Experimental and Analytical Studies of Fixed-Base and Seismically Isolated Liquid Storage Tanks

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Acknowledgements

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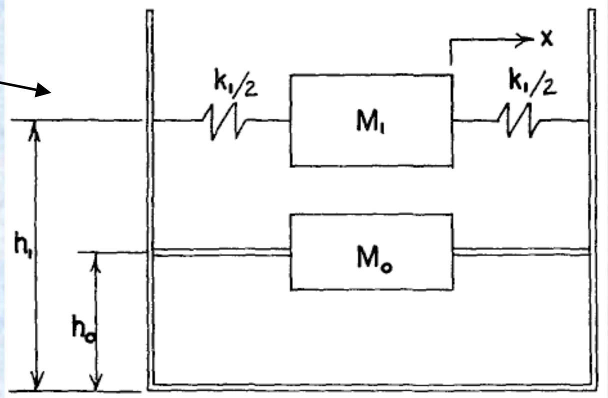
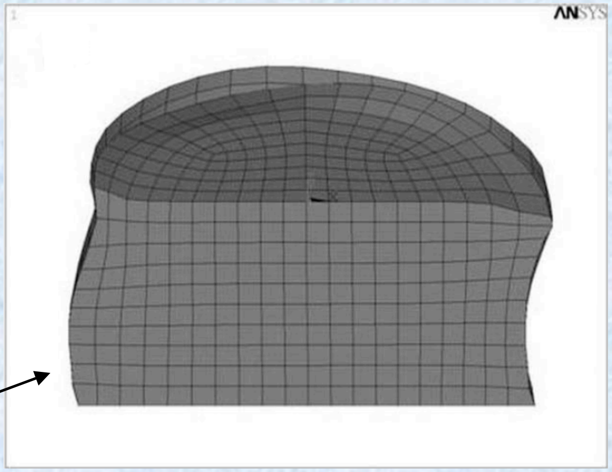
Presentation Outline

- Tank Design and Research Background
- Project Goals
- Experimental Program
- Experiment Results
- Model Validation
- Summary and Conclusions

Tank Research Background

- G.W. Housner (Caltech) – 1957, 1963
- R.W. Clough & students (Berkeley) - 1970s
- A.S. Veletsos (Rice) – 1977, 1984
- M.A. Haroun (UC Irvine) – 1981
- M.S. Chalhoub & J.M. Kelly (Berkeley) – 1988
- Y.P. Wang et.al (Taiwan) - 2001
- M.K. Shrimali & R.S. Jangid (India) – 2002
- V.P. Gregoriou et. al (Greece) – 2005
- I.P. Christovasilis et. Al (Buffalo, NY) – 2008





Tank Design Background

- Based on Rigid Tank Model (Housner, 1963)
  - ACI 350.3
  - AWWA D-100
  - AWWA D-110
  - API 650
- Based on Flexible Tank Models (Veletsos, Yang, 1977) and (Haroun, Housner, 1981)
  - NZSEE
  - Eurocode 8

Project Goals

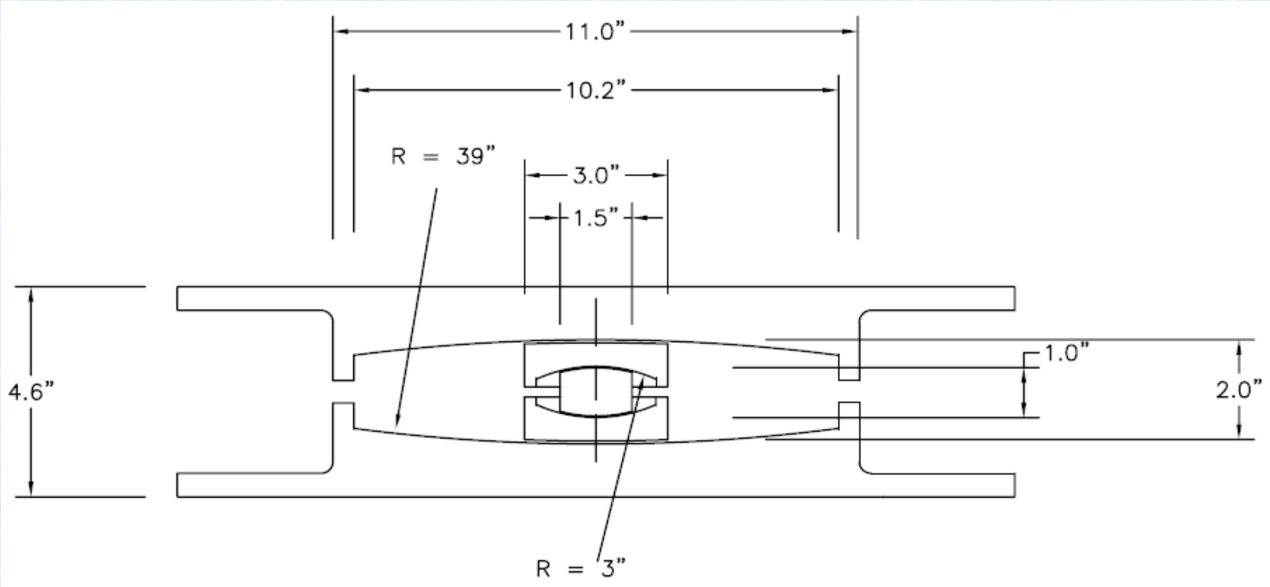
- Perform single and multi-component shaking table tests on fixed-base and seismically isolated tank
- Compare base shear, water sloshing, and tank deformation response for parameters of interest
- Validate numerical mechanical analog tank model
- Compare water sloshing dynamics for 1-, 2-, and 3-component ground motions

Experimental Program

- Vertical Cylindrical Open-Top Steel Tank
  - 6ft dia. x 6ft tall
  - ¼ inch wall and base
  - Unanchored

	empty	18in	36in	54in
Total Weight (kips)	40.58	43.29	46.00	48.71
T1 (sec)	x	1.66	1.45	1.42
T2 (sec)	x	0.83	0.83	0.83
T3 (sec)	x	0.66	0.66	0.66

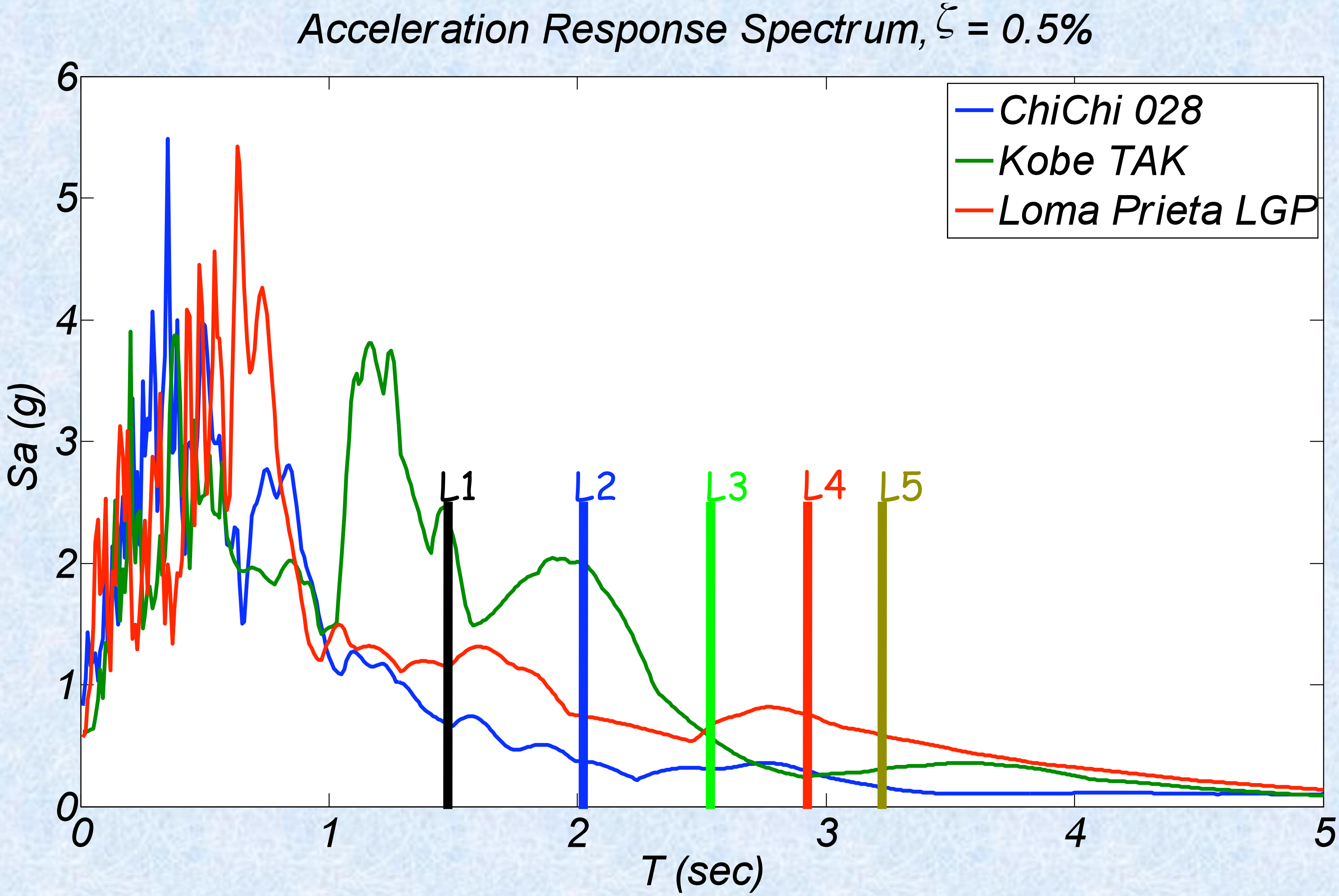
- Seismic Isolators
  - Friction Coefficients [μ_1, μ_2, μ_3] = [0.05, 0.11, 0.11]
  - T_1 = 0.72sec
  - T_2 = 2.03sec
  - T_3 = 2.79sec



Experimental Program

- Ground Motions
  - Loma Prieta (California, 1989)
  - Kobe (Japan, 1995)
  - Chi-Chi (Taiwan, 1999)
- Length Scales 1/5 to 1/2
- Magnitude Scales 1/4 to 1
- Water Levels H/R = 0 (empty) to 1.5 (54in)
- Isolated vs. Fixed Base
- Total of 264 tests conducted

Experimental Program



Different ground motions expected to cause higher water sloshing at different test length scales

Test Setup Construction

Complete Test Setup

Test Setup Construction

The steel frame, isolators, and load cells are carefully assembled in an upside-down position to ensure symmetric and level support.

Test Setup Construction

The supporting structure is flipped and brought to the shaking table using the laboratory crane. The 1-$\frac{1}{4}$"dia. steel rods penetrate table's concrete slab.

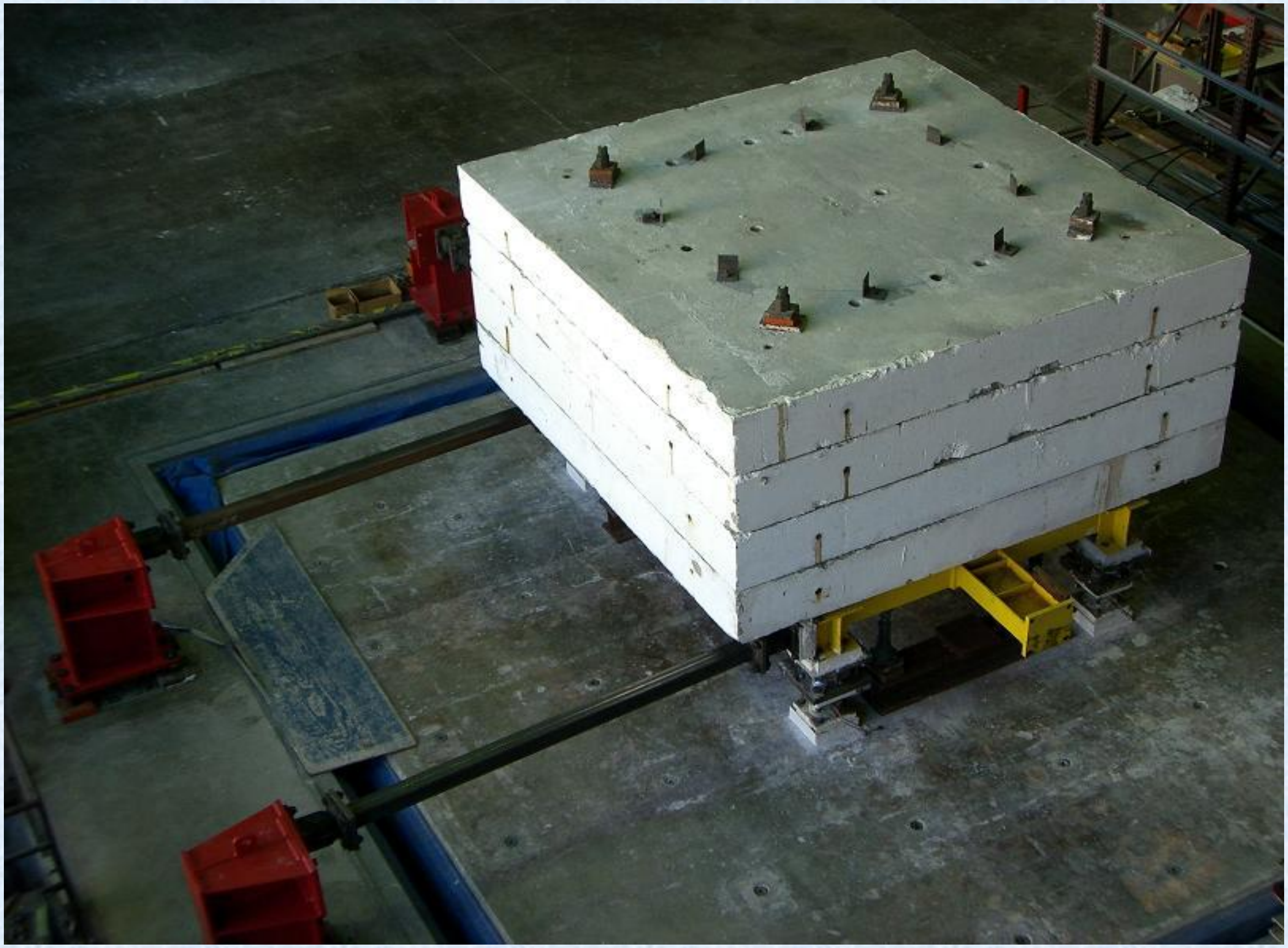
Test Setup Construction

Underneath the shaking table a compressed air gun is used to secure the supporting structure to the table.

Test Setup Construction

17kip concrete blocks are positioned on top of the support. 1-$\frac{1}{4}$"dia. steel rods that will be used to tie the concrete blocks to the steel frame are awaiting their call to duty.

Test Setup Construction



The setup is almost ready for the bearing characterization tests.
The restraining steel braces and two middle concrete blocks
will be removed for the tank tests.

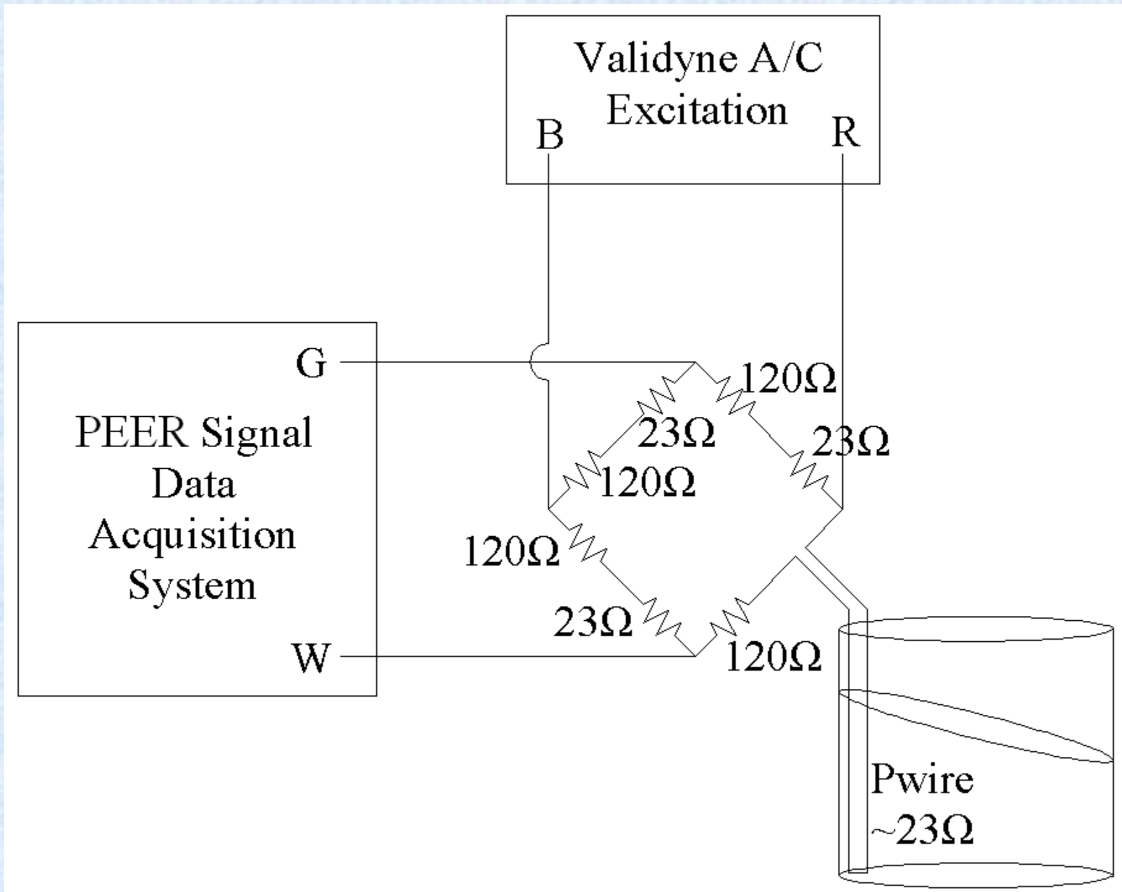
Instrumentation

DCDT's, Linpots and 3-component accelerometers are installed around the base of the tank.

Instrumentation

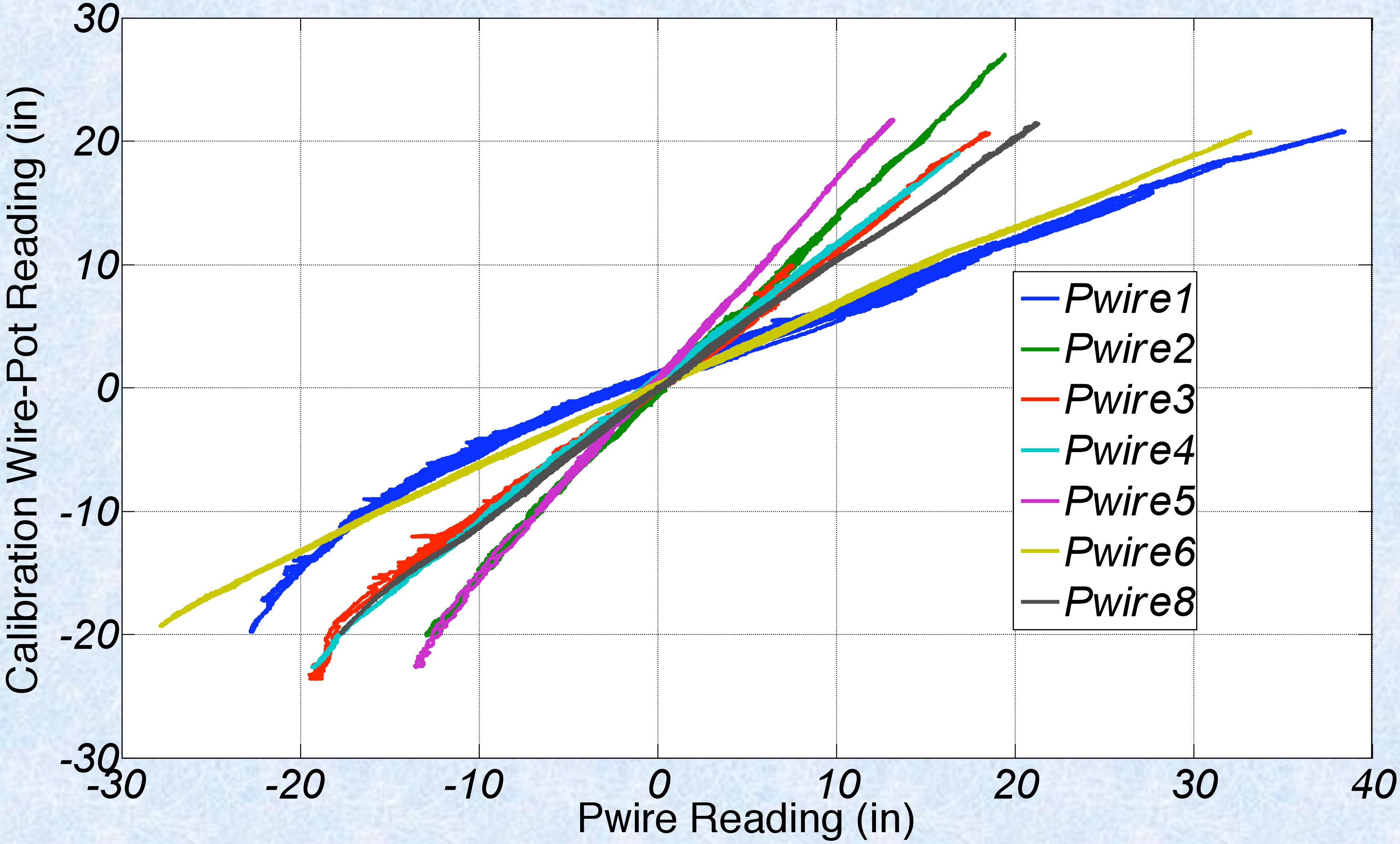
DCDT's, water depth gauges, and 2-component accelerometers
are installed around the top rim of the tank.

Parallel Wire Water Depth Gauge Schematic Representation



The Pwire gauge works as a strain gauge – an imbalance in the Wheatstone bridge is calibrated to change in water depth

Parallel Wire Water Depth Gauge Calibration

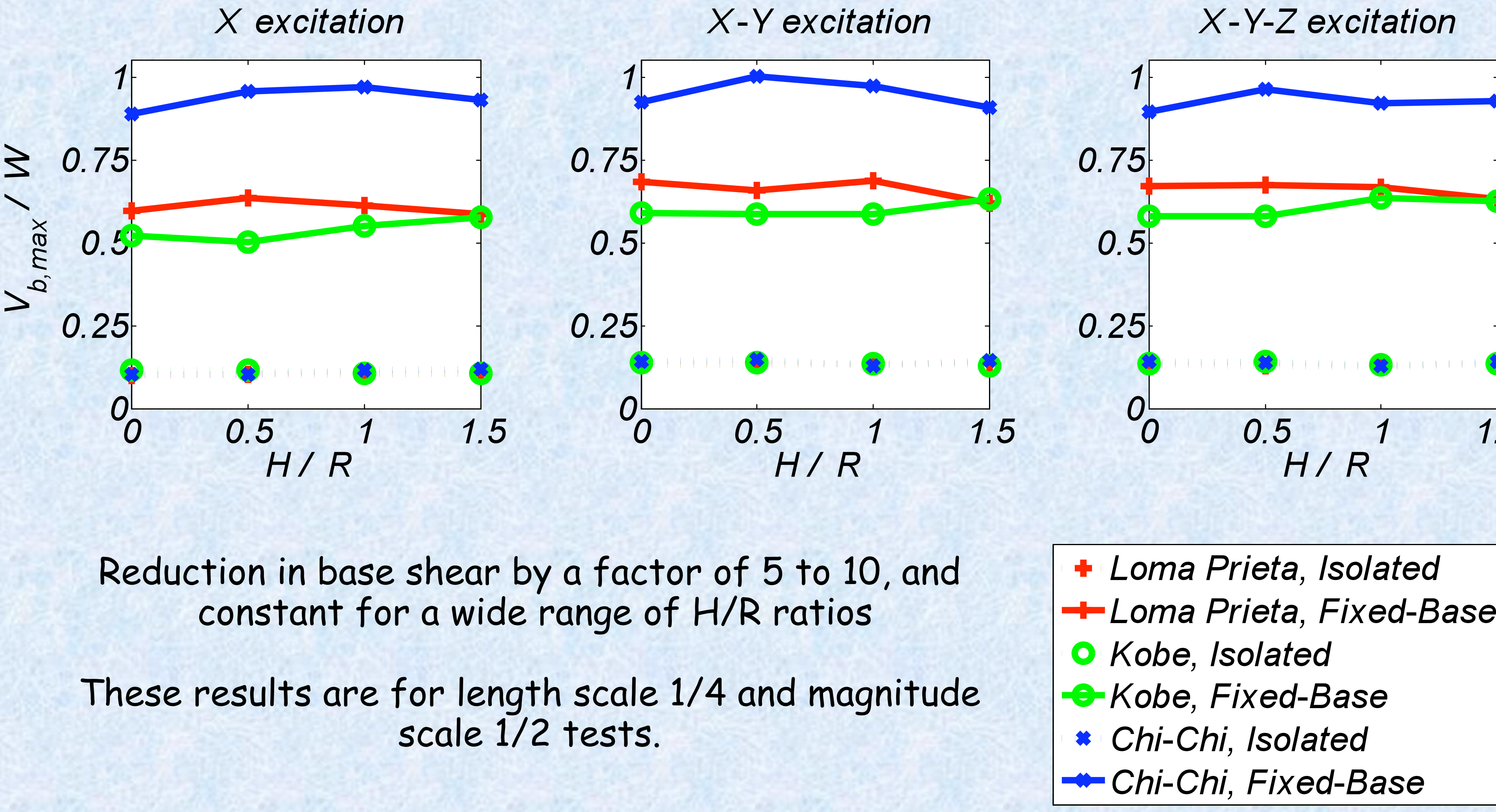


Near-linear Pwire behavior over ±20in range

Complete Test Setup

A total of 264 shaking table tests were conducted.

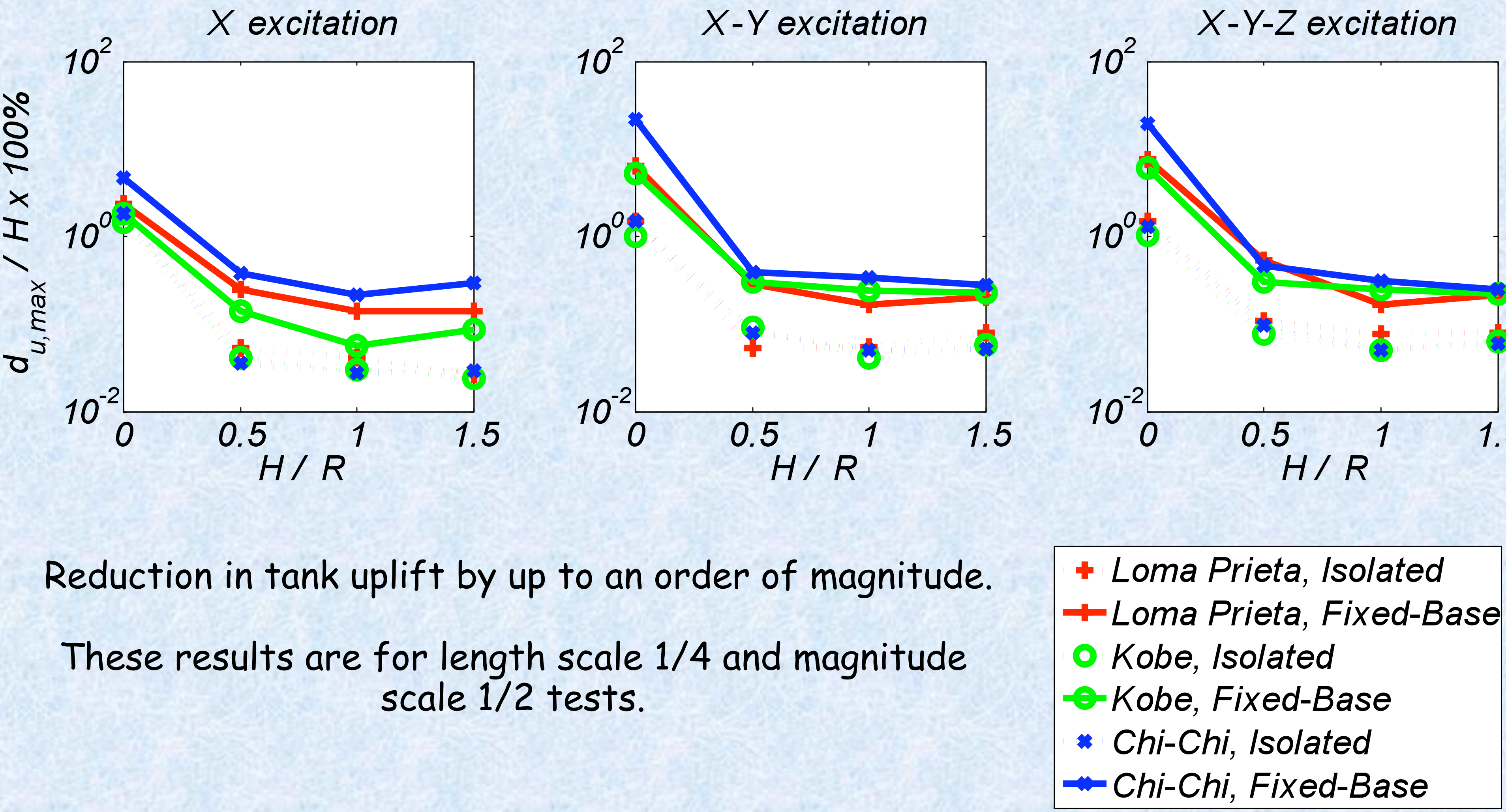
Experiment Results
Base Shear



Reduction in base shear by a factor of 5 to 10, and constant for a wide range of H/R ratios

These results are for length scale 1/4 and magnitude scale 1/2 tests.

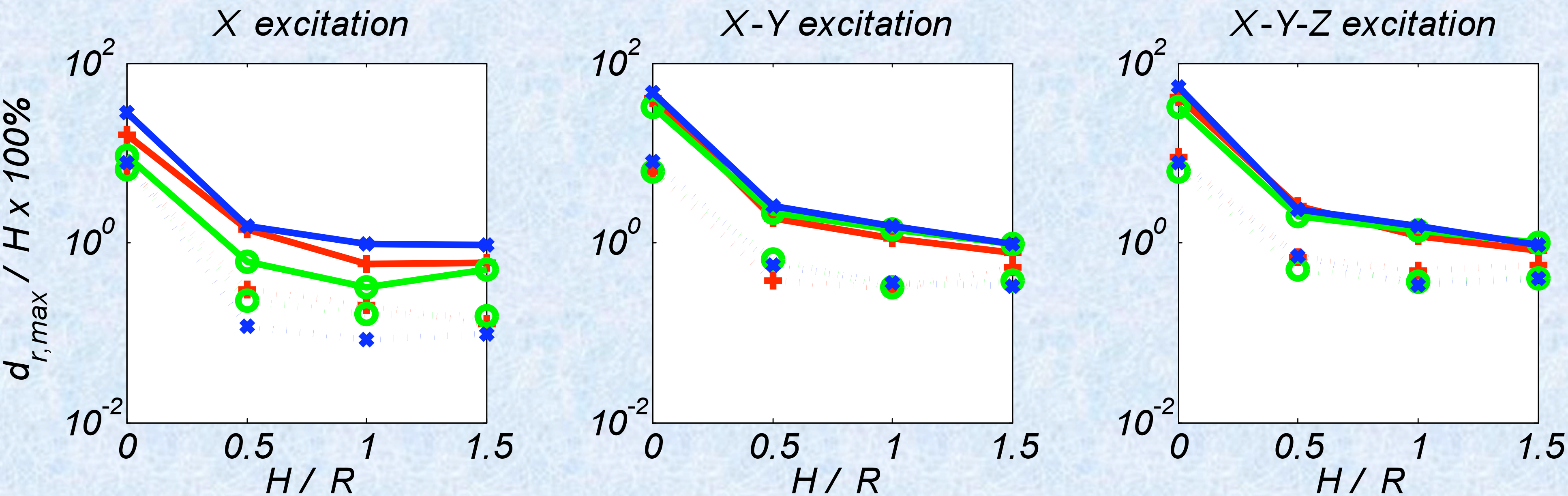
Experiment Results
Tank Uplift



Reduction in tank uplift by up to an order of magnitude.

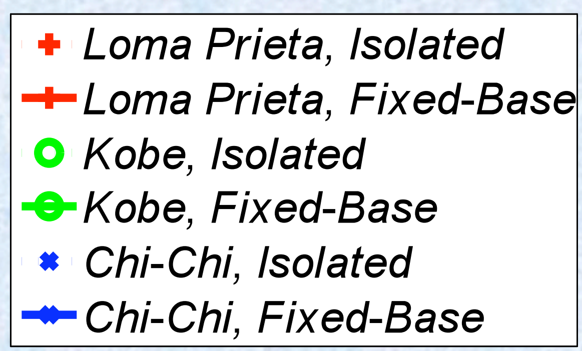
These results are for length scale 1/4 and magnitude scale 1/2 tests.

Experiment Results
Tank Deformation

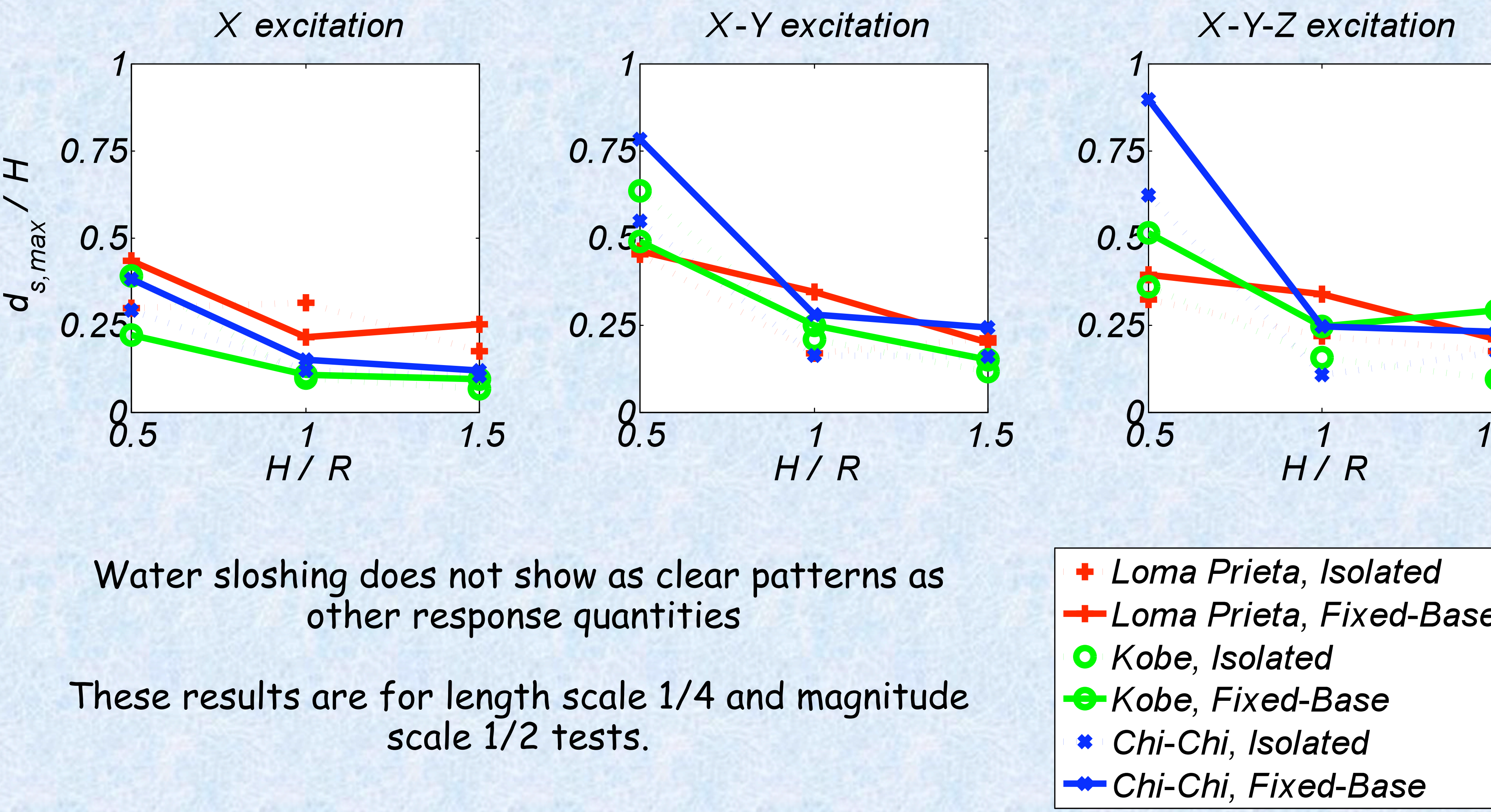


Reduction in tank deformation by up to an order of magnitude.

These results are for length scale 1/4 and magnitude scale 1/2 tests.



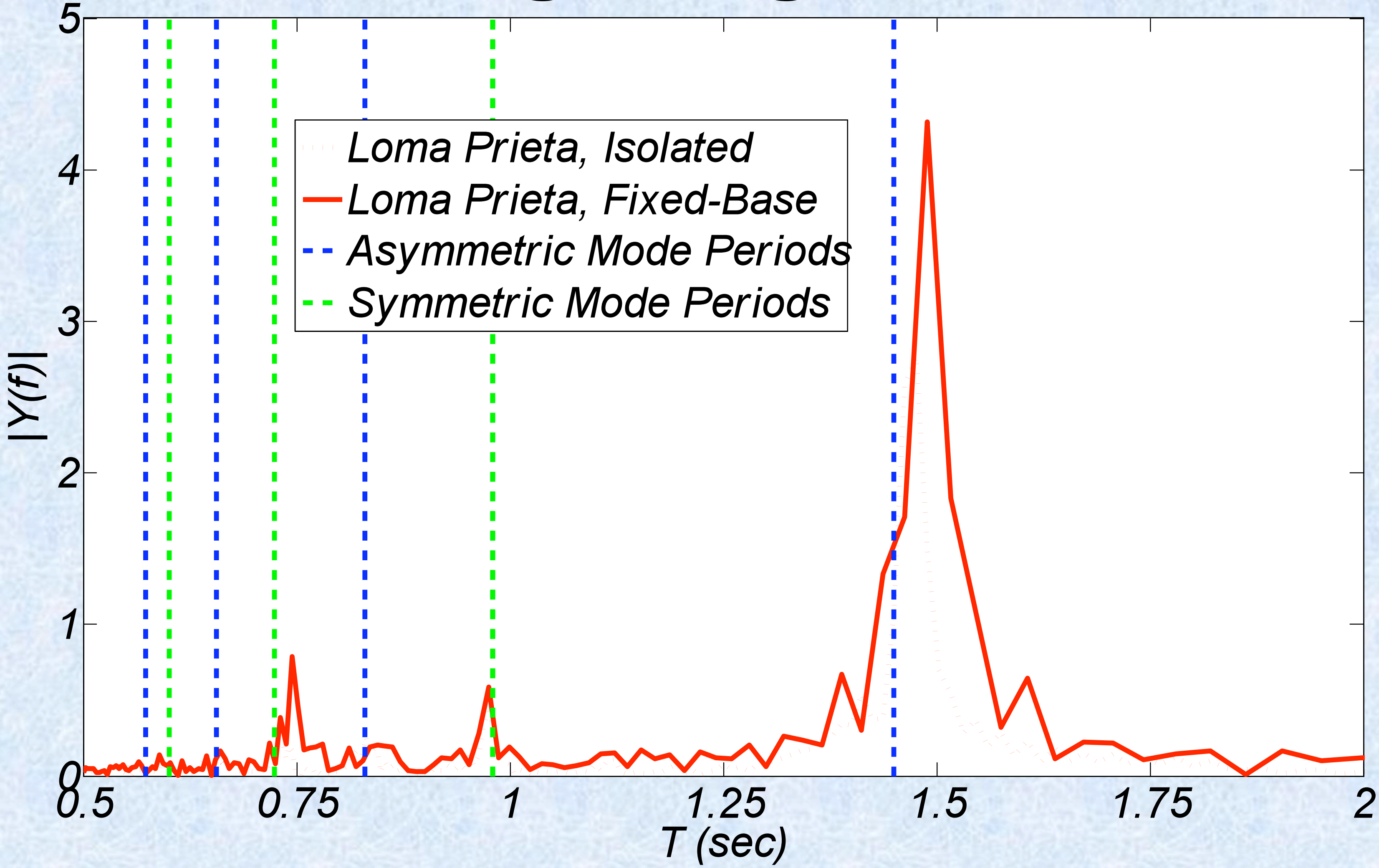
Experiment Results
Water Sloshing Height



Water sloshing does not show as clear patterns as other response quantities

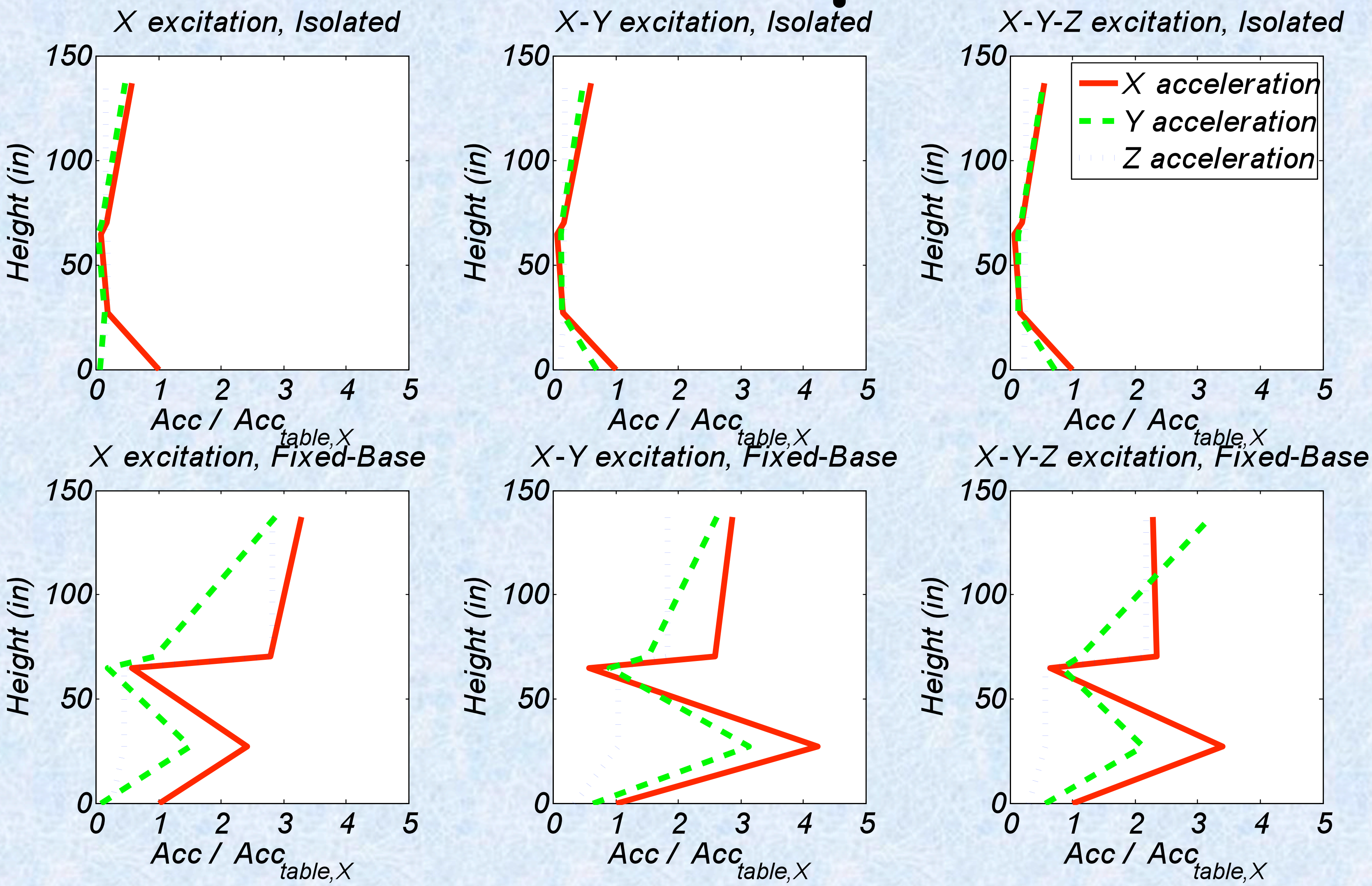
These results are for length scale 1/4 and magnitude scale 1/2 tests.

Experiment Results
Water Sloshing Height: FFT Study



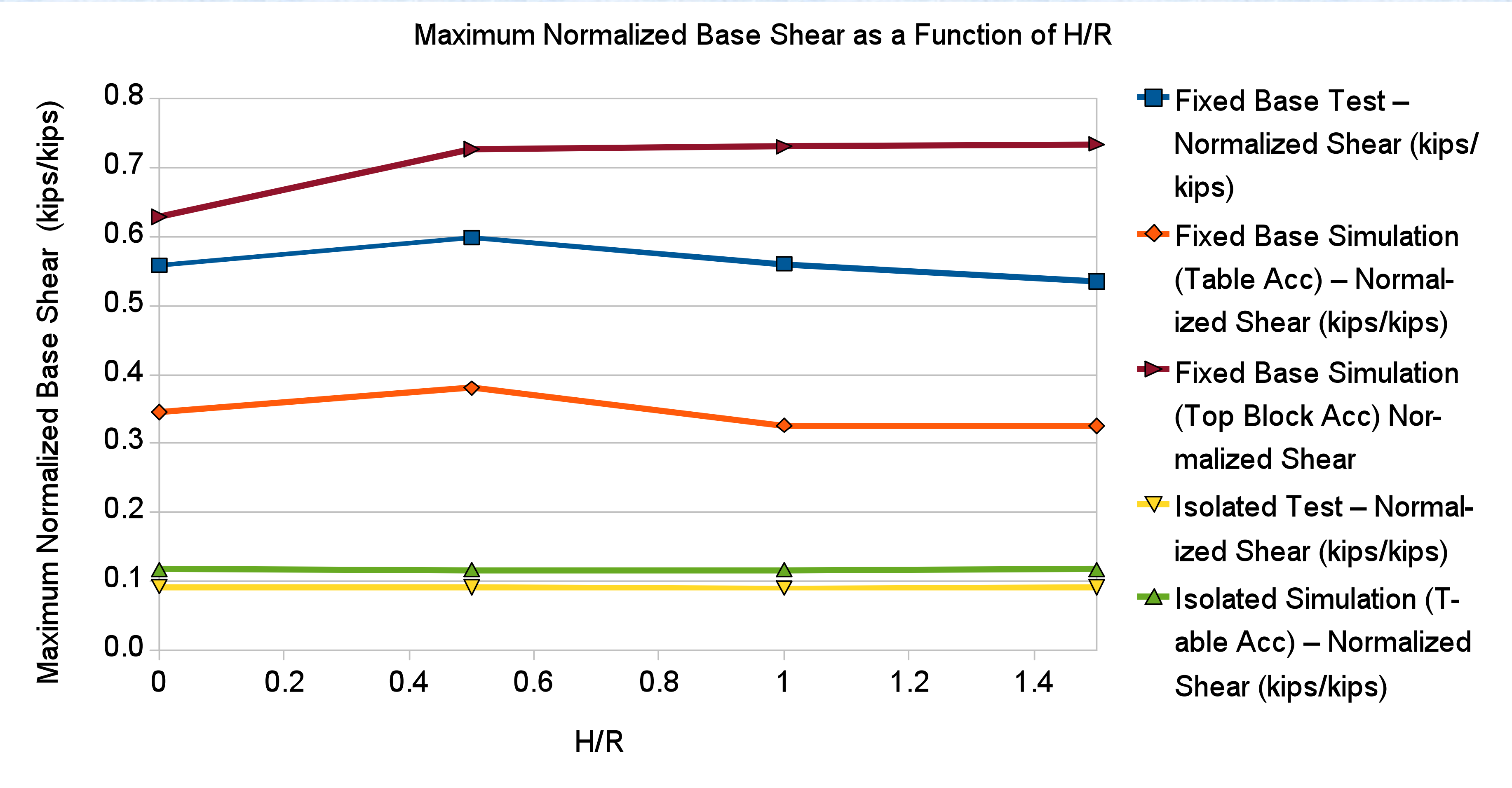
Contribution of symmetric sloshing modes is evident.
Seismic isolation effectively reduces 1st mode sloshing.

Experiment Results
Acceleration Amplification



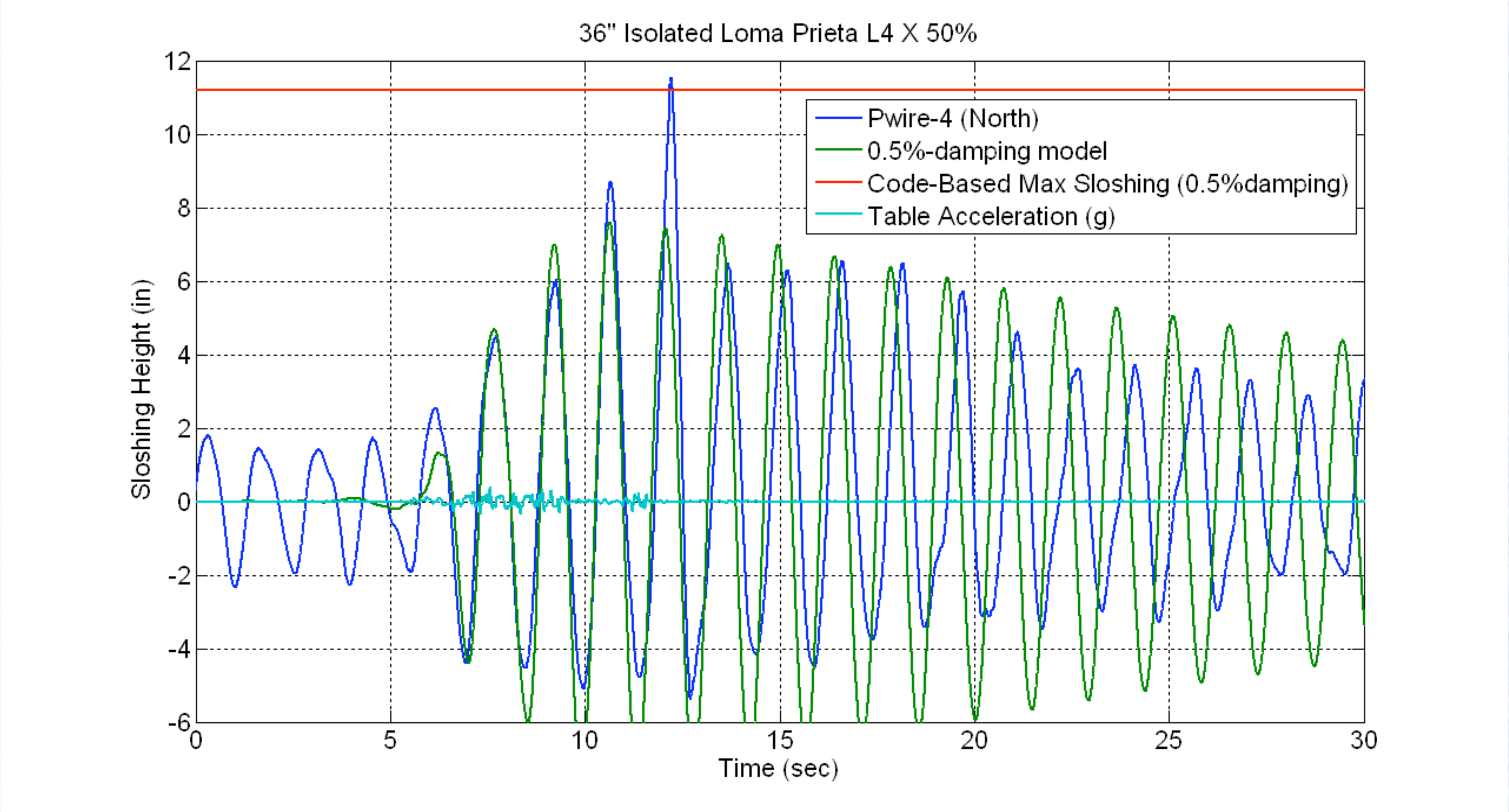
Seismic isolation effectively limits acceleration amplification in the supporting structure and liquid storage tank

Model Validation
Base Shear



Significant acceleration amplification between table top and steel frame due to some rocking and bolt slip is a bummer.

Model Validation
Water Sloshing Height



Code-based estimate for maximum sloshing in fixed-base tank – not bad for isolated tank. Housner model spring oscillation matches test sloshing during excitation.

Project Conclusions

- Seismic isolation is effective in reducing base shear, tank deformation, and tank uplift
- A simple 1-dof Housner model provides a good estimate of base shear for both fixed-base and isolated liquid storage tanks
- Higher sloshing modes important for sloshing dynamics, not for base shear and tank stresses
- SRSS combination of individual 1D simulation responses provides a good estimate of 2D excitation response
- Code provisions for maximum sloshing for fixed-base tanks also valid for isolated tanks
- 2- and 3- component ground motions significantly affect tank uplift and liquid sloshing dynamics

Thank you!

The Following Slides Contain Additional Information Available upon Request

Instrumentation

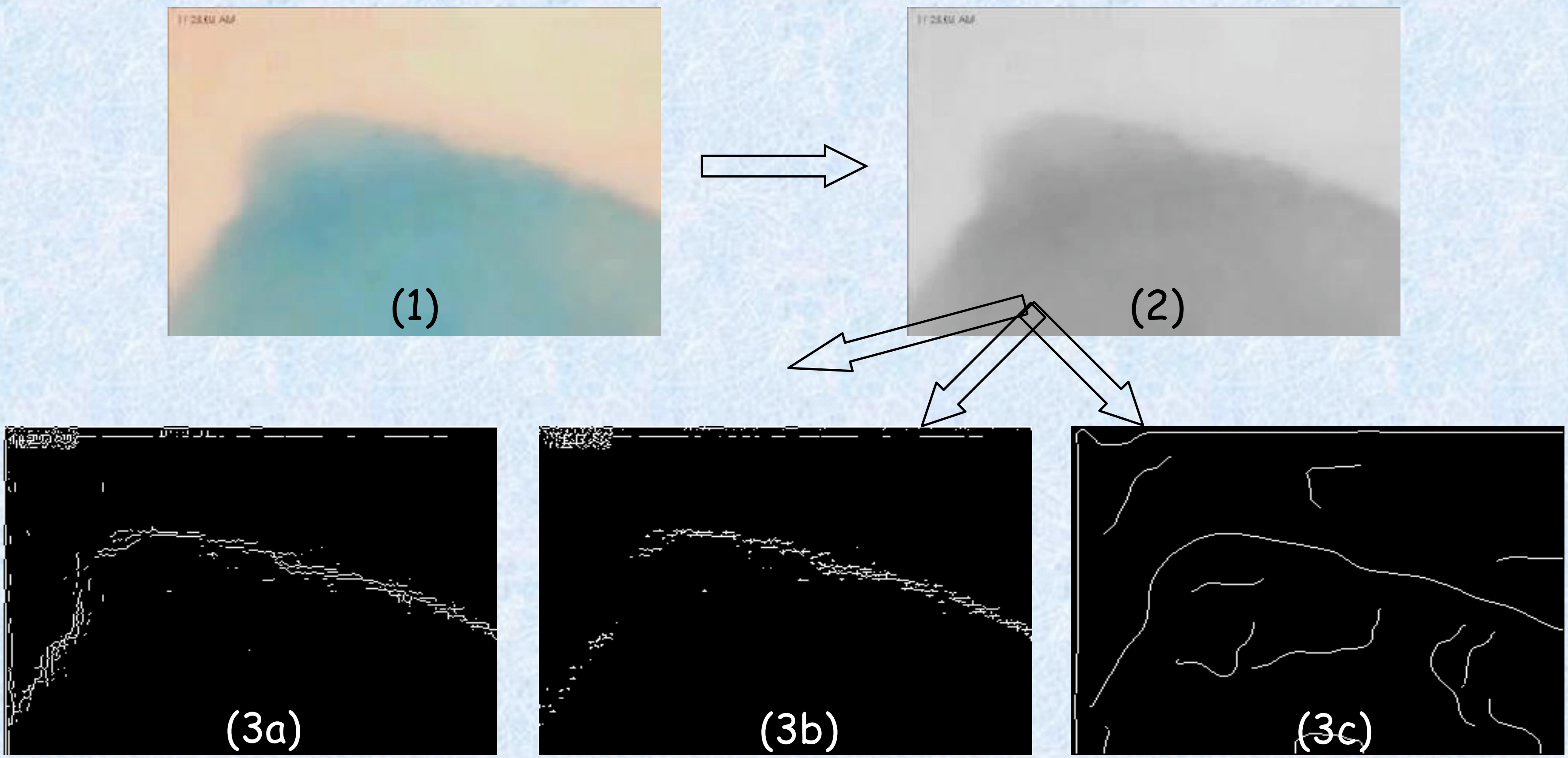
Instrument	Range	Quantity	Location	Measurement
Accelerometer	±5 g's	8	Below table slab	Acceleration in X, Y, and Z
		6	Top of table slab	Acceleration in X, Y, and Z
		4	Plate above isolators	Acceleration in Z
		4	Steel frame	Acceleration in X and Y
		4	Top concrete block	Acceleration in X and Y
		12	Tank bottom rim	Acceleration in X, Y, and Z
		8	Tank top rim	Acceleration in X and Y
DCDT	1 in	8	Plate above isolators	Fixed-base support deformation
		4	Tank top rim	Tank top rim deformation
	3 in	4	Tank bottom rim	Tank walking
HD Camera	72 in	2	Tank top rim	Water surface elevation
Load Cell (5comp)	±50 kip axial, ±20 kip shear, ±350 kip-in moment	4	Between table and bearing	Axial (vertical), shear (horizontal), moment (overturning)
LVDT	±7.5 in	8	Below table slab	Simulator platform displacement
Novotechnik Displacement Transducer (Lin Pot)	1 in	8	Tank bottom rim	Tank uplift
Parallel Wire Gauge (Pwire)	±36 in	7	Along tank wall	Water surface elevation
Wire Pot	40 in	8	Steel frame	Steel frame displacement in X, Y and Z
		4	Top concrete block	Top concrete block displacement in X and Y
		6	Tank top rim	Tank top rim displacement in X and Y

Instrumentation

Instruments used in the experiment

Edge Detection to Measure Water Surface Dynamics

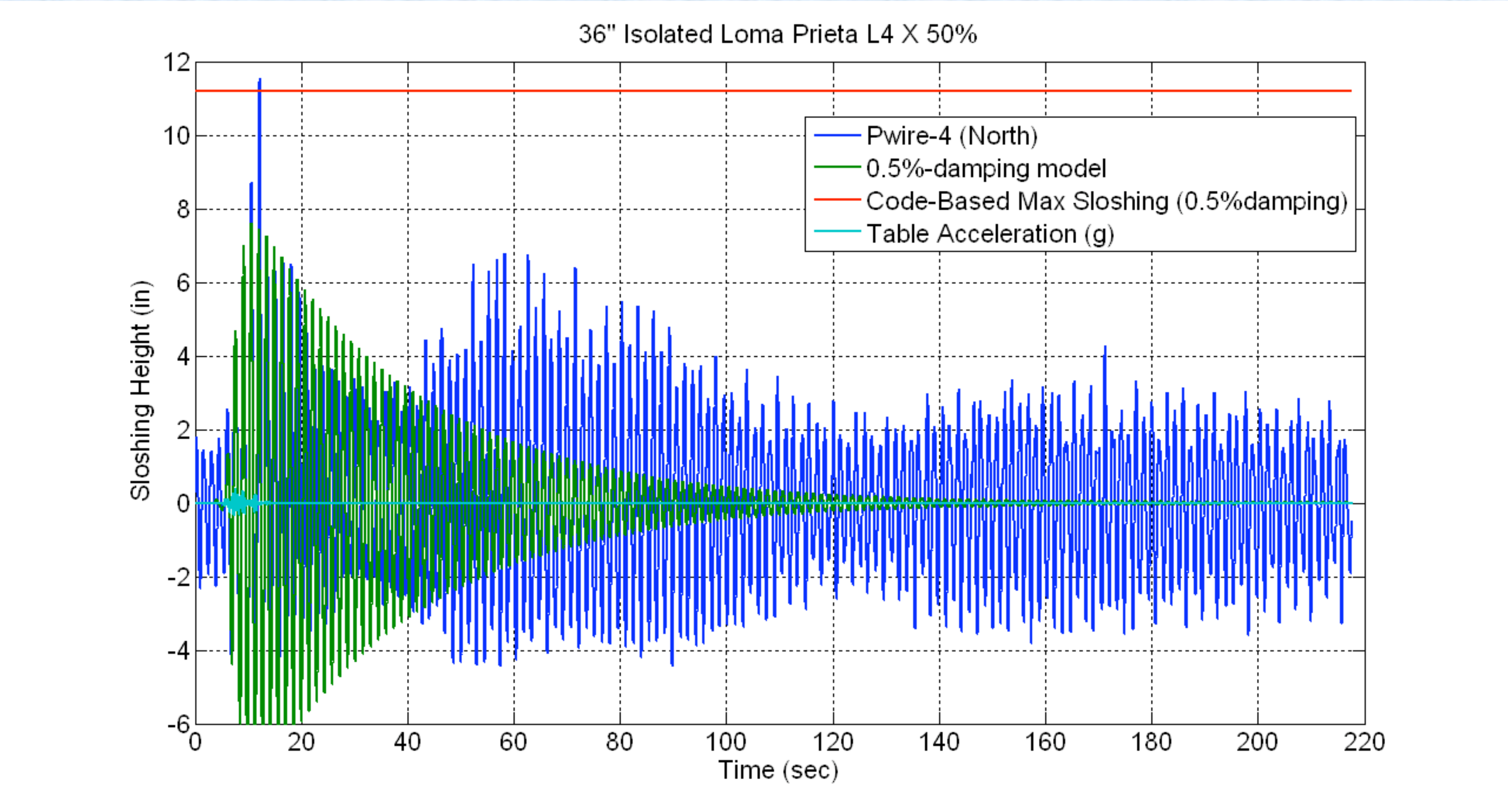
Split video into individual frames. Apply the ED algorithm to each frame to...



...obtain a matrix of mostly zeros (black), and a few ones (white) representing the water surface edge. Calibrate pixels to inches.

Model Validation

Predicting Water Sloshing Dynamics



Code-based estimate for maximum sloshing in fixed-base tank – not bad for isolated tank

Future Work

- More work on edge-detection approach
- Finite element model to compare with mechanical analog models and test data
- Fit tank uplift and deformation test data to existing models
- Interaction of water sloshing with shaking table