Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division III

STUDY ON FLUID-STRUCTURE-SOIL-INTERACTION (FSSI) EFFECTS FOR A DEEPLY EMBEDDED NUCLEAR FACILITY WITH A LARGE-SIZE POOL UNDER SEVERE EARTHQUAKE. PART 2: NONLINEAR SSI

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ABSTRACT

The Part 2 paper investigates the Fluid-Structure-Soil-Interaction (FSSI) effects on the *nonlinear* seismic response of a deeply embedded nuclear structure with a large-size water pool at a high floor elevation under a 0.80g severe earthquake. The nuclear structure is the same BLDG15 used in the Part 1 paper. The reinforced concrete (RC) structure nonlinear modelling is based on the Japanese JEAC 4601-2015 standard requirements. The nonlinear structure SSI analysis is efficiently performed using a fast iterative hybrid approach that is implemented in ACS SASSI NQA Option NON and described in detail elsewhere (Ghiocel et al., 2022a and 2022b). To ensure the highest numerical efficiency for the SSI analysis, the FVROM-INT approach was applied (Ghiocel, 2022). For the water fluid modelling, the ANSYS FLUID80 elements were considered. The ANSYS FLUID80 substructure stiffness and mass matrices were automatically extracted and then added to the ACS SASSI SSI model using ACS SASSI Option AA-F. The paper compares the linear and nonlinear SSI results for the cases of the pool filled with water and empty. It is shown that the nonlinear structure behavior impacts on the global structure seismic response, while the fluid-structure interaction effects are visible only locally, mainly affecting the forces in pool walls, as also shown in Part 1 paper, except for the pool internal wall (baffler) that is largely affected by the surrounding water response motion.

1. FAST SSI ANALYSIS OF DEEPLY EMBEDDED STRUCTURES

The ACS SASSI Flexible Volume Reduced-Order Modeling (FVROM) approach is a "theoretically exact" approach implemented in the ACS SASSI NQA software based on the condensation of the excavated soil impedance matrix at the foundation-soil interface nodes (Ghiocel, 2022). See also Part 1 paper for more details on FVROM-INT.

Since the excavated soil impedance variation in frequency is much smoother than the SSI response variation by the interpolation, it is highly efficient for speeding up the overall computational effort of SSI analysis. Therefore, the FVROM approach is further combined with an efficient interpolation scheme of the reduced-size soil impedance matrix in complex frequency. The FVROM approach combined with the condensed impedance interpolation is named FVROM-INT (FVROM with INTerpolation). For practical application of the FVROM-INT approach, only a reduced number of condensation frequencies of 15-25 are usually sufficient for an accurate soil impedance interpolation.

2. NONLINEAR RC STRUCTURE MODELING PER JEAC 4601-2015 STANDARD

Figure 1 describes the concept of the iterative hybrid frequency-time SSI approach as implemented in ACS SASSI Option NON. The iterative hybrid approach includes at each iteration two coupled analysis steps:

Step 1: Perform an *equivalent-linear SSI analysis* in complex frequency via the SASSI approach to compute the structural displacements for each nonlinear RC wall, and then,

Step 2: Perform a *nonlinear time-domain hysteretic analysis* for each RC wall loaded with the SSI displacements from Step 1, to compute the in-plane shear and bending nonlinear wall responses using the *standard-based back-bone curve (BBC) equations* and the *appropriate hysteretic models from the available software library*.

The *equivalent-linear stiffness and damping for each RC wall* are computed based on the time domain nonlinear responses using either a constant or a variable maximum displacement reduction factor (DRF) applied at each SSI iteration. It should be noted that *Step 1* uses the *original, refined FE SSI model* (left plot) while *Step 2* uses a *reduced-order structural model* (right plot) using macro-mechanics models for simulating the RC wall hysteretic behavior. These macro-mechanics models are called wall panels and include all groups of the shell elements defining the RC wall geometry at each floor level (see wall panels in different colors in Figure 1 left plot).

The RC wall panels include the wall cross-section web and its eventual flanges. Therefore, the Step 2 "true" nonlinear time-domain structure analysis is extremely fast. The reduced-order model idealizes the RC shear wall structure nonlinear behavior by using a macro-mechanics hysteretic modelling for each wall panel. These nonlinear wall panels are defined for each floor level (differently colored in Figure 1) and are assumed to be subjected to uniform in-plane shear and in-plane bending deformation patterns.

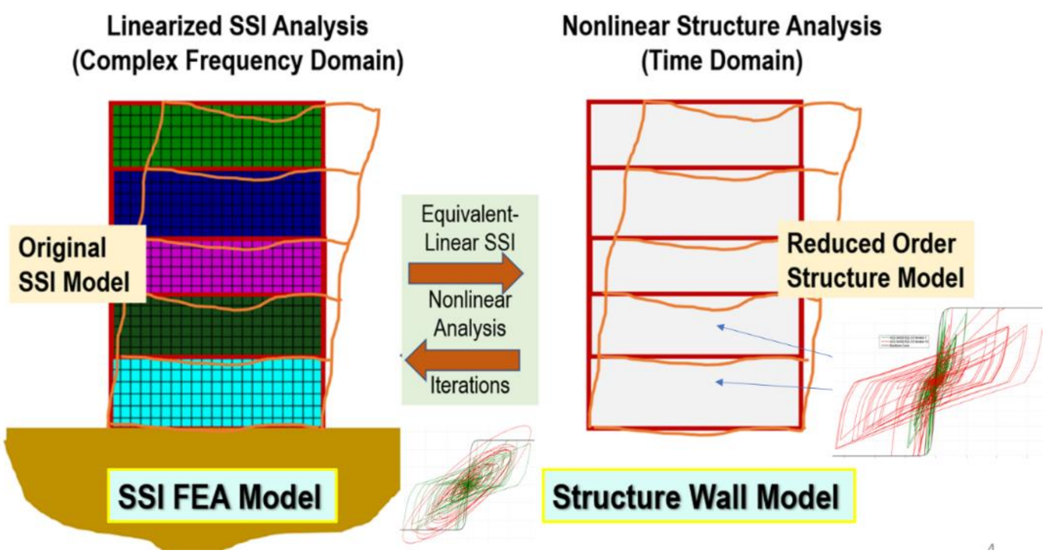

Figure 1 Iterative Hybrid SSI Approach Implemented in ACS SASSI Option NON

The RC wall panel nonlinear modelling includes two major constitutive components (Figure 2):

1. Back-bone curves (BBC) for shear and bending deformation for each RC wall at each floor level per JEAC 4601 App. 3.7 equations or available experimental tests.

2. Hysteretic models (HM) for the shear and bending deformation effects for each RC wall panel is selected per JEAC 4601 standard recommendations or available experimental tests.

The RC wall BBC and hysteretic models are determined based on the JEAC 4601-2015 App.3.7 requirements. The "PO shear" and "PODT bending" hysteretic models used for the nonlinear structure SSI analysis are the maximum point-oriented models described in the JEAC 4601-2015 App.3.7.

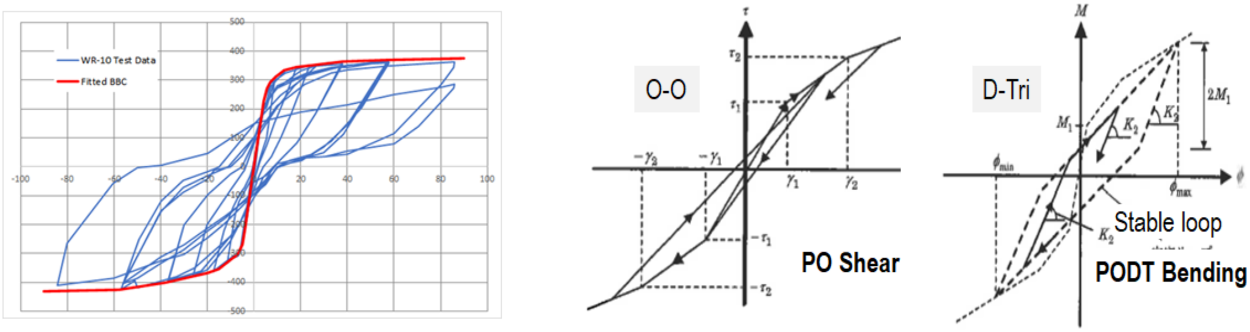

Figure 2 BBC and JEAC 4601-2015 Recommended Maximum Point-Oriented Hysteretic Models

The Option NON software library contains eight types of hysteretic models that can be used for nonlinear RC wall modelling including the JEAC 4601-2015 recommended models:

1) Cheng-Mertz Shear (CMS) model (model 1)
2) Cheng-Mertz Bending (CMB) model (model 2)
3) Takeda (TAK) model (model 3)
4) General Massing Rule (GMR) model (model 4)
5) JEAC 4601 Maximum Point-Oriented (PO) shear model (model 5)
6) JEAC 4601 Maximum Point-Oriented Degraded-Trilinear (PODT) bending model (model 6)
7) Hybrid Shear (HYS) model (model 7)
8) Hybrid Bending (HYB) model (model 8).

The nonlinear SSI analysis general procedure (without the floor cracking option) includes eleven steps, as follows:

1. Prepare 3D FEM structure model
2. For selected nonlinear RC walls, create 3D FEM sub-models
3. Perform linear SSI analysis for gravity and seismic loads to compute structural stresses
4. Perform RC wall cross-section identification for all floor levels at defined sections
5. Perform automatic section-cuts for each wall for gravity and three input seismic loads
6. Compute shear and bending back-bone curves (BBC) for each RC wall and floor level *per* applicable best-practice recommendations by the JEAC 4601-2015 standard;
7. Select appropriate shear and bending hysteretic models from the software library per applicable best-practice recommendations by the JEAC 4601-2015 standard;
8. Perform the nonlinear hybrid SSI approach iterations using separate shear and bending hysteretic wall models as recommended in JEAC 4601-2015 standard;
9. If selected option requires, the computed interacting shear and flexure damage effects in flanges are combined at each iteration;
10. Analyst can also include the floor concrete cracking effects due to the out-of-plane floor bending effects under the seismic and gravity loads;
11. Post-process the final SSI results of 3D FEM for the converged nonlinear responses.

It should be noted that the ACS SASSI Option NON was developed in compliance with the US and Japan standards for nonlinear modeling of the RC structures (Ghiocel et al. 2022a, 2022b). Independent verification and validation studies against experimental testing and other sophisticated nonlinear time domain FEA codes indicated that the iterative SSI equivalent-linearization procedure implemented in the

ACS SASSI Option NON provides a reasonable accuracy and a high numerical efficiency (Niita at al., Ichihara et al., 2022).

3. FLUID MODELING FOR SEISMIC FSSI ANALYSIS

The ACS SASSI Option AA-F should be used to include fluid pool substructure. The fluid elements, which are the ANSYS FLUID80 elements, are extracted by specific automatic procedure as described in Part 1 paper (Sato et al., 2023).

4. BLDG15 STRUCTURE MODEL AND GENERIC SITE CONDITIONS

This section describes the BLDG15 RC structure FSSI modelling and defines the generic site conditions considered for the study. The BLDG15 structure SSI model is described in Figure 3. See Paper 1 for additional details. The ground surface level is marked by the orange horizontal line. A detailed description of the BLDG15 linear 3DFEM SSI model is provided elsewhere (Sato et al., 2023).

The BLDG15 SSI model is considered with and without large-size water pool inside the building at the middle of the second floor (nodes 2143 and 874 are at pool bottom and nodes 5359 and 5053 are at pool top). Figure 3 did not show the pool water elements. Figure 3 (right) shows few selected locations for computing the ISRS responses.

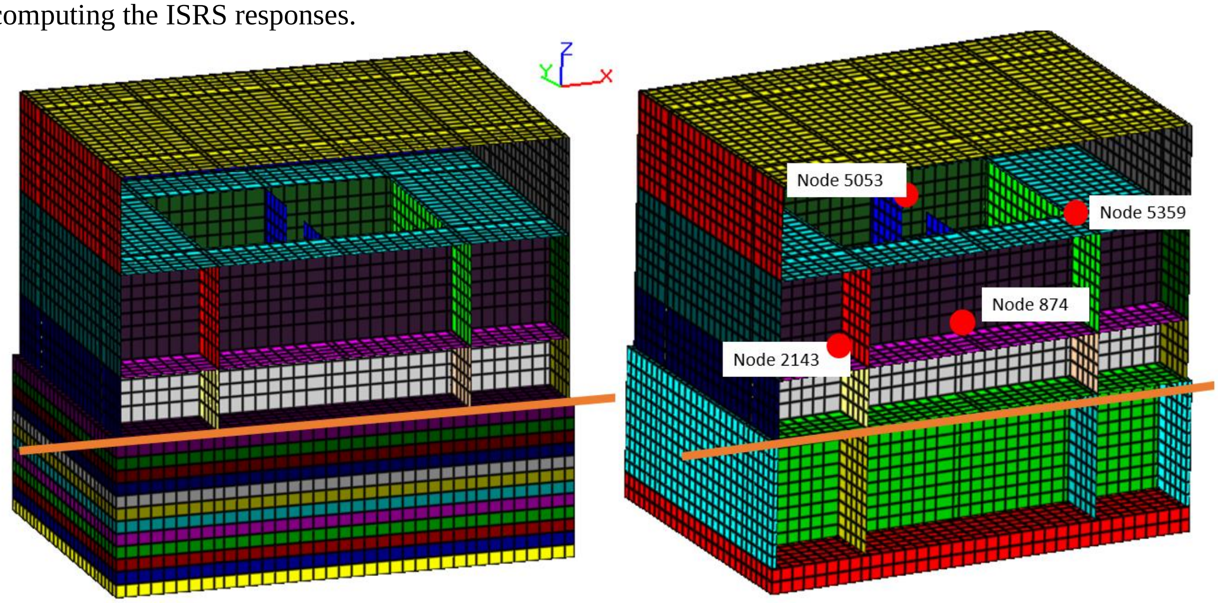

Figure 3 BLDG15 SSI Model Including Excavation (left) and Without Excavation (right)

The generic seismic GRS input at ground surface in the horizontal and vertical directions is shown in Figure 5. This generic GRS is similar to the NuScale SMR CSDRS input anchored to a maximum ground acceleration of 0.50g for horizontal direction and 0.40g for vertical direction. However, for performing the BLDG15 nonlinear structure SSI analysis, the maximum ground acceleration was increased by 60% to a review or beyond design basis earthquake (BDBE) level with 0.80g and 0.64g directional accelerations.

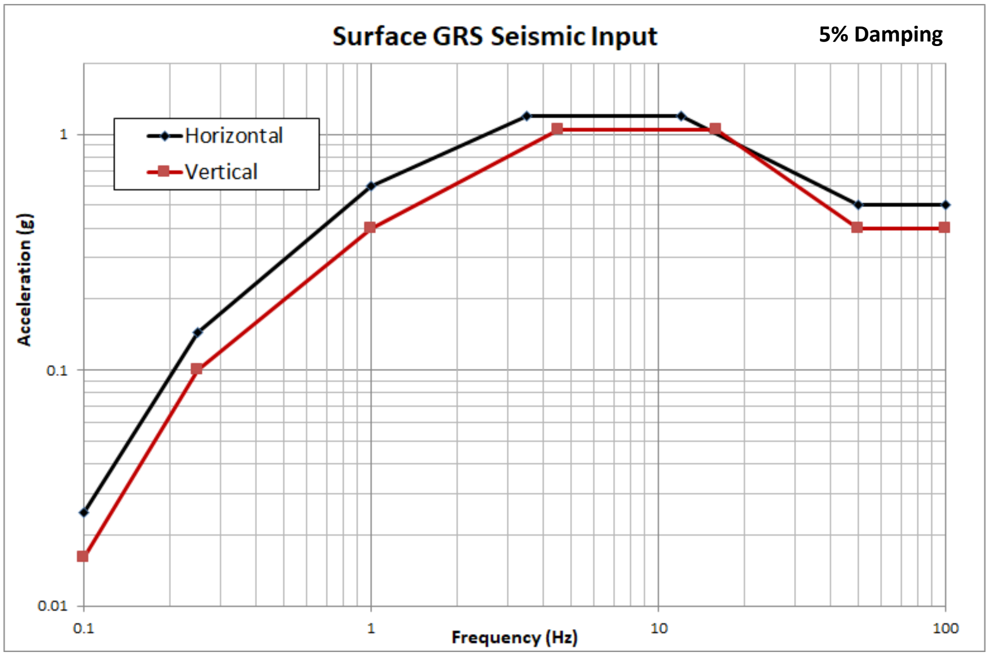

Figure 4 GRS Input for Horizontal and Vertical Direction for 0.50g Ground Acceleration

The generic site soil profile is described by a uniform deep soil deposit with an Vs of 800 m/s, Vp = 1,600m/s, unit weight of 20 kN/m^3 with a S and P wave damping of 2%. These soil properties were considered as the iterated soil properties for the study.

To define the seismic motion input for the SSI analysis of the deeply embedded BLDG15 structure, the in-column or within motions at the foundation level (associated to FIRS) were determined for X, Y and Z directions. To do this, the ACS SASSI SOIL module was run with the outcrop motion defined at foundation level as the user input, and the in-column motion at foundation level requested as the user output. The SOIL module uses SHAKE methodology for computing the in-column soil motions at different depths.

5. BUILDING 15 NONLINEAR STRUCTURE MODELING PER JEAC 4601-2015

Based on the BLDG 15 layout, the structure nonlinear modelling includes the definition of the eight major structure RC wall sub-models with nonlinear hysteretic behavior, as illustrated in Figure 6. The Wall sub-models # 1, 2, 5, 6 are acting for the Y-input transverse direction and the Wall sub-models # 3, 4, 7, 8 for the X-input longitudinal direction.

The final eight RC wall sub-models, including the panel and element group numbering, are displayed in Figures 6 and 7. The panel numbering is set for each wall to be sequentially from bottom up.

The RC wall flanges are determined in accordance with the JEAC 4601 and AIJ RC standard requirements. Further, the RC wall BBC are computed as per JEAC 4601-2015 App.3.7.

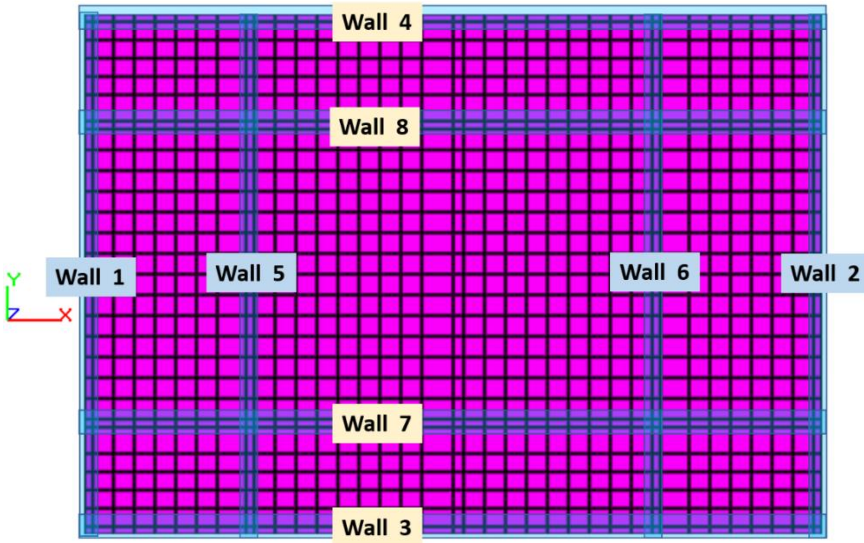

Figure 5 Selection of the BLDG15 Structure Eight Nonlinear RC Wall Sub-models

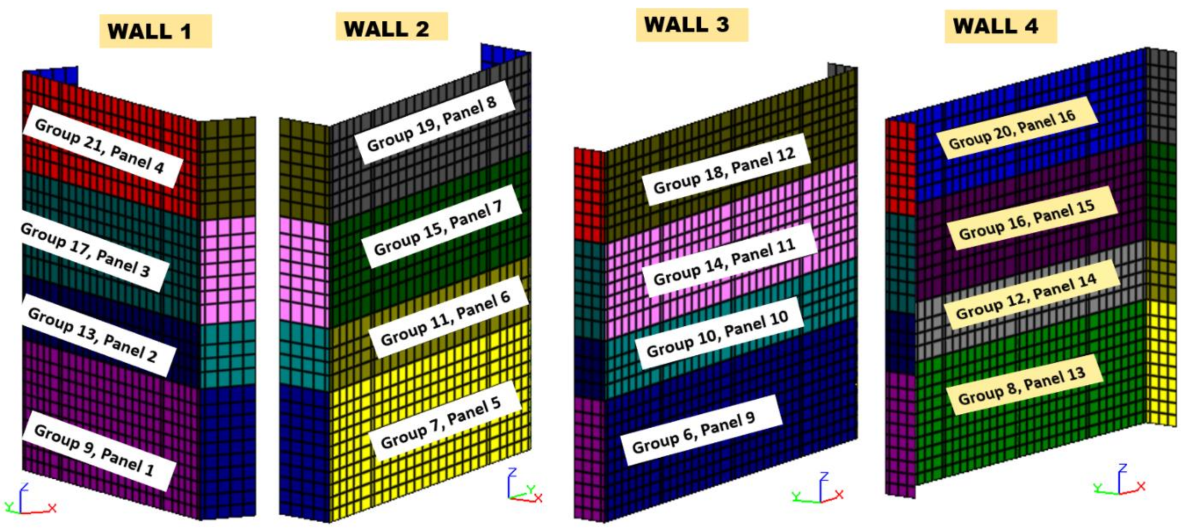

Figure 6 Exterior RC Wall Sub-models 1, 2, 3 and 4

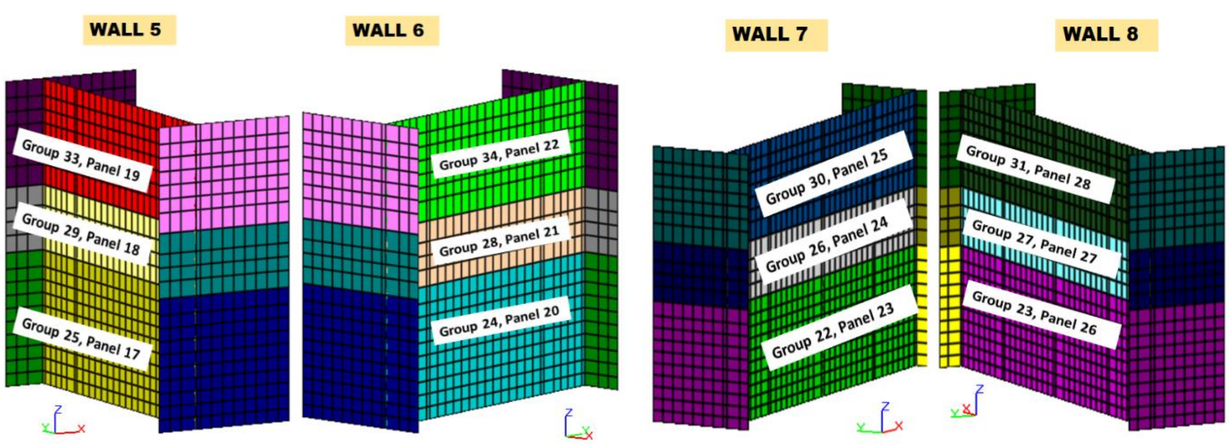

Figure 7 Interior RC Wall Sub-models 5,6,7 and 8

The panel wall relative corner node displacements are used to compute the shear and bending panel deformation. The RC wall reinforcement is input based on the user-defined percentage ratios in the vertical direction for flanges, and the vertical and horizontal directions for web as per JEAC 4601-2015 App. 3.7 equations.

Usually, one to few layers of distributed steel bars can be considered. A single reinforcement median line was considered for the BLDG15 wall reinforcement. To compute the RC wall BBCs at each floor level per JEAC 4601-2015, the cross-sectional wall forces, as N and V (N = gravity axial forces and V = seismic shear forces), and moment, M (M = seismic bending moment) are determined by an automatic section cut algorithm at each floor level. The computed BBC for the transverse exterior wall with and without water pool are shown in Figure 8.

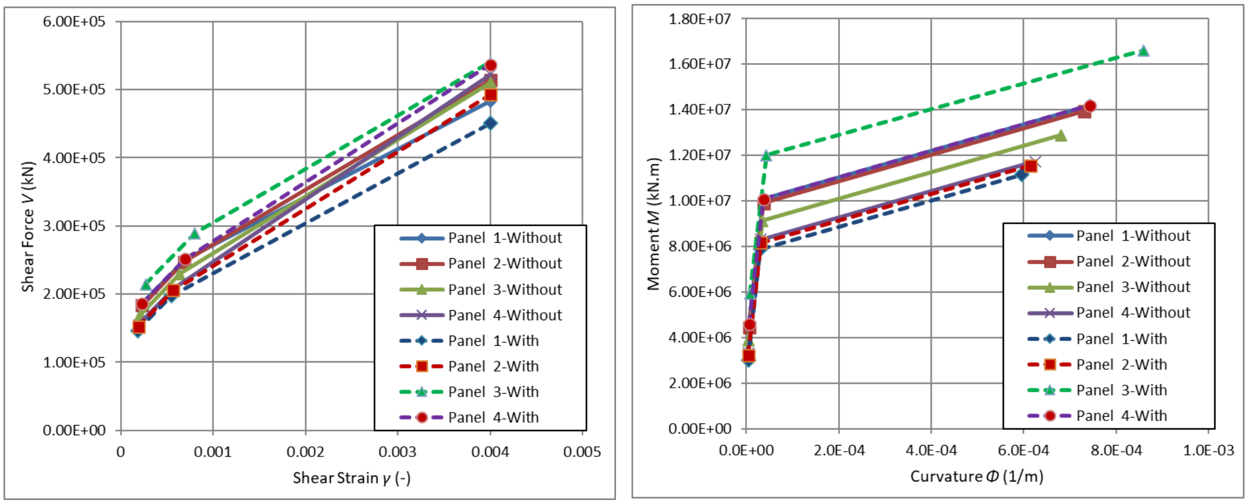

Figure 8 Shear and Bending RC Panel BBC for Exterior Transverse Wall (Wall 1 Sub-model)

As per JEAC 4601 App.3.7 requirements, the PO Shear and the PODT Bending hysteretic models (which are models #5 and #6 in the Option NON hysteretic model library) were applied for the nonlinear structure SSI analysis.

It should be noted that the gravity forces in the BLDG15 structure walls are influenced by the weight of the pool water at the second floor. Therefore, the BBC computed for the structure with fluid and without fluid are slightly different. The water pool was modelled using the ANSYS FLUID80 elements as explained in Section 3.

6. BLDG15 STRUCTURE SSI RESPONSES WITH AND WITHOUT WATER POOL

This section includes a comparison of the BLDG15 structure SSI responses obtained using the linear (uncracked concrete) and nonlinear SSI analysis results (per JEAC 4601-2015) with and without including the filled water pool at the second floor.

Figure 9 shows the computed iterated equivalent elastic modulus (left) and damping (right) properties for all nonlinear wall panels (see the 28 RC wall panels including numbering in Figures 6 and 7) for the severe 0.80g BDBE input motion.

Only 3 iterations were sufficient for reaching solution convergence. It should be noted that for the most damaged RC walls, the iterated stiffness went down to about a quarter of the initial elastic stiffnesses, and the iterated damping ratio went up to 11% from 5% defined for the initial elastic damping.

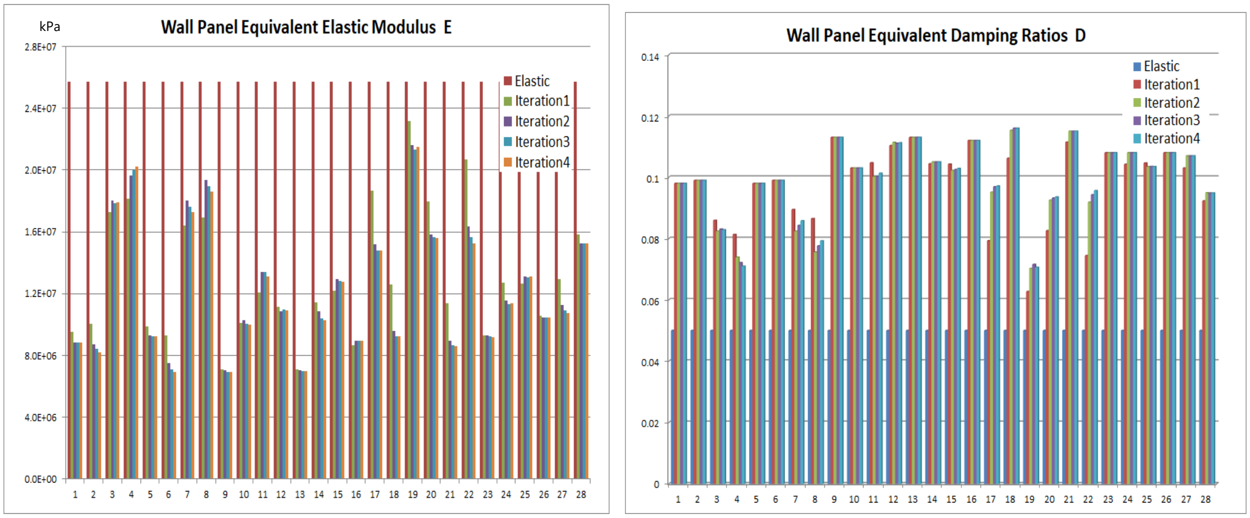

Figure 9 Iterated Equivalent Elastic Modulus (E) and Damping (D) for Nonlinear Wall Panels

Figures 10 and 11 show the computed ARS (Acceleration Response Spectra) at two pool location nodes, specifically, node 874 (pool external wall bottom middle edge) and node 5053 (pool internal wall top corner). It should be noted that the pool water effects are significant only for the node 5053 located at the internal wall top corner in the X-direction which is perpendicular to the internal wall plane. In contrast, the nonlinear structure behavior effects are significant for all structure and pool locations in X and Y horizontal directions. Both the pool water and the nonlinear wall behavior effects are less significant but still visible for the ARS in the Z vertical direction.

Figure 12 shows the computed nonlinear RC wall hysteretic responses for the in-plane shear and in-plane bending deformation for the Panel 24 of the Interior Wall in X direction, just above the ground surface level. It should be noted that RC wall BBC capacities in both shear and bending are larger due to the large pool water weight. The BLDG15 structure and fluid seismic response accelerations and displacements were investigated (Figure 13). Results are close to the linear SSI analysis results detailed in the Part 1 companion paper (Sato et al., 2023).

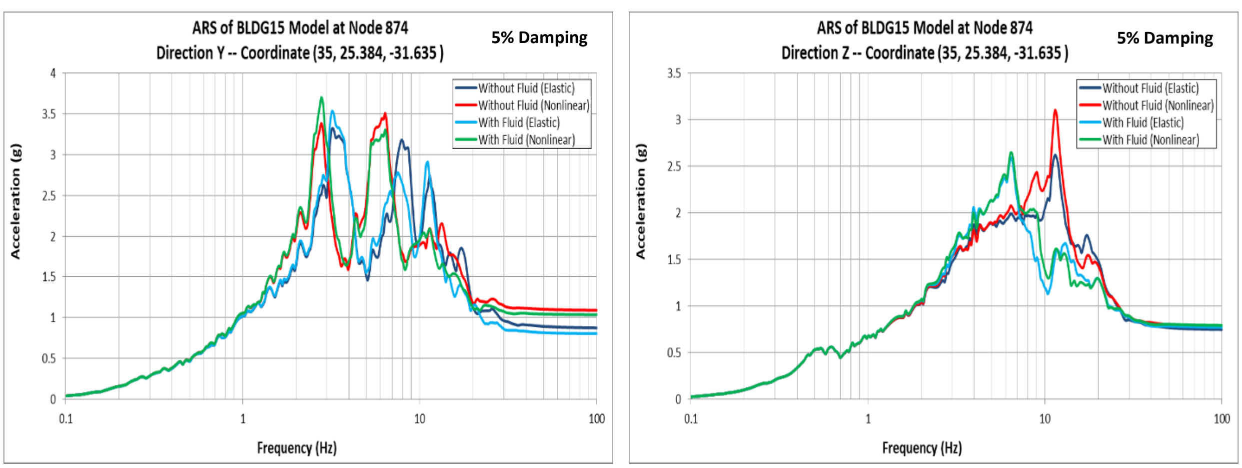

Figure 10 ISRS at Pool Bottom Edge for Linear and Nonlinear SSI Analysis in X and Z Dir

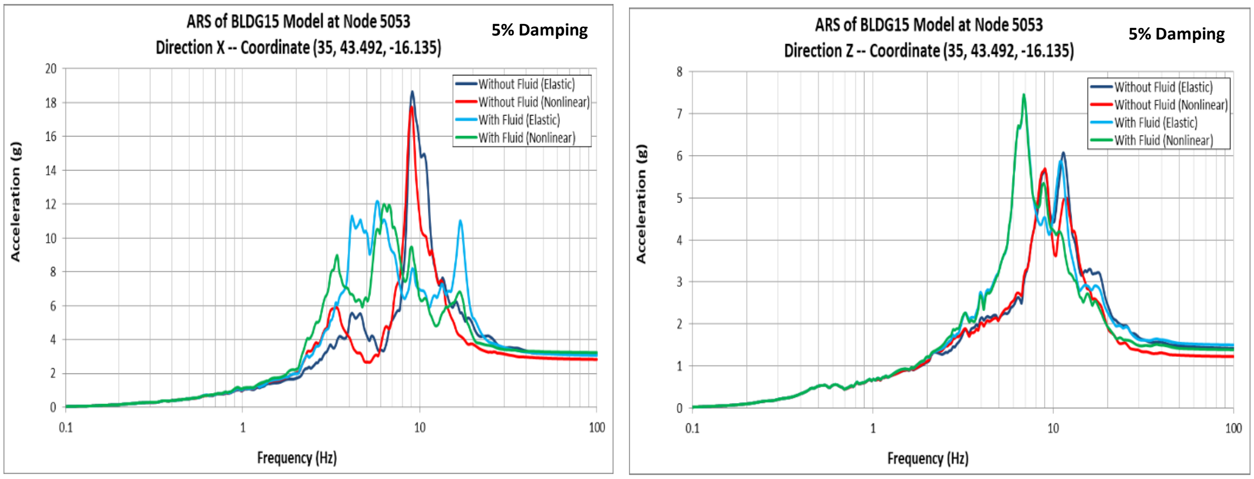

Figure 11 ISRS at Pool Internal Wall Top for Linear and Nonlinear SSI Analysis in X and Z Dir

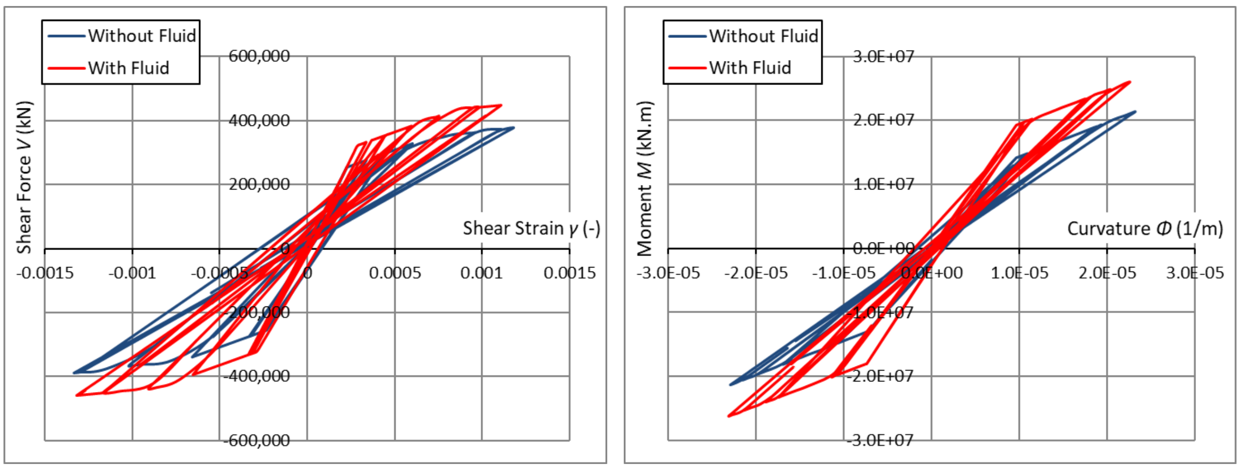

Figure 12 Shear and Bending Hysteresis Responses of Interior Wall Panel 24 (X-Direction)

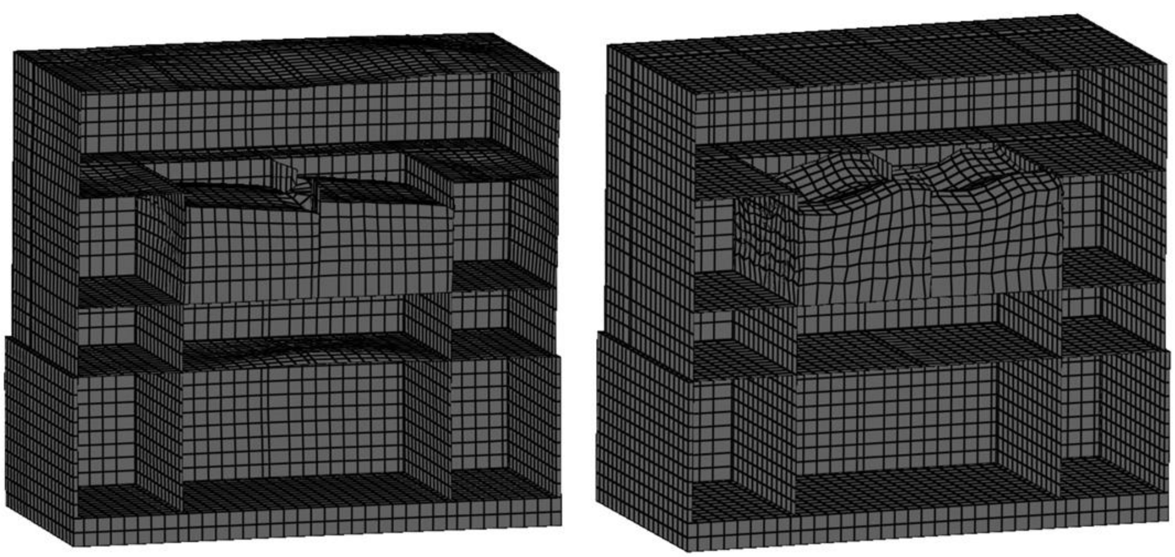

Figure 13 BLDG15 Instant Structural Accelerations (left) and Displacements (right)

It should be noted that the maximum water wave height is about 0.40 m at the left-half pool center and increases to 1.50 m at the pool corners. As expected, the BLDG15 nonlinear behavior affects only negligibly the pool water seismic response motions as shown in Figure 15. The computed pool wall displacements indicate that effects of the nonlinear structure behavior are significantly larger than the effects of the fluid-structure interaction for pool walls, except for the pool internal wall (baffler) top corner (node 5053) in the X-direction, as illustrated in Figure 14 for the 5-10 sec. time interval.

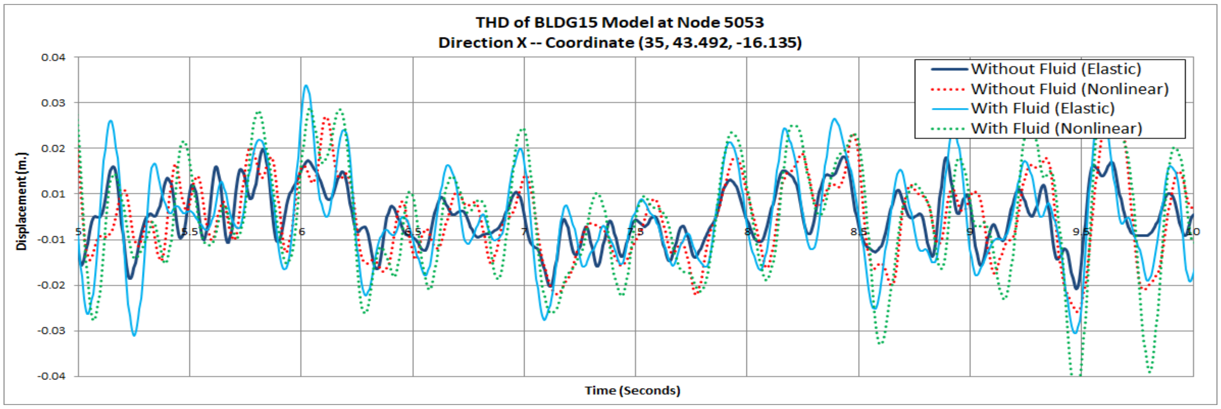

Figure 14 Pool Internal Wall Displacements in X (upper) Directions (Node 5053)

7. CONCLUDING REMARKS

The paper investigates the fluid-structure-soil-interaction (FSSI) effects on the nonlinear RC shear wall structure responses when subjected to severe earthquake motion. The nonlinear structure seismic FSSI analysis was performed extremely efficiently and in full compliance with the Japanese JEAC 4601-2015 standard requirements for the nonlinear RC structure modelling which were implemented in all detail within the ACS SASSI NQA Option NON software.

For the investigated BLDG15 case study, the computed SSI results show that even for a quite large water pool placed at a higher elevation, above at the second floor, the effects of the fluid-structure interaction were basically, localized around the pool, and only minimally transmitted to the rest of the structure responses. In contrast, and as expected, the effects of the RC structure nonlinear behavior affected globally the BLDG15 structure responses increasing the RC wall deformation, floor displacements, and shifting the ARS peaks to lower frequencies.

8. REFERENCES

Ghiocel, D.M, Nitta, Y., Ikeda, R. and Shono, T (2022a, 2022b). *Seismic Nonlinear SSI Approach Based on Best Practices in US and Japan. Parts 1: Modeling and Part 2: Application*, SMiRT26, Special Session, Berlin, July 10-15

Ichihara, Y., Nakamura, N, Nabeshima, K., Choi, B. and Nishida, A. (2022). *Applicability of Equivalent Linear Three-Dimensional FEM Analysis for Reactor Building to Seismic Response of SSI System*, SMiRT26 Conference, Special Session on Nonlinear Seismic SSI Analysis Based on Best Practices in US and Japan, Berlin, July 10-15

Nitta, Y., Ikeda, R., Horiguchi, T. and Ghiocel, D.M. (2022). *Comparative Study Using Stick and 3DFEM Nonlinear SSI Models per JEAC 4601-2015 Recommendations*, SMiRT26, Special Session on Nonlinear Seismic SSI Analysis Based on Practices in US and Japan, July 10-15

Sato Y., Ghiocel D.M, Kataoka S., Sato S., and Morimoto Y. (2023). *Study on Fluid-Structure-Soil-Interaction (FSSI) Effects for A Deeply Embedded Nuclear Facility with A Large-Size Pool Under Severe Earthquakes. Part 1: Linear SSI.* SMiRT27 Conference, Special Presentation Session Division 3, Yokohama, Japan, March 3-7

Japan Electric Association (JEA) (2017). "Technical Code for Seismic Design of Nuclear Power Plants JEAC4601-2015," JEA, Japan. [in Japanese].