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RESPONSE OF A NUCLEAR POWER PLANT BUILDING UNDER INCOHERENT SEISMIC GROUND MOTION EXCITATION

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Abstract

For verification of the seismic safety of the Gösgen-Däniken (Switzerland) nuclear power plant for an updated seismic hazard, a 3D detailed finite-element model of the reactor building is developed and coupled with a model of the main components and piping of the primary coolant system as well as major parts of the secondary system. In this paper, results from verification and validation calculations with the coupled (complete) model are presented. It focuses on few modeling aspects of soil-structure interaction by performing sensitivity analysis with the complete model under spatially incoherent ground motion excitation. A comparison is given for results of surface and embedded foundations; different embedment depths; coherency functions for different soil classes and different sets of ground motion excitation time-histories. Results in terms of response spectra for a characteristic structural node indicate that the effect of assumed embedment depth and incoherent ground motion excitation is minor for the horizontal direction and more pronounced for the vertical direction. The most significant effect on the response spectra for the selected structural node is in the present situation caused by the selection of the ground motion excitation time-history (target spectrum compatible). Benefits and limitations of different modeling assumptions are compared, conclusions are given and recommendations are derived for the upcoming project phase.

Keywords: nuclear power plant; reactor building, primary system, soil-structure interaction; incoherent ground motion

1. Introduction

For verification of the seismic safety of the Gösgen-Däniken (Switzerland) nuclear power plant (NPP) for an updated seismic hazard “ENSI-2015”, a 3D detailed finite-element model of the reactor building is developed and preliminary soil-structure interaction (SSI) analysis are performed, see [1]. In a first step of model development, main components and piping of the primary coolant system (PCS) and parts of the secondary coolant system (SCS) are taken into account solely by their lumped masses. In the second and current step of the project, a 3D model of the primary and secondary circuit components and piping is coupled with the 3D reactor building model. In this paper, results of seismic analysis are presented from step two only. Hence, the focus of this paper is on verification and validation calculations with the coupled (complete) model.

The pressurized water reactor building is an axisymmetric reinforced concrete structure with an outer diameter of about 65 m and a height of about 60 m. The walls of the outer cylinder and dome area of the building are designed for aircraft crash and are correspondingly massive and thick. The base slab is about 3 m thick and is located about 9 m below surface level. The steel containment structure is eccentrically arranged in the building and has an inner diameter of 52 m. The complete mass of the detailed model (building and mechanical components of PCS and SCS) is about 160 000 t.

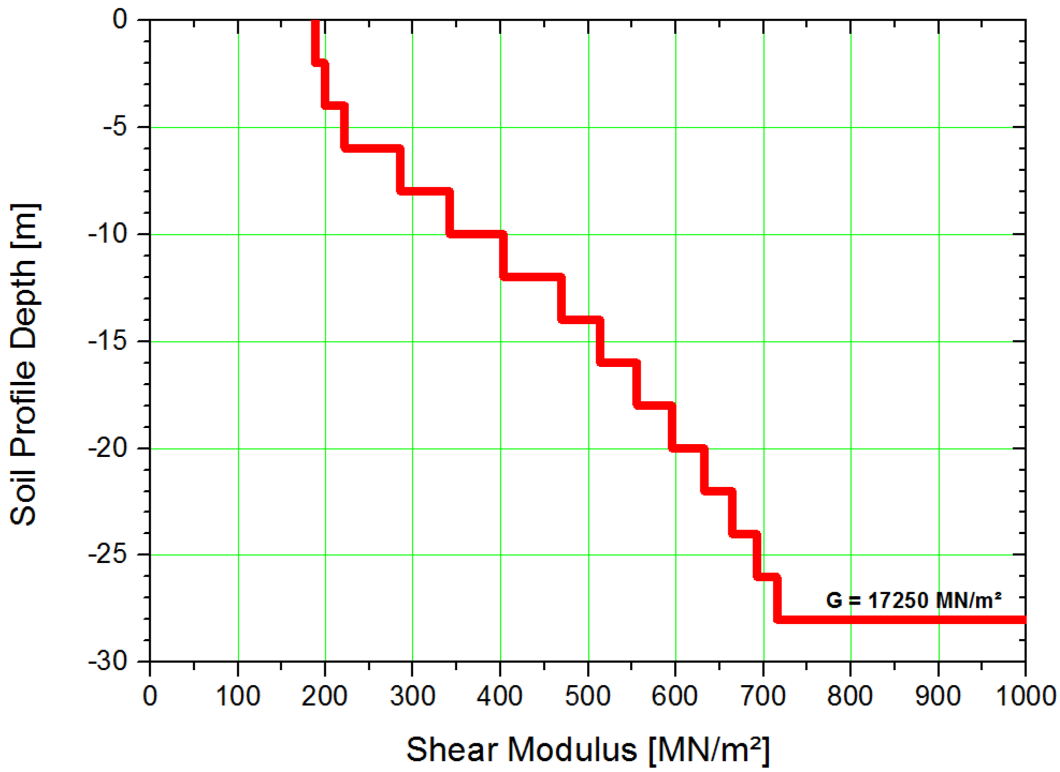

Fig. 1 – Profile of the best estimate soil shear modulus [1]

2. Local Soil Conditions

The base rock (limestone) surface at the site is approximately 25 ÷ 30 m below the ground surface. Layers of dense sandy gravel are overlaying the base rock. Some lenses of silty sand are nestled in the gravel sediment. Their lateral extent depends on the thickness and can reach a range of up to 25 m. The best estimate shear modulus profile is depicted in Fig. 1. The average groundwater level is about 7 m below the ground surface. Thus, the foundation of the building is almost entirely in groundwater.

3. Generated 3D Detailed Finite-Element Model of the Structure

The geometry of the structure is extracted from conventional 2D general overview and formwork drawings and structural surfaces of walls and slabs are generated, see Fig. 2. The structural surfaces are then meshed to develop the finite-element model, see Fig. 3. The mesh size of both soil and structure is sufficiently fine for numerically accurate calculations with a cut-off frequency of about 50 Hz. The detailed 3D finite-element model of the reactor building is characterized by the following data: a) about 63 000 nodes; b) about 73 000 elements; c) about 380 000 degrees of freedom; d) total mass of about 160 000 t. The concrete shear walls and slabs of the structure are modeled by 3D thick-shell elements with three translational and three rotational degrees of freedom per node. The element formulation includes the out-of-plane shear stiffness. The steel containment, the cylindrical part of the reinforced concrete containment and its dome are modeled by 3D thin-shell elements with three translational and two rotational degrees of freedom per node. The out-of-plane translational degree of freedom is also included but neglects transverse shear stiffness. The drilling rotational stiffness of the member is also neglected. Structural columns and girder members are modeled by 3D beam elements with three translational and three rotational degrees of freedom per node. Material properties of concrete (stiffness and strength, incl. strength hardening) are derived from core samples taken from the existing structure.

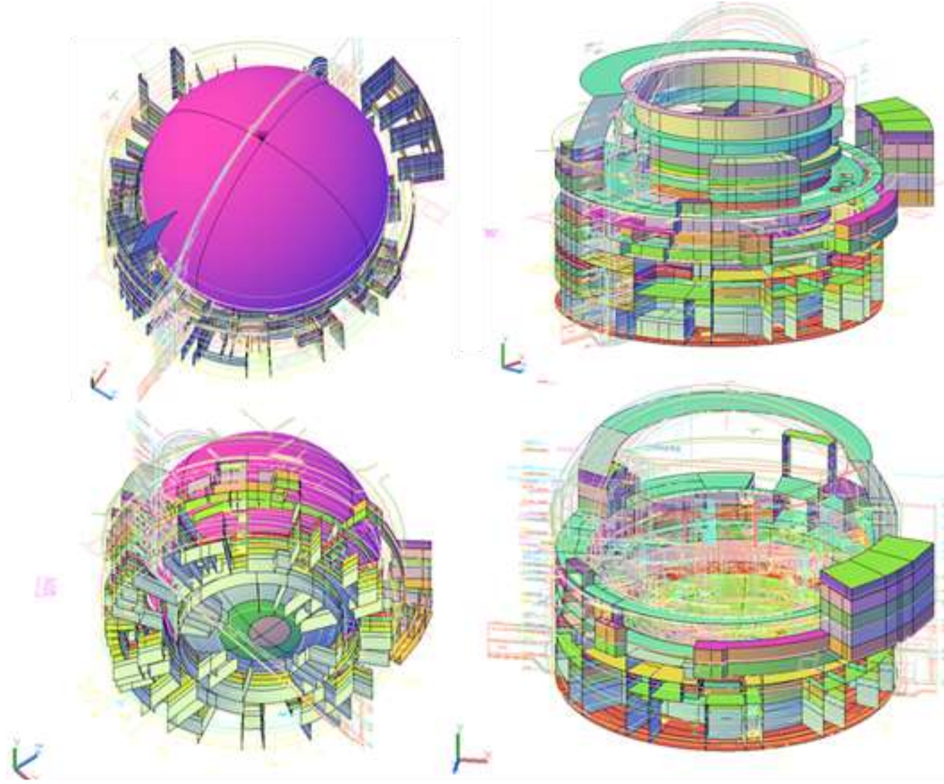

Fig. 2 – Extraction of structural geometry from conventional 2D drawings and generation of structural model surfaces [1]

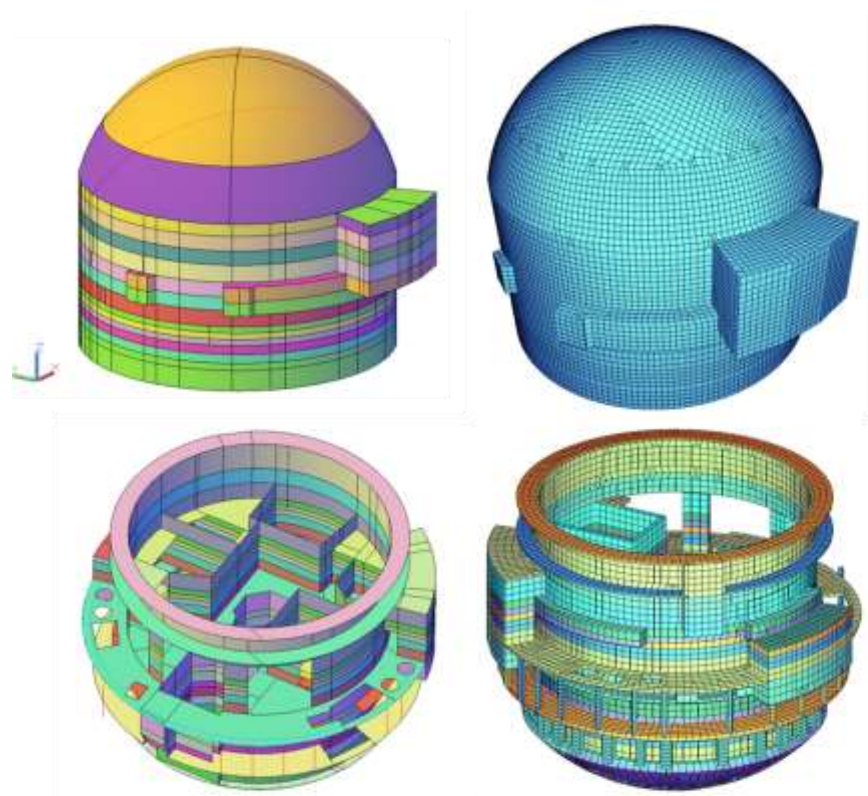

Fig. 3 – Finite-element mesh generation based on the model surfaces [1]

4. Generated 3D Detailed Finite-Element Model of the Primary Coolant System

The primary circuit model consists of: a) reactor pressure vessel, RPV; b) steam generator, SG; c) reactor coolant pump, RCP; d) pressurizer, PZR; e) primary coolant system lines, PCSL; f) pressurizer surge line, PSL; g) main steam system lines to their fix points at the reactor building wall, MSSL; h) feedwater system lines to their fix points at the reactor building wall, FWSL. The finite element model is developed with ANSYS.

Secondary lines which are connected to the primary coolant system components or the PCSL are not taken into account in this model. The admissibility of this assumption is demonstrated in separate calculations. Thereby, the KTA 2201.4 decoupling criteria are applied to prove that the interaction is negligible by checking that "significant natural frequencies calculated in the decoupled system do not differ from those of the coupled system by more than 10%".

The primary coolant system components are modeled by a combination of elastic and rigid beam elements. Component suspensions (cross beams and hangers) are modeled with elastic beam elements. Lower and upper seismic supports are modeled with spring elements. Components' mass (incl. internals as e.g. water filling, heating pipes, etc.) is lumped at selected model nodes. Pipes are modeled with elastic beam elements. Elbow elements (not available in SASSI2010) are modeled with stiffness matrix elements.

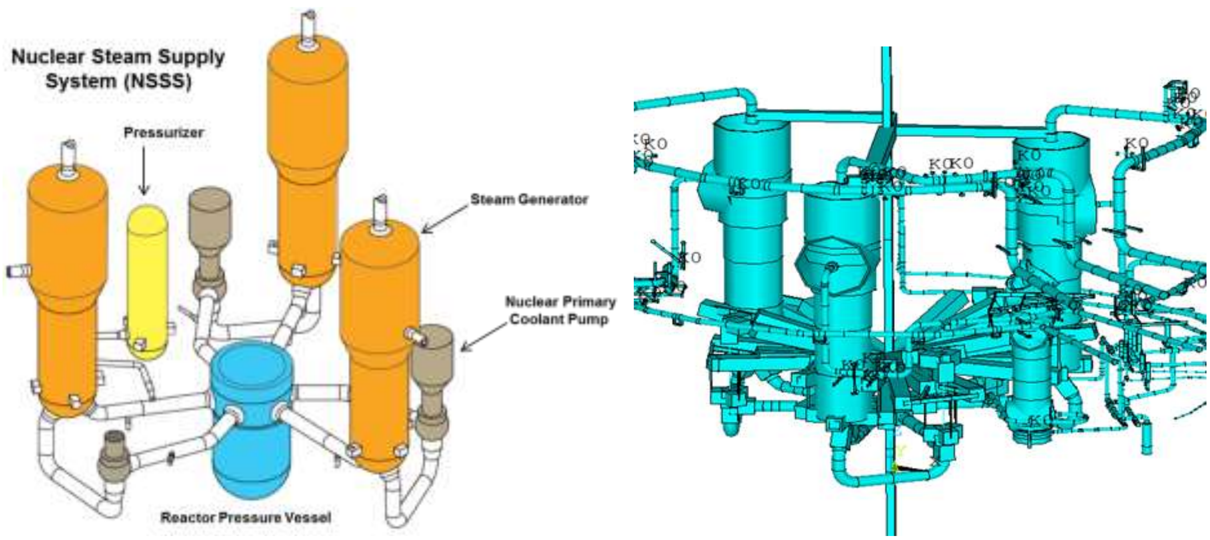

Fig. 4 – Schematic diagram and corresponding finite-element model of the primary coolant system

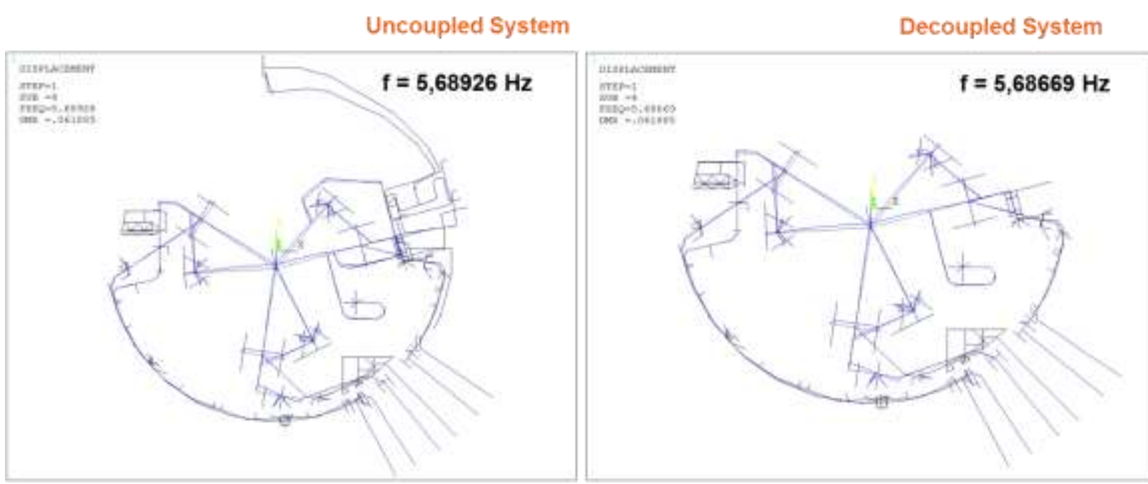

Fig. 5 – With or without the TH system the models have almost identical frequencies (shown 4th mode)

5. Adaptation of the PCS Model and Coupling with the Reactor Building Model

The finite-element 3D detailed building model is developed in SASSI2010. The model of the primary coolant system is developed in ANSYS. An important requirement on the coupled (complete) model is its compatibility to the SASSI2010 software package because of the complex soil-structure interaction analysis which includes ground motion incoherency effects. Therefore, the primary coolant system model available in ANSYS has to be translated into a SASSI2010 model. Here the following modifications of the ANSYS model of the primary coolant system is required: a) conversion of units; b) removal of local coordinate systems; c) transformation of ANSYS elbow elements into SASSI2010 conform stiffness matrix elements; d) transformation of spring, rigid link and stiffness matrix elements defined in local coordinates into elements defined in the global coordinates; transformation of material element damping into complex damping. Except for elbow elements and some rigid links, a matching equivalent of the ANSYS model is found in the element library of SASSI2010.

The models of the primary coolant system and the building are coupled at 189 nodes by rigid beam elements, see Fig. 6 for two examples. In the course of coupling the two models, the compatibility of finite elements with different degrees of freedom is taken carefully into consideration.

6. Verification and Validation of the Adapted PCS and the Complete Models

After implementation of the aforementioned transformation measures, the adapted ANSYS primary coolant system model is compatible to the element library and specific features of SASSI2010. For purpose of verification, modal analysis of the fixed-base original and the adopted PCS models is performed with ANSYS. Natural frequencies and associated mode shapes of both models are calculated and compared numerically by the Modal Assurance Criterion (MAC), see [2]. The MAC value of two equal modal vectors is 1.0. Fig. 7 indicates that the original and adopted PCS models are completely identical since the main diagonal elements of the correlation coefficient matrix are 1.0.

For verification and validation of the correct coupling of the PCS model with the building model time-history calculations with two different analysis methods and software packages are performed, see Fig. 8. In both calculations models only the primary coolant system model can oscillate. In addition to verifying the primary circuit integration into the building model, simultaneously a validation of the software packages is accomplished.

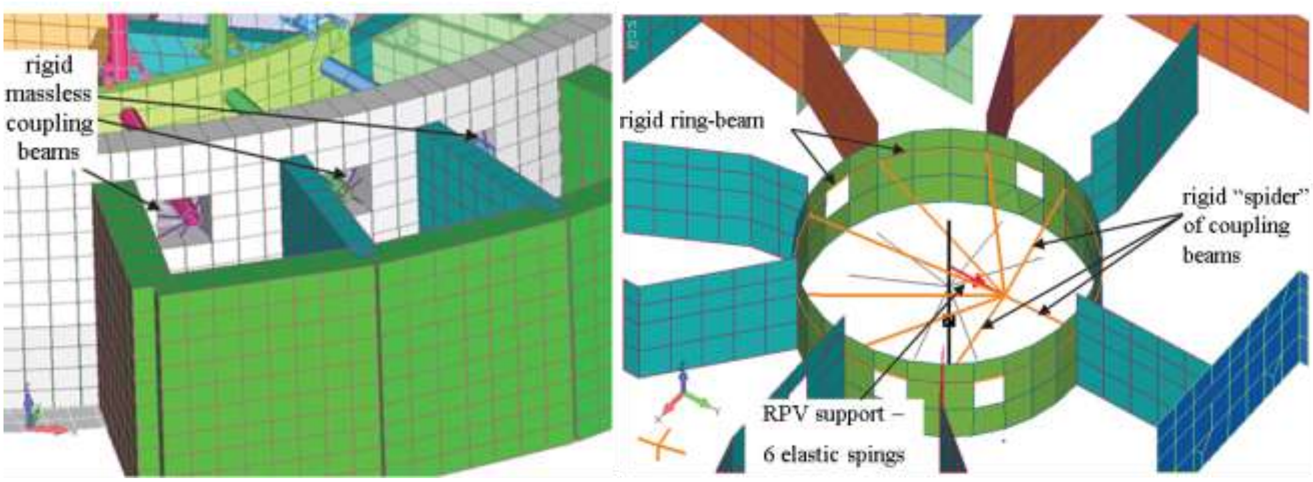

Fig. 6 – Examples of the coupling of the primary coolant system with the building models: a) on the left hand side coupling of the main steam system lines; b) on the right hand side coupling of the reactor pressure vessel

	f=3.172	f=5.248	f=5.647	f=5.738	f=5.992	f=6.635	f=6.757	f=6.767	f=7.005	f=7.401	f=7.5	f=7.583	f=7.648	f=7.695	f=7.786	f=7.863	f=7.965	f=8.213	f=8.709	f=8.824
f=3.172	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00
f=5.248	0.00	**1.00**	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
f=5.647	0.00	0.00	**1.00**	0.00	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00
f=5.738	0.00	0.02	0.00	**1.00**	0.07	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
f=5.992	0.00	0.00	0.14	0.07	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
f=6.635	0.00	0.00	0.01	0.01	0.00	**1.00**	0.00	0.01	0.12	0.00	0.08	0.01	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.00
f=6.757	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
f=6.767	0.00	0.01	0.00	0.02	0.00	0.01	0.00	**1.00**	0.00	0.00	0.00	0.06	0.03	0.00	0.02	0.00	0.00	0.00	0.00	0.00
f=7.005	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	**1.00**	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
f=7.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
f=7.5	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.01	0.00	**1.00**	0.01	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.00
f=7.583	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.06	0.00	0.00	0.01	**1.00**	0.36	0.05	0.74	0.69	0.03	0.00	0.00	0.00
f=7.648	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.03	0.00	0.00	0.02	0.36	**1.00**	0.07	0.64	0.39	0.10	0.00	0.00	0.00
f=7.695	0.00	0.00	0.06	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.03	0.05	0.07	**1.00**	0.00	0.04	0.30	0.00	0.00	0.00
f=7.786	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.74	0.64	0.00	**1.00**	0.79	0.00	0.00	0.00	0.00
f=7.863	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.69	0.39	0.04	0.79	**1.00**	0.05	0.00	0.00	0.00
f=7.965	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.10	0.30	0.00	0.05	**1.00**	0.00	0.00	0.00
f=8.213	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00	0.00
f=8.709	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00
f=8.824	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**

Fig. 7 – MAC values of original PCS model (row) vs. transformed PCS model (column)

The first calculation model is characterized with: a) the complete model of coupled PCS and building structure; b) the building is assumed massless and rigid to eliminate the interaction effects between PCS and building structure; c) the analysis is performed with a time-history in the frequency domain with SASSI2010.

The second calculation model is characterized with: a) the isolated primary coolant system without building structure, b) supported by rigid beams which link locations where the PCS is anchored to fixed nodes at the level of the building basemat; c) the analysis is performed by modal time-history method with ANSYS.

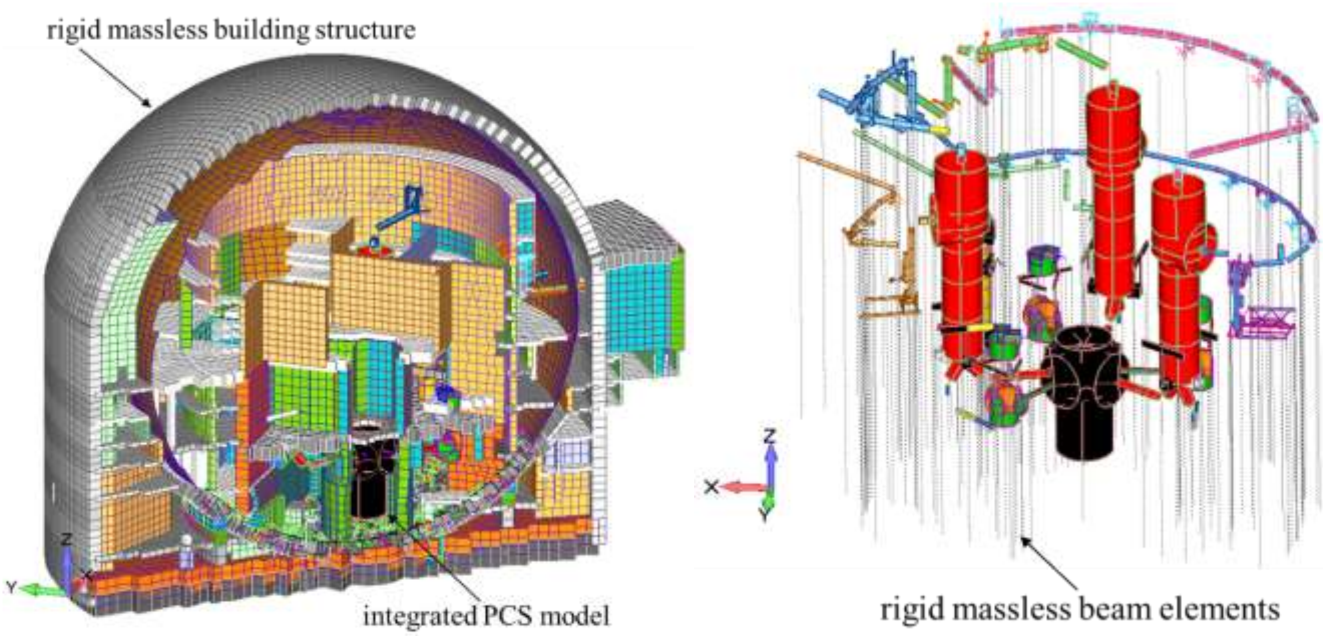

Fig. 8 – Verification and validation of the coupling of the PCS and the building models: a) on the left hand side coupling of PCS model (SASSI2010) to a massless and rigid building structure; b) on the right hand side coupling of PCS model (ANSYS) to rigid vertical beams fixed at nodes at basemat level

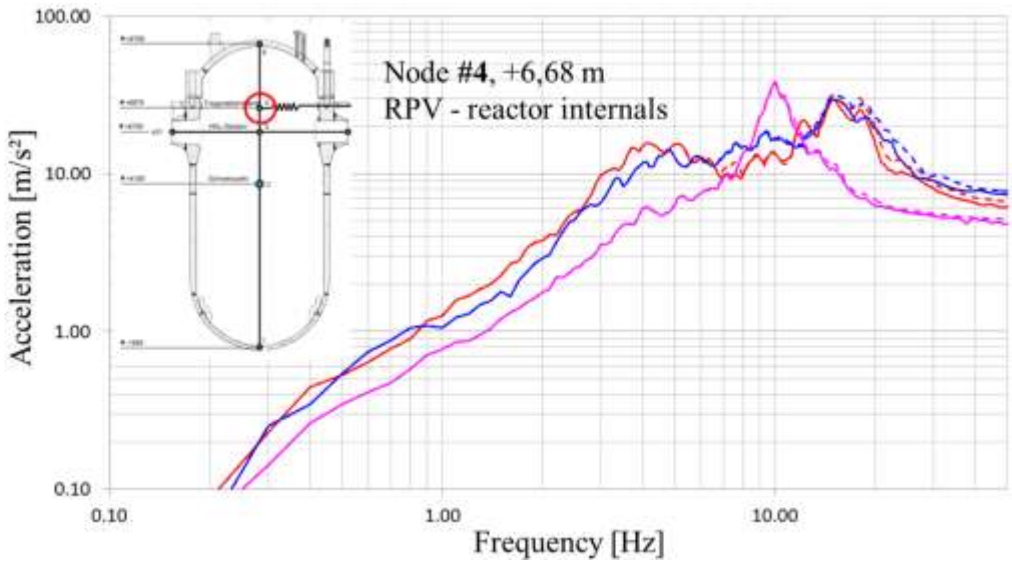

Fig. 9 – Response spectra (D = 4 %) at the decisive node for the reactor internals computed with SASSI2010 (dashed line) and ANSYS (full line) models in the three spatial directions (different colors)

The two models are excited with the same set of 3 time-histories in the two horizontal and the vertical directions. For the sake of simplicity – only in these verification and validation analysis – both concrete and steel structures are attenuated with a damping D = 4 % of critical. Correspondingly, in the frequency domain calculations with SASSI (first model) all elements are uniformly damped with D = 4% as well as in the modal analysis with ANSYS (second model) all modes are damped with a modal damping D = 4%.

The response time-histories in terms of absolute acceleration are computed with both models at 20 characteristic nodes of the PCS components for comparison purposes. Fig. 9 shows the response spectra (D = 4 %) at the characteristic node for the reactor internals inside the RPV calculated with the two models (SASSI2010 – dashed line; ANSYS – full line) in the three spatial directions (different colors). The comparison demonstrates a very accurate match. Slight numerical differences are observed in the high frequency range due to slightly different model implementation and the different methods of calculation, i.e. modal time-history vs. frequency-domain analysis. Based on the results obtained for all 20 characteristic nodes of the PCS components it is concluded that integration of the PCS model into the 3D building model is accurate.

7. Performed Preliminary Soil-Structure Interaction Analysis with the Complete Model

The final verification and validation calculations are performed with SASSI2010 in the frequency domain with the complete model for different modeling assumptions, aiming to investigate the absolute and relative effect of decisive modeling variables such as embedment depth, ground motion coherency model and excitation time-history on the response spectra at two characteristic structural nodes.

The reactor building structure is a heavy, massive concrete building embedded in the surrounding foundation soil. For such heavy and stiff structures the effects of seismic soil-structure interaction are significant. Results at characteristic structural nodes are calculated, post-processed and documented. In the present paper only results for two nodes are given, namely at elevations -6.00 m at top of the basemat and +18.40 m inside the reactor building inner structure (IS).

The seismic excitation is defined by 30 spectrum compatible time-histories with control point at free-field surface. They were generated by the PEGASOS Refinement Project (PRP) [3] for the seismic hazard with an annual probability of exceedance of 10^{-4} and provided to Gösgen NPP. Please note that the seismic hazard developed within the PRP differs from the official seismic hazard “ENSI-2015”. Tentative results shown here are for illustration purposes only.

7.1 Consideration of the Embedment Effect

In calculations without embedment (i.e. surface foundation), the subsystems soil and structure are coupled through the common model nodes located at the interface area under the foundation basemat. The calculation of the impedance matrix of the subsoil is carried out for about 2100 model nodes of the basemat.

Consideration of the embedment requires additionally the idealization of the excavated soil by volume elements. The material properties of soil volume elements correspond to those of the surrounding soil. Coupling of the subsystems soil and structure takes place additionally via the common model nodes at the outer building walls which are in areas with embedment. Calculation of the impedance matrix is then carried out optionally either for all 8500 model nodes of the soil volume (Direct Method) or for the 2700 model nodes of the basemat and the outer building walls (Subtraction Method). When compiling the matrix of the entire system, the finite elements of the excavated soil volume are assigned a negative sign, since in the calculation of the impedance matrix the excavated soil is not considered.

A modification of the Subtraction Method takes into account the model nodes of the upper boundary of the soil volume in the calculation of the impedance matrix. In this so-called Modified Subtraction Method, the 4500 interaction nodes increase the computation time considerably.

The effective embedment depth is varied in the present study between 3 m and 4 m. It is assumed less than half of the physical embedment to acknowledge proximity effects of adjacent buildings. In surface-foundation calculations, the original seismic excitation defined at the control point on the ground surface in the free-field (i.e. at ± 0.00 m), is applied at the level of the foundation basemat (i.e. at -9.00 m). In calculations with embedment, the ground surface is assumed at a level corresponding to the elevation of the foundation basemat increased by the assumed embedment (i.e. at -6.00 m or -5.00 m, respectively). Results presented here are calculated with the Subtraction Method. Because spurious vibration modes in the transfer functions in the frequency range of interest are not observed, transfer functions are obviously reasonably accurate.

7.2 Consideration of the Incoherent Ground Motion Excitation of the Structure

Analysis of seismic signals recorded within an extended area on the ground surface shows differences in their amplitude and phase. Primarily, these differences are caused by the wave passage effect and seismic wave modifications due to inhomogeneous soil properties. The first effect has only a minor influence on the response and is often neglected. An empirical approach based on coherency functions addresses the latter effect. These coherency functions – derived from extensive analysis of databases of recorded seismic motions – describe the incoherent motion between two points as a function of distance and frequency.

For application in seismic calculations corresponding functions have been developed for generic soil (based on data for soft-soil; soft-rock and hard-rock) [4], rock (based on data for hard-rock only) [5] and soft soil (based on data for soft-soil only) [5]. The first two options are implemented in SASSI2010 [6], with the functions for rock describing considerably more coherent ground motion as the functions for generic soil. With a shear wave velocity V_{s30} of about 500 m/s (see Fig. 1) at the site, the generic soil coherency functions are assumed to match best the site-specific soil conditions. Moreover, they are derived from data for all three soil classes and thus inherently comprise the central tendency (average of the soft-soil and hard-rock coherency) recommended in reference [5] for soft-rock (or firm-soil).

To take account of the incoherent seismic excitation in SASSI2010 [6], first a matrix for the translational degrees of freedom of the soil nodes of the computational model is determined, based on the aforementioned coherency functions. This matrix comprises of values between 1 (coherent) and 0 (incoherent) depending on the coherency relationship between nodes of the model. After performing an eigenvalue calculation, this matrix can be represented by a limited number of eigenvectors. Each of these eigenvectors returns a modified load vector for which a seismic calculation has to be performed. Finally, the system responses calculated with the load vectors are superimposed by the SRSS (square root of the sum of the squares) rule.

7.3 Results and Discussion

Transfer functions describe the changes which occur to input signals as they pass through the linear-elastic soil-structure system and emerge as output signals. In particular, as used here, transfer functions describe the modification of the seismic motions between the single control input point (top of free-field) and output points (nodes of the structural model).

Fig. 10 depicts the difference in the transfer functions of nodes 01 and 02 due to different modelling assumptions, namely: a) surface foundation resting on top of the soil layer at – 9.0 m as per Fig. 1; b) embedded foundation in the soil layers between – 6.0 m and – 9.0 m (i.e. embedment depth = 3 m); generic soil coherence functions as per EPRI [4] in addition to embedded foundation. The transfer functions of the basemat (node 01) indicate that the dominant vibration modes of the complete system in the two horizontal directions X and Y are at about 3 Hz and in the vertical direction at about 6.4 Hz. The second peak in the horizontal directions indicates a rocking frequency of near 5 Hz. The stiffening effect due to the embedment of the building structure is evident through the small increase by about 0.1 Hz of the horizontal natural frequencies. The favorable effect of the embedment on the response in vertical direction is clearly demonstrated in the transfer function of the basemat, where a reduction of 16 % (1 – 2.6/3.1) is observed. In addition to the aforementioned response reduction in vertical direction, the consideration of incoherent seismic ground motion excitation grants now at 6.4 Hz a further reduction of 8 % (1 – 2.4/2.6). As expected, the favorable effect of incoherent ground motion excitation on the seismic response is more pronounced in all three directions in the high frequency range above 12 Hz. Here it is worth to mention that the major eigenfrequencies of the primary coolant system are in the frequency range of 6 to 20 Hz.

In Fig. 11 the effect of assumed embedment depth (3 m or 4 m) on the response spectra of node 02 is revealed to be minor. A small favorable effect (peak response reduction) of the embedment is found in the vertical response for frequencies below 8 Hz. Evident is also a stiffening effect of the building structure due to deeper embedment, see e.g. response in vertical direction at frequency of about 18 Hz.

Fig. 12 indicates that the effect of both embedment and incoherent ground motion excitation on the response spectra of node 02 in horizontal direction is negligible. As expected, the effect on the vertical response (inherently in higher frequency range) is slightly stronger for the generic soil than for the hard-rock coherence functions.

Fig. 13 indicates that the strongest effect on the response spectra of node 02 is caused by the selection of the ground motion excitation time-history. In this study 2 sets of time-histories out of provided 30 target-spectrum compatible sets are selected randomly and used as input.

8. Conclusion

Frist, the 3D detailed finite-element model of the reactor building and main components and piping of the primary coolant system and part of the secondary system are coupled to form the complete model. The correct coupling of the primary coolant system model with the building model is verified and validated with two different analysis methods and software packages.

Next, soil-structure interaction calculations with SASSI2010 in the frequency domain are carried out with the complete model for different modeling assumptions, aiming to investigate their absolute and relative effect on the response spectra at two characteristic structural nodes. These sensitivity analyses are performed for 2 different embedment depths plus surface foundation, coherency functions for 2 different soil classes and 2 different sets of ground motion excitation time-histories. The results in terms of response spectra for a characteristic structural node, located on the inner structure at elevation +18.40 m, indicate that the effect of assumed embedment depth and incoherent ground motion excitation is minor for the horizontal direction and more pronounced for the vertical direction. The most significant effect on the response spectra for the selected structural node is in the present situation caused by the selection of the ground motion excitation time-history.

It is suggested to investigate the effect of the aforementioned different modeling assumptions on the internal forces in the complete model (i.e. building with PCS and its piping) in the upcoming project stage.

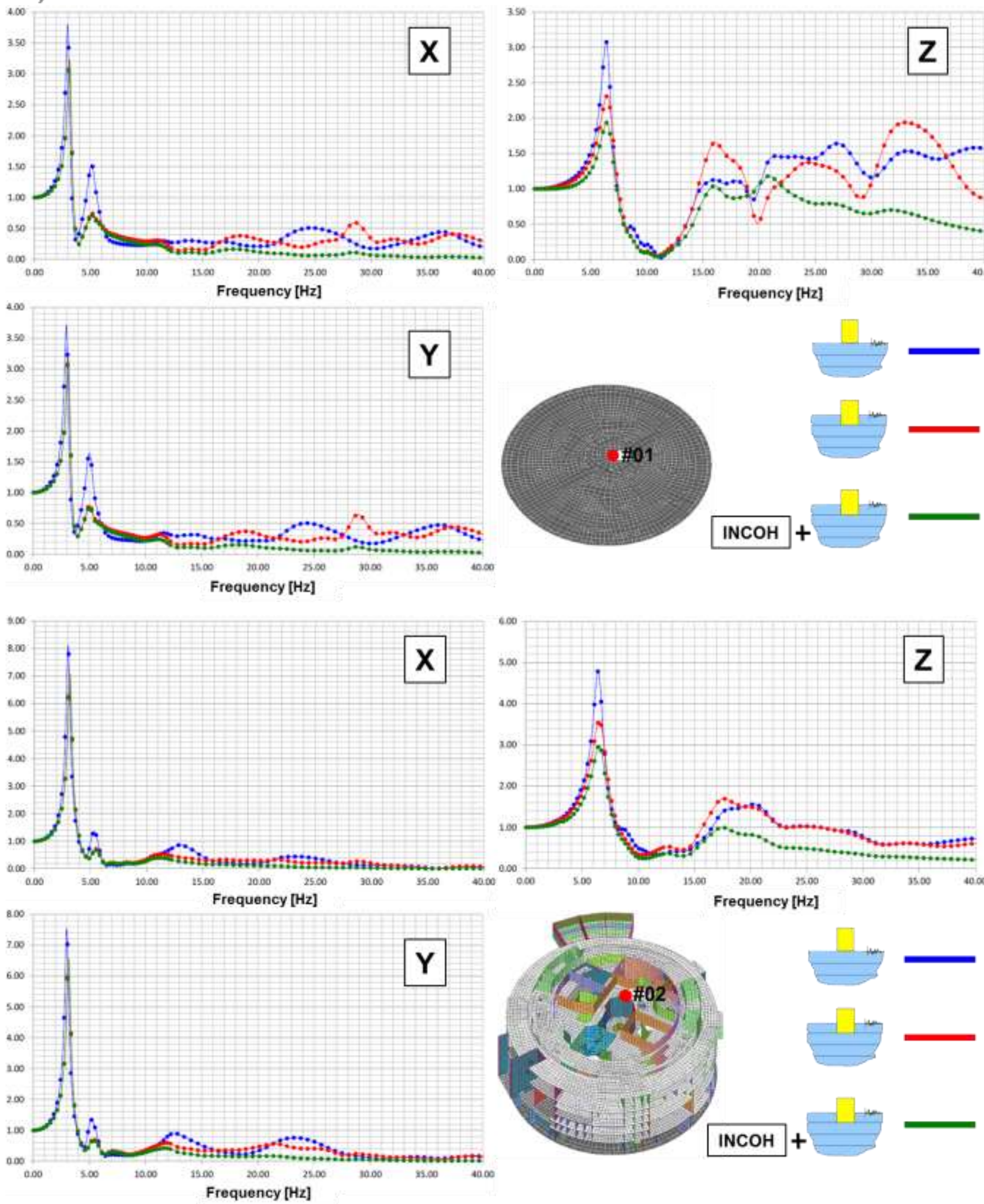

Fig. 10 – SSI modeling effects on the transfer functions of nodes 01 (-6.00 m) and 02 (+18.40 m; IS): a) surface foundation; b) embedded foundation; c) embedded foundation + coherence functions [4]

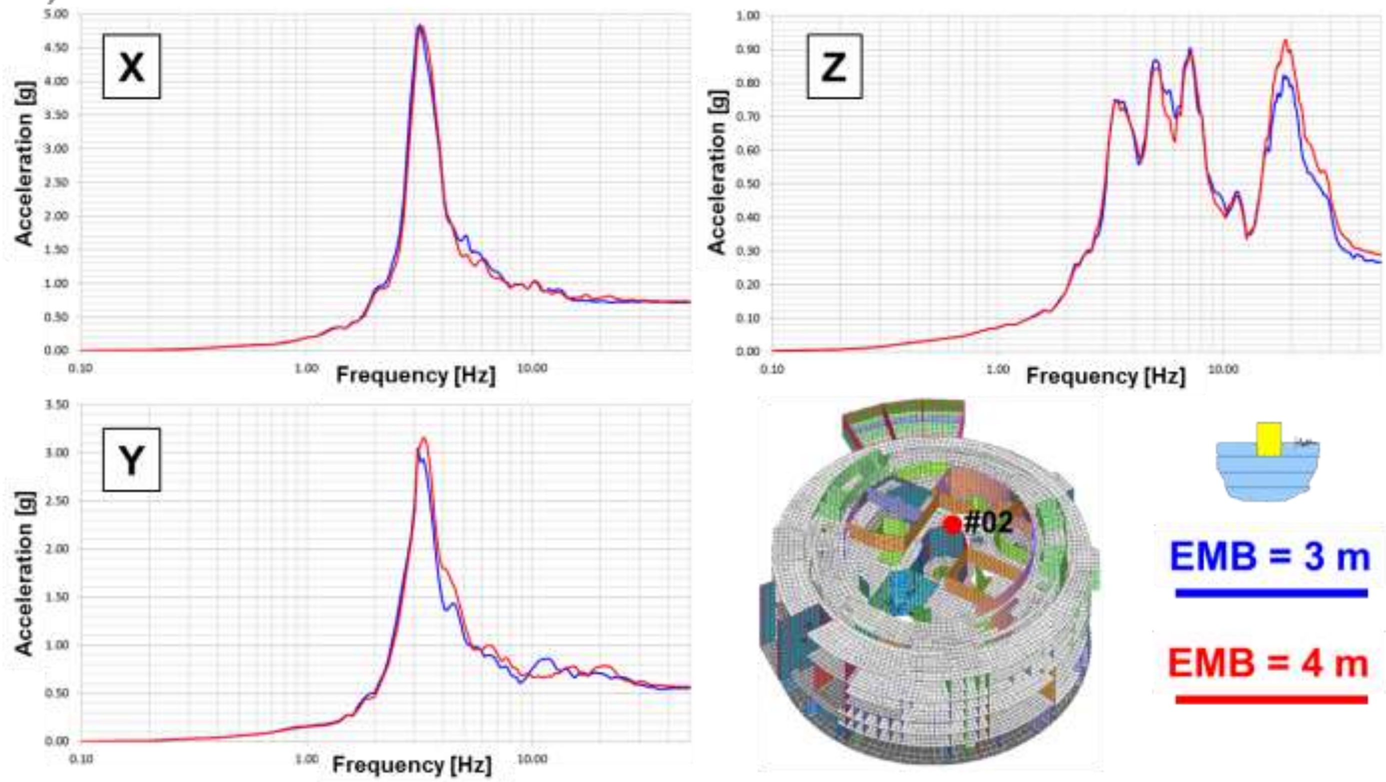

Fig. 11 – SSI modeling effects on the response spectra of node 02 (+18.40 m; IS) due to different embedment depth assumptions: embedment depth of 3 m (blue); embedment depth of 4 m (red)

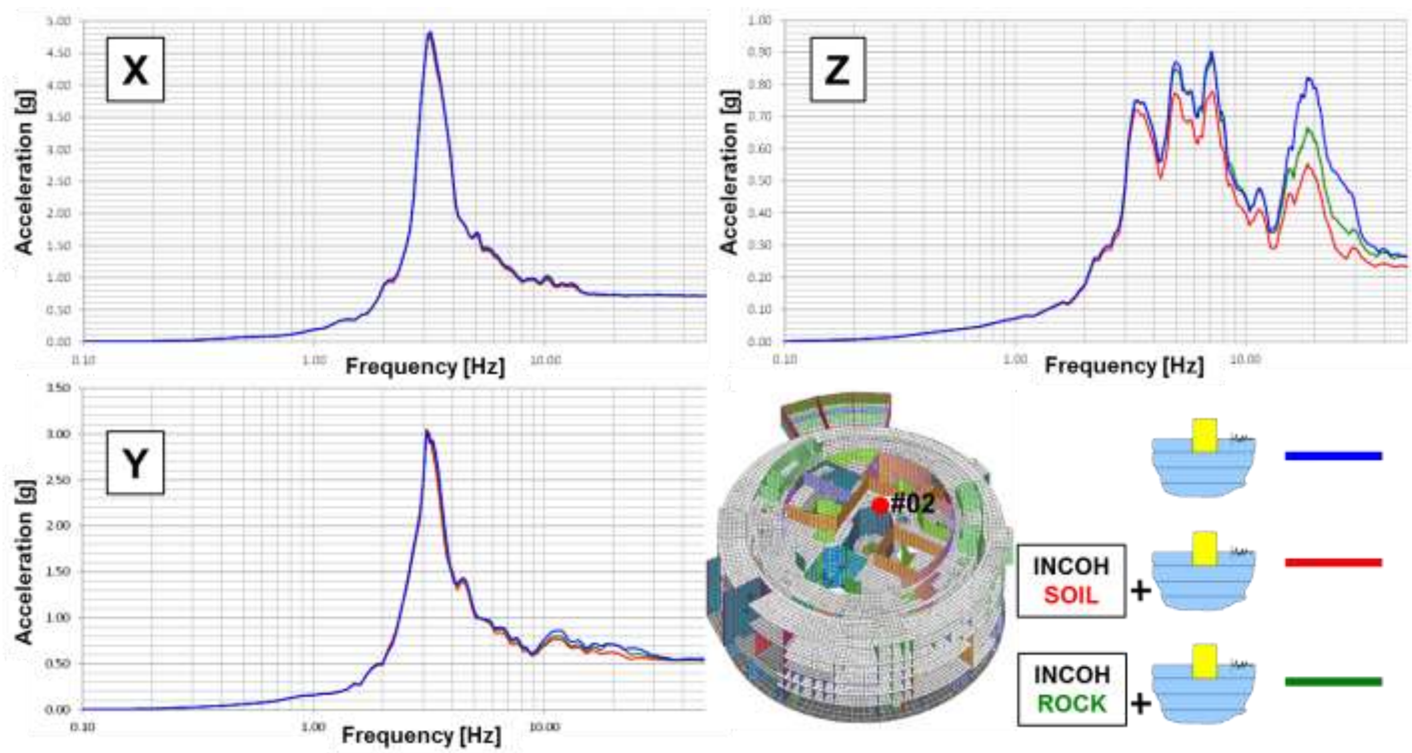

Fig. 12 – SSI modeling effects on the response spectra of node 02 (+18.40 m; IS): embedded foundation (blue); embedded foundation + SOIL [4] coherence functions (red); embedded foundation + ROCK [5] coherence functions (green)

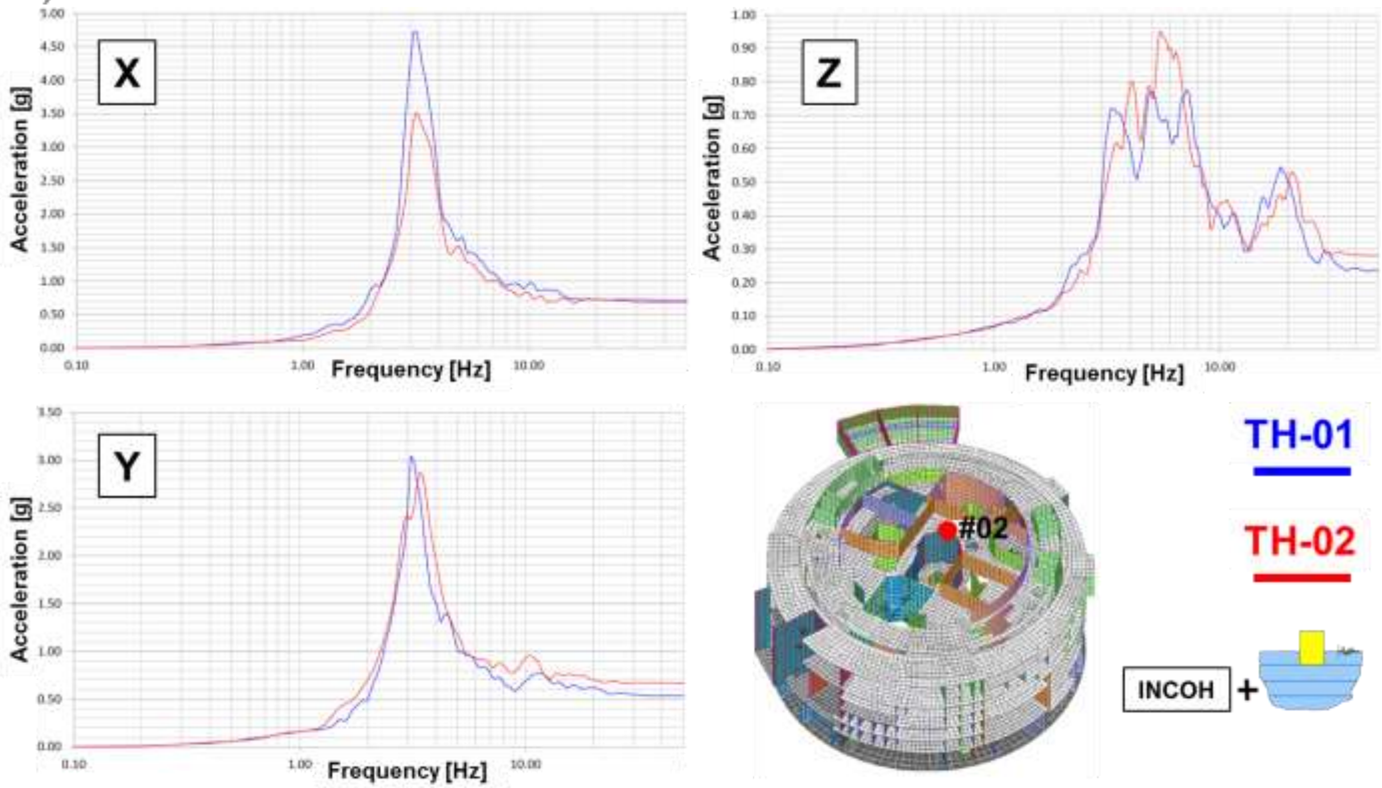

Fig. 13 – SSI modeling effects on the response spectra of node 02 (+18.40 m; IS) due to different ground motion excitation time-histories: time-history set TH-01 (blue); time-history set TH-02 (red)

9. Disclaimer

The opinions expressed herein are those of the authors and do not necessarily reflect the views of the Gösgen-Däniken nuclear power plant.

10. References

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