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EVALUATION OF THE SEISMIC RISK OF A NPP BUILDING USING THE CONDITIONAL SPECTRA APPROACH

Philippe L.A. Renault[1], Dirk Proske[2], Davide Kurmann[3] and Alejandro P. Asfura[4]

[1] swissnuclear, P.O. Box 1663, 4601 Olten, Switzerland
[2] Kernkraftwerk Beznau, 5312 Döttingen, Switzerland
[3] AXPO Power AG, Parkstrasse 23, 5401 Baden, Switzerland
[3] APA Consulting, 181 Rudgear Drive, Walnut Creek, CA 94596, USA

ABSTRACT

A well-known shortcoming of a UHS in the context of seismic PSA studies consists in the fact, that it represents an enveloping spectrum from multiple earthquakes at different spectral frequencies and thus, is rich in energy over the whole frequency band. This source of conservatism can be reduced when using earthquake scenario spectra (Conditional Spectra) with realistic spectral shapes, mainly based on the selection of real recordings. The Conditional Spectra approach has been introduced by Abrahamson & Al Atik (2010) and practical implementation issues have been recently discussed in Carlton & Abrahamson (2014). In Switzerland, seismic PSA studies are the risk assessment tools for nuclear power plants to estimate Core-Damage-Frequency (CDF) and Large-Early-Release-Frequency (LERF) based on the expected seismic hazard at a particular site. The benefit of the Conditional Spectra approach can only be assessed when performing a full PSA and comparing at the end the resulting risk quantities. This paper discusses and compares the performed work and final risk quantities when using both approaches to determine the earthquake scenarios. Furthermore, some practical engineering issues are highlighted which have come up in the implementation for a real structure which have the potential to be improved within the approach. The latter also include the dynamic soil-structure interaction analysis of the building.

INTRODUCTION

This contribution is a continuation of the work presented at SMIRT-22 (Renault & Kurmann, 2013) which has the goal to compare the benefit of using the Conditional Spectra (CS) approach rather than the conventional Uniform Hazard Spectra (UHS) based method for seismic Probabilistic Safety Assessment (PSA). Through the plant specific probabilistic seismic hazard assessment (PSHA) (swissnuclear, 2013) the hazard curves and Uniform Hazard Spectra for the structural analysis are available. Furthermore, within the post-processing of the hazard results plant specific Conditional Spectra were developed.

DEVELOPMENT OF HAZARD CONSISTENT SCENARIO EARTHQUAKES

The classical approach to perform the probabilistic safety assessment requires the selection and development of time histories which are modified to fit the UHS at the desired level of annual probability of exceedance. Different techniques can be used to modify the time histories. Here the spectral matching approach by Abrahamson (1992) was utilized to develop the spectrum compatible acceleration time histories which employs a time domain approach. The goal was to modify an empirical seed input time history (taken from the NGA-West database, http://peer.berkeley.edu/nga/ and the RESORCE database, http://www.resorce-portal.eu/) to be spectrum compatible with a given target spectrum without significantly modifying the non-stationary characteristics of the input seed time history. The initial selection of the candidate seed time histories for the spectral matching process was guided by the results (i.e., both design spectra and hazard deaggregation results) of the design ground motion development. A total of 30 three component sets (i.e., two horizontal and one vertical component) are developed for each uniform hazard spectra at three mean annual frequency of exceedances of 10^{-3}, 10^{-4}, and 10^{-5}. For the spectral matching of the two horizontal components, an additional horizontal-to-horizontal variability was applied to the defined horizontal design spectra. This variability is based on a statistical analysis of empirical data and is defined as a function of spectral period. The spectral matching criteria provided in SRP 3.7.1 (NRC, 2008, McGuire et al., 2001) was followed for this analysis.

The mathematical background for the Conditional Spectra approach is briefly summarized in Renault & Kurmann (2013). Thus, here only the results are shown in order to demonstrate the consistency with the computed seismic hazard. As input to the approach the recordings of the NGA-West2 database (Ancheta et al., 2013) and RESORCE database (Akkar et al., 2013) have been used. In total 4993 spectra matching the requirements given by the deaggregation (dominating magnitude and distance range) and the response spectral shape were retained. The automatic selection resulted in 430 Conditional Spectra to be used to recreate the site specific seismic hazard. The consistency with the horizontal component for nine project relevant frequencies is illustrated as example in Figure 1.

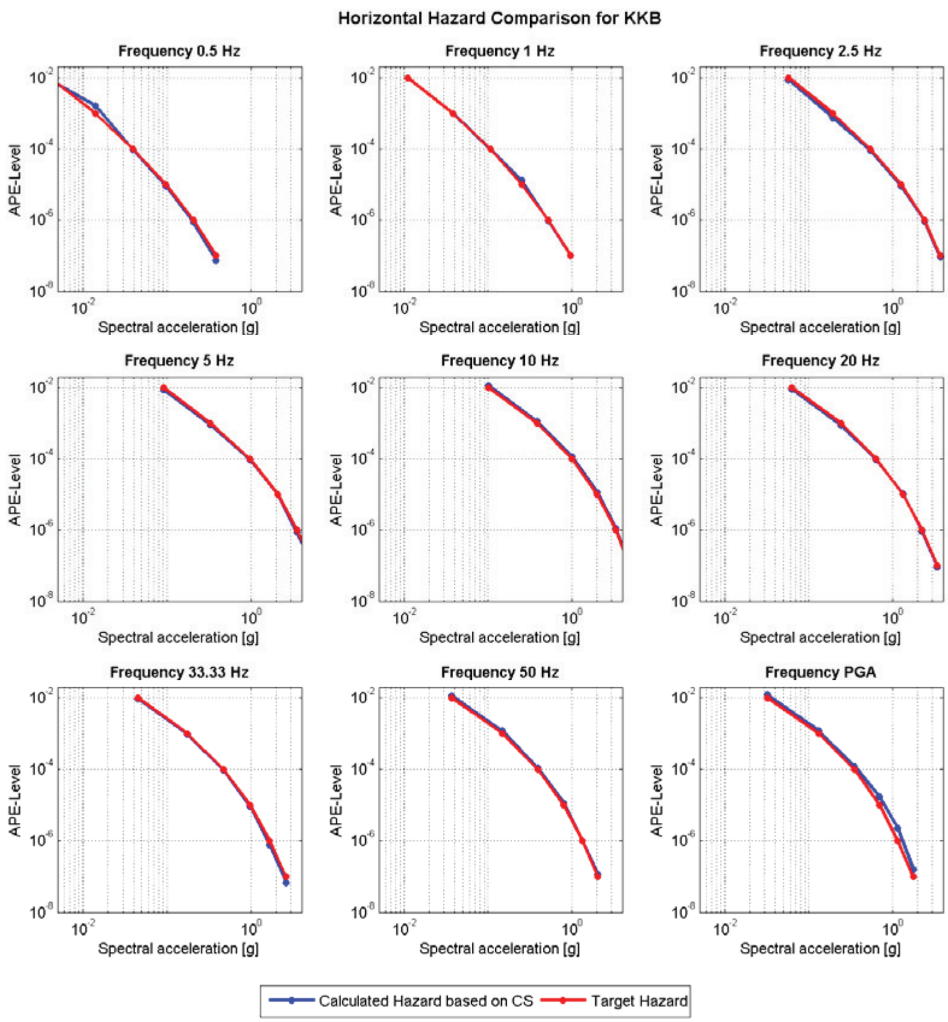

Figure 1. Comparison of target mean hazard curves for different frequencies with the re-computed hazard based on the defined Conditional Spectra.

Within those 430, only 74 time histories are unique and the other 356 represent scaled versions of the 74 ones (those numbers vary for other sites or hazard results, respectively). Thus, the structural analysis needs only to be performed with those 74 time histories and, under the assumption that everything stays linear, the total amount of results can be obtained through scaling of the soil-structure interaction (SSI) results based on the unique time histories. The basic difference in the Conditional Spectra approach is that each of the 430 time histories has an associated rate to it, which sums up to one. In the classical approach where e.g. 30 time histories are used all of them have the same likelihood and are not “weighted” when combined together in terms of results. The resulting 430 response spectra for the horizontal (geometric mean) and vertical component associated with the time histories are shown for Swiss Nuclear Power Plant Beznau in Figure 2. In Figure 3 the consistency with the mean UHS is shown for the annual probabilities of exceedance of 10^{-3} to 10^{-7}.

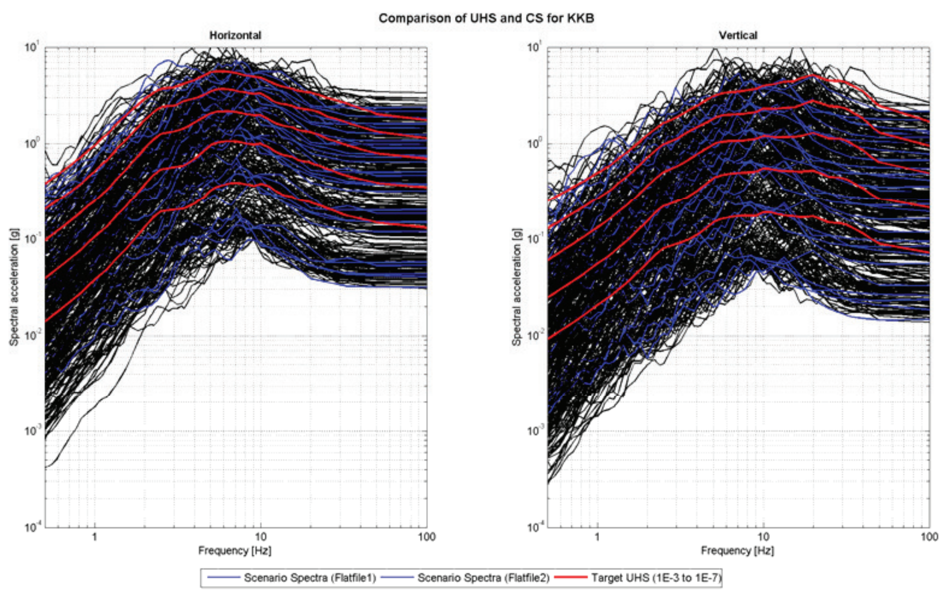

Figure 2. Scenario response spectra for the horizontal and vertical component compared to the target UHS for annual probabilities of exceedance of 10^{-3} to 10^{-7}.

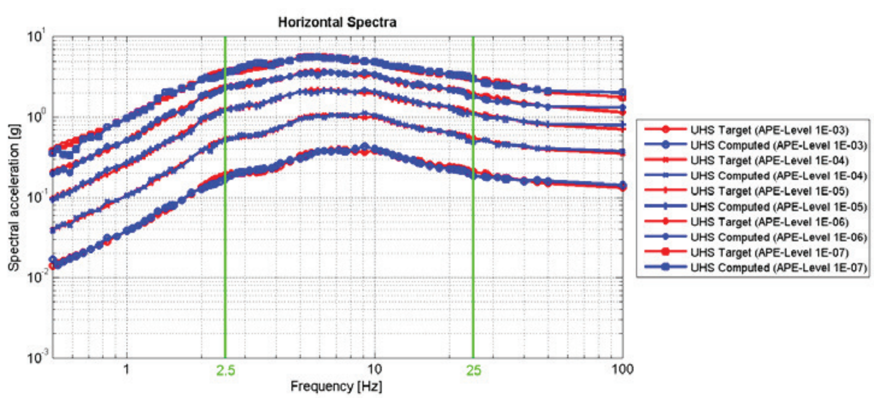

Figure 3. Comparison of the horizontal target UHS (same as the red lines in Figure 2) and the re-computed UHS for discrete points based on the scenario response spectra. Tight matching between the frequencies at 2.5 and 25 was defined in order to represent the range of relevant frequencies for the NPP.

PLANT CONFIGURATION

The Nuclear Power Plant (NPP) Beznau is located in the Northern part of Switzerland and consists of two Westinghouse pressurized water reactors of early design. Unit 1 went into operation 1969 and is actually the oldest operating PWR in the world. Unit 2 started operation in 1971. The net power output per unit is 364 MWe. Both units were extensively backfitted during the last three decades, also with respect to seismic events. The main backfitting measures were:

- Construction of additional safety systems located in a separate bunker building which are fully seismically qualified according to recent standards and which are fully separated from the “old” systems. The seismic design of the new bunker systems corresponds to 0.21 g PGA (equivalent to 0.15 g at the foundation level of the reactor building), while the old plant was designed for an SSE of 0.12 g, but using very simplified methods. The structural design of the new bunker building was mainly driven by aircraft crash load considerations. The bunker systems have their own and independent support systems and control room. This backfit extended the original two-train safety systems configuration to three trains. In addition, the third train is fully diverse and significantly reduced the total CDF.
- Construction of an additional train of emergency feed water
- Installation of containment filtered vent and of passive autocatalytic hydrogen recombiners
- Replacement of old equipment by new one: refuelling water storage tank, steam generators, main condensers, high pressure turbines, many valves, reactor protection system, turbine control, MCR desks
- Currently the emergency power supply system for the “old” plant is replaced by two new diesel generators per unit located in separate buildings (project AUTANOVE)
- Furthermore, the reactor vessel head and the plant information system are currently replaced.

This study uses the PSA-model of the latest plant configuration, but considers the Conditional Spectral approach only for the bunkered systems.

SOIL-STRUCTURE INTERACTION ANALYSIS

Two approaches were followed to perform probabilistic soil-structure interaction analyses in support of a seismic probabilistic risk assessment of a typical nuclear building (Figure 4). The first approach will be referred as the “Classical Approach” and the second one as the “Conditional Approach.”

The building used for these analyses is founded at the surface of the soil profile shown in Figure 5. The input motion is located at a depth of 14 meters below surface.

Issues for the SSI

During the implementation of the time histories based on the Conditional Spectra approach two issues were encountered, which could be resolved and lead to a subsequent modification of the Conditional Spectra approach:

- The development of the strain compatible soil profiles requires knowledge about the ground motion level for the used time histories. For the Conditional Spectra approach there are 430 different ground motion levels and spectral shapes. One solution could be to define groups of response spectra with the same characteristics which lead to the same strain compatible soil profiles.

- The scaling factors for the horizontal and vertical spectra for one 3-component time history are not required to be the same. In consequence this required the SSI to be run for the two horizontal and the vertical component separately, as the results needed to be scaled with their corresponding scaling factors. The Conditional Spectra code has since then be modified to use the same scaling factor for the horizontal and vertical component without losing accuracy in the reproduction of the two hazard components.

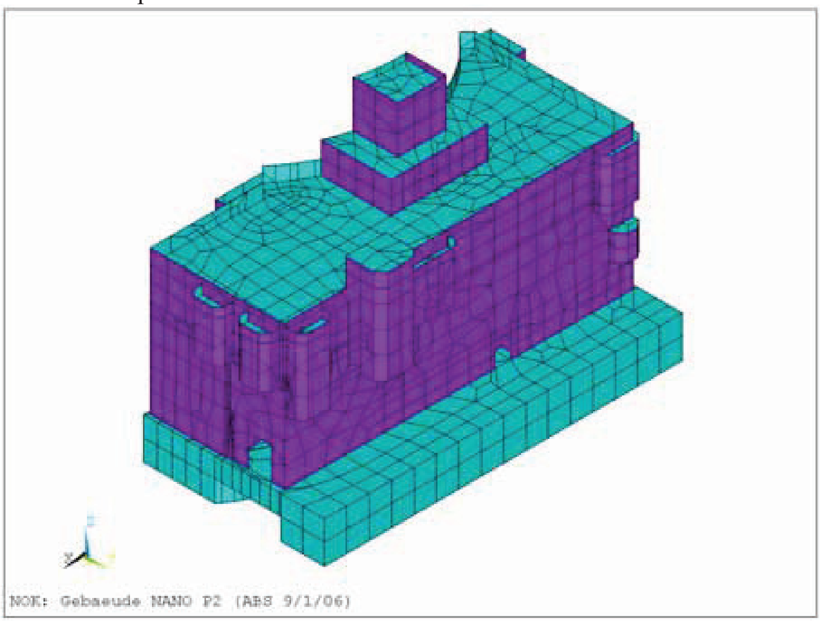

Figure 4. Finite Element Model of the analyzed Bunkered Building.

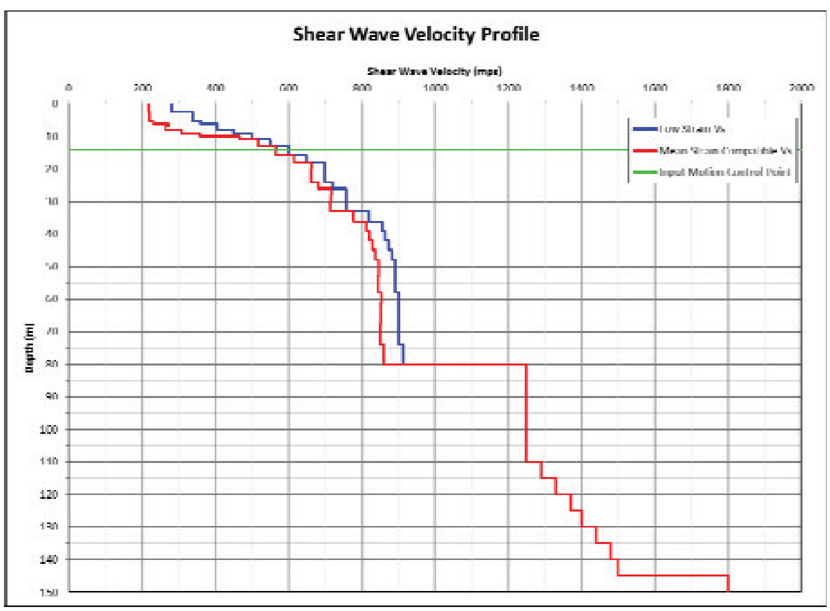

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Figure 5. Shear wave velocity profile and strain compatible soil profile. The input motion was introduced at -14 m depth, depicted by the green line.

SSI for Classical Approach

For the Classical Approach, 30 earthquakes, 3 components each, were developed such that the mean of their pseudo-acceleration response spectra matched the mean 10^{-3}, 10^{-4} and 10^{-5} UHS. As an example, Figure 6 shows the spectra of the first horizontal component of the 30 earthquakes for an annual probably of exceedance of 10^{-4}. In that figure, the thick black line is the mean of the 30 spectra, and the dashed red line is the target mean UHS.

These 30 earthquakes were used to perform 30 site analyses of the soil profile shown in Figure 2 (blue line). Computer code SHAKE was used for these site analyses. The results of these site analyses were 30 strain compatible soil profiles to be used in the probabilistic SSI analysis. The mean of the 30 strain compatible shear wave velocity profiles is shown as a red line in Figure 5.

Thirty SSI analyses of the building shown in Figure 1 were then performed with computer code SASSI, pairing each earthquake with the associated strain compatible soil profile, to obtain 30 sets of dynamic responses at various locations of the building. Figure 7shows an example of the statistics of the response spectra calculated at one location on the building.

SSI for Conditional Approach

For the Conditional Approach, 74 unscaled earthquakes, 3 components each, were used for the SSI analyses. To simplify the SSI analyses, the mean strain compatible soil profile (red line in Figure 5) calculated with 30 earthquakes for the Classical Approach was used for each of the 74 earthquakes. This simplification was considered acceptable since the variation in soil properties for the 30 earthquakes is very small, in average less than 10% for the soil above the control motion location and in average less than 2% for the soil below the control motion location. Then, 74 SSI analyses of the building shown in Figure 4 were performed with computer code SASSI, pairing each earthquake with the mean strain compatible soil profile, to obtain 74 sets of dynamic responses at various locations of the building.

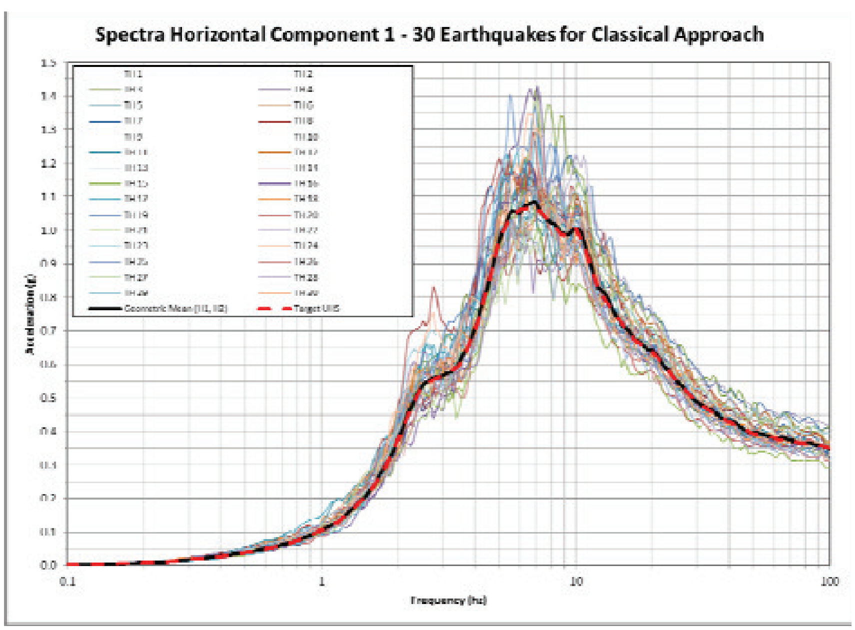

Figure 6. Spectra of used 30 time histories – Horizontal component 1

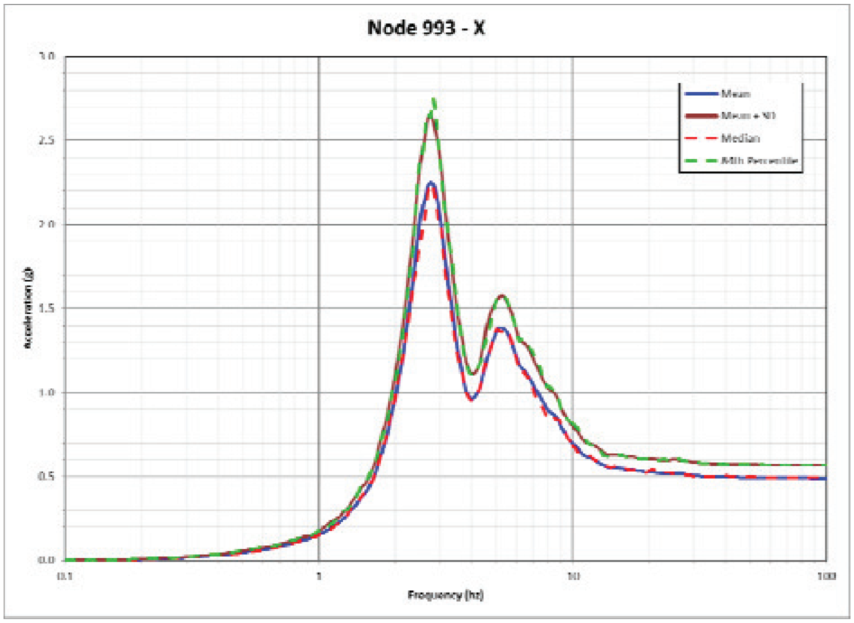

Figure 7. Example statistics of in-structure response spectra at one specific point in the structure – Classical Approach

CURRENT PSA MODEL AND RESULTS

The Nuclear Power Plant Beznau has a strong history in PSA, both in Level 1 and in Level 2 and for full-power and for shutdown conditions. A first Level 1 PSA study was performed in the mid 1980s including all relevant internal events, external events (seismic etc.) and internal plant hazards (fires, floods) at full-power modes. The current full-power PSA model includes nearly 2000 components, over 7000 Basic Events, over 300 Top Events and over 200 initiators. The common PSA software RISKMAN is used. The results of the latest PSA show, that the availability of the components in the bunkered system has a very strong impact on the core damage frequency (CDF) in terms of RAW (Risk Achievement Worth), although the AUTANOVE project decreases the importance. This fact is not surprising, since the bunkered system is excellently protected against external events including seismic events.

However, seismic events dominate the CDF and the LERF. This will be shown by some numbers: According to the latest Level 1 PSA the total frequency of core damage is lower than 10^{-5} per year. Therefore the plant fulfils the Swiss legal requirements for new NPPs. Internal events contribute with slightly more than 10 % to this new CDF value, area events contribute with 1 %, and external events contribute with nearly 90 % to the CDF. The leading contributors from internal events are LOCAs with about 80 % of the contribution and fires dominate the area events. Among the external events, seismic events (95 %) are the most significant contributors, whereas high winds and tornadoes and external floods show a low one digit contribution to the external events contribution.

To summarize, seismic events contribute with about 83 % to the CDF. This contribution is even higher for the LERF. Since major financial efforts have been undertaken to backfit and update the plant, further improvements are difficult to archive. Therefore a more detailed modelling of the plant behavior under seismic loadings using the Conditional Spectra approach may decrease conservative assumptions in the seismic hazard, which are implicit in the Uniform Hazard Spectra approach.

After finishing the latest PSHA project in Switzerland in 2004 (PEGASOS project), Beznau launched a major seismic PSA-study including walkdowns, soil-structure interaction and fragility computations based on the Uniform Hazard Spectra approach. As a result of this study, 790 individual fragility values were developed. However, many of them are identical due to the same floor level. For incorporation of these fragilities into the PSA model, they were merged to 120 fragility families. These 120 fragility families were implemented in 52 individual seismic Top Events into the linked event tree model of the Beznau plant using the RISKMAN Software. As a result, the seismic event tree includes about 300 million individual seismic sequences. Each of them is coupled with the "normal" PSA model for internal events.

Conditional Spectra Approach

In this study of the Conditional Spectra approach, the NPP Beznau has partially investigated the fragilities of the bunkered system (see Figure 4), since the bunkered system components show large CDF importance. However, on the other side, it is the most robust part of the plant. The bunkered system is represented in the Seismic PSA by six fragilities (Bunkered System Equipment, Accumulators, Bunkered System AC Equipment, Bunkered System DC and Venting Equipment, Bunkered System Mechanic and Bunkered System Valves). These fragilities are joined to one seismic Top Event. The study has started with the investigation of the change of the CDF by adapting the bunkered system DC equipment from the Classical Approach to the Conditional Spectra approach.

In the first step, the floor response spectra based on the SSI computation output were summarized and scaled using the SRSS rule. In the SRSS rule, the specific scaling factors for the different cases and directions were applied. The computation was done with a spreadsheet (e.g. Excel) for a limited number of nodes (10 nodes) of the bunkered building for all 74 time histories.

In the next step the fragility for the bunkered system components were computed starting with the DC equipment. Although one could compute the probabilities of failure for a component for a certain time history and a certain hazard level, the fragility approach allows the computation of the probability of failure for one time history for all hazard levels. Furthermore, it is widely accepted and part of common PSA software, such as RISKMAN.

In general, the computation of the fragilities in the Conditional Spectra approach is very extensive. Theoretically, for the Beznau-specific PSA model, one has to compute 74 fragilities for the 120 fragility families yielding to more than 8800 fragilities. If one considers all components from the Seismic Equipment List (SEL) for the NPP Beznau, one would have to compute nearly 60 000 fragilities (790 x 74). However in the investigated case, since the SSI computation was done only for the bunkered building, 5 fragilities for the 74 time histories yield to 370 fragilities. The computation was semi-automatized in a spreadsheet to increase efficiency.

Currently the cutting option for probabilities lower than the HCLPF values (High confidence of low probability) has been used in RISKMAN. This option was reasonable and sufficient for the latest PSA model using the Uniform Hazard Spectra approach. However with the 430 initiators from the Conditional Spectra approach, there are many computations with low seismic ground acceleration. It has been assumed that the used simplification in RISKMAN does not have a significant influence on the result.

The 74 time histories are related to different numbers of hazard levels, in some cases only two, in other cases up to 12. Therefore the traditional approach of the hazard curves in RISKMAN would be applicable to a limited extend. However, in some cases the probability of occurrence is not decreasing for increasing seismic intensity. Even further, in some cases the arbitrary choice of the seismic initiator range in the

Beznau-specific RISKMAN model is not able to distinguish between some hazard levels, which may be very close to each other. However, changing the range of the seismic initiators requires further updating and changing of the Beznau PSA model. For example, the seismic Human Reliability Analysis is related to the range of the seismic initiators. Therefore, the number of seismic initiators is lower than the number of Conditional Spectra, since for example some Conditional Spectra are outside the full seismic initiator range. In our case, 392 seismic initiators were used.

Although RISKMAN creates seismic initiators based on the hazard curve, one can also manually include initiators in RISKMAN. The manual included initiators can be computed outside of the RISKMAN software, for example in a spreadsheet. Both approaches have been used, the hazard curve approach, where applicable, and the manual initiators approach.

As indicated, some parts of the work were carried out outside the common PSA software. Although most of this work can be carried out either in spreadsheets or in mathematical software such as MATHCAD, it would significantly increase the acceptance of the Conditional Spectra approach, if quality-approved software tools were available. Such tools are under development for the creation of the Conditional Spectra, but not yet for the inclusion of the Conditional Spectra approach in seismic PSA software.

Alternatively to the used approach, it is possible to extend the Beznau specific event-tree model in RISKMAN to allow RISKMAN to compute all the required 392 or 430 initiators respectively at once. However, this would require significant changes in the PSA model. Therefore, in the current study only a limited number of seismic initiators has been computed at once.

This computation has not yet been finished, however preliminary results show a decrease of the CDF in the range of 6 to 30 %. A best estimate extrapolation indicates a reduction of the CDF of 15 % to 20 %. It is not yet clear, how strong the Conditional Spectra approach decreases the LERF, since the LERF is usually dominated by strong earthquakes. Here single seismic initiators may have a stronger impact on the results compared to the CDF and since not all the initiators are computed, one cannot give an estimation yet.

One should keep in mind, that the amount of computation required for the Conditional Spectra approach in PSA increases roughly by a factor of 100 compared to the Uniform Hazard approach.

Remarks and Limitations of the Current Study

The validity of the results from the current study is limited by the following items:

- Not all fragilities were used for the preliminary results.
- Not all Conditional Spectra cases were computed, for some cases results were estimated based on comparable cases (for example with low ground acceleration).
- The study does only consider the bunkered system, other buildings have not been considered.
- The fragility concept is not designed for this approach; there are currently some open issues, for example considering the uncertainty modelling.
- The fragility concept yields to very high computation requirements. There is a realistic chance of aberrations in the computation and quality assurance requires major efforts. The development of an automated computation tool would significantly decrease the chance of flaws.

The generalization or the transferability of the results to other plants may be limited due to:

- Specific configuration of the Beznau NPP with some components based on “old” design and major upgrades
- Specific conditions of the seismic loading based on the PEGASOS Refinement Project results (swissnuclear, 2013). Already the results of the PEGASOS Refinement study using the Uniform

Hazard Spectra approach yield to a reduction of the CDF of about 20 % and of the LERF of about 30 %. With this decrease and the decrease caused by the change from the Uniform Hazard approach to the Conditional Spectra approach, the CDF would decline significantly.

CONCLUSION

The performed pilot study had the goal to quantitatively compare two procedures which can be used for the risk assessment of critical infrastructure. The first approach was based on the "classical approach" to select time histories consistent with the UHS and to perform the risk assessment through convolution of this input with the fragility curves. The second approach is based on the procedure to use hazard consistent Conditional Spectra to select candidate time histories. The benefit of the latter is that it should avoid the implicit conservatism of the UHS motions, which assume that high amplitudes occur at all frequencies and orientations in a single ground motion. The cost is that a greater number of structural analyses are required compared to the classical UHS based approach. The implementation revealed some areas of improvement for the practical application. Especially, the change in approach for the input to the risk calculation software has to be revisited in order to be an acceptable approach in a practical environment. The reduction of CDF which has been obtained in this pilot study can be qualified as significant, even though it needs to be further explored if this is the general case or only due to the very specific conditions of the seismic hazard or assessed building. Nevertheless, it has been shown that the additional computational effort for the implementation of the Conditional Spectra approach has shown its value and should be further discussed in the framework of nowadays requested more realistic quantification of uncertainties and risk assessments.

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