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SOIL-STRUCTURE INTERACTION MODELING AND STRUCTURAL RESPONSE FOR LENINGRAD NPP REACTOR BUILDING

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ABSTRACT

The paper is part of the project Leningrad NPP In-depth Safety Analysis. The aim of the paper is to develop the structural response in form of in-structure response spectra for the reactor building of Leningrad nuclear power plant.

First part of the analysis was to develop the impedance functions for the reactor building foundation. The layering of the soil beneath the reactor building was characterized by layer thickness, longitudinal and shear wave velocities in the layer, soil density and by damping coefficients for longitudinal and shear waves in the layer. The impedance functions for the foundation were evaluated for vertical, horizontal, rocking and torsion motions. The resultant impedance functions were distributed in the form of springs and dampers to node points of the base slab of the reactor building model.

The true 3D model for reactor building was developed. The walls and elevations were modeled with the aid of four node shell element. The amount of walls and elevations in the structural model was about ten in both horizontal coordinate directions and in vertical direction. The total number of degrees of freedom in the structural model was about 30 000. The large equipment items were modeled in the form of cylinders and hexahedrons having finite geometric dimensions, specific locations and specific material properties. The small equipment items were modeled in the form point masses. The number of large equipment items in the model was 19 and the number small equipment items in the model was 59. The total weight of the model was about 120 000 tons.

The results of the structural response analysis are presented in the form of floor response spectra for ten elevations inside the reactor building. The spectra are given for damping coefficients of 0.5, 2, 5 and 10% from critical.

INTRODUCTION

In the following, the tasks for the assessment of the seismic core damage risk (PSA Level 1) during full power operation of the unit one of Leningrad Nuclear Power Plant are described .The seismic risk analysis is based to the corresponding Probabilistic Safety Assessment model of internal initiating events. The seismic loading has simultaneous damage potential to several redundant components and systems of a nuclear power plant. The seismic risk analyses have demonstrated that the contribution of seismic risk to the core damage or to the risk of the release to the environment can be significant. The different phases of the seismic risk analysis can be listed as follows:

1. The determination of the seismic hazard of the plant site
2. Scoping study of the seismic fragilities
3. Structural response calculations
4. The identification of seismically vulnerable components in initiating event- and probabilistic safety analysis models
5. Seismic fragilities of selected components
6. The quantification of seismic core damage risk

The scope and accuracy of the seismic risk analysis depend on the level of the seismicity of the investigated plant site and also on the aims of the analysis. If the level of seismicity of the plant site is found to be low it is sufficient to determine the frequency of the seismically induced core damage and to compare this frequency with the core damage frequencies caused by internal initiating events or by other external initiating events. Thus the result of the seismic risk analysis can be presented as the cumulative probability distribution of the annual core damage frequency. If the annual core damage frequency caused by seismic events is high when compared to the core damage frequencies caused by internal or other external initiating events then the seismic Probabilistic Safety Analysis is extended to the levels of 2 and 3. If as a result of this comparison the seismic risk of radioactive release dominates the risk of radioactive release from all initiators and the total risk of release is too high it is necessary to analyze once more those equipment and systems in the release chain that have a high value for failure frequency. In order to calculate fragilities of the plant equipment, it is necessary to obtain seismic responses of structures which support this equipment. The breadth and depth of the response analysis depend on the information existing on analyses performed during the design stage and on the method used to develop component fragilities. The seismic response calculations were carried for the most important structures with regard to seismic safety. The reactor building and turbine/control building of the plant were chosen for the response analysis. The description of the seismic response analysis of the reactor building of Leningrad Nuclear Power Plant is the aim of this paper.

PROCEDURE FOR DEVELOPING PROBABILISTIC FLOOR SPECTRA

The procedure for generating probabilistic floor response spectra follows the methodology developed under the Seismic Safety Margins Research Program (SSMRP) conducted in the early eighties in the U.S. and applied to several seismic probabilistic risk assessments and margin studies. The purpose of probabilistic floor response spectra generating is an explicit treatment of uncertainties in various phases of the analysis procedure -- e.g. specification of free- field ground motion and development of structure model. This approach will provide a complete description of the seismic environment for equipment and piping mounted in the structures and can be used directly whether the required task is a seismic qualification effort, a seismic margin study or a seismic probabilistic risk assessment. For selected nodal points in the structures, spectra will be provided as 50th percentile and 84th percentile amplified response spectra. The median (50th percentile) spectra are used in seismic margins assessments as opposed to conservative design spectra. The uncertainty in structural response is required and this is defined by the 50th and 84th percentile response spectra. Following steps are needed for the definition of control ground motion at site: 1. Define the control point. Generally this is at the ground surface, in which case the free-field motions generated are ground surface motions; 2. Define the peak ground accelerations for each direction in the free-field; 3 Define the number of earthquake simulations to be made for the probabilistic analyses. Thirty simulations are usually performed; 4 Define the spectral shape of the control motions; 5. Define the coefficient of variation of the spectral shape of the control motions;6. Generate a suite of time history sets. The seismic ground motion for the probabilistic seismic safety analysis of the Leningrad NPP will be defined by the acceleration response spectrum described in the reference [1].The spectral shape to be used to define this motion corresponds to a median (50 percentile) spectrum developed for soft soil sites. For the Leningrad plant, the horizontal peak ground acceleration will be assumed to equal to 0.1g. The vertical spectrum will be assumed equal to 2/3 of the horizontal spectrum. The horizontal spectrum is shown in Figure 1.

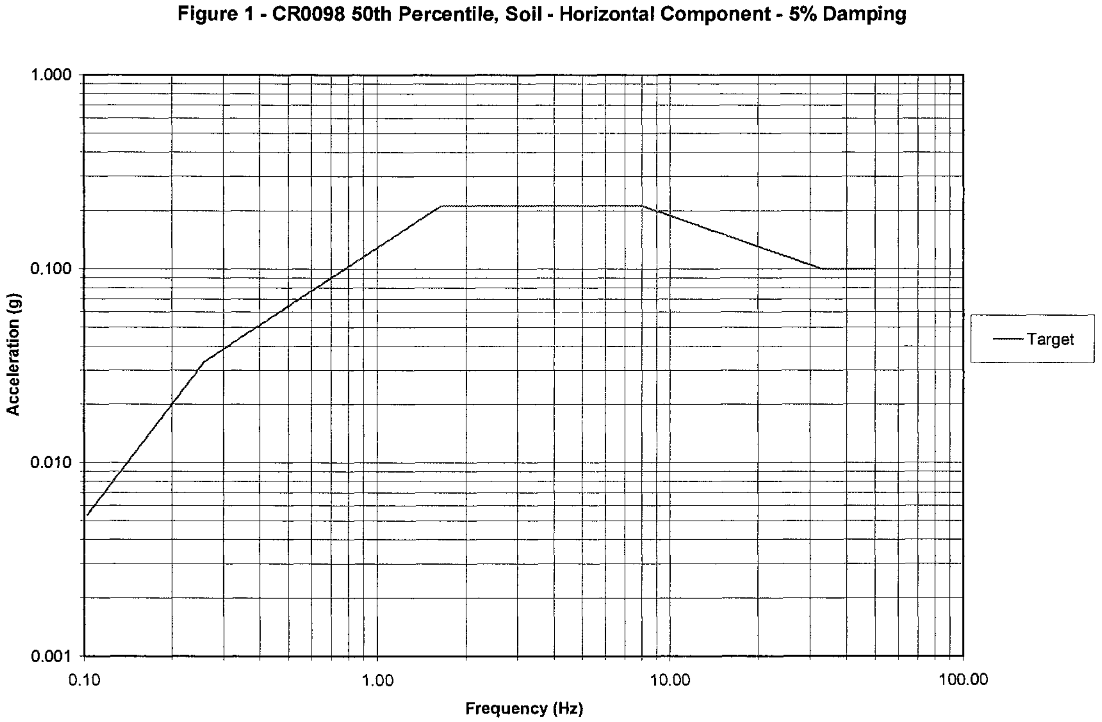

Figure 1 CR0098 50th Percentile, free-field horizontal component, 5% damping

STRUCTURAL MODELING

The first task in structural modelling is to develop fixed-base models of each structure in as much detail as necessary to define adequately the building response at all desired locations. A best estimate model should be made (i.e. best estimates of stiffness, mass and damping properties) and conservative assumptions should be made only if best estimates are not available. The next step in the probabilistic floor response generation is to define the uncertainty in structural properties. This is defined in terms of coefficients of variation (COVs) of the modal frequencies and damping ratios. Generally a log-normal distribution is assumed. The best estimate values define the medians and the COVs define the variability. Normally, a single value is used to define the coefficient of variation of all modes for each of frequency and damping. Typical COVs used in the past PSA studies are: 1)COV(modal frequencies) = 0. 25; 2)COV(modal damping) = 0.35. In this study, the structural models with best estimate material and geometric property parameters for the buildings to be modelled are developed. The layout of the reactor building is depicted in Figures 2 and 3.

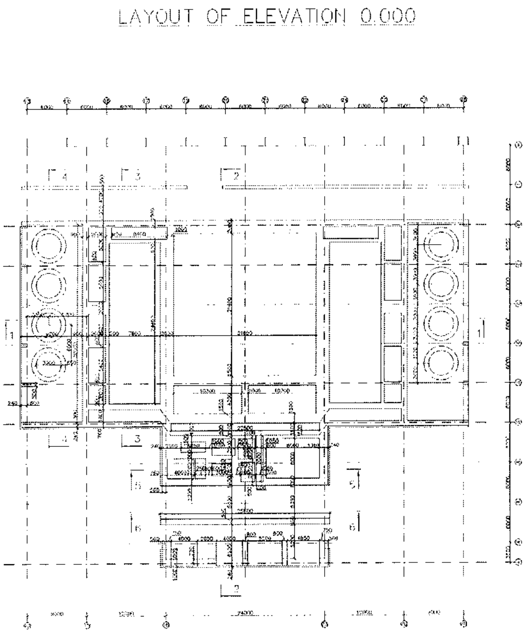

Figure 2 Layout of reactor building elevation +0.00

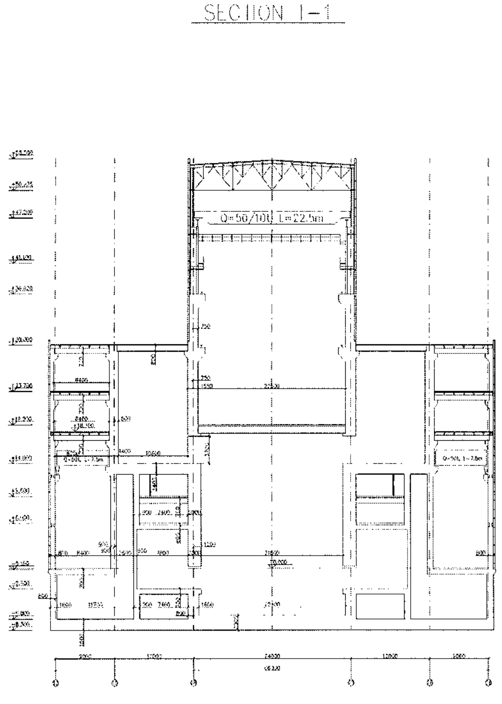

Figure 3 Transversal layout section

CHARACTERISTICS OF THE FEM- MODEL FOR REACTOR BUILDING

In this work the reactor building of the Leningrad NPP has been modeled. Modeling has been carried out by 3-D finite elements. Elements used in modeling were rectangular plate elements QUAD4 with 4 nodes and straight beam elements with standard I-shape (2 nodes). The coordinate system used was standard rectangular XYZ-coordinate system.

QUAD4 plate elements were shell elements, which were been modeled on middle surfaces of the structures in two dimensions and their thickness was given as an element property. Beam elements were modeled on a curve in one dimension and their shape and dimensions were likewise determined as element property. There was 5605 nodes and 7510 elements in the model. Each node in the model has six degrees of freedom, translations in the X-,Y- and Z-directions and rotations around these axes. The number of degrees of freedom was 36630. The thickest plate element in model is 2,04 m and the thinnest 0,23 m. The thickest elements were in two internal partition walls. The thinnest elements were in several inner floors.

Materials used in modeling the reactor building are concrete and steel. Almost the whole building is made from concrete, expect steel roof girders. Concrete's modulus of elasticity is 30 000 N/mm^2 and Poisson's constant 0.2. For steel the modulus of elasticity is 200 000 N/mm^2 and Poisson's constant 0.3. The density for concrete is 2500 kg/m^3 and for steel 7800 kg/m^3. These values are best estimate values for properties used for obtaining the best estimate values for in-structure response. The isometric view of the reactor building model is depicted in Figure 4.

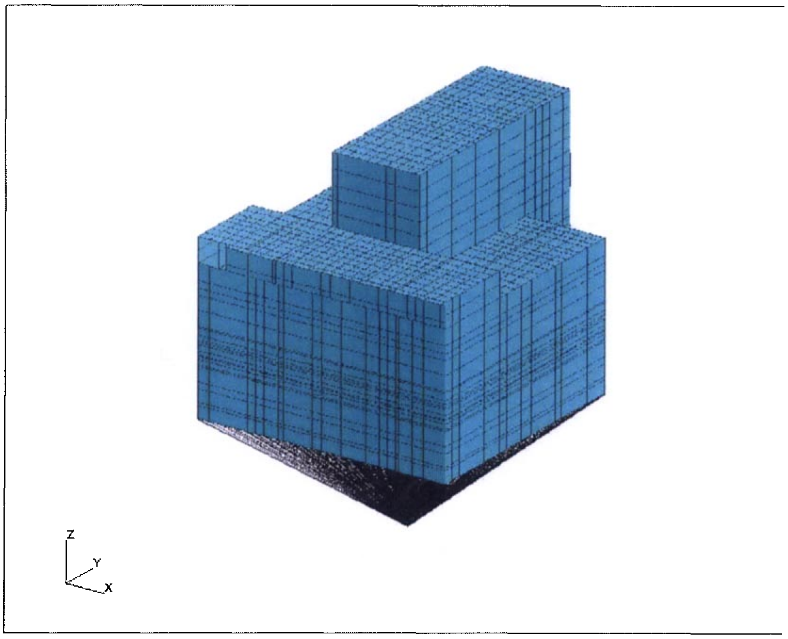

Figure 4 The isometric view of the reactor building model

The analysis of soil-structure interaction in this study is carried out by using the SASSI [2] code. Typical soil profile data for Leningrad NPP site conditions are presented in Table 1 herein, where H - soil layer height, C_p, C_s, D_p, D_s - velocities and logarithmic decrements of longitudinal (p) and lateral (s) waves, ρ - soil density.

Table 1 Soil characteristics of LAES site

• of the layer	H, m	C_p, m/s	C_s, m/s	ρ, g/cm^3	D_p	D_s
1	2	400	180	1,70	0,55	0,60
2	4	1100	250	1,80	0,50	0,60
3	4	1500	350	1,90	0,40	0,50
4	20	2000	350	2,20	0,15	0,40
5	30	2200	450	2,30	0,10	0,35
6	120	2500	650	2,40	0,05	0,05
7	-	5800	3400	3,00	0,0	0,0

The foundation impedances were generated by SASSI and the results for horizontal stiffness impedance and horizontal damping impedance are plotted in the Figures 5 and 6:

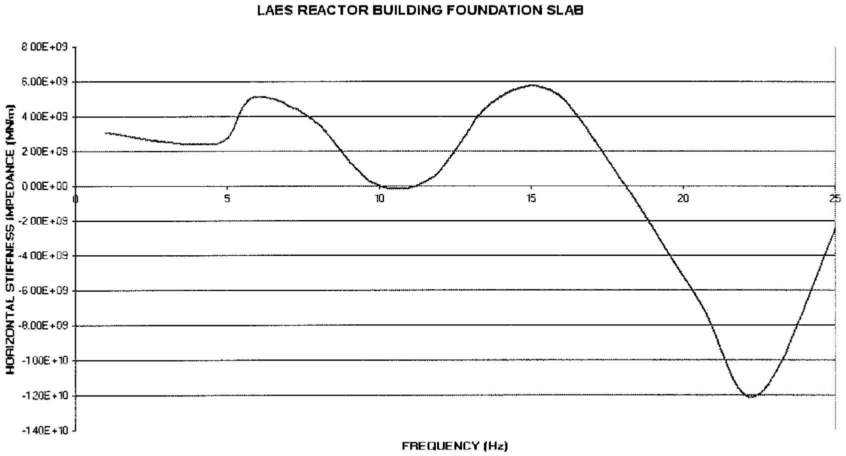

Figure 5 LAES reactor building foundation; real part of horizontal impedance

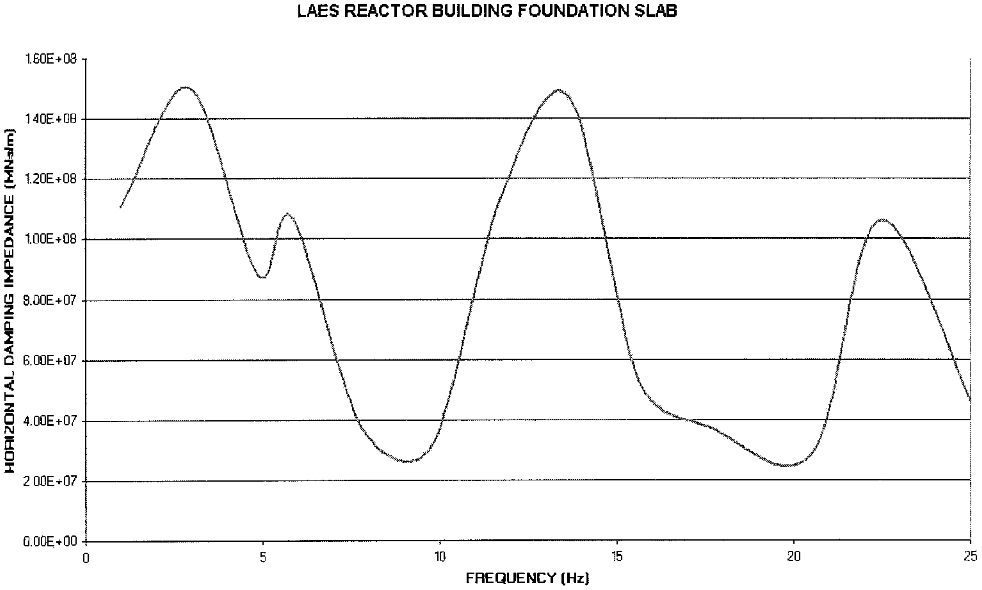

Figure 6 LAES reactor building foundation; imaginary part of horizontal impedance

FLOOR SPECTRA AT SELECTED ELEVATIONS

The floor spectra were calculated for the reactor building using best values for seismic excitation, soil-structure interaction and structural modeling parameters. The spectra were generated for foundation slab elevation –6.00, for reactor support elevation +0.00 for main coolant pump elevation +1.50 , for steam separator elevation +14.40, for main operation deck 19.20 for top of the lower part of the building elevation +30.00 and for top of the higher part of the building elevation +55.20. The resulting spectra for main operation deck in three directions and for damping ratios of 0.5 %, 2%, 5%, 7% and 15 % are given in the Figures 7, 8 and 9:

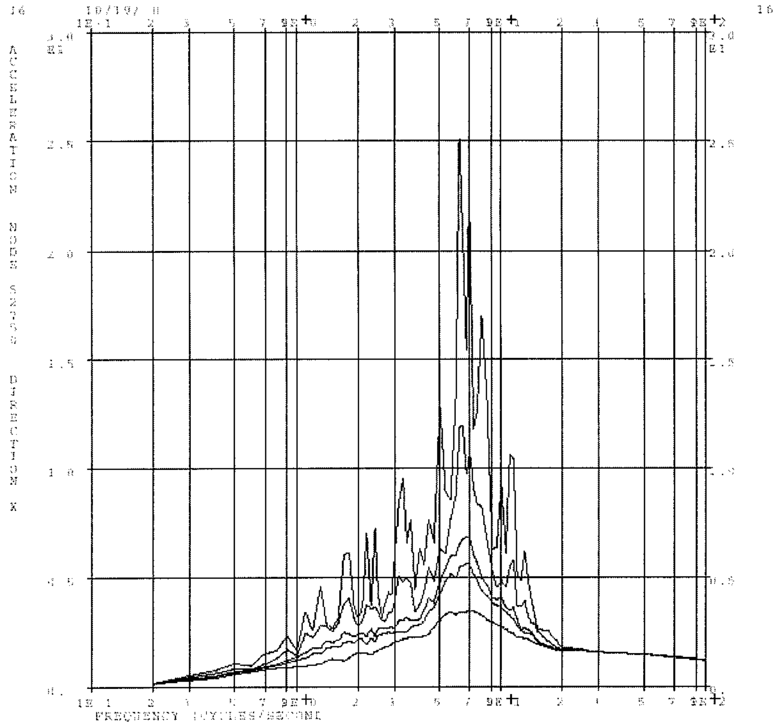

Figure 7 Acceleration response spectra at main operation elevation; x-direction

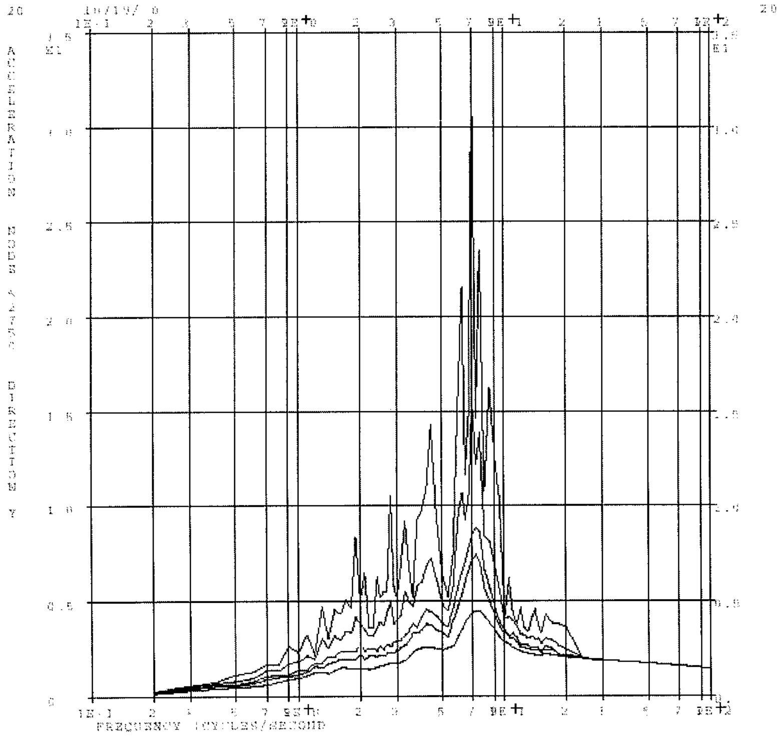

Figure 8 Acceleration spectra at main operation elevation; y-direction

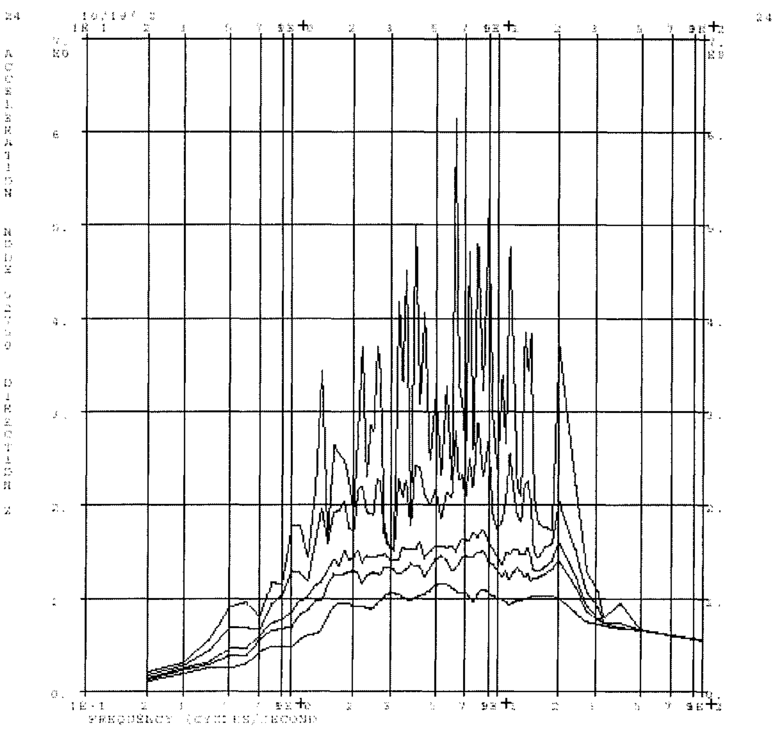

Figure 9 Acceleration spectra at main operation elevation; z-direction

PROBABILISTIC IN-STRUCTURE SPECTRA

Given the COVs for the parameters in the developed structural model (structural frequencies and damping ratios), and assuming a lognormal distribution for each parameter, the Latin Hypercube method can be used to generate a set of multipliers to be applied to the best estimate values for each earthquake simulation. For N simulations, the distribution of each parameter (defined in a normalized space solely by its COV) is divided into N ranges of equal probability. Then, for each simulation, for each parameter, a range is selected at random with exclusion (each range must be selected only once) and a value is randomly selected within that range. These values become the set of multipliers to be applied to the best estimate parameters for that simulation. The N sets of values, along with the free-field time histories constitute the experimental design. The probabilistic response analysis is performed using following steps:

- Using the free-field time histories, the best estimate structural model is used to perform N seismic response analyses.
- For each earthquake simulation, a different set of randomly selected multipliers is applied to the best estimate structural parameters.
- For each simulation, time histories are calculated for each desired response in the structure. Response spectra are then calculated for each of the acceleration time histories.
- On completion of the N simulations, mean and mean-plus-one-standard-deviation spectra are calculated for each desired response by calculating the mean and standard deviation of the N values at each frequency.

The aim of probabilistic floor spectra generation is to determine floor spectra, which can be used in estimating seismic fragilities of components. From a structural point of view the influence of an earthquake depends on its frequency and energy content at the site where the structure is located. The peak ground acceleration can be used in classifying ground shaking but not in describing complete effects of an earthquake. The best method to present the earthquake load is an acceleration time history which includes both the energy and frequency content of an event. The level of the ground motion during the earthquake is defined by the peak ground acceleration. Its frequency content is given by a ground response spectrum and its energy content is finally determined by defining the duration of the ground shaking. Acceleration histories with a given peak value and a given duration are obtained through a numerical simulation from the spectrum selected. The relationship between a time history and a spectrum is not one-to-one relationship. Thus, the ground spectrum used is a random variable presenting the characteristics of earthquakes in average. This random nature has to be preserved during the response generation process and it has to be included in the time-histories generated. In addition to the excitation, floor spectra depend also on structural properties and on modeling assumptions. Some of the factors affecting the spectra are stiffness, damping, boundary conditions, mass distribution, constitutive laws and the method of a dynamic analysis. Usually, the linear behavior of structures can be assumed. This simplifies the analysis since the properties of a linear oscillator are perfectly determined by its eigenfrequency, mass and damping. Dynamic analyses can be made by using the mode superposition technique in which the system is described as a group of uncoupled linear oscillators. The factors selected to represent the randomness of the structure and its modeling are usually eigenfrequency and damping. Floor spectra can be calculated for selected in-structure locations. The spectra can be evaluated for different damping ratios, for instance 2%, 5% and 10%. The distribution of each spectrum can be described by calculating the mean and the standard deviation at every frequency considered. If normal distribution is assumed the mean plus the one standard deviation spectrum represents the 84% non-exceedance probability percentile of the distribution. Usually, mean and mean + one standard deviation spectra depicted for every in-structure spectrum by calculating the mean and standard deviation for the values of spectral accelerations.

LATIN-HYPERCUBE SAMPLING

One method to generate the in-structure response spectra is the Latin hypercube sampling. The random variables are excitation, damping and frequency of the mode. Typical for the Latin hypercube method is a fixed number of samples, say 30 is used. Next step is to divide the distributions of the damping and frequencies into 30 intervals with an equal probability and to take one observation of the input variable from each interval using random sampling. Thus, there are 30 observations with an equal probability for each input variables. The first sample of the input variables are formed by selecting randomly one of the thirty loads and combining it with the randomly selected observation for the damping. The frequency of each mode is also randomly selected and the combination of the modal frequencies, damping and load is the first sample. To get the second sample, one of the remaining loads is selected at random and combined with one of the remaining observations on the damping and the modal frequencies. This procedure is continued to obtain 30 samples which include all the observations. The 30 samples cover the whole range of the distributions of the variables and form the Latin hypercube sample for the system. It can be interpreted that the results relating to each sample carry a subjective probability of 1/30. The main advantage of the Latin hypercube sampling method is that the entire range of each control variable is sampled with a fixed number of samples. The estimate obtained for the mean is unbiased and only slightly biased for the variance. Thus, the method is a valid alternative for Monte Carlo simulation where a large number of samples is needed to describe continuous probability distributions. The time-history analyses are very labor intensive and it is necessary to restrict the number of calculations to be as small as possible.

CONCLUSION

The in-structure response spectra for the Leningrad NPP were generated. The method to extend the analysis for probabilistic response generation was described. The soil-structure interaction effects in generating the structural response were accounted for. The modeling approach was true 3D modeling and the next step in ongoing Probabilistic Safety Assessment effort is the fragility analysis of heavy equipment with the aid of coupled model including heavy equipment and structures.

REFERENCES

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