Theme Report on Topic 8

EARTHQUAKE RESISTANT DESIGN OF NUCLEAR POWER FACILITIES

by

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Failure of nuclear installations can result in the spread of radioactive contamination to the environment, affecting the population around. Safety is ensured by an amount of conservatism in the design arising out of a high reliability requirement. Such an approach can lead to unwarranted increase in cost. The limited experience of the performance of such structures during strong earthquakes and the qualitative nature of the historical data on their occurence also add to the uncertainties of the problem. Mathematical idealisation of the system, and its solution have also become possible through the use of computers. Experimental work on scale models is also being used to understand the complex behaviour of these structures, systems and components during simulated strong vibratory ground motions. While some information is available on the performance of nuclear power plants during earthquakes, it is still insufficient to enable any general conclusions to be drawn for the design of future installations. The degree of conservatism built in the present approaches to the design of these facilities is therefore not evident.

We have for discussion at this session 19 papers : 7 of them deal with the determination of design earthquakes and their conversion into design information; 10 on the approaches to the idealisation and analysis of the structures and systems and 2 on the analysis of components. As there is no paper covering the observations made on nuclear power stations that have experienced strong earthquakes, we shall look forward to receiving some information during this session.

The paper "Seismic evaluation of critical facilities at the Lawrence Livermore Laboratory" by R.C. Murray and F.J. Tokarz deals with the approach to the seismic analysis of facilities which have a potential for release of radioactive materials. To start with, the potential earthquake magnitude is determined, basically from empirical correlations between the rupture length and the earthquake magnitude after a thorough review of both the geology and the seismicity of the area surrounding the sites. The determination of design earthquakes is carried out using the following three methods:

(i) Extrapolation of the recorded surface motions from past earthquakes at some epicentral distance to arrive at the surface motions at the site.

(ii) Computation of the surface motion from the estimated bedrock motion based on the soil properties.

(iii) Direct estimation from empirical correlations.

The method of analysis is chosen with reference to the nature and importance of the structure, the consequence of failure, and the type of structural system being analysedp The correct response characteristics of these structures are reflected in a mathematical model. The analysis is performed using the equivalent static, the spectral response and the time-history methods. On the basis of the studies carried out so far, the authors conclude that the structures designed on the basis of a seismic coefficient adopted as per the Uniform Building Code performed well, when checked for the more severe earthquake conditions imposed in the study. Most of the inadequacies observed are related to the connection details, particularly at the joint between the wall and roof. They further recommend that while considering any increased loading on the roof due to the addition of mechanical and electrical equipment the consequent increase in the earthquake loading needs also to be taken into account.

The second paper "Effects of site conditions on Floor Response Spectra" by R.R. Kumar and P.J. Beresford describes the results of a parametric study on floor response due to the influence of the variation in ground conditions ranging from exposed bedrock to a thick soil cover with two intermediate situations of a thin and medium soil cover bedrock. These four site configurations are analysed for varying values of the shear wave velocities and the soil damping. An artificially generated time history input matching the USNRC Response Spectrum at the foundation level and the finite element linear elastic analysis approach have been adopted in the study. To restrict the number of site configurations in the study, the soil models do not account for layering, material anisotropy, depth dependent properties and water table. The material properties of the soil have been defined by the shear wave velocity, damping ratio, poisson's ratio and mass density. The values assigned to them are based on a statistical analysis of data logs for 60 nuclear power plant sites in the USA supplemented with information derived from semi-empirical equations and other published data. The analysis does not indicate any statistical preference of the shear wave velocity with site configuration. Hence from the range of values established after idealising the datalogs, average values of the shear wave velocity have been in the study. Similarly, reliance has been placed on published data for the damping ratios while choosing a value of 5% in soil and 2% in rock, for this study. The axisymmetric reactor structure has been considered as an equivalent two - dimensional structure for the purpose of finite element modelling. Soil structure interaction has been considered in the modelling by the adoption of viscous elements at the bottom soil boundary in order to represent the infinite boundary conditions. Further, the sizes of the soil elements in the vertical direction are such as would ensure an effective frequency transmission of 33HZ. A constant damping ratio has been adopted for all the models. A comparison of the floor response spectra for all site conditions at the basement level indicates that as the soil stiffness decreases, the structure modifies the motion at the basement level more and more. The following conclusions are drawn by the authors on the basis of this study:

(a) A foundation shear wave velocity greater than 6000 ft/sec will not significantly influence the behaviour of the structure (i.e.) there is little or no soil-structure interaction.

(b) The basemat response spectra is significantly different from the spectra of the input ground motion for soft and medium soils. The differences become larger as the soil stiffness decreases.

(c) The site condition has a considerable influence on the resonant peaks of the structural response. The first natural frequency of the combined soil-structure system reduces considerably as the soil gets softer (i.e.) as interaction increases.

The third paper "An approach to probability evaluation of Design Earthquakes for Nuclear Plants" by A.S. Patwardhan, L.S.Cluff and D. Rocher deals with two distinct approaches in the determination of the Safe Shutdown Earthquake (SSE) and the Operating Basis Earthquake(OBE) for seismic design of nuclear power plants. One is the capable fault approach and the other, the tectonic province approach. Both are based on predominantly deterministic procedures involving uncertainties in the selection of parameters and relationships. A procedure for assessing the probability of two primary characteristics; magnitude or intensity, and peak acceleration has been suggested in this paper. The SSE and OBE are each defined by four characteristics determined somewhat sequentially : 1. maximum magnitude or maximum source intensity. 2. peak acceleration. 3. response spectra. 4. duration. The maximum magnitude or intensity is defined based on source conditions alone, whereas the rest of them include in addition to the source, geometry and the properties of the materials in the source to site path as well as at the site. The probability evaluation of design earthquakes is important as they form the bases for the seismic design of nuclear power plant structures and equipment, and therefore, influence their safety analysis. For ensuring consistency in approach probability evaluation of design earthquakes provides a useful comparison with the probability of other safety-related design bases. As design earthquakes are defined by more than one characteristic, each one of which may have a different significance to the nuclear power plant structures it is difficult to define a single "probability of a design earthquake". Thus it is convenient to assess separately the probability of earthquake magnitude and peak acceleration as well as the probabilities of response spectra and duration.

The paper addresses the first step. In the tectonic province approach the maximum SSE intensity is chosen to exceed the maximum historical intensity within the area of interest with a certain conservatism. The estimation of the degree of conservatism in terms of probabilities is difficult, as the selected value is generally an extrapolation beyond available data resulting in high probability values for intensities MM VIII-X and is a matter of subjective judgment. The peak acceleration associated with the selected maximum intensity is estimated from intensity acceleration correlations. In the capable fault approach, earthquakes are associated with capable faults. The maximum earthquake on each fault will vary depending upon material properties, strain rate, rupture length, size of rupture surface and stress drop. The distribution of rupture lengths, and hence that of magnitudes on a fault vary considerably. The maximum rupture lengths and earthquakes associated with each fault can be established by either of the following methods:

(1) Through a knowledge of material properties,s train rates and stress conditions in the source region.

(2) Through an extremal value analysis.

(3) Through a compilation and analysis of historical data on length of surface rupture and length of aftershock zones, supplemented by interpretations of the quarternary geologic record.

(4) Through subjective assignment of probabilities of rupture lengths.

The peak acceleration at the site can then be calculated by utilising deterministic relationship between acceleration, the length of rupture and the minimum significant distance from the fault. The probability of the peak acceleration is then determined from known formulae.

The authors conclude that the probability of design earthquakes comprises of interrelationships between different characteristics. As it is difficult to estimate the maximum magnitude or intensity of earthquake from deterministic data, they prefer to estimate earthquake corresponding to a given level of probability for each structure or tectonic province. This also facilitates estimation of OBE. In the opinion of the authors the capable fault approach is likely to result in a narrower range of probabilities than the tectonic province approach and hence the former is to be preferred.

The fourth paper, "Probabilistic Dynamic Earthquake Analysis of Nuclear Power Plants" by H.E. Ermutlu uses normal mode analysis to develop power spectrum responses of physical variables of elastic structures to earthquakes described as stationary Gaussian random distributions. It assumes that a specific site dependent design acceleration power spectral density of earthquake can be obtained considering the seismic activity of the region and tectonic and geologic characteristics of the construction site. For this purpose it establishes a direct conversion possibility between acceleration power spectral density and velocity response spectrum. It is feasible to obtain an average normalised power spectral density curve applicable for values of damping commonly used in design. The authors conclude that the method is well suited for the design of nuclear power plants as it takes into account the random nature of the earthquake phenomenon and provides a direct approach eliminating the need for time history analysis in the seismic design of equipment.

The paper "Artificial Earthquake Generation for Nuclear Power Plant Design" by A.C.Y.King and C. Chen describes a detailed method for generating time history consistent with a specified design spectra. The advantages claimed for the method are, (i) frequency content of the time history is well under control (ii) the correlations among the three components of earthquakes at a site would simulate closely the actual recorded time histories (iii) a single time history can be generated to match a spectra for different damping values. The paper also gives methods of achieving a better matching between the target spectrum and calculated spectrum for single degree of freedom systems.

The next two papers deal with the requirements of regulatory agencies with regard to earthquakes resistant design. The one on "Comparison of site dependent and regulatory agency earthquake input motion used in the design of Nuclear Power Plant" by Joseph A. Fischer et al. concludes as a result of a study on a break water for a floating nuclear power plant that the use of the USNRC regulatory guide 1.60 is conservative. In the opinion of the authors such conservatism may needlessly penalise sites otherwise suitable for nuclear facility construction.

In their paper "Earthquake Safety of Nuclear Power Plants - An interpretative review of current design practice and the related regulatory system in West Germany" M.Bork and K. Neu have given a brief description of the scope of the proposed German nuclear Safety standard KTA 2201 which takes into account the comparatively low seismicity of the Federal Republic of Germany.

The next set of ten papers deal with the various methods of analyses in the earthquake resistant design of these structures and bring out the relative differences in the various approaches adopted.

The first paper "Seismic analysis of Reactor Building of an atomic power plant on alluvial soil" by Anand S. Arya, A.R.Chandrasekaran, S.K. Thakkar, D.K. Paul and A.D. Pandey deals with the determination of the base raft motion of a reactor building structure modelled as a multimass branched system. The influence of the variation in the shear wave velocity, modulus of subgrade reaction, weight and lever arm of the internal structure and the inertial force on the earthquake response has been studied. The analysis reveals that for the structure under consideration, the first mode is predominantly of the rocking type, the second, translational and the other higher modes are of the structural type. The authors conclude that softness of the soil has a considerable influence on the time periods of the structure. For values of shear wave velocities higher than 1200 m/sec. they feel that the assumption of fixity at the base of the structure may be acceptable.

The second paper "Seismic analysis of reactor internals of Narora atomic power plant, India" by A.S. Arya, A.R. Chandrasekaran, S.K. Thakkar, D.K. Paul and A.S. Warudkar is a case study of the improvements made in the structural system for increasing the rigidity and thereby controlling the interstorey displacements within acceptable values from the point of view of system design under the design earthquakes.

The third paper "Elastic-plastic dynamic analysis of reactor buildings" by Hajime Umemura and Hiroshi Tanaka relates to the reactor building of a Mark II BWR plant. The paper describes the nonlinear dynamic analysis using lumped mass models performed in this case. The nonlinear moment (M) - rotation (Ø) and shear stress ( ) = shear deformation ( ) characteristics of walls used in the analysis are determined by experiments on structural models. An experimental investigation has been performed to determine the strength and force-deflection characteristics of box and conical shell type concrete wall arrangements considered in this case. The geometrical nonlinearity of equivalent soil spring for rocking due to foundation separation has also been considered in the analysis. Trilinear skelton curves are assigned to the shear stress - shear deformation and the moment-rotation relationships. The mathematical model considered in the analysis is a single cantilever lumped mass model supported by rocking and horizontal springs, equivalent to the underlying soil. It is found that the maximum shear stress and overturning moment obtained by nonlinear analysis, are smaller in the middle and lower portion of the building and may be larger in the upper portion compared to the results of a parametric analysis. The authors also observe on the basis of results of a parametric study using 8 earthquakes that the standard deviations of the maximum response in each portion of the building are approximately 10 - 20%. As soil becomes harder the standard deviation of the maximum response in the upper portion increase and the standard deviations in the lower portion decrease. The effect of the parameter change is smaller in nonlinear analysis than in linear analysis.

The fourth paper "Overturning behaviour of nuclear power plant structures during earthquakes" by J.S. Dalal and P.R. Perumalswami considers the transient nature of the problem and draws distinction between rocking, tipping, and overturning. The current USNRC guidelines relating to factors of safety against overturning viz. 1.1 for SSE and 1.5 for OBE are reviewed in the context of the highly transient nature of earthquake forces. Factors of safety smaller than unity in these cases indicate only minimal base rotations, considerably smaller than those necessary for structures to overturn. The authors suggest that for structures on rock, impact forces should be appropriately considered when tipping is permitted and further that the increased bearing pressures in the foundation medium due to tipping should be accounted for in the design.

The fifth paper "A nonlinear seismic design procedure for nuclear facilities" by H.Kamil and V.V. Bertero describes an earthquake resistant design procedure for an efficient economic and reliable design of nuclear facilities. For frame type auxiliary and turbine buildings, a nonlinear, inelastic optimum design procedure consists of several steps including preliminary design, analysis of the preliminary design, final design with optimisation, and the determination of the reliability of the final design using probabilistic methods. Most of the factors affecting the design viz. fundamental period, ductility factor, damping coefficient, seismic coefficient story drift etc. are included thereby enabling the design procedure to exert far greater control over the seismic design than the conventional design approaches. Reliability of the structural system for the design safety level earthquake can be reasonably estimated by the use of probabilistic methods. In the case of the containment structure where radiation safety is involved, the authors suggest that the design be carried out in the linear, elastic range, and the reliability of the design be estimated using probabilistic methods".

The sixth paper "Seismic analysis of a complex turbogenerator building including torsion" by Anand S. Arya, Brijesh Chandra and Satyendra P. Gupta considers three analytical models for the structure. The results of the analysis reveal that the block model and the plane frame model give different natural periods and seismic forces for the building. It also shows that the effect of joint rotations and axial deformations is to elongate the periods which do affect the seismic response considerably. This aspect is quite significant and must be considered in the analysis. Torsion due to unsymmetrical configuration of structural elements must be considered for determining final shears in the frame and therefore the member forces. In the opinion of the authors, a choice of the model for the determination of member forces, will depend on the type of framing and concentration of loads over the building at various floors.

The Seventh paper "Seismic effect on modularised spent fuel storage facilities" by R.G.Dong and F.J. Tokarz deals with the investigations conducted at the Lawrence Livermore Laboratory on the effects of modularization on earthquake resistant design. The pool sizes considered in the study are 240 ft x 160 ft in plan and 40 ft deep either below or above ground. The two modularised pool configurations considered in plan are 40 ft x 80 ft and 80 ft x 80 ft. The site condition considered is a hard soil well above water table. A shear wave velocity of 350 ft/sec. is considered to represent the site conditions. The comparison is based on certain definite thicknesses of walls, definite embedment and a consideration of the extension of the soil mass upto 1000 ft. on the sides and bottom to reach the free field conditions. Hydrodynamic pressure is accounted for as equivalent mass added to the storage racks. Slosh effect is also considered in the study. The authors conclude that in the case of embedded pool, the effects of modularisation on earthquake resistance must be evaluated on a case by case basis. The effects cannot be relied upon to be beneficial as it is dependent on the pool configuration. For the above ground situation, modularisation consistently results in increased earthquake resistance for the configurations examined. However, structural loads are higher in the above ground pools, more so in the external walls. Dynamic amplification is significant except in external embedded walls. On the basis of the findings of the study, the authors conclude that modularisation may or may not be advantageous in terms of structural loads depending on the pool configuration and installation.

The eighth paper "Seismic response of floating nuclear power plant equipment" by Ish. K. Aneja presents the results of dynamic analysis of a 1200MW turbine-generator foundation of a floating nuclear power plant subjected to vertical ground motion. The analysis has been performed using a finite element computer program. The paper gives a brief description of the method of analysis used to obtain the upper bound of seismic forces generated at the turbine deck level, journals and corresponding bearing housing at the rotor level, due to a typical ground shock spectrum applied in the vertical direction at the level of the column foundations.

The ninth paper "Dynamic Structure-medium Interaction of Underground Nuclear Reactor Containments" by D.V. Reddy, D.E.Moselhi and S.A.E.Sheha deals with the dynamic finite element analysis of underground nuclear reactor containments subjected to blast excitation. The parametric studies of the structural characteristics of the four principal underground concepts (a) Cut-and-cover, (b) Unlined cavity, (c) lined cavity, and (d) Lined cavity with annular filling of soft material indicate (i) the horseshoe shape to be the best profile, (ii) active rock bolting superiod to all other types of cavity reinforcement, (iii) considerable decrease in liner membrane forces and stresses in the medium due to isolation and (iv) significant reduction of stresses in the structure and the medium by proper combination of the density and elasticity of the backfilling in the cut-and-cover concept.

The tenth paper "Dynamic Behaviour of Embedded Structures" by A.R. Chandrasekaran and D.K. Paul presents a parametric study for embedded structures having varying depths of embedment and varying soil properties such as the shear wave velocity and the modulus of subgrade reaction. For this study the continuum approach has been used, in modulling the soil structure system. The soil at the side and at the base has been represented by equivalent springs and dashpots based on the modulus of subgrade reaction of the soil and the elastic half space theroy. The parametric studies show that the response of the structure is very much affected by the type of bottom soil and depth of embedment whereas the type of side soil is relatively less influenced on the response.

With that we come to the close of the second group of 10 papers.

In the third and the last group of two papers, the one "Design evaluation of reactor components for seismic disturbances" by S.K. Shrivastava, S. Nandakumar and V.M. Patwardhan deals with the calandria and end shields of a CANDU type reactor system. In the new design of the component consisting of an integral calandria end shield assembly with annular plate supports, the inner edges are welded and the outer edges are grouted into the walls of the reactor vault. Adequate flexibility has been built in the system to limit the effects of thermal expansion while at the same time providing sufficient rigidity to the system to restrict the deflections during the design earthquakes within acceptable limits. The modified design is initially being adopted on a 200 MWe reactor with provision for scaling it up for a 500 MWe unit in future.

The second paper "Two dimensional vibration test for a vertical slice model of HTGR core" by Kiyoshi Muto and Takashi Kuroda describes an analytical and experimental forced vibration test on shake table conducted on a one-fifth scale vertical slice of a high temperature gas cooled reactor core model. The seismic behaviour turns out to be complicated due to interblock collisions. The dynamic properties like resonant characteristics and vibration modes of the core, lumping of blocks, collision patterns of blocks and the response distribution of the graphite reflector reactions have been studied in a forced vibration test on a model. Computer simulation of the test is also done which establishes that the collision behaviour of the core can be analysed using a computer.

All the 19 papers are now open for discussion. We look forward to the presentation of valuable information collected in the many operating nuclear facilities during actual earthquakes experienced by them, so that the earthquake resistant design of nuclear power facilities can be performed with a greater awareness of the critical areas of the plant. This can lead to more economical designs in future.