

Overview of Soil-Structure Interaction Analyses at Lawrence Livermore National Laboratory

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Disclaimer

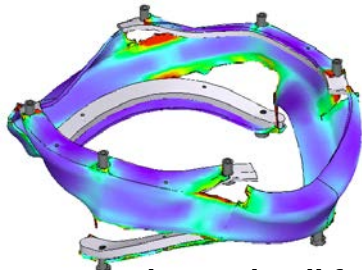
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- **ParaDyn/DYNA3D**
 - **Explicit Solid and Structural Mechanics**
 - **Massively Parallel**
 - **Extensive use at LLNL and in the DoD**
- **DIABLO**
 - **Parallel Implicit Multiphysics**
 - **Solid/Structural Mechanics, Heat Transfer, EM**
 - **Use at LLNL and other DOE facilities**
 - **Part of NEAMS/SHARP Reactor Physics Code Package**
- **Related Codes: ALE3D (Parallel ALE Multiphysics)**
- **Legacy Codes:**
 - **NIKE3D (implicit solids), TOPAZ3D (heat transfer)**

ParaDyn provides explicit, nonlinear structural dynamics modeling on high-performance platforms

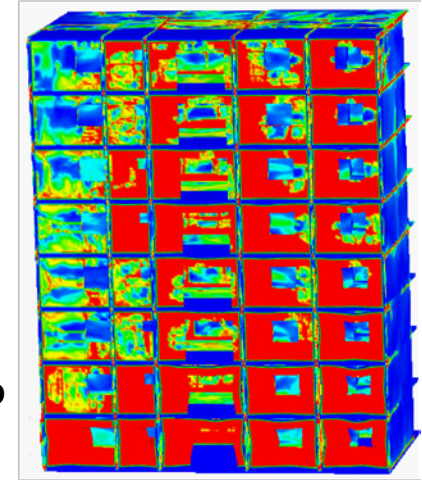
- ParaDyn heavily used on LLNL platforms – *over 18 million CPU-hours in CY2010*
- Supports engineering assessments & decisions



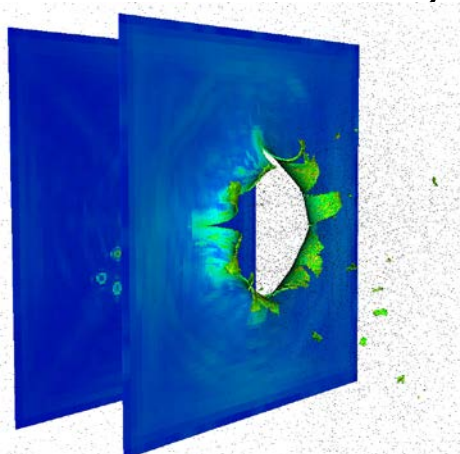
Flange detail from a transportation container
courtesy D. Badders, LLNL



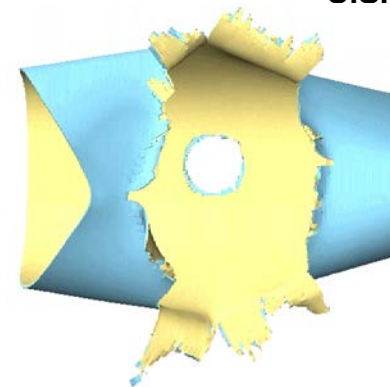
Early support
included a DoD
CHSSI project



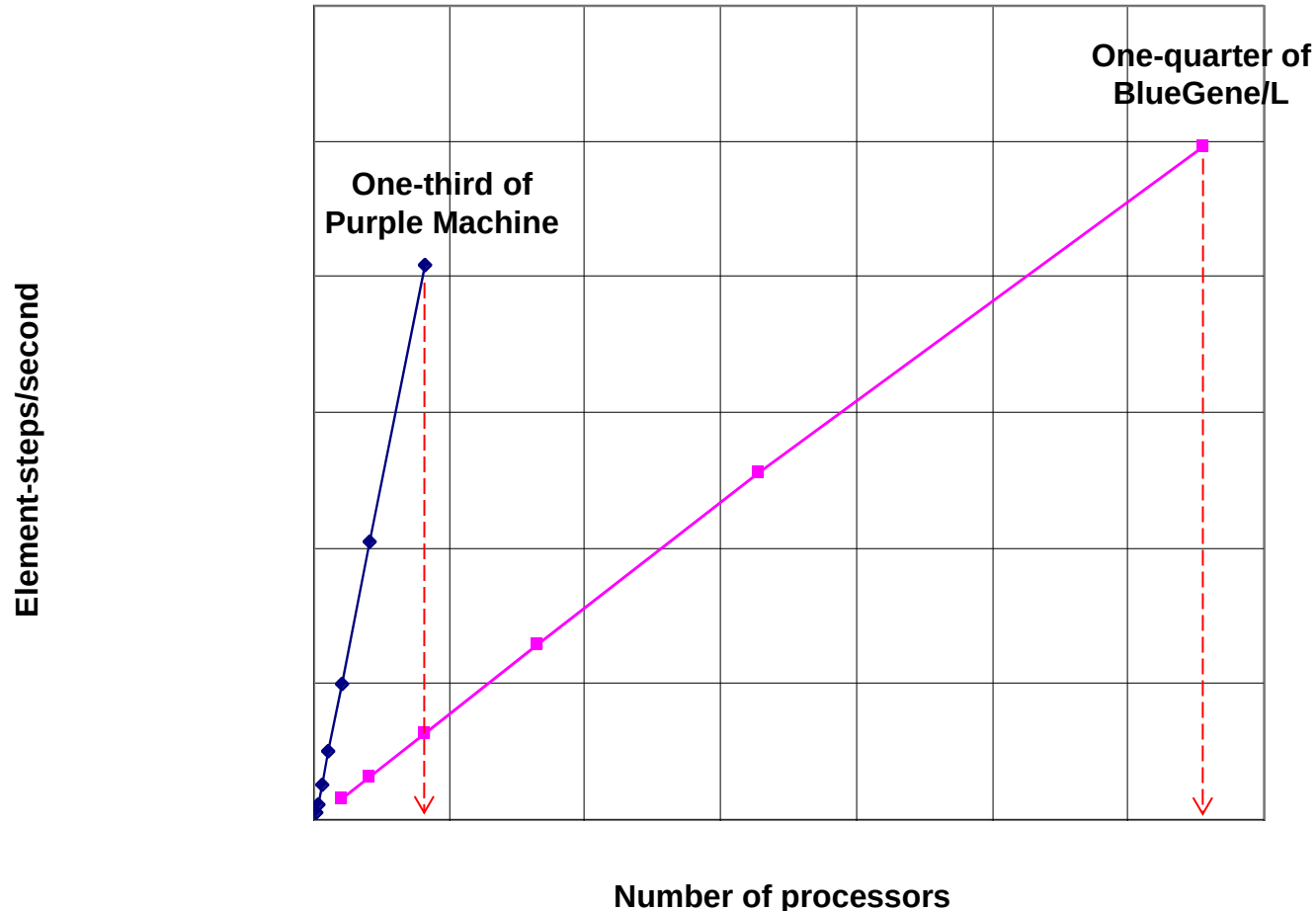
courtesy P. Papados,
U.S. Army ERDC



Hypervelocity impacts
courtesy D. Faux & E. Kokko



ParaDyn's excellent baseline scalability illustrated by a 90 million element benchmark



Simple problems first used to explore new architectures and flush out potential bottlenecks

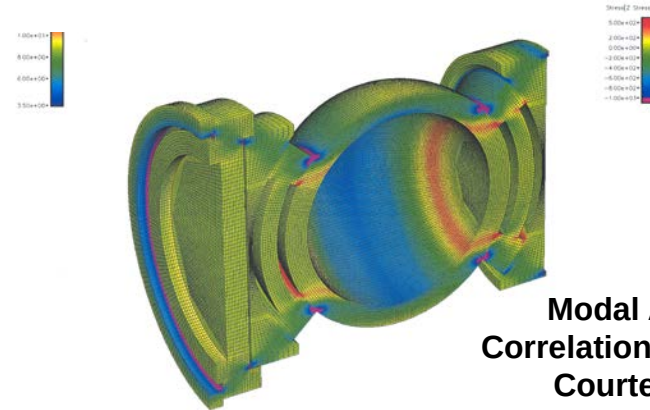
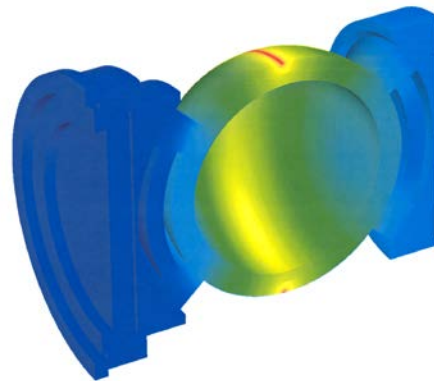


The Diablo code is a complement to ParaDyn with implicit time integration and focused multi-physics



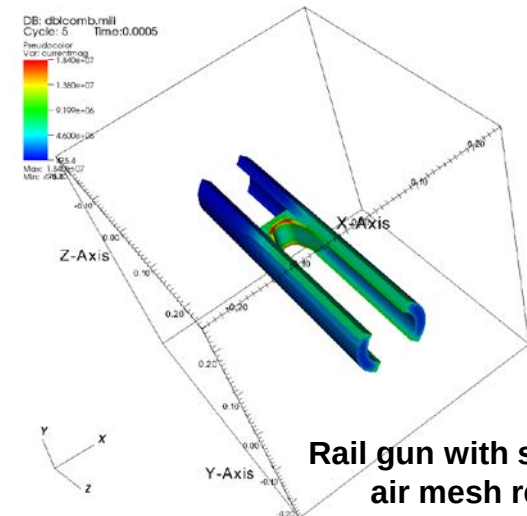
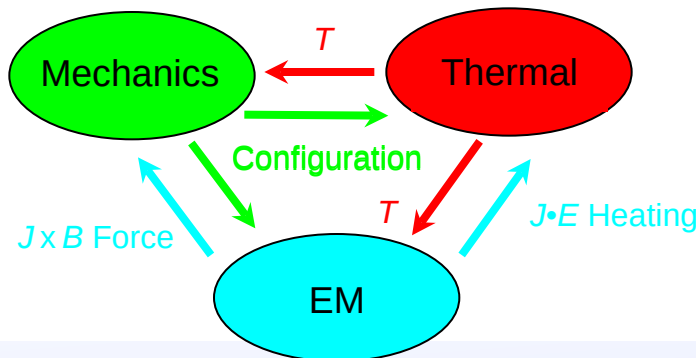
■ Thermo-mechanical response is an important driver for LLNL programs

Thermal and stress response to heat flux at waist of assembly



■ Thermo-chemical for surface corrosion

■ Electro-thermo-mechanical

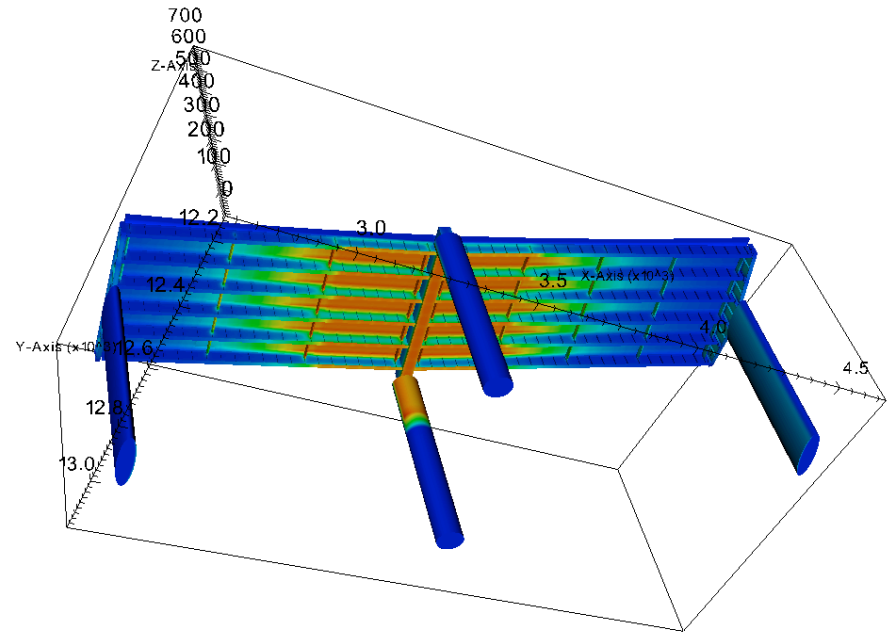


Diablo Example: McArthur Maze Collapse

(Part of eastern approach to S.F. – Oakland Bay Bridge)



- Coupled thermal-mechanical



Only modeled to incipient failure – would want to go explicit for final crunch

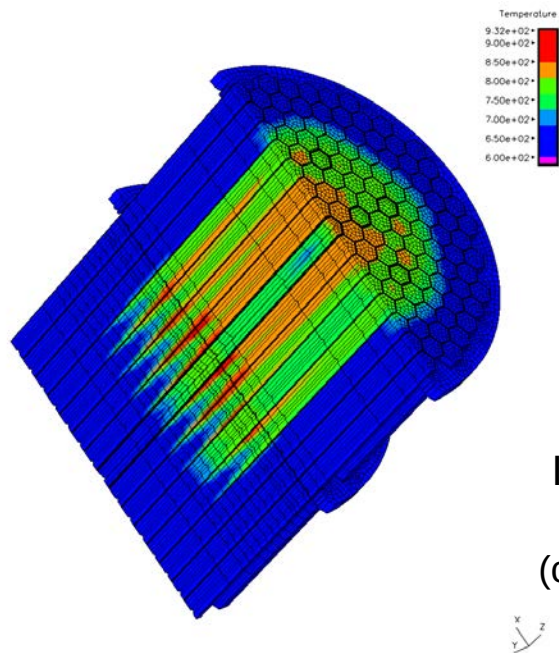




DIABLO used as the structural mechanics driver for the SHARP reactor modeling toolkit

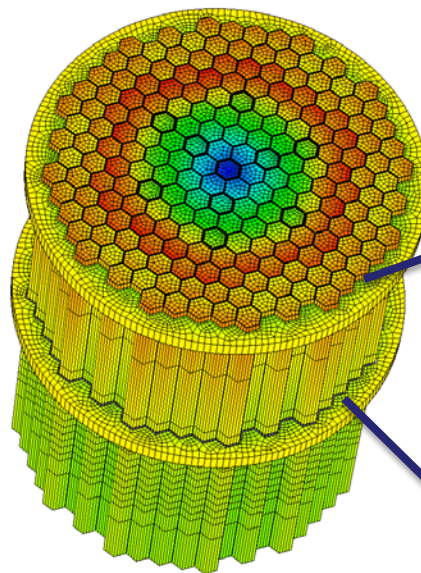
■ High Level of Complexity:

- 199 assemblies
- 398 contact surface

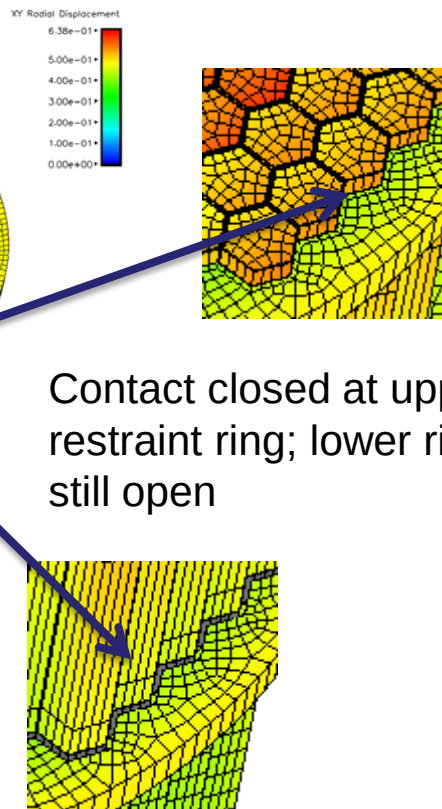


Initial temperature field and
structural deformations
(contours of radial displacement)

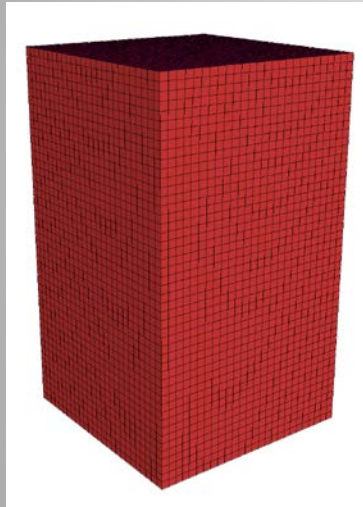
Ref state: initial geom.



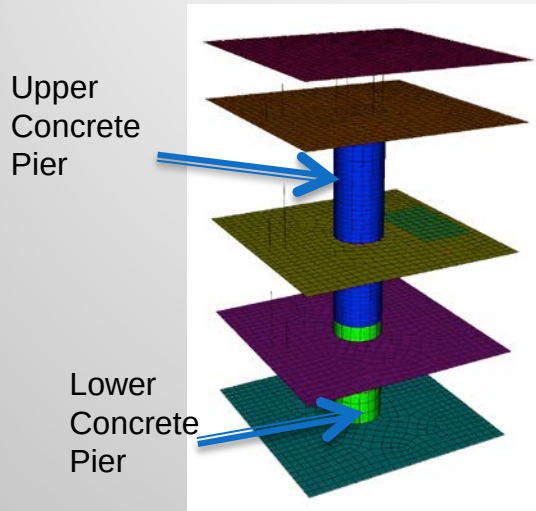
Contact closed at upper
restraint ring; lower ring
still open



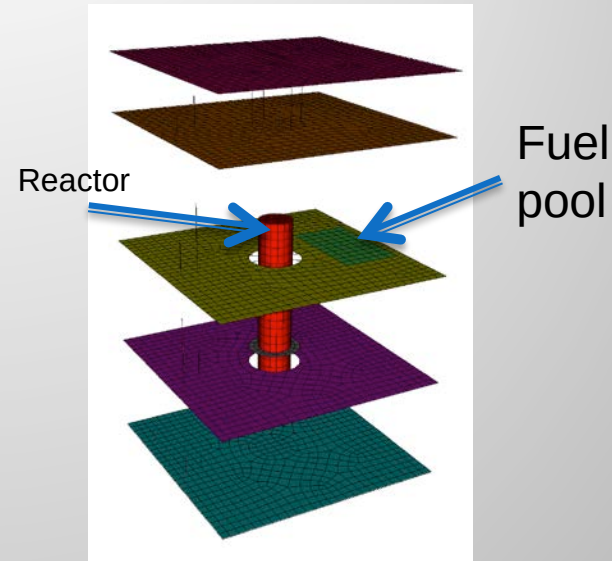
Time Domain SSI Analysis of Notional Small Modular Reactor



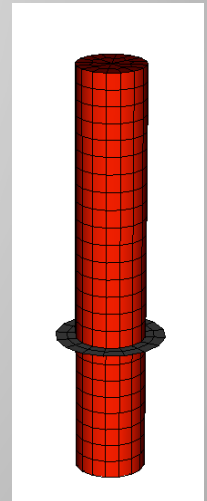
Reactor Building



Inside Reactor Building - Concrete pier structures



Inside Reactor Building – Concrete piers removed



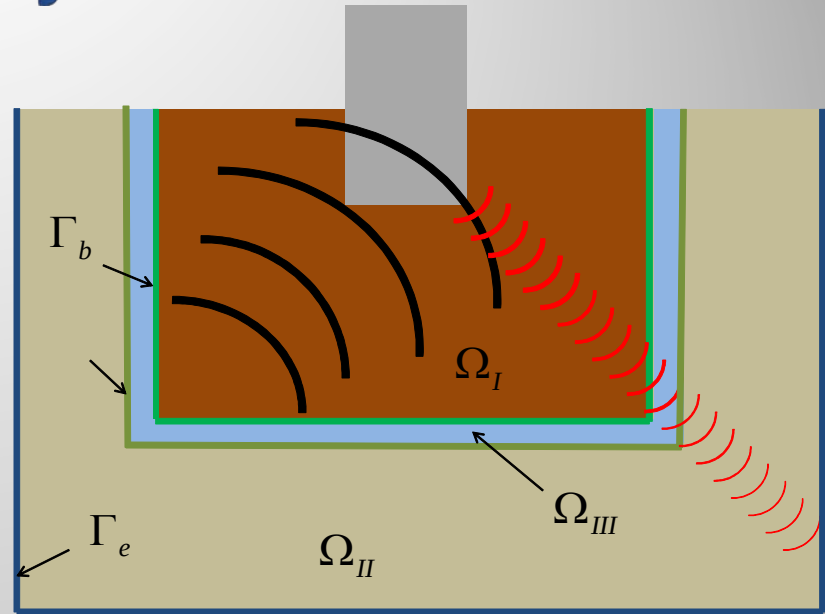
Reactor Vessel with support ring

Reactor model also incorporates 8 stick models for equipment, 4 floor support columns, 8 reactor restraint beams, and fuel pool on floor 3

The Bielak Method – an Improvement over Absorbing Boundary Conditions

- Developed by Bielak and coworkers (1984, 2003)

1. Drive the problem at the intermediate boundary, Γ_b
2. Absorb scattered waves at the external boundary, Γ_e
3. Requires intermediate layer 1-element thick, between Ω_{III}

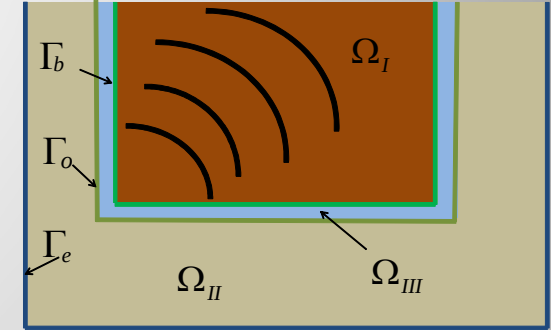


Advantages

- Can drive seismic input exactly for linear materials
- External B.C. only needs to absorb scattered waves at some distance
 - Absorbing B.C. does not have to be “perfect”

Recast the Bielak Method for Nonlinear Materials

- Assume the extended soil island w/o structure
- Let u^e be the exact (discrete) displacement field created by a particular **earthquake** motion
- **Do not** assume Ω_{III} is one element thick
- Assume, within Ω_{III} a scaled solution $\tilde{u} = \alpha(\mathbf{x})u^e$



$\alpha(\mathbf{x})$ a smooth monotonic function satisfying

$$\alpha(\mathbf{x}) = 1 \forall \mathbf{x} \in \Omega_I \cup \Gamma_b$$

$$\alpha(\mathbf{x}) = 0 \forall \mathbf{x} \in \Omega_{II} \cup \Gamma_o$$

$$0 < \alpha(\mathbf{x}) < 1 \forall \mathbf{x} \in \text{Int}(\Omega_{III})$$

The general discrete nonlinear equations $\mathbf{R}^I = \int_{\Omega} \rho \ddot{\mathbf{u}} N^I d\Omega + \int_{\Omega} \boldsymbol{\sigma}(\nabla^s(\mathbf{u}), \text{history}) \bullet \nabla^s N^I d\Omega = \mathbf{F}^I$

$$\mathbf{F}_I^I = 0 \forall I \mid \mathbf{x}^I \in \text{Int}(\Omega_I) \quad \mathbf{F}_{II}^I = 0 \mid \mathbf{x}^I \in \text{Int}(\Omega_{II})$$

$$\mathbf{F}_b^I = \left(\int_{\Omega_{III}} \rho \ddot{\mathbf{u}}^e N^I d\Omega + \int_{\Omega_{III}} \boldsymbol{\sigma}(\nabla^s(\mathbf{u}^e), \text{history}) \bullet \nabla^s N^I d\Omega \right) \forall I \mid \mathbf{x}^I \in \Gamma_b$$

Set

$$- \left(\int_{\Omega_{III}} \rho \alpha(x) \ddot{\mathbf{u}}^e N^I d\Omega + \int_{\Omega_{III}} \boldsymbol{\sigma}(\nabla^s(\alpha(x)\mathbf{u}^e), \text{history}) \bullet \nabla^s N^I d\Omega \right)$$

$$\mathbf{F}_{III}^I = \left(\int_{\Omega_{III}} \rho \alpha(x) \ddot{\mathbf{u}}^e N^I d\Omega + \int_{\Omega_{III}} \boldsymbol{\sigma}(\nabla^s(\alpha(x)\mathbf{u}^e), \text{history}) \bullet \nabla^s N^I d\Omega \right) \forall I \mid \mathbf{x}^I \in \text{Int}(\Omega_{III})$$

$$\mathbf{F}_o^I = \left(\int_{\Omega_{III}} \rho \alpha(x) \ddot{\mathbf{u}}^e N^I d\Omega + \int_{\Omega_{III}} \boldsymbol{\sigma}(\nabla^s(\alpha(x)\mathbf{u}^e), \text{history}) \bullet \nabla^s N^I d\Omega \right) \forall I \mid \mathbf{x}^I \in \Gamma_o$$

Then

$$\begin{bmatrix} \mathbf{R}_I \\ \mathbf{R}_b \\ \mathbf{R}_{III} \\ \mathbf{R}_o \\ \mathbf{R}_{II} \\ \mathbf{R}_e \end{bmatrix} = \begin{bmatrix} 0 \\ \mathbf{F}_b \\ \mathbf{F}_{III} \\ \mathbf{F}_o \\ 0 \\ \mathbf{F}_e \end{bmatrix}$$

With $\mathbf{F}_e$ (again) from your favorite absorbing boundary condition

Need to modify the strain definition in the intermediate layer

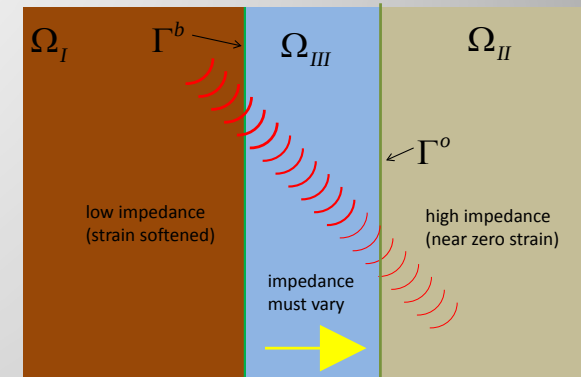
- Define the strain within the intermediate layer as the modified function

$$\varepsilon_{III}(u) = \nabla^s u - (\nabla \alpha(\mathbf{x}) \otimes u^e)^s$$

Then developed strain if $\tilde{u} = \alpha(\mathbf{x})u^e$

$$\begin{aligned}\varepsilon_{III}(\tilde{u}) &= \alpha(\mathbf{x})\nabla^s u^e + (\nabla \alpha(\mathbf{x}) \otimes u^e)^s - (\nabla \alpha(\mathbf{x}) \otimes u^e)^s \\ &= \alpha(\mathbf{x})\nabla^s u^e\end{aligned}$$

Now the strain varies smoothly within Ω_{III} !

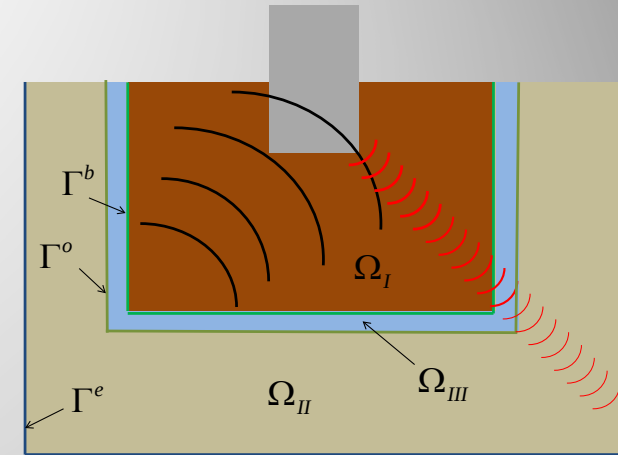


Consistently re-defining the strain in the intermediate layer results in an effective strain (and hence a stress level) that smoothly varies – and hence the impedance will smoothly vary!

Result – the Bielak Method for Nonlinear Materials

For a nonlinear material and the island w/o the structure:

- Recover the exact solution within the inner soil island Ω_I
- Recover the zero-solution in the outer soil island Ω_{II}



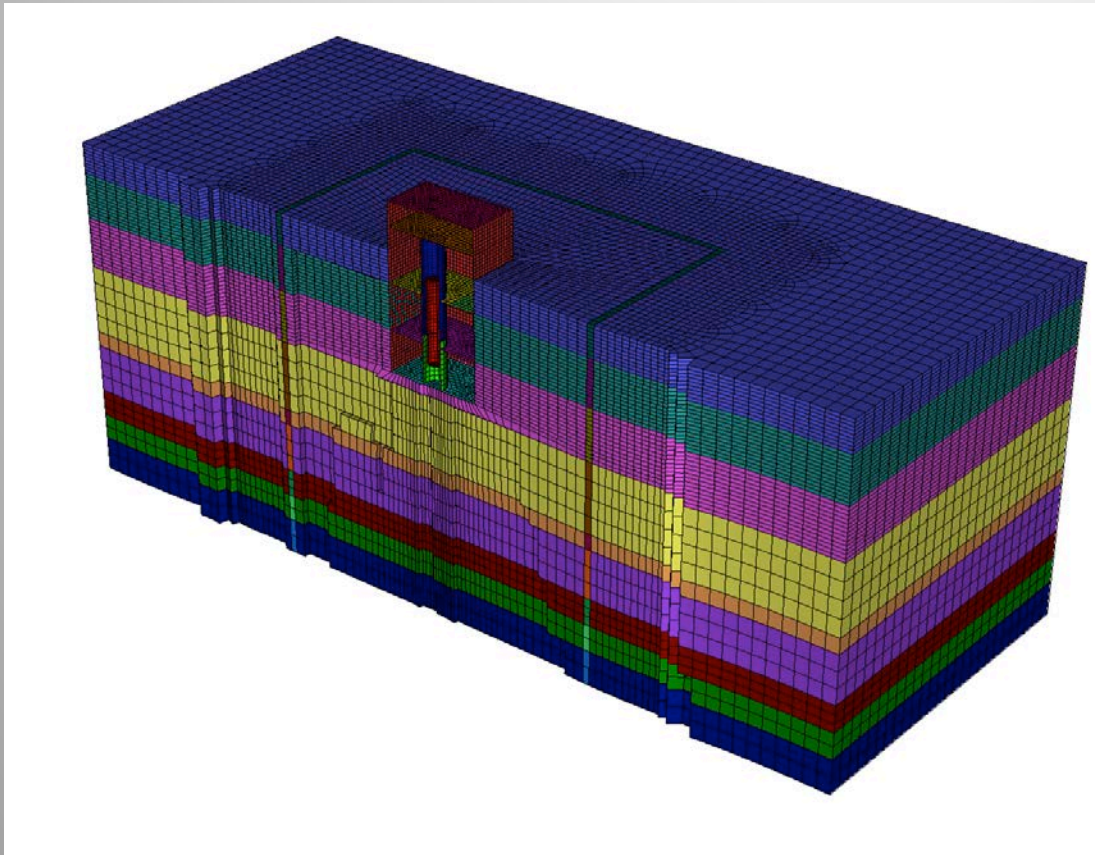
Now insert the structure into the region

- Recover - the perturbed solution within the inner soil island Ω_I
- Recover - the waves scattered by the structure in Ω_{II}
- Impedance varies smoothly in Ω_{III} resulting in no spurious reflections

- The boundary displacement u_e^p will be (again) of small magnitude
- The absorbing boundary condition F_e^p does not have to work very hard

- Have to evolve 3 different history variables in Ω_{II}
 - Corresponding to $u^e, \tilde{u}, u^p$
- Three separate assembly steps per element in Ω_{II}

9-layer Notional Soil profile (Derived from Savannah River Data)



Slice through X symmetry plane

467,140 nodes
444,478 brick elements
132 beam elements
9,542 shell elements

Typical analysis:
16 computer nodes, 128
processors

Implicit, Quasi-Newton solver
3 iterations/step
0.625 ms time step

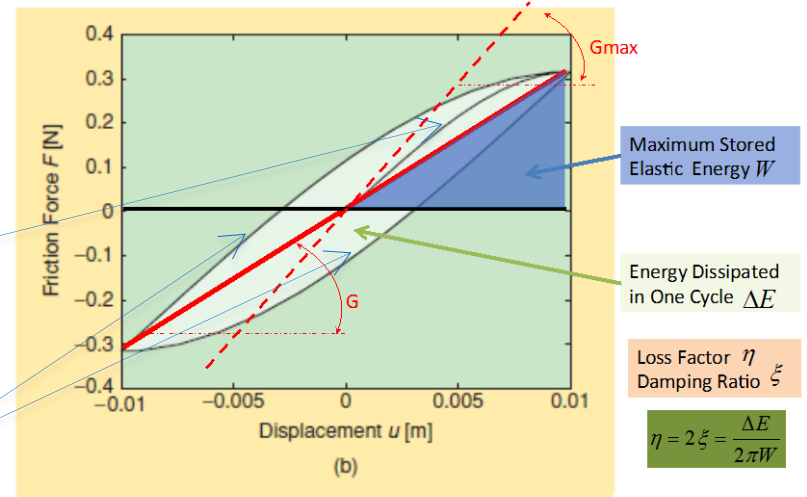
26.2 minutes of “shake time”
requires 12 hours of “wall
time”

Simple Non-Linear Material Model - Ramberg-Osgood

- Ramberg-Osgood (RO) model (Ramberg, 1943)
 - Simple 1D “Masing model” used to model hysteretic response of structures and soils
 - Can match typical hysteretic behavior and shear modulus degradation
 - Nonlinear down to zero strain

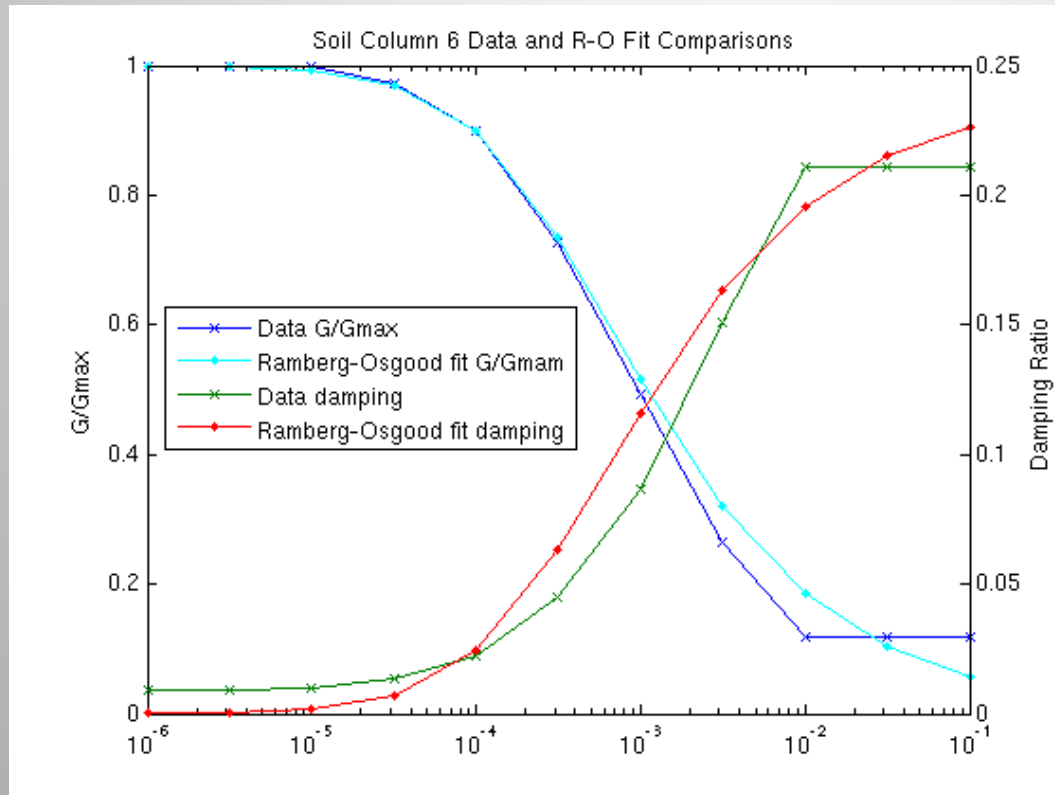
$$\frac{\gamma}{\gamma_y} = \frac{\tau}{\tau_y} \left(1 + \alpha \left| \frac{\tau}{\tau_y} \right|^{r-1} \right) \quad (\text{initial loading})$$

$$\frac{\gamma - \gamma_0}{2\gamma_y} = \frac{\tau - \tau_0}{2\tau_y} \left(1 + \alpha \left| \frac{\tau - \tau_0}{2\tau_y} \right|^{r-1} \right) \quad (\text{subsequent loading and reloading})$$



- An LLNL computer code, RAMBO (Ueng, 1992), is used to match measured EPRI data (G/Gmax and Damping curves) to Ramberg-Osgood coefficients α and r
- Very simple
 - Does not capture pressure-dependence, anisotropy, or cyclic degradation
 - Captures response for 1D vertically propagating shear waves well
 - Good candidate for proof-of-principle match to SASSI data
- Offers a **Proof of Principle** that DIABLO time domain calculations can benchmark to SASSI calculations

Ramberg-Osgood Fits (Using RAMBO) to Savannah River Site Soil-Column Data



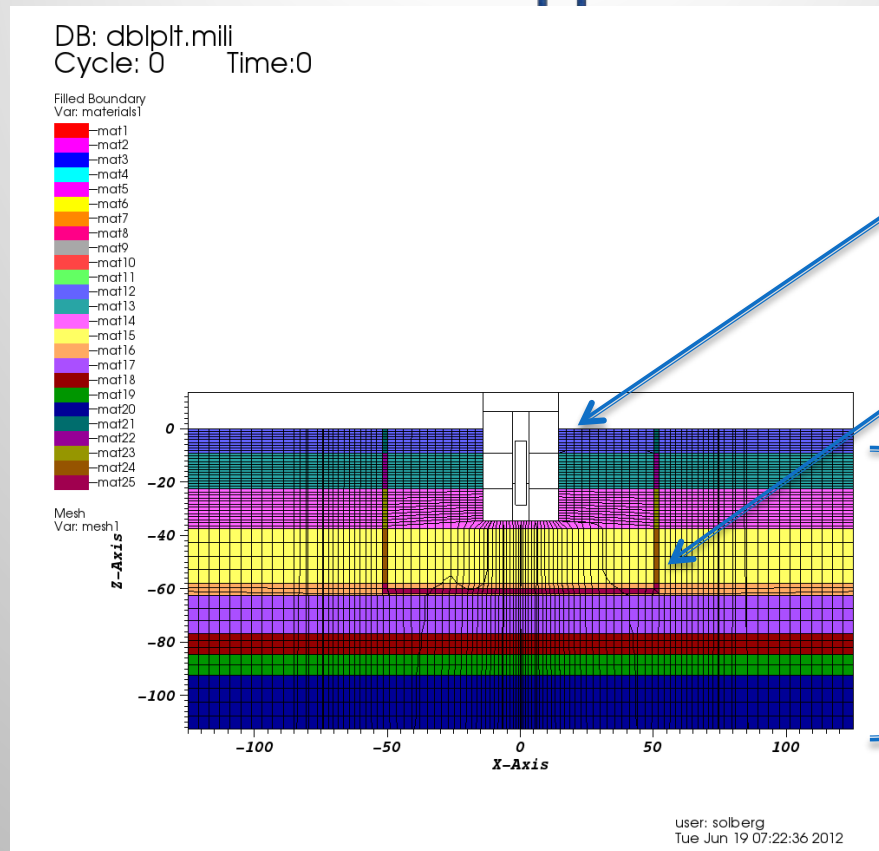
1 of 9 soil layers in the SRS soil column is shown. The other column curve fits have qualitatively similar appearance

- Generally the match is good
- The mismatch of damping at very low strain levels is physically due (at least in part) to viscous effects, which we include separately

Nonlinear Bielak Method Applied to Soil + Reactor - 1

Entire model

- < 500k elements
- Runs overnight



LLNL-developed
Small-Scale Reactor
Model, embedded in Soil

Bielak Layer

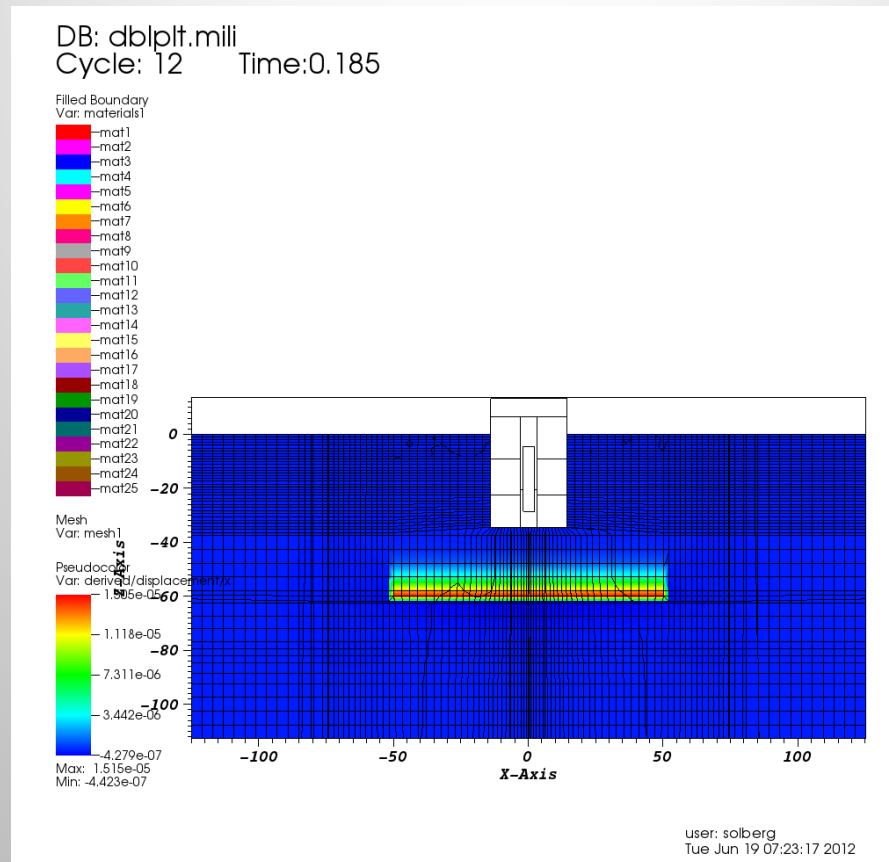
Nine material layers
(matching Savannah
River Site data)

Three nominal earthquake levels applied: 0.2g, 0.5g, 0.9g

Vertical Propagating Shear Wave as the Seismic Source

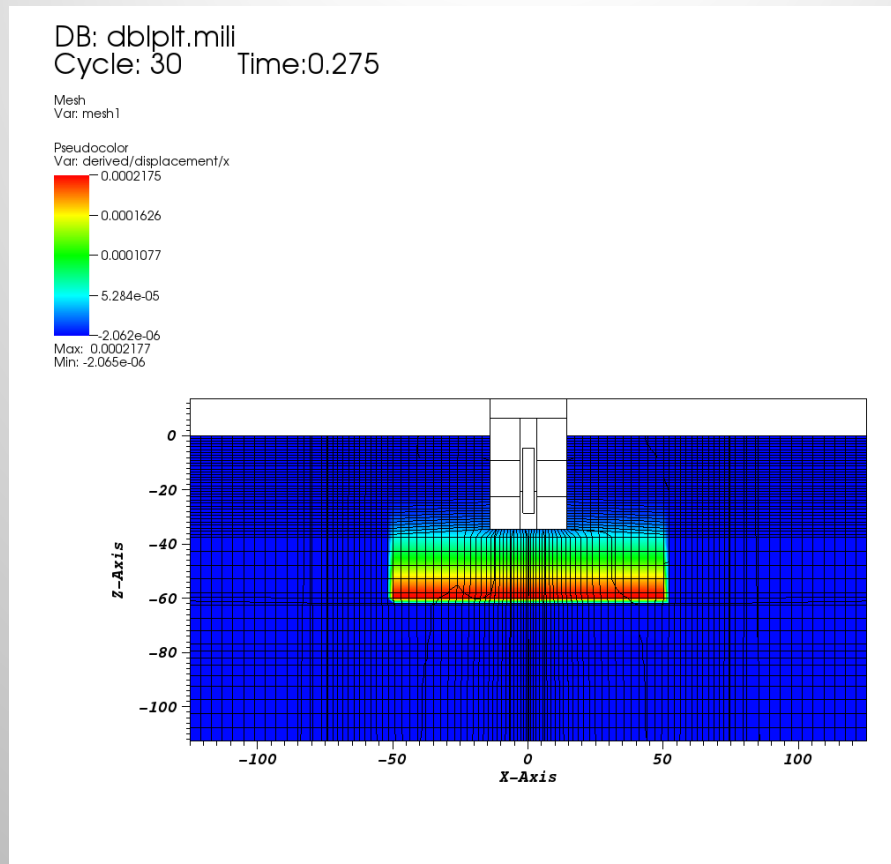
Direct Comparison with equivalent SASSI Runs

Nonlinear Bielak Method Applied to Soil + Reactor - 2



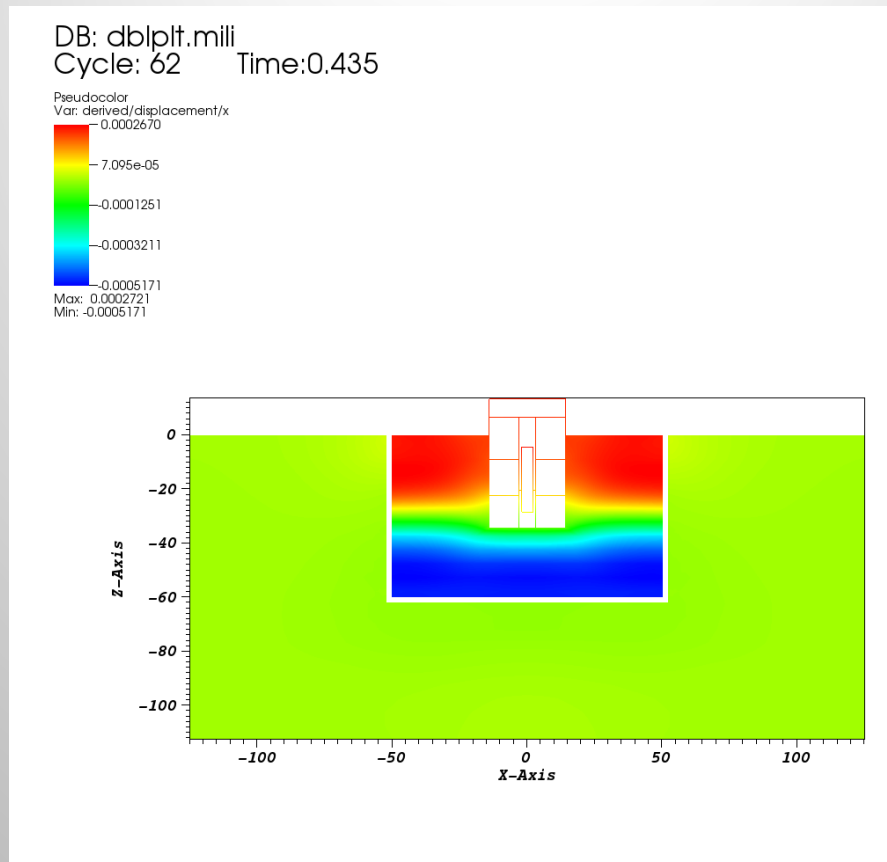
Vertically-propagating shear wave emanates from the base of the Bielak layer uniformly before it reaches the reactor building

Nonlinear Bielak Method Applied to Soil + Reactor - 3



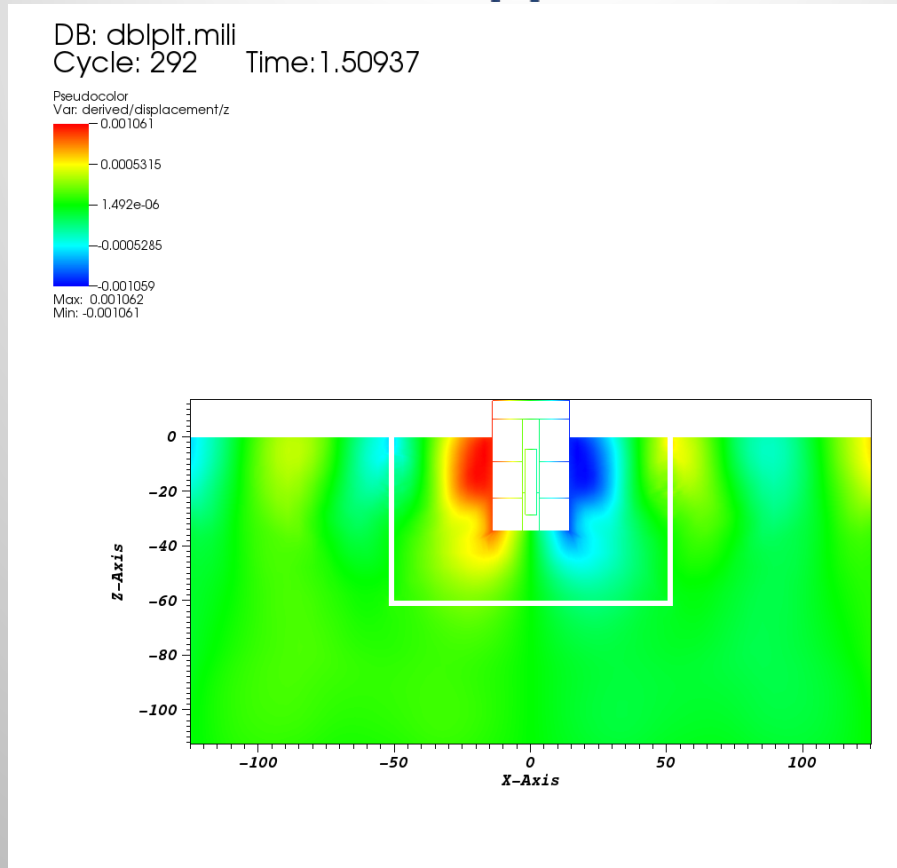
Vertically-propagating shear wave, just as it reaches the reactor building base

Nonlinear Bielak Method Applied to *Soil + Reactor*



Vertically-propagating shear wave disperses even as additional wave peaks/troughs are introduced from the base of the Bielak layer

Nonlinear Bielak Method Applied to *Soil + Reactor*

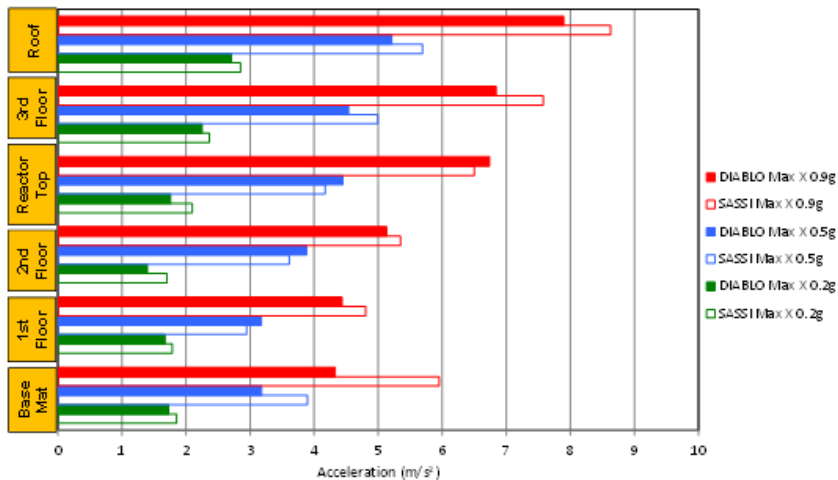


Vertical
(z) displacement
shown

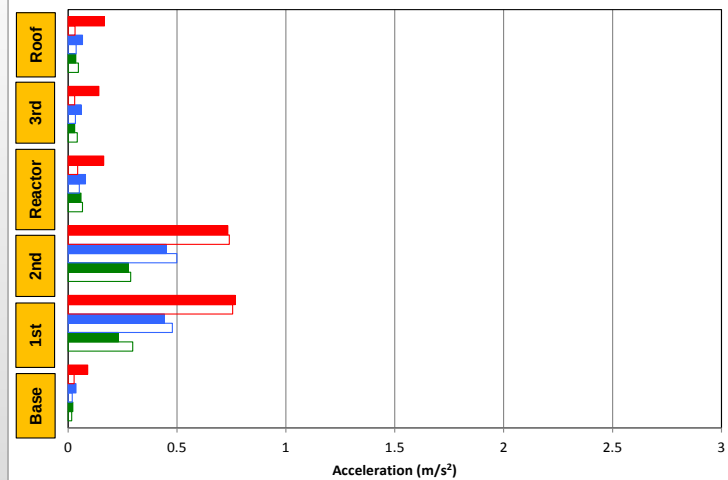
Vertically-propagating shear wave induces a “rocking motion” – z displacement, as it interacts with the reactor – this motion would not be present in the absence of the structure

Peak Accelerations from SASSI and DIABLO

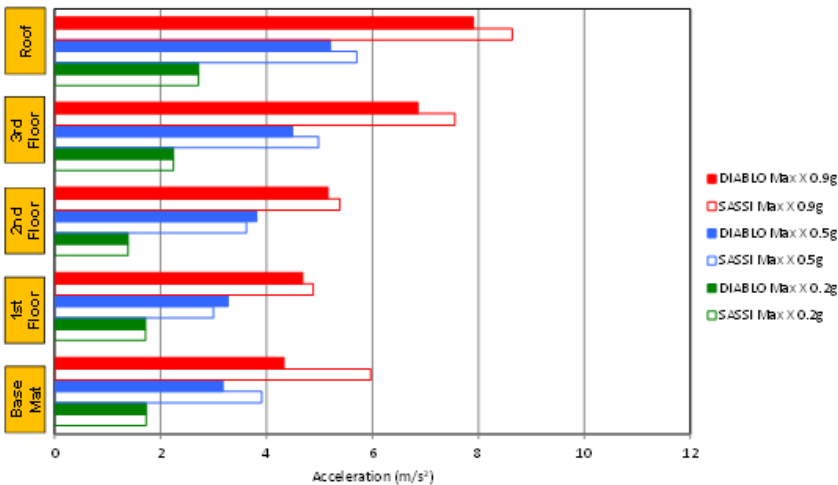
Peak X Accel at Structure Centerline



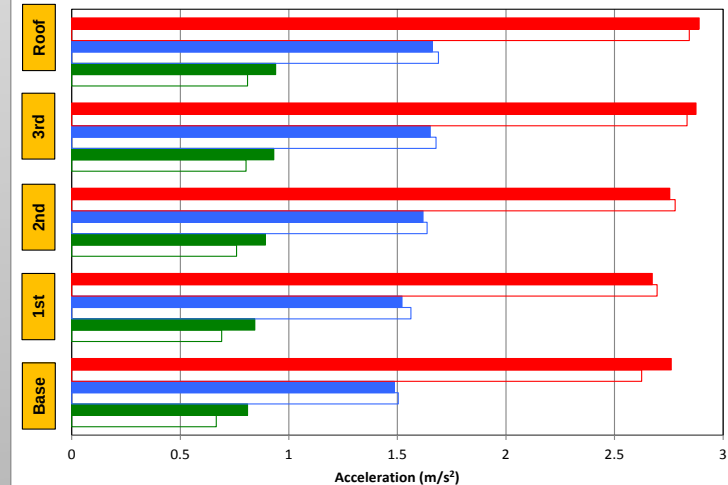
Peak Z Accel at Structure Centerline



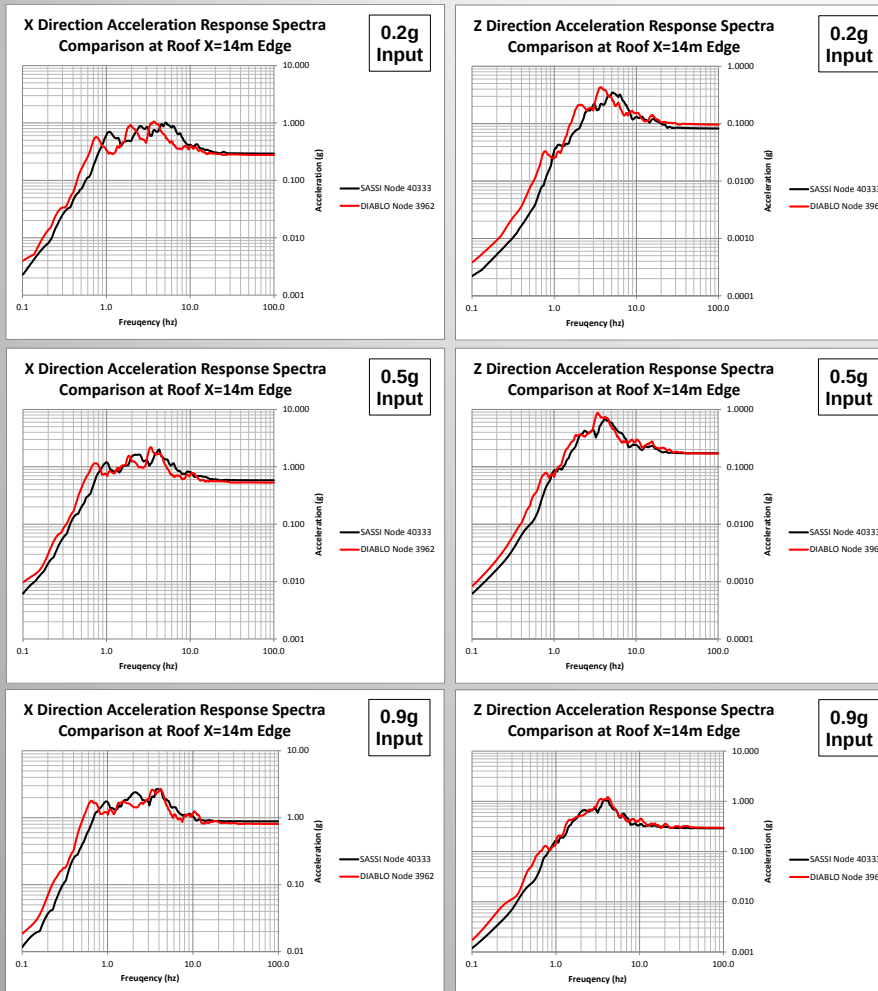
Peak X Accel at Structure Edge (X=14m)



Peak Z Accel at Structure Edge (X=14m)



Comparison with SASSI – Offset Position, Roof



X Direction

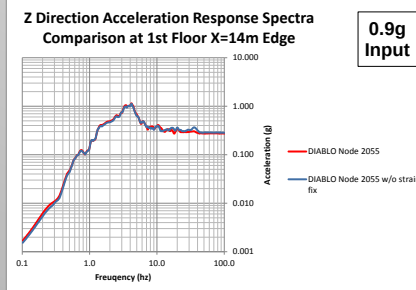
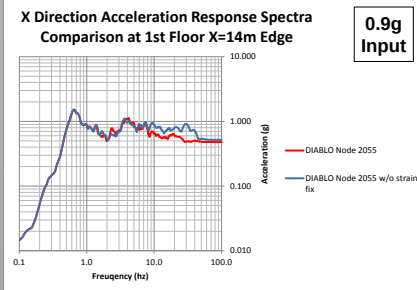
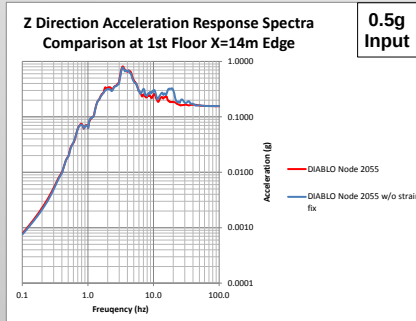
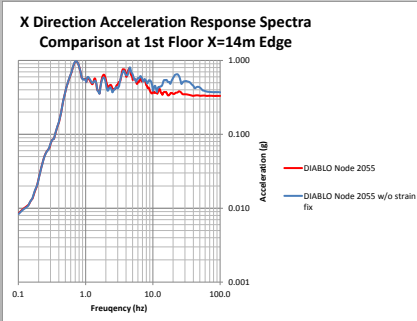
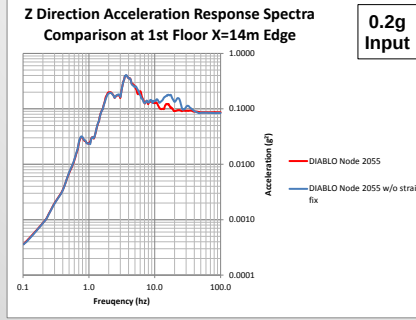
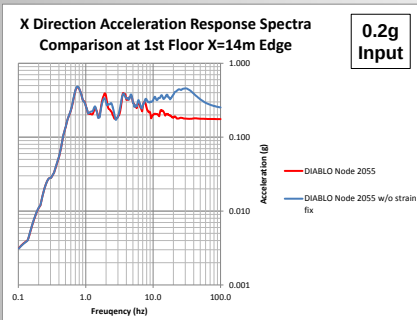
Z Direction

Match is generally good across the board

The magnitudes are generally high at this location

Large rocking motion is evident -> would lead to nonlinear effects at the basemat for pressure-dependent materials

These runs have also demonstrated the value of the improved Bielak method (impedance matching)



X Direction

Z Direction

**Comparison
Offset Position, 1st Floor**

**Improved Bielak Method
(with impedance matching)**

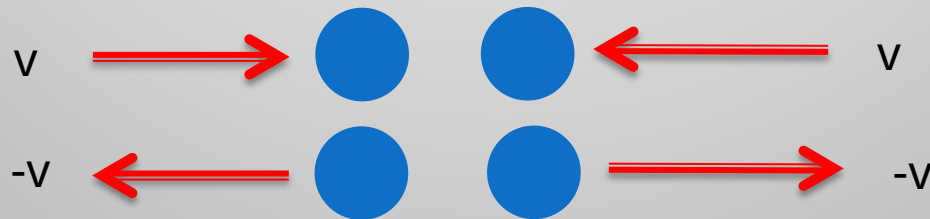
versus

**Nonlinear Version of
“standard” Bielak Method**

**High frequency response is
greater for the “standard” method
– due to spurious wave reflection**

Future work - Contact/Impact Techniques

- Long time duration simulations are most amenable to implicit calculations
- Discrete contact/impact suffers from a well-known pathology: chatter
 - Standard implicit time integration techniques (midpoint, Newmark, HHT) strive to conserve energy (as makes sense for the continuum problem)
 - Independent of the underlying continuum approximation, standard displacement-based techniques result in discrete masses discretized on the boundary (most easily seen in the case of lumped nodal masses, though consistent mass matrices suffer from the same pathology)
 - Conservation of energy requires velocity reversal at impact, leading to chatter



- Elimination of chatter requires specifying an effective “coefficient of restitution” of 0 for the nodal impact
- Time integration techniques emanating from the study of DAE’s (Gear, Petzold, et. al.) are required – application of these to this problem is the focus of current work
- These improvements align also with NEAMS work so have a funding path.

Need – Improved Material Models

- Ramberg-Osgood formulation is overly simplistic
 - Doesn't include pressure dependence
 - Individual shear-stress terms each follow their own Ramberg-Osgood curve
 - Decoupling non-physical
- Desired: A Family of (Nonlinear) Material Models
 - Level 1 – Duplicates SASSI behavior (fixed dissipation)
 - **Level 2 – (Ramberg-Osgood) – Duplicates Modulus & Damping Curves**
 - Level 3 – Pressure Dependence
 - Level 4 – Damage Accumulation & other advanced nonlinearities
 - Level 5 – Coupling with Soil Fluid (Pore Pressure)
- We don't have any funding for material model development in this area currently
 - But are willing to partner

Summary

- Nonlinear Time-Domain analysis has been developed and validated
 - Modified Bielak Method with Impedance Matching
- Can drive soil models which are nonlinear down to zero strain
- Arbitrary input motions (3D input wave fields)
- Excellent comparison to SASSI using very simple nonlinear model
- Path forward to more complex models
 - Important that **traceability** exists to SASSI and other frequency-domain codes
 - Allows for evaluation of the effects of added complexity
- Additional sophistication is on the way (modulo funding/manpower)
 - More complex and realistic soil models
 - Nonlinear structural elements
 - Contact Gap Opening/Closing – the focus of current work
- Acknowledgements:
 - Carl Costantino (BNL) for SHAKE runs
 - Jinsuo Nie (BNL) for SASSI runs
 - Boris Jeremic (UCD) for conversations/advice that inspired this work