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Division III

PROBABILISTIC SSSI ANALYSIS OF REACTOR AND AUXILIARY BUILDING WITHOUT AND WITH INCOHERENCY EFFECTS

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ABSTRACT

For the reactor building (ZA) and the auxiliary building (ZC) of the Leibstadt nuclear power plant (NPP), realistic relative displacements in the gap between the two buildings are determined to evaluate whether a mutual impact can occur in the event of an earthquake. For this purpose, a probabilistic SSSI (Structure-Soil-Structure interaction) calculation is performed for the new Swiss earthquake hazard ENSI-2015. The existing ACS SASSI calculations of the two individual buildings form the basis. These are merged to a common SSSI model and 30 probabilistic calculations are performed. In a further step, these 30 calculations are repeated considering incoherency for hard rock (Abrahamson, 2007). The mutual influence of the two buildings can be seen in the Floor Response Spectra (FRS). Due to the larger vibrating mass and the larger number of substructures/natural frequencies in the SSSI calculation, the FRS results in a broadening of the peak shape and a more uniform curve shape, as well as a slight shift into the low-frequency region. The additional influence of incoherency is noticeable, but rather of minor importance. An evaluation of the relative displacement yields a maximum of 39.6 mm with an existing gap of 50 mm. Consequently, mutual impact is not possible. Figure 1 gives an overview of the calculations performed.

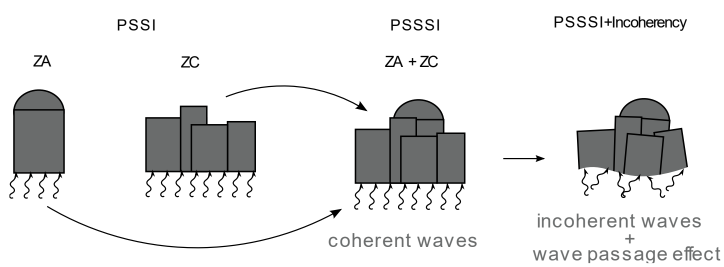


Figure 1. Variation of the calculations.

INTRODUCTION

In 2015 a group of experts determined and established new uniform hazard spectra, called ENSI–2015, for all nuclear power plant sites in Switzerland in accordance with the current state of the art, as part of a regular reassessment of the seismic hazard. Subsequently, all affected nuclear power plants calculated new floor response spectra and thus updated their probabilistic (PSA) and deterministic safety analyses (DSA). In this context, the calculation of the floor response spectra was performed at all four power plant sites using detailed SASSI building models and, if necessary, taking into account the embedding in the ground. Either a deterministic approach with 3x3 calculations (LB/BE/UB & 3xMatched-THs) according to KTA2201 (2011) or a probabilistic approach with 30 calculations according to ASCE4-16 (2017) was followed by the individual operators.

The present article deals with the determination of realistic relative displacement in the gap between reactor building (ZA) and auxiliary building (ZC) in the Leibstadt NPP within the framework of the reassessment. The aim is to evaluate whether mutual bumping is possible. For this purpose, a SSSI (Structure-Soil-Structure interaction) calculation is performed for the new Swiss seismic hazard ENSI-2015. Basis are the two previous ACS SASSI calculation models of these buildings. These two individual models are transferred into an overall model with ZA and ZC buildings and SSSI calculations are performed.

THEORETICAL BACKGROUND

An earthquake is caused by the release of large amounts of energy during a shear rupture (Figure 2). Different types of waves release this energy into the environment. A probabilistic description of the complex influencing variables such as soil properties can be considered state of the art. Here, the so-called Probabilistic Soil Structure Interaction (PSSI) is presented. It is extended by considering another building nearby (PSSSI) and including incoherency effects.

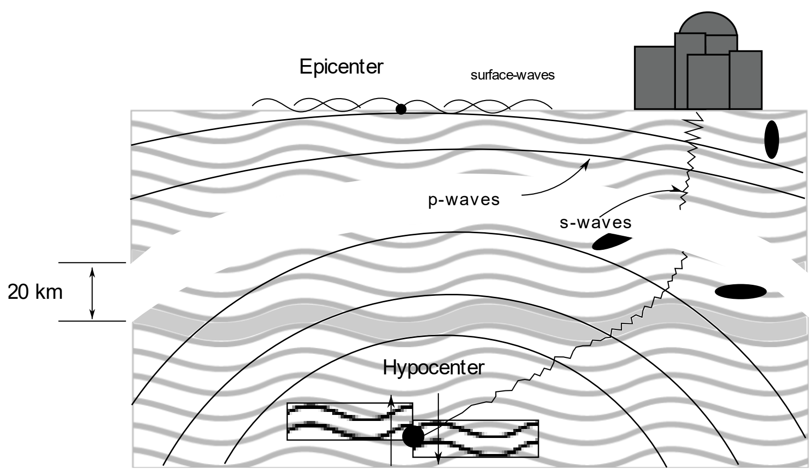


Figure 2. Schematic representation of earthquake waves (P,S,R) in the ground.

Probabilistic Soil-Structure Interaction (PSSI)

In the probabilistic approach according to ASCE4-16 (ASCE, 2017), all relevant parameters (excitation, soil properties, building properties) of the soil-structure interaction are varied and calculated in several computational runs with these scattered parameters. In the present case, 30 calculations are performed. The excitation is varied using the acceleration time histories of recorded strong earthquakes (seeds). These are iteratively matched to the specified free-field spectra (matches), for obtaining site-specific spectra-compatible earthquake time histories. For the variation of soil and building parameters, the respective best-estimate values are scattered using Latin hypercube sampling (LHS), hence providing stochastic sets of model properties each together with a randomly chosen excitation. The evaluation of the individual SASSI calculations is then also performed using statistical tools. The median value for the PSA and the 84th percentile for the DSA are evaluated from the individual results.

Structure-soil-structure interaction (SSSI)

In dynamic soil-structure interaction, the mutual influence of building and soil is calculated as a function of frequency. Normally, it is assumed that the building in question is located in the free field and that this free field - i.e., the soil - is homogeneous in each layer. In the past decades, such computationally intensive SSI problems could only be calculated at all by simplifications. In many cases, these simplifications are permissible, but interfering factors like e.g.

- a large or heavy structure in the immediate vicinity,
- a ravine or a deep crevice in the ground,
- or a strongly inhomogeneous or not horizontally layered soil

require the use of detailed SSSI models. In this case, the disturbance factor (e.g., a tunnel, a large neighboring building, an inhomogeneous soil confinement...) above or in the soil is also modeled in the computational model and thus the interaction between disturbance factor, soil and structure is considered.

Modelling of incoherency effects

Usually, in a SASSI calculation, the assumption is made that the earthquake waves, generated by the tectonics of continental plates, are coherent (equal in frequency and phase) at the point of action per soil layer. Therefore, the ground can be modeled in a simplified way as a one-dimensional column. In the nuclear industry, shear waves acting vertically in the X-direction (SV), shear waves acting horizontally in the Y-direction (SH), and compression waves acting in the Z-direction (P) are assumed to be the loading magnitudes (ASCE standard). However, two aspects can lead to the fact that the coherence of the earthquake waves at the point of action is no longer given:

- Wave Passage Effect: Depending on the dimensions of the structure and the ground stiffness or shear wave velocity, phase shifts result due to different travel times of the shear waves at opposite edges when passing the foundation (Figure 3).
- Wave Scattering Effect: As a result of disturbances in the upper 500 m of the soil, there is a scattering of the shear waves. The greater the variability of the soil layers in the horizontal direction, the greater this scattering or incoherency. Topographic features (e.g., inclination of the soil layers) are also important. The distance between two considered points on the surface (separation distance) and the frequency are the main influence parameters of the incoherency.

Earthquakes usually occur at a depth of 10 km to 50 km. The shear wave velocity is more or less high in the ground and decreases only on the last 200 m to 500 m - the shear waves are strongly decelerated. Figure 3 shows an example of an earthquake area and the vs ground profile in the upper 1000 m of ground. Because of this sharp decrease in shear wave velocity, inhomogeneities in the ground are of particular importance to incoherency, especially in the upper ground region. In general, the source (point/line) does not affect the incoherency of two neighboring points at the target due to the large distance (see Figure 3). However, especially in the case of strong, nearby earthquakes, the incoherency of the waves at the target may be amplified.

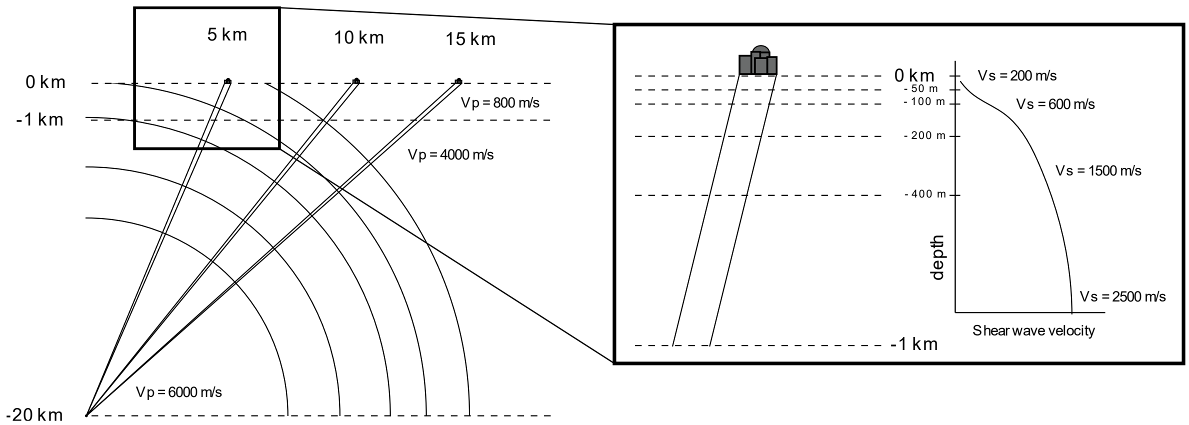


Figure 3. Illustration of an earthquake with the shear wave velocity profile.

All causes of wave scattering are difficult to detect without measurement of actual earthquakes since this requires knowledge of the point of origin or the direction of propagation as well as a detailed image of the ground including local faults in the near field of the considered location (up to max. 500 m depth). Furthermore, calculations with physical models according to Abrahamson lead to an overestimation of the incoherency for small distances. Therefore, it is more advantageous to consider the incoherency by probabilistic approaches. Abrahamson has done extensive research on this, summarized in Abrahamson (2007), and developed appropriate coherence curves for probabilistic calculations. Application of these are a good compromise compared to the effort that would be required to determine site-specific coherence functions.

The mathematical description of incoherency is briefly summarized in Table 1. A more comprehensive introduction can be found, for example, in Ghiocel et al. (2017).

Table 1. Brief mathematical introduction of modelling incoherency effects.

<table>
<tr><th colspan="2">Mathematical description</th></tr>
<tr><td colspan="2">The seismic spatially varying stochastic field S_{U_j,U_k} is described as a space-time stochastic process with a Gaussian probability distribution (Equation 1). It is computed by taking the power-spectral density description S w.r.t. two soil locations i, j times the coherence function of those points:

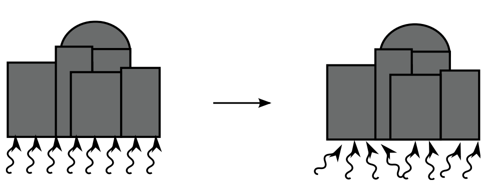
$$S_{U_j,U_k} = \underbrace{\left[S_{U_j,U_j}(\omega) S_{U_k,U_k}(\omega)\right]^{1/2}}_{\text{local random variation}} \quad \underbrace{\Gamma_{U_j,U_k}(\omega)}_{\text{coherence function}} . \tag{1}$$</td></tr>
<tr><th colspan="2">local random variation</th></tr>
<tr><td>

Figure 4. Variation of the seismic load vector.</td><td>The seismic load vector is varied with respect to direction and magnitude using a stochastic approach (e.g., Monte Carlo) as shown in Figure 4. In this way, inhomogeneities in the soil (e.g. faults, variation in soil layers) are mapped.</td></tr>
</table>

coherence function

The coherence function (Equation 2) is computed by the plane wave coherence and (optional) times the wave passage function:

$$\Gamma_{U_j,U_k}(\omega) = \underbrace{\Gamma_{PW\,U_j,U_k}(\omega)}_{\text{plane wave coherence}}\ \underbrace{exp\left[i\omega\left(X_{D,j} - X_{D,k}/V_D\right)\right]}_{\text{wave passage fct.}}. \tag{2}$$

plane wave coherence

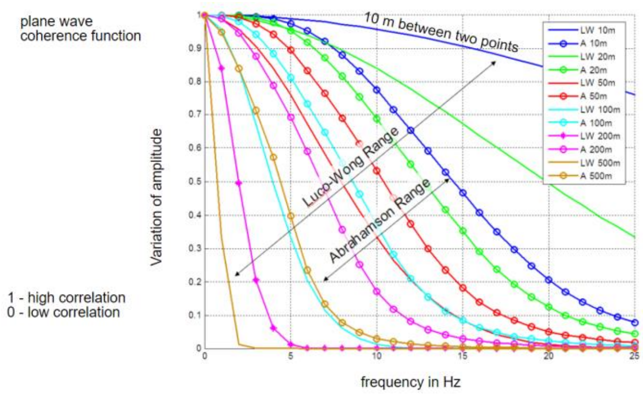


Figure 5. Coherence functions. Extracted from Ghiocel et al. (2007).

The plane wave coherence functions (depicted in Figure 5 describe the influence of two points on each other. Two points close to each other show a strong correlation of the amplitude over the entire frequency range. Points far away show high correlations only at low frequencies (Figure 6).

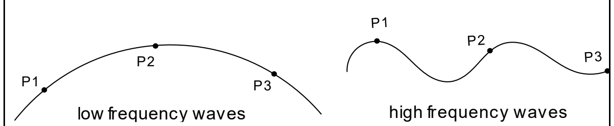


Figure 6. Sketch concerning the variation of points as a function of the wave frequency.

wave passage function

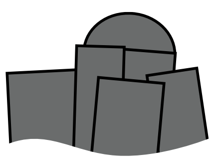


Figure 7. Wave passage effect.

Depending on the dimensions of the structure and the soil stiffness or shear wave velocity, phase shifts occur due to different travel times of the shear waves at opposite edges when passing the foundation (compare Figure 7).

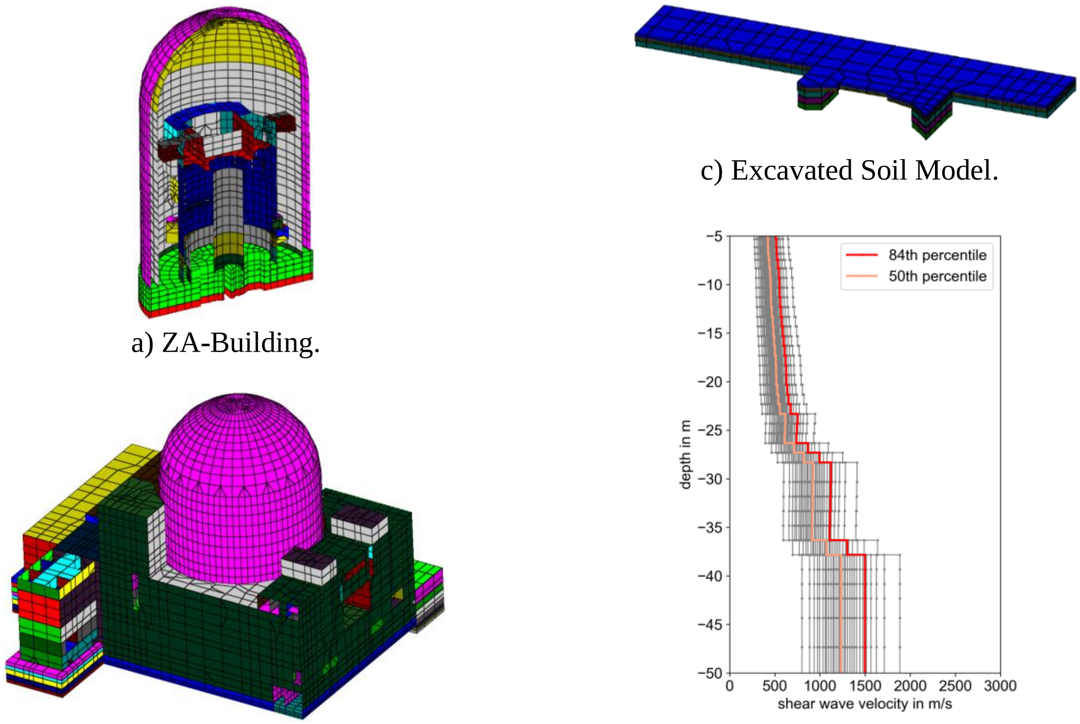
MODEL DESCRIPTION

Building model

For the determination of the relative movements between the reactor building (ZA) and the auxiliary building (ZC) of the Leibstadt nuclear power plant, the two individual models of the buildings are merged. In the process, the two soil models, in particular the layer thicknesses, are also aligned and combined into a single soil model. Due to the surrounding buildings, embedment is only considered from -10 m.

The ZA building has a circular plan with a diameter of about 42 m and is shallowly founded at -9.8 m (Figure 8 a). The ZC building (Figure 8 b) is a collection of different interconnected buildings of varying depths with a more or less rectangular shaped floor plan. The exterior dimensions are approximately

74 m x 54 m. In the center there is a circular recess into which the reactor building is inserted. The foundation is deeper than -10 m only in the northern area, where it is modeled as embedded (Figure 8 c). The two buildings are not structurally connected and have a distance of about 50 to 100 mm from each other.



a) ZA-Building.

b) ZA- and ZC-Building complex.

c) Excavated Soil Model.

d) vs–Soil–Profile.

Figure 8. SSSI building model.

Soil model

For the soil model (Figure 8 d) the properties (stiffness, damping) from extensive soil investigations carried out at the site over the past decades were applied. The geological conditions in the immediate vicinity of the site were used to create the best estimate soil model. In addition, strain-compatible soil properties are calculated utilizing the defined free-field spectra.

Latin Hypercube Sampling Multipliers

In the framework of the probabilistic SSI analysis the following variables, that governs the overall system response, have been selected for generating Latin Hypercube Sampling (LHS):

- soil shear wave velocity (profile),
- soil material damping (profile),
- structural Young's modulus E of concrete (or steel) and
- structural material damping ratio of concrete.

According to the general methodology a total of 30 intervals have been defined for the scope. This implies, that a total of 30 SASSI Input-Models will be generated to estimate the statistical distribution of the different results quantities arising from the probabilistic SSI analysis of each structure. The LHS is a statistical method for generating a near-random sample of parameter values from a multidimensional distribution. The sampling method is used in the framework of this project to generate a representative sampling of N variables dived into M intervals. When sampling a function of N variables, the range of each variable is divided into M equally probable intervals. M sample points are then placed to satisfy the Latin hypercube requirements. Note that:

- this forces the number of divisions M to be equal for each variable,
- this sampling scheme does not require more samples for more dimensions (variables).

The latter point (independence) is one of the main advantages of this sampling scheme. Another advantage is that random samples can be taken one at a time, remembering which samples were taken so far. The single variables have been assumed to be log-normal distributed. In statistics the term cross-correlation is used for referring to the correlations between entries of two random vectors X and Y. The definition of correlation always includes a standardizing factor in such a way that correlations have values between -1 and +1. The logarithmic standard deviations (beta) for the variables 1 to 4 were set equal to:

- variable 1 $\beta = 0.199$ and COV = 0.20,
- variable 2 $\beta = 0.340$ and COV = 0.35,
- variable 3 $\beta = 0.294$ and COV = 0.30 ,
- variable 4 $\beta = 0.340$ and COV = 0.35.

The results of the LHS multipliers are documented in Table 2. The multipliers lead to an acceptable range of the effective (real) values for the four parameters. The ensemble of the developed 30 shear wave velocity and soil damping profiles (strain compatible level) for NESK3 are then obtained by multiplying the property values with their corresponding LHS multiplier.

Table 2. Latin hypercube sampling (LHS) parameters.

COV (input) Case no.	**0.2 Soil vs. Layer**	**0.35 Soil damping**	**0.3 E-Modulus structure**	**0.35 Structure damping**
1	1.1	0.51	0.82	0.64
2	0.65	1.39	0.96	1.09
…	…	…	…	…
29	0.86	0.92	1.06	0.93
30	0.99	1.18	0.53	1.16
Min	0.65	0.48	0.53	0.52
Max	1.53	1.86	1.87	1.59

Incoherency parameters

For incoherency, the 2007 Abrahamson model is used for hard rock sites. The wave propagation is isotropic (in ACS SASSI 0° radial angle to the X-axis). As mentioned previously, the addition of incoherency in the LHS procedure does not increase the number of samples. It merely adds another column of incoherency to Table 2. The Python scripts used to create and compute the 30-input sets and post-processing can be used from the coherent SSSI calculation.

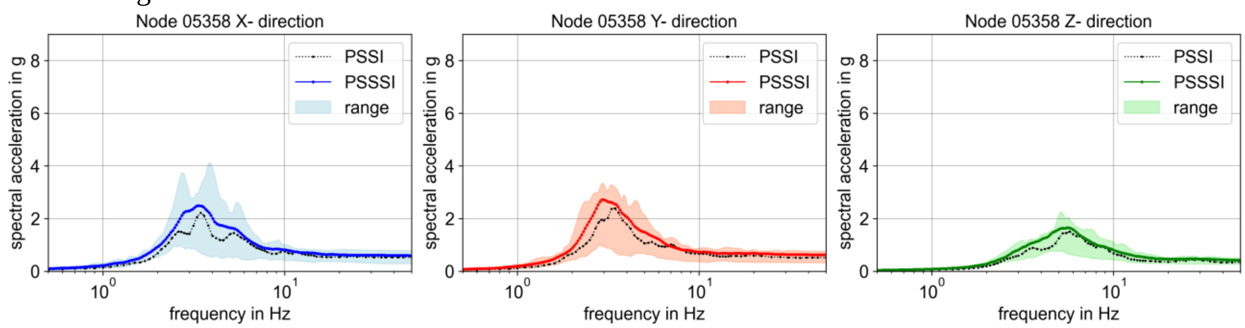
RESULTS

Figure 1 provides an overview of the calculations performed. The results of the individual calculations are presented and compared with each other. In addition to the determination of the relative displacements for the evaluation of a possible impact, the floor response spectra are compared with each other.

Comparison of the response spectra of SSI and SSSI

Figure 9 shows the response spectra (84th percentile, range from all 30 calculations) for the ZC and ZA buildings at the height of the ground surface. Compared to the individual SSI calculations, the spectra of the SSSI calculation are more uniform and tend to be slightly shifted into the low-frequency range with their peak. It is noticeable that the ZA reactor building enclosed in the SSSI calculation experiences an amplification of the vertical acceleration. The horizontal accelerations remain at a constant low level.

ZC-Building



ZA-Building

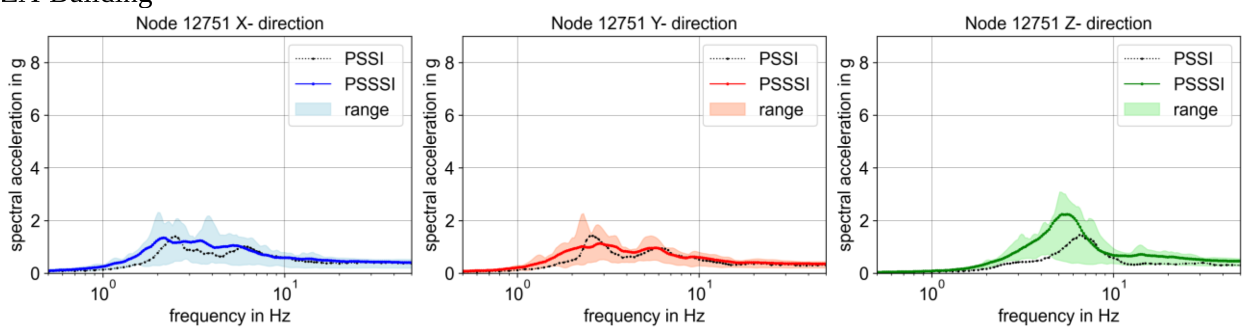
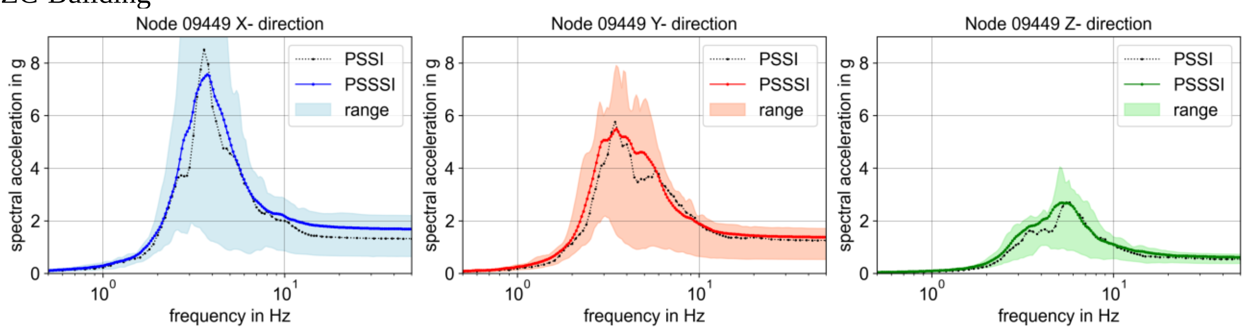


Figure 9. FRS at ground level, a) ZC building -2.5m, b) ZA building +3.2m.

The response spectra at the elevated ZC building node (see Figure 10 a) show good agreement with the SSI calculation, while the spectra at the ZA building node deviate significantly (Figure 10). The influence of the interaction of the buildings becomes clear here. The ZC building, as the dominant building in terms of mass and due to its enclosing geometry, imposes its oscillation on the ZA reactor building.

ZC-Building



ZA-Building

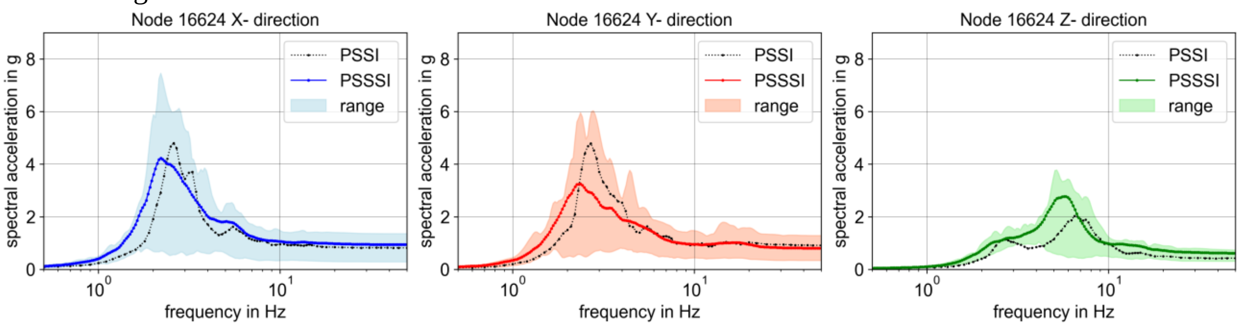
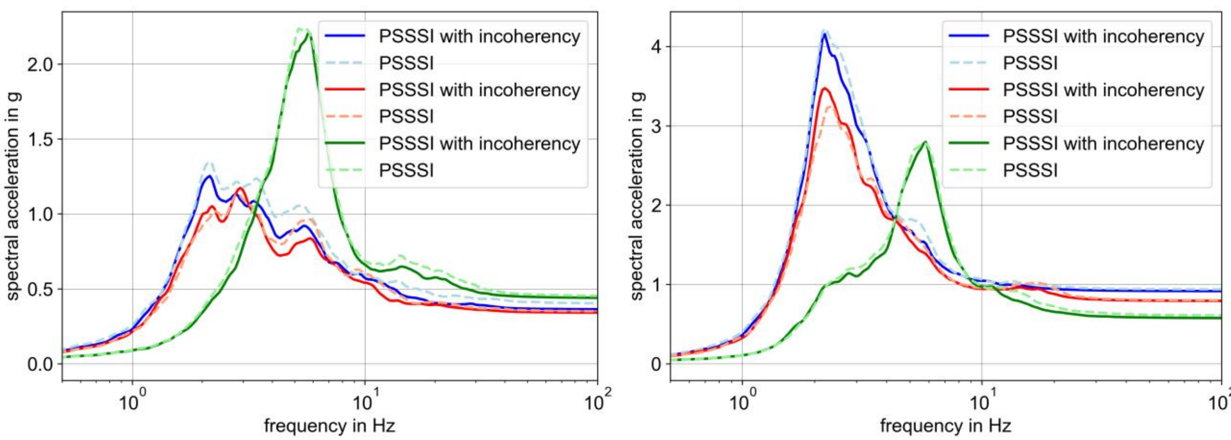


Figure 10. FRS at high level, a) ZC building 28.6 m, b) ZA building 29.9 m.

From the above images, it can be observed that the SSSI mainly affects the spectra of the ZA building. Compared to the stand-alone SSI calculations, the SSSI model partially gives different results independent of the SSI calculations. The mutual influence in the PSSSI calculation is complex and no general statement on the validity of PSSI calculations can be made from it. Due to the larger oscillating mass and the larger number of substructures, and thus natural frequencies, there is a broadening of the peak shape and a more uniform curve.

Comparison of the spectra of SSSI without and with incoherency

Figure 11 shows the influence of incoherency in the SSSI calculation. Again, a node near the ground and a node at high altitude are shown. It is to be noted that at both altitudes only minor influences of incoherency are shown in the response spectra. At the same time, no tendency of reduction or exaggeration can be observed in the very similar curve shape.



a) Node 12751 (3.2 m) ZA Building.

b) Node 16624 (29.9 m) ZA Building.

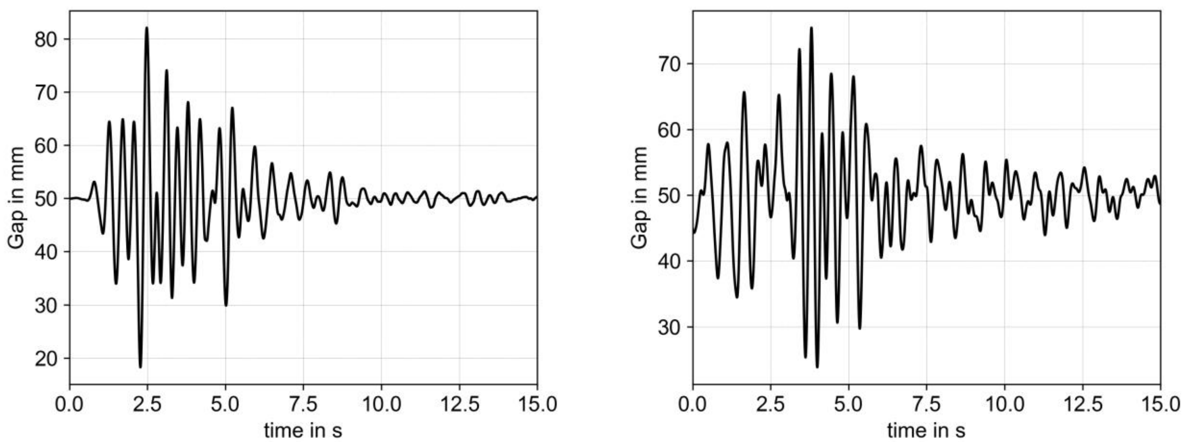
Figure 11. FRS from PSSSI.

Relative displacement between reactor and auxiliary building

For the determination of the relative movements between ZA and ZC, two adjacent building nodes are considered at approx. 21.5m. From the SSI calculations, a conservatively determined relative movement of 51 mm results with a building gap of 50 to 100 mm, which requires more precise considerations.

For the evaluation of a possible mutual impact of the two buildings due to earthquake movements, the radial relative movement of the two nodes mentioned above (8996-ZC, 15459-ZA) is relevant. The SSSI calculation results in an 84-percentile value of 39.9 mm (compared to 36.6 mm for SSSI+Incoherency) as the maximum displacement with respect to each other. The 84-percentile value was determined from the respective displacement maxima of the 30 calculations. Therefore, an impact of the buildings is excluded.

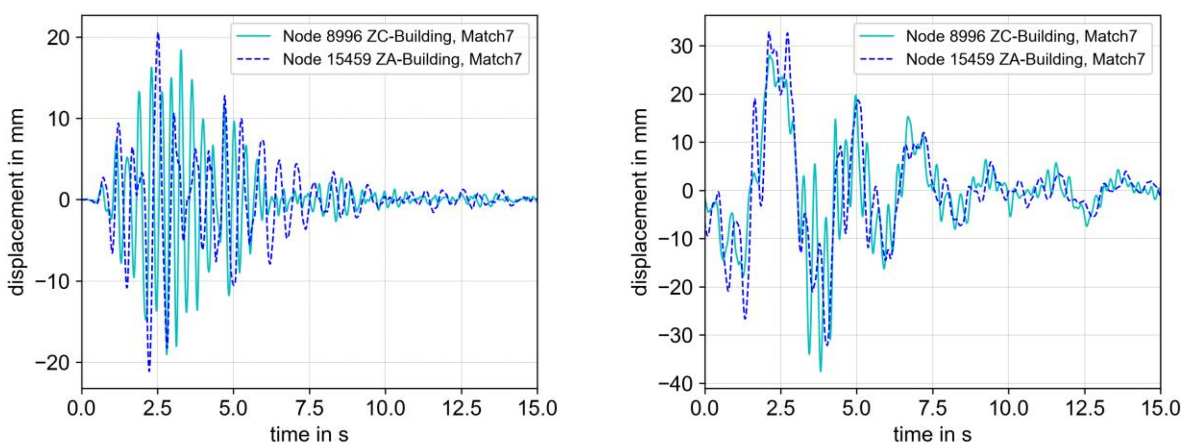
Figure 12 depicts the gap opening distance over time. An initial opening of 50 mm is assumed.



a) SSSI. b) SSSI with incoherency.

Figure 12. Resultant gap between neighboured ZC- and ZA-nodes for Match 7.

Although the resulting gap magnitude between SSSI and SSSI + incoherency is very similar, Figure 13 b) depicts large-wave low-frequency seismic waves, which do not occur in figure a). Thus, an effect of incoherency is clearly visible. It results from low frequency wave propagation, which is accounted for in the incoherent variant, while the ground moves uniformly up and down as a rigid unit in the coherent variant. Since the resulting displacement is relative to the moving ground, the uniformly moving soil filters the low frequency waves.



a) SSSI. b) SSSI with incoherency.

Figure 13. Time history displacement of neighboured ZC and ZA nodes.

CONCLUSION

Both effects, the additionally considered building interaction as well as the incoherency are part of a more realistic overall consideration. It could be shown that these effects do not reduce or build up conservatism but lead to independent and different results.

As expected, the explicitly considered gap width between the buildings reacts particularly sensitively to the consideration in an SSSI model and the resulting relative displacements are reduced. This has an influence on subsequent calculations (e.g., pipe calculations) in which otherwise large conservatism is introduced and which may lead to extensive and unnecessary renovations.

Summarized, the results show the great relevance of the SSSI consideration. For the considered model, the realistic influence of incoherency could be reproduced. However, the influence on the initial question of relative displacements is minor.

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