Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division V

DEVELOPMENT OF THE COUPLED SOIL-STRUCTURE INTERACTION (SSI) ANALYSIS MODEL OF A REACTOR BUILDING USING DOMAIN REDUCTION METHOD (DRM)

Yogesh Rathod[1], Yigit Isbiliroglu[2], Olivier Nusbaumer[3], Matthew Haapala[4], Sai Chowdeswara Rao Korlapati[1], Nish Vaidya[5], Jacobo Bielak[6], Holger Senechal[7], Davide Kurmann[8]

[1] Structural Engineer, RIZZO International, Pittsburgh, PA, USA (yogesh.rathod@rizzointl.com)
[2] Engineering Director, RIZZO International, Pittsburgh, PA, USA
[3] Principal Engineer and Technical Expert SES, Kernkraftwerk Leibstadt AG, Switzerland
[4] Senior Engineer, RIZZO International, Pittsburgh, PA, USA
[5] Vice President/Fellow, RIZZO International, Pittsburgh, PA, USA
[6] Emeritus Professor, Carnegie Mellon University, Pittsburgh, PA, USA
[7] Structural Mechanics & Managing Director, KAE GmbH, Hausen, Germany
[8] Leiter Engineering Bautechnik, AXPO, Zürich Area, Switzerland

ABSTRACT

This paper presents the development of a coupled model of a reactor building (RB) at a soil-founded nuclear power plant (NPP) employed in the seismic soil-structure interaction (SSI) analysis using the Domain Reduction Method (DRM). The coupled model incorporates the reactor pressure vessel (RPV), selected RPV internals and the pressurized enclosure of reactor coolant system (RCS). The resulting coupled model includes a total of 215,150 nodes, 47,537 shell-elements, 8,926 beam elements, 129,895 solid-elements and 13,688 mass-elements. The seismic verification of the RB structures, systems and components is performed using the stress level seismic response directly extracted from the analysis of the aggregate coupled model.

The coupled model seismic SSI analyses have been performed in the time domain using the DRM as presented in Bielak et al. (2003). The present paper briefly describes the development of the DRM analytical model including the representation of the subsurface soil, integration of the RB structure and application of the seismic environment. This is accomplished in the following consecutive steps:

1. Development of the free-field model and verification by means of site response analysis assuming 1-D wave propagation,
2. Development of the RB Standard Model, where the RPV and RCS are represented by lump masses, using the above-mentioned DRM free-field model,
3. Sensitivity study to investigate the parameters related to domain size and attenuation and verification using available ACS-SASSI (2018) Standard Model calculation,
4. Development and seismic analysis of the SSI coupled model.

The SSI coupled model is developed and analysed using the advanced capabilities of ANSYS 2020 R1 (2020) including its high-performance computational platform (HPC), choice of finite element formulations and processing of seismic response quantities. The DRM model and method is satisfactorily validated, and on this basis used as the analysis of record. To the authors knowledge, this is one of the first applications of the time-domain DRM SSI approach to obtain the seismic response of NPP structures. The effectiveness of this approach is demonstrated by comparing floor response spectra (FRS) to the FRS obtained using traditional methods.

INTRODUCTION

Seismic risk analysis is currently the general practice to assess seismic safety of NPPs. However, the requirements in Switzerland are among the most stringent, requiring re-analysis using realistic representation of building structures dynamic behaviour relative to models and methods used in design. In this regard, the development of a fully integrated model of Reactor Coolant System (RCS) equipment and containment, as required by the Swiss nuclear safety inspectorate (ENSI), is to our knowledge unique.

The current regulatory requirements present major new opportunities and challenges, such as including sufficient modelling details, whilst keeping the model as simple as possible for optimal usability. Accordingly, a comprehensive aggregate coupled model is developed for the seismic soil-structure interaction (SSI) analysis of the entire Reactor Building (RB) and major equipment. Consistent with guidance ENSI-AN-8567 (2014), the aggregate model combines the reactor pressure vessel (RPV), all relevant reactor internals, equipment and piping of the pressure boundary up to the second isolation valve, and the structure. The model is sufficiently detailed to allow the direct extraction of component level responses accounting for dynamic coupling.

The aggregate model is developed in ANSYS APDL (2020) for use in Domain Reduction Method (DRM) (Bielak et al., 2003). Using DRM, the seismic SSI analysis can be readily performed in time domain for specified input ground motions. Here, the input ground motion is defined by ENSI-2015 (PROSEIS, 2015) uniform hazard spectra (UHS) for an annual probability of exceedance of 10^{-4}.

Seismic input motion is represented by horizontal and vertical ground motion response spectra (10^{-4} UHS) characterized by peak ground accelerations (PGA) of 0.35 g, and 0.24 g, respectively. The horizontal 5% damped UHS peaks around 5 Hz with maximum spectral accelerations about 1.1 g.

The paper describes the development of the RB coupled model and its integration into the DRM SSI model. The paper also presents the primary attributes of the SSI model development and the results obtained from the DRM SSI analysis.

DEVELOPMENT OF RB COUPLED MODEL

The intent of the SSI analysis of the coupled model is to support the realistic deterministic proofs for safety relevant Structures, Systems and Components (SSC's) including the effects of coupling on the response quantities.

The different parts of the model as shown in Figure 1 are identified below:

- RB structure model, which is sufficiently refined to accommodate the coupling points (e.g., steel platforms) for connecting piping;
- RPV model, including internals in sufficient detail to allow extraction of seismic forces, moments and stresses;
- Piping models including the recirculation loops of the RCS, the feed water and the main steam lines up to second isolation valve, Emergency Core Cooling System injection lines and related piping;
- A detailed polar crane and a fuel storage rack models developed as part of the project;
- The finite element model of the reduced soil domain to facilitate the integrated DRM SSI analysis in the time-domain.

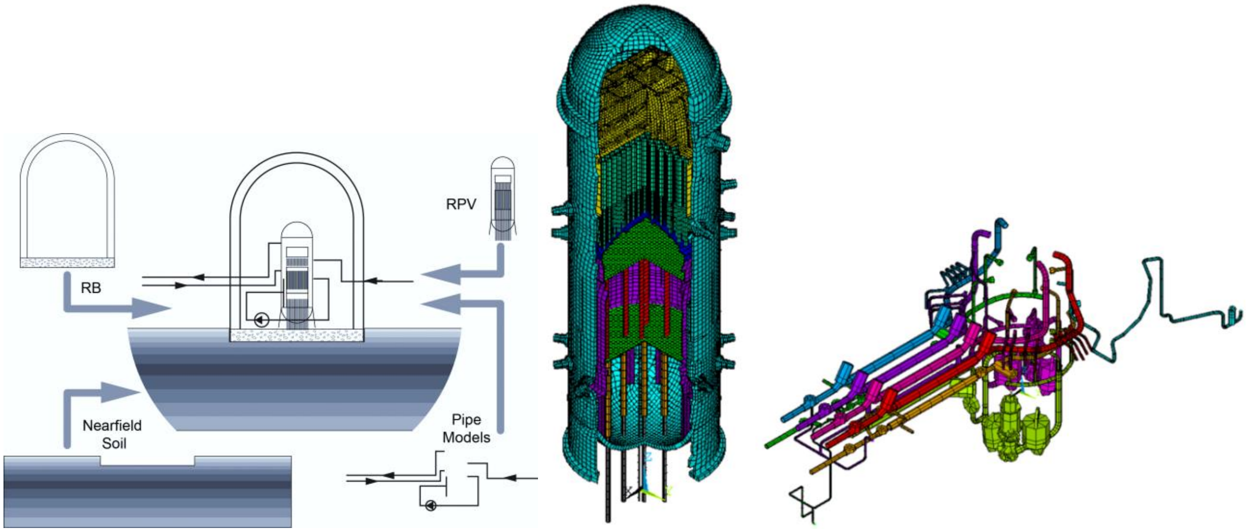

Figure 1. Schematic of coupled model development (left). Detailed RPV model (middle). Detailed piping models (right)

One of the project challenges was the need to refine the traditional two-step verification approach. The traditional approach consists of first calculating the seismic deformations and loads using an appropriate analytical model of the coupled system, and in a second step to apply the response quantities as boundary conditions to more detailed models of various parts of the coupled model. The second step supports the deterministic safety verifications of the parts. Due to the technical challenges and intrinsic conservatisms of the traditional approach, a refined approach is considered here with the aim of solving both steps simultaneously.

- Because the coupled model already represents the safety relevant components, it allows the extraction of component level responses (accelerations, displacements and stresses). The coupled model (Figure 2) is developed with sufficient details to fulfil the regulatory requirements, whilst keeping it as simple as possible for optimal usability and maintenance.
- The seismic SSI analysis is performed using the ANSYS (2020) time-domain method. The subsequent stress evaluations are scripted based on the ANSYS (2020) outputs. The capabilities of automation with ANSYS (2020) in combination with own scripting language was also an important aspect for this decision.

In addition to the typical SSCs like the RB structure, RPV and piping, more complex elements like steel structures inside and outside Drywell are also incorporated for the correct coupling of pipe supports to the building structural concrete. Another complex modelling aspect is the need to consider the water masses and movement in water pools. This is done by representing the pool water as convective and impulsive masses as well as the hydrodynamic component on submerged elements ASCE 4-16 (2017).

In order to ensure the coupled model achieves the necessary quality standards, independent reviews were performed during its development including readouts of as-built conditions from comprehensive walkdowns. Table 1 presents some relevant statistics about the number of nodes and elements used for the sub-models and illustrates the comprehensive scope of the coupled model. Table 1 also presents the mass of major sub-model components and the percentage with respect to the total mass, excluding the DRM soil. ANSYS (2020) High Performance Computing (HPC) capability is utilized to perform the runs, which resulted in a speedup about three (3) times compared to basic license run performance.

Figure 2. Fixed base RB coupled model

Table 1: Model element statistics and mass of mass of major sub-model components

Model part	Nodes	Solid	Shell	Beam	Mass	Mass (ton)	% of total mass
RB	25,609	3,969	18,966	1,070	1,734	73,900	96.8
RPV	32,802	–	26,123	5,067	11,161	1,410	1.8
Pipes	2,439	–	–	1,554	217	620	0.8
Polar Crane	901	–	–	174	23	66	0.1
Fuel Rack	2,009	–	–	1,051	16	314	0.4
DRM Soil	147,584	161,942	–	–	–	-	-
Total	211,344	165,911	45,089	8,916	13,151	76,310	100

DRM MODEL CALIBRATION

The DRM SSI model consists of the RB and a reduced domain subsurface soil model. This model includes the near field soil in which a marginal region - the so-called crust - is defined, on which the seismic force field is applied. The crust is a layer of elements with a specified thickness that separates the subsurface soil model into an inner and an outer region. The region within the crust is sufficiently large to adequately represent the SSI. The seismic force field on the crust is determined on the basis of the seismic displacements obtained from free-field calculation, at both the inner and outer nodes.

The region outside the crust represents the far field; here, the seismic motion due to scattering is allowed to radiate out and eventually decay sufficiently at the model exterior boundaries. From a modelling standpoint, this is realized using Lysmer absorbing elements (Lysmer and Kuhlemeyer, 1969).

The DRM model is developed in two (2) steps. The first step defines the free-field model using the following model parameters: i) Domain size; ii) Position of the crust within the domain; and iii) Damping model and respective parameters. The parameters of the free-field model are iteratively calibrated so that the seismic motion interior to the crust is the same as the reference free-field motion, and the motion outside the crust is zero.

The second step initially uses the Standard building model (without coupling) to develop the "Standard" DRM SSI model (Figure 3). This model is verified with respect to reasonableness of the SSI response relative to the fixed base as well as comparison with the ACS-SASSI (2018) responses, as available. Major observations and insights gained from several sensitivity runs are briefly outlined below and are utilized in the development of the "Coupled" DRM SSI model.

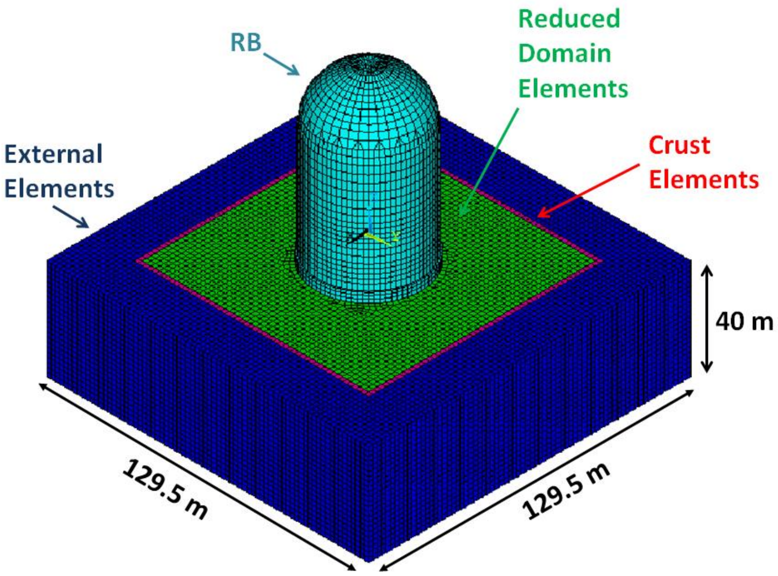

Figure 3. ANSYS-DRM RB model

Effect of horizontal domain size

The effects of the horizontal model size on the SSI response are assessed by comparing the results from the analysis of three (3) different domain size models shown in Table 2.

Table 2. Sensitivity analysis for horizontal model size

Run Id	**Total/Int. Domain Size m x m x m**	**Soil Rayleigh Damping** 1	**Struct. Rayleigh Damping** 1
28	80x80x40/63x63x30	Target matched at 2.5Hz and 25Hz	Target matched at 2.5Hz and 15Hz
33	129x129x40/91x91x30	Target matched at 2.5Hz and 14Hz	Target matched at 2.5Hz and 15Hz
36	259x259x40/238x238x30	Target matched at 2.5Hz and 14Hz	Target matched at 2.5Hz and 15Hz

1) Rayleigh damping ratios are targeted at the same values used in the SASSI model, unless otherwise noted

The comparison shown in Figure 4 for a node at bio-shield wall illustrates how the response at higher frequency (12Hz) is progressively reduced and converges towards the ACS-SASSI (2018) response. The above comparison illustrates that a model size 129m x 129m x 40m is sufficiently representative. Still, dominant SSI mode at 6 Hz appears to be underdamped due to the choice of Rayleigh damping parameters.

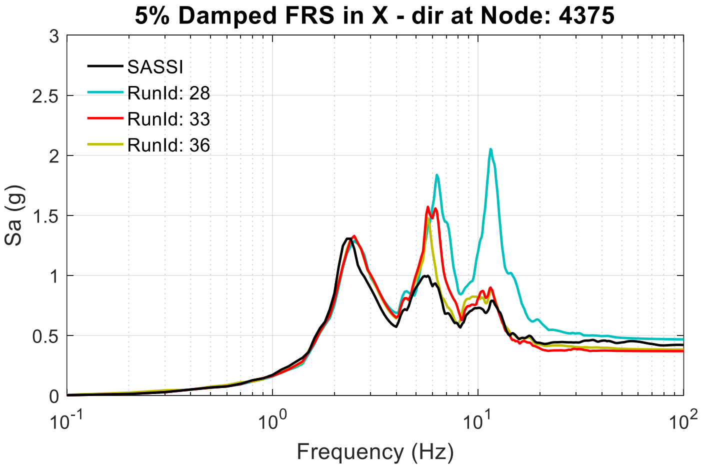

Figure 4. Effect of horizontal model size on horizontal Floor Response Spectra (FRS)

Effect of damping representation

Several sensitivity studies were performed to provide insights into the effects of damping representation in DRM on the predicted response in the important modes of the SSI system. Accordingly, the damping parameters for soil elements are selected to reflect the effective damping in the SSI modes accounting for material and radiation damping. On the other hand, the damping parameters in structural concrete are selected to represent the respective damping values in the important structural modes (modified by the supporting soil). The damping sensitivity studies, in addition to Run 33, are identified in Table 3.

Table 3. Sensitivity analysis for damping parameters

Run Id	**Total/Int. Domain Size m x m x m**	**Soil Rayleigh Damping** [1]	**Struct. Rayleigh Damping** [1]
38	129x129x40/91x91x30	Target matched at 2.5Hz [2]	Target matched at 2.5Hz [2]
43	129x129x40/91x91x30	1.5xSCD matched at 2.5Hz and 20Hz	Target matched at 2.5Hz and 6Hz
45	129x129x40/91x91x30	Target: 1.75xSCD [3]	Target matched at 2.5Hz and 6Hz

1) Rayleigh damping ratios are targeted at the same values used in the SASSI model, unless otherwise noted. SCD=Strain Compatible Damping
2) Run 38 uses stiffness proportional damping targeted at a single frequency
3) Rayleigh parameters are set to minimize error between 2.5 & 19.5Hz

All of the sensitivity runs identified in Table 3 are performed for seismic input along X-direction only (SH Wave) represented by a 10-second-long acceleration time history. With the exception of Run 45, the Rayleigh damping parameters target the soil Strain Compatible Damping (SCD) values at one (1) or two (2) selected frequencies. Run 45, on the other hand, uses Rayleigh damping parameters set to minimize the difference between the Rayleigh damping and the constant damping in the specified frequency range of interest.

Based on the comparison of the representative FRS shown in Figure 5, it is concluded that the parameters used in Run 45 result in a response that is conservative relative to the response from ACS-SASSI yet sufficiently precise and representative for the single direction seismic input. Run 45 reflects a more or less constant soil material damping of about 8% in the range of frequencies from 4 Hz to 6 Hz in the first few soil layers at the dominant SSI modes.

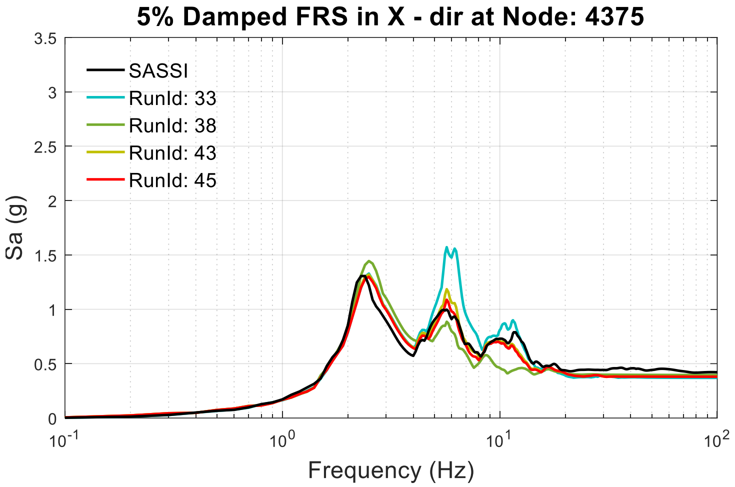

Figure 5. Effect of damping representation on horizontal Floor Response Spectra (FRS)

Effect of simultaneous input motion in three (3) directions

Several sensitivity studies were performed to obtain insights into the effects of simultaneous inputs in the three directions (SH waves in X- and Y-directions, SV wave in Z-direction), where the response quantities are obtained by algebraic summation of co-directional responses. The focus of these sensitivity runs was to assess the conclusions regarding damping representation based on the sensitivity studies discussed previously recognizing that neither SASSI nor the DRM results can be assumed to be the "correct" values a-priori. The sensitivity runs as identified in Table 4 are performed for total duration of 20 seconds and use Rayleigh damping parameters which minimize the difference between the Rayleigh damping and the strain compatible constant damping at dominant SSI frequencies, as discussed above.

Based on the comparison of the representative FRS shown in Figure 6, it is concluded that the parameters used in Run 66 result in a response that is sufficiently close to the response from ACS-SASSI (2018) analysis. Run 66 reflects a more or less constant soil material damping equal to the SCD in the range of frequencies from 4 Hz to 6 Hz in the first few soil layers (similar to SASSI).

Table 4. Sensitivity analysis for simultaneous input motion in three (3) directions

Run Id	**Total/Int. Domain Size m x m x m**	**Soil Rayleigh Damping** [1]	**Struct. Rayleigh Damping** [2]
63	129x129x40/ 91x91x30	Target: 1.75xSCD	Target matched at 2.5 and 6.0Hz
65	129x129x40/ 91x91x30	Target: 1.5xSCD	Target matched at 2.5 and 6.0Hz
66	129x129x40/ 91x91x30	Target: 1.15xSCD	Target matched at 2.5Hz and 6.0Hz

1) Rayleigh parameters set to minimize error bet. 2.5 & 19.5Hz. SCD=Strain Compatible Damping
2) Rayleigh damping ratios are targeted at the same values used in the SASSI model.

Figure 7 compares the Rayleigh damping curves associated with the Runs performed in the previous section, including the Model of Record (Run 66), with respect to the target strain compatible damping at the top soil layer used in the SASSI analysis. As shown in Figure 7, Model of Record (Run 66) effectively minimizes the error between the specified constant and Rayleigh damping at the dominant SSI rocking frequency at 5.8 Hz, and the dominant horizontal and vertical SSI modes of about 6 Hz and 6.5 Hz, for which modes the soil damping could in general be important.

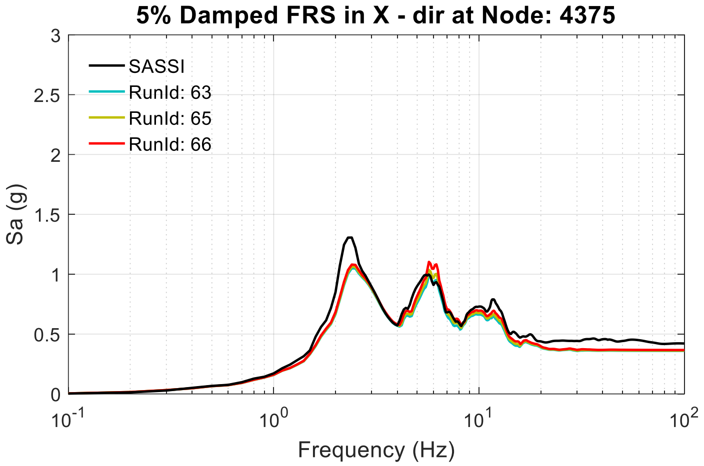

Figure 6. Effect of using simultaneous input motion in three (3) directions on horizontal Floor Response Spectra (FRS)

Figure 7 also indicates that the approach for modelling the damping over-estimates the damping at higher frequencies. This is not expected to affect the response of the SSCs because the FRS over the entire range of frequencies is determined primarily by the dominant SSI modes and the significant structural modes. These modes lie in the frequency range less than about 15 Hz.

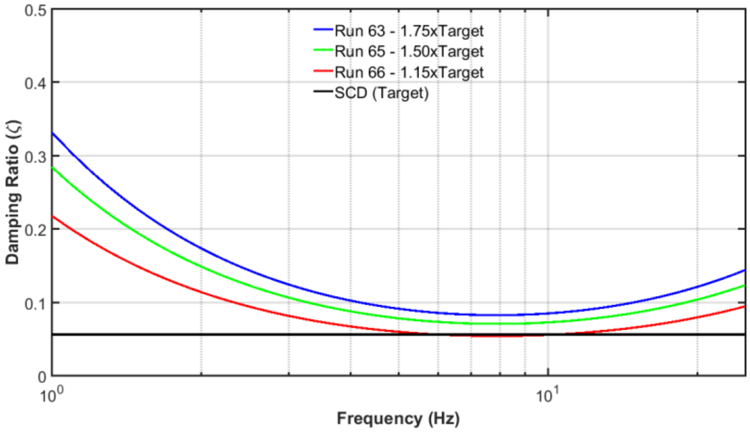

Figure 7. Comparison of minimum error Rayleigh damping to target strain compatible damping (SCD) for the top soil layer

Conclusion for DRM model calibration

The DRM seismic analysis of the soil-structure system is accomplished in the time-domain using ANSYS implicit integration scheme (HHT time integration method with gamma set to 0). The integration time step of 0.005 sec and the soil finite element mesh size of 1.75 m are in accordance with the recommendations in ASCE 4-16 (2017) for a cut-off frequency of 25 Hz.

Modal analysis of the DRM SSI model indicates that the significant SSI modes engage the soil layers to an approximate depth of about 20 m. These soil layers are characterized by a material damping of about 6%. Comparison with ACS-SASSI (2018) analysis indicates that the DRM may slightly under-represent the radiation damping in some cases. This under-representation is attributed primarily to the absorbing boundary elements.

The total system damping in DRM may be aligned with SASSI by means of adjusting the material damping and the Rayleigh parameters as in the case of Run 45 model in this study. This allows the use of a reasonable model size as well as the use of traditional absorbing elements at the boundaries of the model. Alternatively, the absorbing boundaries can be refined to minimize possible reflections of outgoing waves at the model boundaries.

The simultaneous application of input in three (3) directions (Run 66) may mitigate the need to adjust material damping if SASSI is taken to be taken as the “correct” solution. This is attributed to the possible beneficial effects of algebraic summation of the structural response due to torsion and rocking of the SSI system.

Based on the sensitivity analyses discussed above the DRM model represented in Run 66 is selected as the “Model of Record” to be used in the SSI analysis when seismic input is applied in three (3) orthogonal directions simultaneously.

CONCLUDING REMARKS AND INSIGHTS

The ENSI requirements in ENSI-AN-8567 (2014) state that the RB seismic response should be evaluated using the coupled model with the expectation that the predicted seismic demand on systems and components (e.g., FRS) in the building is more realistic and mitigates possible conservative and optimistic biases.

This paper describes the methodology and approach to accomplish those requirements in an efficient manner. Alternative to more commonly used frequency domain ACS-SASSI (2018) approaches, the DRM (Bielak et al, 2003), (Kontoe et. Al, 2008), (ASCE 4-16, 2017) is utilized here with success, after verifying the reasonableness of the SSI response relative to ACS-SASSI (2018) response.

Based on the project requirements, the DRM SSI analysis affords certain advantages relative to more traditional approaches as compared in Table 5 for major quality attributes. DRM can be performed entirely in ANSYS, without the need to interface with and transfer intermediate responses from other software. Additionally, the SASSI approach is limited to linear analysis because of its frequency-based solution. As such, further advanced analysis (e.g., full non-hybrid non-linear analysis) need to be performed by means of equivalent linear approaches or localized partial non-linearity (Ghiocel D. M., 2015). In addition, site complexities such as irregular soil layers and 3D seismic input are more directly treated in DRM.

These aspects may become important as part of the required fragility analysis in the long term. Accordingly, DRM is increasingly recognized as a good alternative to performing SSI as illustrated in several recent publications and research activities in the field.

Table 5. DRM advantages

Methods / Attributes	**DRM**	**SASSI**	**Direct Method**	**Soil Springs**
Analysis Approach	**Time**	**Freq.**	**Time**	**Time/ Freq.**
Realistic SSI	✓[1]	✓	✓	✗
Calculation Efficiency	✓	✓	✗	✓
Task Automation / Scripting	✓	✓	✓	✓
Advanced Post-Processing	✓	✓	✓	✓
Advanced /Equivalent Linear Analysis	✓	✓	✓	✓
Full Nonlinear Analysis	✓	✗	✓	✗
Local Soil Phenomena	✓	✓	✓	✗
Literature availability	✓	✓	✓	✓

1) The DRM approach requires the use of absorbing elements on the outside boundaries to eliminate the spurious reflection of residual waves due to SSI response of the structure. These residual waves are typically small and concentrate around the SSI frequencies. Typically, Lysmer boundaries are sufficient (Lysmer and Kuhlemeyer, 1969). If needed however, absorbing boundaries can be refined to minimize possible outgoing wave reflections at the boundaries.

REFERENCES

ACS-SASSI (2018). Advanced computational software for 3D Dynamic analysis including soil-structure interaction user manual revision 10 version 3. Ghiocel Predictive Technologies, Inc., USA.

ANSYS (2020). Computer software ANSYS 2020 R1. Canonsburg, PA USA.

ASCE 4-16 (2017). Seismic Analysis of Safety-Related Nuclear Structures. American Society of Civil Engineers. Reston, VA USA.

Bielak, J., Loukakis, K., Hisada, Y., and Yoshimura, C. (2003). Domain reduction method for three-dimensional earthquake modelling in localized regions. Bulletin of the Seismological Society of America 93, 817–824.

ENSI-AN-8567 (2014). Methodik deterministischer Nachweis der Schweizer Kernkraftwerke für Erdbeben der Störfallkategorie 2 und 3. 10.KEX.APFUKU1-10/12/012, Switzerland

Ghiocel D. M. (2015). Fast Nonlinear Seismic SSI Analysis Using a Hybrid Time-Complex Frequency Approach for Low-Rise Nuclear Concrete Shearwall Buildings. SMiRT-23, Manchester, United Kingdom, 2015.

IAEA INSAG-25 (2011). A Framework for an Integrated Risk Informed Decision-Making Process, International Atomic Energy Agency (IAEA), Vienna.

Kontoe, S., Zdravkovic, L., and Potts, D. (2008). The domain reduction method for dynamic coupled consolidation problems in geotechnical engineering. International Journal for Numerical and Analytical Methods in Geomechanics 32, 659–680.

KTA 2201.3 (2013). Design of nuclear power plants against seismic events; Part 3: Civil structures. Nuclear Safety Standards Commission. Germany.

Lysmer, J., Kuhlemeyer, R.L. (1969). Finite Dynamic Model for Infinite Media. Journal of the Engineering Mechanics Division 95-4, 859–878.

PROSEIS (2015). Calculation of the seismic hazard at the four NPP sites based on the Hybrid SED – PRP model. PS-TA-1587 Rev. 0, September 2015, 0909/1600571.