Нумеричка анализа интеракције тла и конструкције услед дејства земљотреса

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Српско Удружење за земљотресно инжењерство
СУЗИ
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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

Early Work on ESSI

- Professor Kyoji Suyehiro
- Ship engineer (Professor of Naval Arch. at U. of Tokyo),
- Witnessed Great Kantō earthquake, Tokyo, 01Sep1923 11:58(7.5), 12:01(7.3), 12.03(7.2), shaking until 12:08
- Saw earthquake surface waves travel and buildings sway
- Became founding Director of the Earthquake Engineering Research Institute at the Univ. of Tokyo,
- His published records (ASCE 1932) show four times more damage to soft wooden buildings on soft ground then same buildings on stiff soil

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

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 Earthquakes, Soils Structures and their Interaction.

Real-ESSI is used for:

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

`http://real-essi.us/`

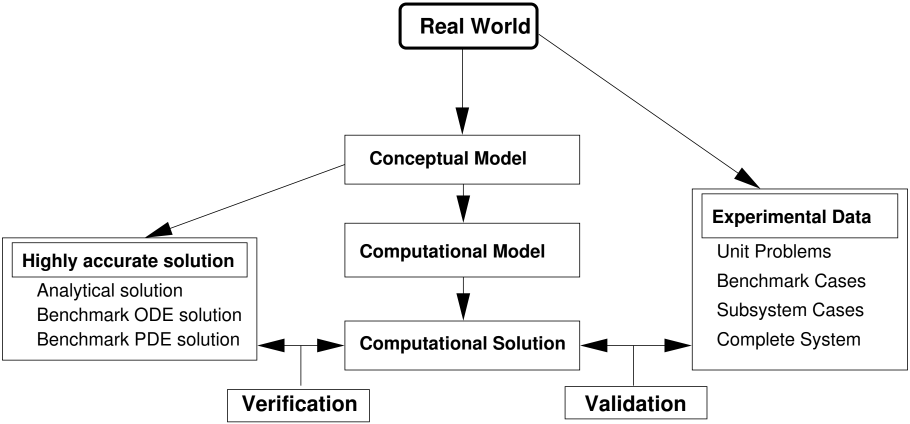
Verification and Validation

- Verification: provides evidence that the model is solved correctly. Mathematics issue.
- Validation: provides evidence that the correct model is solved. Physics issue.
- 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.
- How good are our numerical predictions?
- Use simulation tools to improve safety and economy?

V & V Motivation

- How much can (should) we trust model implementations (verification)?
- How much can (should)d we trust numerical simulations (validation)?
- 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

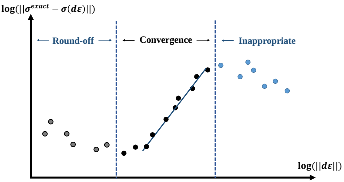
- W. L. OBERKAMPF, T. G. TRUCANO, AND C. HIRSCH. Verification, validation and predictive capability in computational engineering and physics. In Proceedings of the Foundations for Verification and Validation on the 21st Century Workshop, pages 1–74, Laurel, Maryland, October 22-23 2002. Johns Hopkins 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.

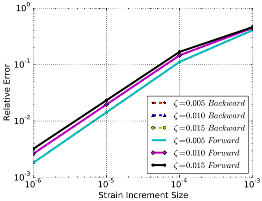
Verification

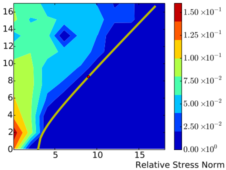
- Source code management
- Source code verification
- Constitutive integration
- Static and dynamic behavior of single phase solids
- Static and dynamic behavior of fully and partially saturated, fully coupled, porous solid-pore fluid problems
- Static and dynamic behavior of structural elements
- Static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

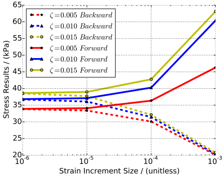
Constitutive Integration Verification

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

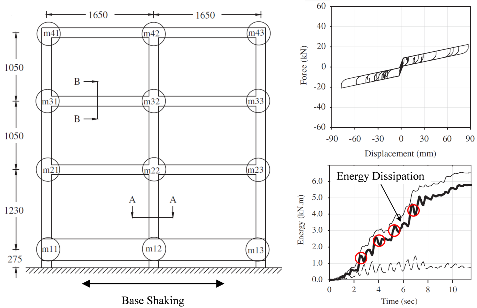








Energy Dissipation Verification: Plastic Work $\neq$ Plastic Dissipation



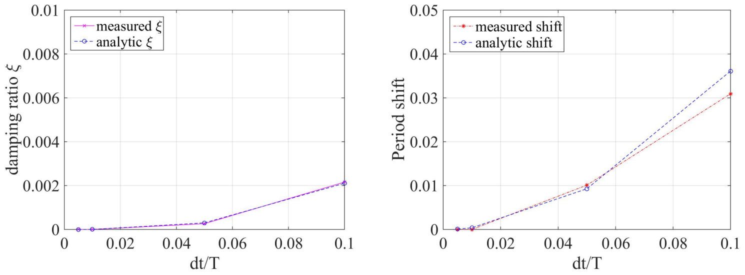
From a paper on *Soil Dynamics and Earthquake Engineering* (2011)

Direct violation of the second law of thermodynamics

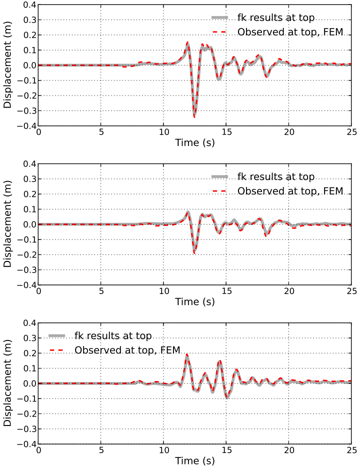
600 papers since 1990 (!?!) repeat this error

Dynamic Time Stepping Verification

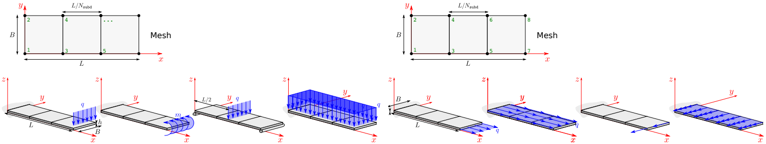
Based on the amplification matrix **A**, to calculate the analytical solution of damping ratios and period shift.
Example: Hilber-Hughes-Taylor $\alpha = -0.1$



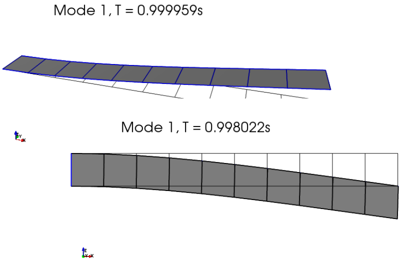
Seismic Input Verification, DRM, EW, NS, UD



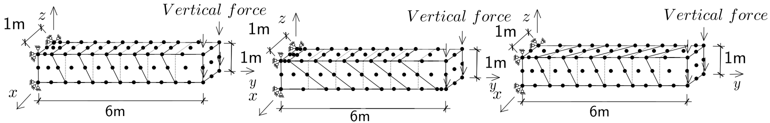
Verification: ANDES Shell



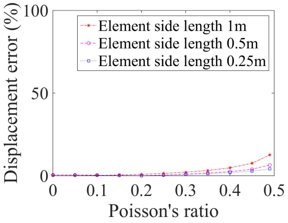
N_{subd}	u_z
2	96.2118
7	100.096
101	100.002



Verification: Irregular Solids and Poisson's Ratio

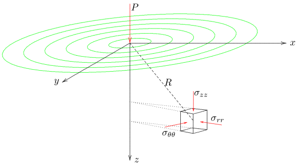


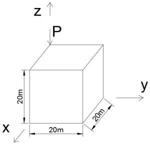
Force direction	Shape 1	Shape 2	Shape 3
Vertical (z)	0.40%	0.85%	0.60%
Transverse (y)	0.54%	3.67%	0.46%



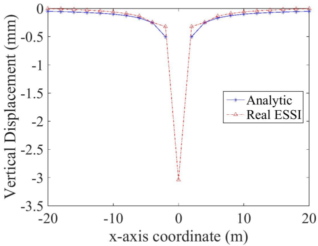
Poisson's ratio	27NodeBrick displacement	Theory displacement	Error
0.00	8.797E-04 m	8.784E-04 m	0.15%
0.05	8.801E-04 m	8.791E-04 m	0.11%
0.10	8.799E-04 m	8.799E-04 m	0.01%
0.15	8.792E-04 m	8.806E-04 m	0.16%
0.20	8.778E-04 m	8.813E-04 m	0.40%
0.25	8.758E-04 m	8.821E-04 m	0.71%
0.30	8.730E-04 m	8.828E-04 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 using Boussinesq Solution

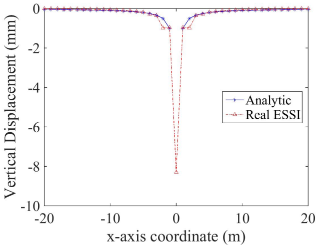




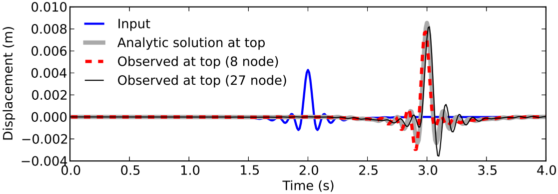
8NodeBrick

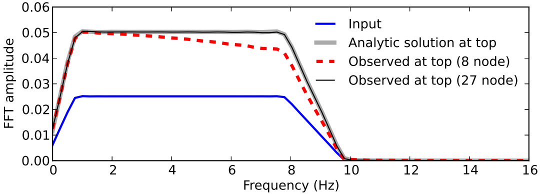


27NodeBrick



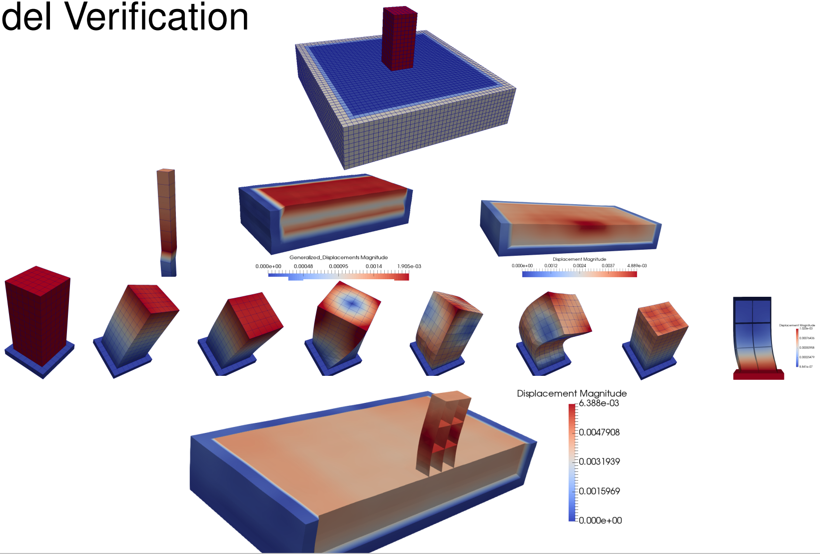
Wave Propagation, Mesh Size Effects





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

Model Verification

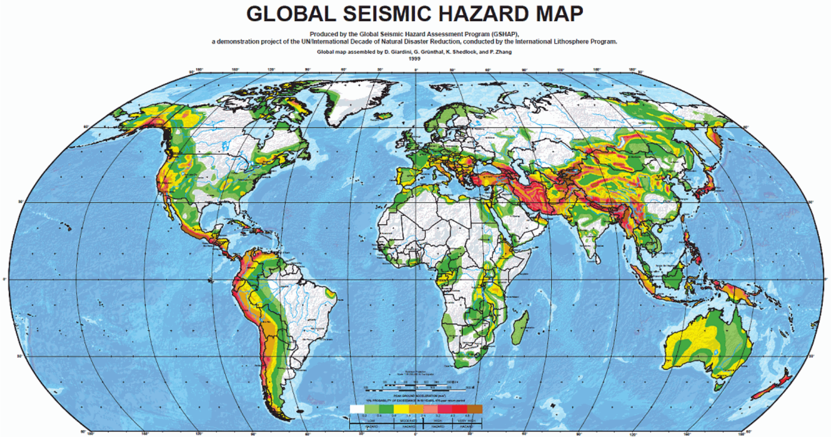


V & V Summary

- 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 important, essential

Outline

Seismic Hazard, World

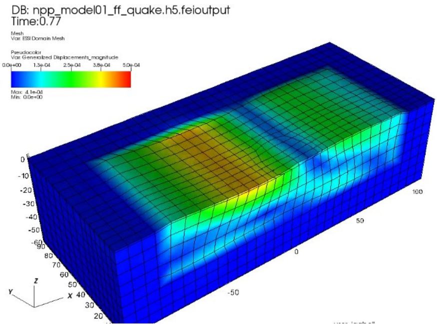


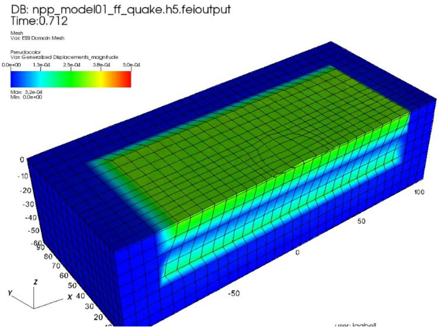
Earthquake Ground Motions

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

1C vs 6C Free Field Motions

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





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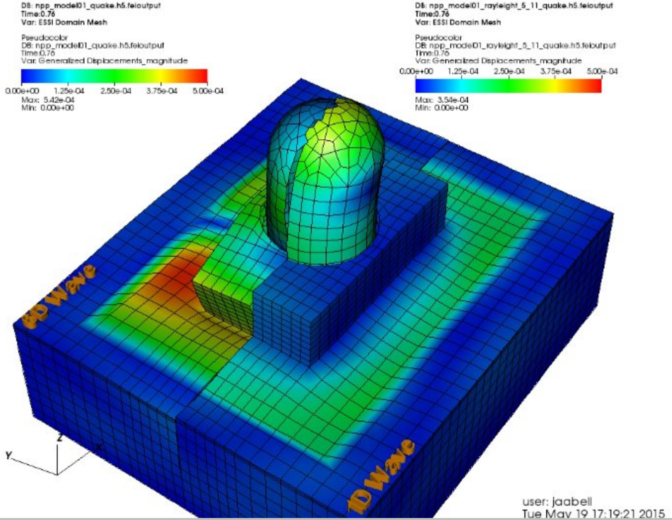
6C vs 1C NPP ESSI Response Comparison



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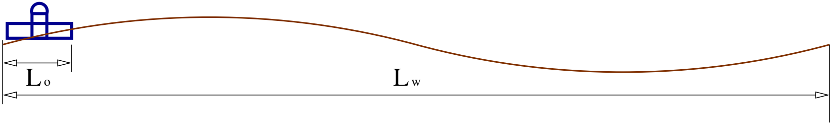
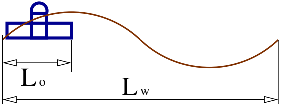
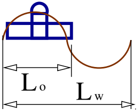
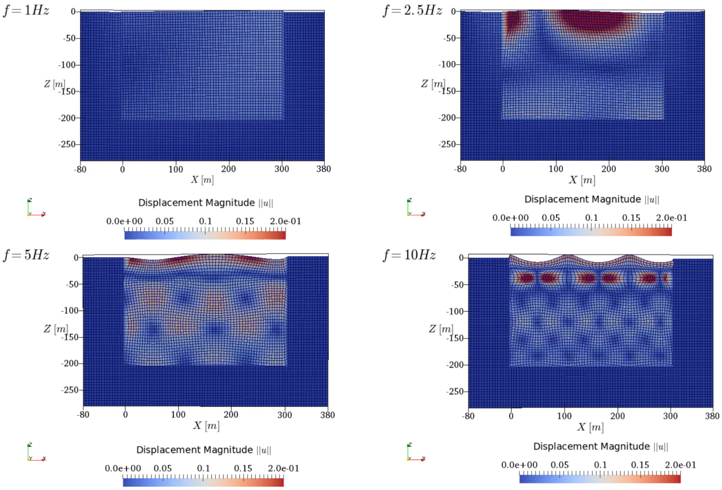
When to use 3C and/or 3×1C







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



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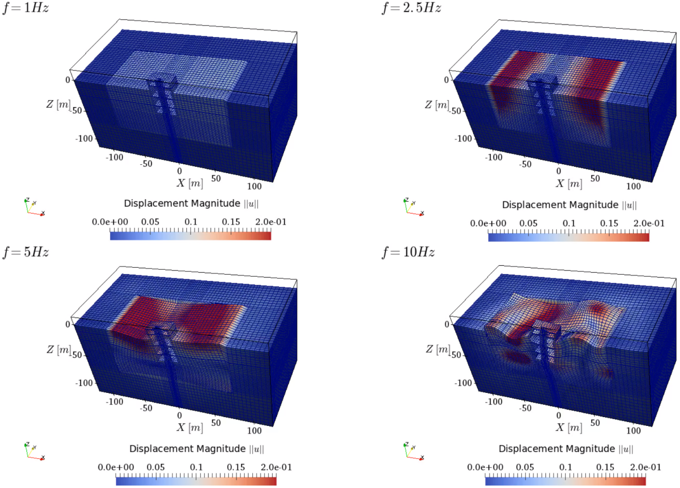
SMR ESSI, Variation in Input Frequency, $\theta = 60^o$



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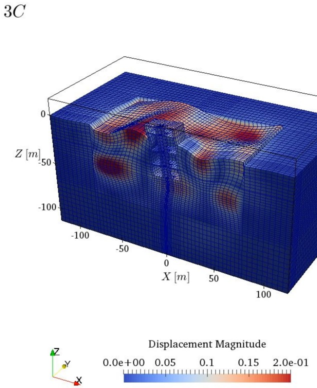
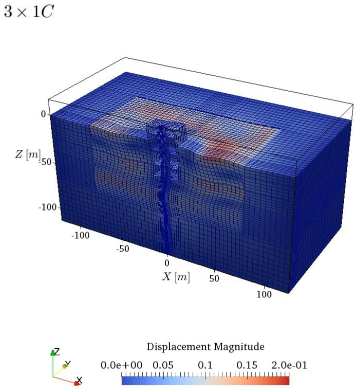
SMR ESSI, 3C vs 3×1C





(OGV)

Outline

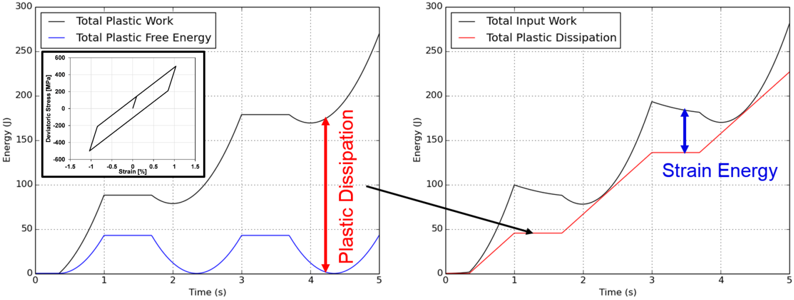
Energy Input and Dissipation

- 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, interfaces, structure, dissipators
  - Viscous coupling with internal/pore, and external fluids
- Numerical energy dissipation/production

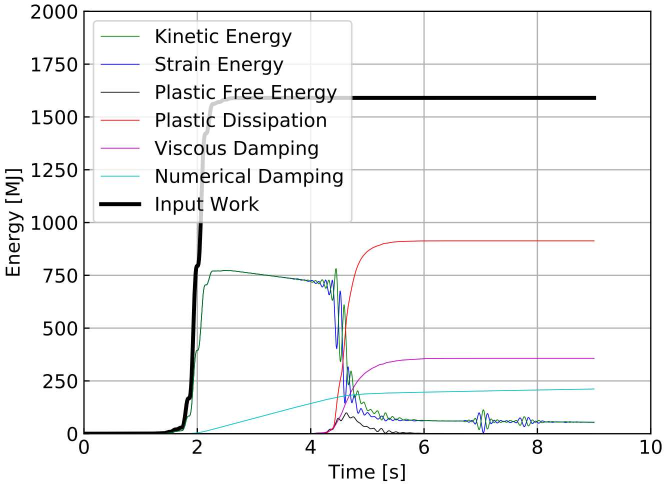
Plastic Energy Dissipation

Single elastic-plastic element under cyclic shear loading

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



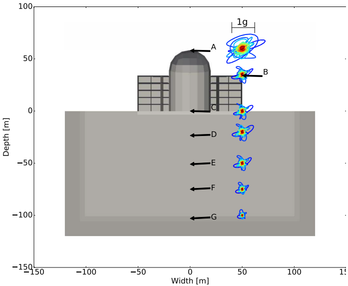
Energy Dissipation Control

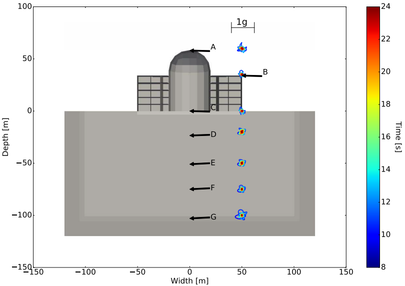


Inelastic Modeling of Soil Structure System

- Soil, inelastic, elastic-plastic
  - Dry, single phase
  - Unsaturated, partially saturated, and fully saturated
- Interface/Contact/Joint, inelastic, gap open/close, slip
  - Dry, single phase,
  - Fully saturated, suction, excess pressure, buoyant force
- Structure, inelastic, damage, cracks, ASR...
  - Nonlinear/inelastic 1D concrete, steel, 3D fiber beams
  - Nonlinear/inelastic 3D concrete, steel, 3D solids, 3D shells
- Solid/Structure-Fluid interaction, open surface

Acceleration Traces, Elastic vs Inelastic

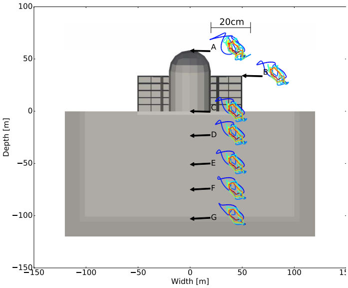


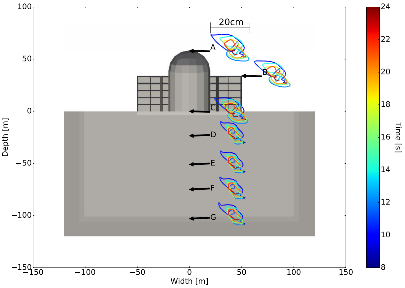


Elastic

Inelastic

Displacement Traces, Elastic vs Inelastic

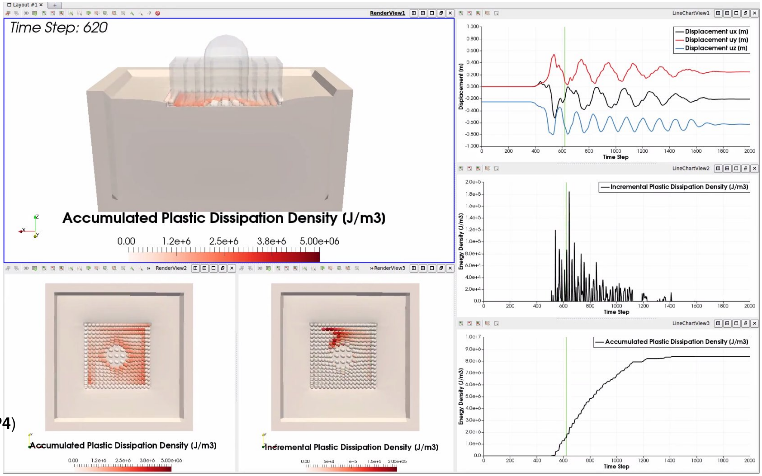




Elastic

Inelastic

Energy Dissipation in a Large-Scale Model



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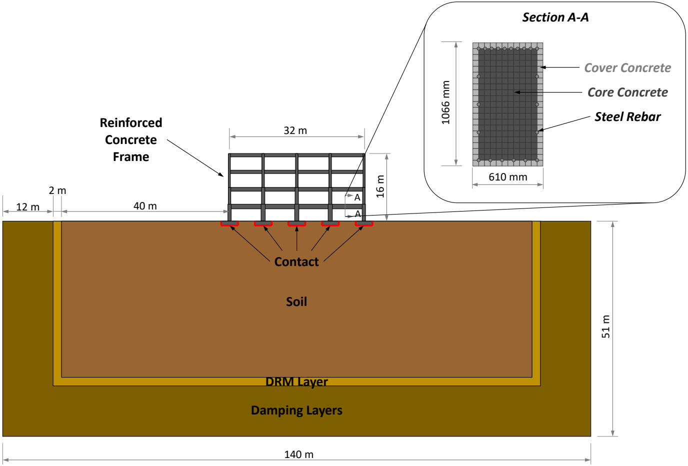
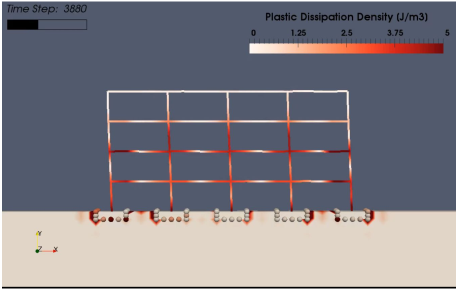
Energy Dissipation for Design



Design Alternatives



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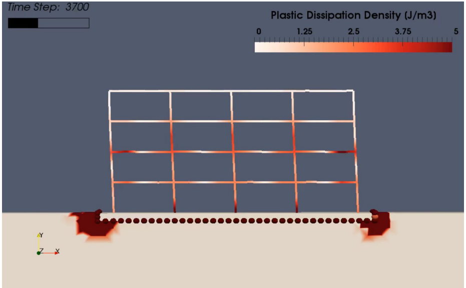

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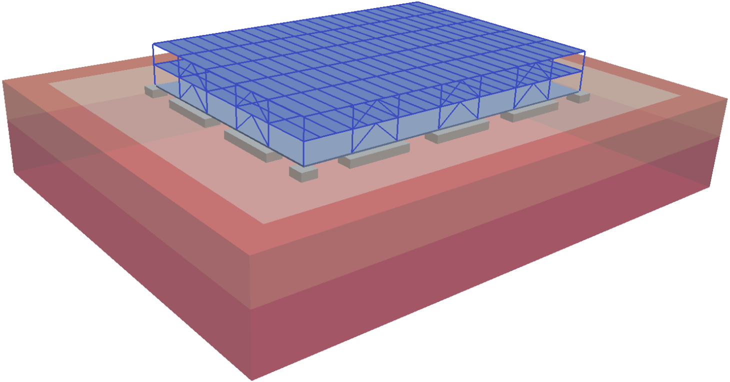
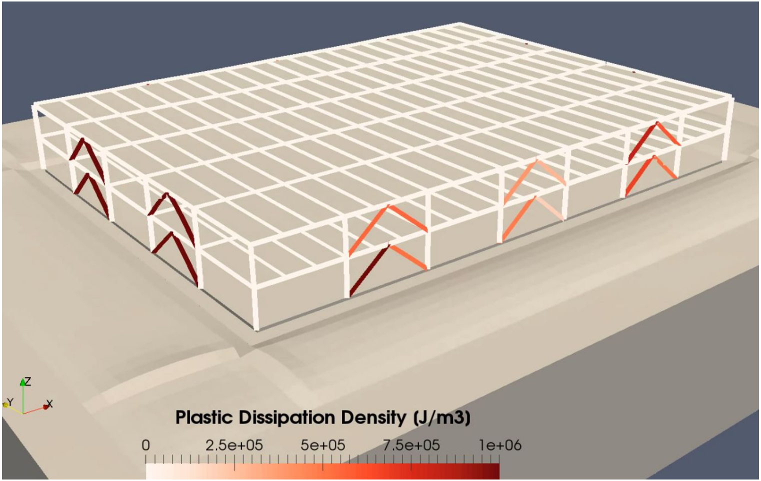
ASCE-7-21: Low Building



ASCE-7-21: Low Building Energy Dissipation



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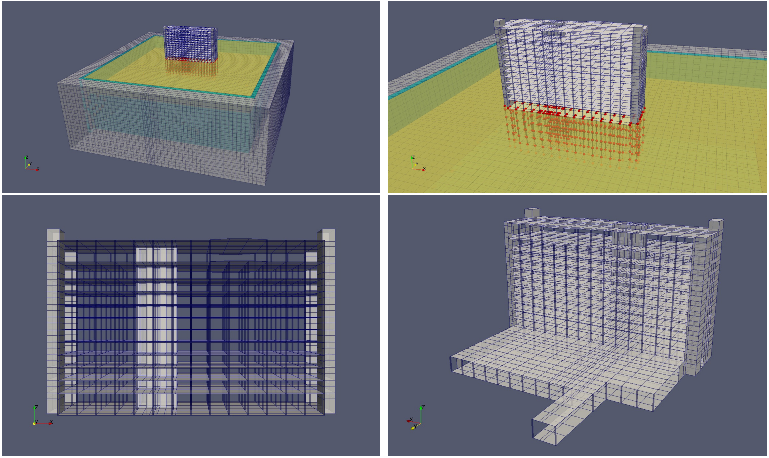
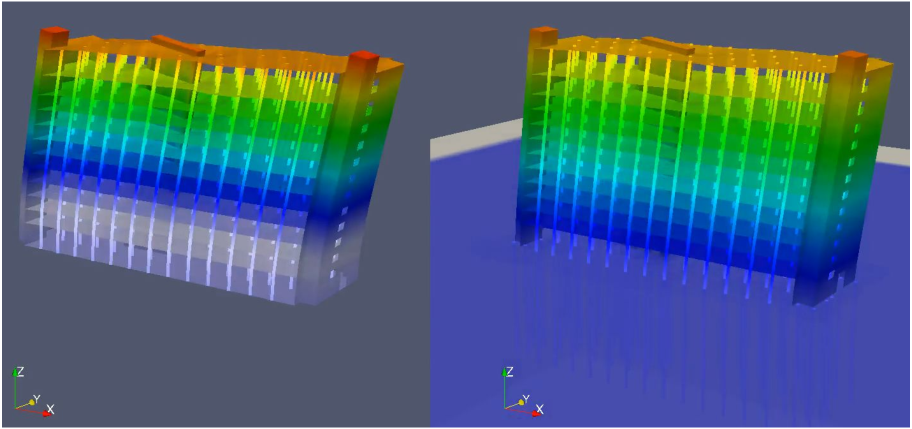
Ventura Hotel, Northridge Earthquake



Ventura Hotel, Northridge Earthquake, SSI vs nonSSI



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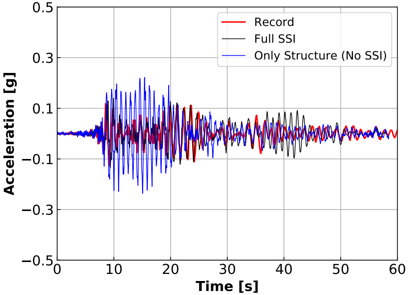
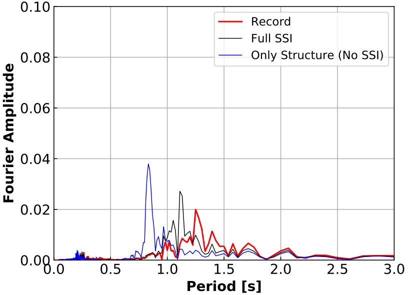
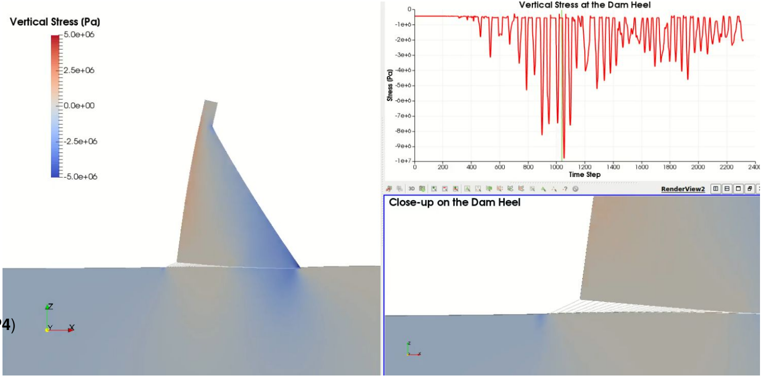
Ventura Hotel, Northridge Earthquake, SSI vs nonSSI

Top floor, long axes response





Pine Flat Dam, Inelastic Interface, Hydrostatic



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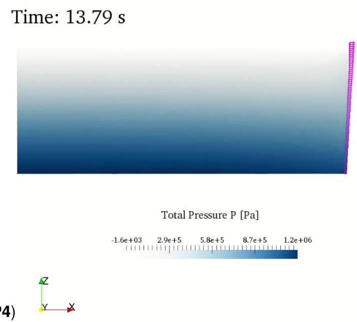
Pine Flat Dam, Hydrodynamic Pressure



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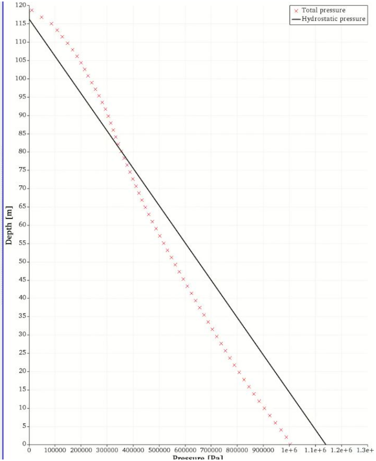

Outline

Закључак

- Numerical modeling to predict and inform, rather than fit
- Инжењер море да зна све о објекту, систему
- Education and Training is the key!
- Collaborators: Feng, Yang, Behbehani, Sinha, Wang, Wang, Pisanó, Abell, Tafazzoli, Jie, Preisig, Tasiopoulou, Watanabe, Luo, Cheng, Yang.
- Хвала СУЗИ на организацији предавања!
  `http://suzi-saee.rs/`

Хвала на Пажњи

http://sokocalo.engr.ucdavis.edu/~jeremic/za_SUZI_predavanje_Apr2020

http://real-essi.us

http://sokocalo.engr.ucdavis.edu/~jeremic