

Seismic analysis and design of nuclear power plants

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ABSTRACT: An assessment of seismic analysis and design methodologies of nuclear power plants (NPP) designed prior to or during the 1970s and specially located in the eastern United States (EUS) is made. Analysis of NPPs involves multiple operations in stages starting from generation of free-field response spectrum to floor spectra generation to qualification of supporting systems for piping and equipment. Due to lack of analytical techniques and field data from earthquakes, the analysis and design of these plants were performed with conservative assumptions. As new data on earthquakes become available and new numerical analysis techniques are applied to reanalyze these plants, it is consistently revealed that the structures and components are adequate to resist the imposed seismic/dynamic loading.

1 INTRODUCTION

Generation of electrical energy from controlled thermo-nuclear reactions is a complex process and needs many structures and components, the safety and functionality of which must be maintained both during and after an anticipated earthquake. For most of the NPPs built up to the mid-70s the analysis and design of the safety-related structures and components were performed with the available codes and standards in that period. However, to account for the lack of complete understanding of the nature of seismicity of the region and the behavior of the complex components under seismic/dynamic loading, 'defense-in-depth' was adopted in every aspect of the design process. The complexity of the seismic evaluation process is shown in Fig. 1. Only some of the principal aspects will be discussed in this paper.

2 FREE FIELD SPECTRA

Earthquakes are caused by tectonic processes contributing to crustal stresses. For the EUS this geomechanical phenomenon leading to stress concentration and thus causing earthquakes are not very well-defined as the western United States (WUS) or some other regions of the world. No recognizable plate boundar-

ies exist along the eastern seaboard, therefore no incipient rifting is expected. Earthquakes of large magnitude are infrequent and so there is a lack of free field data of strong motion. The ground response spectra of these plants were mostly generated by synthesizing and averaging several WUS earthquakes and making sure it enveloped the smoothed spectrum. An example:

At Indian Point site in southern N.Y. State, the ground response spectrum was based on the average of four normalized response spectra

1. El Centro, California, Dec. 30, 1934
2. El Centro, California, May 18, 1940
3. Olympia, Washington, April 13, 1949
4. Taft, California, July 21, 1952

However, scaling down the key parameters like peak acceleration, velocity or displacement from the WUS data results in over-conservatism specially at low frequencies (1), the frequency range of interest for the NPP-structures.

Some advances in analytical techniques utilizing probabilistic mechanics let us generate artificially simulated ground response spectra which are closer to EUS and eliminates the need for 'exporting' the WUS earthquakes. Probabilistic seismic hazard

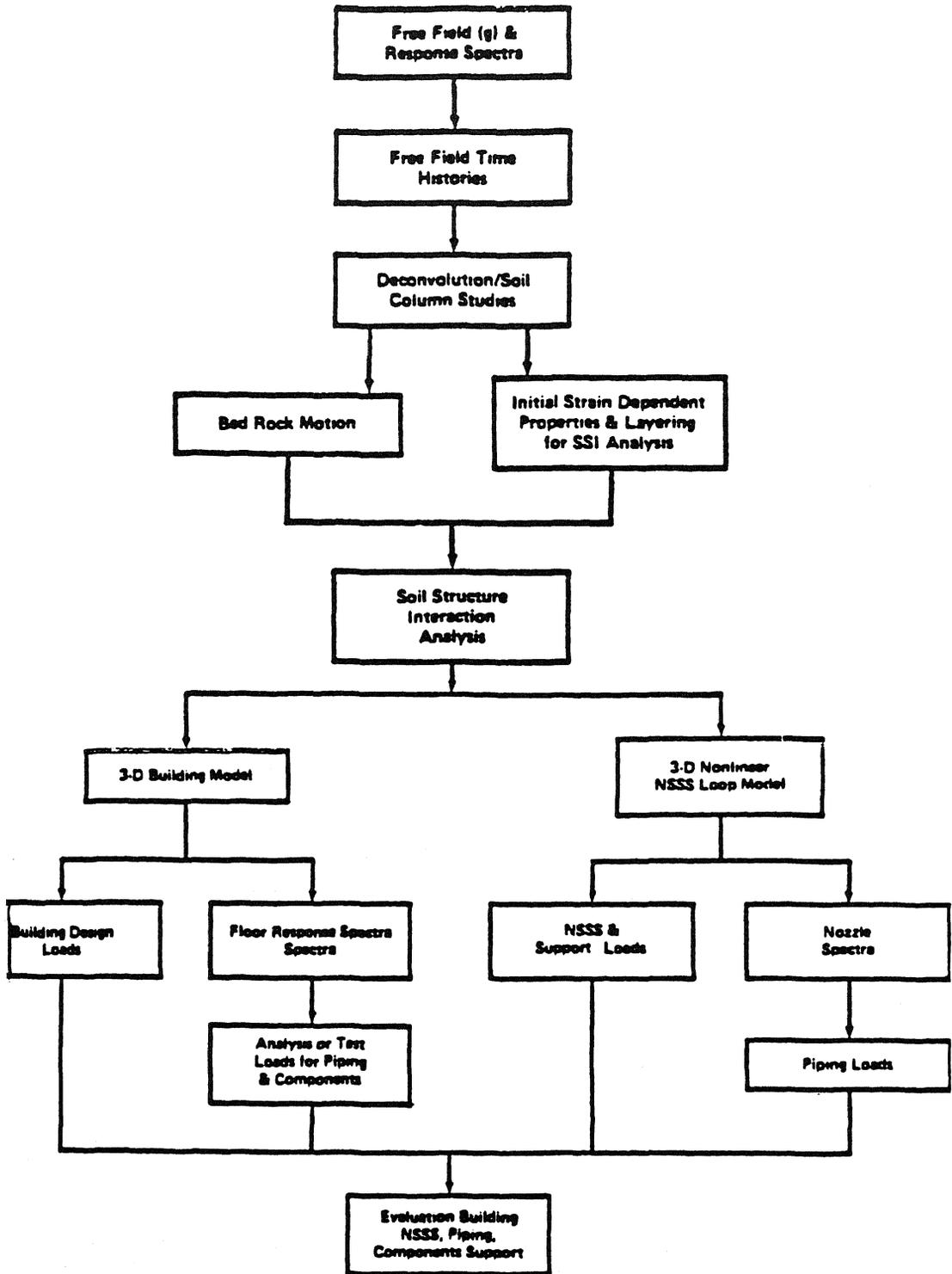


Figure 1 : Seismic Evaluation Flow Diagram
 (From a presentation by the Westinghouse Electric Corporation to the N.Y. Power Authority, 1989)

re-evaluation of all EUS sites was performed in response to the "Charleston Issue". The United States Geological Survey (USGS) noted in 1982 that since Charleston earthquake of 1886 was not caused by well-defined crustal feature, an earthquake of same magnitude may happen at any EUS site (2). This led both the utilities and the United States Nuclear Regulatory Commission (USNRC) to the probabilistic re-evaluation (3, 4). Both studies concluded that seismic hazard at most NPP-sites was unaffected, although all NPP-sites will be required to perform Seismic Margins Assessment (5). This assessment will determine the margin above the design basis earthquake existing in operating plants.

3 ATTENUATION

Attenuation was not considered at all for determining design basis earthquakes at the NPP-sites. For many EUS sites the design basis values meet or exceed the Charleston magnitude although they are located hundreds of miles away; and consideration of an exponential decay would have reduced them to at 50% or more. Again, for the lack of realistic instrumental data from any damaging earthquake at reasonable distances, theoretical approaches are utilized for attenuation analyses; e.g., physical model of energy release, wave propagation, source scaling etc. For EUS plants of the vintage under consideration, the method of ground response spectrum generation is shown in Fig. 2.

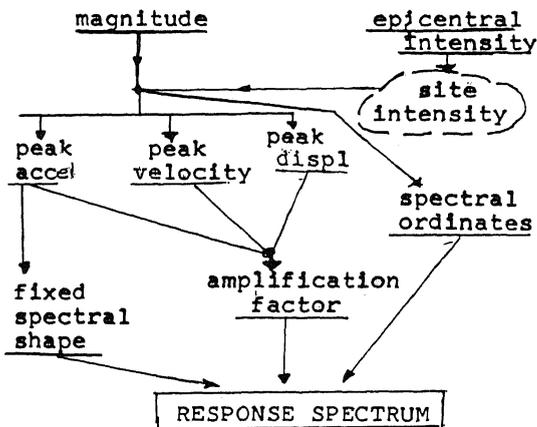


Figure 2. Ground motion determination (6)

Absence of attenuation between the epicenter and the site and conservative local amplification factors led to the overly conservative site design response spectra.

4 SOIL STRUCTURE INTERACTION

By deconvolution of free field accelerations, soil-structure-interaction (SSI) provides realistic base mat loads that must be used for equipment and components supports design of NPPs. Inherent difficulties of SSI have been the strain-dependent properties of soil (soil structure model), three dimensional semi-infinite half space, foundation embedment etc, which was compounded by inaccurate modelling of seismic input motions. For many of the earlier plants the absence of SSI was compensated by response spectra peak widening. Acceptable methodologies of SSI analysis include: single lumped mass-spring approach for rock or deep soil foundations, multiple lumped-mass-springs or finite elements analysis (7). However no test data existed to validate the approaches until the Electric Power Research Institute (EPRI) and the Taiwan Power Company performed 1/4 and 1/2 scale NPP containment model testing (8). This research resulted in a guideline for SSI analysis in five steps: site response, foundation scattering, structural modelling, foundation impedance and interaction response. This research is still continuing in an International collaboration.

5 FLOOR SPECTRA DEVELOPMENT

The mechanical analogy of floor spectra development is the collection of maximum responses of a number of mass spring oscillators with dampers attached to a rigid mat. The conservatism used in earlier NPP floor spectra development was in the analytical modelling for the dynamic analysis, e.g., decoupling criteria between supporting structure/supported structure, smoothing and broadening criteria, assumption of damping percentages etc. Also neglected were the interaction effect i.e., mass ratio between mat and oscillators; and non-classical damping i.e., oscillator and mat lumped together in spite of their inherent difference in damping values. EUS plants with floor spectra developed in this manner show very high peaks in floors close to the ground, whereas researches of later date show that

ground response spectra may be utilized for floors upto 40 feet or even higher(9). Fig.3 shows the floor response spectrum of an EUS plant at 35 feet above effective grade compared to ground response spectrum.

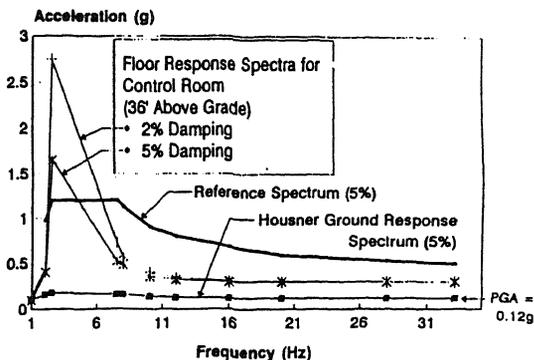


Figure 3. Floor spectrum and ground spectrum compared

6 EQUIPMENT AND PIPING DESIGN

Analysis and design of equipment and components at NPPs have gone through similar evolution as the main structures discussed above. Older plants basically had no definitive requirement for seismic analysis of equipment; except that, random (single) failures were accommodated by system design i.e., redundancy, diversity etc and periodic routine maintenance of equipment. Methodologies adopted involved analysis, testing and/or a combination. In older plants response spectra analysis to determine loading of the equipment normally involved peak of floor response spectrum times a factor of 1.5 or 2; to account for higher modes. As noted under floor spectra discussion, equipment damping was arbitrarily selected at 1% or even 0.5%. This led to overdesign of equipment support system by several hundred percent depending upon properties of supporting structure and supported equipment mass, damping frequencies etc. Some plants used modal analysis technique; however, very rarely time-history was adopted for equipment seismic analysis. Most safety-related piping systems were analysed by dynamic modal response spectrum method. Reanalysis and comparison to piping and equipment system performance in actual earthquakes (10) show that

for earthquakes upto the design basis magnitudes, all plants in the EUS will need extremely minor modifications, if any. Of course this is an ongoing evaluation and results may not be exactly known until mid-1990s. (11).

7 CONCLUSIONS

1. The adoption of the defense-in-depth design philosophy in earlier NPP seismic analysis and design has proven to be an appropriate methodology for that period.
2. Performance of equipment and components in actual earthquakes, which serve as the ultimate shake tables, must be incorporated in future design and re-evaluation of existing and operating NPPs.

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