasised during the proceedings. To address the current state of nuclear engineering practice and its emphasis on facility seismic re-evaluation, the workshop also focused on the regulatory aspects of the most recent developments in geophysical research including elements of probabilistic seismic hazard analysis and treatment of uncertainties. Recent advances in earthquake engineering analysis of structures, both experimental and numerical, and the potential for adopting non-linear considerations in the future design were explored.

In this report, the thrusts and findings of each workshop will be summarised separately and presented in different chapters. However, since several key elements were common to all three workshops (such as regulatory considerations of scientific progress in the different fields and implications on earthquake engineering design practice) a section will be dedicated in addressing the progress in these fields over the time span of the three workshops.

The last section of this report summarises the regulatory impact of these complimentary seismic fields based on the progress and new findings. In particular, the need for an enhanced role for probabilistic models and methods within the framework of regulatory guidelines is discussed. Also, discussed is the potential for allowing non-linearities to be considered in nuclear seismic design by relying on complex, three-dimensional modelling capabilities and analysis aided by increased computing capacity. Further, the need for large-scale experimental and field studies that provide a common platform for seismologists and earthquake engineers to address seismic problems affecting nuclear facilities is addressed.

1. INTRODUCTION

A series of three international Workshops were held between 1999 and 2004 to bring together the advancements in seismology and earthquake engineering that have been realised in recent years in a forum where the link between the two complimentary aspects of the seismic issue could be established for better defining seismic hazard and seismic input to a real facility. These workshops attempted to closely examine and discuss progress in three key areas that potentially have the most influence in the field of seismic safety of nuclear installations, namely: (1) the engineering characterisation of seismic input, (2) the relation between seismological data and seismic engineering, and (3) the incorporation of most recent data from geological/geophysical studies into the determination of seismic input motions for nuclear facilities. While each workshop had a clearly defined main thrust and seismic topic, inevitably, because of the close connection between the various fields, several important topics were common to all three workshops. Primarily these common topics addressed the regulatory implications and the current seismic engineering practice.

The first workshop was organised by the U.S. Nuclear Regulatory Commission (USNRC) and held by Brookhaven National Laboratory (BNL) in November 1999 [Ref. 1]. The primary objective of the workshop was the engineering characterisation of the seismic input based on new seismological models. These models attempt to re-examine the seismic hazards at nuclear plant sites on the basis of: (a) detailed assessment of fault systems and their capabilities, (b) improved models of seismic spectra generation especially for regions of low seismicity by relying on information from earthquake-rich regions, (c) implementation of uncertainties in source characterisation and propagation, and (d) earthquake observations. The trend of seismic input characterisation seen at the time in the US, Japan and Europe were presented through the contents of this section of the proceedings. Along with the seismological considerations, the contribution of site characteristics and site response toward the determination of the appropriate seismic input at a given nuclear facility was discussed. Specifically, site response evaluations based on observed data from various tests sites with down-hole seismic array data were presented as well as observations of local amplification effects during actual earthquakes. The validity of simulation models for site response and motion amplification was tested against the actual earthquake data and the test site data. These efforts provided a glimpse of the maturity and capability of the seismic simulation field that is linked to the engineering rather than just "seismological" characterisation of the seismic input. In addition, research studies estimating site response factors, establishing the relation between uniform hazard response spectra on soil and on rock in assessing site-specific response and the motions in deep soil sites due to near-by earthquakes contributed to the establishment of the current state (at the time) of site response. The trend of incorporating non-linear effects in assessing site response, either from soil characterisation and its liquefaction potential or from source and wave propagation characteristics, was also presented. While the seismological and site response considerations provided the state and maturity of these two important fields towards the characterisation of input motion, the "engineering" characterisation of ground motion formed the primary thrust of the proceedings. This section included both deterministic and probabilistic characterisation of ground motions as considerations of risk-consistent spectra. Worth mentioning is the initiation of discussion about near-field earthquakes and its implication on the seismic design practices. As will be discussed later in the report, "near-field" earthquakes have been generally ignored by seismic codes and practices due to their low magnitude (< 5.5 M). The regulatory considerations, i.e., position of entities like the International Atomic Energy Agency (IAEA) and USNRC on the developments in the areas covered by the workshop and the potential adoption of findings into the regulations, were discussed by focussing on the fact that revisions to the regulations and standards need to be adopted to accommodate re-evaluation of existing nuclear plants or siting of new ones. This need stems from the better understanding of the mechanisms, the supporting data, the new simulation models and not least the need to introduce risk as well as probabilistic treatment into the overall characterisation. The primary conclusions of this workshop were that: (a) there has been significant improvement in the understanding of the mechanisms of earthquakes and enrichment of the observation database and thus the codes and regulations must incorporate these findings, (b) emphasis needs to be placed on probabilistic seismic hazard analysis and added to the deterministic approaches, and (c) resulting from both observations and progress in the area of site response, site-specific response spectra and/or uniform hazard spectra may form the basis for the revised engineering practice.

The second workshop in the series was hosted by Turkiye Atomic Enerjisi Kurumu (TAEK) and held in Istanbul, Turkey in October of 2002 [Ref. 2]. It had as a primary objective the establishment of the important link between the seismological data and seismic engineering. While the establishment of the above link was the central idea, several other areas of interest, such as damaging capacity of seismic motions, characterisation of seismic input motions based on seismological approaches but aiming to provide the final product in a form appropriate for earthquake engineering analysis, and the regulatory implications of the advancements made in these two preceding topics. The damaging capacity of seismic motions, re-examined and discussed based on recent very damaging earthquakes such as the Kocaeli earthquake near Istanbul, focused on the near-field or near-source earthquakes. These types of earthquakes, discussion of which were initiated during the first workshop proceedings, have been receiving increased attention in recent years, especially by the earthquake-engineering field. The reason behind the renewed interest is the uncertainty that surrounds the damageability of these ground motions that typically exhibit a pulse-type structure in their signal (what puzzles seismologists is the fact that the pulse-structure is not always present leading to the continuation of the debate for characterising these earthquakes). On the basis that these ground motions are the result of activity on faults in the vicinity of a nuclear facility that are capable of producing earthquakes of magnitude > 5.5 M (otherwise the nuclear facility would not have been sited near a fault that is capable of producing earthquakes of magnitudes > 5.5 M), these motions and their accompanying damageability to the nuclear facilities have generally been ignored. As will be discussed later in the report, the renewed interest has materialised in the form of a closer examination of the database of these earthquakes that fit the general characterisation of "near-field", and in the form of specific experiments aiming to compare the structural response and damage with the damaging capacity of "far-field" earthquakes that form the basis of nuclear seismic engineering practice to-date.

Progress in the area of deducing seismic input motions for nuclear design purposes was reported during the proceedings. Specifically, results of several studies prompted by the most recent damaging earthquake of Kocaeli, Turkey, aiming to reconstruct the strong motion part of the signal were presented. As a general observation, the feeling amongst the research teams analysing this very damaging earthquake, was that the lack of sufficient recording stations along a well-established fault resulted in the loss of the opportunity to unravel the nature of these complex and catastrophic earthquakes. Several research studies focussed on the generation of synthetic strong earthquake ground motions either using composite source models or inversion techniques. Of particular interest is the attempt to establish the characteristics of three-dimensional strong ground motions through a combination of analytical tools that describe the correlation between components and an actual earthquake database that exhibit three-directional nature in the strong-motion part of the signals. The primary goal is the establishment of well-defined strong-motion input that can be used in actual testing of structures to assess the damage potential. In addition, and in an effort to establish input motions that reflect new information on the source and path characterisation, local site response and effects of soil type, research focusing in the establishment of a well-defined methodology to produce hazard-consistent free-field motions at a site was presented. Further, generation of response spectra for design purpose of stiff structures on rock sites (a combination that covers the bulk of nuclear facilities) were discussed.

The regulatory aspects of the recent research in the areas of: (a) seismic hazard analysis (especially for zones of diffused seismicity), (b) the development of risk-informed design basis earthquake (DBE), (c) improvement of guidelines and of nuclear engineering standards, and (d) in-plant instrumentation were discussed. As in the first workshop, the main driver for incorporating both the experience accumulated over the years of operation as well the progress in several seismic-safety related fields into the guidelines and practice is the need for re-evaluation of existing nuclear facilities. The connection between the lessons learned from dedicated experiments that explore the damaging capacity of earthquakes on different types of test structures and the current state of seismic engineering practice was also explored. It should be pointed out that the general feeling surrounding the implementation of significant progress made in the areas of establishing more site-specific seismic-input and the understanding of structural damage is that the nuclear engineering community has fallen behind in adopting and utilising such progress and adopting it in its codes and regulations. For many years the nuclear engineering community has been the leader of this field.

The third workshop was hosted by the Japanese National Research Institute for Earth Sciences and Disaster Prevention (NIED) and was held at NIED in Tsukuba, Japan in 2004 [Ref. 3]. In addition to covering topics also discussed in the two previous workshops such as site response, probabilistic hazard approaches, earthquake damage potential, etc., it focused most of its attention on the most recent deep geological studies on source characterisation, fault structure and fault capability and the way the these studies might influence the definition of seismic input for seismic re-evaluation or design. Particular attention was paid on the characterisation of asperities and especially in ways of establishing the link between asperities and strong motions. As a phase in understanding the role of asperities in earthquake mechanics, locating them along faults, through advanced large-scale imaging techniques, will provide an excellent tool for predicting earthquake occurrence, but the uncertainty level in establishing the controlling parameters is still high. The synergy of exploratory field data, inversion techniques and validated simulation models on the basis of real measurements can help bridge the gap and reduce uncertainty. Therefore, the need for deep borehole research, including technical guidelines for optimisation of such undertaking, is paramount and was emphasised during the proceedings.

To address the current state of nuclear engineering practice and its emphasis on re-evaluation of seismic capacity, the workshop also focused a portion of its attention on the regulatory aspects of the most recent developments in geophysical research including elements of probabilistic seismic hazard analysis and treatment of uncertainties. Recent advances in both experimental and numerical earthquake engineering analysis of structures and the potential for adopting non-linear considerations in the future design were explored. Emphasis was placed on the results of several experiments and the ability to “match” the structural behaviour through numerical methods.

Seismic safety considerations, including defence-in-depth, recognition of uncertainties in seismic hazards, and the use of simulation tools to evaluate the response of actual plants to actual recordings were discussed.

As in the two previous workshops, the regulatory considerations centred on probabilistic seismic hazard analysis, the treatment of uncertainties and the need for upgrading the regulatory guidance to reflect both the recent findings and also the need for seismic re-evaluation of existing NPPs.

While the three workshops were held with a different main theme in mind for each, there has been a lot of commonality in the topics that touch upon. The common thread included: (a) the characterisation of the seismic input, (b) site effects, (c) seismic engineering design, (d) experiments and benchmarking of simulations, (e) regulatory aspects, and (f) the challenges that progress in the various seismic fields poses in the revising/upgrading of the regulations and seismic engineering practice. This commonality in topics provides an excellent basis to track progress in these fields over the span of approximately five years, the time span of these workshops.

In preparing the summary of these three workshops, an emphasis is placed on the impact that all these developments in geological/geophysical studies, structural damage tests and advanced numerical treatments have on the regulatory aspect and the need to implement them in the regulations and seismic engineering practice. Some of these findings challenge the established concepts of seismic design especially in the areas of: (a) accepting and dealing with non-linearities in nuclear systems, (b) probabilistic seismic hazards, (c) risk-informed methodology, (d) site-specific spectra, (e) description of ground motions from scenario-type earthquakes, and (f) acceptance/treatment of uncertainty. The summary and the deduced recommendations are included in a separate chapter at the end of this report.

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2. ENGINEERING CHARACTERISATION OF SEISMIC INPUT

The workshop, organised by the USNRC and held by Brookhaven National Laboratory in the Autumn of 1999, brought together in a single forum seismologists and earthquake engineers. The workshop was aimed at establishing an accepted characterisation of seismic input that better addresses the engineering need in the analysis and design of nuclear systems. The "re-visiting" of the seismic input is primarily influenced by progress in a variety of fields such as seismology (fault mechanisms, path, and attenuation), better understanding of the local site effects and the refinement of the seismic response methods assisted by the advancements in numerical methods.

The workshop proceedings covered four key areas, namely:

- regulatory status and trends,
- progress in seismological research relevant to the nuclear systems,
- progress in the understanding of local site response and its implications,
- engineering characterisation of the seismic input and its potential influence on seismic design practices.

Regulatory trends in the US, Japan, UK, Russia and the IAEA were presented during the proceedings.

During this particular period the IAEA has undertaken the enormous task of generating seismic safety guidelines that will provide the agency with a baseline tool for siting of new nuclear plants as well as re-evaluation of existing plants with diverse designs. The IAEA activities encompasses the following areas: (a) concept of "low seismicity" regions, (b) compilation of geological and seismological database, (c) seismotectonic models and sources, (d) levels of design basis ground motion, (e) deterministic versus probabilistic hazard analysis, and (f) response spectra. In the process, and with the need to re-evaluate a number of nuclear plants in Eastern Europe and other parts of the world, emphasis was placed on the ability of the regulatory guides to be widely applicable and in particular be able to address the re-evaluation of existing nuclear power plants. The evolution of the IAEA guidelines and in particular the expert panel review is still an ongoing process.

The USNRC perspective on "**Design Ground Motion**" is linked to the amended regulations brought about in an effort to update the criteria for nuclear plant siting, applicable to new plant applications received in 1997 and thereafter. A key element forcing the changes was the need to include probabilistic seismic hazard concepts in conjunction with the deterministic hazards required in the 10 CFR 100. In particular, the large uncertainties in seismic sources, earthquake magnitude and ground motion estimates were not taken into account in the original rule, Appendix A to 10 CFR Part 100. Revisions in the rules and guidelines include both seismological and site response considerations. The seismological side of the revisions include: (a) a detailed procedure encompassing both rock and non-rock sites for geologic/seismic siting, and (b) the target exceedance probability or reference probability (RP) as the key parameter in implementing a probabilistic method. This probability was established by considering the design basis of the 35 most recently licensed plants in the central-eastern US (CEUS). (This material describes R.G. 1.165, *Identification and Characterisation of Seismic Sources and Determination of Safe Shutdown Earthquake ground Motion,* which is being complimented by R.G. 1.208, *A Performance-Based Approach to Define* *the Site-Specific Earthquake Ground Motion*.) Revisions to design response spectra aimed to develop state-of-the-art recommendations on the design ground motions link the current state of knowledge in seismological aspects and the nuclear engineering needs. The NRC at that time had undertaken a serious effort to develop up-to-date seismic design spectra and aimed to: (1) update the standardised design spectra by including effects of magnitude, tectonic condition, distance and site, (2) assemble a database of strong motion records appropriate for use in seismic design analyses, (3) devise procedures for scaling of ground motions to consistent spectra, (4) devise an appropriate methodology for performing site response analysis, and (5) explore ways to derive design spectra that provide consistency in risk assessment.

The Japanese perspective on the need to re-assess regulatory and seismic design procedures is centred around the results of two comprehensive studies undertaken under the overall objective of "Siting Reliability Study" linked to the design of nuclear power plants. The two studies, *Evaluation Methods for Seismic Wave Propagation Characteristics* and *Evaluation Methods for Strong Ground Motion in the Near-Field Region* were initiated in 1994 and 1998 respectively. Prompted by observations of earthquakes such as the Kobe Earthquake where directivity and asperity characteristics, along with the geological structure are dominant and are necessary factors to be estimated in order to simulate the destructive nature of earthquakes, it became apparent that more research work needs to be done on the seismological side of the equation.

The Seismic Wave Propagation Characteristics study, in an effort to validate what is defined as design basis ground motion, focused on:

- investigating of soil/rock profiles down to bedrock carrying the seismic waves through extensive geophysical/laboratory studies,
- installing vertical accelerometer arrays at boreholes down to seismic bedrock,
- evaluating different methods of propagating waves from the bedrock to rock outcrop while utilising collected data.

The very destructive near-field nature of the Kobe Earthquake prompted the study of Strong Motion in the Near-field which focused on:

- available methods geared specifically to near-field strong motions,
- examination of previous earthquakes and their near-field strong motion characteristics,
- analysis of strong motion records in the near-field rock outcrop while correlating them to various fault models.

Upon completion of these studies, it is expected that recommendations for revision to the procedures used in establishing the design basis earthquake ground motions S_1 and S_2 will result.

The evolution of the regulatory guidelines in the UK for development of ground response spectra to be used both for design and re-evaluation were also presented. The database for developing such spectra, given the absence of strong motion data in the UK, needs to be "imported" by records in other parts of the globe and therefore they cannot match exactly the geo-tectonic conditions as well as attenuations. However, efforts have been undertaken to revise the spectra so they can be used for both design and re-evaluation of existing nuclear plants. The approach adopted in the UK is in line with what IAEA is trying to accomplish with the seismic guidelines.

Efforts undertaken in Russia to revise the three governing documents on nuclear plant designs, namely: (1) Standards of Seismic Stability Design of Nuclear Power Plants, (2) Location of Nuclear Power Plants

Fundamental Safety Criteria and Requirements, and (3) Definition of Initial Seismic Ground Fluctuations for Design Basis Safety Guide where presented. Emphasis is placed on the introduction of probabilistic safety analysis including seismic PSA to augment the currently deterministic methodologies in the codes.

The seismological considerations section of the workshop focused on:

(a) Estimation of ground motions caused by active faults as well as the deduction of the **extreme design** earthquake.

(b) Addressing of uncertainties in characterising seismic sources for use in PSHA studies as well as uncertainties associated with ground motion prediction on the basis of numerical techniques.

(c) Models and methodologies that can provide ground motion estimates in regions with very limited strong-motion data records.

(d) Methodologies for developing design response spectral shapes for different regions and different soil conditions (soil and rock).

(e) Efforts to quantify hazards at nuclear plant sites through trial analyses.

(f) Efforts characterising seismic input over wide areas based on the use of actual records that allow extraction of key earthquake parameters and the use of simulation tools to create the wide area maps.

The estimation of ground motions caused by active faults mentioned in the above list relies on the numerical treatment/models of the processes taking place during fault rupture and propagation. The mechanisms for generating strong motions include the introduction of asperities in the source model and the use of Green's functions that link the source with the site. The use of well-mapped faults and the wealth of recordings near the "source" during earthquakes along these faults, such as the Kobe and Chi-chi earthquakes, provide an excellent base to compare recorded with simulated strong motion data and allow the refinement of these prediction models.

Emphasis was placed on the site response and its contribution toward the ground motion estimation. A wealth of data, primarily from downhole array data as well as re-evaluation of existing databases through improved models of seismic site response and from benchmarking of simulation models on recent earthquakes, had become available by the time of the workshop. In addition, advancements in computational methods allowing the description and treatment of 3-D, complex sites made it possible to explore the non-linear nature of some of the mechanisms associated with site response.

The site response session included an overview of the processes used to-date, including 1-D treatment of the site, implementation of non-linear behaviour, modulus reduction and damping curves and variability effects of key properties, and highlighted potential problem areas that still need careful considerations. It was assessed that the simple 1-D approach, supported by sufficient information on the site conditions can capture the principal magnitudes and frequencies of the response but only for horizontal motions. Modifications to the site response factors contained in NEHRP97 [Ref. 4] for certain soil/bedrock conditions were deduced on the basis of extensive site response analyses at the SRS site.

In an effort to develop site specific soil motions for engineering design, which reflected a degree of conservatism that is uniform across structural frequencies and to accommodate a degree of uncertainty in the controlling parameters such as source, path and site conditions, and achieving hazard-consistent soil spectra as a result, a comprehensive site response study was reported. Specifically, the study, in the context of probabilistic seismic hazard analysis, compared motions using rock outcrop UHS with site specific soil UHS. The analysis, via the suite of case studies performed, aimed to address two major issues associated with the use of rock outcrop UHS to deduce site-specific soil motions, namely: (1) the validation of procedures used to develop hazard-consistent soil spectra, and (2) the effect of baserock versus rock outcrop control motions on soil spectra. Through analysis of several deep profiles it was concluded that a conventional soil UHS can result in unrealistically large motions at high frequencies. On the other hand use of broadband rock UHS as control motions may under-predict high frequency motions.

Observations of very high amplification in the range of 4-7 Hz at various locations during the 1997 Umbria-Marhe earthquake led to a numerical investigation aiming to explain such effect and its damage potential on certain types of structures, by duplicating the amplification levels at locations with available recorded data. By implementing a 2-D numerical scheme, capable of reproducing amplifications in zones characterised by simple geometry, certain assessments were made, namely: (a) direction of waves is the most important parameter, and (b) the response in an alluvial valley may be twice as that in the rock outcrop. These assessments however are deduced from a rather simple model. Complexity in the soil structure and uncertainty in the properties need to be dealt with enhanced, 3-D computational tools.

A case-study resembling near-field effects has been presented. In particular, the motions at a deep soil site neighbouring the source location of a large magnitude earthquake were estimated by utilising equivalent linear procedures for the soil profile for the site of interest and comparing the resulting spectral shapes with those that would have resulted at the site from the Imperial Valley and Northridge earthquakes. The important conclusion that came out of this study is that equivalent linear procedures perform quite well if the level of shaking does not exceed 0.75 g or the maximum strain in the deposit 0.5 %. At higher input accelerations and thus induced strains, the accelerations at the surface could deviate significantly from the true value. More research work that ties “equivalent” characterisation of deposits to actual observations is needed to ensure the applicability of the methodology to a wider strain range.

An extensive down-hole array at Borrego Valley, CA provided the basis for comprehensive site response observation and analysis. Specifically, extensive instrumentation (vertical and horizontal array) to observe earthquake ground motions from bedrock to soil surface was installed in a fault zone adjacent to San Andreas Fault. The study is comprised of geological/geophysical evaluation of the site, recording of seismic events including micro-tremors and site response analyses. 1-D, 2-D and 3-D geophysical studies were conducted to characterise the subsurface. Using 1-D, 2-D and 3-D models site amplifications were estimated and compared with the actual measurements. The goal was to assess the appropriateness of the numerical schemes to capture the key parameters associated with the ground motion. Based on the extensive record of micro-tremors recorded H/V ratios were deduced and compared to those estimated directly from the geotechnical data. In addition, wave propagation in the valley was simulated on the basis of the 3-D visco-elastic model as well as with much simpler 2-D and even 1-D models. The important finding is that 1-D formulation is “generally” in good agreement with the observations in terms of motion amplification. However, 1-D and even 2-D models seriously under-predict the third acceleration component. 3-D models on the other hand, while computationally expensive, can capture key features of the wave propagation and its interaction with the walls of the basin.

A similar study utilising down-hole array data focussed attention on the effects that the near-surface geology has on the strong motion. It has long been assumed that the near-surface geology (a few tens of meters) is a dominant factor in controlling the amplitude of strong motions and the damage patterns of large earthquakes. The study relied on linear wave propagation models in an attempt to replicate the amplification and attenuation of small to moderate earthquakes while taking into account the geotechnical characterisation of the site. The calibration of the linear wave propagation model was deemed a crucial step towards the generation of non-linear model that will permit the prediction of the site response during large earthquakes inducing large strains. A different study that utilised the down-hole data used to calibrate the linear model, explored the non-linear effects of the site response that are evident in the accelerograms. The primary goals of this study were: (a) the understanding of the nature of the non-linear effects (i.e., pore pressure built-up), and (b) the validity and calibration of a 1-D non-linear model that captures the site motion at different depths. Comparison between non-linear and "equivalent linear" as to how closely they can predict ground motion showed that the "equivalent-linear" model misses important features of the site response when strains are large. This is a very important finding given the extensive use of "equivalent-linear" models. Therefore, a "threshold" value of soil strain needs to be established beyond which the non-linear behaviour can only be described or captured with non-linear models.

The evolution of engineering characterisation of ground motion and its effect of nuclear design practice session of the workshop covered a variety of topics which address:

a) The need or appropriateness of probabilistic or risk-based methodologies in arriving at design spectra.
b) New needs in the design codes to account for new classes of earthquakes that were traditionally excluded from the spectra derivation process (such as near-field earthquakes).
c) The value of large-scale tests involving realistic structures and site conditions in defining seismic input motions as well as observation of structural responses resulting from the choice of motions.

The value of purely deterministic approaches in generating synthetic accelerograms, which can be used in hazard assessments for regions with scarce data, was discussed. Specifically, by utilising the wealth of data in source, propagation, attenuation and site that have resulted from studies in different parts of the world, acceleration time histories can be deduced, deterministically, for areas with little seismic history. When this is accompanied by deterministic seismic zoning, then hazard assessments for urban sites can be performed without waiting for large event to occur in that area. The use of earthquake parameters from a large database, although not related to the region of interest, will ensure that the destructive characteristics of these generated earthquake signals will be inherent to the hazard evaluation process.

Methodologies that can lead to approximately risk-consistent seismic design spectra at a site by scaling UHS have been applied at several sites with different seismic hazard characteristics. The proposed methodologies exhibited consistency in establishing design spectra. Issues however still remain and are centred in the selection of annual frequencies and the mean UHS. Following resolution of the remaining issues, this very promising methodology can lead to implement-able design response spectra for a site based on purely probabilistic seismic hazard analysis and with consistency across the entire frequency range. The broadness of the Newmark-Hall spectra to assure that for design purposes adequate frequency bands is considered was also discussed.

Renewed interest in near-field earthquakes and their effects on nuclear structures has led to a series of tests which hope to extract the damageability of these ground motions. The ground motions have very strong directivity dependence, often exhibit a dominant pulse but have been classified as low magnitude (< 5.5 M) earthquakes. The specific tests were prompted by the French seismic code revision. (Extensive discussion on this subject is presented in the next chapter of this report.)

In an attempt to understand SSI effects and seismic input motions large-scale tests involving a 1/10-scale reactor building were conducted. The test model including soil was subjected to induced vibrations and naturally occurring earthquakes. Measurements of structural response as well as site response adjacent to the structure(s) were made. In addition, simulation attempts were made to validate models and processes used. The results of the various studies indicate that simulation of vibration tests produced satisfactory results as compared to the simulation of earthquakes. While great effort was dedicated in improving the soil model at the surrounding site, there is significant disagreement with the earthquake observations. This is a significant finding reconfirming both the complexity of actual earthquakes and the uncertainties that surround the evaluation of site properties. Given that the effort is ongoing with a series of tests planned, the data that will be generated will, hopefully, shed more light into the process and help calibrate simulation tools capable of capturing the SSI effects due to actual earthquakes. This will be a great step forward, especially because of the presence of a realistic structure, in characterising seismic input motions.

In summary, the workshop covered progress in: (a) the seismology and its link with ground motions applicable to nuclear engineering design, (b) site response studies (both theoretical/simulation-based and experimental including observations from large down-hole arrays), and (c) attempts to better characterise the ground motions (either deterministically or probabilistically/risk-based) and through large scale tests. In addition, revisions to design codes have prompted discussions on the near-field effects, a topic that was explored in greater depth during the two workshops that followed.

3. RELATIONS BETWEEN SEISMOLOGICAL DATA AND SEISMIC ENGINEERING

This workshop was organised by OECD/NEA and was hosted by the Turkish Atomic Energy Agency in Istanbul, Turkey in October of 2002. A key reason for the location of the workshop was the proximity of the venue to the location of the devastating Kocaeli earthquake of 1999. Therefore, the choice of venue provided an opportunity to the workshop participants to visit and observe the devastated areas first hand.

The second workshop built on the progress in the field reported during the first workshop where seismological and site response issues were addressed in order to deduce the "engineering" characterisation of seismic input as well as on the experience drawn from most recent strong earthquakes. This workshop focused on (a) the damaging capacity of seismic motions and in particular near-field earthquakes, (b) generating seismic input motions for design purpose, and (c) the regulatory or design practice implications of the most recent assessment plus the re-examination of procedures. These included displacement-based approach and performance-based design and their potential use in nuclear engineering practice (primarily in the re-evaluation of nuclear-related structures). The above three areas were explored by taking into account recent observation and experimental data. As was the case in the first workshop, a primary objective was the establishment of communication between the seismological world and the engineering world aiming toward the characterisation of the seismic input for a nuclear facility, input that deals with uncertainties in the various elements of the process (source, path, site, etc.).

By addressing the applicability of "simplified" seismic evaluation procedures, such as displacement-based approaches or performance-based design which have started to enjoy visibility within the conventional design sector primarily for re-evaluation purposes, the use of time histories, non-linear design, etc., the meeting hoped to open a dialogue regarding the position of the nuclear design sector and therefore of the regulatory bodies. A current, but long-standing feeling has been that the nuclear industry, despite the wealth of observations, tests, and improvements in "realistic" modelling of complex systems/structures and in the "calibrated" simulation tools, has been very slow to adopt the necessary changes in the design practice to maintain pre-eminent position stature in the forefront of engineering design practice.

The understanding of the mechanisms of the near-field earthquakes, of the seismic input motions associated with them, and of their damage potential on structures was discussed extensively during this workshop. As mentioned earlier in the report, re-surfacing of the near-field earthquake issue occurred during the first workshop. Key reasons behind the renewed interest were the severe damage observed in recent earthquakes that occurred near urban areas and the interest of some regulatory codes to include the effects of near-field earthquakes into their provisions. In particular, the French code is undergoing revisions and in order to establish the damage potential of this type of strong motions to lightly reinforced structures, a comprehensive test (CAMUS) has been undertaken. The test aimed to assess the damage potential of near-field earthquakes (earthquakes that most often, but not always, exhibit a dominant pulse in the strong motion part of the acceleration record) as compared to far-field earthquakes that typically make up the seismic hazards. While there is still debate as what exactly characterises a near-field earthquake, nevertheless the experimental effort undertaken, which involved the shaking of multi-storey lightly reinforced double shear wall, allowed not only damage potential assessments to be derived but also generate a wealth of structural response data based on which traditional structural response evaluation models can be calibrated.

The following represent some of the objectives of the undertaken experimental effort that cover a wide range of topics with links to nuclear engineering design:

- Numerical methods and constitutive models, particularly for reinforced concrete, addressing the post-linear state of a structure and predicting the damage induced on a complex structure due to earthquake loading.
- Suitability of non-linear static analyses in analysing complex structures.
- Maturity of displacement-based approaches and their prospect in being adopted by the nuclear engineering practice, or in other words, play a larger role than the present performance-based criteria established for non-nuclear facilities.
- Assessment of Spectral Analysis methods and identification of the level of conservatism introduced by their adaptation into the analysis of a structure.
- Maturity of non-linear dynamic analysis approaches in dealing with large, complex structures, especially reinforced concrete structures, and their potential integration into the nuclear engineering practice guidelines.
- Near-field earthquake damage potential assessment. By introducing different types of motions, near-field and far-field-type earthquake motions, provided probably the first opportunity to directly compare the damage induced by the different motions.

While the term near-field earthquake implies that the ground motion recording has been made in the vicinity of an active source, it is the fact that these ground motions contain distinct pulses in acceleration, velocity and displacement histories that characterise them in the conventional sense. However, as actual recordings have shown, it is the directivity focusing that is responsible for the appearance of the distinct or "killer" pulses. Specifically, for a strike-slip earthquake and fault rupture propagating toward a recording station, large values of ground velocity and displacement are possible in the direction normal to the fault. This stems from the coherent manner that long-period waves travel. Associated accelerations for such situations are not large for being controlled by short-period waves that are less coherent. Therefore, the consideration of such earthquakes in terms of acceleration only could be very misleading. Also, because of the dependence on the recording station location and the rupture propagation direction, a given or recorded earthquake may not be able to characterise the local seismicity and its effects on structures. In addition, the proximity to the source is not a controlling parameter in defining a near-field earthquake. For the nuclear industry and based on its interpretation, near-field earthquakes have been characterised as low magnitude earthquakes (< 5.5 M) and generated by faults in the vicinity of a nuclear facility that have deemed incapable of generating stronger motions and therefore incapable of inducing damage to the nuclear facility. Consequently, if a fault were capable of generating earthquakes of magnitude (> 5.5 M) then the site for the nuclear facility would have been excluded in the first place. Recent earthquakes, however, recorded near nuclear facilities (i.e. Japan) and improved characterisation of fault capacities have led to the re-evaluation of these ground motions as a potential seismic hazard.

Significant effort has been devoted over the last decade in addressing the damage capacity of near-field ground motion. Progress in this field was reported and was extensively discussed during the proceedings. In particular, the reporting on this subject covered the following areas:

- quantification of the effect of low magnitude, near-field earthquakes,
- seismic response of structures to near-field ground motion,
- damaging effects of near-field and far-field earthquakes on reinforced concrete shear walls,
- response of structures subjected to damaging pulse-type ground motion,
- effects of near-field ground motion on degrading systems,

- near-source strong motions of the 1999 Kocaeli earthquake,
- estimation of main shock from recorded aftershocks in the near-source of the Kocaeli earthquake.

Quantification of the low-magnitude, near-field effects was done through a statistical study that used a large strong motion database. The process focused on the damage induced by these earthquakes on reinforced concrete structures. The accelerograms in the database were characterised by local magnitude M and hypocentral distance. The statistical process revealed that near-field low magnitude earthquakes exhibit high peak ground accelerations and velocities at high frequencies with short duration Arias intensity. In assessing damage to RC structures, evidence is that the near-field earthquakes are less damaging than far-field, higher magnitude even when the dominant frequencies coincide with structural frequencies. The primary reason/explanation is that the high acceleration (occurring during the dominant pulse) induces plasticity effects on the structure causing lowering of the structural frequencies for the remainder of the event.

In an effort to compare response spectra of NFE records from recent events to the standard spectra used in the design of nuclear structures, a study was performed focusing on the response of structures. What the various analyses showed is that near-field earthquakes have more impact on the response of long-period (low-frequency) structures. This is an important feature when evaluating the need for including this type of earthquake in nuclear design. Nuclear facilities have frequencies in a higher range. However, given that acceleration may not be the best indicator of the potential to cause damage, but rather that the velocity pulse magnitude and duration of these records may be better indicators, the issue of NFEs being a "no, never mind" for nuclear facility design needs further evaluation. Also, given that the uniform hazard spectrum when used in design raises concerns for underestimating the seismic demand in the long period range, considerations of NFEs in the design, which have high seismic demand in the long period range, may help resolve the controversy. A different study also focusing on the damage potential of near-field earthquakes concluded that it is indeed the velocity, displacement and energy parameters that are the true indicators of the damage potential and similarly as above in the long period range. Further, as noted in numerous studies, it is the forward directivity that matters most.

To make the connection between the extensive damage to buildings observed in the 1999 Kocaeli earthquake and the ground motion that resulted during the event, studies were performed in an effort to reconstruct the strong motion of the main event using empirical Green's functions and aftershock recordings. The validity of the process that produced the synthesized strong motion record at the heavily damaged areas was confirmed by reproducing the strong motion accelerations at various record stations near the fault. A separate study aimed to also reconstruct the main shock using aftershock records and inversion techniques revealed that very strong accelerations were observed normal to the fault. The excessive accelerations observed are attributed to site amplification effects.

In the area of seismic input motions appropriate for design, the topics covered during the workshop included: (a) evaluation methods leading to design-basis earthquake, (b) generation of synthetic strong ground motions, and (c) probabilistic/stochastic models appropriate for the extraction of key parameters as well as hazard assessment.

In particular, studies that rely on earthquake observations using down-hole arrays and focusing on the two distinct aspects shown below have been launched:-

- Evaluation methods for seismic wave propagation, a study initiated in 1994 and using array data from the Kobe area and with major objective to verify currently used methods for evaluation ground motions on the basis of seismic wave propagation data.
- Evaluation methods of strong ground motion in the *near-field* region, a study relying on near-field strong motion data mainly from California.

Recent studies sponsored by the USNRC resulted in a set of recommendations for developing response spectra shapes and subsequently seismic ground motions for design and analysis of nuclear facilities. The methodology was based on rock site conditions (for both western and central/eastern US). Procedures that will lead to response spectra at soil sites and derived from rock site spectra have also been developed as part of this USNRC effort

To arrive at hazard-consistent free-field design spectra at a facility (in-structure design spectra generation is still under way), the recommended approach in this study incorporates:

- a probabilistic seismic hazard analysis for **rock site** conditions,
- a uniform hazard spectrum at an appropriate for nuclear facilities annual frequency of exceedance,
- de-aggregation of seismic hazard at 1 Hz and 10 Hz structural frequencies (while incorporating recommended spectral shapes into the PSHA attenuation model),
- scaling of spectral shapes to match the UHS amplitudes.

To link the hazard-consistent spectra to the design of a nuclear structure founded on rock, the UHS can be modified by a scale factor that ensures consistency in the frequency of component failure across a wide range of structural frequencies. To develop site-specific spectra for soil sites various options are recommended but with the commonality that the UHS rock spectra developed for the site are used as the starting point. In brief, these options include:

- use of rock UHS as the rock outcrop control motion (simplest approach),
- use of the de-aggregated spectra at 1 Hz and 10 Hz scaled to UHS as control motions,
- development of mean transfer functions through convolution or development of soil (rather than rock) UHS using site-specific soil attenuation models.

Along the same lines with the USNRC initiative above, an empirical method for evaluating response spectra and time-dependant features of both horizontal and vertical ground motions on the free-field of rock sites has been proposed. The uniqueness of this empirical approach relies on a matrix consisting of four (4) magnitudes and four (4) hypocentral distances at a control point in the seismic bedrock. The response spectra associated with different magnitude and hypocentral distance are determined by interpolation between values in the selected matrix. After establishing the control point spectra, the free-field spectra (rock) are deduced from horizontal and vertical wave amplification analysis. In exercising this method, of particular interest have been the studies on near-field or near-source effects and the identification of special correction factors that can be applied to the spectra generated by the proposed method in order to account for near-field effects. Attempts to match spectra from Kobe and Kocaeli earthquakes were made.

In assessing the damaging capacity of earthquakes, following observations from the recent damaging earthquakes, and their implications for the seismic engineering practice used to-date, results and observations from specific tests aiming to evaluate the damage resistance of structures (not necessarily nuclear structures) such as lightly reinforced, multi-storey, shear-wall structures or masonry infill frames were reported. The latter is prompted by the necessity to identify the connection between the reinforced concrete frame and the infill, non-structural wall typically an un-reinforced masonry panel. New evidence suggests that there is indeed a significant effect on the R/C frame, especially in its global response (torsional behaviour) as well as “local” interaction (exertion of shear and normal loads on the R/C frame members). While this issue, as mentioned above, is not as relevant to the nuclear design and practice but it affects conventional structures in many parts of the world experiencing strong earthquakes.

In addition, efforts relying on empirical models and damage observations on multi-storey structures during earthquakes have attempted to correlate the damage with earthquake controlling parameters which may not necessarily coincide with those assumed in practice to-date. A key finding, prompting recommendations for a change in the way structural damage is linked to earthquake key features, is that peak ground velocity rather than peak ground acceleration may be a more valid indicator. Research work focusing on the validation of empirical and/or analytical models and combined with further damage assessment on structures is needed before the seismic engineering practice can adopt these new indicators as guidance in the design of nuclear or even conventional facilities.

The evolution and trends in regulatory guidance resulting from recent seismological studies, experimental efforts, empirical/analytical model development, but primarily from earthquake observations and their effects on nuclear as well as conventional facilities, were also discussed. Key themes in the reporting from the various regulatory entities were the adoption, or not, of probabilistic hazard assessment procedures in establishing ground motion and/or design basis earthquakes for nuclear facilities. IAEA seismic safety guides, which are in the process of being revised, have adopted the position that PSHA approaches be adopted and guidance for linking PSHA to the development of uniform hazard response spectra. It should be pointed out that the development of response spectra in the seismic hazard analysis is treated separately from the response spectra in the seismic design guide (the former being linked to the NPP site and the latter to the resulting “local loads”). The reasoning behind the push in the revised IAEA guidance of probabilistic seismic hazards is the trend that exists in a number of the member states following IAEA guidelines for conducting external event PSAs. PSA studies, conducted during the time of the workshop for a number of existing NPPs, primarily in the former Soviet Union countries, as part of safety re-evaluation require seismic hazard curves which can extend to lower event frequencies per year were discussed during the workshop. Of interest to mention is the recommendation to examine paleoseismological data in a region of interest more carefully as it represents the link between historical seismology and neotectonic studies. Adaptation of the IAEA guidelines in member states that are undergoing safety re-evaluation of existing NPPs was also reported.

The possibility of the implementation of risk-informed design basis earthquake ground motions is being entertained in Japan through the modernisation of the Examination Guide for Seismic Design. What has prompted this discussion is the controversy surrounding the existing guidelines in defining the S_2 level earthquake (or design basis extreme earthquake) and the damage experienced by densely populated areas during the 1995 Kobe and 2000 Tottori-ken Seibu earthquakes. In particular, the S_2 earthquake is defined, according to the existing code, as a 6.5 magnitude earthquake at 10 Km hypocentral distance and resulting from a blind fault. This guideline has been applied to the design of all existing NPPs in Japan. The destructive nature of the “near-field” 1995 earthquake at Kobe as well as the 2000 Tottori-ken Seibu, which resulted from a previously unknown fault, has called into question the criteria used in establishing the S_2 earthquake for NPP design. The on-going revision process is considering the advancements made in recent years in seismology, geology and earthquake engineering to ensure seismic safety performance of NPPs from risk management standpoint. In particular, the revision process is considering the establishment of a site evaluation earthquake S_s to establish reactor safety by the plant seismic capacity based on criteria associated with high confidence low probability (HCLPF). It appears, however, that a number of sticky points exist before the application of the proposed probabilistic approaches apply to the Examination Guide, namely:

- limited understanding of earthquake occurrence to allow the determination of DBE through probabilistic methods,
- quantification of uncertainties and consequently risk stemming from (a) seismological/geological/site data, and (b) variability in the success of the functionality of safety systems.

The USNRC involvement in the evolution of seismic regulatory guidance has at this stage materialized in the form of recommendations (NUREG/CR-6728) on design ground motion spectra that are hazard and risk consistent [Ref. 5]. Recommendations for response spectra shapes and rock conditions have been generated for western and central/eastern U.S. Procedures through which spectral shapes for soil conditions, deduced from rock spectra derived for a given site, have also been identified and recommended for use.

4. SEISMIC INPUT MOTIONS INCORPORATING RECENT GEOLOGICAL STUDIES

This third workshop in the series of three was hosted by NIED in Tsukuba, Japan in November, 2004, focused considerable discussion and attention to the results of most recent deep geological studies aiming at seismic source characterisation, fault structure and fault capability and at assessing how these findings might influence the definition of seismic input for seismic re-evaluation or design [Ref. 3]. The regulatory implications to member countries, some of which are in the process of revising their guidelines, and the engineering considerations (stemming from either the findings of the deep explorations and their connection with the design input or from advancements within the practice that derive from the better understanding of damage mechanisms, structural response and the aiding of fast advancing numerical models) occupied the balance of discussions.

In a comprehensive overview of the state of knowledge of fault structures and their direct link to strong ground motions, observations from recent earthquakes (such as the 1999 Kocaeli, 1999 Chi-Chi and 2002 Denali) were presented along with results from field studies aimed at characterising the mechanics of special fault structures (such as the one near Corinth, Greece). Also, presented were closer examinations of the Parkfield and the Chuetsu, Niigata Earthquake. Specifically, it has been assessed that the 1999 and 2002 earthquakes accompanied by large surface slip exhibited weak ground motions at short and intermediate periods, reconfirming observations from previous earthquakes. These earlier earthquakes made the connection between earthquake asperities and strong ground motions. It has long been suspected that earthquakes with deep asperities induce stronger ground motions than those of shallow asperities. This is very significant given that the recent wave of fault explorations is aiming at asperity characterisation and therefore the implications are that these studies have to focus deeper into the fault to draw conclusions about the presence of asperities and their potential for strong motion generation.

Several studies have been recently launched in Japan aiming at the characterisation of asperities and their tendency to reform or be the source of subsequent events as well as the establishment of the link between asperities and strong motions. Specifically, studies based on double-difference tomography were conducted at the site of two large, shallow earthquakes. Based on the earthquake aftershocks, a detailed velocity structure near the fault plane was deduced. From the velocity mapping it was concluded that for both events large slip areas (or asperities) are distributed near high velocity pockets. This is significant because it provides a path toward the identification of locations along a fault where large slips can potentially occur by associating them with velocity distribution along the fault ahead of the occurrence. To address the same point, i.e. location and categorisation of asperities from seismicity pattern changes prior to large earthquakes, a field study involving a 20-year close monitoring of the micro-seismic activity in a seismic-prone zone was conducted. Key controlling parameters were revealed indicating the state of the “locked” zone. In particular, changes in the in the seismicity rate were observed as well slow “slipping” around the edge area. The study is attempting to correlate these observations resulting from background seismicity and to extract information on a potential asperity that could be the instigator of the next large slip on the fault. Also, reported was an ambitious geophysical study that involves a very deep (1000 m) borehole near an active fault with the goal of measuring initial stresses and observing crustal activity. The installation of the instrumentation had just been completed and therefore no long-term observation results were available at the time of the workshop. Realising the potential for large earthquake prediction along a known fault, studies adopted semi-empirical and analytical models which when validated against observations can be used to estimate asperity effective stresses for inland earthquakes generated by large strike-slip faults.

While considering that the understanding of asperity formation, locating them along faults through advancements in large-scale imaging techniques will provide an excellent tool of predicting earthquake occurrence. The uncertainty level in establishing the controlling parameters is still high. The synergy of exploratory field data, inversion techniques and simulation models validated on the basis of real measurements can help bridge the gap and reduce uncertainty. Therefore, the need for deep borehole research, including technical guidelines for optimisation of such undertaking, is paramount.

Also reported was the evolution of the regulatory positions in different agencies prompted by the experience and analysis of the recent earthquakes. The main theme, which has been common to all three workshops, is the maturity of probabilistic approaches and their slow implementation into the guidelines. IAEA in particular has been involved in a process of revising its guidelines (*Evaluation of Seismic Hazards for Nuclear Power Plants*) and has recommended increased emphasis in the probabilistic treatment of seismic hazard and in the use of paleo-seismological studies. The French seismic guidelines which are based on deterministic approaches have been recently modified to account for progress made in the fields of paleo-seismology and site effects. In Japan, a process has been initiated to assess what changes to the *Examination Guide for Aseismic Design of Nuclear Power Reactor Facilities* are necessary given the wealth of earthquake experience of the last twenty years and the advancements in both technology and analysis tools. A focal point in this process is the definition of seismic input motion for NPP design. Also, efforts are under way to generate hazard maps for the whole of Japan using two approaches, one probabilistic that involves frequency of occurrence of strong earthquakes, and the other deterministic based on approaches using scenario earthquakes.

In the field of seismic engineering an array of experimental studies on systems as well as simulation-based analyses were presented. Experimental efforts have been looking at:

- Obtaining real-time displacements of large structures and through the establishment storey drift ratios allow damage assessment of the structure by comparison with pre-determined threshold stages of progressive damage (process could be termed “structure health-monitoring”). The method has been implemented through a pilot study at a high-rise building.
- Experimental and simulated response of nuclear piping systems. The experimental side of the effort is performed on a shake table where simplified piping system is subjected to excitations. Simple piping elements are tested with displacement-controlled cyclic bending. The analytic models attempt to predict the structural degradation.
- A large-scale experiment was recently conducted at the European Test Site in Greece. The experiment aimed in assessing the effects of flexible support conditions to the global dynamic response of a structure (in the particular case a bridge pier). The secondary scope of the test was the validation of numerical simulations (i.e., dynamic analysis finite element codes) against a controlled test.

The theoretical/numerical efforts represented progress in the characterisation of input ground motions for sites with spatially variable soils and in understanding how such variability may affect soil-structure interaction. A process enabling the enveloping of combined uncertainties associated with the variability in the soil properties and in the input motion was identified. Also, presented were efforts to generate artificial time histories that are appropriate for non-linear seismic analysis of structures.

5. SUMMARY AND RECOMMENDATIONS

5.1 Workshop conclusions

The three workshops brought together earth scientists (seismologists, geologists, geotechnical engineers) and earthquake and structural engineers and launched an extensive discussion on all the components of seismic safety of nuclear facilities including seismology, site effects, and structural response. Advances in:

a) the characterisation of faults through geological studies and the fitting of data from existing databases into refined models,

b) detailed geophysical/geotechnical analyses of sites in conjunction with earthquake monitoring and tests,

c) significant improvements in modelling and simulation of structural response as well as large-scale tests.

have highlighted the need to re-examine accepted seismic design practice and to implement ways to improve safety. During the course of the three workshops the regulatory aspects and implications of the recent developments in the various components of seismic safety (seismic input, probabilistic approaches, etc.) were identified along with the current status and trends of the different regulators regarding implementation of new findings into the safety guidelines.

While each workshop had a particular focus area (such as the engineering characterisation of seismic input, the relation between seismological data and seismic engineering, or seismic input motions incorporating recent geological studies), the presentations and deliberations covered a variety of topics allowing for a degree of overlap among the workshops and in the regulatory implications of the studies reported. Such overlap provided the basis for observing progress or trends in particular areas, especially trends in the evolution of regulatory guidelines, within the timeframe encompassed by the three workshops.

A comprehensive review of the issues discussed during these workshops and of the recommendations offered by the three involved groups (seismologists, earthquake engineers and regulators) to resolve outstanding seismic questions, has led to the following conclusions.

The extensive research and its results, which at times challenge the accepted philosophy of the current regulatory guides and earthquake engineering practice, need to influence the revisions of these guidelines in ways that include probabilistic seismic hazard analysis and assessment along with the traditional deterministic approaches. Deterministic models that have been used to establish extreme level earthquakes (i.e. S_2 earthquake for analysis of NPPs in Japan or SSE in the United States) may not account for the set of uncertainties surrounding a single deterministic scenario. On-going revisions of seismic standards are either recommending greater involvement of probabilistic measures in the process (e.g., at IAEA where a significant portion of the focus is on the safety re-evaluation of existing NPPs or on sites where a PSHA is needed for PSA analyses) or are entertaining the greater involvement of probabilistic measures (i.e. Japan) with reservations stemming from the uncertainties inherent to the process or with earthquake occurrence, NPP safety system functionality, or the establishment of safety goals.

Ongoing studies on seismic response of sites employing extensive down-hole arrays and/or deep drilling into fault lines to determine:

a) the role of asperities in strong ground motion generation, as well as the mechanism of their evolution,
b) the connection between asperities and the next fault slip,
c) initial fault stresses,
d) the presence/capability of buried faults.

these will all help shed light onto the uncertainties that continue to impede the full acceptance of probabilistic measures into practice.

The fact that it is the input motion on which the design or re-evaluation of an NPP will be based or judged is central to the seismic safety process. The identification of controlling earthquake parameters (or NPP site-specific ground motion) and their coupling with the structural characteristics still remains an issue of continuing debate. Experimental efforts on structures subjected to ground motion or field tests involving typical NPP structures on sites experiencing natural earthquakes and/or induced vibrations have identified features that are not accounted for in the current practice. In particular, under question are:

a) the use of peak accelerations in the earthquake record as the key indicator for structural damage or its replacement by indicators based on the peak velocity and velocity pulse duration as well as energy in the earthquake signal,
b) the appropriateness of response spectra to represent the input for the design of nuclear structures,
e) the role of non-linear effects in the structural response and damage assessment.

The wealth of research efforts dedicated to ground motion simulation and to benchmarking of the sophisticated models that deal with either NPP site response, structural response indicate that the field has reached a significant level of maturity. This level of maturity may be such to allow the design process to move to the next level where accounting for or allowing of non-linear behaviour is acceptable. In a recent report on an IAEA sponsored research project [Ref. 6], the capability of these sophisticated new models to incorporate complex constitutive relations and geometries was demonstrated. The fact remains, however, that the significant progress in the modelling/simulation field, which has taken advantage of the explosion in computing capacity and sophistication in recent years, has been instigated by the conventional rather than the nuclear design sector.

5.2 Workshop recommendations

Most recent catastrophic earthquakes appear not to follow anticipated behaviour that has influenced the seismic design philosophy. In particular, near-field effects and the connection of vertical motions with structural damage are in need of further examination. A flurry of activity to re-evaluate the damage potential of low magnitude (< 5.5 M) near-field earthquakes (NFE) has been in progress since introduced during the first workshop. As noted earlier in the report, these low magnitude earthquakes were played down or de-emphasised during NPP siting considerations on the basis that the nearby faults that produce them were thought to be incapable of inducing larger magnitude earthquakes. However, further examination into this type of earthquake revealed that it may not be the magnitude alone that defines their damage potential but their directivity accompanied by the presence of a dominant, low frequency pulse in the velocity trace of the motion. Experiments on structures using near-field type inputs [e.g., CAMUS shaking table test performed by CEA and described in Ref. 6] attempted to assess the damageability of these earthquakes and compare them to damage caused by their far-field counterparts that are used in the seismic design guidelines. The consensus of several analysts attempting to draw conclusions from the experiment is that of lesser damage potential, more research that looks into the response of other types of structures to these classes of earthquakes is needed.

Further, there is need for re-examination of the role of vertical motions on structures. Closer examination of damage caused by the recent catastrophic earthquakes and of the delineation of the individual contributions to damage from horizontal and vertical motion is paramount. There are several field studies based on extensive down-hole arrays that are focusing in on the H/V ratios. The findings of these field studies are essential for the development of widely accepted vertical site response methodologies. Field studies, presented at the workshops and discussed earlier in the report, point out that equivalent non-linear models may not be applicable (an approach that has been used extensively) and there is need for implementation of purely non-linear models with non-linear properties deduced from laboratory experiments. On top of that, 3-D models are the only reliable way to proceed. The now available computing capacity can make that possible.

Risk-informed or performance-based design approaches warrant further attention and consideration as they are implemented in upcoming revisions of regulatory guidelines. The seismological community, by relying on the wealth of new field data and improved models, has made great strides in the area of probabilistic seismic hazard assessment. These advancements have resulted in both epistemic uncertainty reduction and is seismic micro-zonation that can influence the definition of the seismic input at a nuclear site.

While advancements have been realised in both fields, i.e., earth sciences and earthquake engineering, as a result of new earthquake and geological data, dedicated experimental efforts, and analytical modelling, they have yet to be adopted into the regulatory guidelines and actual engineering practice. Therefore, in order for these advancements to make in rows into the nuclear seismic safety practice and design and thus have a positive influence on the nuclear field in general, they would need the strong endorsement of regulatory bodies which are effectively responsible for allowing the integration of new findings affecting the nuclear practice into the regulatory guidelines. This may be achieved by:

1) Maintaining the dialogue between earth scientists and earthquake engineers. The reality, which also became apparent during the course of the three workshops, is that there is lack of appreciation between them regarding the value of the research conducted separately in the two disciplines. This may stem from the fact that the earth science side is influenced by uncertainty while the earthquake engineering side must design with certainty. To allow for the two views to converge, a regulatory body can be the bridge between the two disciplines by (a) closely following advancements made in the two areas, and (b) establishing the overlap. An excellent example of overlap or cross-communication is the establishment of site-specific spectra or site response where both seismological models and earthquake engineering analysis models can be used.

2) Allowing for the regulatory guidelines to be more conducive to change and adaptation of new methods of either design or safety assessment of nuclear facilities. By allowing the implementation of new findings that challenge the established practice, the nuclear industry will catch-up to other sectors which have capitalised on new research and on computational advancements. The ability today to understand and model non-linear processes and complex systems in three-dimensional space, stemming from computational advancements and computing power, may allow for non-linearities to be considered, in part, in the seismic response of nuclear structures or the introduction of 3-D representation in the modelling and analysis in the place of idealised “stick” models.

3) Supporting or facilitating participation in large-scale experimental and field studies. Often dedicated experiments on test structures, while undertaken to understand the behaviour of certain types of nuclear structures under seismic loads, utilise earthquake characteristics that are well understood by the seismological side. An excellent example of both the value of wide-based experimental efforts and of the close communication between seismologists and earthquake engineers is the experimental study on the response of lightly reinforced shear walls to near field earthquakes organised by the IAEAC [Ref. 6].

6. REFERENCES

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