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Advances in Full Fidelity Soil-Structure-Fluid Interaction Simulation for Nuclear Structures

PEER DOE Workshop: May 17-18, 2021

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University of Nevada, Reno

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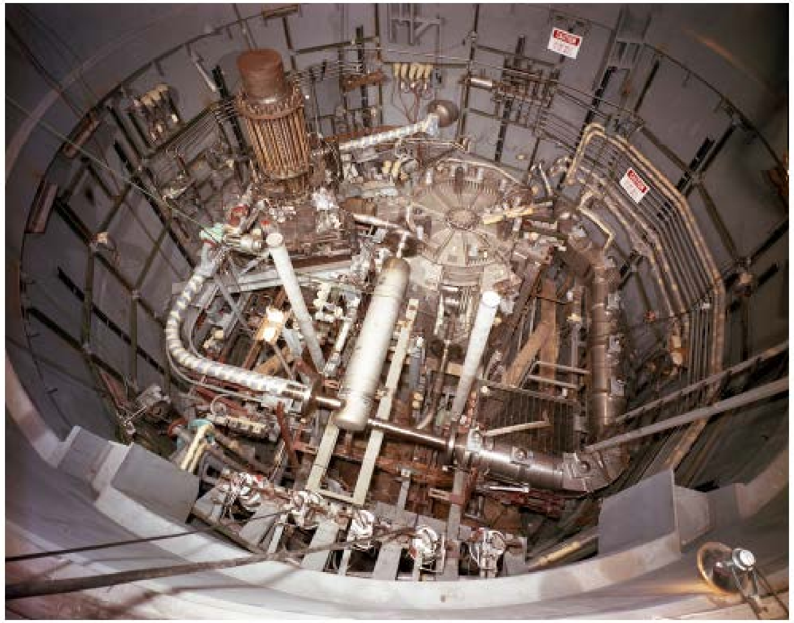
Analysis Needs for Next Generation Reactors

- Coupled Soil Structure Fluid Interaction (SSFI)
- Combined SSFI and operating load analysis
- Leverage capabilities of commercial FEM codes
- Reduce analysis cycle time
- Single analysis model
  - Same FEM model for operational and seismic loads
  - Eliminate two step analysis solution
  - Reduce model maintenance effort



A top view of the Molten Salt Reactor Experiment (MSRE) at Oak Ridge National Laboratory.

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Analysis Needs for Next Generation Reactors

- Equivalent Linear vs Nonlinear Analysis
  - Should we design for significant inelastic deformation during a structures life?
  - Operating basis should remain elastic
  - Safe shutdown may have limited inelastic deformation
    - ASCE 43 Limit State C
    - Most designs are targeting elastic response
      - Regulatory precedent
  - Nonlinear analysis is valuable for beyond (original) design basis events
    - Seismic demand 25 years after construction

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Existing Analysis Tools

- SASSI
  - Very good for developing frequency domain soil impedance and load vectors
  - Lacks many state-of-the-art analysis features
  - Narrow userbase
- Commercial FEM
  - Excellent element libraries
    - Ability to perform fluid-structure interaction with acoustic elements
  - Excellent constraints, etc. for model development
  - Graphical pre and post processing
  - Wide userbase

Buildings designed using SASSI and commercial FEM

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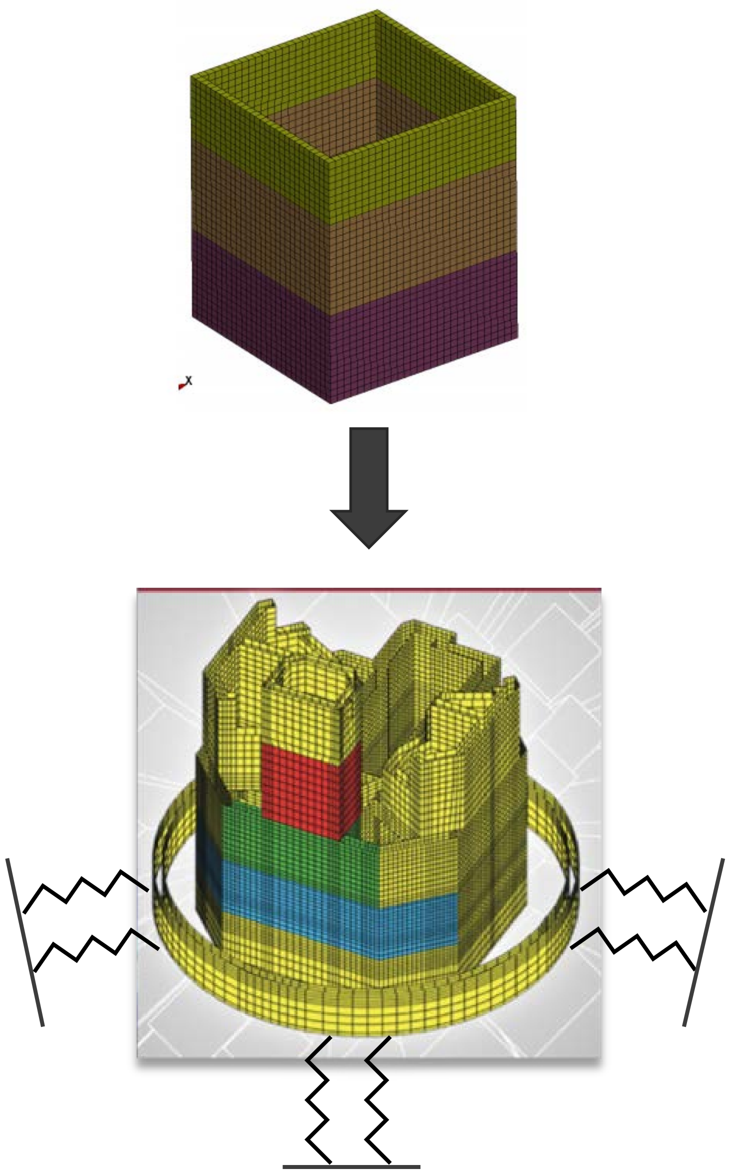
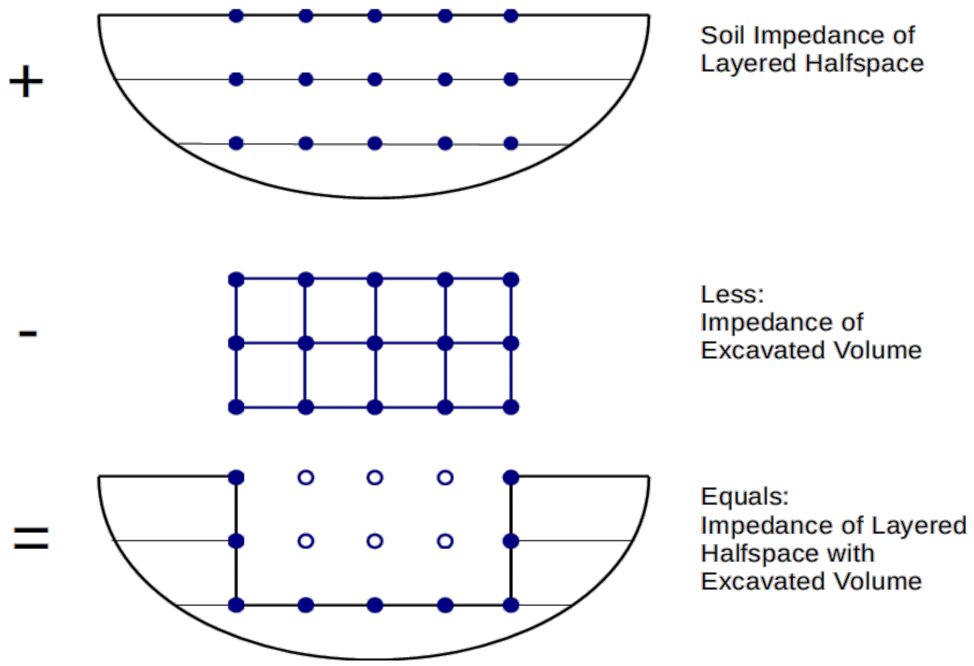
Proposed Solution

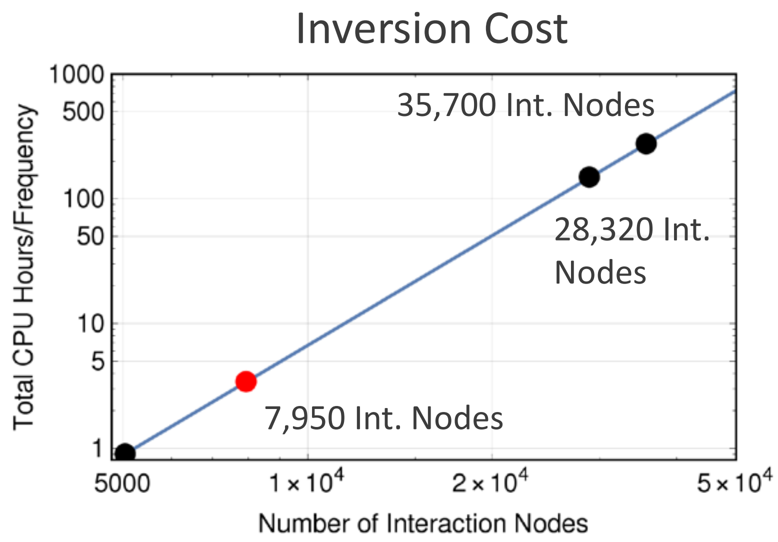
- Combine the best of SASSI and Commercial FEM
  - Use SASSI to develop soil impedances and load vectors for a given excavation and site profile
    - Store in a soil library
  - Use a commercial FEM code to
    - Develop building model
    - Generate operational demands
    - Generate seismic demands in the frequency domain
      - Post processing to convert frequency domain to time domain
    - Combine operational and seismic demands

- Functionally equivalent to a SASSI solution



SASSI Soil Impedance





*Use SASSI House bricks with mixed lumped and consistent mass

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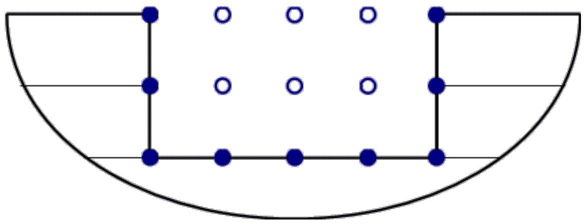
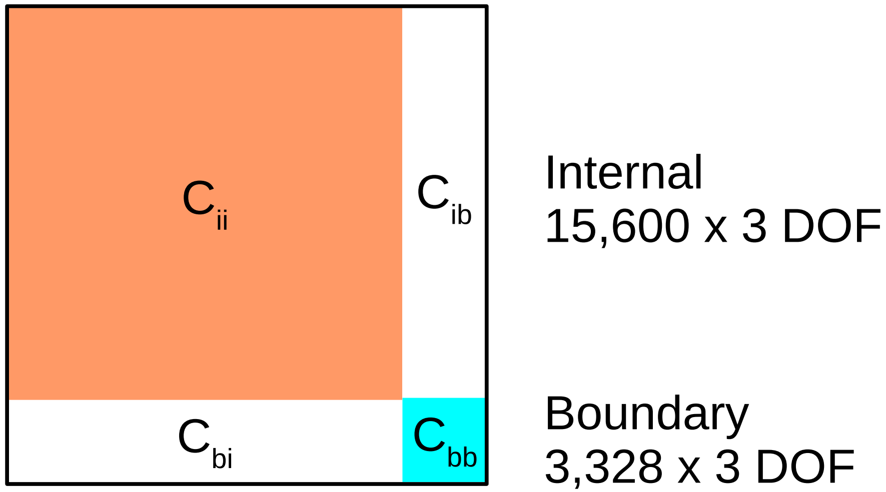
Impedance Matrix Storage

- Full Storage can be large
- Condense out internal DOF to reduce storage



Case 2, 18,928 Interaction Nodes



	Case 1		Case 2		Case 3	
	Full	Reduced	Full	Reduced	Full	Reduced
Nodes	5,168	1,360	18,928	3,328	35,280	5,085
File Size GiB	1.7	0.12	24	0.72	84	1.7
Size Ratio	14		32		48	

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Impedance Matrix Storage

- Condensed Impedance

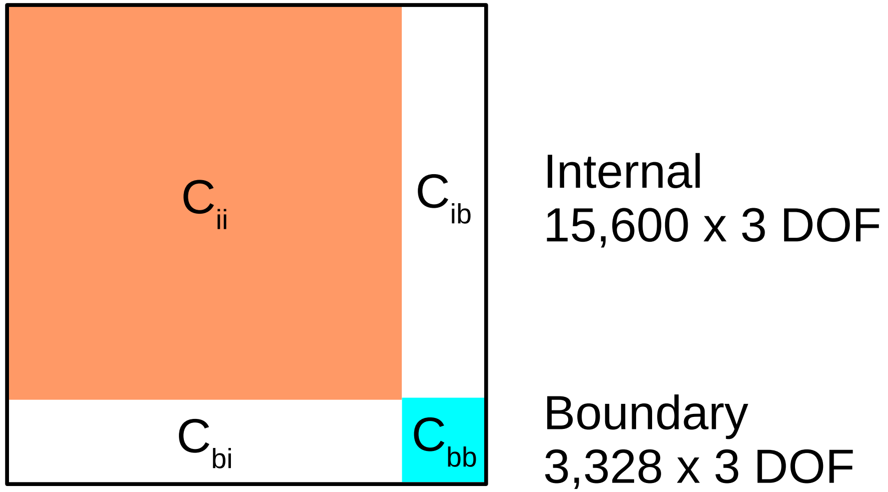
  $$[C_{Red}] = [C_{bb}] - [C_{bi}]\,[C_{ii}]^{-1}\,[C_{ib}]$$

  - Let $[X]$ be the solution of

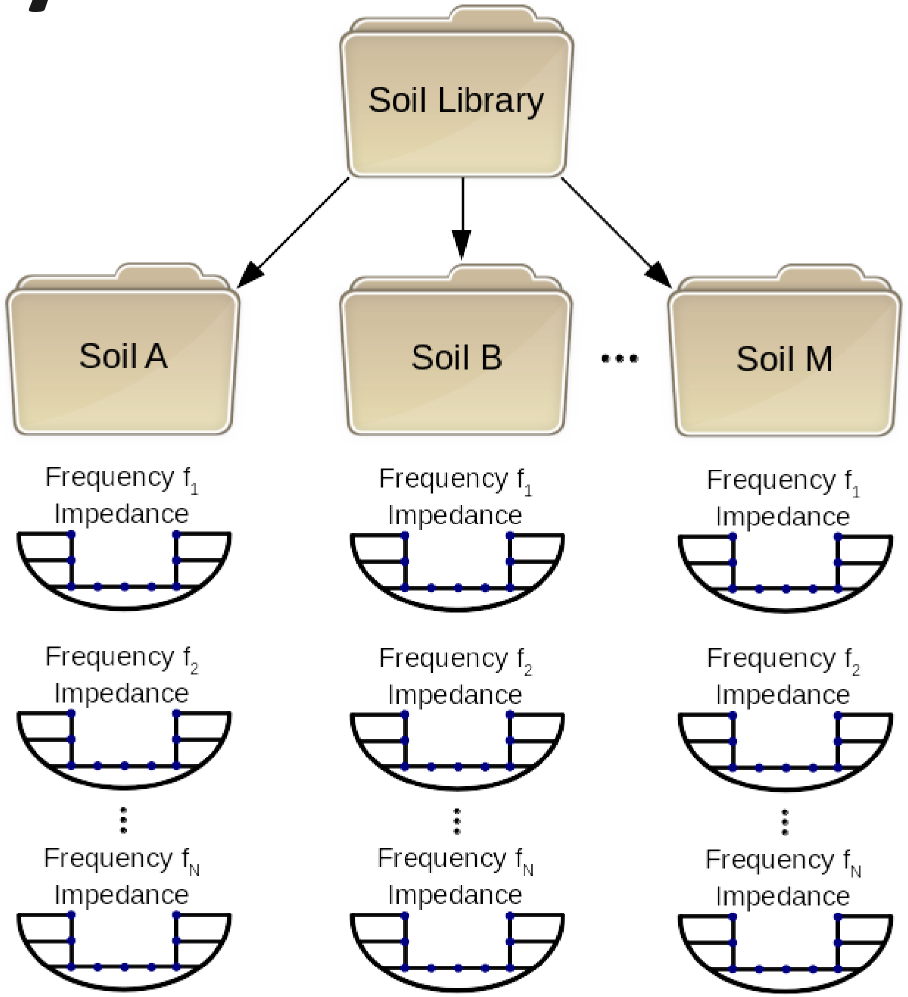
    $[C_{ii}][X] = [C_{ib}]$, then

    $$[C_{Red}] = [C_{bb}] - [C_{bi}][X]$$

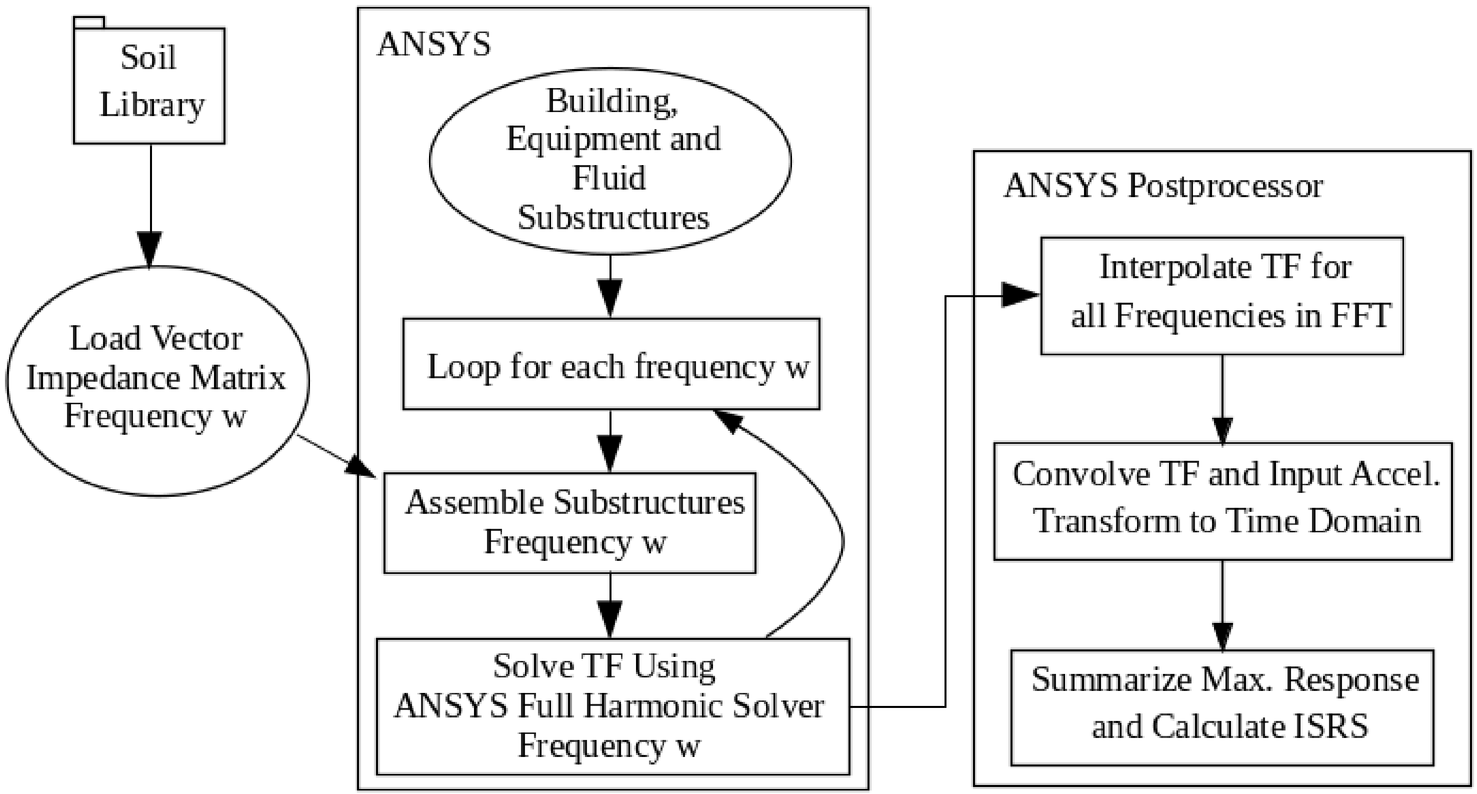
Case 2, 18,928 Interaction Nodes



Store Impedances and Load Vectors as Soil Library



Commercial FEM Solution (ANSYS)



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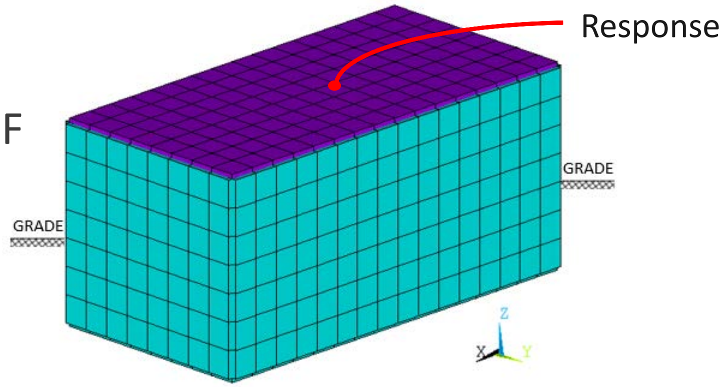
Embedded Building

- Simple Concrete Building
  - 95’x47’x44’, Embedded 19’
  - Open interior, dry
  - Stiff soil, low damping
  - Use ANSYS building stiffness and mass in SASSI

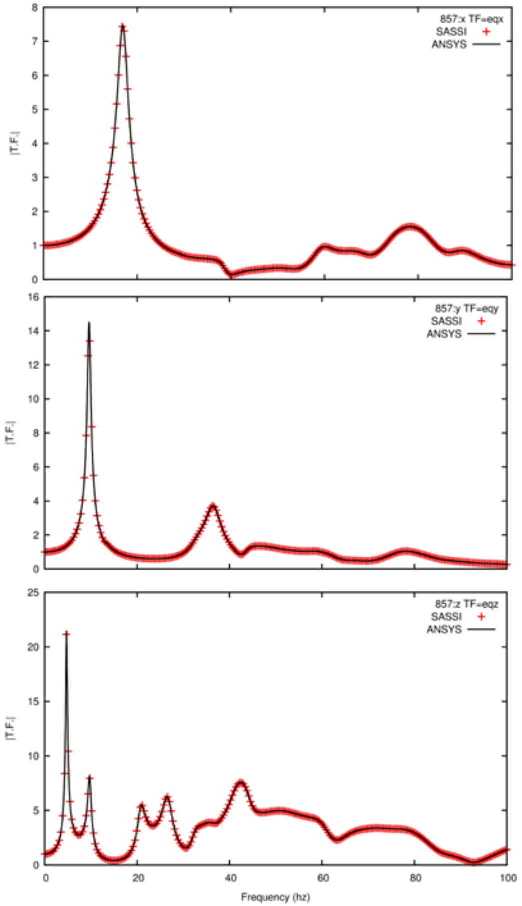
Large number of building DOF wrt to soil impedance
Use sparse solver



X Transfer Functions

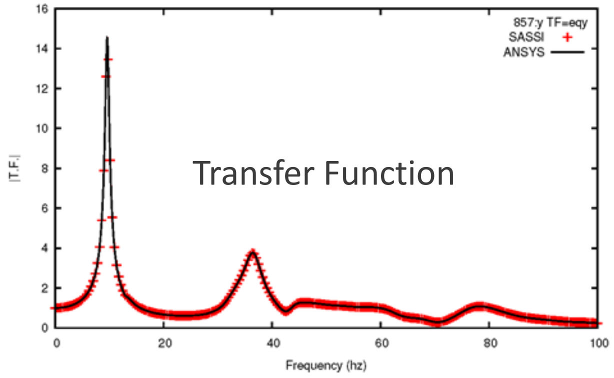
Y Transfer Functions

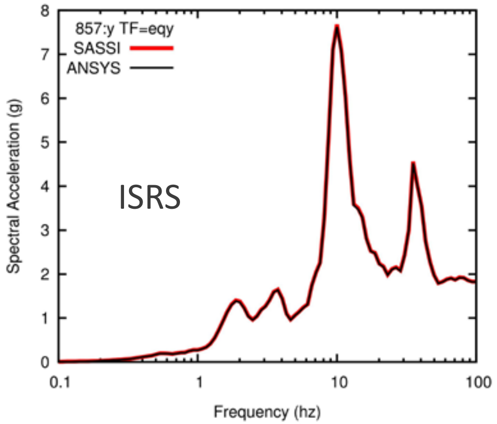
Z Transfer Functions

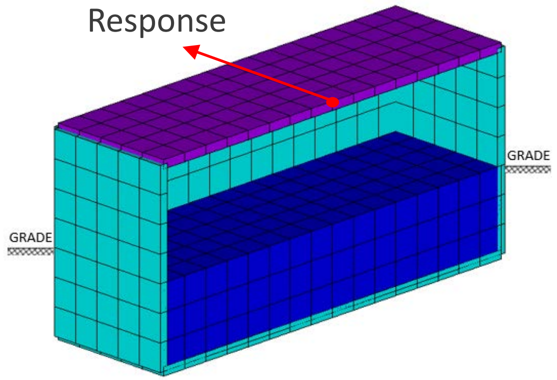


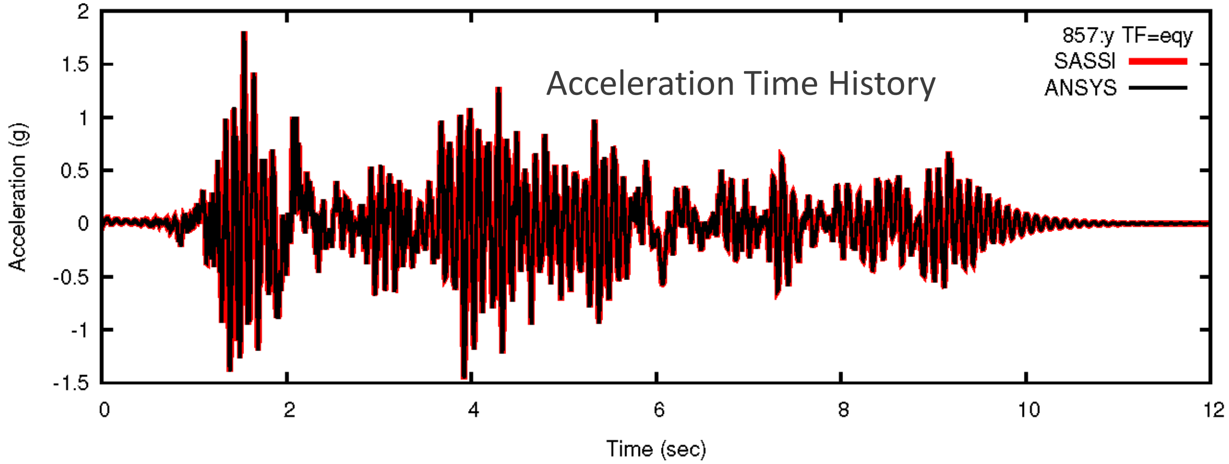
Embedded Building with FSI

- With a pool up to grade
- Center roof response





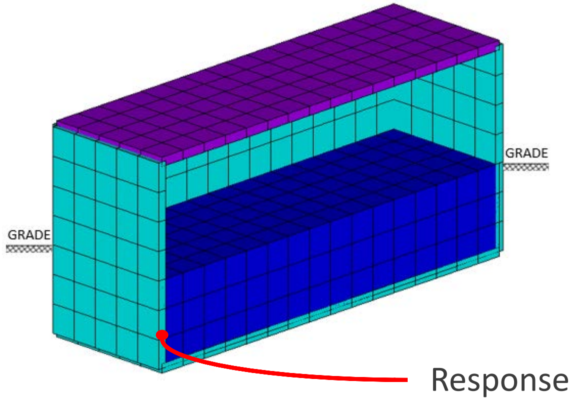


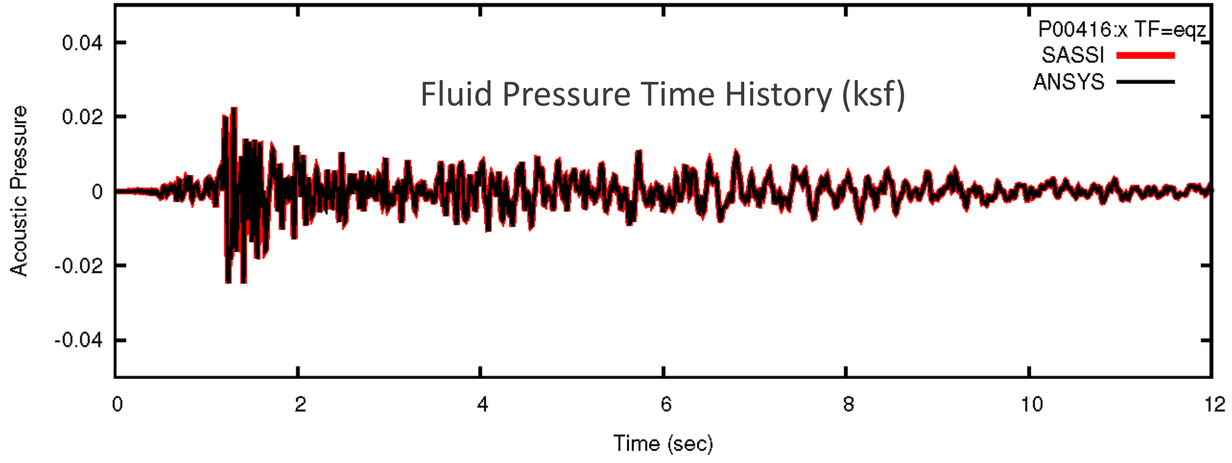


- Fluid modeled with acoustic elements
- Unsymmetric mass and stiffness

Embedded Building with FSI (cont)

- With a pool up to grade
- Fluid response to vertical motion





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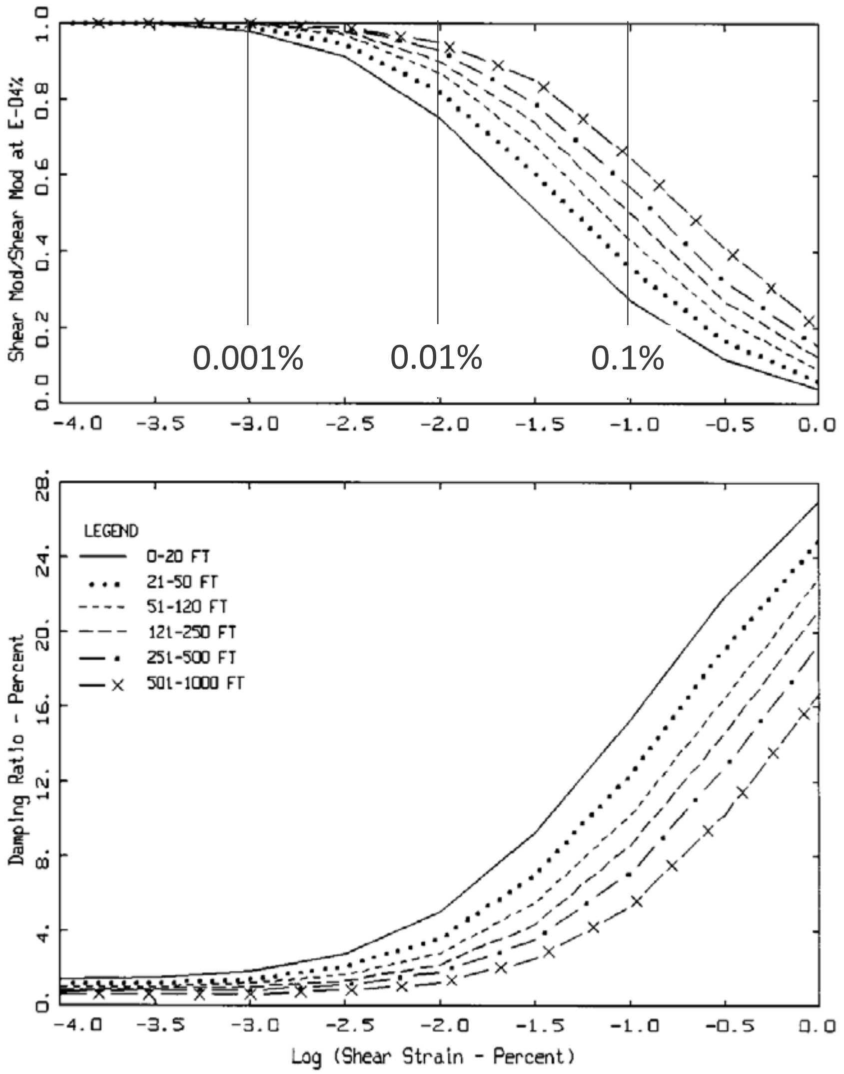
Experimental Needs

- Validation of Analysis Methods
  - Soil box seismic environment w/o building
    - Not a halfspace
    - Need to fully characterize the response of a soil box
  - Range of soil strain levels
    - Operating basis – low strain (boring, but important test)
    - Design basis – moderate strain
    - Beyond design basis – high strain
  - Soil box with test structure
    - Focus on SSI interaction
    - Wall tractions with waterproofing
    - Soil pressure on wall
    - Foundation rocking



MODULUS REDUCTION AND DAMPING CURVES
EPRI SOIL

Experimental Validation (Proposed)

Partially embedded structure containing fluid with a free surface. Immersed dummy component

Examples:

- Reactor vessel with supercritical steam/water
- Molten salt reactor with free surface
- Reactor vessel immersed in water
- Liquid metal cooled reactor
- Spent fuel pool

Experimental Validation (Proposed)

- Specimens
  - Empty container
  - Partially filled container
  - Full container
- Instrumentation
  - Soil pressure and tractions
  - Fluid Pressure
  - Component Acceleration
  - Anchorage Load
  - Structure Acceleration and Relative Displacement
  - Fluid Level Indicator

Experimental Validation (Proposed)

- Analytical preparation
  - Create soil impedance functions
  - Frequency Domain Solution
  - Time Domain Solution
  - Target range of soil strain
    - 0.1g, 0.5g, 1.0g, 2.0g PGA
- Experimental Runs
  - 0.1g, 0.5g, 1.0g, 2.0g PGA
  - Monitor divergence from analytical runs

Experimental Validation (Proposed)

- Results
  - Identify acceptable range for equivalent linear analyses
  - Validate coupled time domain solution
  - Establish method to qualify Gen IV reactors with Soil-Fluid-Structure interaction
- Possible expansions
  - Isolation and damping
  - Pebble bed fuel
  - Cask tipping

Conclusions

- Practical solution for Soil-Structure-Fluid Interaction problems
  - Based on existing, proven, technology
  - Methodology is functionally equivalent to a SASSI solution
- Demonstration problem
  - Excellent results comparisons
    - Transfer functions
    - Acceleration time histories and response spectra
    - Structural member design forces
    - Acoustic pressure time histories
- Experimental verification will strengthen our understanding
  - Confirm what we know
  - Identify what we don't know