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"Mechanics for Sustainable and Resilient Systems"

Nonlinear Response History Analysis of Seismic Soil-Structure and Fluid-Structure Interactions for Buried RC Fluid Storage Structures

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Overview

- Soil-Structure Interaction: state of practice
- Consideration of nonlinear time domain continuum models as a feasible alternative.
- An example of sophisticated modeling of a buried full RC reservoir.
- Important modeling details and unique possibilities offered by such sophisticated models.
- Summary

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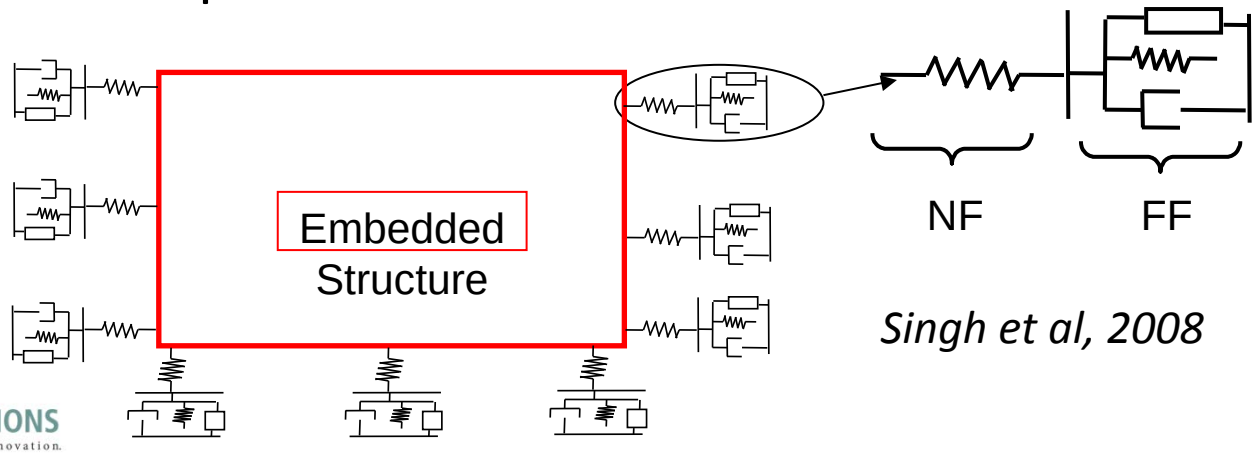
Introduction

SSI Analysis: State of Practice

- Usually separate analyses (in multiple software programs) are performed to calculate the properties of SSI discrete analogs.
- The analogs are used in detailed analysis of the structure in an FE program.
- The above analyses are usually performed by different entities/companies in practice.
- Design changes/updates/iterations are very costly.
- Simulations prone to inconsistencies.



Singh et al, 2008

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Why Nonlinear SSI?

- Soil response during MCE events on U.S. west coast would be highly nonlinear. Response obtained via Equivalent linear approaches deviate from nonlinear.
- Nonlinearities at soil-structure interface i.e. Gap and sliding.
- Structural damage is expected and usually allowed per projects' performance criteria.
- Other characteristics of real-world problems: Topography, Soil pore water, …

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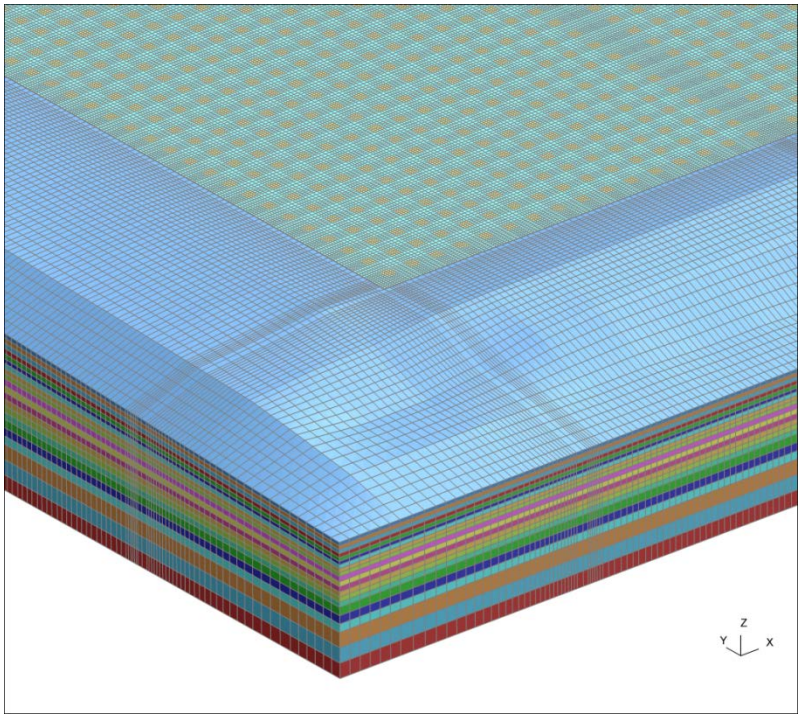
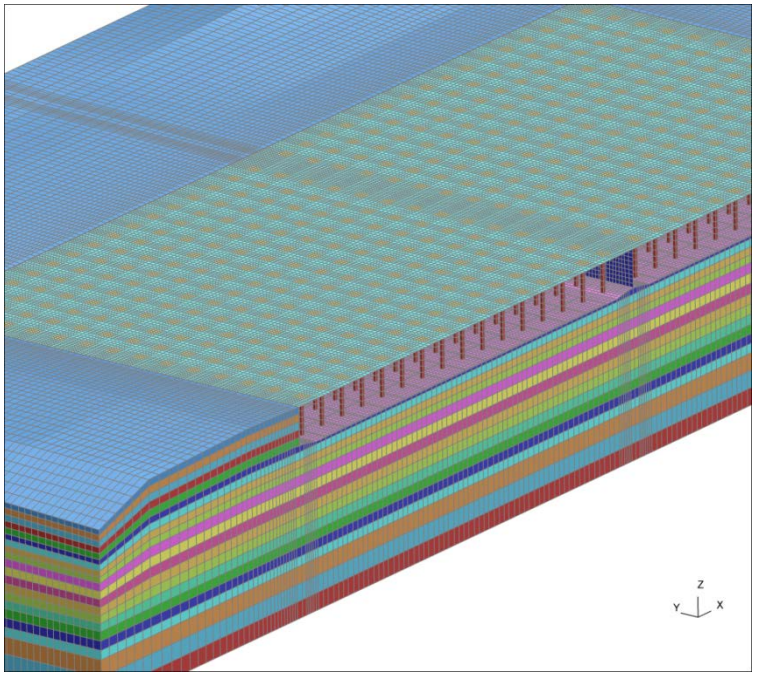
Buried Water Storage Reservoirs

LS-DYNA Global all-in-one FE Model

- 1.2M solid elements, ~6M DOFs
- All components nonlinear
- Explicit time integration
- Analyzed using Massively Parallel Processing (MPP) on SCS HPC





Full reservoir (water not shown for clarity)

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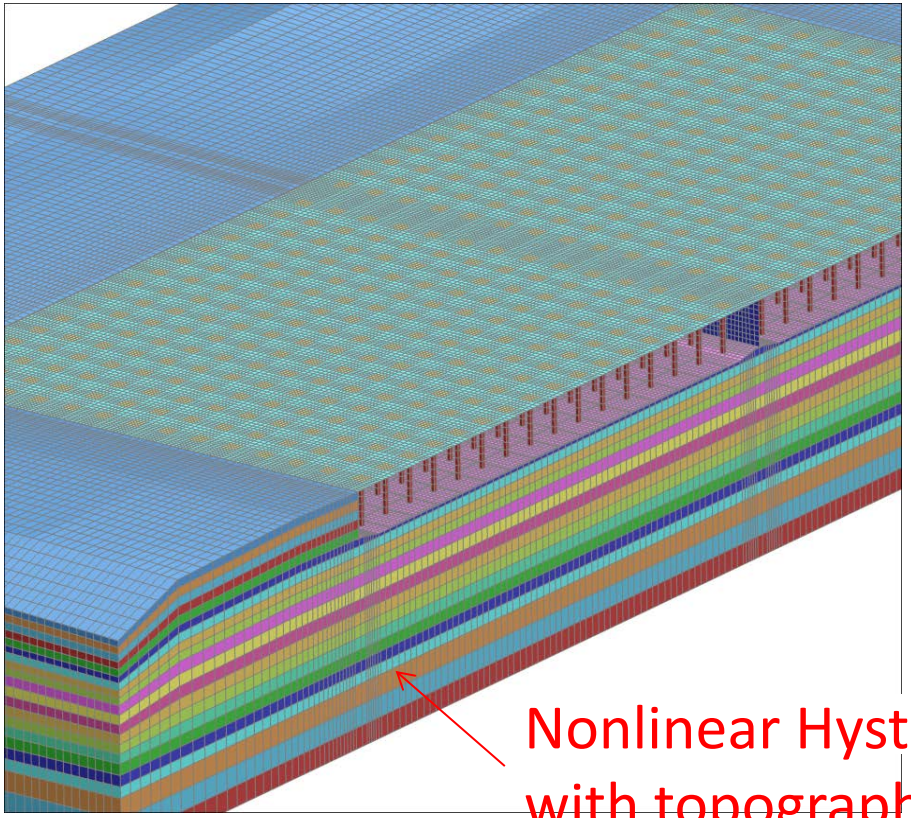
Modeling the Soil

- Proper seismic waves propagation from bedrock to the structure (nonlinear Free-field soil response due to intense shaking)
- soil nonlinear response near the structure (secondary nonlinearity)



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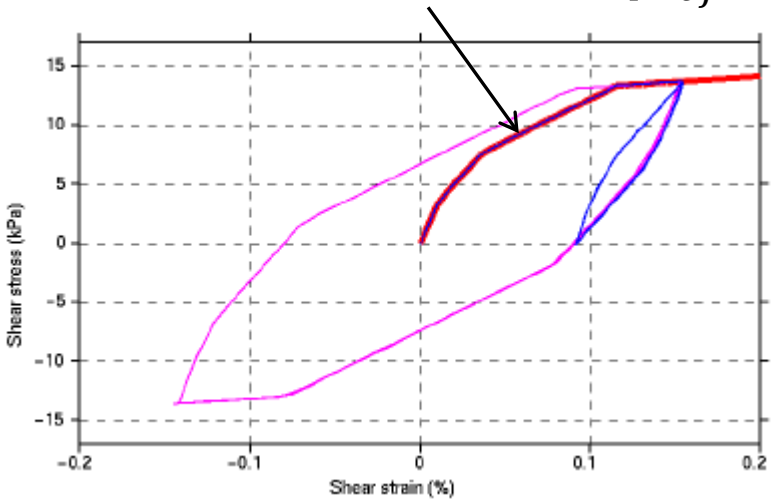
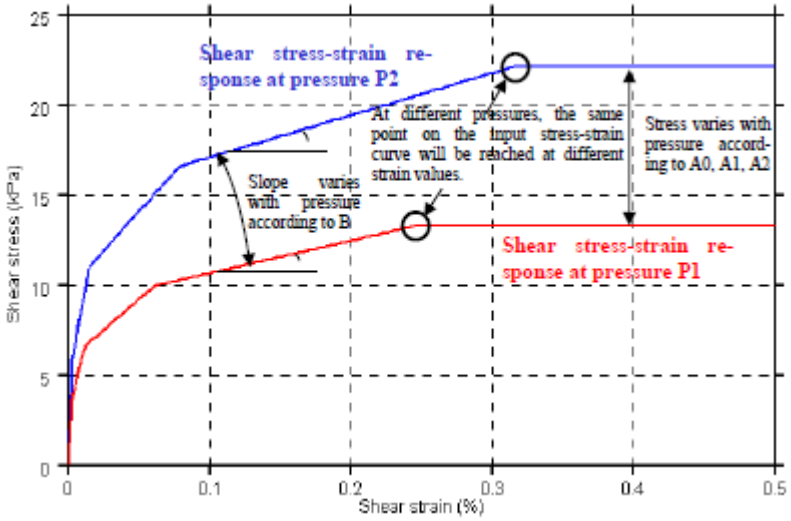
Soil Constitutive Model

- A nested multi-surface hysteretic plasticity model with effective pressure-dependent stiffness and strength.
- Hysteretic damping based on Masing rule.

Soil shear stress-strain at p_{ref}:





$$G(p) = \frac{G_0(p - p_0)^b}{(p_{ref} - p_0)^b}$$

$$K(p) = \frac{K_0(p - p_0)^b}{(p_{ref} - p_0)^b}$$

$$\frac{\tau(p,\gamma)}{\tau(p_{ref},\gamma)} = \sqrt{\frac{[a_0 + a_1(p - p_0) + a_2(p - p_0)^2]}{[a_0 + a_1(p_{ref} - p_0) + a_2(p_{ref} - p_0)^2]}}$$

Ref. LS-DYNA user manual (Hallquist, 2006)

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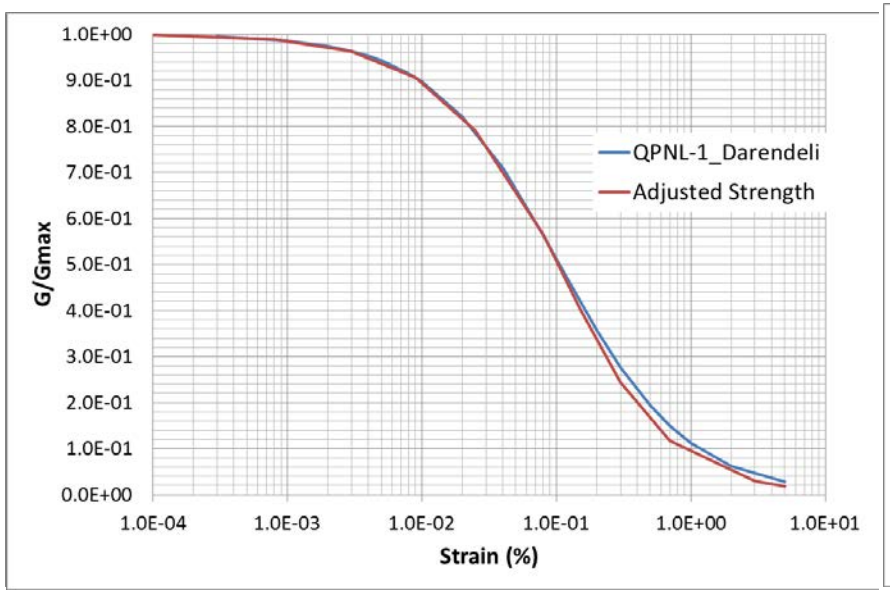
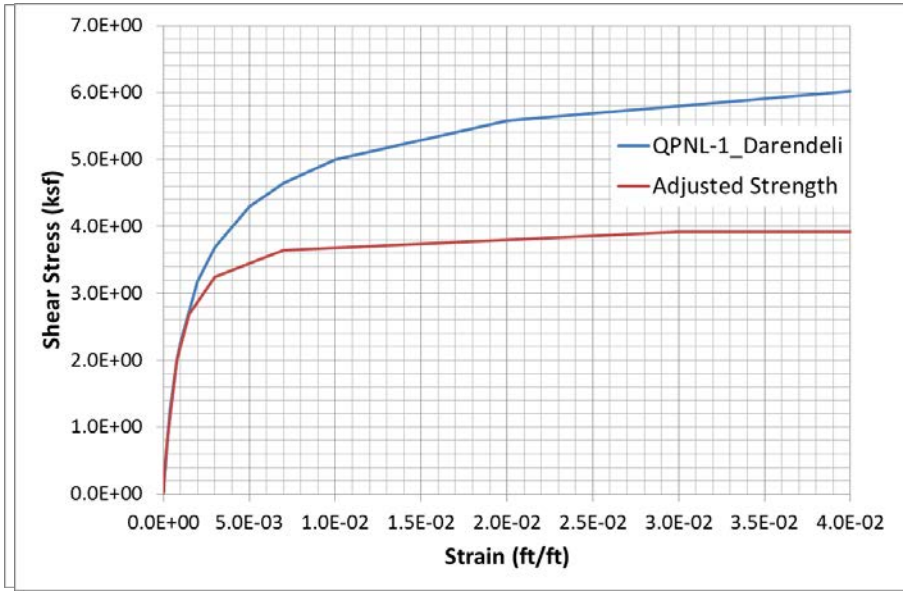
Soil Modeling: Improving the State of Practice

- Disconnect between small-strain and large strain response of the soil in geotechnical engineering practice.
- Marriage between the two is necessary for large seismic events. (Stewart et al 2008)

G/Gmax: small strain seismic SRA



Shear stress-strain: Static limit state and stability analysis



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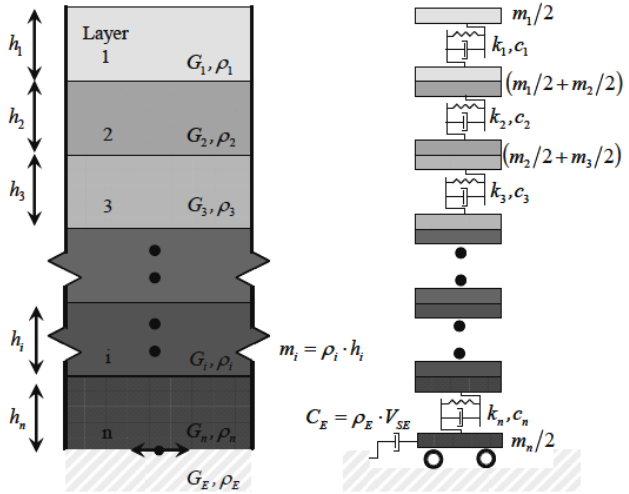
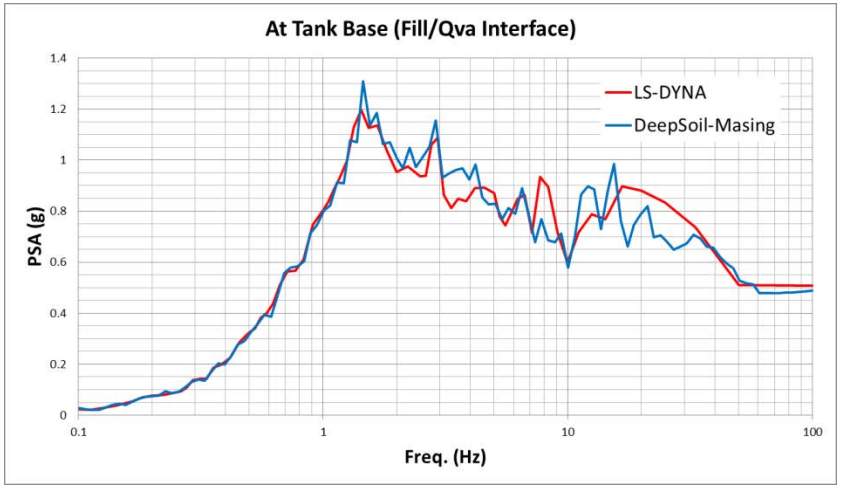
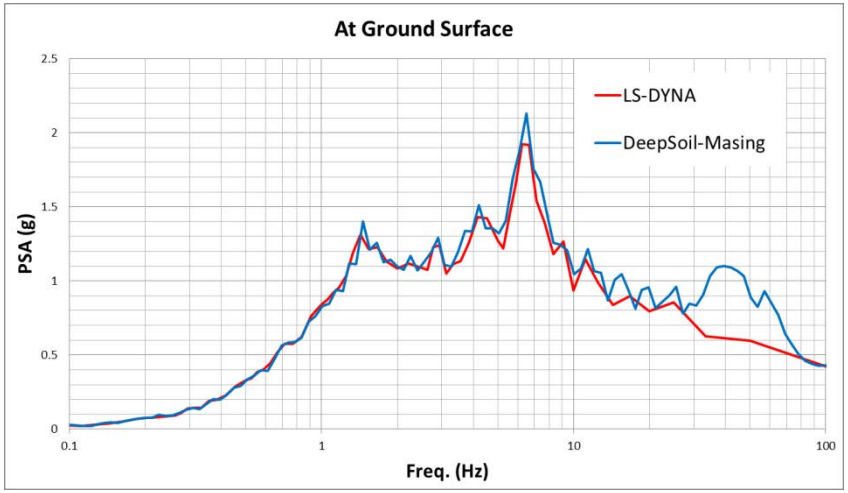
SRA

Deepsoil 1D SRA (Hashash et al, 2010)



Soil Column in LS-DYNA





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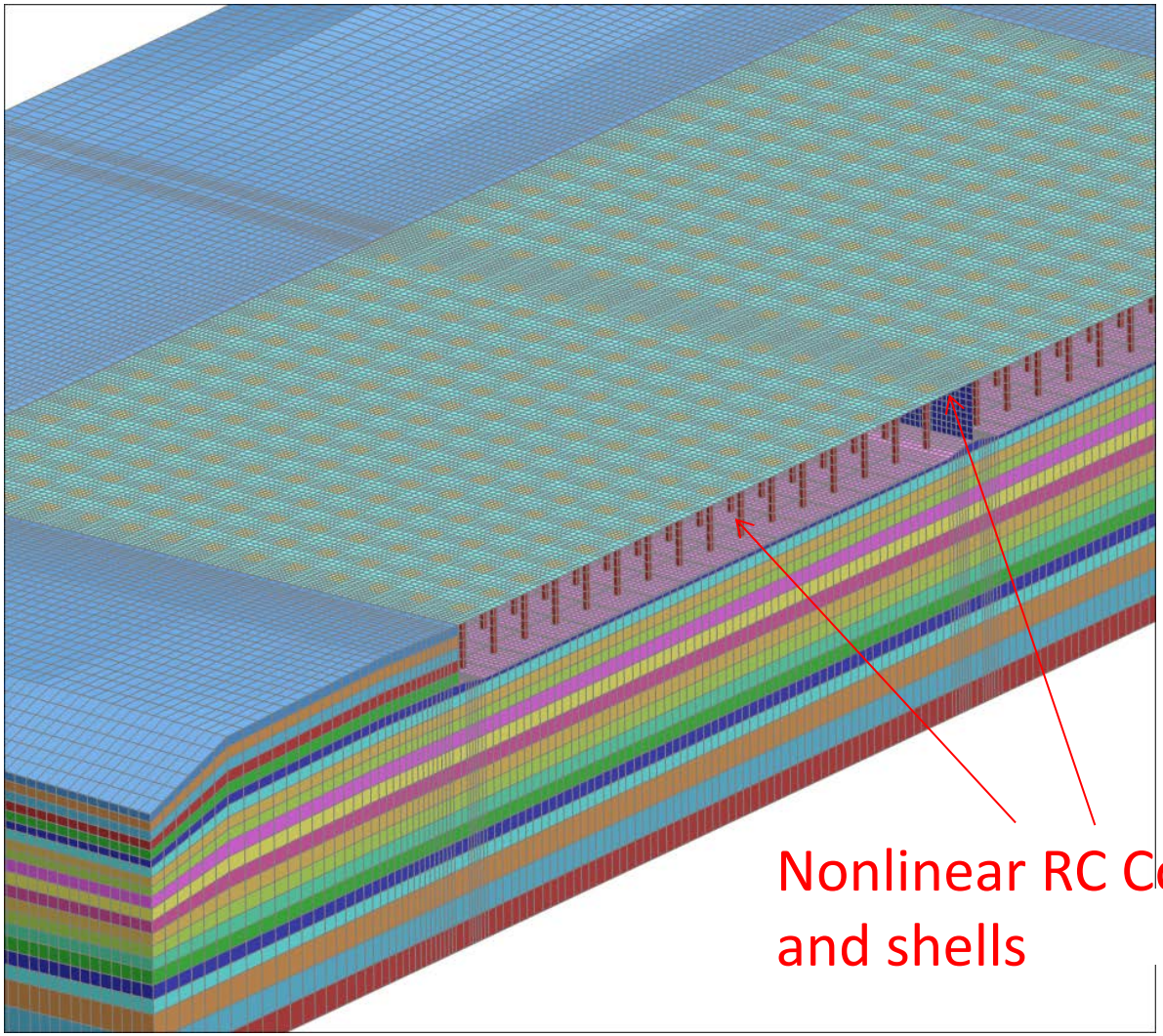
Structural Components



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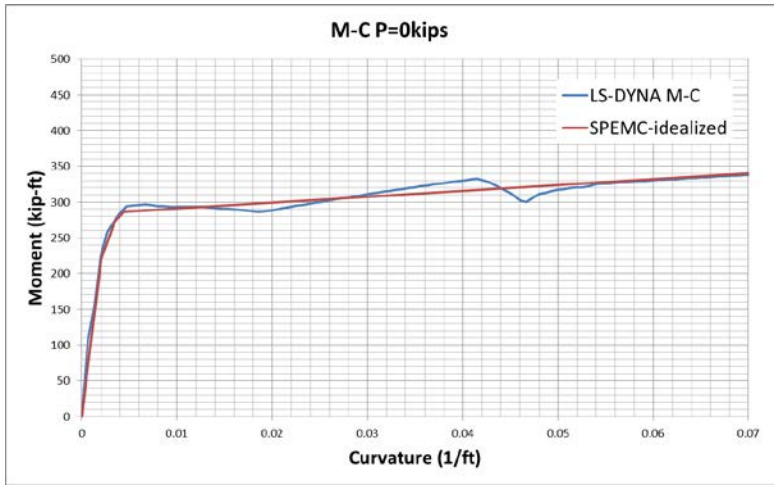
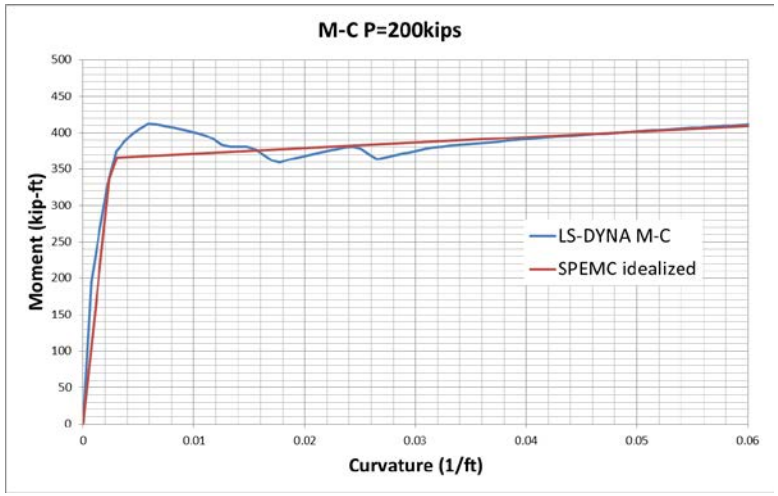
Reservoir RC Components

- Fiber-based integrated beam and layered composite shell finite elements used to model the RC structural components.
- Mander or Kent-Park model used for concrete fibers.





SPEMC: SCS in-house section analysis program.

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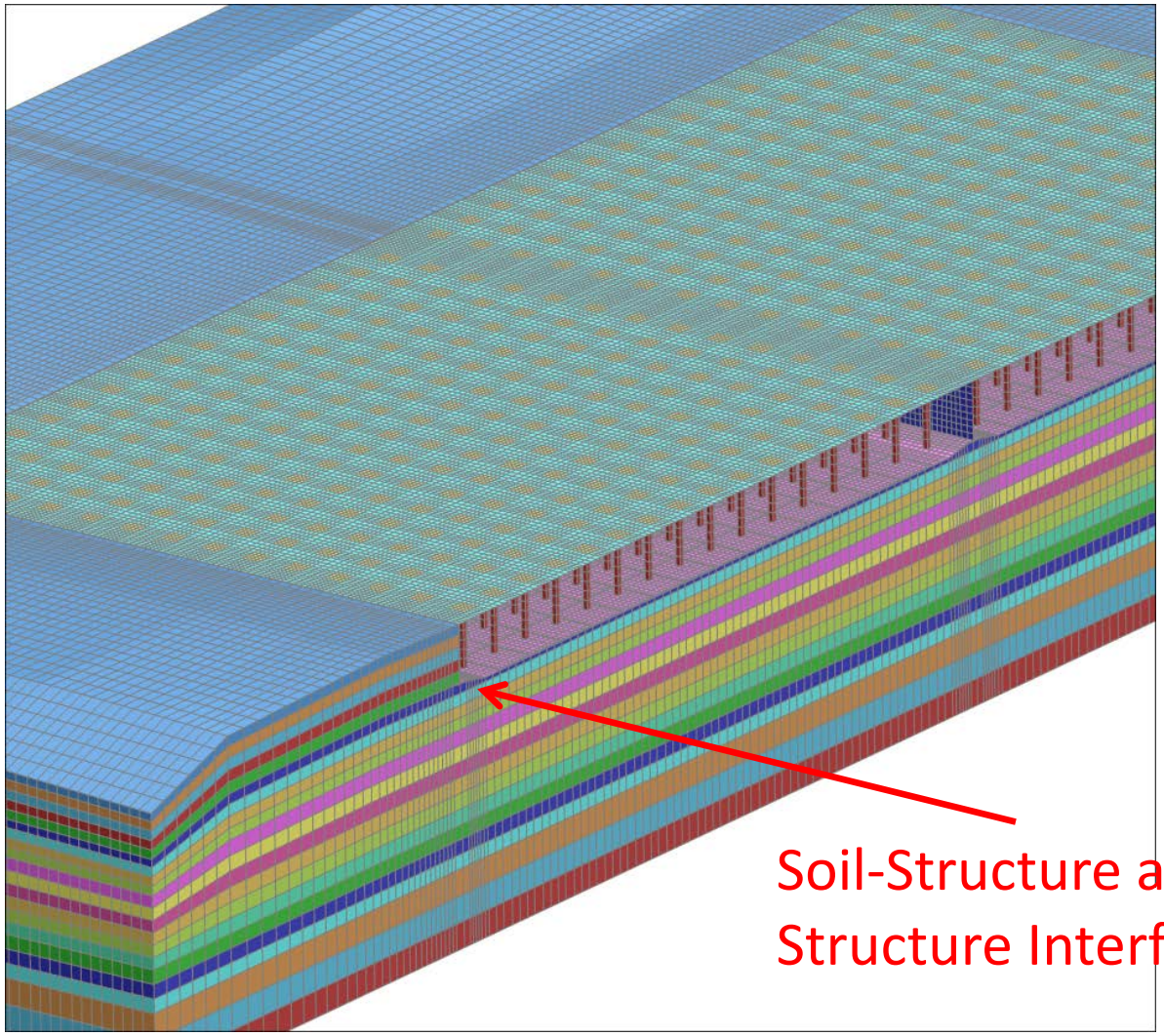
SSI &FSI interfaces



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Contact at Soil-Structure Interface

- Penalty based contact algorithms with coulomb friction is used.
- In SSI-FSI simulations, contact between two materials with dissimilar stiffnesses should be effectively modeled.
- Penetrations may occur when standard approach based on FE elements' material stiffness is used to calculate the contact stiffness.
- Consideration of other formulations may be necessary.

Contact stiffness for Brick elements based on material properties:

$$k_c = \frac{\alpha K A^2}{V}$$

Alternative Contact stiffness:

$$k_c = \frac{\beta m}{\Delta t}$$

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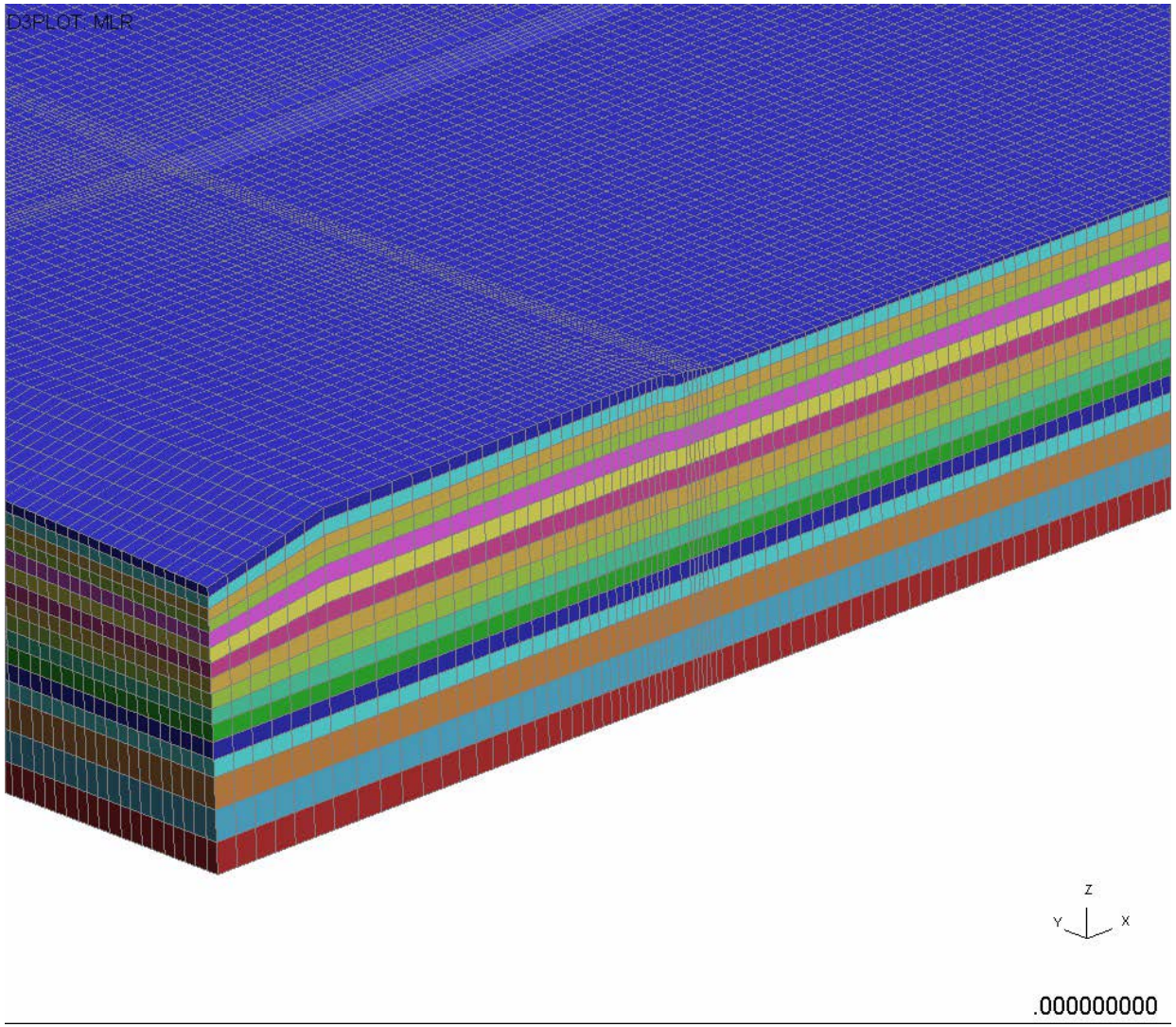
Construction Staging



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Pore Pressure/Effective Stress Analysis

- The effect of pore fluids can be modelled via introducing nodal springs in the solid domain.
- The pore fluid behavior can be expressed by Terzaghi soil effective stress definition.

$$\sigma = \sigma' + \mathrm{u}$$

- Excess pore pressure is developed in the loaded soil elements designated as undrained.

$$\Delta\sigma = \Delta\sigma' + \Delta\mathrm{u}$$

- Undrained: $\Delta\sigma$ is taken by the soil skeleton and water in proportion to their bulk modulus values.
- Drained: $\Delta\sigma = \Delta\sigma'$

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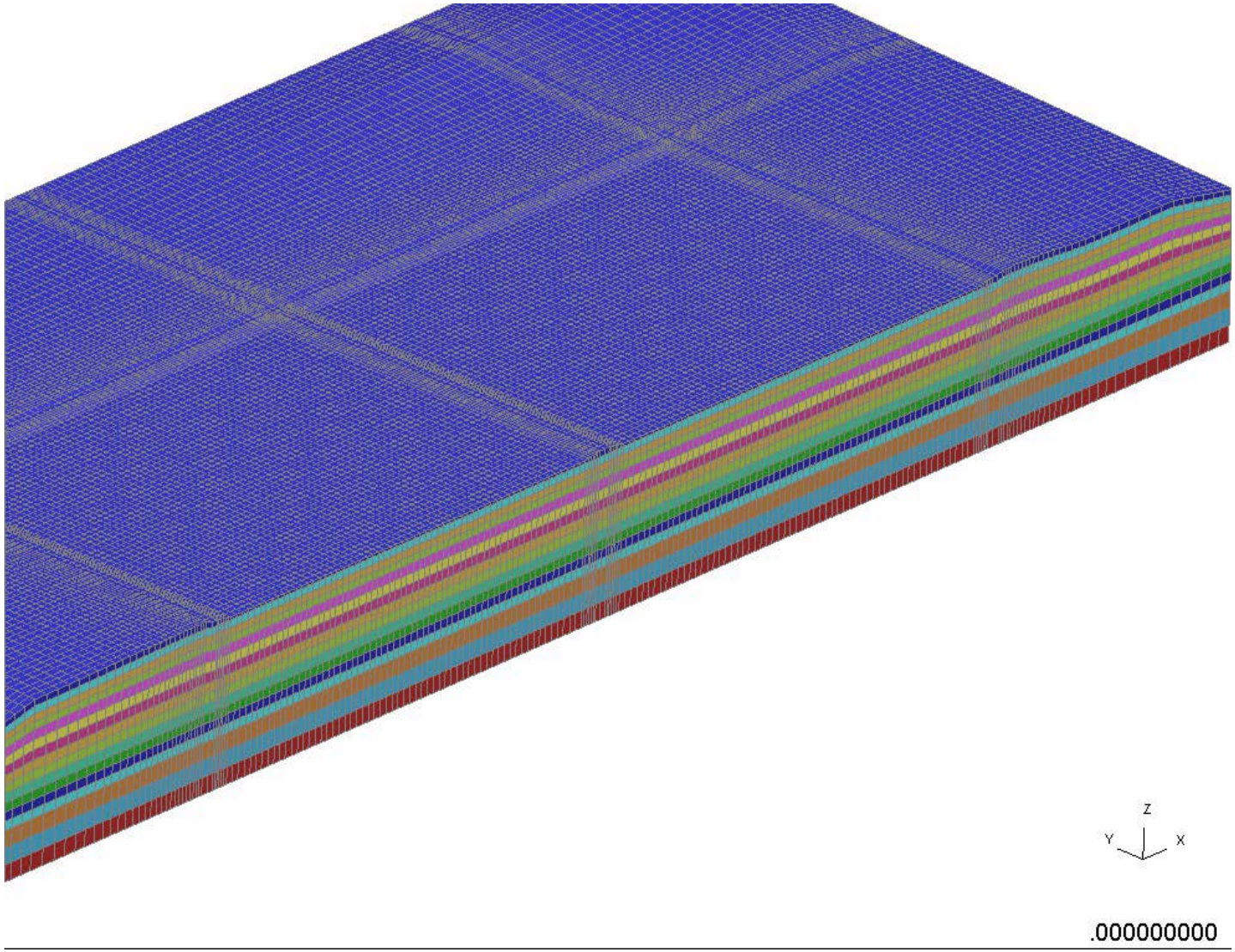
Seismic Response History Analysis



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Summary

- Soil material model used in seismic simulations under large earthquake events should effectively capture the soil behavior over a wide range of shear strains from very small-strains to soil shear strength.
- The presented simulations are being performed within the demanding schedule and budget of modern infrastructure projects (even in design-build environment).
- Global all-in-one SSI-FSI models are not necessarily more expensive. Design updates and parametric studies can be accommodated efficiently.

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Summary

- Highly nonlinear material response, large deformations, site topography, pore water drainage effect, and construction staging can all be included in global SSI model.
- High-Performance Computing (HPC) is becoming mainstream.

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