Quality Assurance of Inelastic Numerical Analysis for Soils and Structures

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Outline

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Motivation

- Improve analysis and design for infrastructure
- Credible numerical analysis
- Predict and inform, Engineer needs to know!
- Design, build and maintain sustainable objects
- Civil engineering objects are important
- Civil enginering analysis better than "rocket science"

Long Lasting Infrastructure




Prediction under Uncertainty

- Modeling, Epistemic Uncertainties
  - Modeling simplifications
  - Low, medium, high sophistication modeling and simulation
  - Modeling sophistication level for confidence in results
  - Verification and Validation
- Parametric, Aleatory Uncertainties
  - $M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$
  - Uncertain: mass M, viscous damping C and stiffness K^{ep}
  - Uncertain loads, $F(t)$
  - Results are PDFs and CDFs for σ_{ij}, ϵ_{ij}, u_i, $\dot{u}_i$, $\ddot{u}_i$

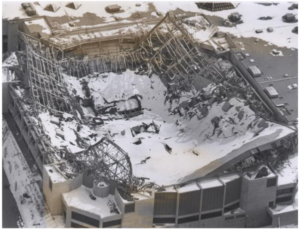
Analysis Governance

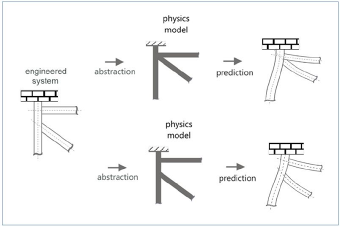
- Numerical analysis is fragile
- Engineer's competency and expertise
- Model verification
- Solution verification, program-mathematics inaccuracies
- Validation, program-physics inaccuracies

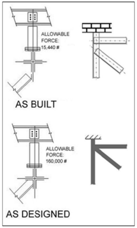
Engineer, Analyst

- Sound engineering judgement
- Assess various analysis sophistication levels
- Engineer is in full control of the model and the analysis
- Engineer uses models to investigate designs
- Confidence in all modeling choices
- Confidence in all model components
- Confidence in all analysis results

Expert Analyst, Engineer







Hartford Coliseum Collapse, 1978 (Martin and Delatte, ASCE-JPCF (2001))

Analysis Program

- Hierarchy of model sophistication
- Hierarchy of simulation/algorithmic capabilities
- Full (!) Verification
- Extensive Validation
- Confidence in analysis results

Under the Simulation Hood

- Commercial programs benchmark examples
- Commercial programs verification (?)
- Surprises under the simulation hood



Commercial Programs

Oberkampf and Trucano, SAND2007-0853 note:

- Commercial programs with large number of benchmark examples
- Primary goal is to demonstrate "engineering accuracy"
- However (!) verification should carefully quantify the numerical error in the solutions

Outline

Analysis Program Errors

- Analysis Programs might have feature/errors
- Analysis Program quality control/assurance/management
- Open-source programs without quality control are dangerous!
- Fitting a curve does not mean that results are accurate (2.0+2.0=4.0; 1.9+2.1=4.0; 2.51+1.51=4.02)

AIAA Editorial Policy

Editorial policy of the American Institute of Aeronautics and Astronautics (AIAA) Journal: The AIAA journals will not accept for publication any paper reporting:

- Numerical solution of an engineering problem that fails adequately to address accuracy of the computer results, or
- Experimental results unless the accuracy of the data is adequately presented

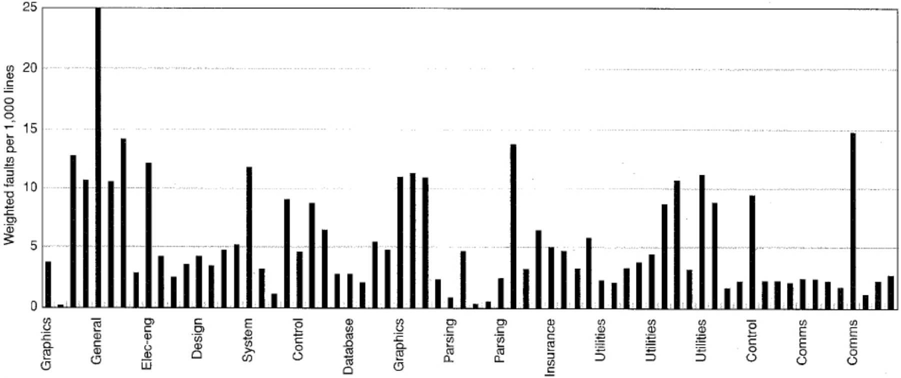
The T Experiments

- Les Hatton: The T experiments, Errors in scientific software. IEEE Computational Science and Engineering, 4(2):27-38, April-June 1997.
- "Extensive tests showed that many software codes widely used in science and engineering are not as accurate as we would like to think."
- "Better software engineering practices wold help solve this problem,"
- "Realizing that the problem exists is an important first step."
- Large experiment over 4 years measuring faults (T1) and failures (T2) of scientific and engineering codes

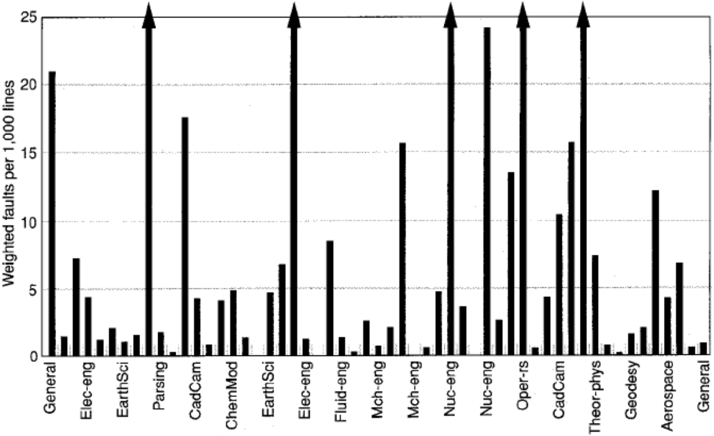
The T1 Experiments

- Measured defects without running the code, measuring formal consistency of 3,305,628 lines f77 and 1,928,011 lines of C
- 100 codes, 40 application areas: graphics, nuc. mech. chem. aero. civil engineering, comms, DBs, med. systems
- Safety–critical and non–safety–critical codes
- Applications with and without internationally standardized systems of quality control
- Mature codes (1 - 20 years old), in regular use
- Some errors: function call argument sequence, finite precision arithmetic misunderstanding, code complexity

T1: C Sources


25
20
15
10
5
0
Weighted faults per 1,000 lines
Graphics
General
Elec-eng
Design
System
Control
Database
Graphics
Parsing
Parsing
Insurance
Utilities
Utilities
Utilities
Control
Comms
Comms

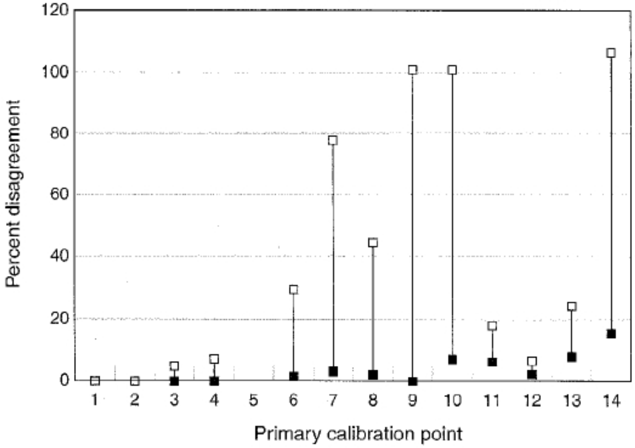
T1: f77 Sources



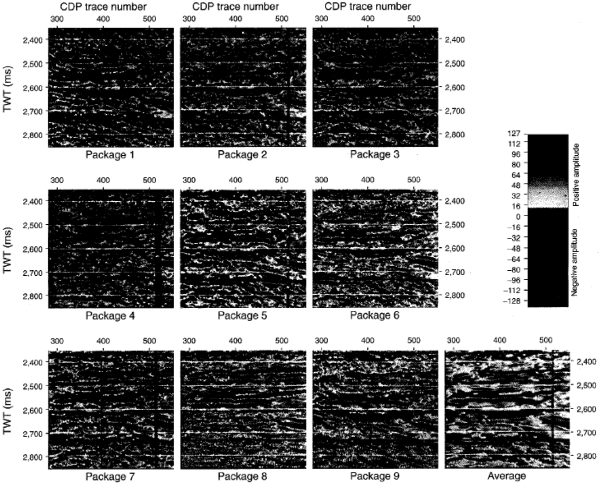
The T2 Experiments

- Application area: seismic inverse analysis
- Echo sounding of underground
- Reconstruct "images" of subsurface geologic structure
- Nine mature programs
- Using the very same set of algorithms
- Same input data set!
- 14 primary calibration points for results check
- Results "fascinating and disturbing"

T2: Disagreement at Calibration Points

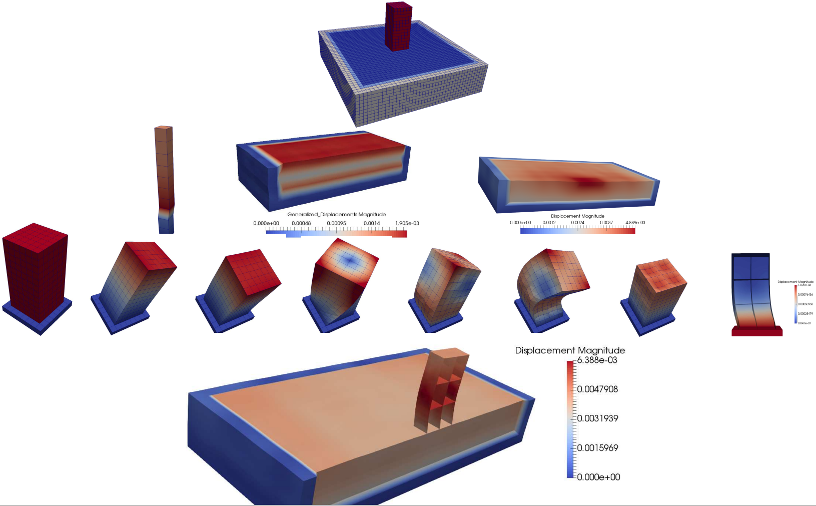


T2: Stage 14, Interpretation of Data



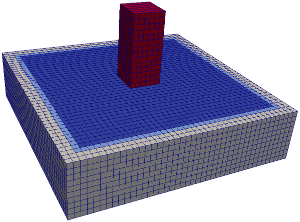
Outline

Analysis Modeling Phases



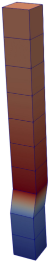
ESSI Modeling Phases

- Account for all model physical components
- Solids, structures and fluids
- Elastic, inelastic materials
- Static loads
- Dynamic loads
- Response quantities
- Engineer/Analyst builds confidence in analysis
- No surprises and no "reliance" on good luck!



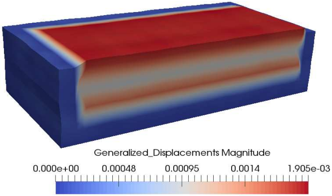
ESSI Modeling Phases

- 1D, 1C free field response
- Linear elastic material
- Inelastic material



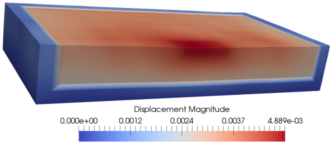
ESSI Modeling Phases

- 3D, 1C free field response
- Linear elastic material
- Inelastic material



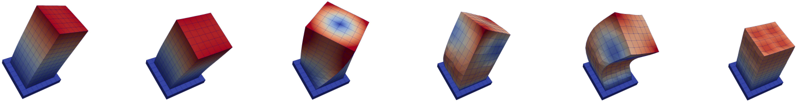
ESSI Modeling Phases

- 3D, 1C, part of SSI response
- 3D, 1C, add
  SSI components
- Linear elastic material
- Inelastic material



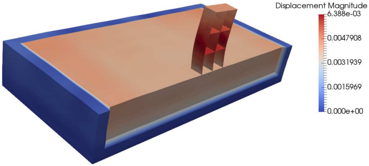
ESSI Modeling Phases

- Eigenvalue analysis

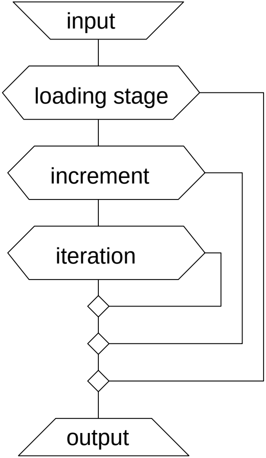


ESSI Modeling Phases

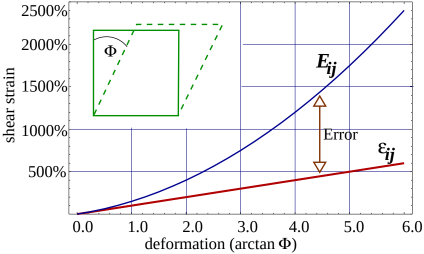
- Synthesis: full ESSI model



Nonlinear Modeling, Loading Stages



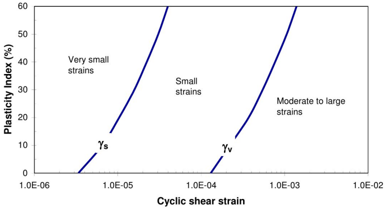
Small Deformation Theory!



$$\text{Real deformation: } E_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i} + u_{i,k}u_{k,j}\right)$$

$$\text{Small deformation: } \epsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$$

Equivalent Linear Soil Modeling



CYCLIC SHEAR STRAIN AMPLITUDE γ		BEHAVIOUR	ELASTICITY and PLASTICIY	CYCLIC DEGRADATION in STAURATED SOILS	MODELLING
Very small	$0 \le \gamma \le \gamma_s$	Practically linear	Practically elastic	Non degradable	Linear elastic
Small	$\gamma_s \le \gamma \le \gamma_v$	Non-linear	Moderately elasto-plastic	Practically non-degradable	Viscoelastic Equivalent linear
Moderate to large	$\gamma_v \le \gamma$	Non-linear	Elasto-plastic	Degradable	Non-linear

(Pecker, Johnson, Jeremić. Seismic Soil Structure Interaction for Design and Assessment of Nuclear Installations. ISBN-978-92-0-143021-2, UN-IAEA-TECDOC-1990, 2022)

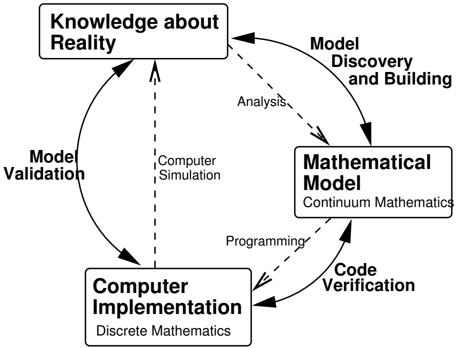
Quality Assurance: Verification and Validation

- Verification: provides evidence that the model is solved correctly, Mathematics issue.

- Validation: provides evidence that the correct model is solved, Physics issue.

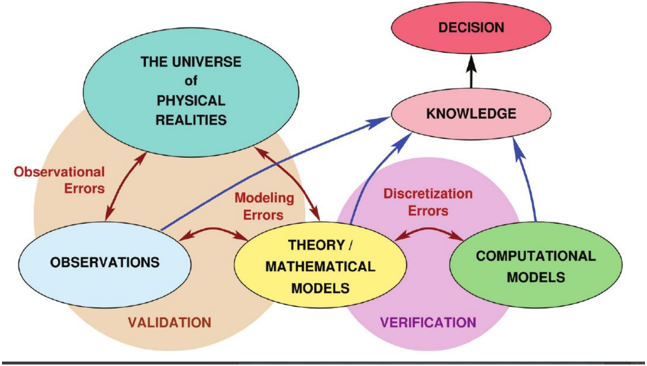
- Prediction: use of computational model to foretell the state of a physical system under consideration under conditions for which the computational model has not been validated.

Role of Verification and Validation



Oberkampf et al.

Role of Verification and Validation



Oden et al.

Outline

Code Verification

- Process of determining that the numerical algorithms are correctly implemented in the computer code and that these algorithms are functioning as intended (ASME V&V 10)
  - Highly accurate analytical solutions needed
  - Method of manufactured solutions
  - Simple physics, simple BC, mesh refinment
  - Tested features are uncoupled from other code options

Solution Verification

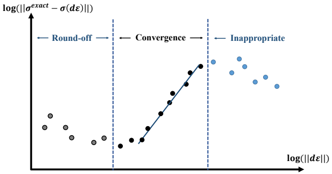
- Numerical error estimation, using methods different accuracy methods
  - Richardson extrapolation
  - Recovery methods
  - Sensitivities

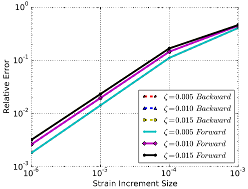
Verification

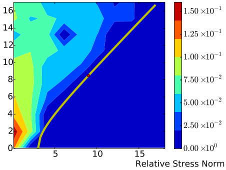
- Constitutive integration
- Static and dynamic behavior of single phase solids
- Static and dynamic behavior of fully and partially saturated, fully coupled, porous solid-pore fluid problems
- Static and dynamic behavior of structural elements
- Static and dynamic behavior of special elements (contacts-interface/gap-frictional/dry-saturated,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

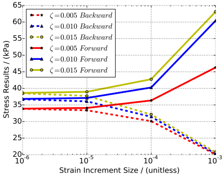
Constitutive Integration Verification

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



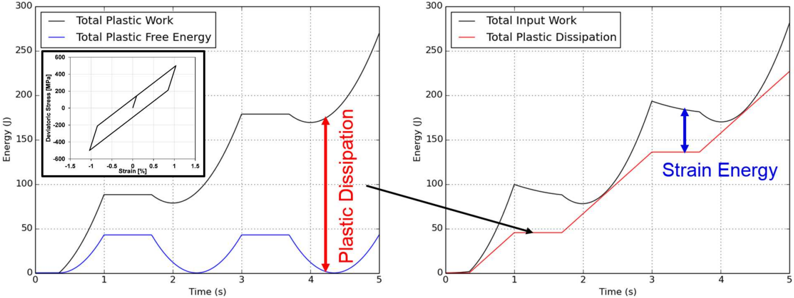




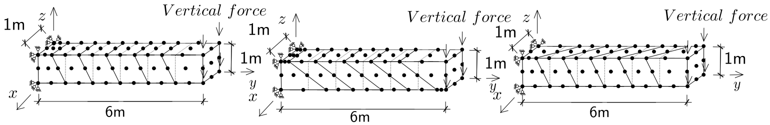


Plastic Energy Dissipation

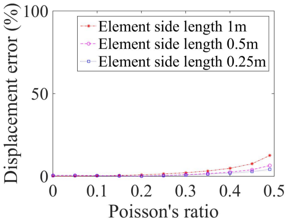
- Single elastic-plastic element under cyclic shear loading
  - Difference between plastic work and plastic dissipation
  - Plastic work can decrease
  - Plastic dissipation always increases



Verification: Irregular Solids and Poisson's Ratio

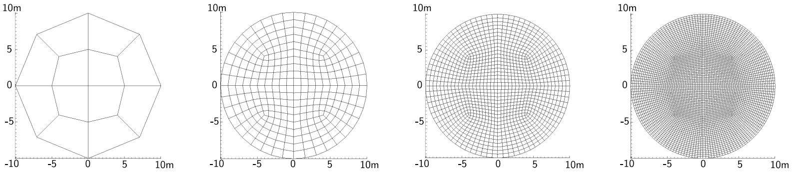


Force direction	Shape 1	Shape 2	Shape 3
Vertical (z)	0.40%	0.85%	0.60%
Transverse (y)	0.54%	3.67%	0.46%

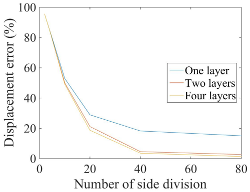


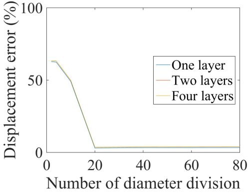
Poisson's ratio	27NodeBrick displacement	Theory displacement	Error
0.00	8.797E-04 m	8.784E-04 m	0.15%
0.05	8.801E-04 m	8.791E-04 m	0.11%
0.10	8.799E-04 m	8.799E-04 m	0.01%
0.15	8.792E-04 m	8.806E-04 m	0.16%
0.20	8.778E-04 m	8.813E-04 m	0.40%
0.25	8.758E-04 m	8.821E-04 m	0.71%
0.30	8.730E-04 m	8.828E-04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

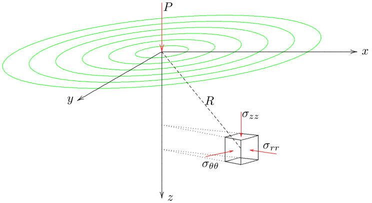


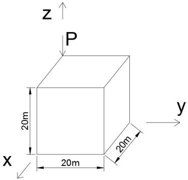
- Simply supported and clamped ends
- Timoshenko's analytic solutions

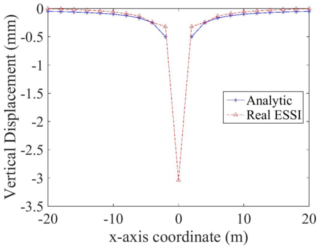


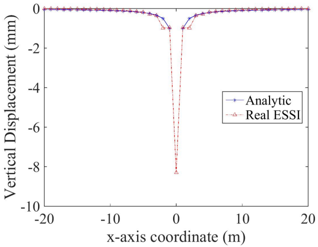


Verification of Boussinesq Problem

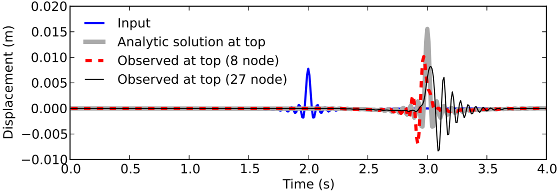


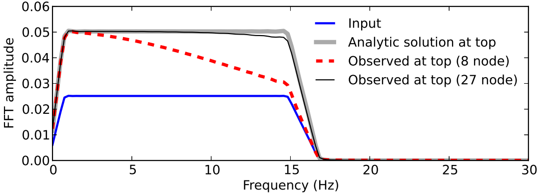






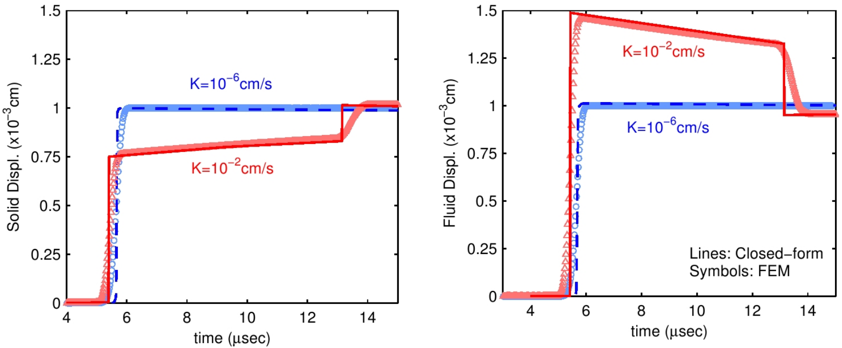
Wave Propagation, Mesh Size Effects





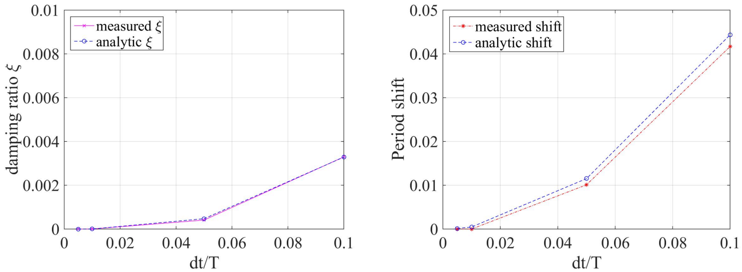
(Case 1, Vs = 1000 m/s, Cutoff Fq. = 15 Hz, E. Size = 20 m)

Verification for Fully Coupled Problems

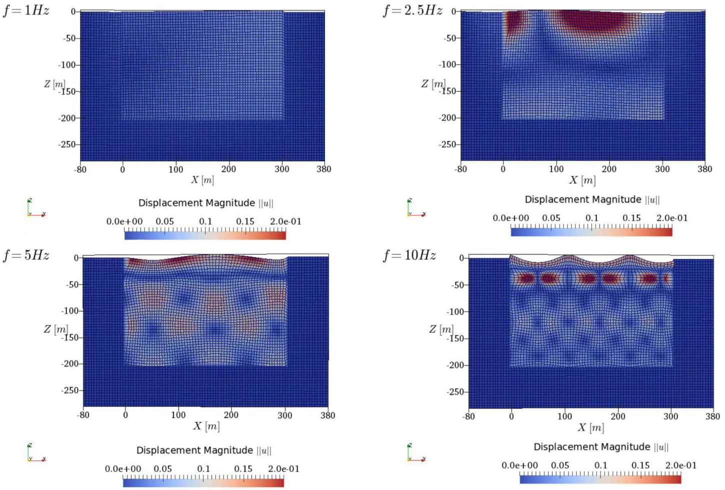


Dynamic Time Stepping Verification

Hilber-Hughes-Taylor $\alpha = -0.2$

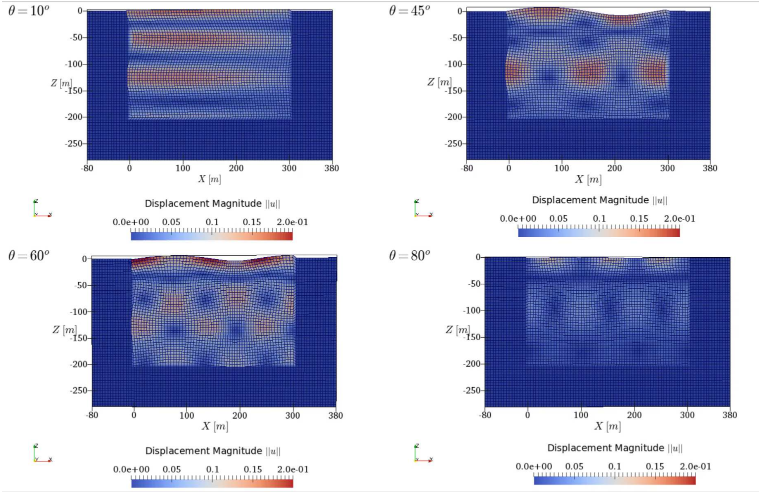


Free Field, Variation in Input Frequency, $\theta = 60^o$



(MP4)

Free Field, Variation in Input Wave Angle, $f = 5$Hz



(MP4)

Outline

Validation

Quantification of uncertainties and errors in the computational model and the experimental measurements

- Goals on validation
  - Tactical goal: Identification and minimization of uncertainties and errors in the computational model
  - Strategic goal: Increase confidence in the quantitative predictive capability of the computational model
- Strategy is to reduce as much as possible the following:
  - Computational model uncertainties and errors
  - Random, precision errors in the experiments
  - Bias, systematic errors in the experiments
  - Incomplete physical characterization of the experiment

Types of Physical Experiments

- Traditional, physics discovery experiments

- Validation experiments

Traditional Experiments

- Improve the fundamental understanding of physics
- Improve the mathematical models for physical phenomena
- Assess component performance

Validation Experiments

- Model validation experiments
- Designed and executed to quantitatively estimate mathematical model's ability to simulate well defined physical behavior
- The simulation tool (SimTool) (conceptual model, computational model, computational solution) is the customer!

Validation Experiments

- A validation experiment should be jointly designed and executed by experimentalist and analyst
  - Need for close working relationship from inception to documentation
  - Elimination of typical competition
  - Complete honesty concerning strengths and weaknesses of both experimental and computational simulations
- A validation experiment should be designed to capture the relevant physics
  - Measure all important modeling data in the experiment
  - Characteristics and imperfections of the experimental facility should be included in the model

Validation Experiments (contd)

- A validation experiment should use any possible synergism between experiment and computational approaches
  - Offset strength and weaknesses of computations and experiments
  - Use high confidence simulations for simple physics to calibrate of improve the characterization of the experimental facility
  - Conduct experiments with a hierarchy of physics complexity to determine where the computational simulation breaks (remember, SimTool is the customer!)
- Maintain independence between computational and experimental results
  - Blind comparison, the computational simulations should be predictions
  - Neither side is allowed to use fudge factors, parameters

Validation Experiments (contd)

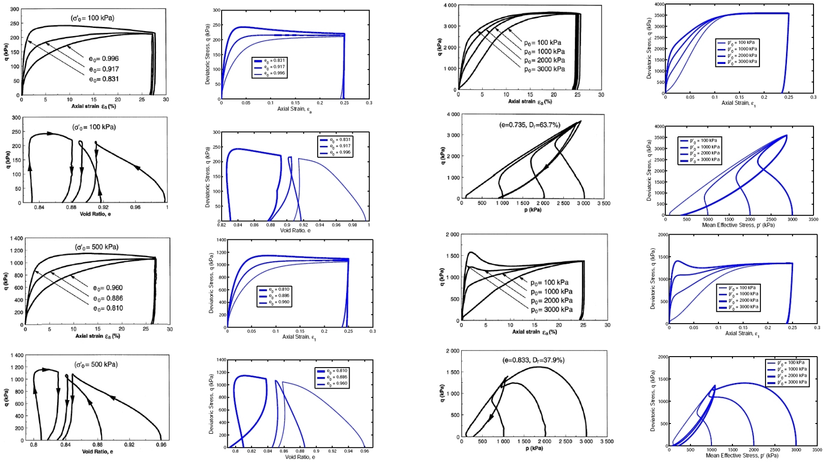
- Validate experiments on unit level problems, hierarchy of experimental measurements should be made that present an increasing range of computational difficulty
  - Use of qualitative data (visualization) and quantitative data
  - Computational data should be processed to match the experimental measurement techniques

- Experimental uncertainty analysis should be developed and employed
  - Distinguish and quantify random and correlated bias errors
  - Use symmetry arguments and statistical methods to identify correlated bias errors
  - Make uncertainty estimates on input quantities needed by the SimTool

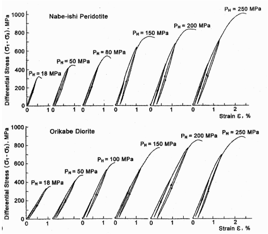
Validation Experiments

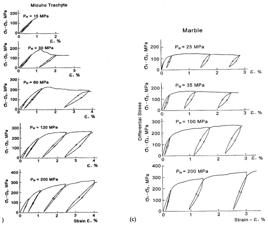
- Experimental data for all components of infrastructure systems
- Laboratory or real object measurement data
- Unit tests
- Subsystem tests
- Complete infrastructure system test

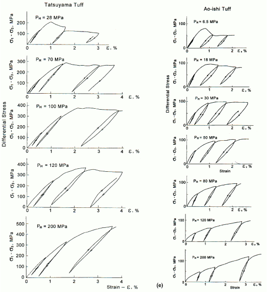
Validation, Material Behavior, Sand



Nonlinear, Inelastic Behavior of Rock

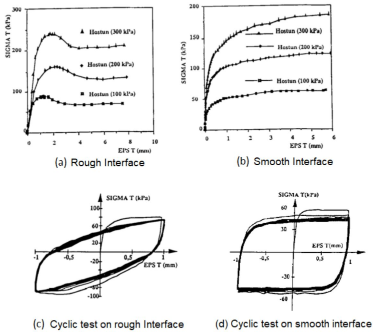






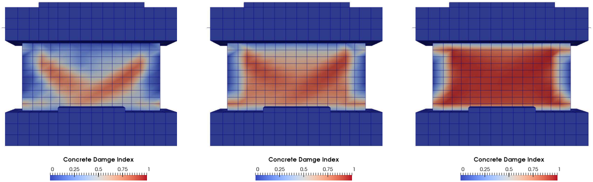
(Stavrogin et al 2001)

Nonlinear, Inelastic Behavior of Interfaces/Joints

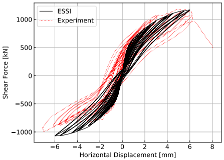


(Shahrour and Rezaie (1997))

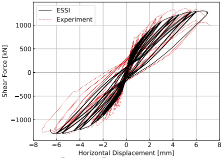
Validation, Material, ASR Concrete



damage at: u_y = 1.4 mm u_y = 1.8 mm u_y = 3.0 mm



Regular concrete



ASR Concrete

Outline

Summary

- Quality Control and Assurance is of utmost importance for numerical analysis
  - Engineer controls analysis quality
  - Analysis program
- Modeling, epistemic uncertainties
- Parametric, aleatory uncertainties
- Physics Discovery and Validation experiments
- TJU NFEES will make significant contribution !