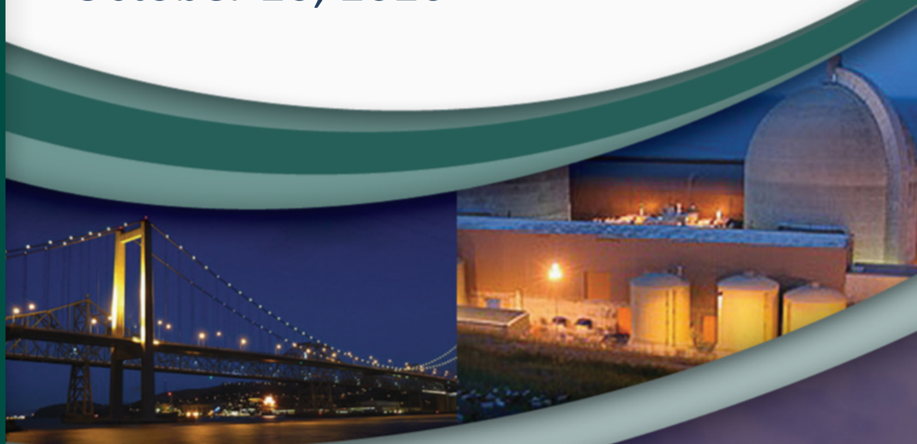
Integrated Nonlinear SSI Analysis: the CGD Challenge

Natalie Doulgerakis, SC Solutions
Payman Tehrani, PI, SC Solutions
Ben Kosbab, SGH
Andrew Whittaker, Consultant
Michael Cohen, TerraPower

October 20, 2020



Acknowledgement

This material is based upon work supported by the Department of Energy under Award Number DE-NE0008857.

Disclaimer: This material was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

REDUCE COST of new reactors

by enabling

modern **SEISMIC ANALYSIS**

through **SOFTWARE CGD** guidance

and increased

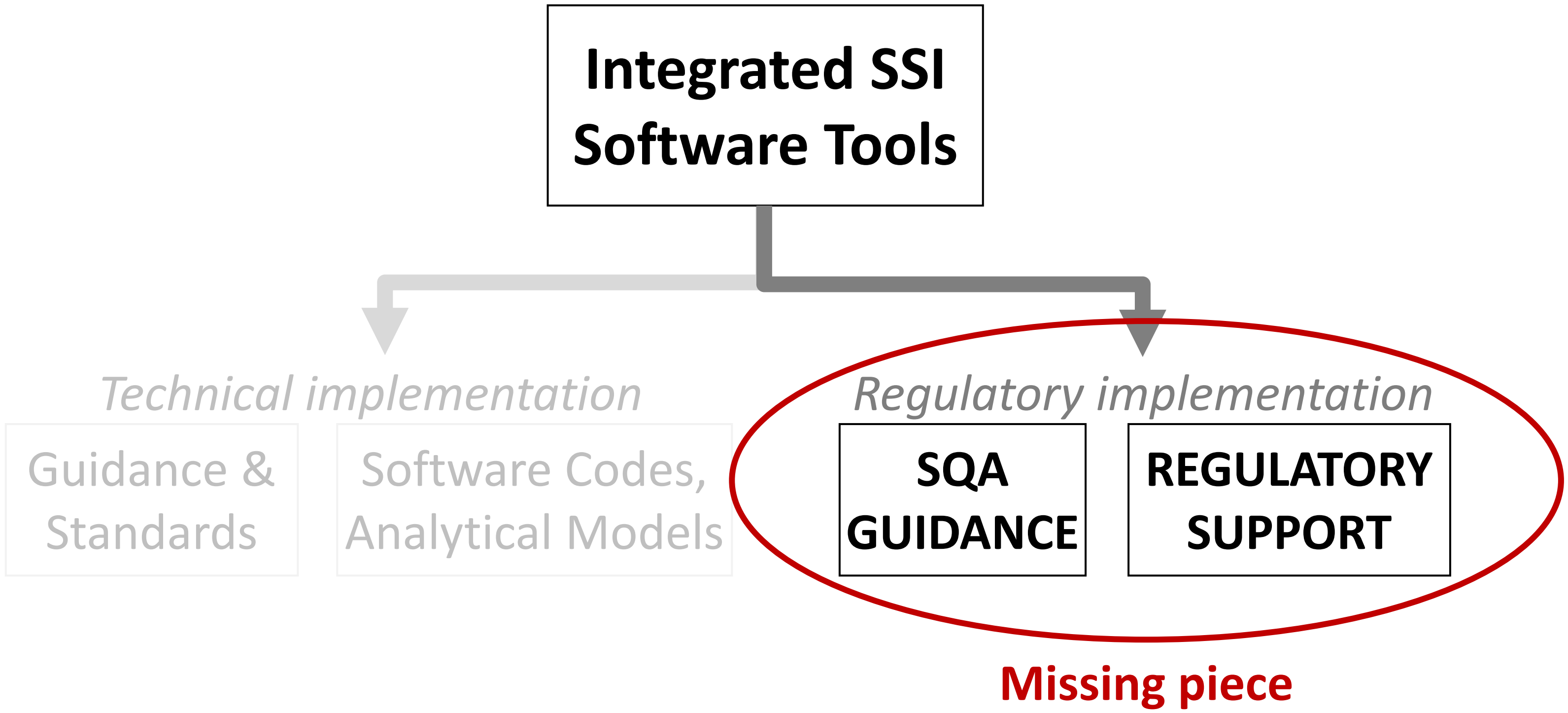
REGULATOR CONFIDENCE.

Licensing framework

Integrated SSI Software Tools

- *Technical implementation*
  - **Guidance & Standards**
  - **Software Codes, Analytical Models**
- *Regulatory implementation*
  - **SQA GUIDANCE**
  - **REGULATORY SUPPORT**

Licensing framework



Project outcomes

U.S. Department of Energy
Federal Identification Number: DE-NE0008857

CGD Guidance Document

Test Matrix			
Nonlinear Behavior	**Software Feature**	**Response Mode**	**Test Cases**
Seismic Isolation	Elastomeric isolator element	Horizontal cyclic shear	
		Vertical axial stiffness	
	Sliding isolator element	Horizontal cyclic shear	
		Vertical axial stiffness	

Test Cases

Hysteretic response of a lead-rubber isolator subjected to harmonic and three-directional earthquake time series.

Objective:

To verify the capability of an isolator element to simulate the nonlinear hysteretic response of a lead-rubber (LR) isolator subjected to sinusoidal and three-directional earthquake inputs.

Problem des

The LR bear … s, and a central lead core tha … e modeled as a combination … r of the central lead core. Th … 6) and extended by Nagarajai … the basic hysteretic model of the LR bearing in shear. It is characterized by the strength at zero-displacement (Q_d), (i.e., characteristic strength), post-yield stiffness (k_s), and the elastic stiffness (k_i). The yield strength and yield displacement are denoted by F_y and u_y, respectively.

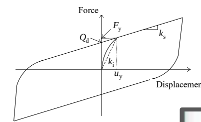


Figure 1. Hysteretic behavior of the LR bearin

Kumar *et al.* (2015) developed a mathematical model for LR isolator wi hysteretic response in shear, strength degradation due to heating of the l cavitation in axial tension, and buckling in axial compression.

Herein, the isolator element need simulate only bilinear hysteretic respo shown in Figure 1, and exhibit linear elastic behavior in the axial, rotatic For the test cases, the isolator is to be modeled as a two-node element w node. The axial direction (i.e., vertical orientation) of the isolator elemer directions are the local-*y* and local-*z* axes.

Case 1: A massless LR isolator element is fixed at node 1. A three-cycle with increasing amplitudes of 100 mm, 150 mm, and 200 mm, is applied direction (see Figure 2a), at a frequency of 0.5 Hz. The rotational degree restrained.

Case 2: A massless LR isolator element is subjected to three-directional earthquake inputs at node 1 as shown in Figure 2b. The rotational degree

Outreach

Legacy SSI approach

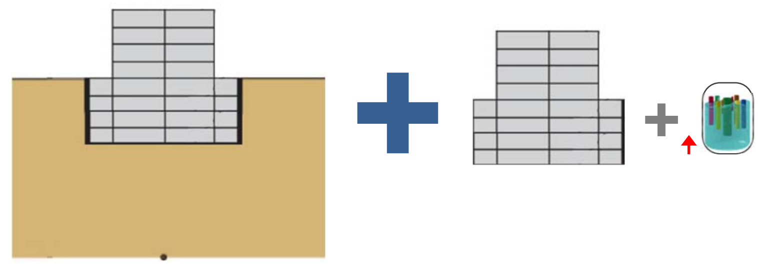
Design demands

SSI

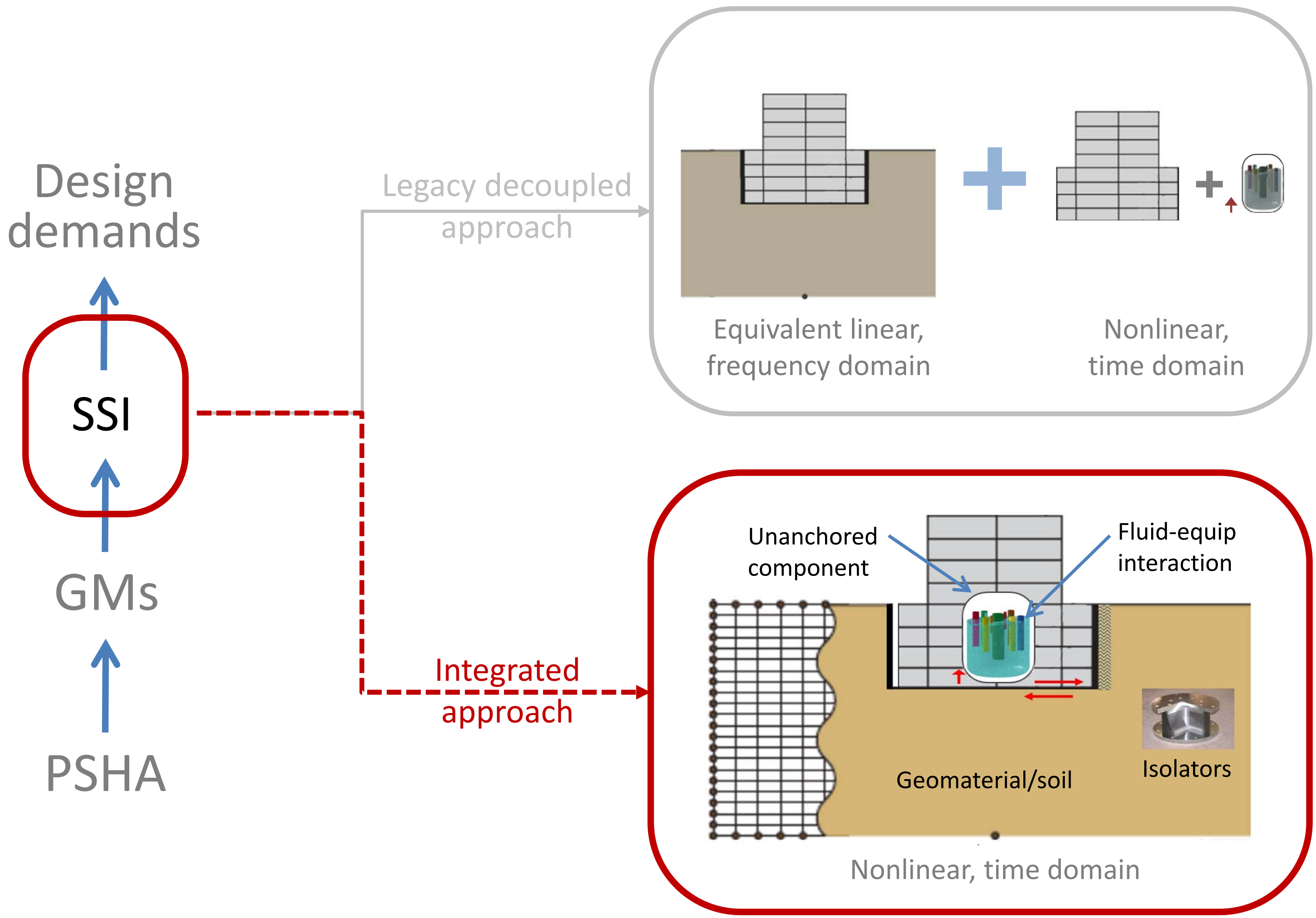
GMs

PSHA

Legacy decoupled approach



Integrated SSI approach



Commercial grade dedication

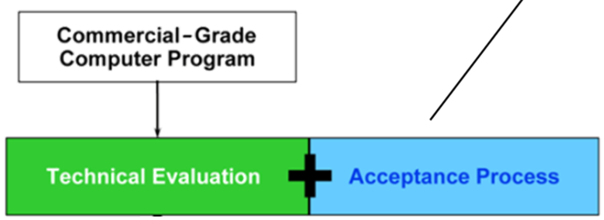
10 CFR Part 21: Dedication

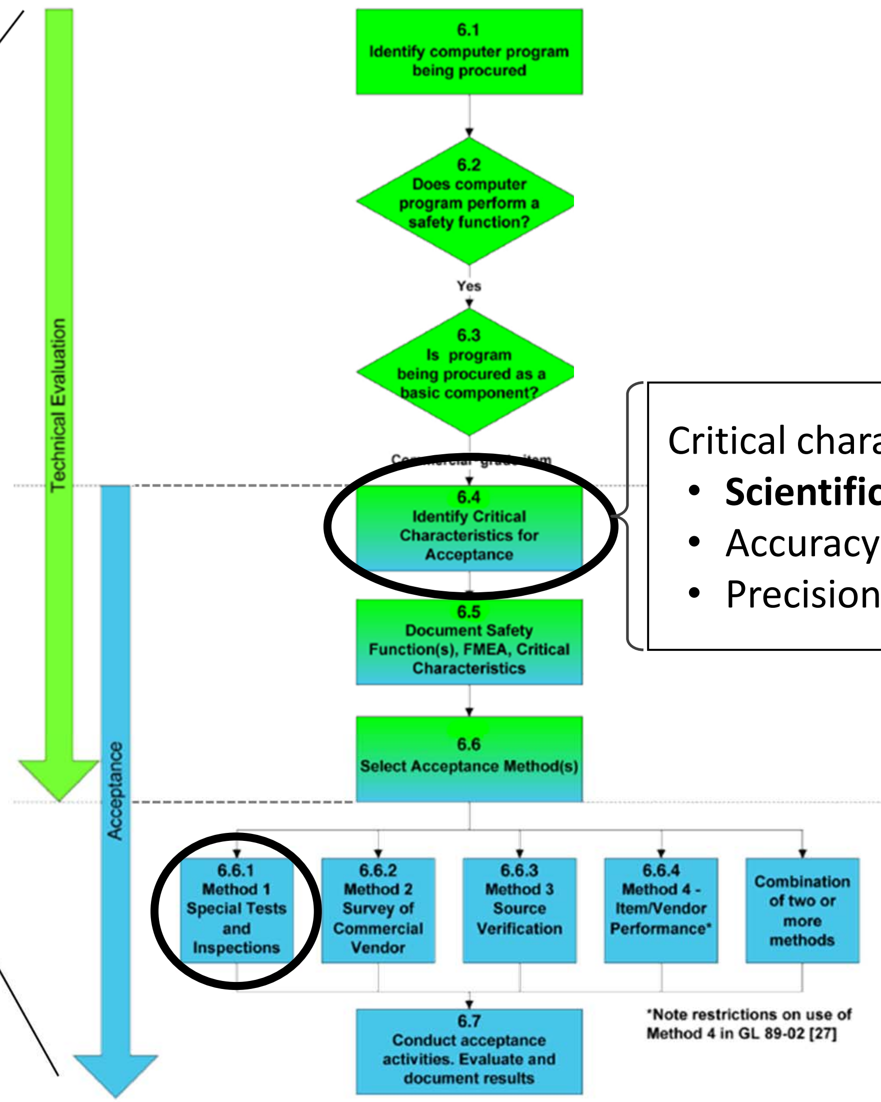
Provide reasonable assurance item will perform its intended safety function

Achieved by identifying and verifying acceptability of critical characteristics

CGD of analysis software

EPRI 1025243, Rev. 1
NRC Reg. Guide 1.231



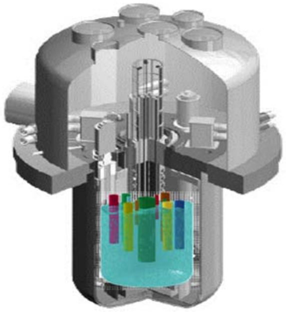


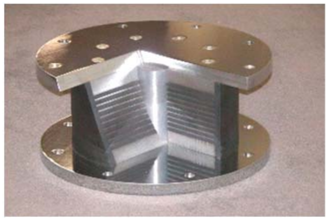
Critical characteristics

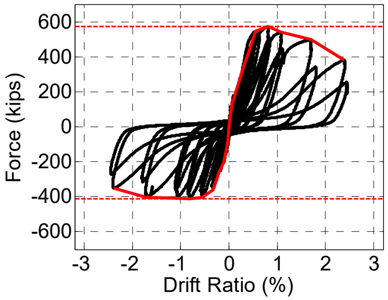
- **Scientific basis**
- Accuracy
- Precision

Prioritized nonlinear behaviors

- Fluid-structure interaction
- Seismic isolation and damping systems
- Geomaterials (i.e., soil)
- Reinforced concrete
- Structural steel
- Interface/contact (incl. RV support)
- Deep embedment



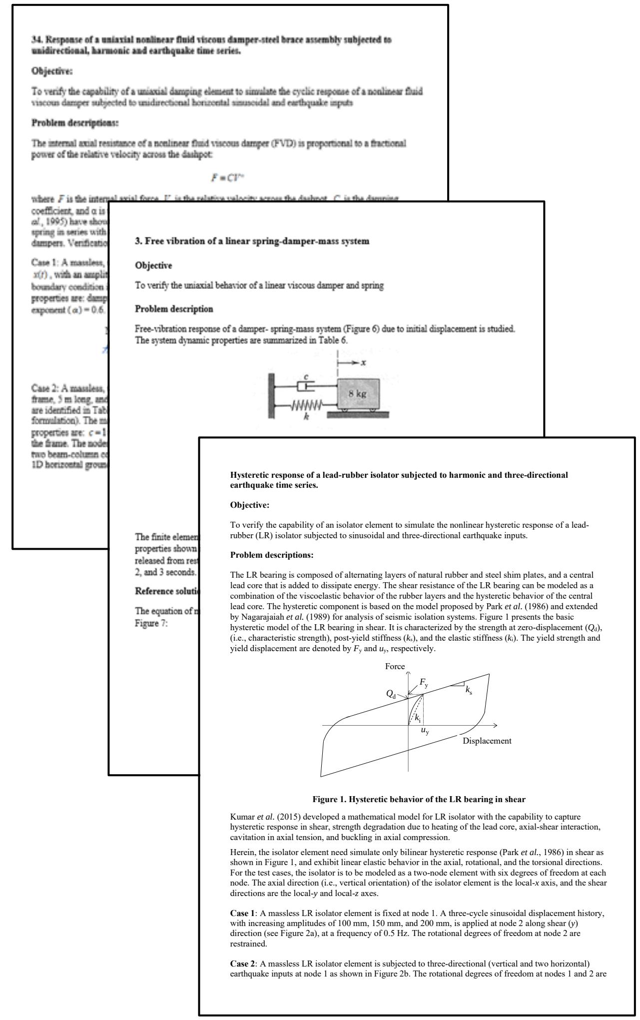




Test matrix excerpt

Test Matrix Excerpt			
Nonlinear Behavior	**Software Feature**	**Response Mode**	**Test Cases**
Seismic Isolation	Elastomeric isolator element	Horizontal cyclic shear	2, 3, 12
		Vertical axial stiffness	3, 12
	Sliding isolator element	Horizontal cyclic shear	3, 13
		Vertical axial stiffness	3, 13

Test Cases



34. Response of a uniaxial nonlinear fluid viscous damper-steel brace assembly subjected to unidirectional, harmonic and earthquake time series.

Objective:

To verify the capability of a uniaxial damping element to simulate the cyclic response of a nonlinear fluid viscous damper subjected to unidirectional horizontal sinusoidal and earthquake inputs

Problem descriptions:

The internal axial resistance of a nonlinear fluid viscous damper (FVD) is proportional to a fractional power of the relative velocity across the dashpot:

$$F = CV^{\alpha}$$

3. Free vibration of a linear spring-damper-mass system

Objective

To verify the uniaxial behavior of a linear viscous damper and spring

Problem description

Free-vibration response of a damper- spring-mass system (Figure 6) due to initial displacement is studied. The system dynamic properties are summarized in Table 6.

Hysteretic response of a lead-rubber isolator subjected to harmonic and three-directional earthquake time series.

Objective:

To verify the capability of an isolator element to simulate the nonlinear hysteretic response of a lead-rubber (LR) isolator subjected to sinusoidal and three-directional earthquake inputs.

Problem descriptions:

The LR bearing is composed of alternating layers of natural rubber and steel shim plates, and a central lead core that is added to dissipate energy. The shear resistance of the LR bearing can be modeled as a combination of the viscoelastic behavior of the rubber layers and the hysteretic behavior of the central lead core. The hysteretic component is based on the model proposed by Park *et al*. (1986) and extended by Nagarajaiah *et al.* (1989) for analysis of seismic isolation systems. Figure 1 presents the basic hysteretic model of the LR bearing in shear. It is characterized by the strength at zero-displacement (Q_d), (i.e., characteristic strength), post-yield stiffness (k_s), and the elastic stiffness (k_i). The yield strength and yield displacement are denoted by F_y and u_y, respectively.

Figure 1. Hysteretic behavior of the LR bearing in shear

Kumar *et al*. (2015) developed a mathematical model for LR isolator with the capability to capture hysteretic response in shear, strength degradation due to heating of the lead core, axial-shear interaction, cavitation in axial tension, and buckling in axial compression.

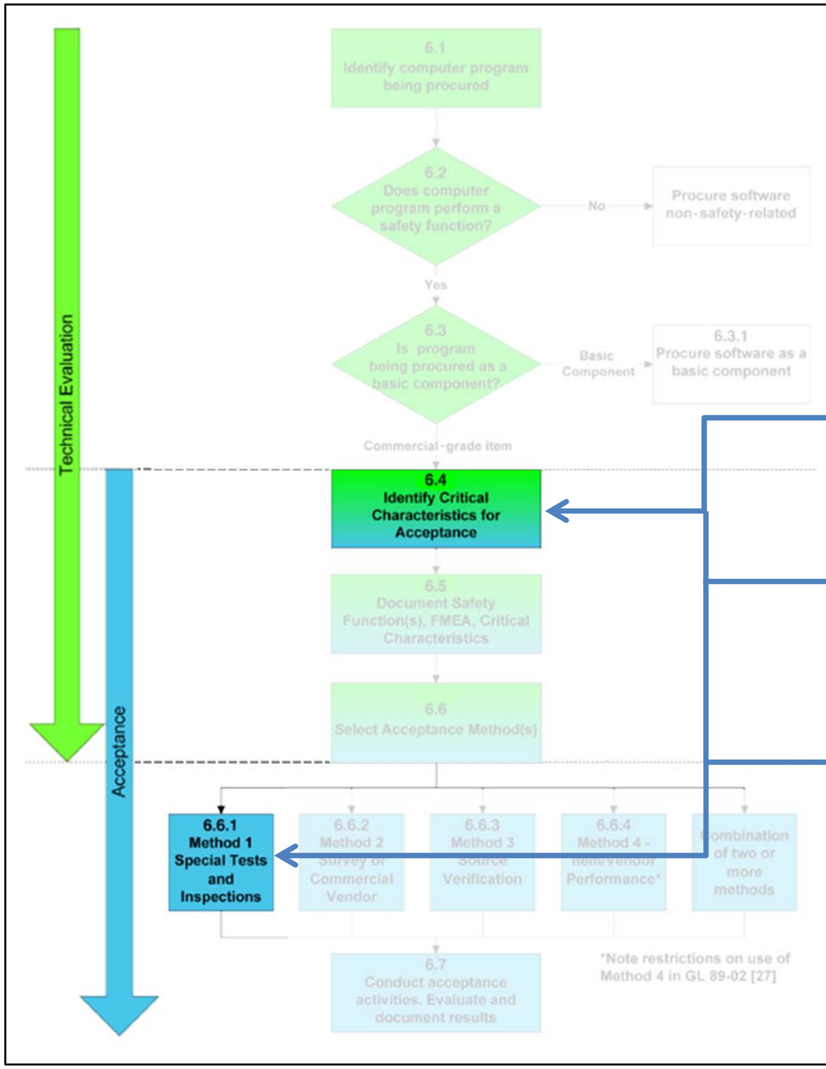
Herein, the isolator element need simulate only bilinear hysteretic response (Park *et al*., 1986) in shear as shown in Figure 1, and exhibit linear elastic behavior in the axial, rotational, and the torsional directions. For the test cases, the isolator is to be modeled as a two-node element with six degrees of freedom at each node. The axial direction (i.e., vertical orientation) of the isolator element is the local-*x* axis, and the shear directions are the local-*y* and local-*z* axes.

Case 1: A massless LR isolator element is fixed at node 1. A three-cycle sinusoidal displacement history, with increasing amplitudes of 100 mm, 150 mm, and 200 mm, is applied at node 2 along shear (*y*) direction (see Figure 2a), at a frequency of 0.5 Hz. The rotational degrees of freedom at node 2 are restrained.

Case 2: A massless LR isolator element is subjected to three-directional (vertical and two horizontal) earthquake inputs at node 1 as shown in Figure 2b. The rotational degrees of freedom at nodes 1 and 2 are

End-user software CGD

Software CGD



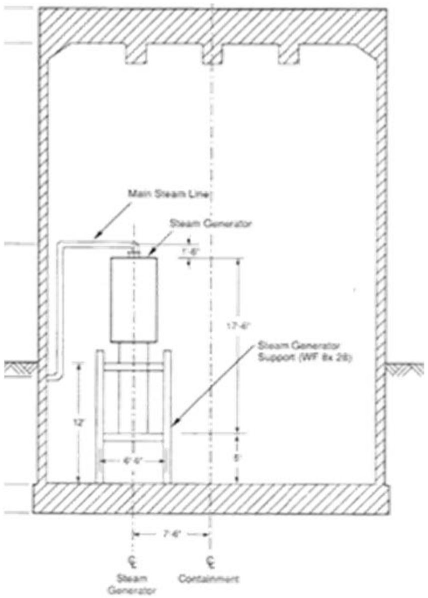
Test matrix and problems

#	Software Feature	Response Mode	Response Parameter	Test Case
1	Fluid element	Impulsive (acoustic)	Frequency and magnitude of pressure waves	(8), (9), (10), (11), (20)
		Convective (sloshing)	Frequency and magnitude of fluid displacement	1, (8), (9)
2	Fluid-structure coupling algorithm	Normal	Force/stress resultant on flexible structure	(8), (9), (10), (11), (20)
3	Elastomeric isolator element	2D horizontal (cyclic shear)	Cyclic force-displacement	2 (12)
		Vertical/axial stiffness	Force-displacement	2 (12)
4	Sliding isolator element	2D horizontal (cyclic shear)	Cyclic force-displacement	(13)
		Vertical/axial stiffness	Force-displacement	(13)
5	Viscous damper	uniaxial, linear		3
6	Metallic yield damper	uniaxial	Cyclic force-displacement	(14)
		Cyclic pure shear (Simple shear)	Cyclic force-displacement	4
7	Geomaterial constitutive model	Wave propagation/SRA, equivalent linear	Free-field response spectra, strain/acc. profile with depth	(15), (21), (25?), (26), (27)
		Inertial/kinematic SSI response, equivalent linear	In-structure response	(21), (26)
		Wave propagation/SRA, nonlinear	Free-field response spectra, strain/acc. profile with depth	(16), (25?), (27?), (28)
		Inertial/kinematic SSI response, nonlinear	In-structure response	(26?)
		Lateral soil pressure	Pressure resultant on structure	(17)
		Uniaxial compression		
		Triaxial compression		

Example Test Cases

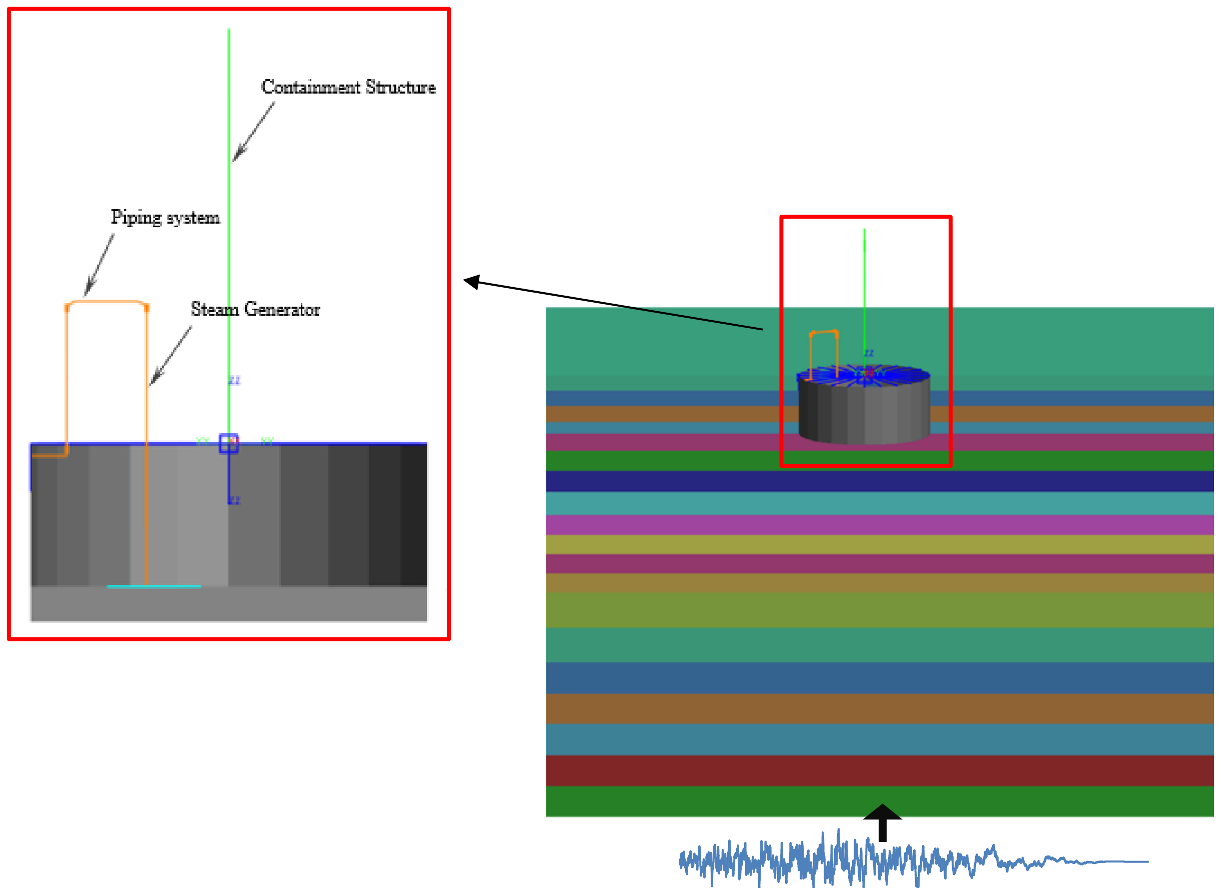
Feature	Software Feature	Response Mode	Response Parameter	Test Case
1	Fluid element	Impulsive (acoustic)	Frequency and magnitude of pressure waves	8, 9, 10, 11, 20, 22
		Convective (sloshing)	Frequency and magnitude of fluid displacement	1, 8, 9
2	Fluid-structure coupling algorithm	Normal	Force/stress resultant on flexible structure	8, 9, 10, 11, 20, 22
3	Elastomeric isolator element	2D horizontal (cyclic shear)	Cyclic force-displacement	12, 2
		Vertical/axial stiffness	Force-displacement	12, 3
4	Sliding isolator element	2D horizontal (cyclic shear)	Cyclic force-displacement	13
		Vertical/axial stiffness	Force-displacement	13, 3
5	Viscous damper	uniaxial, linear		34, 3
6	Metallic yield damper	uniaxial	Cyclic force-displacement	14
7	Geomaterial constitutive model	Cyclic pure shear (Simple shear)	Cyclic shear stress-strain	4, 25, 37
		Wave propagation/SRA, equivalent linear	Free-field response spectra, strain/acc. profile with depth	15, 21, 26, 27, 36
		Inertial/kinematic SSI response, equivalent linear	In-structure response	21, 26
		Wave propagation/SRA, nonlinear	Free-field response spectra, strain/acc. profile with depth	16, 27, 28, 37
		Inertial/kinematic SSI response, nonlinear	In-structure response	26
		Lateral soil pressure	Pressure resultant on structure	17
		Uniaxial compression	TBD	TBD
		Triaxial compression	TBD	TBD
8	Beam fiber section	Axial	Force-displacement	6
		Flexure	Force-displacement	5, 6
		Shear	Force-displacement	5, 6
9	Beam with plastic hinge	Axial	Force-displacement	5, 31
		Flexure	Force-displacement	5, 31
		Shear	Force-displacement	5, 31
10	Shell layered section	In plane membrane actions	Force-displacement	19, 32
		Flexure	Force-displacement	19, 32
11	Concrete material model (Nonlinear/cyclic)	Uniaxial cyclic	Cyclic force-displacement	6
		In-plane membrane cyclic	Cyclic force-displacement	19, 32
12	Rebar material model	Uniaxial cyclic	Cyclic force-displacement	6, 14
13	Structural steel material model	Uniaxial cyclic	Cyclic force-displacement	14
14	Contact algorithm	Normal	Nonlinear compressive and tensile response	23, 24, 35
		Tangential Friction	Static and dynamic contact force	7, 24, 35
15	1D spring elements	uniaxial, linear	Force-displacement	3
		Uniaxial, cyclic nonlinear	Force-displacement	14

Test case: soil-structure response

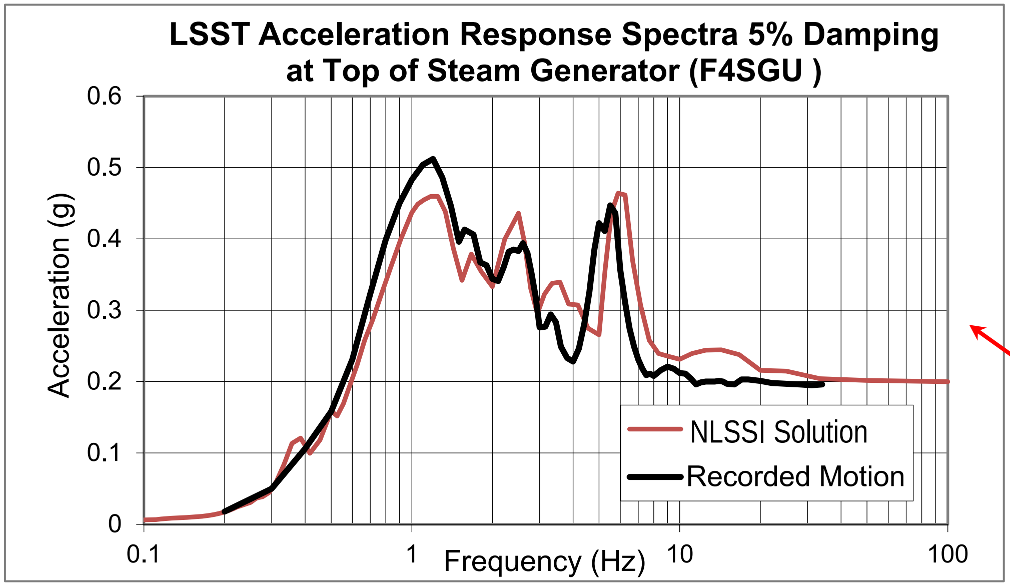


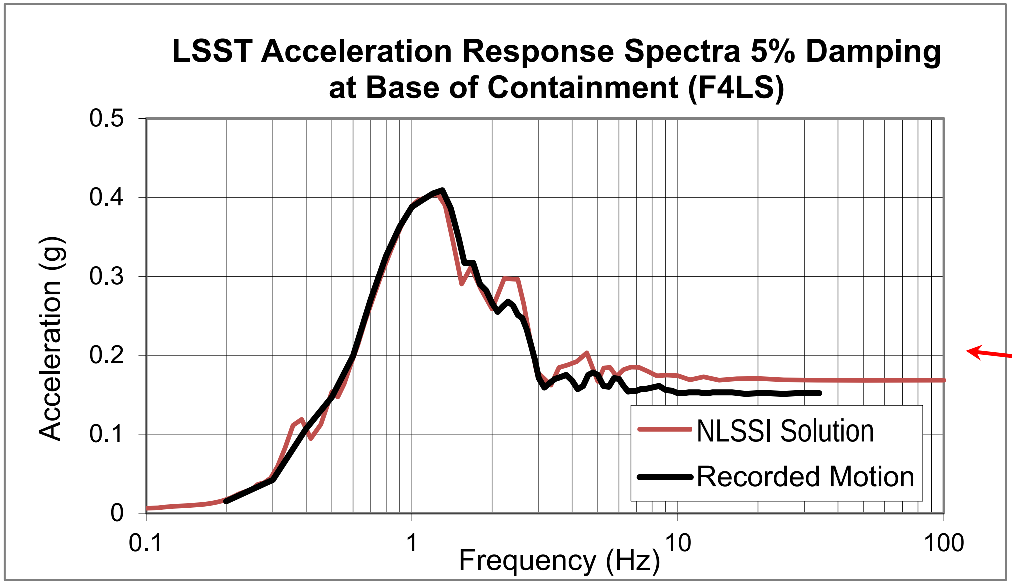
Lotung large scale seismic test SSI experiment

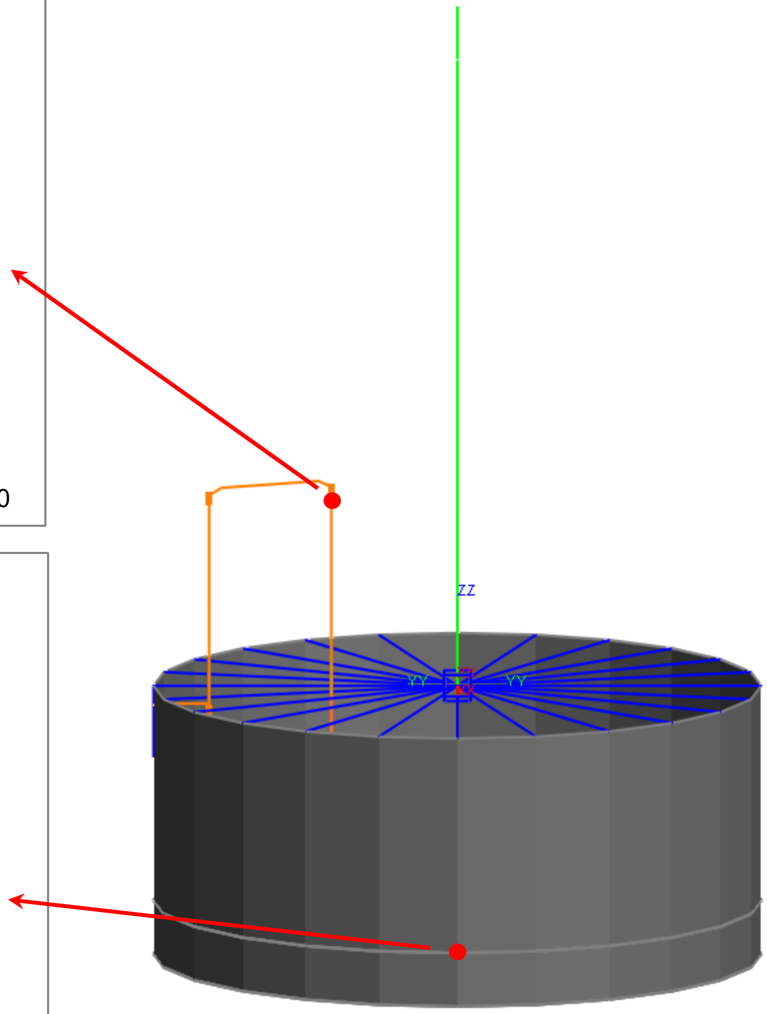
- Equivalent-linear soil properties
- Comparison with recorded response during seismic event



Test case: soil-structure response



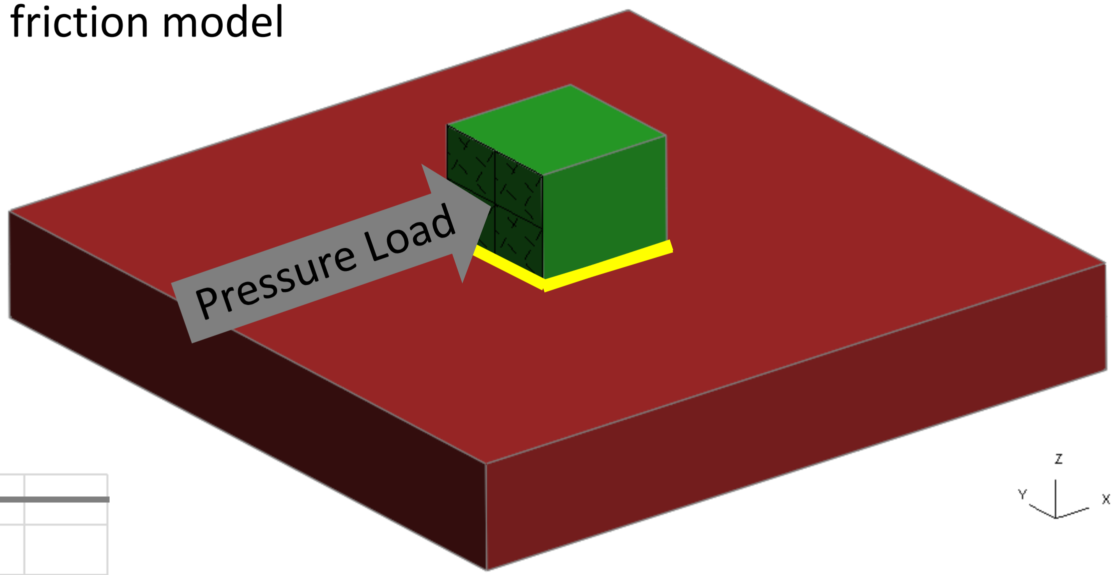


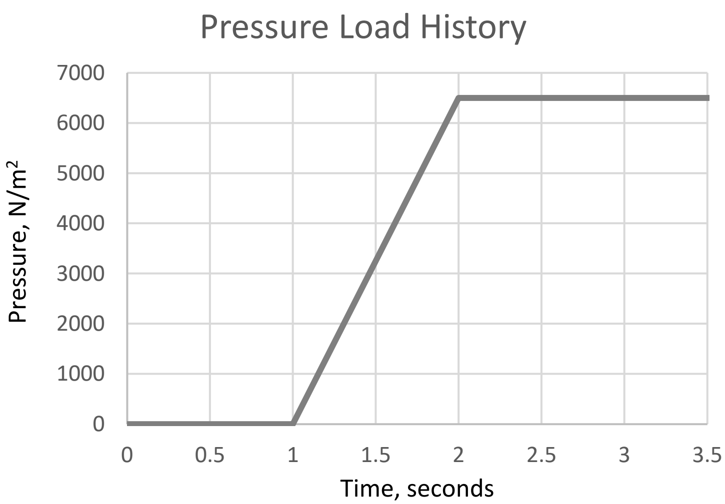


Test case: contact surface sliding

Sliding response of a solid cube

- Contact surface (penalty-based)
- Comparison with Coulomb friction model

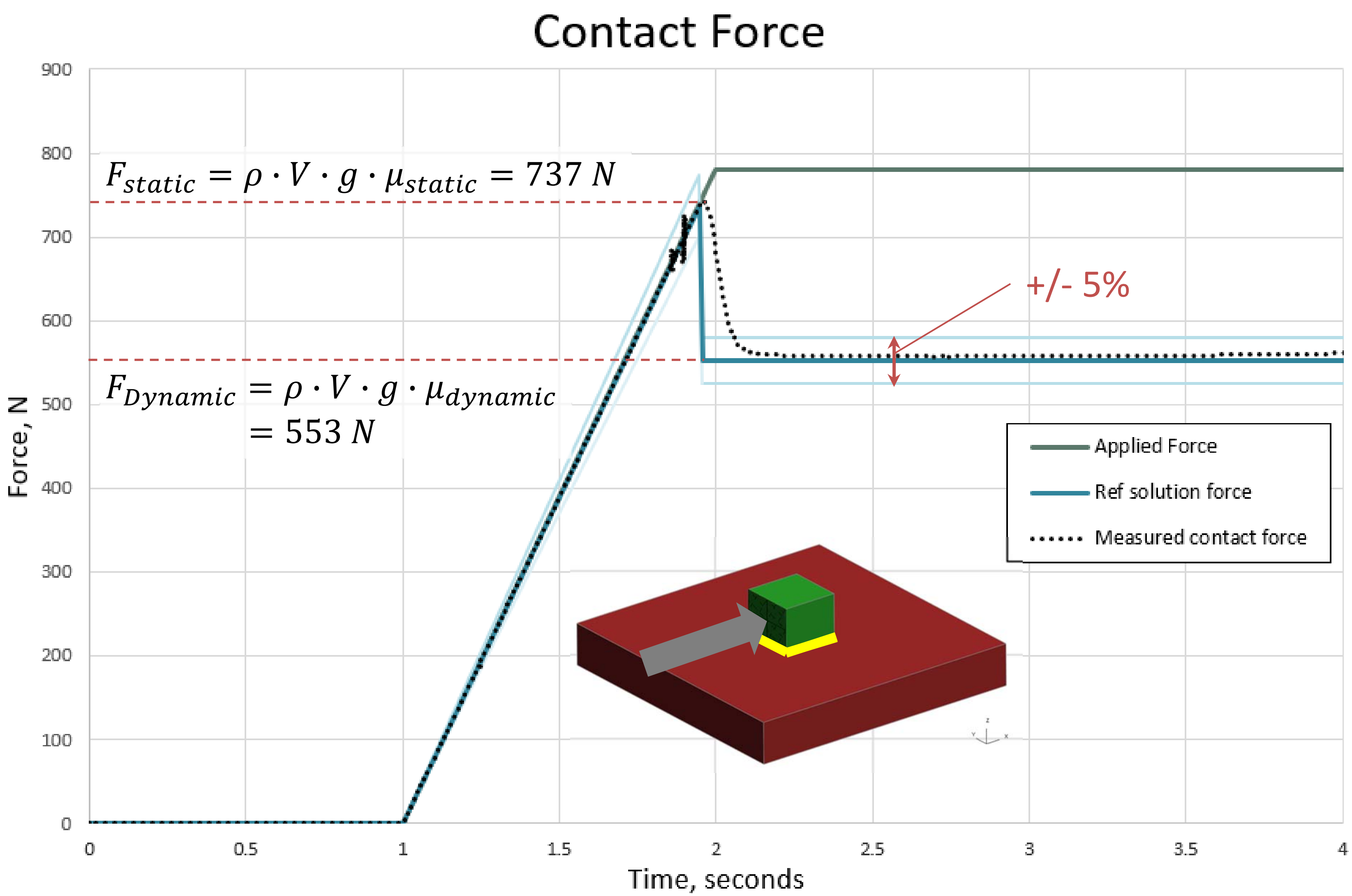




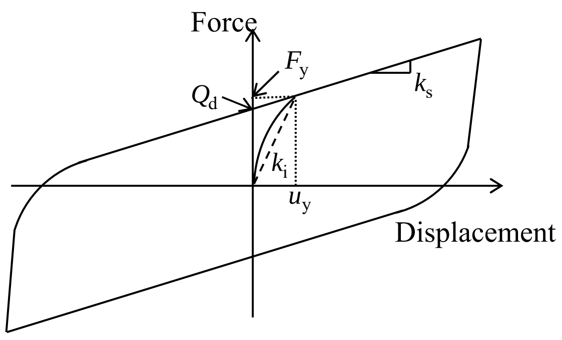
$$F_{static} = \rho \cdot V \cdot g \cdot \mu_{static} = 737\ N$$

$$F_{Dynamic} = \rho \cdot V \cdot g \cdot \mu_{dynamic} = 553\ N$$

Test case: contact surface sliding



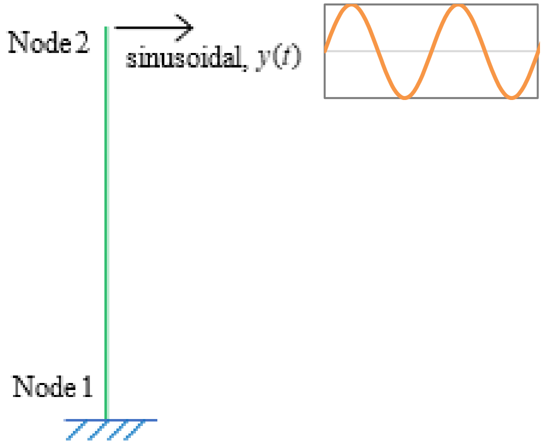
Test case: elastomeric bearing response



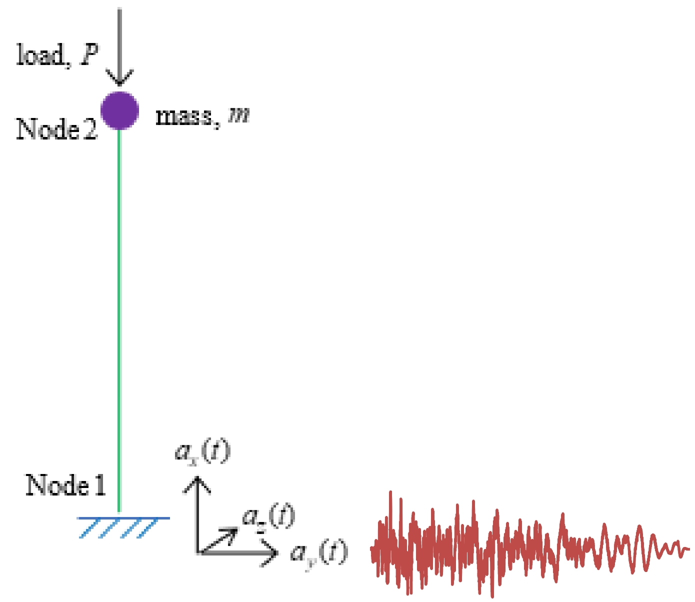
Hysteretic response of lead-rubber isolator

- Bilinear hysteretic shear response
- Linear elastic axial response
- Code-to-code verification

<u>Case 1: 1D sinusoidal displacement</u>

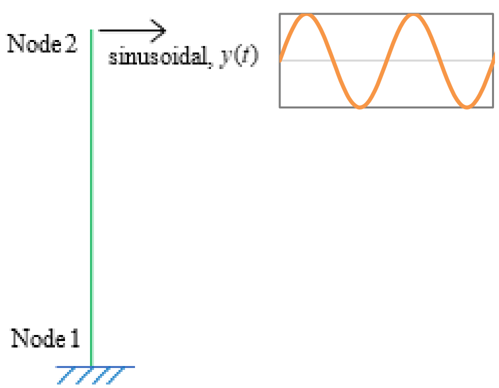


<u>Case 2: 3D EQ acceleration input</u>

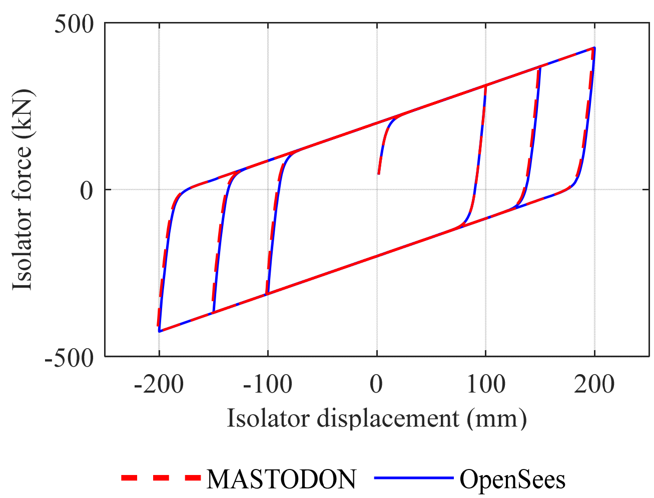


Test case: elastomeric bearing response

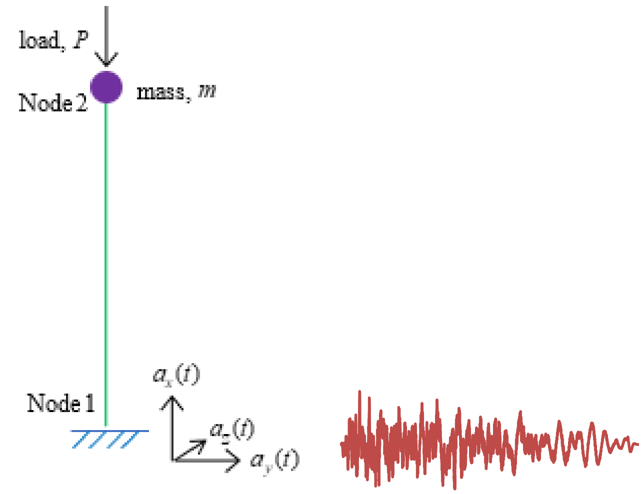
Case 1: 1D sinusoidal displacement



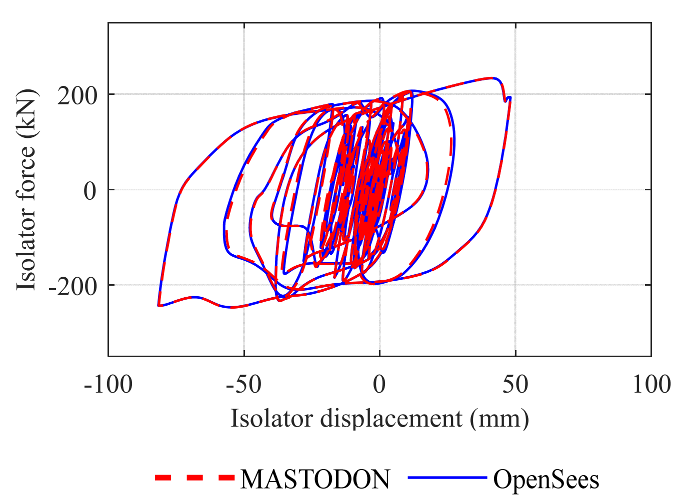
Y direction



Case 2: 3D EQ acceleration input



Y direction



Q&A + DISCUSSION

For Additional Information, Please Contact:

Natalie Doulgerakis, Senior Engineer

ndoulgerakis@scsolutions.com / (408) 962-4028