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EFFICIENT SEISMIC FSSI ANALYSIS METHODOLOGY FOR LARGE-SIZE TANKS ON PILES INCLUDING SOIL AND STRUCTURE NONLINEAR HYSTERETIC BEHAVIOR

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ABSTRACT

The paper describes an efficient and accurate seismic SSI analysis methodology for large-size storage tanks founded on piles. The paper investigates the effects of the nonlinear fluid-structure-pile-soil interaction for a typical large-diameter fluid storage tank. The fluid inside the tank is modeled using fluid finite elements. The fluid-soil-structure interaction analysis (FSSI) was performed using the ACS SASSI Option AA-F software. The pile foundation mesh including the inter-pile soil is optimized using a specialized PILEGEN module which is a part of the suite of ACS SASSI toolboxes. The paper present results for a case study of a 88 m diameter storage tank founded on 505 concrete piles. The seismic SSI analysis results for the tank with and without fluid are compared. The FSSI analysis runs also included the effects of the adjacent soil nonlinear hysteretic behavior.

FAST SSI ANALYSIS OF DEEPLY EMBEDDED STRUCTURES

The Flexible Volume Reduced-Order Modelling (FVROM) approach is a “theoretically exact” new SSI 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). The FVROM approach is a spectacular improvement of the SASSI methodology for deeply embedded structures, applicable to embedded SMRs, deep pile foundations, deep caissons, buried waste storage tanks, and others.

The FVROM matrix condensation can be further combined with an efficient interpolation of the reduced-size soil impedance matrix in complex frequency. Such an approach which combines matrix condensation with fast interpolation is named FVROM-INT (FVROM with INTerpolation). Since the excavated soil impedance variation in frequency is much smoother than the SSI response variation, interpolating it is highly efficient for speeding up the overall computational effort of SSI analysis. Only a reduced number of frequencies can be used for accurately computing the condensed soil impedance matrix and seismic load vector, and then, interpolating them for the rest of all other SSI frequencies. Runs are tens of times faster.

For most of the practical applications using the FVROM-INT approach, only a reduced number of condensation or key frequencies of 15-25 are usually sufficient for accurate interpolation of the excavation condensed impedance interpolation. After the SSI response is computed, say for 200-250 SSI frequencies, this response is further interpolated for all Fourier frequencies used for describing the input motion data in the frequency domain which may include 8,192, 16,384 or 32,768 Fourier frequencies, or even a larger number. It should be noted that the FVROM-INT approach implementation can be used in conjunction with the “exact” FV method, but also other “approximate” methods as the different options of the Extended Subtraction Method (ESM) which are acceptable in practice. For latter case, the solution approximations inherent to the ESM method for the full-size SSI system are transmitted to the reduced-size SSI system. The FVROM-INT implementation has three computational steps:

1) *Identify key or condensation frequencies* based on free-field soil analysis results,
2) *Compute condensed excavation impedance matrices and seismic load vectors* for key frequencies to produce the frequency-dependent reduced impedance matrix and reduced load vector (for

FVROM), and further *interpolate the reduced the excavation impedance matrix and seismic load vector* for all SSI frequencies (for FVROM-INT),

3) *Compute the SSI system solution* using the reduced excavated soil impedance matrices and seismic load vectors for all SSI frequencies.

FLUID MODELING FOR SEISMIC FSSI ANALYSIS

The ACS SASSI Option AA-F should be used to include pool fluid substructure. The fluid elements, which are the ANSYS FLUID80 elements, are extracted by specific automatic procedure. Using ACS SASSI UI ANSYS model converter, two FE models topologically identical to the ANSYS model including structure and fluid were generated for ACS SASSI. The ANSYS 8-node FLUID80 elements were converted to 8-node ACS SASSI SOLIDF elements These SOLIDF are "fake" SOLID elements, used as place holders for the FLUID80 substructure matrices inclusion, being used only for a model topology and equation mapping between the ANSYS and the ACS SASSI models. The application of Option AA-F includes two stages:

Stage 1: *PREPARE ANSYS and ACS SASSI FSSI MODELS*: Prepare the ANSYS FSSI FE model including a single or multiple FLUID80 element substructures (such as pools or vessels), and then, convert this model into an ACS SASSI model with "fake" SOLIDF. Then, delete all the non-fluid elements to retain only the FLUID80 substructures for which the dynamic property matrices can be extracted and assembled with ACS SASSI model matrices using a specialized ANSYS macro (called "gen_fl80_kmc.mac"). This ACS SASSI FSSI model creation step is visually described in Figure 3.

Stage 2: *RUN ACS SASSI FSSI ANALYSIS:* Run FSSI analysis using the ACS SASSI FSSI model with the FILE80 substructure matrices integrated within the FSSI system matrices.

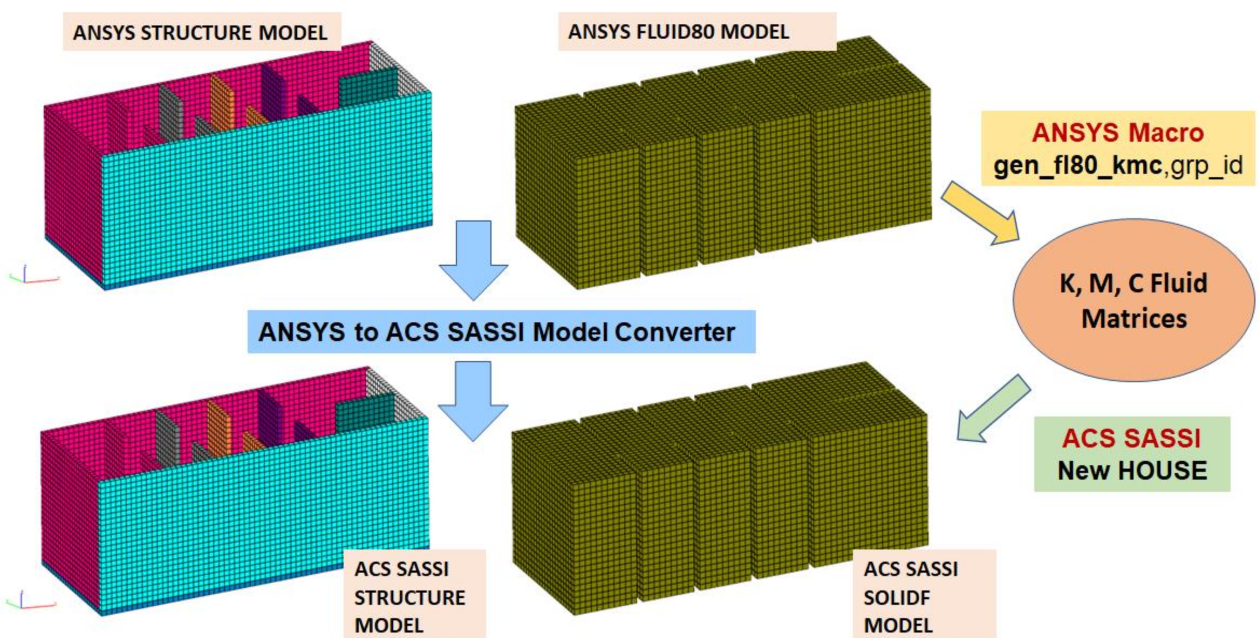

Figure 1. Description of the Option AA-F Procedure for Building ACS SASSI NQA FSSI Model

LARGE-SIZE TANK SSI MODELING INCLUDING PILES AND FLUID

The ACS SASSI entire tank FSSI model, including the tank structure, deep piles and internal fluid, plus the excavated soil model, is shown in Figure 2. It is a detailed FE model including a total of 197,304 nodes. The concrete tank has a diameter of 88m with a wall thickness of 0.30m and a basemat thickness of 1m. The total tank height is 54.6m and the fluid height inside tank is 35m. The soil deposit includes a 39m soft soil layer with Vs = 300m/s above a rock formation with Vs=2,000m/s. The seismic input was defined by the RG1.60 spectrum anchored at a 0.30g surface ground acceleration. The seismic SSI input was defined by the in-column motion at the bottom of soil layer at 39m depth from ground surface.

The tank is founded on 505 concrete piles with 0.40m diameter with a length of 42m. The piles are hinged at the top end and fixed in the rock at the bottom end. The pile foundation including the surrounding soil is shown in Figure 3. The large tank structure model with fluid including the deep piles is visualised in Figure 4. The surrounding soil elements are not included.

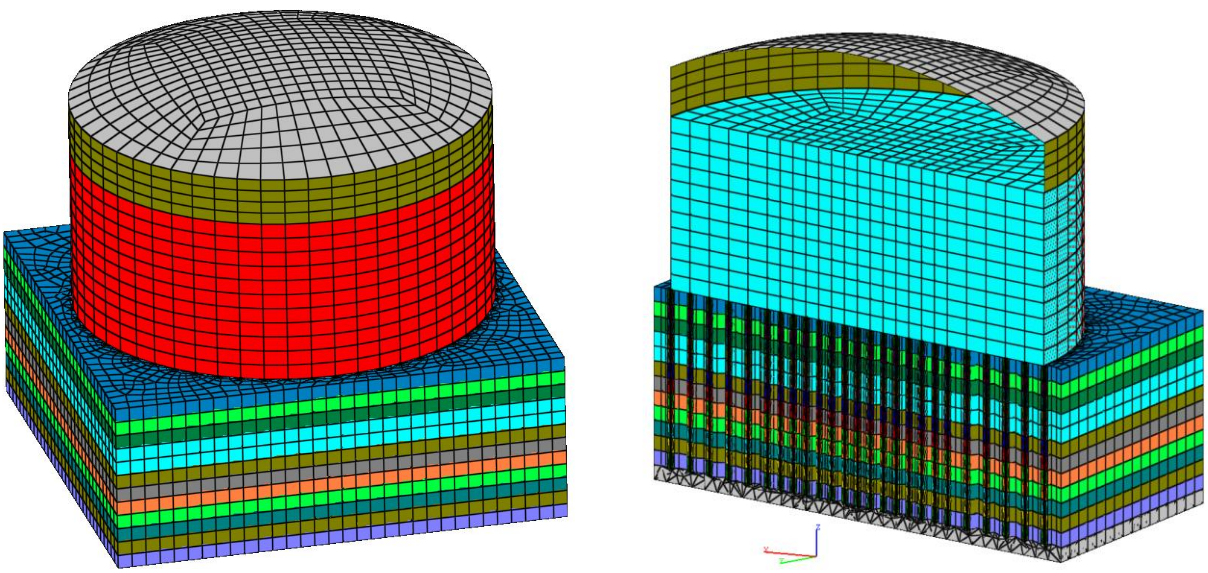

Figure 2 ACS SASSI Larg-size Tank FSSI Model on Piles Including Fluid Inside

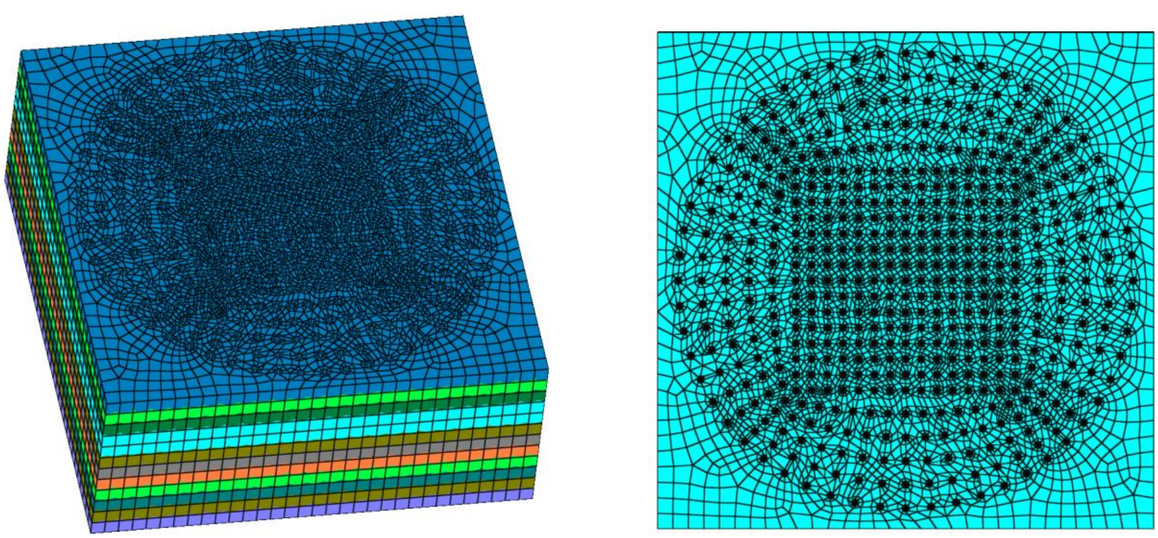

Figure 3 Pile Foundation Model Including Concrete Piles and Inter-pile Soil

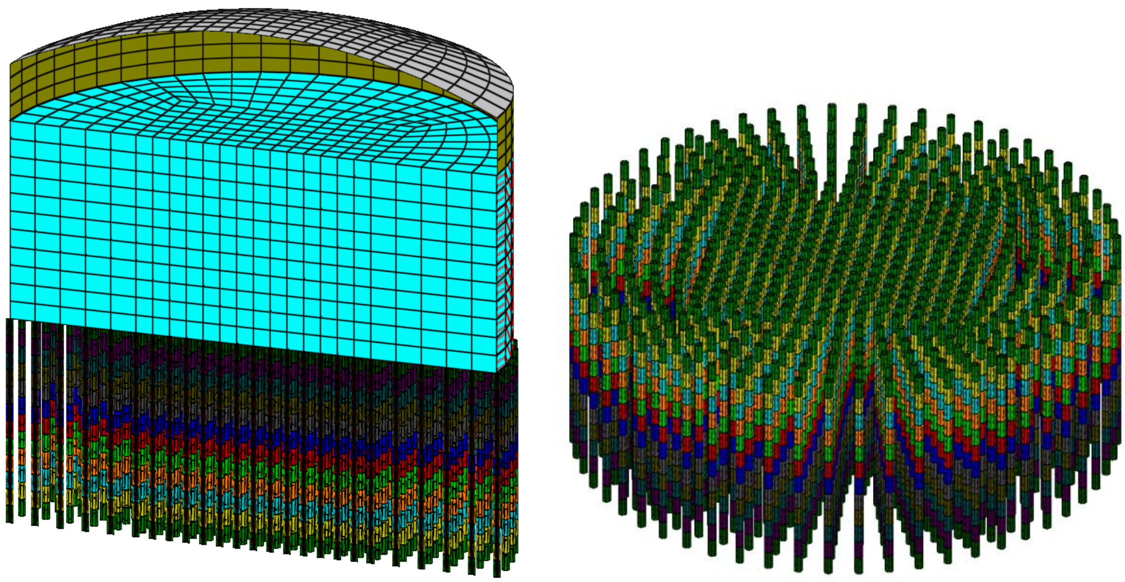

Figure 4 Large-size Tank Structure with Fluid on Deep Piles (left) and Deep Piles Only (left)

The excavated soil was sized to include entire the pile foundation volume plus a limited extension for the soil outside the pile foundation. The excavated soil model is shown separately in Figure 5. The soil mesh extension outside the pile foundation is necessary as a transition mesh to ensure that the excavated soil mesh is a regular mesh as required by the USNRC BNL Consultants (Nie et al., 2013). Previous Figure 3 shows the pile foundation mesh transition to the excavation regular mesh at the interface boundaries with the far-soil layering. The pile foundation mesh including the optimized transition mesh was automatically generated using the ACS SASSI NQA PILEGEN module based on a very simple user input including the pile locations and diameters.

The pile foundation mesh shown in Figure 3 (left) and the excavated soil mesh shown in Figure 5 (left) are connected at the lateral and bottom surface boundaries. The excavated soil boundaries at the interface with far-field soil are modeled by the Kausel-Waas perfectly abstorbant boundaries implemented only in the complex frequency domain. The complex frequency formulation also ensures a perfect parallel scalability for SSI solution.

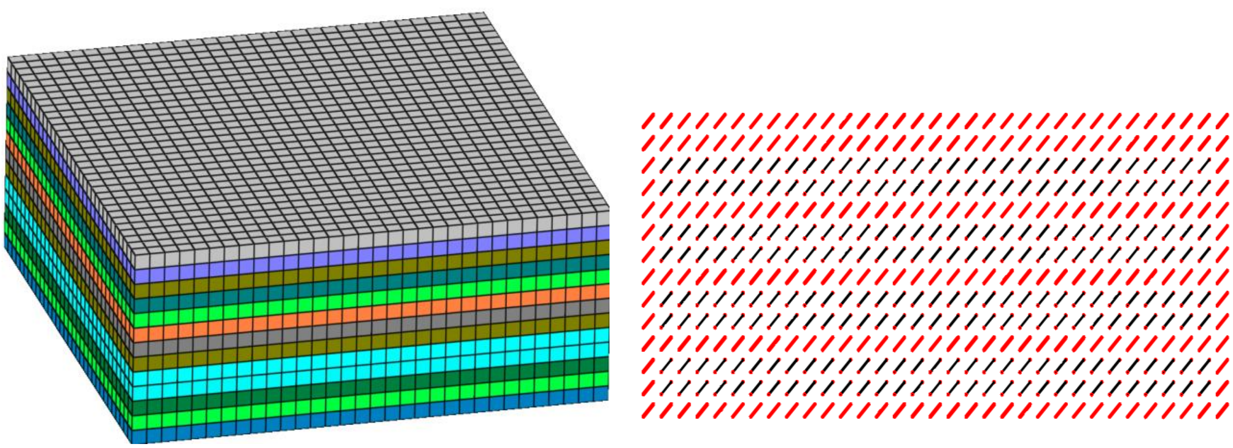

Figure 5 Excavated Soil Model (left) and Selected FFV Interaction Nodes (right, red dots)

Figure 5 (right) shows the excavation interaction nodes (red dots) based on the ACS SASSI NQA Fast-Flexible Volume (FFV) method. The FFV meethod is a special case of ESM method recommended by ASCE 4-16, including as interaction nodes all the excavation outer surface mesh nodes, plus internal excavation layers, herein, four internal node layers being selected.. Due to the optimized excavation meshing the total number of excavation nodes was only 15,246, and the nuumber of FFV interaction nodes only 7,558. To obtain the best numerical efficiency, the FVROM-INT approach was used in conjunction with the FFV method. The number of the condensation interaction nodes was only 2,553. The number of identified condensation frequencies was 17 in comparison with 206 for all SSI frequencies used for the FSSI analyses.

For this tank on piles SSI case study, the use of *the FVROM-INT approach reduced the overall SSI analysis runtime by a speed-up factor larger than 30 times in comparison with the standard SASSI methodology runtime!*

COMPARATIVE RESULTS

The tank seismic SSI responses were computed for the empty tank and filled tank with fluid. The responses were computed at different locations on the tank structure and in the fluid as shown in Figure 6. Figure 7 shows acceleration transfer function (ATF) computed for tank shell response at fluid height (Node 1073).

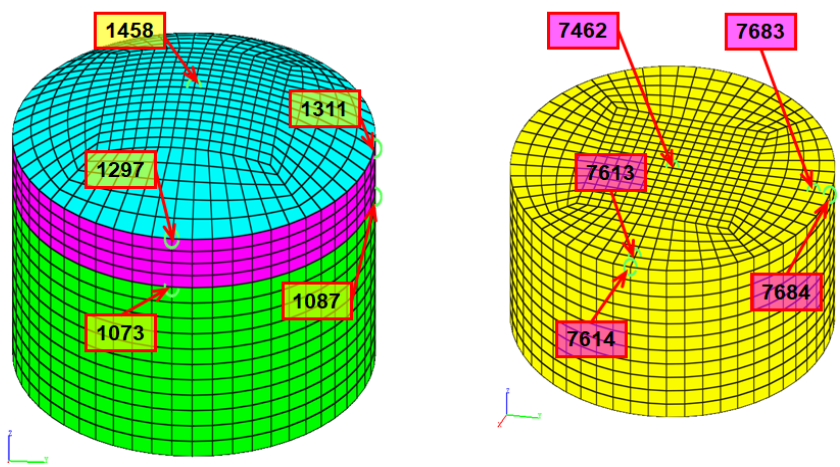

Figure 6 Locations Selected for Computing Tank Seismic SSI and FSSI Reponses

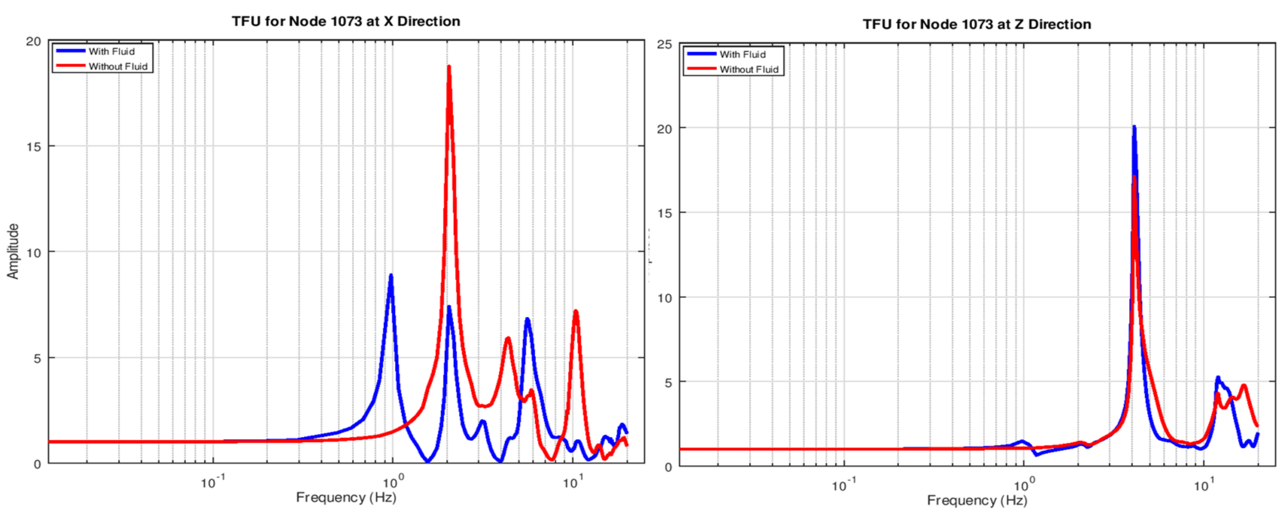

Figure 7 ATF Computed for Tank SSI Structure Response With and Without Fluid for X and Z Direction at the Fluid Height Level at Node 1073

Figure 8 shows the computed relative displacements at same location (Node 1073) in X and Z directions with respect to the seismic input motion soil displacement defined at the pile foundation level. The flexible tank structure displacement close to the top level shows values up to 12-13 cm for the tank with fluid and less than 5 cm for the tank without fluid. The tank with fluid is a much more flexible than empty tank. The tank response frequency drops to about 1 Hz when filled with fluid.

Figure 9 shows the 5% damped acceleration response spectra (ARS) at the same location (Node 1073) for the tank with fluid and without fluid. As expected, the effects of the fluid on tank response is large for horizontal direction and negligible for vertical direction..

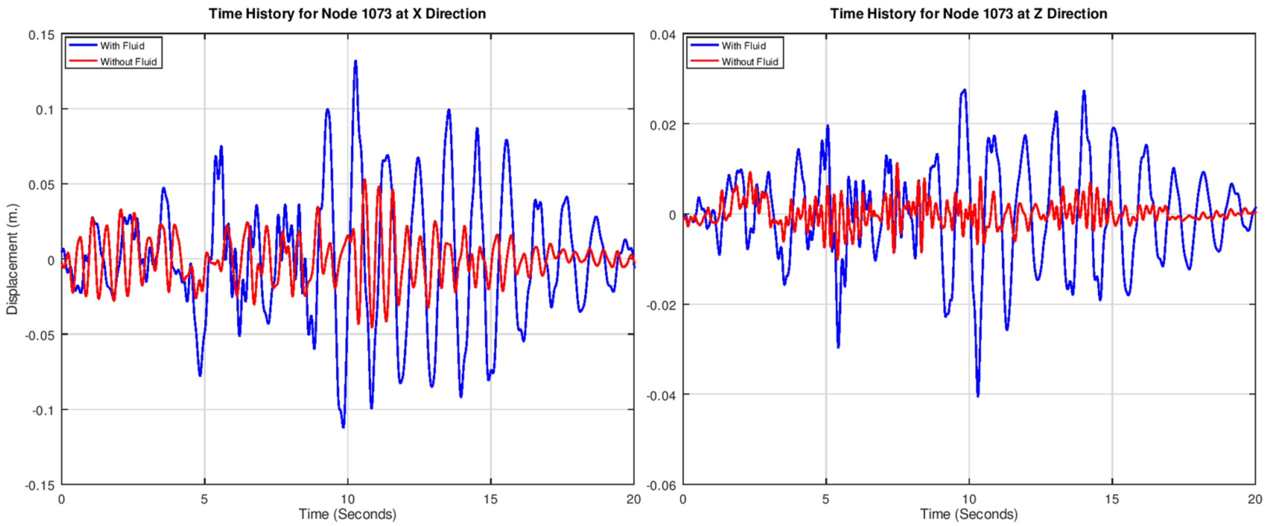

Figure 8 Tank Shell Displacement at the Fluid Height Elevation in X and Z Directions at Node 1073

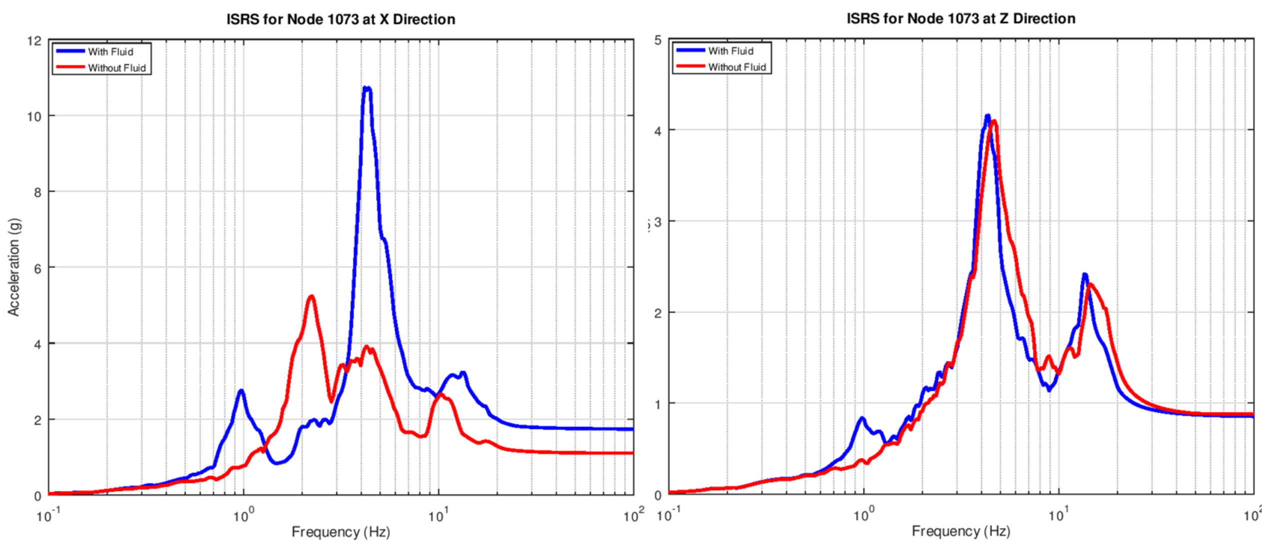

Figure 9 Tank Shell ATF at the Fluid Height Elevation in X and Z Directions at Node 1073

Figure 10 shows the ARS computed in X and Z directions at the fluid surface at a location (Node 7614) which is close to the tank location at the fluid height (Node 1078). See Figure 6 for these locations. It should be noted that the ARS shape for the tank structure with fluid in X direction (normal to the tank shell surface) follows the ARS shape of the fluid motion with two major spectral peaks at 1 Hz and 4.1 Hz. The fact that the same spectral peaks are also visible in the Z direction indicates that fluid motion amplitudes are coupled in the X and Z directions, which suggests that the two fluid modes are global rotational slosing modes.

Figure 11 shows the fluid surface sloshing motion "frozen" and upscaled at two time instants, which are dominated by the 1 Hz frequency fluid oscillation mode (see also Figure 8 showing that the tank shell displacement is dominanted by the 1 second period or 1 Hz frequency mode).

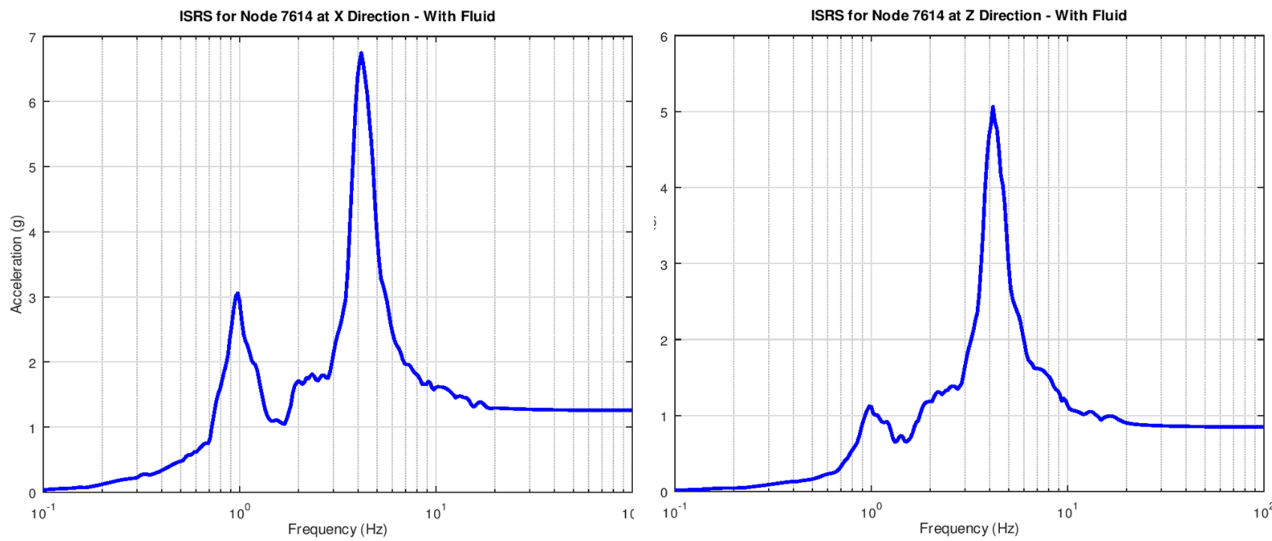

Figure 10 Fluid Motion ARS at the Fluid Height Elevation in X and Z Directions at Node 7614

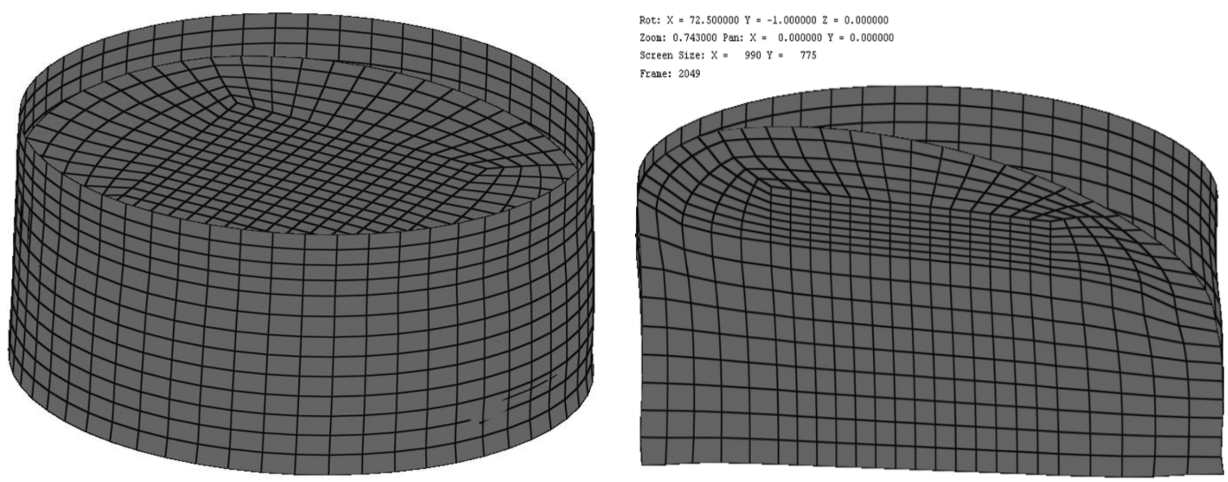

Figure 11 Fluid Sloshing Motion at Two Time Instants; The 1 Hz Frequency Sloshing Mode Dominates

SSI EFFECTS OF ADJACENT SOIL NONLINEAR HYSTERETIC BEHAVIOR

The dense 505 concrete piles of 0.40m diameter with a 41m length are peak-bearing piles with the peak bottom end fixed into the bedrock formation. The pile foundation is very stiff, so that SSI effects due to the 39 m soil layer flexibility are highly reduced. From this point of view this tank case study may not the most appropriate case to illustrate quantitatively the SSI effects, which for other cases could be much larger.

This tank case study was selected for illustrating the application of the new efficient FSSI methodology for large-size tanks filled with fluid and founded on hundreds of piles, The FSSI methodology used herein could include the soil nonlinear hysteretic behavior using an efficient, fast convergent iterative SSI analysis procedure.

This iterative SSI procedure implemented in ACS SASSI NQA is an extension of the SHAKE 1D equivalent-linear soil modeling to a 3D equivalent-linear soil modeling using the soil shear modulus and damping computed for each soil element as a function of the element octahedral shear strain. At each iteration, the octahedral strains computed for the X and Y seismic input directions are combined.

Figure 12 shows the variation with depth of the iterated soil shear modulus and damping in the top 39m soil layer above the bedrock including all soil elements which were adjacent to the concrete piles (about 45000 soil elements adjacent to 505 piles as shown in x-axis). The green lines indicate the initial soil shear modulus and damping values of 1,976 x 1e5 kPa and 4%, respectively. It should be noted that the iterated soil shear modulus values vary between 1,600 x 1e5 at the top and 1,000 x 1e5 at the bottom of soil layer. The iterated damping values vary from 4% at the top to 10% at the bottom of soil layer. The convergence was reached in only two fast SSI iterations based on the FVROM (Step 3 restart with 2,553 interaction nodes only).

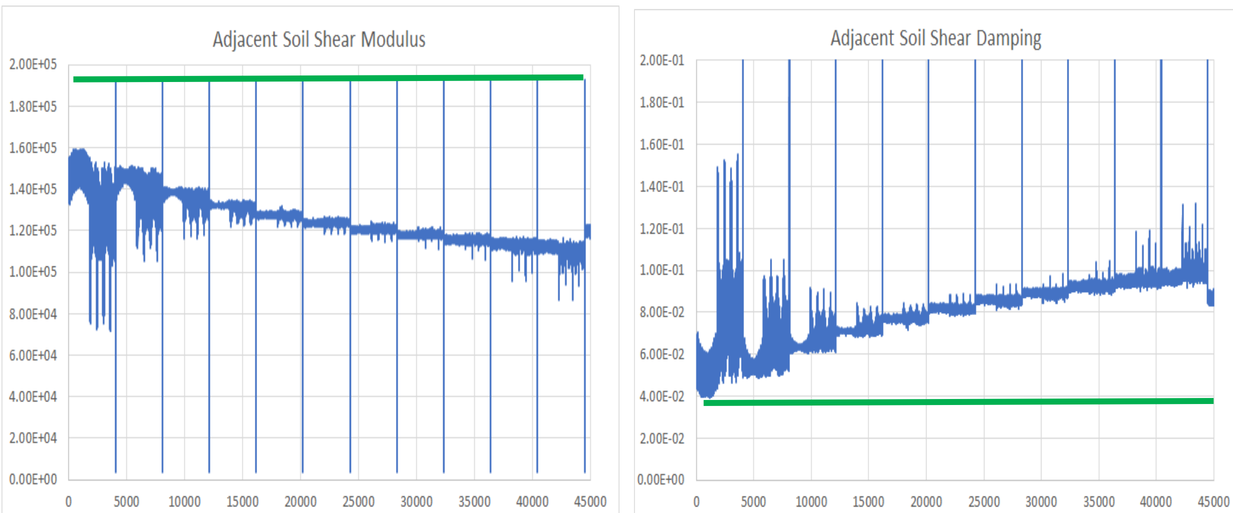

Figure 12 Iterated 39m Soil Layer Shear Modulus and Dampling Variation with Depth

For comparing the nonlinear soil SSI versus linear SSI results, the seismic forces and moments in the tank shell were computed. The linear SSI analysis values were based on the initial soil shear modulus and shear strain. Two lines of vertical shell elements were selected for seismic each input direction to compute the shell element forces and moment as shown in Figure 13.

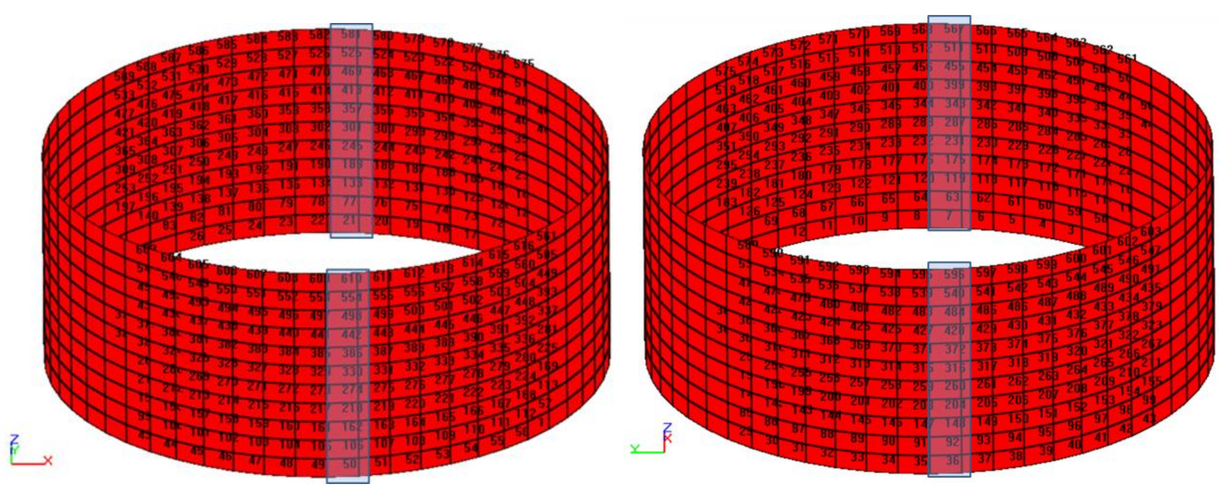

Figure 13 Selected Tank Shell Element Sets for X and Y Input Directions to Compare Nonlinear Soil vs. Linear Soil Results

Figure 14 shows that variation of the tank shell in-plane forces (NXX, NYY, NXY) and out-of-plane moments (MXX) for one the vertical line of shell elments. The variation is plotted from the tank top to the tank bottom. Basically, for the investigated tank case study, the nonlinear soil hysteretic behavior of the soil layers above the bedrock adjacent to the piles has a negligible influence.

This is mainly due by the fact that for this flexible shell tank founded on a stiff peak-bearing pile foundation sitting on the hard rock, the SSI effects are minimal.

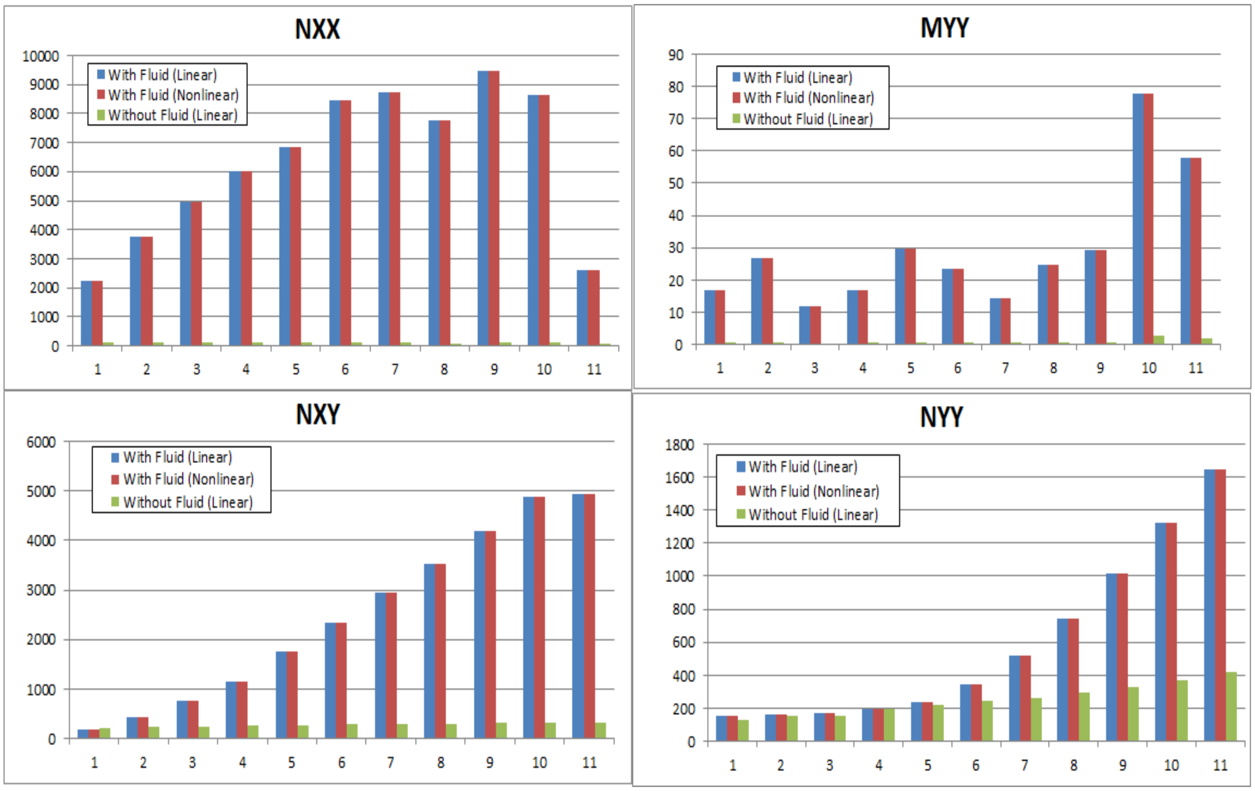

Figure 14 Nonlinear Soil vs. Linear Soil Effect on Tank Shell Forces and Moments

It should be noted that using the ACS SASSI Option NON, the concrete tank structure can be also considered as shown in some recent papers (Ghiocel, 2022, Ghiocel et al., 2022, Ichihara et al., 2022, Nitta et al., 2022, and Sato et al., 2024). Unfortunately, at the time of this paper submission, the nonlinear tank structure SSI runs were not fully completed. These nonlinear results will be presented at the SMIRT27 and published in future elsewhere.

CONCLUDING REMARKS

Although the SSI effects are minimal for the flexible tank case study presented herein, the paper demonstrates the new seismic FSSI methodology, based on a significant speed and functionality extension and improvement of the standard SASSI methodology, specific to large-size tanks on pile foundation applications, including the soil and concrete material hysteretic behavior.

The large-size tank FSSI analysis study was entirely performed using the ACS SASSI NQA code toolboxes including Options AA-F and NON. Using the FVROM-INT SSI approach, the nonlinear soil FSSI analyses were performed in several hours which is only a very small fraction of the runtimes required by a “true” time-domain nonlinear FSSI analysis using other state-of-the-art general-purpose FEA codes, such as ANSYS code, or LS-DYNA code.

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