The Real-ESSI Simulator System

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Outline

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Motivation

Improve modeling and simulation for infrastructure objects

Reduction of modeling uncertainty

Choice of analysis level of sophistication

Goal: Predict and Inform rather than fit

Engineer needs to know!

Hypothesis

- Interplay of the Earthquake, Soil/Rock and Structure in time domain, plays a major role in successes and failures
- Timing and spatial location of energy dissipation determines location and amount of damage
- If timing and spatial location of the energy dissipation can be controlled (directed), we could optimize soil structure system for
  - Safety
  - Economy

ESSI: Energy Input and Dissipation

Energy input, dynamic forcing

Energy dissipation outside SSI domain:
- SSI system oscillation radiation
- Reflected wave radiation

Energy dissipation/conversion inside SSI domain:
- Inelasticity of soil, contact/interface zone, structure, foundation, dissipators
- Viscous coupling, porous solid-pore fluids, solids/structures-external fluids

Numerical, algorithmic energy dissipation/production

Prediction under Uncertainty

- Modeling Uncertainty, Simplifying assumptions

  Low, medium, high sophistication modeling and simulation

  Choice of sophistication level for confidence in results

- Parametric Uncertainty, $M\ddot{u}_i + C\dot{u}_i + K^{ep} u_i = F(t)$,

  Uncertain mass M, viscous damping C and stiffness K^{ep}

  Propagation of uncertainty in loads, $F(t)$

  Results are PDFs and CDFs for σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$

Goal: Reduction of Modeling Uncertainty

- Modeling Uncertainty: introduced with unnecessary and unrealistic modeling simplification
- Simplified (or inadequate/wrong) modeling: important features are missed (3C (6C) seismic ground motions, inelasticity, etc.)
- Modeling simplifications are justifiable if one, two or higher level sophistication model demonstrates that features being simplified out are not important
- Use of HPC for low modeling uncertainty and direct probabilistic modeling and simulations

Fully Coupled Formulation, u-p-U

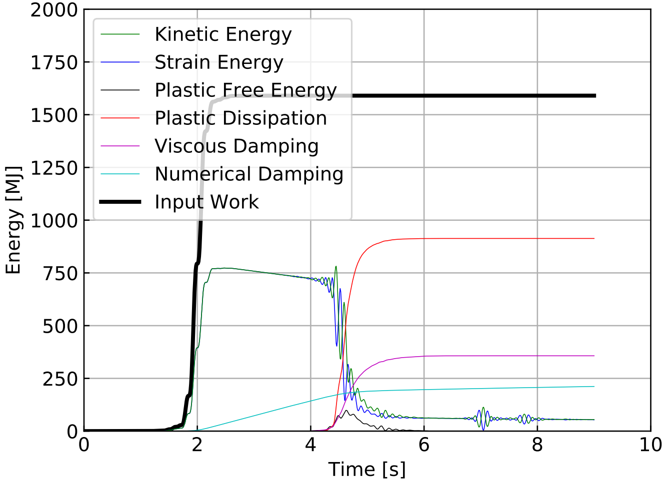
$$
\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix}
\begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_{N} \\ \ddot{\bar{U}}_{Lj} \end{bmatrix}
+
\begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix}
\begin{bmatrix} \dot{\bar{u}}_{Lj} \\ \dot{\bar{p}}_{N} \\ \dot{\bar{U}}_{Lj} \end{bmatrix}
$$

$$
+
\begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\ -(G_1)_{LjM} & -P_{MN} & -(G_2)_{LjM} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix}
\begin{bmatrix} \bar{u}_{Lj} \\ \bar{p}_{M} \\ \bar{U}_{Lj} \end{bmatrix}
=
\begin{bmatrix} \bar{f}^{solid}_{Ki} \\ 0 \\ \bar{f}^{fluid}_{Ki} \end{bmatrix}
$$

Fully Coupled Formulation, u-p-U

$$
\begin{aligned}
(M_s)_{KijL} &= \int_\Omega H_K^u (1-n)\rho_s \delta_{ij} H_L^u d\Omega \quad (M_f)_{KijL} = \int_\Omega H_K^U n \rho_f \delta_{ij} H_L^U d\Omega \\
(C_1)_{KijL} &= \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^u d\Omega \quad (C_2)_{KijL} = \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^U d\Omega \\
(C_3)_{KijL} &= \int_\Omega H_K^U n^2 k_{ij}^{-1} H_L^U d\Omega \quad (K^{EP})_{KijL} = \int_\Omega H_{K,m}^u D_{imjn} H_{L,n}^u d\Omega \\
(G_1)_{KiM} &= \int_\Omega H_{K,i}^u (\alpha - n) H_M^p d\Omega \quad (G_2)_{KiM} = \int_\Omega n H_{K,i}^U H_M^p d\Omega \\
P_{NM} &= \int_\Omega H_N^p \frac{1}{Q} H_M^p d\Omega
\end{aligned}
$$

Energy Dissipation Control



Outline

Real-ESSI Simulator System

The Real-ESSI, **Real**istic Modeling and Simulation of **E**arthquakes, **S**oils, **S**tructures and their **I**nteraction Simulator is a software, hardware and documentation system for time domain, linear and nonlinear, elastic and inelastic, deterministic or probabilistic, 3D, modeling and simulation of:

- statics and dynamics of soil,
- statics and dynamics of rock,
- statics and dynamics of structures,
- statics of soil-structure systems, and
- dynamics of earthquake-soil-structure system interaction

Used for:

- Design, linear elastic, load combinations, dimensioning
- Assessment, nonlinear/inelastic, safety margins

Real-ESSI Simulator System

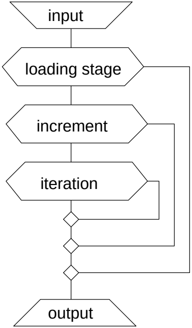
- Real-ESSI System Components
  - Real-ESSI Pre-processor (gmsh/gmESSI, X2ESSI)
  - Real-ESSI Program (local, remote, cloud)
  - Real-ESSI Post-Processor (Paraview/pvESSI, Python)
- Real-ESSI System availability: Linux Executables, AWS, DesignSafe/TACC
- Real-ESSI education and training: theory and applications
- Real-ESSI documentation and program available at `http://real-essi.info/`

Real-ESSI Modeling Features

- Solid elements: dry, (un-)saturated, elastic, inelastic
- Structural elements: beams, shells, elastic, inelastic
- Contact/interface/joint elements: Bonded, Shear/Frictional (EPP, EPH, EPS); Gap/Normal; linear, nonlinear, dry, coupled/saturated,
- Super element: stiffness and mass matrices
- Material models: soil, rock, concrete, steel...
- Seismic input: 1C and 3C, deterministic or probabilistic
- Energy dissipation: elastic-plastic, viscous, algorithmic
- Solid/Structure-Fluid interaction, full coupling, OpenFOAM
- Intrusive probabilistic inelastic modeling

Real-ESSI Simulation Features

- Static loading stages
- Dynamic loading stages
- Restart, simulation tree
- Solution advancement methods/algorithms, on global and constitutive levels, with and without enforcing equilibrium
- High Performance Computing
  - Fine grained, template mataprograms, small matrix library
  - Coarse grained, distributed memory parallel



Real ESSI Simulator: Domain Specific Language, DSL

- Domain Specific Language (DSL), Yacc & Lex
- English like modeling and simulation language
- Parser and compiler, can define functions, models, etc.
- Can extend models and methods
- Requires units!

DSL: English Language Binding Modeling Parser

```
// Defining variables
x = 7; // x is double−valued variable with adimenisional units.
y = 3.972e+2; // Decimal and scientific notation is supported.
// Operations: All standard arithmetic operations (Unites!)
a = x + y; // Addition
b = x − y; // Subtraction
c = x*y; // Product
d = x/y; // Quotient
e = y%x; // Modulus (how many times x fits in y)
// Predefined variables. For example, the variable 'm' defines 'meter'.
L1 = 1*m;
L2 = 40*mm; // Defines L2 to be 40 millimiters.
L3 = 3.14*cm;
L4 = 3.14;
A5 = 3.14*cm^2;
```

DSL: English Language Modeling Parser

```
F1 = 10*kN; // Define few forces.
F2 = 300*N;
F3 = 4*kg*g; // Here g is the predefined acceleration
                    // due to gravity.
// Operations are sensitive to units. For example,
foo = L1 + F1; // Produces an error because units are
                       // not compatible. However,
L4 = L1 + L2 + L3; // is OK.
// Multiplication (division and modulus) always work
// because the result produces a quantity with new units
// (except when the adimensional quantity is involved).
A = L1*L2;
pressure = F1 / A;
// All numbers are converted to SI units (kg − m − s)
// and internally stored in that system.
```

DSL: ESSI Input Language, Basics

- Angle brackets `<>` denotes user input
- Expected unit (dimension) is given (example: `<L>`, for length unit)
- Symbol `<.>` represents the adimensional quantity.
- Vertical bar `|` (“OR” sign)) is used to separate two or more keyword options, i.e. `[a|b|c]` is used indicate keyword options `a` or `b` or `c`.
- The symbol `|...|` is used to denote where several long options exist and are explained elsewhere (an example of this is available below in a material model definitions).

DSL: ESSI Input Language, Units

All commands require unit consistency. Base units, SI or other (British Imperial) can be used

- length, symbol L, units [m, in, ft]
- mass, symbol M, units [kg, lb],
- time, symbol T, units [s]

Derived units can also be used:

- angle, symbol rad (radian), unit [$dimensionless, L/L$]
- force, symbol N (Newton), units [$N, kN, MN, M * L/T^2$],
- stress, symbol Pa (Pascal), units [$Pa, kPa, MPa, N/L^2, M/L/T^2$]
- strain, symbol (no symbol), units [L/L]
- mass density, symbol (no symbol), units [M/L^3]
- force density, symbol (no symbol), units [$M/L^2/T^2$]

DSL: ESSI Input Language, Loading Stages

Start a new loading stage with

new `loading stage` "loading_stage_name";

Example, starting a new loading stage called *"self weight load"*

new `loading stage` "self weight load";

DSL: Beam Example, Model

Real ESSI DSL Example

```
model name "SmallTestModel";
new loading stage "First_static";
// Nodal Coordinates
add node # 1 at (0*m, 0*m, 0*m) with 6 dofs;
add node # 2 at (0*m, 0*m, 1*m) with 6 dofs;
add element # 1 type beam_elastic with
  nodes (1, 2) cross_section=1.0*m^2
  elastic_modulus=1.0e5*KN/m^2
  shear_modulus=2.0e4*KN/m^2
  torsion_Jx=2*0.083*m^4
  bending_Iy=0.083*m^4 bending_Iz=0.083*m^4
  mass_density=2500.0*kg/m^3
  xz_plane_vector = (0, -1, 0)
  joint_1_offset = (0.0*m, 0.0*m, 0.0*m)
  joint_2_offset = (0.0*m, 0.0*m, 0.0*m);
```

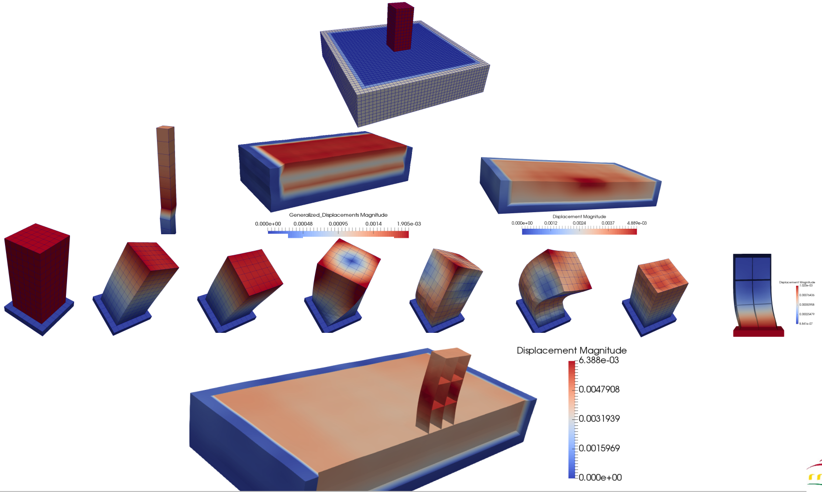
Real ESSI DSL Example

```
fix node No 1 dofs all;
add load # 1 to node # 2 type
  linear Fx=−9*kN;
define load factor increment 0.01;

define solver UMFPack;
define convergence test
  Norm_Displacement_Increment
  tolerance = 1e−5
  maximum_iterations = 20
  verbose_level = 4;
define algorithm Newton;
simulate 100 steps using static algorithm;

bye;
```

Real-ESSI Model Development

- Pre-Processing, model development gmsh/gmESSI
- Existing model translation, SASSI→Real-ESSI
- Self documenting input language
- Units required for all input variables
- All variables and constants need to be defined by user
- Sophistication level of choice
- Model developed in phases
- Verify model components
- Build confidence in inelastic modeling

Real-ESSI Modeling Phases



Real-ESSI Results Post Processing

- All output is saved (stress, strain, displacements, energy...)
- Time histories, scripts to plot or extract in preferred format
- 3D visualization, Paraview with pvESSI plugin

Real-ESSI Core Functionality

- Introduction to inelastic, nonlinear analysis for practicing engineers
- Use of prescribed, required (low, medium, high) fidelity numerical models to analyze ESSI behavior
- Set of suggested modeling and simulation parameters
- Investigate sensitivity of response to model sophistication
- Investigate sensitivity of response to model parameters

Real-ESSI Core Functionality Components

- Structural elements: Truss, Beam, Shell, Super-Element
- Soil, solids: elastic, G/G_{max}
- Contacts/interfaces/joints: Bonded, Frictional (EPP, EPH, EPS), Gap open/close
- Loads: Static, Dynamic (earthquake, 1C or $3\times$1C), Restart
- Simulation: Explicit no-equilibrium, Implicit equilibrium
- Core Functionality Application programs: APPs

Real-ESSI Education and Training

- Real-ESSI Eduction
  - Online courses
  - Educational short videos
  - Professional practice
  - Practical examples available in lecture notes, and documentation
  - Documentation, Lecture Notes: (I) Theory and Computational Formulation, (II) Software and Hardware System, (III) Verification and Validation, (IV) Modeling and Simulation Examples, (V) Application to Practical Engineering Problems.
- Lecture notes available online through `http://real-essi.info/`

Outline

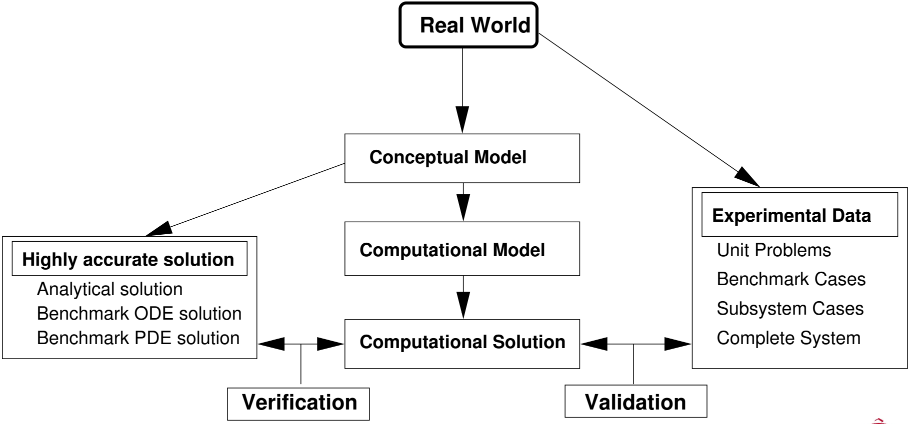
Verification and Validation

- Verification: provides evidence that the model is solved correctly. Mathematics issue. Well developed for the Real ESSI Simulator.
- Validation: provides evidence that the correct model is solved. Physics issue. Work in progress, US-DOE project.
- Prediction: use of computational model to foretell the state of a physical system under consideration under conditions for which the computational model has not been validated.

V & V Motivation

- How much can (should) we trust model implementations (verification)?
- How much can (should) we trust numerical simulations (validation)?
- How good are our numerical predictions?
- Can simulation tools be used for improving safety and economy?
- V & V procedures are the primary means of assessing accuracy in modeling and computational simulations
- V & V procedures are the tools with which we build confidence and credibility in modeling and computational simulations

Fundamentals of Verification and Validation



Important Sources

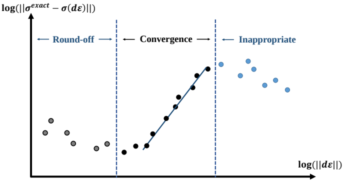
- W. L. OBERKAMPF, T. G. TRUCANO, AND C. HIRSCH. Verification, validation and predictive capability in computational engineering and physics. In Proceedings of the Foundations for Verification and Validation on the 21st Century Workshop, pages 1–74, Laurel, Maryland, October 22-23 2002. Johns Hopkins University / Applied Physics Laboratory.
- P. J. ROACHE. Verification and Validation in Computational Science and Engineering. Hermosa publishers, 1998. ISBN 0-913478-08-3.
- William L. Oberkampf and Christopher J. Roy. Verification and Validation in Scientific Computing. Cambridge University Press, 2010.

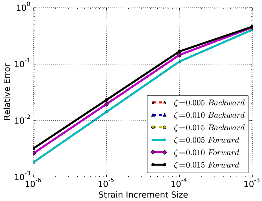
Verification

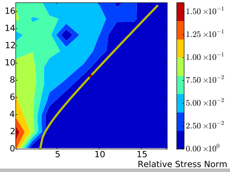
- Source code management
- Source code verification
- Constitutive integration
- Static and dynamic behavior of single phase solids
- Static and dynamic behavior of fully and partially saturated, fully coupled, porous solid-pore fluid problems
- Static and dynamic behavior of structural elements
- Static and dynamic behavior of special elements (contacts-interface/gap-frictional/dry-saturated, isolators/dissipators)
- Static and dynamic FEM solution advancement
- Seismic wave propagation problems
- FEM Model verification, hierarchy of models

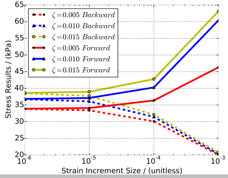
Constitutive Integration Verification

- Asymptotic regime of convergence
- Richardson extrapolation
- Grid convergence index

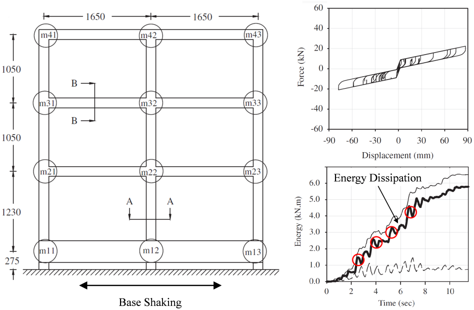








Energy Dissipation Verification: Plastic Work $\neq$ Plastic Dissipation



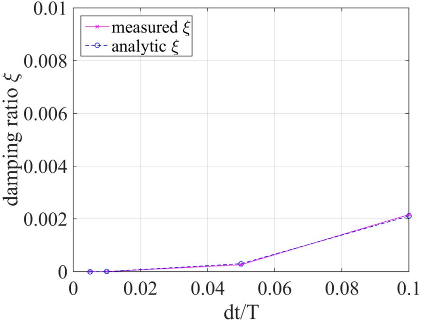
From a paper on *Soil Dynamics and Earthquake Engineering* (2011)

Direct violation of the second law of thermodynamics
600 papers since 1990 (!?!) repeat this error

Dynamic Time Stepping Verification

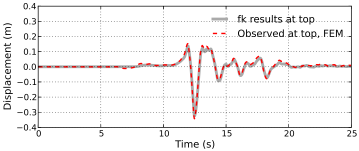
Based on the amplification matrix **A**, to calculate the analytical solution of damping ratios and period shift.

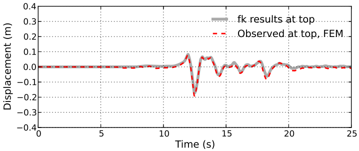
Example: Hilber-Hughes-Taylor $\alpha = -0.1$

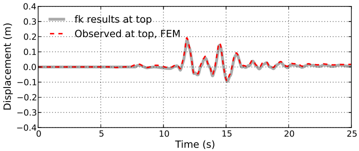


0.05

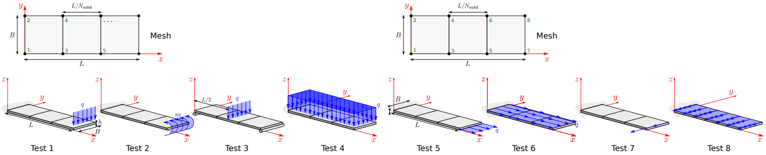
Seismic Input Verification, DRM



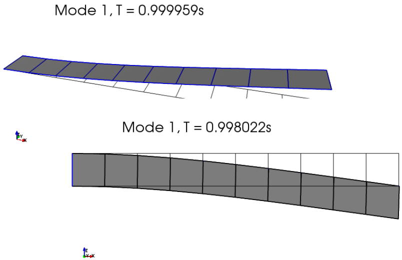




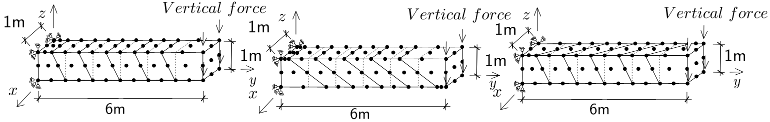
Verification: ANDES Shell



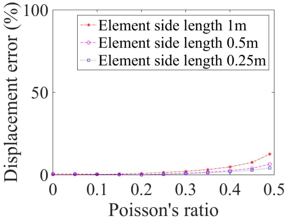
N_{subd}	u_z
2	96.2118
7	100.096
101	100.002



Verification: Irregular Solids and Poisson's Ratio

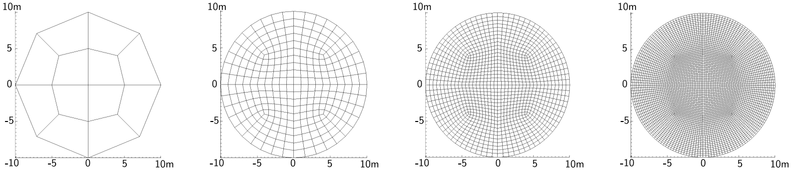


Force direction	Shape 1	Shape 2	Shape 3
Vertical (z)	0.40%	0.85%	0.60%
Transverse (y)	0.54%	3.67%	0.46%

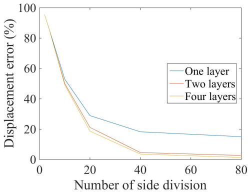


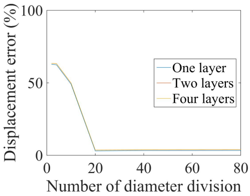
Poisson's ratio	27NodeBrick displacement	Theory displacement	Error
0.00	8.797E-04 m	8.784E-04 m	0.15%
0.05	8.801E-04 m	8.791E-04 m	0.11%
0.10	8.799E-04 m	8.799E-04 m	0.01%
0.15	8.792E-04 m	8.806E-04 m	0.16%
0.20	8.778E-04 m	8.813E-04 m	0.40%
0.25	8.758E-04 m	8.821E-04 m	0.71%
0.30	8.730E-04 m	8.828E-04 m	1.12%
0.35	8.692E-04 m	8.836E-04 m	1.63%
0.40	8.641E-04 m	8.844E-04 m	2.29%
0.45	8.567E-04 m	8.851E-04 m	3.21%
0.49	8.452E-04 m	8.857E-04 m	4.58%

Verification of Solid Shell/Plate

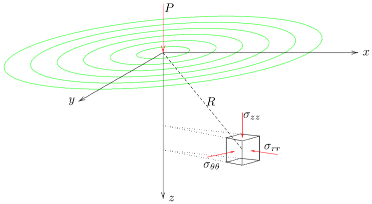


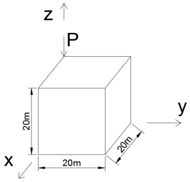
- Simply supported and clamped ends
- Timoshenko's analytic solutions

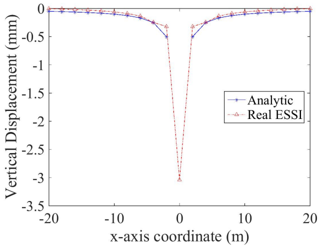


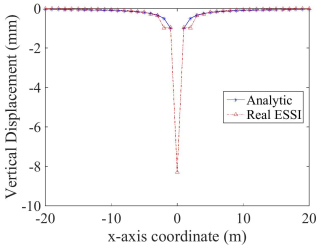


Verification of Boussinesq Problem

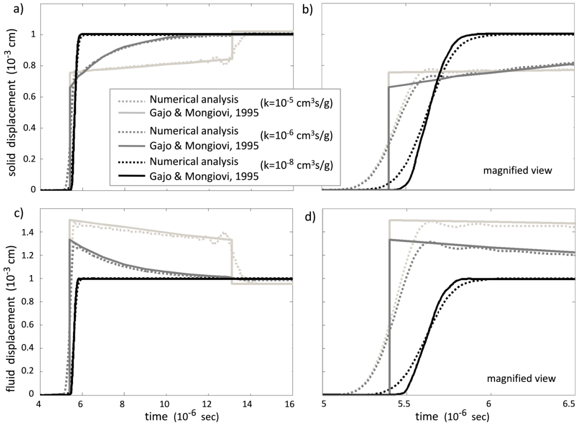




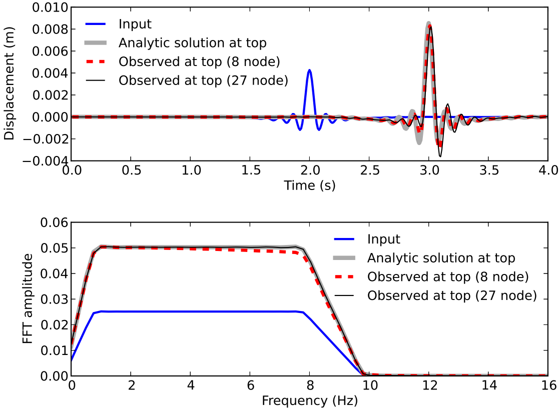




Verification for Fully Coupled Problems

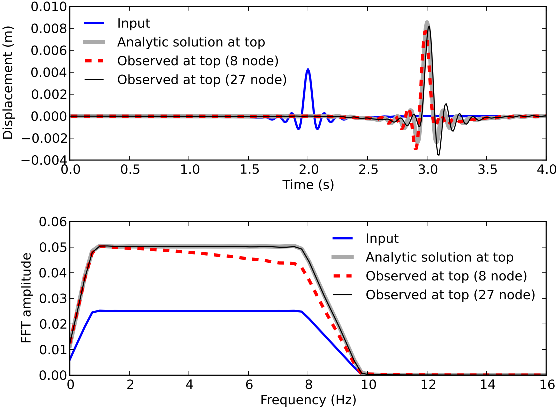


Wave Propagation, Mesh Size Effects



(Case 1, Vs = 1000 m/s, Cutoff Fq. = 8 Hz, E. Size = 10 m)

Wave Propagation, Mesh Size Effects



(Case 1, Vs = 1000 m/s, Cutoff Fq. = 8 Hz, E. Size = 20 m)

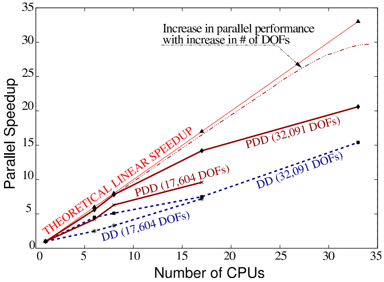
V & V Summary

- V&V most important for providing confidence in results
- Numerical modeling program(s) should not be used without extensive/full V&V
- V&V of FEM models is also essential
- Real ESSI Simulator has an extensive Verification database, and a smaller Validation database

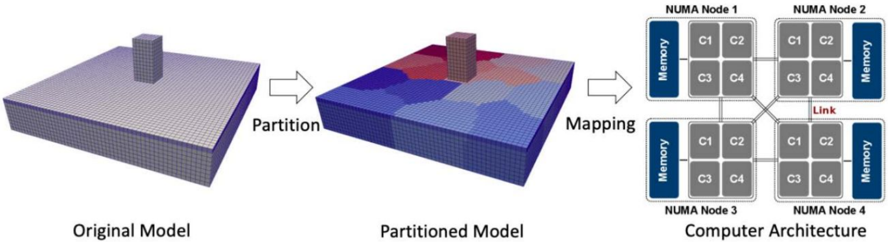
Outline

Course Grained and Fine Grained HPC

- Hardware Aware Plastic Domain Decomposition (HAPDD) Method
- Small Tensor Library

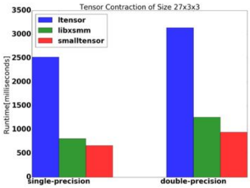


HAPDD

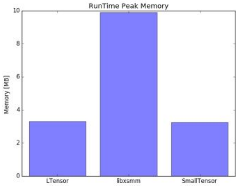

Partition
Mapping
NUMA Node 1
NUMA Node 2
NUMA Node 3
NUMA Node 4
Memory
C1
C2
C3
C4
Link
Original Model
Partitioned Model
Computer Architecture

Small Tensor Library

- Benchmark Libraries
  - **LTensor** – Target library
  - **LIBXSMM** – State-of-Art Small Linear Algebra for Machine Learning.
  - **SmallTensor** – Our Small Tensor Library for Computational Mechanics.
- Runtime Performance Comparison



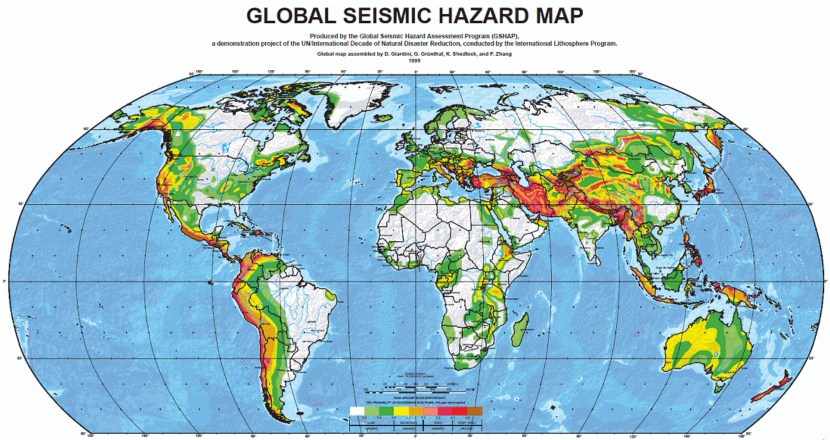
Runtime Performance



Peak Memory Usage

Outline

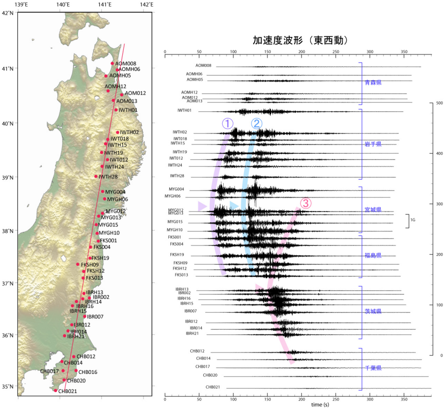
Seismic Hazard, World

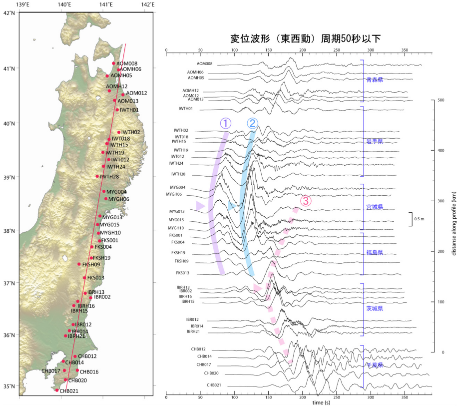


Earthquake Ground Motions

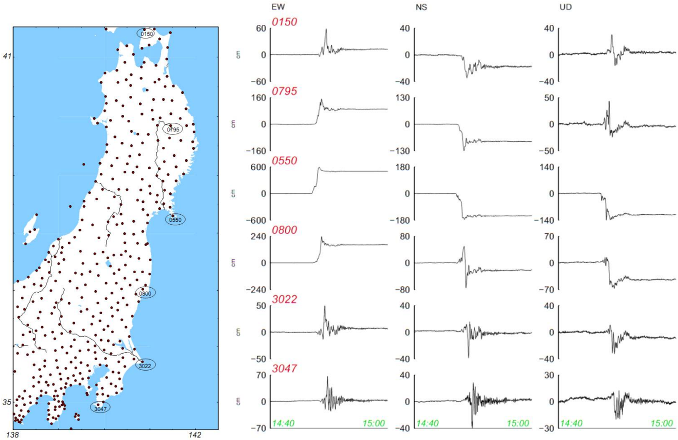
- Real earthquake ground motions
  - Body, P and S waves
  - Surface, Rayleigh and Love waves
  - Lack of correlation, incoherent motions
  - Inclined waves
  - 3D/6D waves
- What are the effects of real earthquake ground motions on soil-structure systems ?!

Tohoku Earthquake, Acc, Disp





ohoku Earthquake, 3D Motions

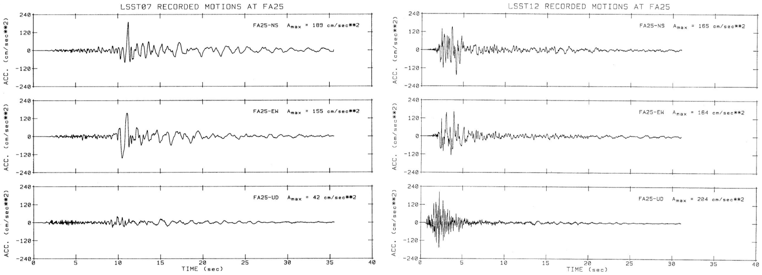


1C, 2C, 3C, 6C Seismic Motions

- All (most) measured motions are full 3C, 6C
- What is the effect of neglecting, simplifying out to 1C
- One example of an almost 2C motion (LSST07, LSST12)

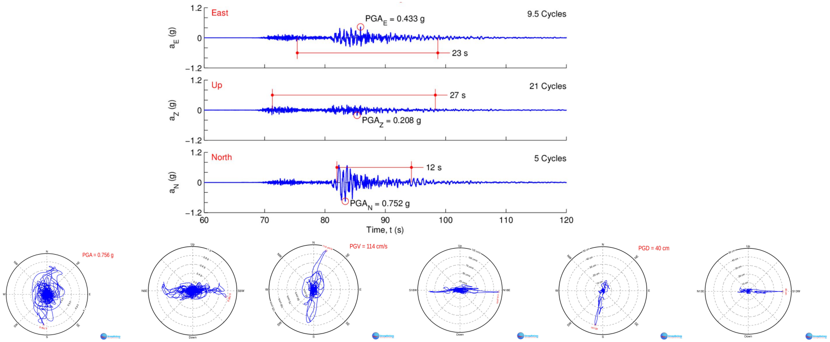
Lotung, Taiwan ('86) Motions

- Example of 2C motion (?), LSST07, LSST12



San Pablo, Guatemala (2017) Motions

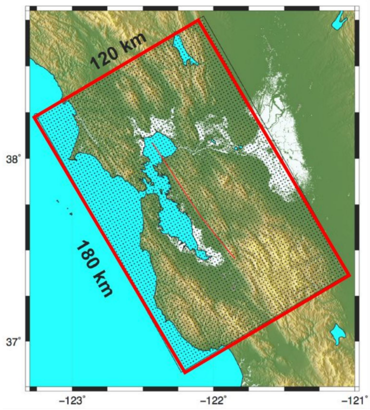
data from `http://www.strongmotioncenter.org/`

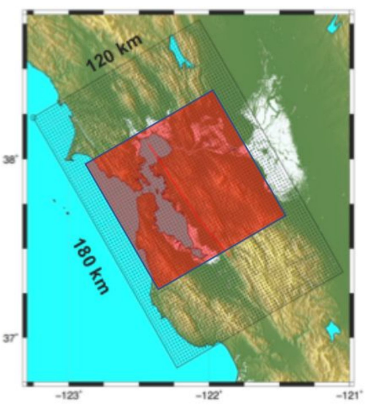


Regional Geophysical Models

- Free Field seismic motions on regional scale
- Knowledge of geology (deep and shallow) needed
- Developed using SW4 and/or Real-ESSI
- Collaboration with LLNL: Dr. Rodgers, Dr. Pitarka and Dr. Petersson

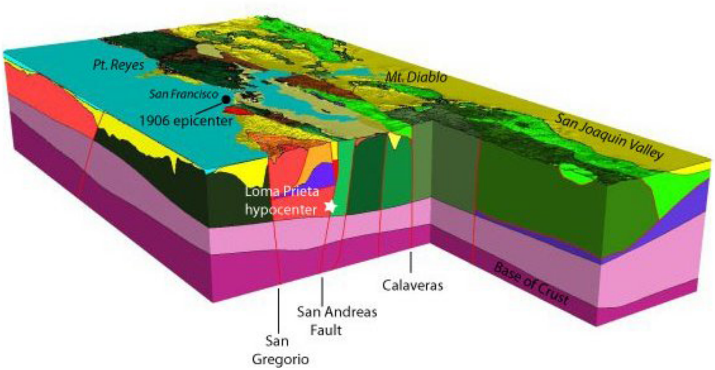
Regional Geophysical Models





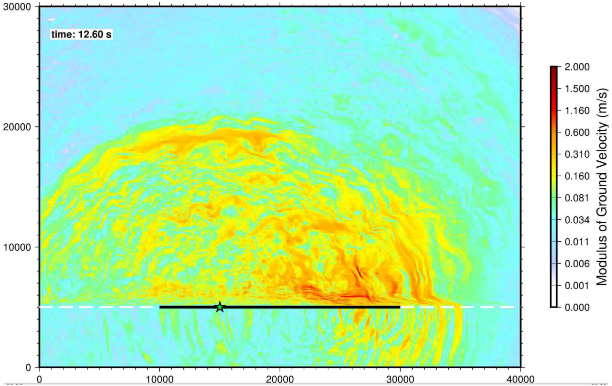
Rodgers and Pitarka

Regional Geophysical Models



USGS

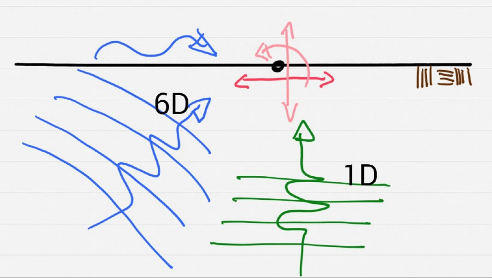
Example Regional Model (Rodgers)



(MP4)

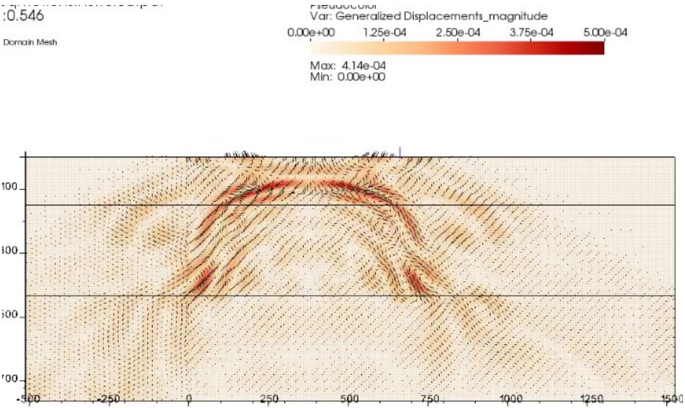
ESSI: 6C or 1C Seismic Motions

- Assume that a full 6C (3C) motions at the surface are only recorded in one horizontal direction
- From such recorded motions one can develop a vertically propagating shear wave (1C) in 1D
- Apply such vertically propagating shear wave to same soil-structure system



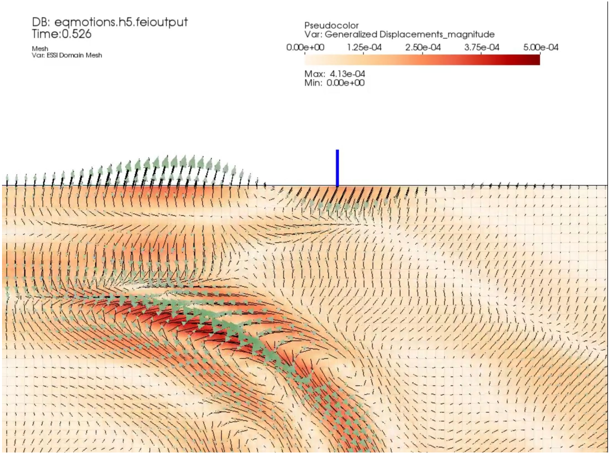
Realistic Ground Motions

- Free field seismic motion models



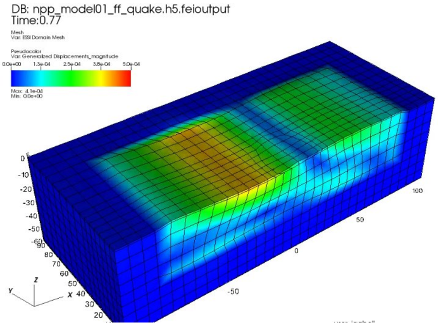
Development of Realistic Motions

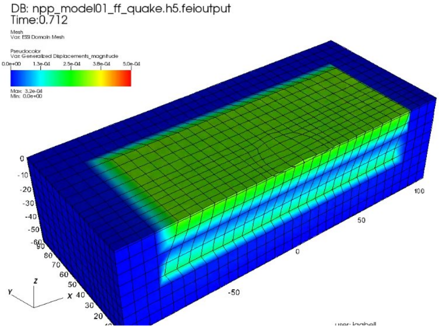
- Sources will send both P and S waves



1C vs 6C Free Field Motions

- One component of motions, 1C from 6C
- Excellent fit





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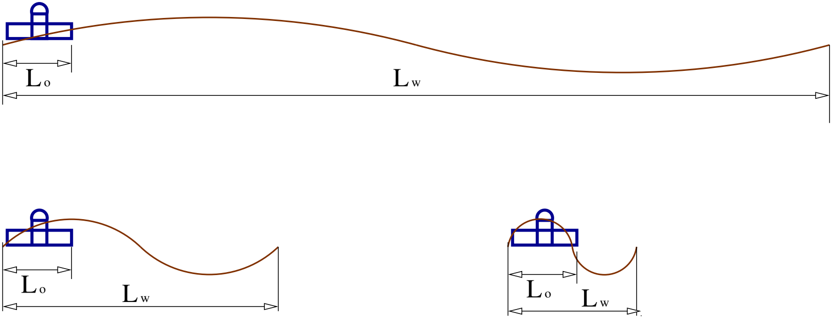
1C vs 3×1C vs 3C Seismic Motions

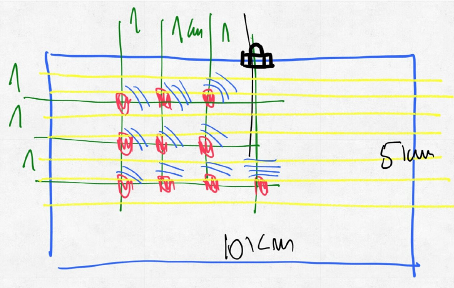
- 1C is required by the code
- 3×1C can be used depending on frequency/wave length of interest,
- 3C is more realistic, however it is challenging to define motions in full 3C

When to use 3C and/or 3×1C

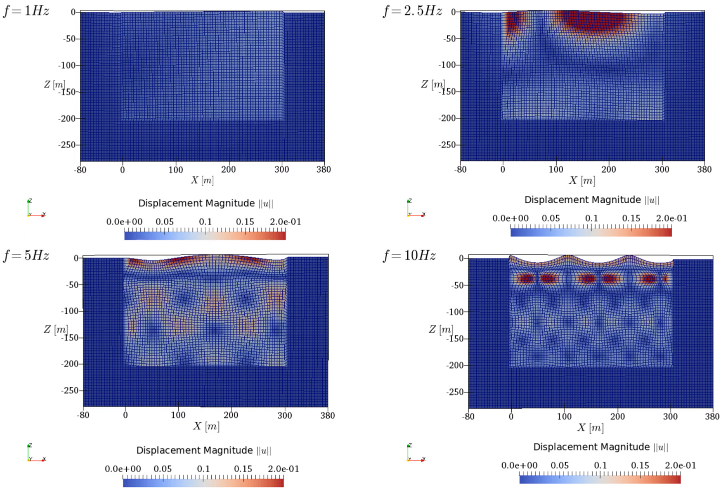


Seismic Motions

- Variation in inclination, frequency, energy, duration...
- Deterministic and Probabilistic
- Stress test the soil-structure system



Free Field, Variation in Input Frequency, $\theta = 60^o$



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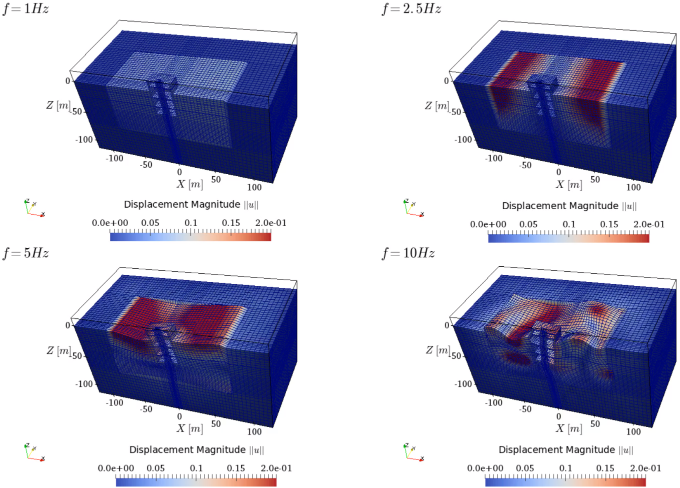
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$



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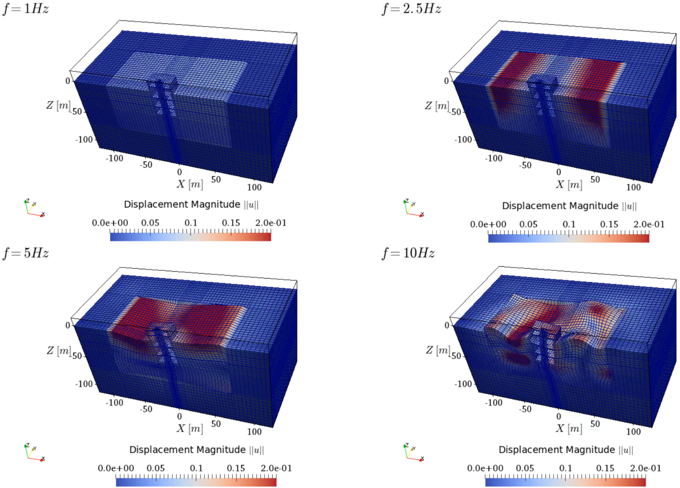
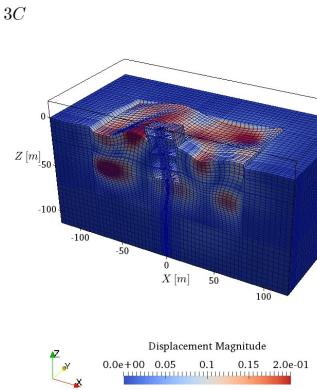
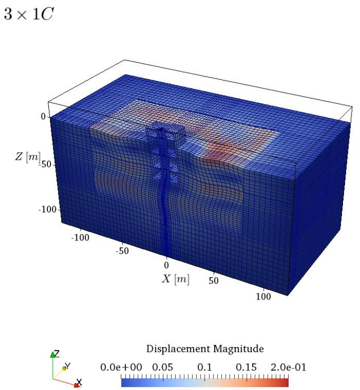
SMR ESSI, Variation in Input Frequency, REAL TIME



(MP4)

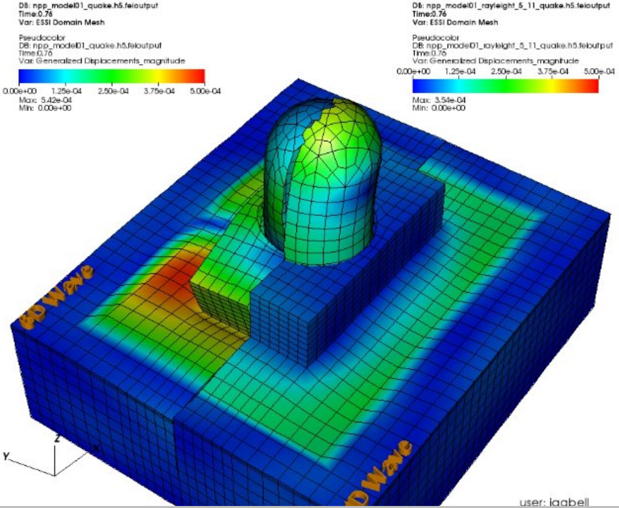
SMR ESSI, 3C vs 3$\times$1C





(OGV)

6C vs 1C NPP ESSI Response Comparison



(MP4)

Outline

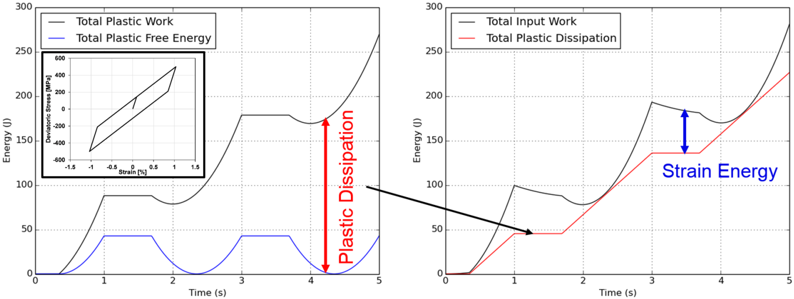
Energy Input and Dissipation

- Energy input, dynamic forcing
- Energy dissipation outside SSI domain:
  - SSI system oscillation radiation
  - Reflected wave radiation
- Energy dissipation/conversion inside SSI domain:
  - Inelasticity of soil, contact zone, structure, foundation, dissipators
  - Viscous coupling with internal/pore fluids, and external fluids
- Numerical energy dissipation/production

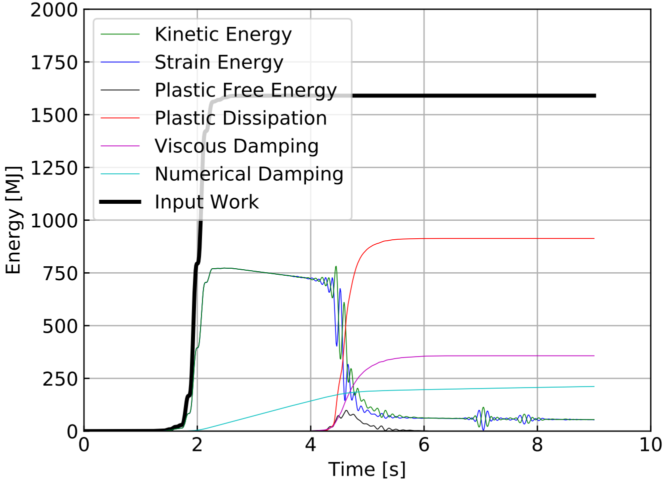
Plastic Energy Dissipation

Single elastic-plastic element under cyclic shear loading

- Difference between plastic work and plastic dissipation
- Plastic work can decrease
- Plastic dissipation always increases



Energy Dissipation Control

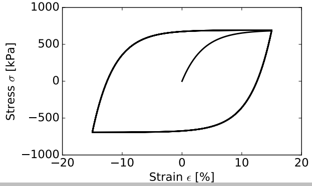


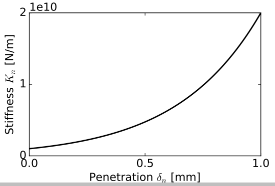
Inelastic Modeling of Soil Structure Systems

- Soil, inelastic, elastic-plastic
  - Dry, single phase
  - Unsaturated, partially saturated
  - Fully saturated
- Contact/interface/joint, inelastic, soil/rock – foundation
  - Dry, single phase,
    - Normal, hard and soft, gap open/close
    - Friction, nonlinear
  - Fully saturated, suction, excess pressure, buoyant force
- Structure, inelastic, damage, cracks
  - Nonlinear/inelastic 1D reinforced concrete fiber beam
  - Nonlinear/inelastic 3D reinforced concrete solid element
  - Alcali Silica Reaction concrete modeling

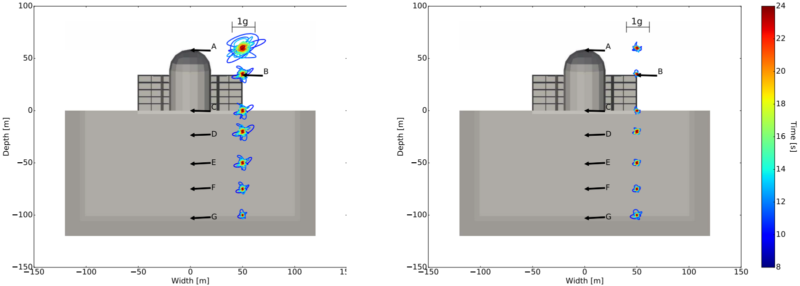
Inelastic Soil and Inelastic Contact/Interface/Joint

- Shear velocity of soil $V_s = 500 m/s$
- Undrained shear strength (Dickenson 1994) $V_s[m/s] = 23(S_u[kPa])^{0.475}$
- For $V_s = 500 m/s$ Undrained Strength $S_u = 650 kPa$ and Young's Modulus of $E = 1.3 GPa$
- von Mises, Armstrong Frederick kinematic hardening ($S_u = 650 kPa$ at $\gamma = 0.01\%$; $h_a = 30 MPa$, $c_r = 25$)
- Soft contact (concrete-soil), gaping and nonlinear shear





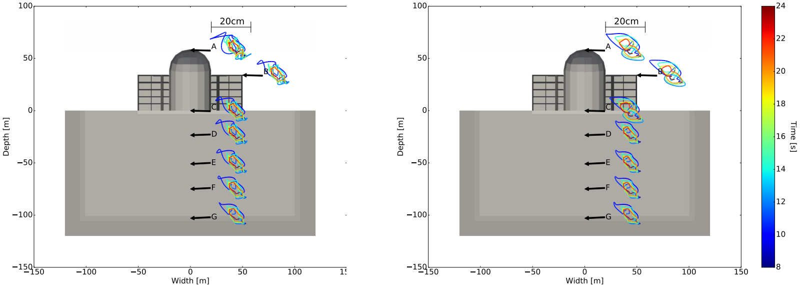
Acceleration Traces, Elastic vs Inelastic



Elastic

Inelastic

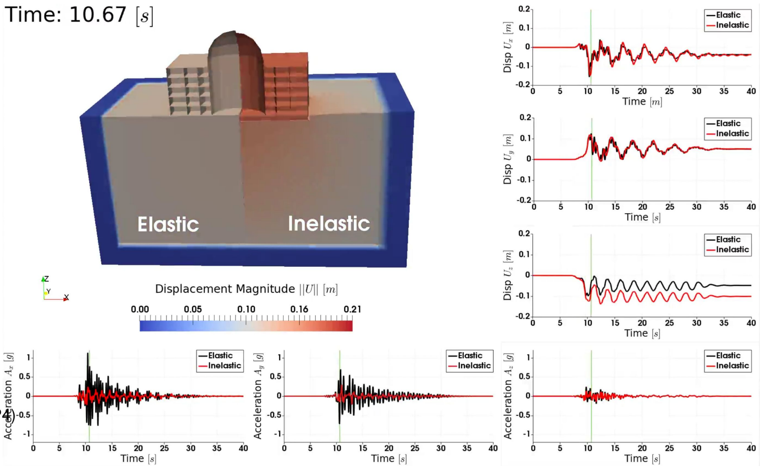
Displacement Traces, Elastic vs Inelastic



Elastic

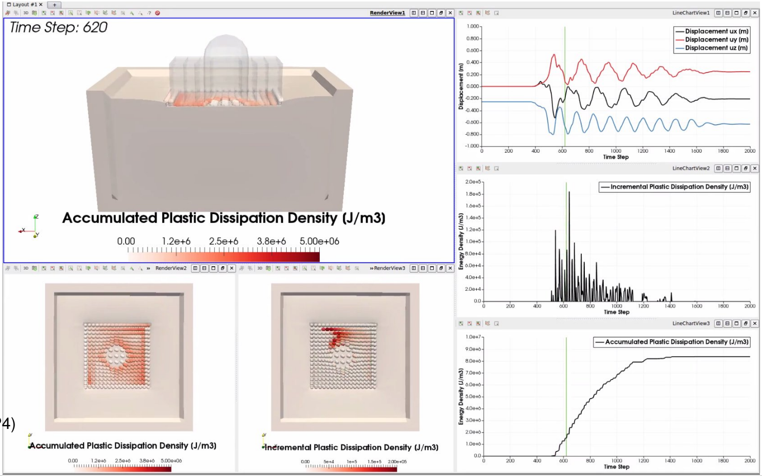
Inelastic

Elastic and Inelastic Response: Differences



(MP4)

Energy Dissipation in a Large-Scale Model



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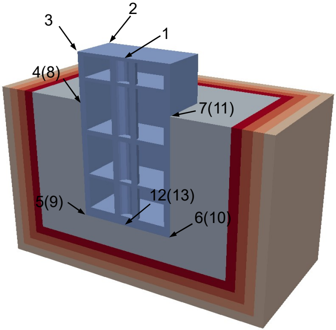
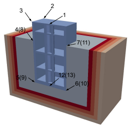
Deeply Embedded Structures

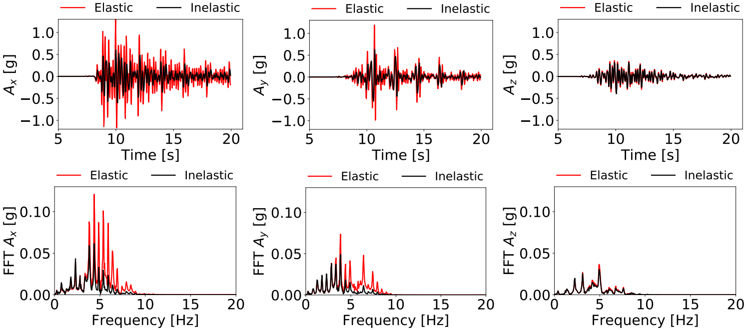


Location of points

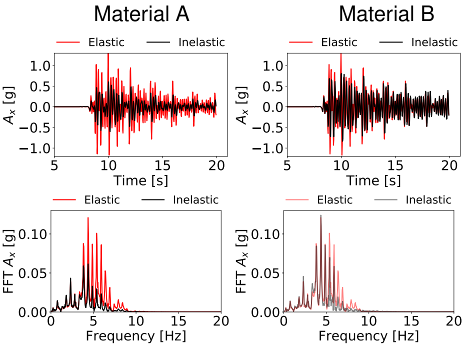
Point ID	X (m)	Y (m)	Z (m)	layer
1	0	0	14	structure
2	15	15	14	structure
3	0	15	14	structure
4	0	15	0	structure
5	0	15	-36	structure
6	0	-15	-36	structure
7	0	-15	0	structure
8	0	15	0	surrounding soil
9	0	15	-36	surrounding soil
10	0	-15	-36	surrounding soil
11	0	-15	0	surrounding soil
12	0	0	-36	structure
13	0	0	-36	surrounding soil

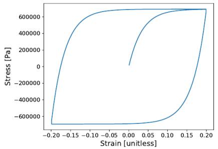


SMR: Inelastic ESSI Effects, Top Center

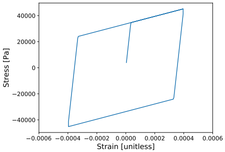


SMR: ESSI Effects, Material Modeling



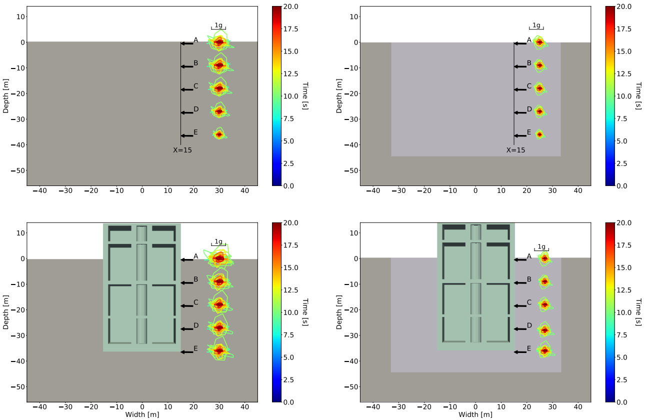


Material A: nonlinear, vM - AF



Material B: Bilinear

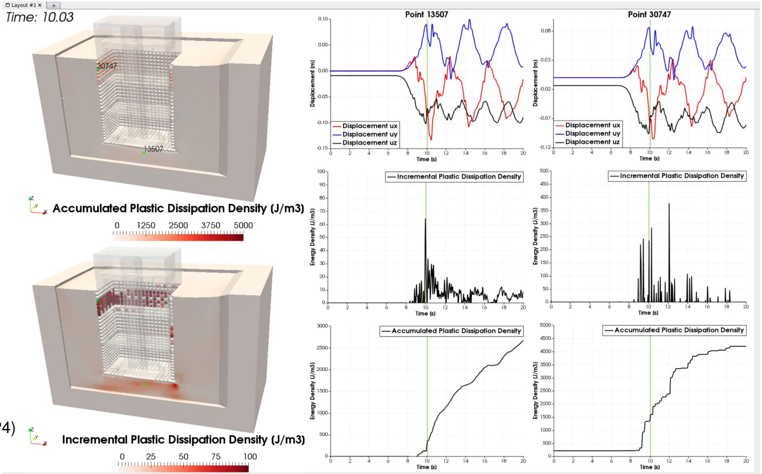
SMR: Accelerations Along Depth



Nonlinear site effects

SSI effects

Energy Dissipation for an SMR Model



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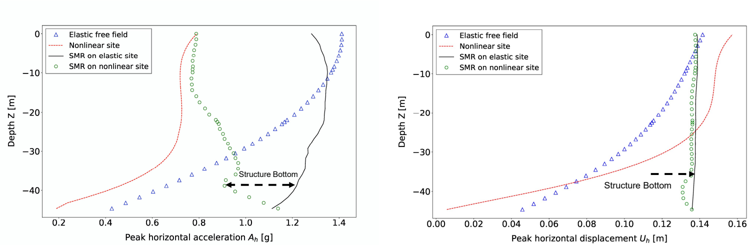
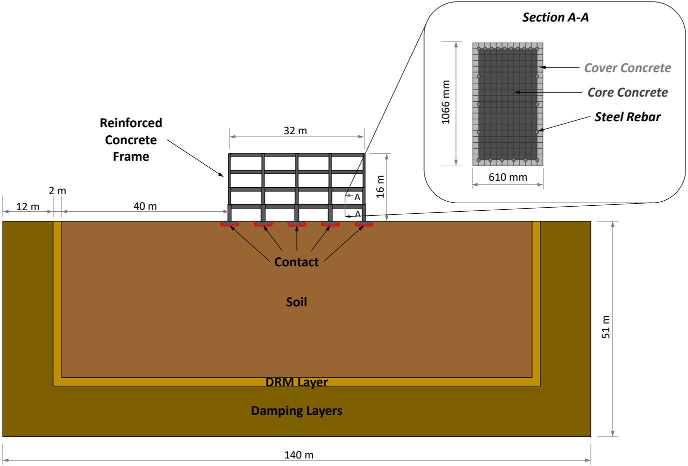
Depth variation - PGA & PGD

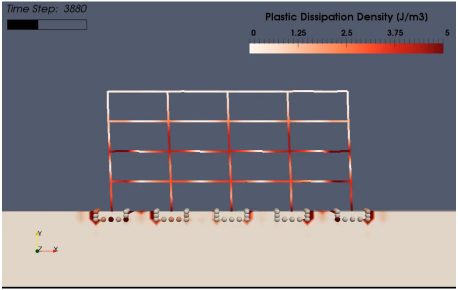


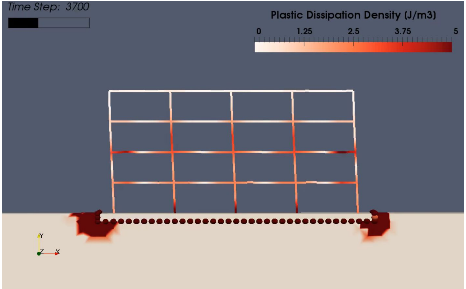
- The PGA & PGD of SSI systems are (very) different from free field motions,
- Material nonlinearity has significant effect on acceleration response.

Energy Dissipation for Design



Design Alternatives





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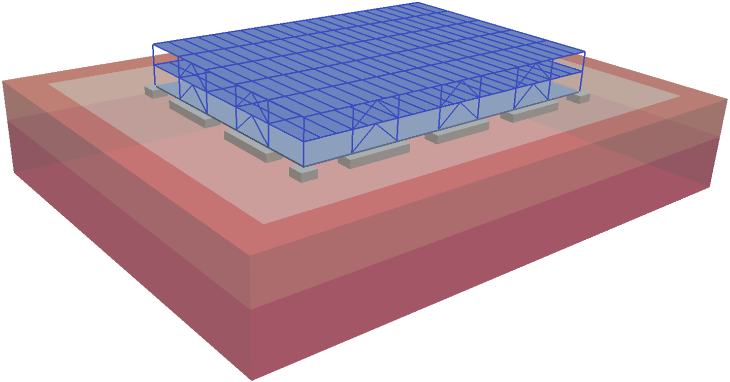
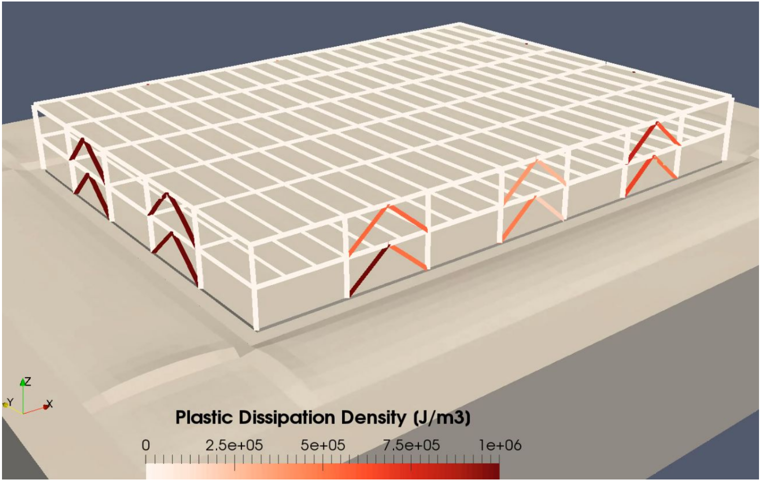
ASCE-7-21: Buildings and Models, Low Building



ASCE-7-21: Low Building Energy Dissipation



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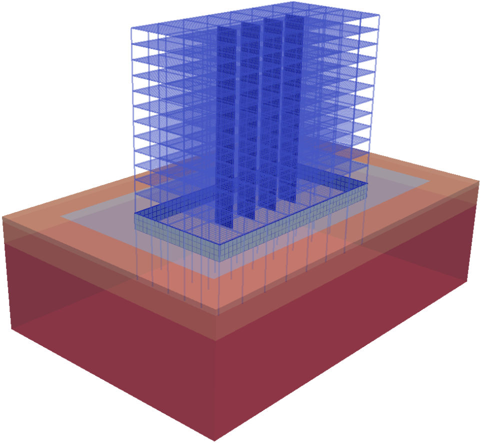
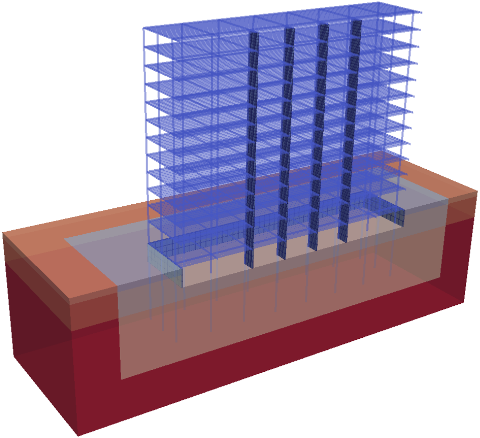
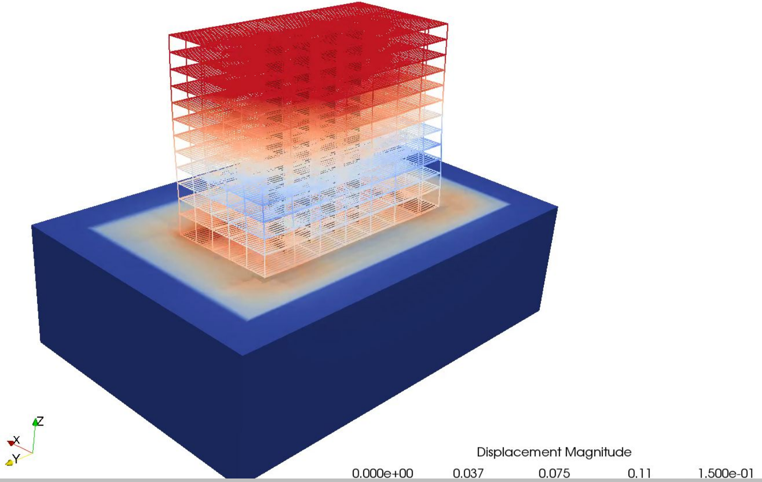
ASCE-7-21: Tall Building



ASCE-7-21: Buildings and Models, Tall Building



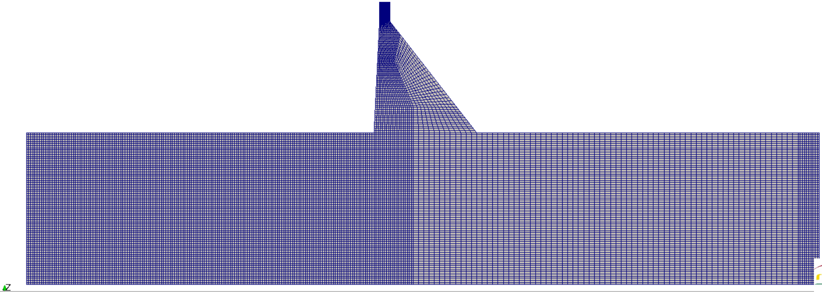
ASCE-7-21: Tall Building Response



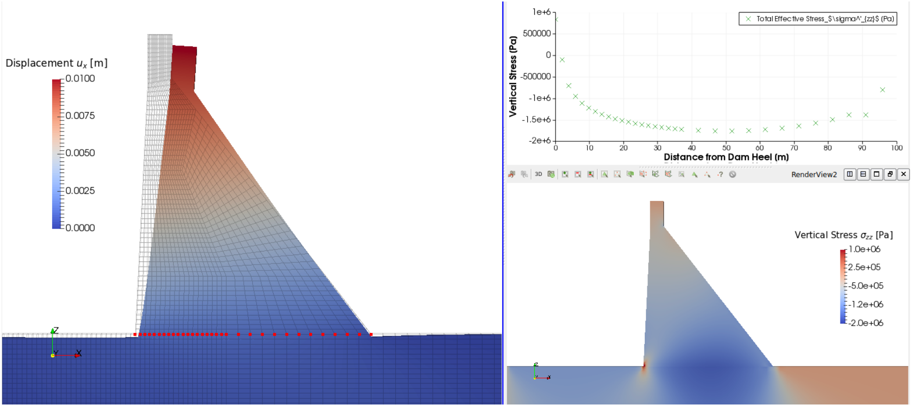
Outline

Pine Flats Dam, Model

- Material properties provided
- Motions applied through DRM, from bottom
- Energy dissipation, Viscous, Numerical, Radiation
- Load cases as provided

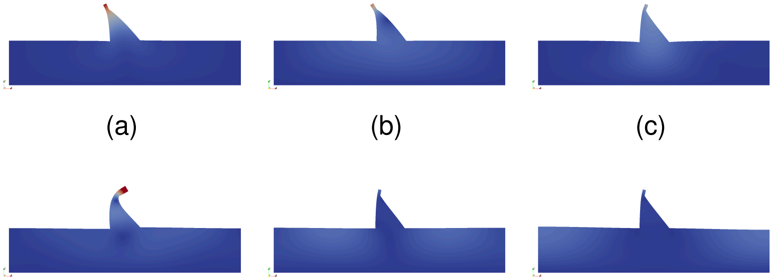


Static, Displacements and σ_V



Eigen Analysis, Dry

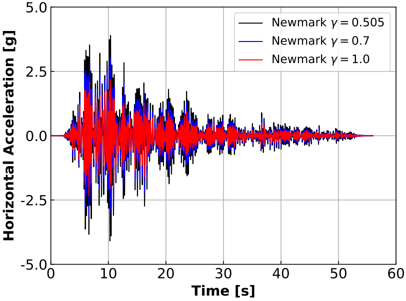
- Eigen frequencies:
  (a) 2.46945 Hz, (b) 3.82403 Hz, (c) 4.48795 Hz,
  (d) 5.25455 Hz, (e) 5.32023 Hz, (f) 5.60061 Hz,

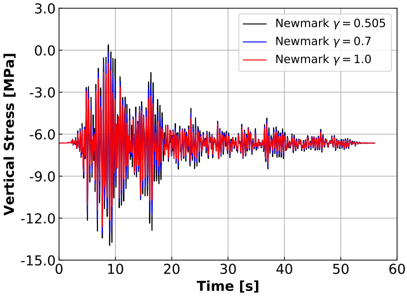


(a) (b) (c)

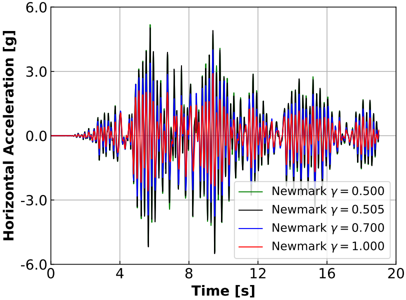
(d) (e) (f)

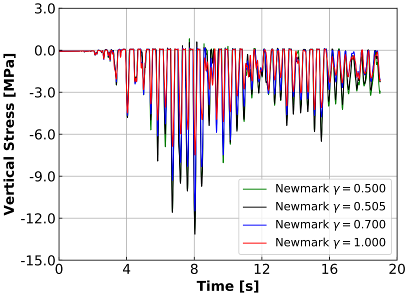
Numerical Damping Effects, Elastic $\ddot{u}_{hor}^{top}$, σ_v^{heel}



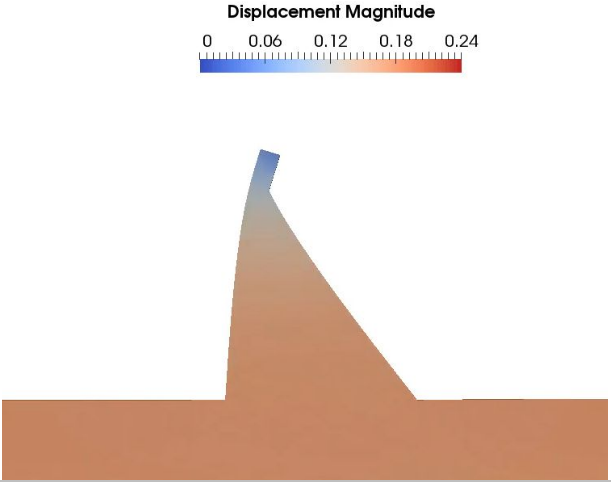


Numerical Damping Effects, Inelastic $\ddot{u}_{hor}^{top}$, σ_v^{heel}



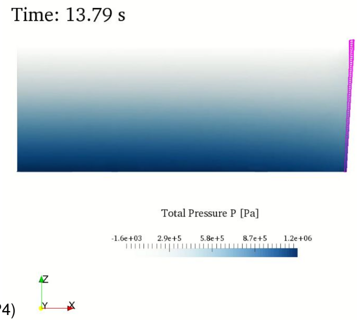


Pine Flat Dam, Dynamic Response with Reservoir

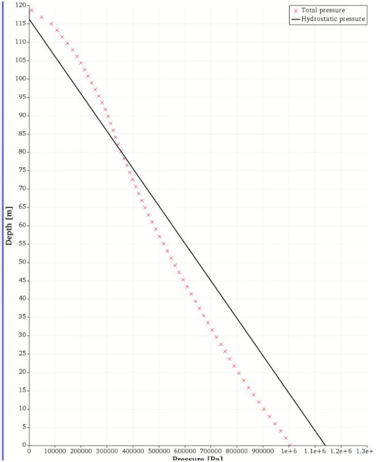


(MP4)

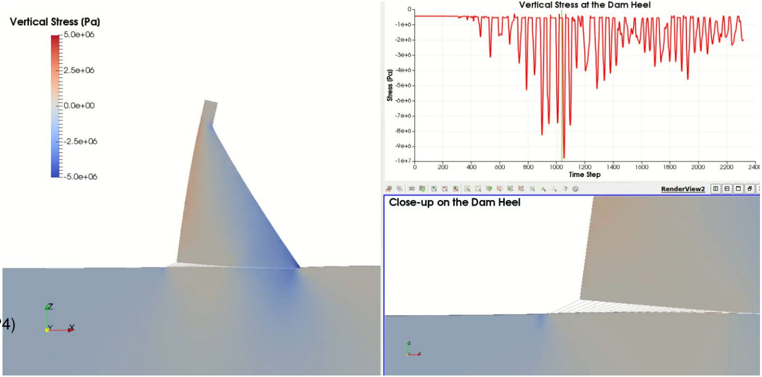
Pine Flat Dam, Hydrodynamic Pressure



(MP4)

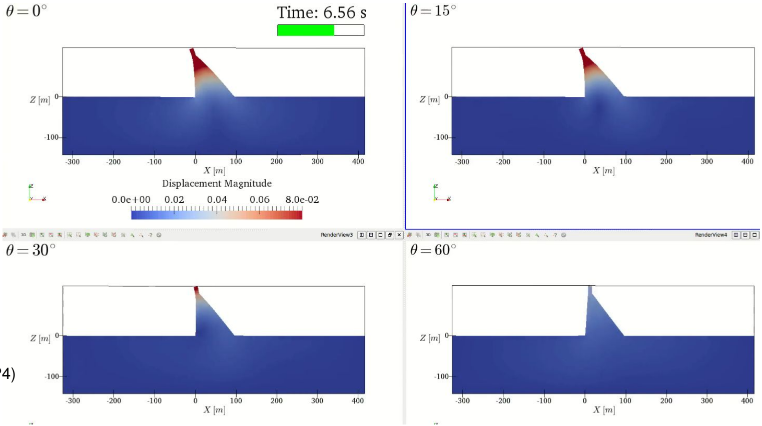


Pine Flat Dam, Inelastic Interface, Hydrostatic



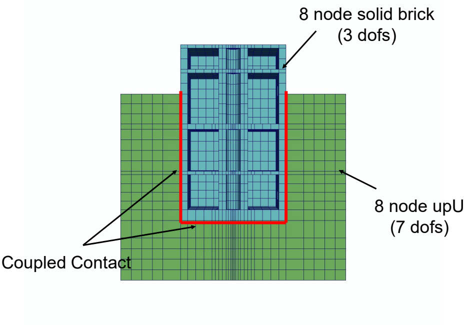
(MP4)

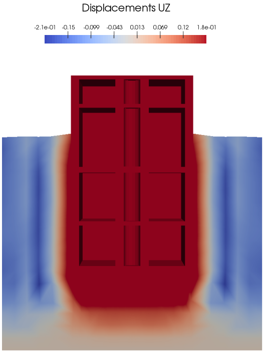
Pine Flat Dam, Inclined Plane Waves



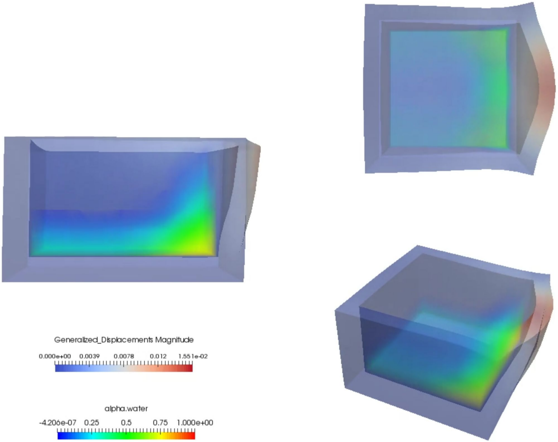
(MP4)

Buoyant Force Simulation



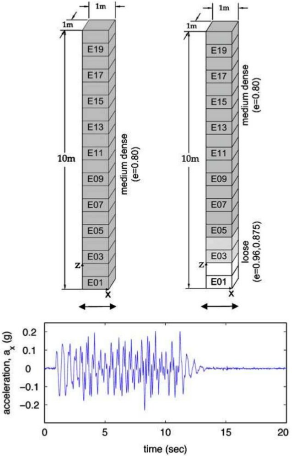


Solid, Structure-Fluid Interaction, Example

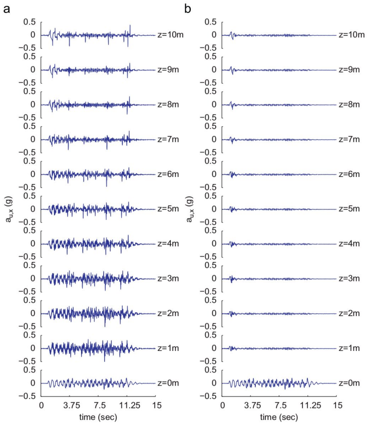


(MP4)

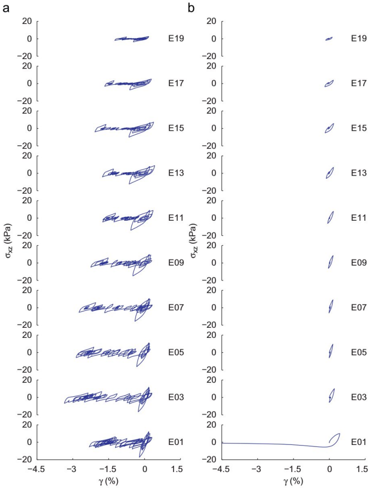
Liquefaction as Base Isolation, Model



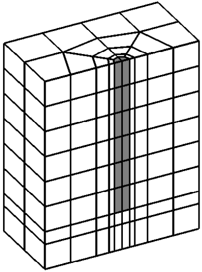
Liquefaction, Wave Propagation

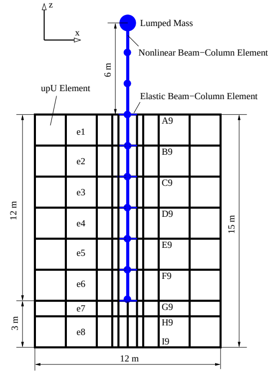


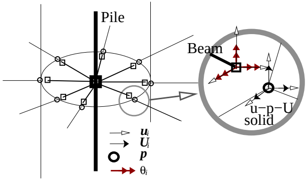
Liquefaction, Stress-Strain Response



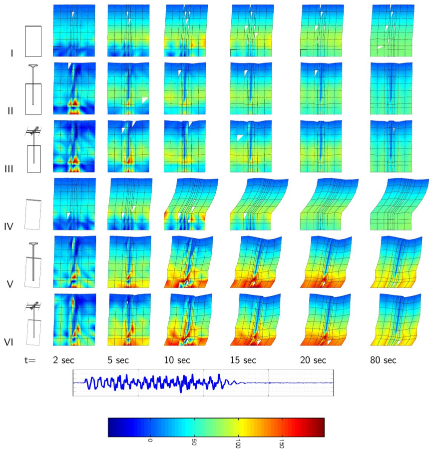
Pile in Liquefiable Soil, Model







Pile in Liquefiable Soil, Results



Outline

Real-ESSI Simulator System

The Real-ESSI, Realistic **M**odeling and **S**imulation of **E**arthquakes, **S**oils, **S**tructures and their **I**nteraction. Simulator is a software, hardware and documentation system for high fidelity, high performance, time domain, nonlinear/inelastic, deterministic or probabilistic, 3D, finite element modeling and simulation of:

- statics and dynamics of soil,
- statics and dynamics of rock,
- statics and dynamics of structures,
- statics of soil-structure systems, and
- dynamics of earthquake-soil-structure system interaction

Summary

- Numerical modeling to predict and inform, rather than fit
- Sophisticated inelastic/nonlinear modeling and simulations need to be done carefully and in phases
- Education and Training is the key!
- Collaborators: Feng, Yang, Behbehani, Sinha, Wang, Wang, Pisanó, Abell, Tafazzoli, Jie, Preisig, Tasiopoulou, Watanabe, Luo, Cheng, Yang.
- Funding from and collaboration with the ATC/US-FEMA, US-DOE, US-NRC, US-NSF, CNSC-CCSN, UN-IAEA, and Shimizu Corp. is greatly appreciated,
- `http://sokocalo.engr.ucdavis.edu/~jeremic`