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Three Dimensional Probabilistic Soil-Structure-Interaction Analyses for Buildings of NPP Beznau

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ABSTRACT

In the framework of new evaluation of fragilities for the seismic probabilistic safety analysis of the Beznau NPP, three-dimensional probabilistic seismic response analyses including the soil-structure interaction effects are performed for ten safety-related buildings using computer code SASSI2000. The generation of Acceleration Response Spectra (ARS) for seismic design and re-qualification of safety-related components is based on deterministic analyses according to the state-of-the-art methods in the mid eighties using simple lumped-mass stick models of structures with frequency-independent soil springs and dampers. This paper presents the assumptions for the probabilistic response analyses and comparisons of ARS from the probabilistic analyses and the earlier deterministic design analyses. The results of the probabilistic SSI-analyses are basis to evaluate seismic fragilities for structures and components.

INTRODUCTION

Current requirements for Swiss NPP's include a full-scope Level 1 and Level 2 PSA Study for full-power modes, for shutdown and low power states. Any of these has to include seismic events. The first Beznau PSA study was started in 1983 and included the scope of seismic PSA from the beginning. Based on this study several seismic upgrades were performed in the years after. Consequently in 1992 and 1993 additional bunker systems were added to the Beznau Units. Later on a full-power PSA was conducted by implementing new seismic fragilities. At the same time a project to perform some seismic upgrades was started. Independently from Beznau fragility analyses, a complete reevaluation of the seismic hazard at Swiss NPP sites was performed during 2000 – 2004, the so-called PEGASOS project [1]. This project was conducted according to the Guidelines in NUREG/CR-6372 for SSHAC as a Level 4 study and to replace the earlier hazard analyses [2]. A follow-up project to improve the seismic hazard results is intended to be started soon. As a first step of seismic PSA fragilities will be updated. The overview on updating fragilities will be presented in a separate paper in Division: M. Structural Reliability, Probabilistic Safety with the Title: "Updating of Seismic PSA of Beznau Nuclear Power Plant" [3]. In the framework of updating fragilities, probabilistic seismic response analyses for ten buildings of NPP Beznau were performed. These are Reactor Building, Auxiliary Buildings A and C, Spent Fuel Building, Intermediate buildings D and E, Turbine Building East Structure, Notstand Building, Boric Water Tanks Building, Feed Water Tanks Building.

METHODOLOGY

The purpose of the SSI-analyses was to generate probabilistic seismic responses of the buildings included in the seismic PSA for the Beznau NPP. The computer Code SASSI2000 was used to perform 3D probabilistic SSI-Analyses [4]. The analyses were performed using the aggregated surface Uniform Hazard Spectra at an annual probability of exceedance of 10^{-5} scaled to a horizontal peak ground acceleration (PGA) of 1.0g. The results of the analyses were scaled to the desired input level for fragility calculation. The mains steps to perform probabilistic SSI-Analyses were the following:

a) Selection of input motion and probability level
b) Development of median strain compatible soil profile
c) Development of median structural model
d) Development of an ensemble of 30 earthquake time histories
e) Development of Latin Hypercube multipliers for soil and structural parameters
f) Development of the ensemble of 30 SSI problems according to a Latin Hypercube sampling
g) Perform 30 SSI-analyses with Computer Code SASSI2000
h) Statistical evaluation of seismic responses

Selection of Input Motion and Probability Level

The horizontal and vertical aggregated UHS at an annual probability of exceedance 10^{-5} defined at the surface of Beznau site were selected as input motion. In the development of seismic fragilities, the input spectral shape is the controlling element for the evaluation of the seismic demand. Typically, the spectral shapes corresponding to earthquakes occurring at different distances from the site in question could be different due to predominant low frequency waves content in distant earthquakes and the predominant high frequency waves in the near earthquakes. According to the results of

PEGASOS-Project, the spectral shapes for earthquakes at different distances are practically identical. Thus, it is clear that seismic analyses performed using any of the spectra, aggregated or disaggregated, when the input scaled to the same level will produce, for all practical effects, the same seismic responses. Furthermore, since the seismic demand will be obtained by probabilistic analyses, any small differences between various spectral shapes will be covered by the differences in the spectral shapes of the thirty input motions used in the probabilistic analysis.

The median motion at the surface was selected as the input motion for the probabilistic SSI-Analyses. The methodologies used to develop UHS considered the characteristics of the soil layers. Most of the structures at Beznau are founded at or near the surface, so for these structures the surface time history is the right selection. Any other assumption will result in unrealistic and conservative results. The Reactor Building founded at -15 m has a soil-structure horizontal frequency about 2.7 Hz. At that frequency, the horizontal PEGASOS spectrum at the surface and the horizontal spectrum evaluated from propagated motions are practically the same. Thus, no large differences in responses will occur by using either of the input motions.

Similar to the explanation for the disaggregated spectral shapes, the spectral shapes for the UHS for different annual probability of exceedance are very similar. This is shown in Figure 1. There, it can be also observed that the UHS for an annual probability of exceedance of 10^{-3} is much lower than the UHS for 10^{-5} and is unable to cause damage in an engineered nuclear structure. In the SSI-analysis, the parameters that will be mostly affected by the seismic level are the strain compatible median soil properties. To compare the effects that the 10^{-4} and 10^{-5} levels will have in the analysis, strain compatible soil properties were calculated for both levels and compared in Figure 2. It is concluded that the soil properties for both seismic levels are close enough and that the difference in median soil properties will not have, for all practical purposes, an effect in the seismic responses (when the input motions associated to both annual probability of exceedance are scaled to the same maximum ground acceleration). These differences in the median soil properties are negligible in the context of the probabilistic SSI –analyses where the soil properties are varied by a much larger amount.

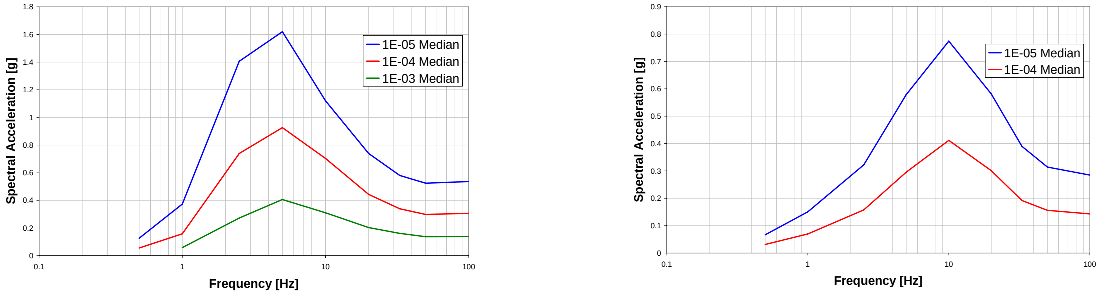

Figure 1: Beznau UHS at soil surface for 5% damping, left horizontal component, right vertical component

Development of Median Strain Compatible Soil Profile

In the framework of PEGASOS-Project all existing site and laboratory investigations for soil and rock had been checked and compiled. Experts for site response analyses reviewed all material and decided to use three different soil profiles for shear wave velocities and one set of degradation curves from laboratory tests as median soil properties. Based on median soil properties, site response calculations had been performed using different methodologies. Then experts gave their assessments individually for the amplification factors basing on different soil profiles. The soil profile 1 was highly ranked by experts. Therefore the same profile was used to develop median strain compatible soil profile and as input for SHAKE calculations [5]. This is shown in Figure 2. Since the water table could be considered as another random variable it was decided to maintain constant the ratio between P- and shear-wave velocities (equivalent to maintain constant the Poisson’s ratio) to somehow capture the possible variation in P-Wave velocities in soil layers. The highest Poisson’s ratio used is 0.474 well within the range for accurate SASSI results.

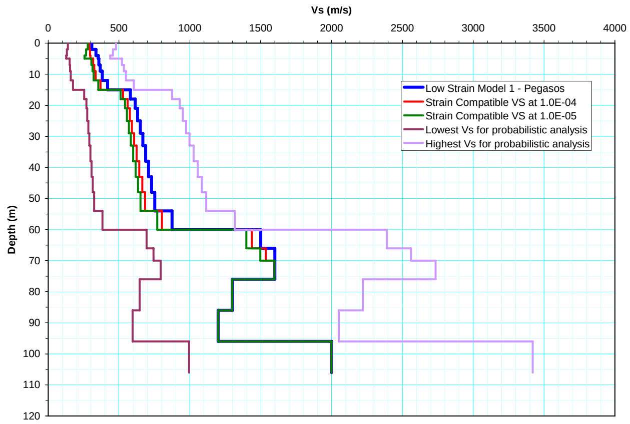

Figure 2: Shear wave velocity profiles

Development of Median Structural Model

The three-dimensional finite element structural models which were used for deterministic stress analyses for the seismic re-qualification of the buildings were converted to SASSI and used as median structural models. Some simplifications of the models at the interfaces of the foundation and soil medium were necessary to limit the number of interaction nodes in the SASSI models.

Development of Ensemble of 30 Input Motions

In order to perform the probabilistic SSI analyses, an ensemble of 30 earthquake records with 3 components each were chosen from the European earthquakes catalog with magnitudes ranking from 5 to 6.4 and distances varying from 0 to 125 km. These acceleration time histories were modified such that the median and 84th percentile of their response spectra matched the median and 84th percentile of the surface UHS with an annual probability of exceedance of 10^{-5} but scaled to a horizontal peak ground acceleration (PGA)of 1.0g. Figure 3 shows all ensemble of time histories and the comparison between the median and 84th percentile UHS and the median and 84th percentile of the response spectra from this ensemble of time histories. However, since the 84th percentile UHS which is derived from different sets of seismic hazard curves from PEGASOS has accounted for the uncertainty in the seismic hazard modeling, and since that uncertainty will be explicitly modeled in the risk quantification, that uncertainty was eliminated from the 84th percentile spectra used to develop the ensemble of 30 time histories. This is to avoid double-counting the same uncertainty. Instead, a logarithmic standard deviation of 0.20 is used to account for peak-to-valley variability of the median UHS. This results in an 84th percentile spectrum that is approximately equal to 1.22 times the median UHS. The median spectral accelerations from the 30 time histories have a good match for all frequencies below 30 Hz. The median of all the PGA values in horizontal direction is about 1.2g, 20% higher than PGA of the scaled UHS.

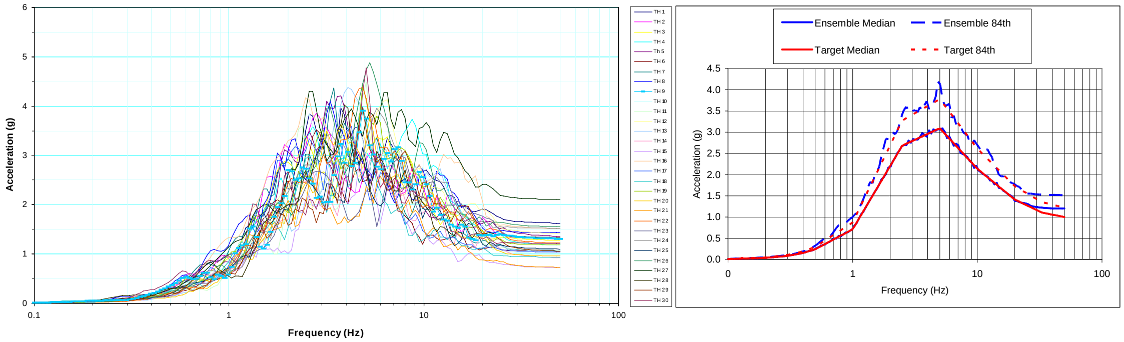

Figure 3: Right: TH ensemble for horizontal component X, Left: ARS of TH is matched to E-05 UHS

Development of Latin Hypercube Multipliers for Soil and Structural Parameters

To model the uncertainties in the structural and soil models, two structural and two soil parameters are varied: These are frequencies and damping for structures; and damping and shear modulus for soils (G). The variation of the selected parameters not only represents the variation in their numerical values but also the uncertainty in the modeling and analysis. In the development of the Latin-Hypercube soil-property parameters, iterations were performed to try as much as possible to get increasing shear modulus factors with decreasing soil damping parameters and vice-versa.

According to a PEGASOS report a factor of 1.3 over the median shear wave velocity represents the 2σ range. This factor of 1.3 for median shear wave velocity is equivalent to a factor of 1.69 (1.3^2) for median shear modulus G. Assuming for lognormal distribution for G, a coefficient of variation for G (COV_G) results as 0.33. For the soil shear modulus G, the variation associated to the basic shear wave velocity and the variation in the degradation curve should be combined. Thus, the total lognormal standard deviation of G is estimated at 0.50. Again according to PEGASOS experts a lognormal standard deviation of 0.35 will represent the $\pm\sigma$ range for degradation curves for soils, this implies a COV_{ξ} for soil material damping. However, the uncertainty in the soil damping was judged to be at least as high as the uncertainty in the soil shear modulus, thus for developing the soil profiles samples for the probabilistic analysis, the soil damping COV was increased to 0.5.

The variation of structural parameters will be represented by the variation of the structural damping and the structural frequencies. The variation in structural frequencies is assumed to represent the variation in stiffness and masses which depends on the concrete strength and structural modeling i.e., estimating the masses, numerical modeling of structural elements. The typical concrete strength COV is about 15%. Assuming that COV ascribed to modeling is about equal to this, the overall variability in structural frequencies is estimated to be 22%. Conservatively, the COV is increased to 0.25.. The median damping value for reinforced concrete structures at or near yield is estimated at 10% and the one standard deviation lower bound damping is 7% [6]. Thus the COV for damping of reinforced concrete structures is estimated at 0.35.

Development of Ensemble of 30 SSI problems according to Latin Hypercube Sampling

The median strain compatible soil properties and median structural models properties are multiplied by these factors to generate an ensemble of 30 soil and structure models to be used in SSI analyses as follows: The probability distribution of each variable with unit median and assigned COV is discretized into 30 equal probability intervals. A single value is sampled at random from each interval. This process is repeated for all the four variables, one factor is randomly selected and used to scale the soil and structural parameters to develop a new soil-structure model for analysis. One set of earthquake time histories is randomly selected and input to the new soil-structure model. The selected factors and earthquake are eliminated from their sets and the process is repeated 30 times.

Perform SSI Analyses with Computer Code SASSI

One case by setting all factors of Latin Hypercube multipliers to 1.0 is called “median centered case”. For this and each of the other thirty trials a deterministic SSI analysis is performed with the computer code SASSI. The frequencies up to 40 Hz are considered in the analyses. The main responses were extracted as in-structure response spectra, maximal accelerations, and maximum displacements at selected locations and maximum stresses at selected structural members. The maximum forces in structural members were obtained by integrating the stresses in structural members. Totally 31 sets of SASSI analyses for each building were performed.

Statistical Evaluation of Seismic Responses

The last step of the probabilistic seismic response analysis was the calculation of median and 84th percentile of the responses, including the global response of the buildings, i.e., story shears and overturning moment, story accelerations and displacements, and in-structure floor response spectra, using the results of the thirty trials.

FINITE ELEMENT MODELS OF STRUCTURES

Structure models were generated using ANSYS [7]. They include all horizontal and vertical structural members. The beams and columns are represented by three dimensional beam elements, slabs and walls with shell elements. The foundation of the reactor building was modeled by using solid elements. Live loads were added to the slabs. The components were modeled as three dimensional mass elements at their supports. The size of finite elements varies between 1.0 m to 5.0 m. The reactor building model is shown in Figure 4.

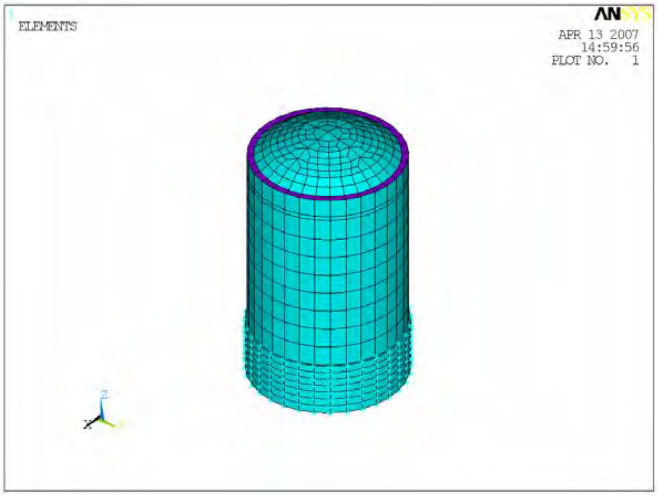

Figure 4: Finite Element Model of Reactor Building

COMPARISON OF RESULTS

The plausibility of the probabilistic SSI-analyses results capturing the global dynamic behaviour of the soil-structure system is checked by comparing the results with that of deterministic design response analyses. Furthermore, the comparisons of RSA allow a first judgment (not precise)of seismic margins due to differences in the spectral shape, calculation methods and dynamic models. Acceleration response spectra from the probabilistic SSI analyses for all buildings were compared with those from deterministic analyses. The assumptions for deterministic and probabilistic analyses are given in Table 1. For comparisons of ARS median results from probabilistic SSI-analyses were used. Deterministic analyses had been performed to generate ARS for SSE using simplified 3D lumped mass models soil springs and dampers. Seismic input for SSE was one set of time history with three components which was matched to USNRC Regulatory Guide 1.60-Spectrum scaled to 0.15g at the foundation level of the reactor building and 0.21g at the surface. Therefore for comparisons the ARS from deterministic analyses were scaled adequately for 1.0g max accelerations in horizontal and 0.67g vertical input. The scale factors are calculated as ratios of spectral accelerations between the PEGASOS median UHS for NEP 10^{-5} and SSE spectral acceleration at the dominant SSI system frequencies for 5% damping in horizontal and vertical directions. The linear scaling of the SSE ARS at higher ground acceleration may be somewhat optimistic because of nonlinearity of soil. However, it is to be noted that the purpose of the comparisons is to check the plausibility and to illustrate the tendencies. The results of the comparison will not be used numerically in any safety analyses or to scale the existing fragilities..

Table 1: Comparison of assumptions for deterministic and probabilistic analyses

	Deterministic Design	Probabilistic
Structure Model	Lumped mass model	Detailed plate and shell model
Soil model	Soil springs and dampers	3D Soil model consisting horizontal layers and half space
Seismic Input	1 set of TH (3 components)	30 sets of TH's (3 components)
Spectral Shape	US-NRC 1.60 [8]	PEGASOS, site specific UHS

The buildings of NPP Beznau can be categorized according their design and construction periods as old and new buildings. Old buildings were designed and constructed four decades ago. However they are re-qualified for seismic actions two decades ago and consequently Auxiliary Building A is upgraded. The new buildings are erected in the framework of seismic upgrading of the plant beginning of nineties. Seismic design of new buildings are based on more conservative assumptions like neglecting of embedment, reducing the damping values, using surface ground motion level at the depth compared to the realistic assumptions for the seismic re-qualification of the old buildings. The results are compared for Reactor Building and Auxiliary Building A representative for the old buildings and for Notstand Building representative for the new buildings.

The ARS at the operating floor of the reactor building from deterministic and probabilistic analyses are shown in Figure 5. As it can be seen the scaled deterministic analysis overestimates the median responses in all three directions. Due to an embedment of 15 m the reactor building has especially in vertical direction relatively high geometric damping. In the deterministic analyses the geometric damping was limited to be on the conservative side.

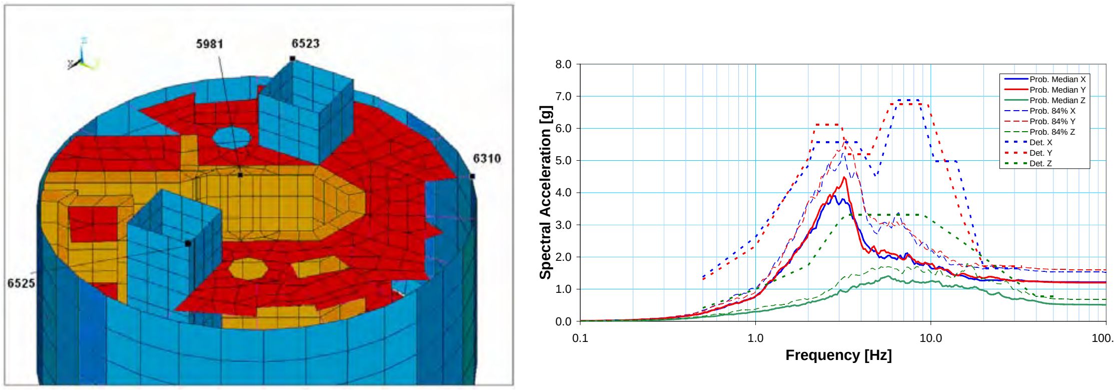

Figure 5: Part model of Reactor Building, comparison of ARS for 5% damping at Node 5981 (Elev. +13.00 m) from probabilistic and deterministic analyses.

The FE-model of Auxiliary Building A and the comparison maximum accelerations from the deterministic and probabilistic analyses are shown in Figure 6. With exception of Y-direction at the top of the roof structure the scaled deterministic analyses results envelope the results of median and 84th percentile results. The differences are due to different analysis assumptions. The ARS from the scaled deterministic and the probabilistic analyses are compared at the foundation and roof elevation in Figure 7. With exception of a narrow frequency band between 3.6 and 3.8 Hz at the roof level the ARS from deterministic analyses envelope the median results from probabilistic analyses. The shell model of the Auxiliary Building A coupled with the soil is flexible than the lumped mass model with the soil springs. The stiffness of soil springs were determined for a lower level of ground motion than the actual ground motion level.

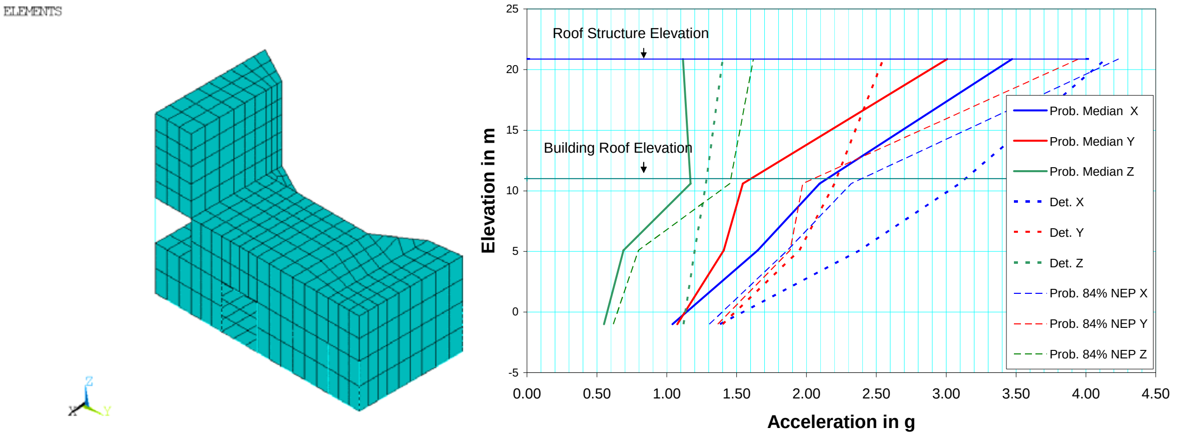

Figure 6: Auxiliary building A Left. FE-Model, Right: Comparison of Maximum Accelerations over the height

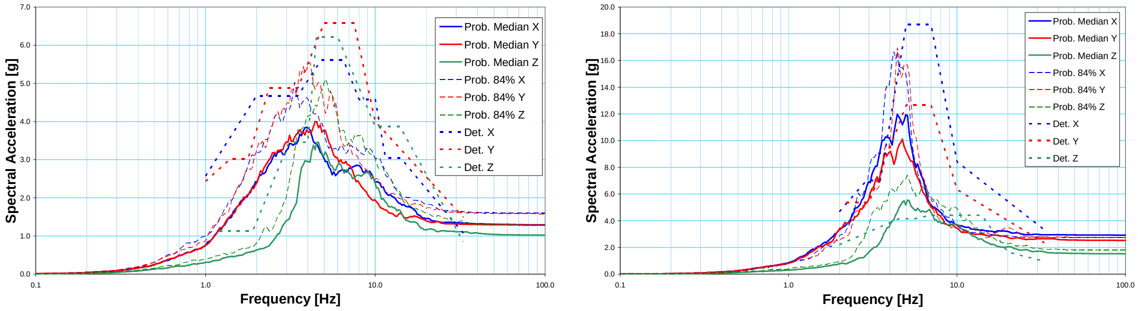

Figure 7: Comparison of ARS for 5% Damping in Auxiliary Building A, Left: Foundation level at elev. -1.00 m, Right: Roof level at elevation +11.00 m.

The FE-Model for Notstand Building, representative for new buildings and the comparison of the maximum accelerations over its height are shown in Figure 8. For this case median and 84% fractile values of probabilistic analyses are shown. The ARS from probabilistic analyses at the Elevation +13.00 m and the comparison of median with the scaled deterministic ARS is shown in Figure 9. Due to conservative assumptions in the deterministic analysis, the scaled deterministic results envelope all probabilistic results including those for 84% fractile.

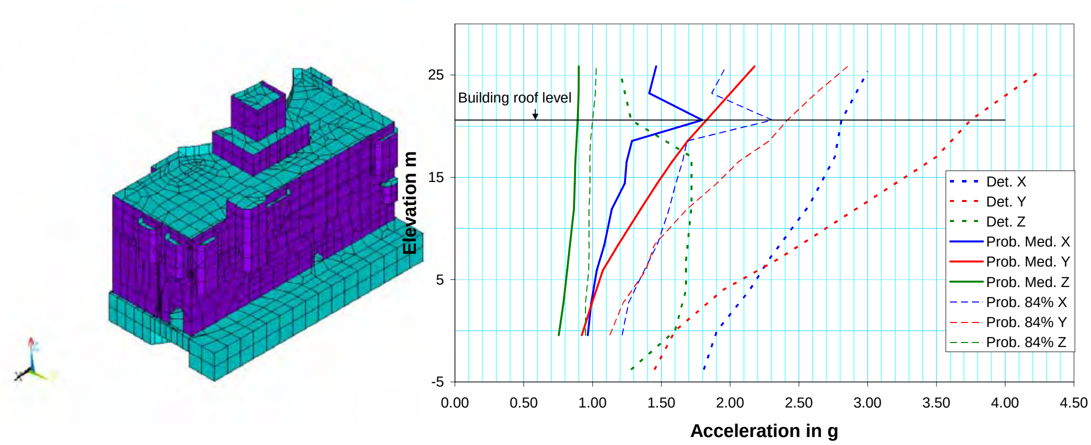

Figure 8: Left FE-Model of the Notstand Building, Right: Comparison of PGA-values over the height of Notstand Building

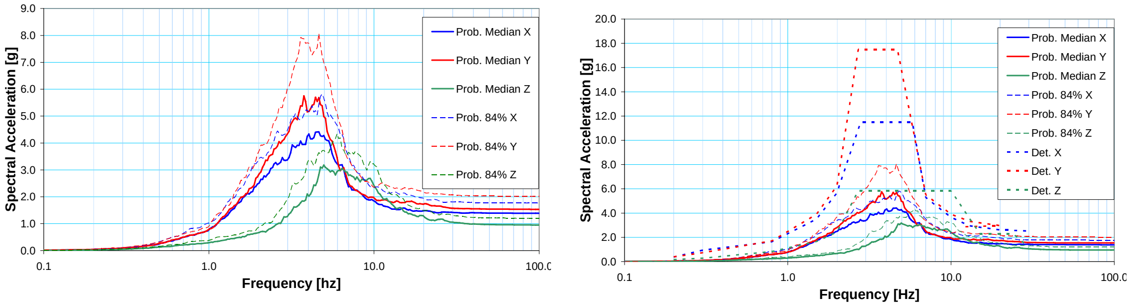

Figure 9: Notstand Building operating Floor Elev. +13 m. Acceleration response spectra for 5% damping, Left: RSA from probabilistic SSI, Right: comparison of RSA from probabilistic and scaled deterministic analyses

Furthermore, the maximum accelerations for median case over the height of each building as well as their linearized “trend lines” are shown in Figure 10. As expected the floor zero period accelerations of the stiff and massive structures are amplified less than the flexible and lighter structures. As shown in Figure 10, the amplification factor is about 2.6 at 63 m height of the reactor building. This factor amounts to about 4.2 at the height of 14.0 m of Building D. This and similar charts for spectral accelerations for different damping ratios can be generated and utilized for a quick estimate of accelerations and spectral accelerations at each floor for different seismic input.

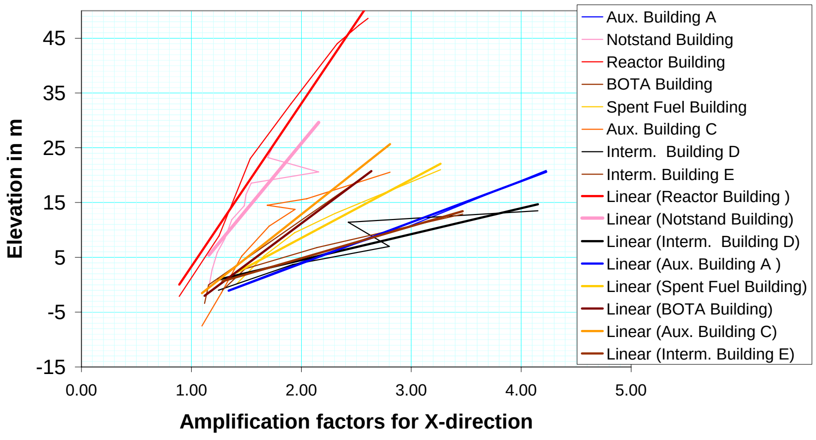

Figure 10: Amplification factor for median PGA-values over the height of buildings together with their trend lines

CONCLUSIONS

Probabilistic seismic response analyses including the effects of soil-structure interaction were performed for the Beznau structures. The methodology presented in the paper explicitly accounted for variability in the seismic input motion, soil modeling, and structure modeling. Thus the analyses provided realistic prediction of seismic response at the shaking level where failure is expected also realistic estimates of the associated randomness and uncertainty variability. The results enabled the fragility analysts to better estimate seismic fragilities of safety-related buildings and equipment.

By comparing the median values of the probabilistic results with that of the scaled deterministic design SSE analyses, one is able to confirm that dynamic characteristics of the SSI models and the results are consistent, in a qualitative manner, with the previous design analysis results obtained by the plant. For most of the buildings, the scaled deterministic ARS envelope the median ARS of the probabilistic SSI response analyses. This is due to conservatism in the design methodology using simplified models and conservative assumptions.

NOMENCLATURE

ARS : Acceleration Response Spectra
COV: Coefficient of variation
NEP: Non-exceedance probability
PEGASOS : Probabilistic Seismic hazard Analysis for Swiss Nuclear Power Plant Sites
PGA : Peak Ground Acceleration
SSI: Soil Structure Interaction
TH : Time History of Accelerations
UHS: Uniform hazard Spectrum

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