SEISMIC RESPONSE ANALYSIS OF THE MÜHLEBERG NUCLEAR POWER PLANT STRUCTURES FOR THE PEGASOS REFINEMENT PROJECT

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ABSTRACT

The Mühleberg Nuclear Power Plant (KKM) is located in Mühleberg, Switzerland. KKM has undergone periodic updates to the probabilistic safety assessment (PSA). A previous PSA, identified as MUSA 2010, was completed in 2010. This included an update to the seismic PSA (SPSA) where the seismic hazard was defined by the PEGASOS Project. To support the SPSA, probabilistic seismic response analyses were performed for major plant structures using then state-of-the-art methods and available subsurface data. These seismic response analyses were used for the fragility evaluations of the buildings, as well as to develop probabilistic in-structure response spectra for seismic fragility evaluation of systems and components.

Recently, updated seismic hazard and subsurface data were developed for the KKM site by the PEGASOS Refinement Project (PRP). This hazard information is currently under review by the regulatory authority, Eidgenössisches Nuklearsicherheitsinspektorat. The structures’ seismic response analyses were updated for the PRP ground motion to support fragility evaluations of structures, systems, and components. This 2014 response update was performed using current state-of-the-art methods and updated subsurface information. Key features in this update included: (1) rigorous treatment of the site response problem starting with foundation level outcrop response spectra to develop hazard-consistent randomized strain-compatible soil profiles and associated acceleration time histories for the structures, and (2) probabilistic soil-structure interaction analyses using the Latin Hypercube Sampling method for embedded and surface-founded structures. This paper highlights refinements in the 2014 update, as well as differences between the 2010 and 2014 seismic analysis results.

INTRODUCTION

The Mühleberg Nuclear Power Plant (KKM) is a single unit General Electric Mark I boiling water reactor located in Mühleberg, Switzerland. A previous seismic probabilistic safety assessment (SPSA) for KKM, MUSA 2010, considered seismic hazard based on results from the PEGASOS Project (2004). Probabilistic seismic response analyses were performed for the major plant structures using the methodology described by Nakaki, et al. (2010). The probabilistic structure response analysis results were used for the fragility evaluation of structures, systems, and components (SSCs).

The PEGASOS Refinement Project (PRP) (2013) presented updated seismic hazard and subsurface data for the KKM site. These results are currently under review by the Swiss regulatory authority, Eidgenössisches Nuklearsicherheitsinspektorat (ENSI). To support updates to the fragility evaluations of
SSCs, the seismic response analyses of the major structures were revised for the PRP ground motion and the strain-compatible subsurface material properties. The updated seismic response analyses generally followed the same approach as for MUSA 2010. Both median-centered deterministic and probabilistic soil-structure interaction (SSI) response analyses were performed. In the probabilistic analyses, Latin Hypercube Sampling (LHS) was employed to construct families of response simulations from which the response probability distributions were obtained. Some notable refinements were incorporated into the update. Starting with foundation-level outcrop response spectra, rigorous site response analysis was performed to obtain hazard-consistent randomized strain-compatible soil profiles and associated acceleration time histories for the SSI analyses. Separate probabilistic response analyses were performed considering the variability due to the randomness of the ground motion alone, as well as for the composite variability of ground motion randomness and uncertainty in key properties of the soil-structure system. The response analyses of two KKM structures are highlighted, including the SUSAN Building, a partially embedded structure, and the Operations Building West Segment, which is a surface-founded structure.

**SEISMIC RESPONSE ANALYSIS APPROACH**

Seismic response analyses of the KKM structures, including the effects of SSI, were performed following the general approach described by Nakaki, et al. (2010). Computer program CLASSI (Luco and Wong, 1980), which applies the substructure approach, was used to perform the SSI response analyses. The basic elements of the SSI analysis approach include:

- Free-field ground motion
- Site soil properties
- Structure fixed-base models
- Foundation impedance and scattering
- Seismic SSI response analysis

The probabilistic seismic response analyses were performed using computer program CLASSI and implemented LHS as documented in NUREG/CR-2015 (Johnson, et al., 1981). Random variables in the analyses include the ground motion, soil stiffness and damping, structure frequency, and structure damping. The randomness of the ground motion was captured by an ensemble of thirty acceleration time history sets. The probability distributions of the soil and structure variables were defined as follows:

- The thirty randomized soil profiles represented the distribution of soil stiffness and damping
- Thirty scale factors representing the distribution of structure frequency. The probability distribution was defined by a median value of 1.0 and a coefficient of variation.
- Thirty scale factors representing the distribution of structure damping defined similar to those for structure stiffness.

Two types of probabilistic response analyses were performed. In the first, all variability was considered, including ground motion, soil stiffness and damping, structure frequency, and structure damping. This analysis captured the composite variability from both randomness and uncertainty. Thirty simulations were constructed by randomly sampling from each of the variables without replacement. In the second analysis, the soil stiffness and damping, structure frequency, and structure damping were assigned their median values and only the ground motion was varied. This analysis captured only the randomness contribution of the earthquake motion. SSI response analyses were performed for each of the thirty simulations. In-structure response spectra (ISRS) were computed at locations of components in the SPSA. For the composite variability and randomness variability analyses, the median (50%) and 84% nonexceedance probability spectral accelerations were determined.
FREE-FIELD GROUND MOTION OF THE 2013 PRP

The PRP update (Swissnuclear, 2013) presented the KKM free-field ground motion in terms of uniform hazard spectra (UHS). The UHS were developed as outcrop response spectra defined at three horizons: Elevation (-14 m), Elevation (-7 m), and the soil surface at Elevation 0 m. For the fragility evaluations, the Reference Earthquake ground motion was defined by the 1.0E-04 UHS. Figure 1 shows the 5% damped horizontal and vertical 1.0E-04 UHS at Elevation (-)14 m and the soil surface at Elevation 0 m. For comparison, the corresponding UHS from the PEGASOS project (2004) are also shown. At Elevation (-)14 m, the response spectra for PRP and PEGASOS are generally similar in shape, but the PRP horizontal motion has lower spectral accelerations across all frequencies, and the PRP vertical motion has substantially lower spectral accelerations at frequencies greater than 10 Hz. At Elevation 0 m, the PRP horizontal spectrum peaks at a lower frequency than PEGASOS. The PRP vertical UHS has much lower spectral accelerations in the frequency range between 6 Hz and 35 Hz.

For the probabilistic response analyses, a suite of thirty sets of acceleration time histories compatible with the mean 1.0E-04 UHS at each horizon was generated. Each set consisted of two horizontal and one vertical component. The time histories were conditioned such that the median spectral accelerations of the ensemble matched the mean 1.0E-04 UHS over the frequency range of interest.

SUBSURFACE MATERIAL PROPERTIES AND SITE RESPONSE ANALYSIS

The KKM site conditions consist of sandy and gravelly soil over sandstone and marl bedrock. The soil-rock interface occurs at a depth of about 7.5 m to 9.5 m below plant grade (Elevation 0 m). Groundwater is typically located at a depth of about 4 m. AMEC (2014) developed site soil properties for the seismic response analysis using updated site-specific geotechnical, geologic, and geophysical data and site response analyses. Probability distributions of the seismic strain-compatible shear moduli and soil material damping were developed, as well as median values of the material density and Poisson’s ratio. Because the PRP site response analyses utilized a logic tree approach to develop the site amplification functions, the approach documented in Appendix B to EPRI 1025287 (EPRI, 2013) was implemented to maintain consistency between the PRP seismic hazard results and the strain-compatible soil properties. Median strain-compatible soil properties and lognormal standard deviations were developed by AMEC (2014) as a function of depth. Thirty randomized strain-compatible soil profiles were developed for input to the probabilistic seismic response analysis. Figure 2 shows the properties of the thirty random profile realizations and the relative scatter about the median properties. AMEC (2014) also verified that the randomized soil profiles adequately replicated the PRP seismic hazard.

For the response analysis of the embedded structures, acceleration time histories within the soil column at Elevation (-)14 m were required. The ensemble of thirty outcrop accelerations spectrally-matched to the UHS at Elevation (-)14 m were converted to in-column motions. Each time history set was randomly paired with one soil profile, without replacement, and site response calculations were performed with the strain-compatible properties, without iteration. As a result, each of the in-column acceleration time history sets has an associated unique randomized soil profile. In-column time histories were also generated considering ground motion randomness only. For these calculations, the thirty Elevation (-)14 m acceleration sets were converted to in-column motions using the median soil profile.

Several significant differences are noted from the comparison of the soil properties developed by AMEC for PRP and PEGASOS, which are summarized in Figure 3 and highlighted below.

- The PEGASOS soil properties developed by AMEC for the response analysis were based on limited data available at the time. The PRP soil properties considered updated geotechnical data.
• The PRP median shear wave velocities exhibit an abrupt change at the soil-rock interface at a
depth of 8 m. For PEGASOS, the median shear wave velocities show a gradual increase with
depth.
• The PRP median shear wave velocities are generally lower than those for PEGASOS. The
significant differences are observed in the uppermost 8 m where the PRP velocities are
proportionately much smaller than for PEGASOS.
• The PRP median compression wave velocities are higher than for PEGASOS at depths between
4 m and 8 m, where the lower bound velocity was limited to 1,500 m/s for water.
• The PRP lognormal standard deviations for the shear wave velocity are substantially higher than
for PEGASOS in the uppermost 8 m.

SUSAN BUILDING

Structure Fixed-Base Model

The SUSAN Building is a reinforced concrete shear wall structure with rectangular plan dimensions of
19 m and 27.25 m in the Y- (east-west) and X- (north-south) directions, respectively. The foundation is a
1.2 m thick base slab bearing on rock at Elevation (-)12.25 m. The floors are located at nominal
Elevations (-)7.3 m, (-) 4 m, 0 m, and 3.5 m. The highpoint of the concrete roof slab is located at
Elevation 7.5 m. Plant grade is located at Elevation 0 m. The building has a very robust lateral force-
resisting system with an essentially symmetric shear wall arrangement. Figure 4 shows an isometric view
of the fixed-base finite element model of the SUSAN Building. In this model, the base of the structure is
restrained at the top of the foundation. The fundamental frequencies in the global Y- (east-west) and X-
(north-south) directions were found to be 9.50 Hz and 10.8 Hz, respectively. These modes captured 73%
and 78% of the total building mass, respectively.

Foundation Impedances and Scattering

The SUSAN Building is embedded in the soil profile. The hybrid method described by Johnson, et al.
(2010) and Nakaki, et al. (2010) was implemented to determine the foundation impedances and scattering
matrices considering the effects of embedment. In this approach, the embedded portion of the structure
was approximated as rigid. This was considered reasonable since the building is very stiff relative to the
soil in which it is embedded. The input motion control location was defined at the bottom of the
foundation. For the probabilistic response analysis, impedance and scattering matrices were developed
for each of the thirty randomized soil profiles. Also, the impedance and scattering matrices were
computed for the median soil profile.

Probabilistic Soil Structure Interaction Analyses

For the embedded SUSAN Building, the thirty LHS simulations with composite variability (ground
motion randomness, and soil and structure uncertain properties) were assembled with the impedance and
scattering matrices and the associated in-column earthquake time histories paired for each of the thirty
soil profiles. This was done to preserve their unique linkage through each soil profile. For the LHS
simulations considering ground motion variability only, the thirty in-column time history sets were run
with the median-centered SSI model. Figure 5 shows a comparison of PRP ISRS with composite
variability and randomness only at the foundation level and at Elevation 0 m. At the foundation level, the
median randomness ISRS has a valley at 4.5 Hz and a peak at 7 Hz, which resulted from the properties of
the median soil profile. The median composite ISRS has a lower amplitude and broader peak that occurs
at about 6 Hz. The reduced peak and greater broadness resulted from the increased variability of the
randomized soil profiles in the composite analysis.
Figures 6 and 7 show representative median and 84% nonexceedance probability ISRS of the SUSAN Building for both the PRP and PEGASOS input. Figure 6 shows the foundation X- (north-south) and YY-rotation ISRS. In the X-direction, the median PRP and PEGASOS ISRS are similar in shape with the PRP spectral values slightly lower for frequencies below approximately 8 Hz, which is consistent with the differences in the Elevation (-)14 m outcrop UHS. In the YY-rotation spectra, a rocking frequency of about 8 Hz is identified in both the PRP and PEGASOS results. However, substantially higher rocking amplitude was obtained in the PRP update. This is attributed to the much lower stiffness of the side soil in the upper 8 m surrounding the building. Figure 7 shows X-direction floor spectra at two elevations in the building. For both PRP and PEGASOS, the peak spectral accelerations occur at about 8 Hz. The peak spectral acceleration of the median PRP ISRS in Figure 7 exceeds that for PEGASOS, although the input UHS spectrum has lower amplitude. The higher PRP response is likely due to the increased rocking response noted in the YY-rotation foundation spectra. From a comparison of the 84% ISRS in Figure 7, much lower variability is observed in the peak spectral accelerations for PRP.

OPERATIONS BUILDING WEST SEGMENT

Fixed-Base Structure Model

The Operations Building West Segment is a reinforced concrete shear wall structure having rectangular plan dimensions of 17 m and 41 m in the X- (north-south) and Y- (east-west) directions, respectively. The top of the foundation slab is located at Elevation (-)3.0 m. The building has floors located at nominal Elevations 0.0 m, 3.5 m, and 8.0 m with the roof at 12.6 m. Plant grade is located at Elevation 0 m. Figure 8 shows an isometric view of the finite element model. The model is restrained at the top of the foundation slab. The building has a C-shaped shear wall layout, which results in coupled horizontal fundamental modes. The fundamental frequency of 4.38 Hz corresponds to coupled positive X and positive Y displacement (northeast-southwest direction). The second fundamental frequency of 4.66 Hz is associated with positive X and negative Y displacement (northwest-southeast).

Foundation Impedances and Scattering Matrices

The Operations Building West Segment was modelled as a surface-founded structure. The impedance and scattering matrices were computed using the CLASSI (Luco and Wong, 1980) methodology in which the foundation is considered rigid. Impedance and scattering matrices were determined for each of the thirty randomized soil profiles and for the median profile.

Probabilistic Soil Structure Interaction Analyses

Figure 9 presents a comparison of the PRP foundation ISRS considering composite variability and randomness. Both the composite and randomness spectra exhibit peaks at approximately the same frequency. The peak spectral values are higher for the case with randomness only. As observed for the SUSAN Building, this results from the use of the single median-centered SSI model. In the composite variability response, the increased variability resulted in lower and broader peaks.

Figure 10 shows a comparison of the probabilistic foundation ISRS for the Operations Building West Segment for both the PRP and PEGASOS input. In the X-direction ISRS, the PRP spectral accelerations exhibit a distinct shift to lower frequencies and amplitudes relative to the PEGASOS results. This is associated with the lower stiffness of the PRP soil profile. At frequencies higher than about 7 Hz, the PEGASOS X-direction spectral accelerations are higher than PRP. In the PEGASOS response, significant amplification occurred in the frequency range between 10 Hz and 15 Hz. For PEGASOS, this amplification occurred at higher frequencies due to the higher stiffness of the soil overburden. The PRP foundation YY-rotation ISRS similarly shows a shift to a slightly lower frequency relative to the
PEGASOS ISRS. Figure 11 shows comparisons of the ISRS in the X- and Y-directions at an upper floor in the building. The peaks of the PRP ISRS correspond to frequencies that are slightly lower than those of the PEGASOS ISRS. The shift to lower frequencies in the PRP ISRS is attributed to the increased soil flexibility. In the 3.5 to 5 Hz range where these peaks occur, the PRP and PEGASOS free-field input UHS are similar in amplitude with the PRP spectral value being slightly higher. However, as shown in Figure 11, the peak values of the median PRP ISRS are lower than those for PEGASOS in that frequency range. Similarly, the 84% PRP ISRS exhibit lower peak values than for PEGASOS. The peaks of the PRP ISRS are also slightly broader than those for PEGASOS. The lower peak amplitudes and broader peaks are the result of the higher variability of the PRP soil properties relative to PEGASOS.

CONCLUSIONS

The PRP presented updated seismic hazard and subsurface data for the KKM site. To support updates to the SPSA, the seismic response analyses of the major KKM structures were revised for the PRP ground motion and compatible subsurface material properties. The probabilistic response analyses followed the general approach described by Nakaki, et al. (2010) but included some refinements. Primary differences between the PRP and PEGASOS seismic response analysis are summarized below:

- **Ground Motion Input**: The amplitudes and shapes of the mean 1.0E-04 UHS from the PRP and PEGASOS seismic hazard are different.
- **Strain-compatible Soil Properties**: For the PEGASOS response analysis, the soil properties were based on very limited available geotechnical data. For the PRP update, updated site-specific geotechnical data were applied to develop the strain-compatible properties. Rigorous site response analyses were performed to develop hazard-consistent randomized soil profiles for the probabilistic SSI analyses. The randomized PRP soil profiles exhibited substantially higher variability than that for PEGASOS. As noted with the results, this increased variability tended to reduce peak amplitudes and broaden peaks in the ISRS.
- **Control Location**: In the PEGASOS response analysis of the embedded structures, the control motion was applied at the soil surface. In the PRP analysis, the control location was defined at the bottoms of the embedded foundations. This refinement in the PRP analysis maintained consistency between the UHS seismic hazard definition and SSI input.
- **Composite and Randomness Variability Response Analysis**: In the PEGASOS response analysis, the probabilistic SSI analysis considered composite variability only. In the PRP response analysis, additional probabilistic SSI runs were included to consider randomness only, as well as composite variability. This refinement allowed the fragility analyst the ability to evaluate both the composite and randomness variability of the structure response.

REFERENCES


**ILLUSTRATIONS**

![Figure 1](image1.png)

Figure 1 – 1.0E-04 Uniform Hazard Spectra at Elevation (-)14 m and Soil Surface Elevation 0 m

![Figure 2](image2.png)

Figure 2 – Thirty Randomized Strain-Compatible Soil Profiles Consistent with PRP 1.0E-04 UHS
Figure 3 – PRP and PEGASOS Median Shear and Compression Wave and Lognormal Standard Deviation Profiles

Figure 4 – SUSAN Building Fixed-Base Finite Element Model, Looking Northeast

Figure 5 – Comparison of SUSAN Building PRP Composite and Randomness Variability Probabilistic In-Structure Response Spectra
Figure 6 – Comparison of SUSAN Building PRP and PEGASOS Composite Variability Probabilistic Foundation In-Structure Response Spectra, X (North-South) and YY Rocking

Figure 7 – Comparison of SUSAN Building PRP and PEGASOS Probabilistic In-Structure Response Spectra, Elevations (-)4 m and 0 m, X- (North-South) Direction

Figure 8 – Operations Building West Segment Fixed-Base Model, Looking Southwest
Figure 9 – Comparison of Operations Building West Segment Composite and Randomness Variability Probabilistic Foundation In-Structure Response Spectra

Figure 10 – Comparison of Operations Building West Segment PRP and PEGASOS Probabilistic Foundation In-Structure Response Spectra, X (North-South) and YY Rocking

Figure 11 – Comparison of Operations Building West Segment PRP and PEGASOS Probabilistic In-Structure Response Spectra, Elevation 8 m