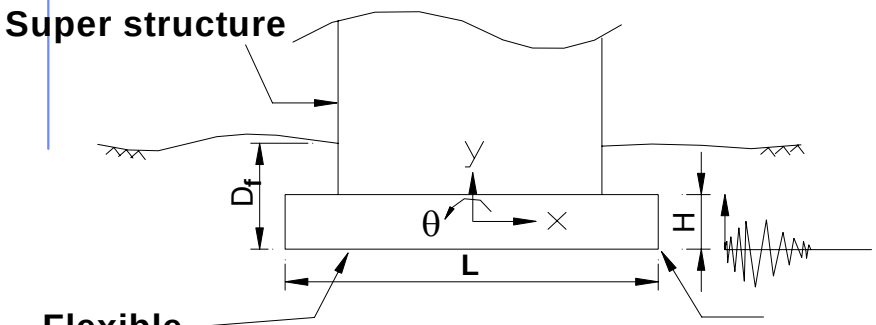
New Tools for Structural and Geotechnical Practitioners on the Horizon

Tara C. Hutchinson

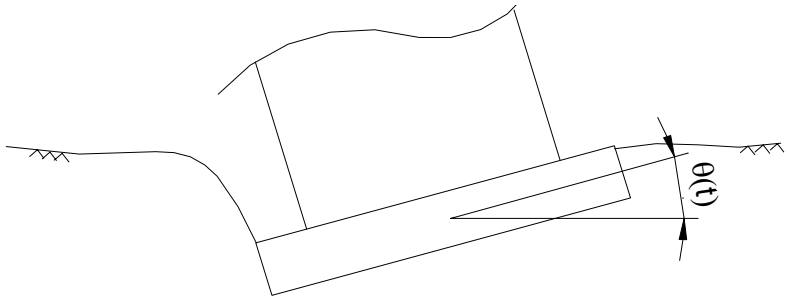
Collaborative Project

- UCD (Kutter), UCLA (Stewart), UCSD (Hutchinson), USC (Martin)
- Graduate Students: Rosebrook, Phalen, Gajan, Raychowdhury, Harden, Chang
- Support provided by PEER

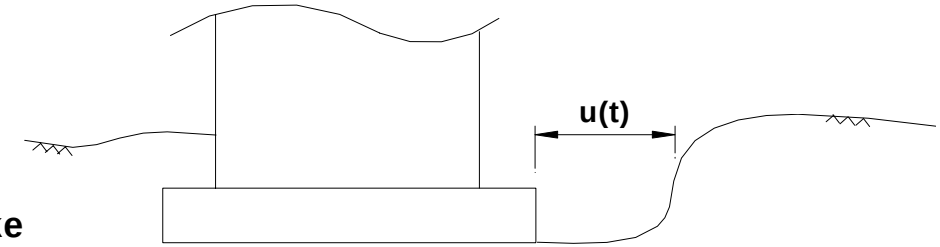
Modes of Foundation Deformation



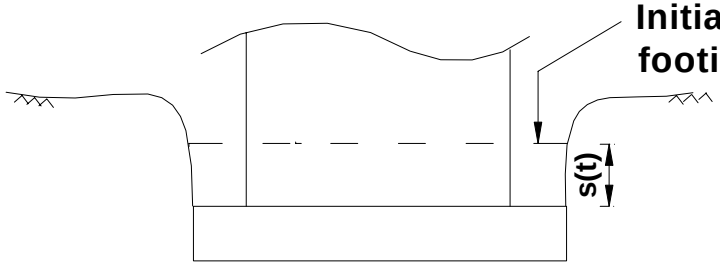
L = length of footing
B = width of footing
H = thickness of footing
D_f = depth of embedment



Rocking mode



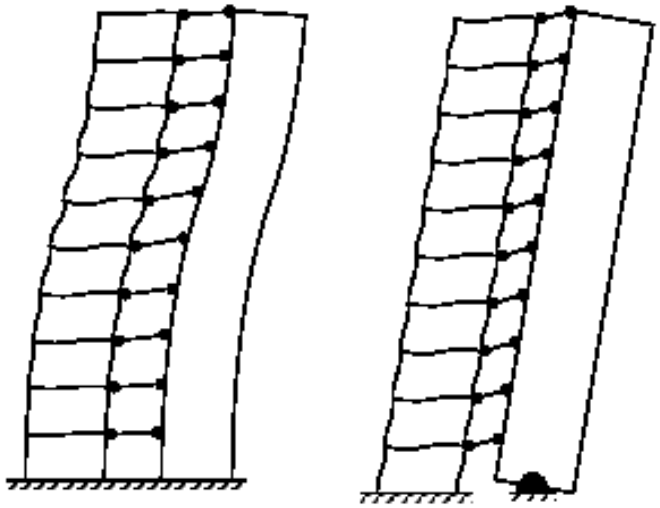
Sliding mode

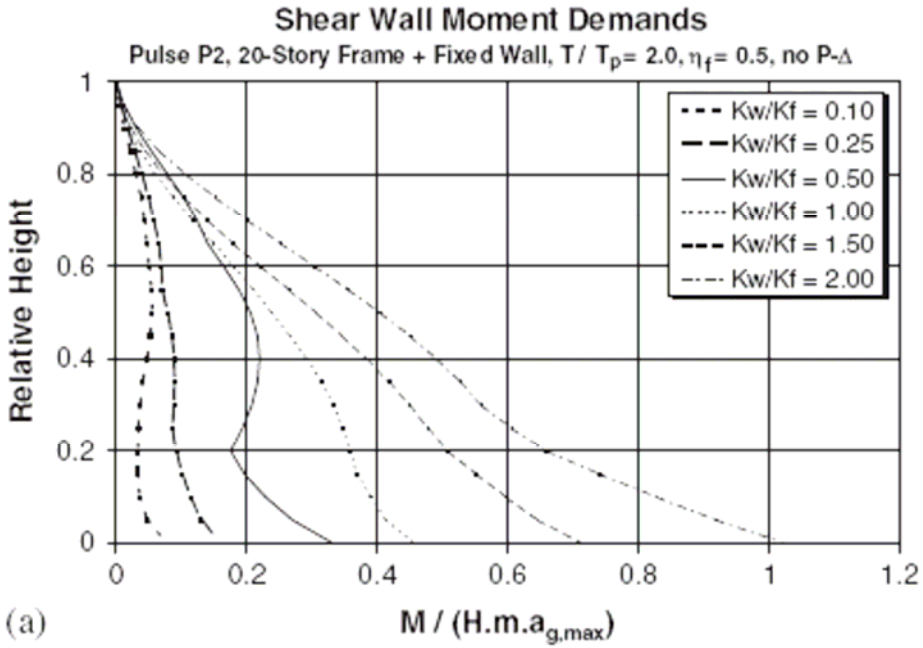


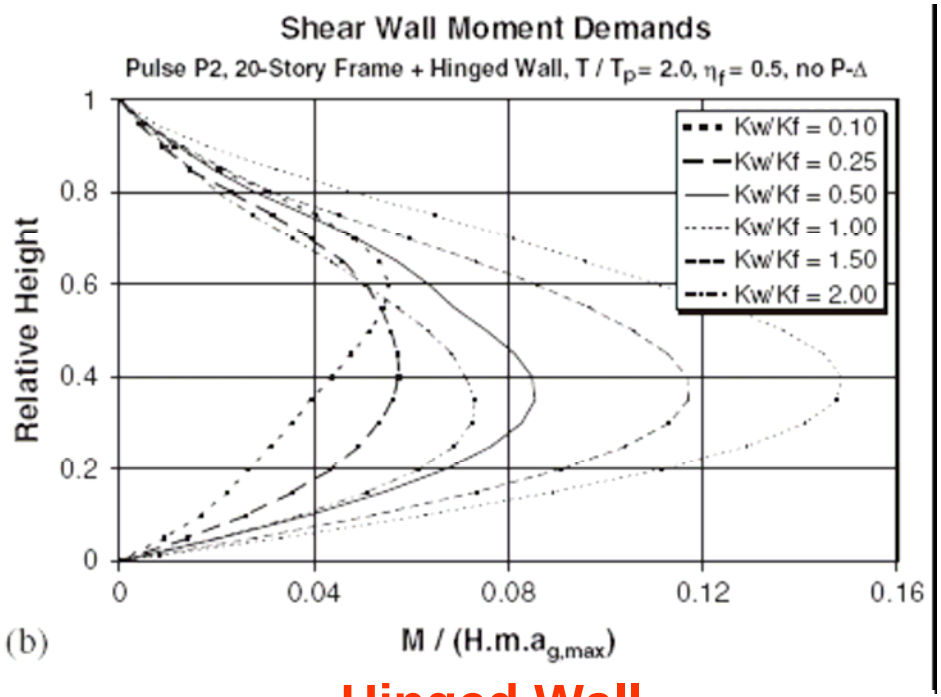
Vertical mode

Rocking: Base Hinging

- Shear walls fixed and perfectly hinged at the base
- Hinges at base decrease moment, shear, and drift to wall







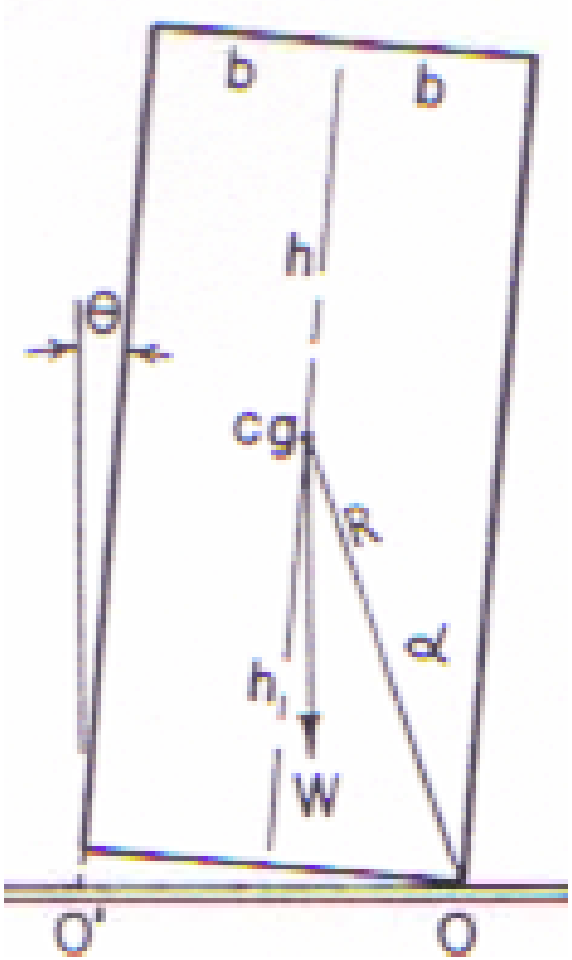
Fixed Wall

Hinged Wall

Alavi and Krawinkler (2004)

Early Work

Reduction in kinetic energy by the impact:



$$r = [I - \frac{mR^2}{I_0}(1 - \cos 2\alpha)]^2$$

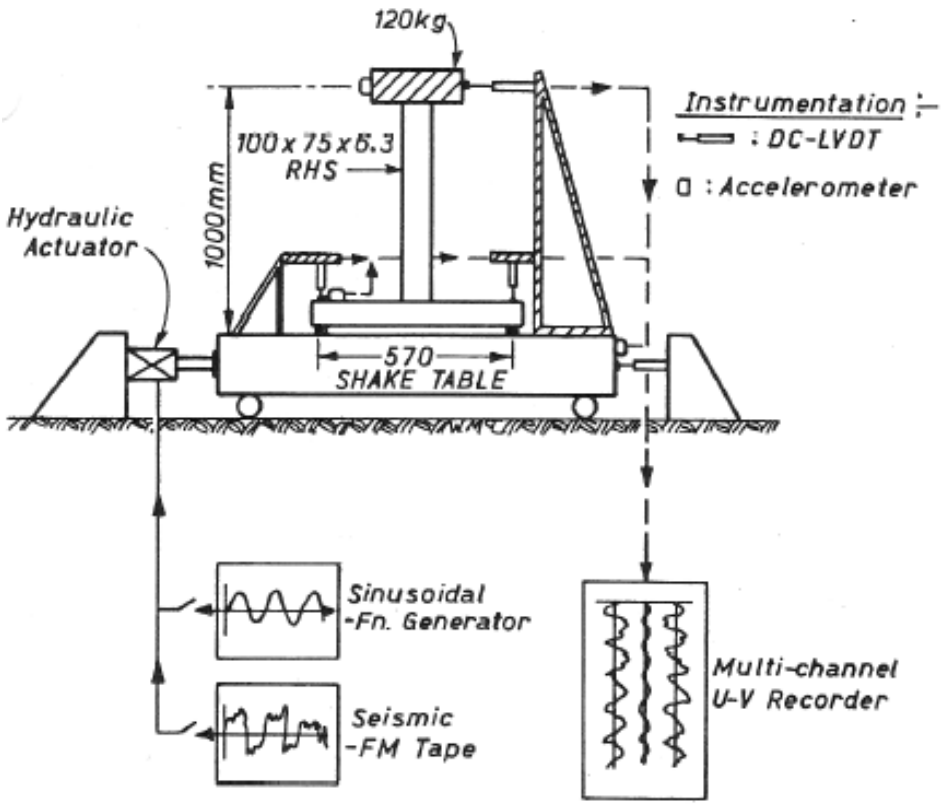
- ***Energy dissipated by rocking block = f(amplitude, frequency) of the rocking motion***

- ***In 1963, no known method to design a rocking structure with reliable stability.***

Housner (1963)

Early Work

- Experimental validation of Housner's work
- Theoretical "r" in good agreement with average experimental value.



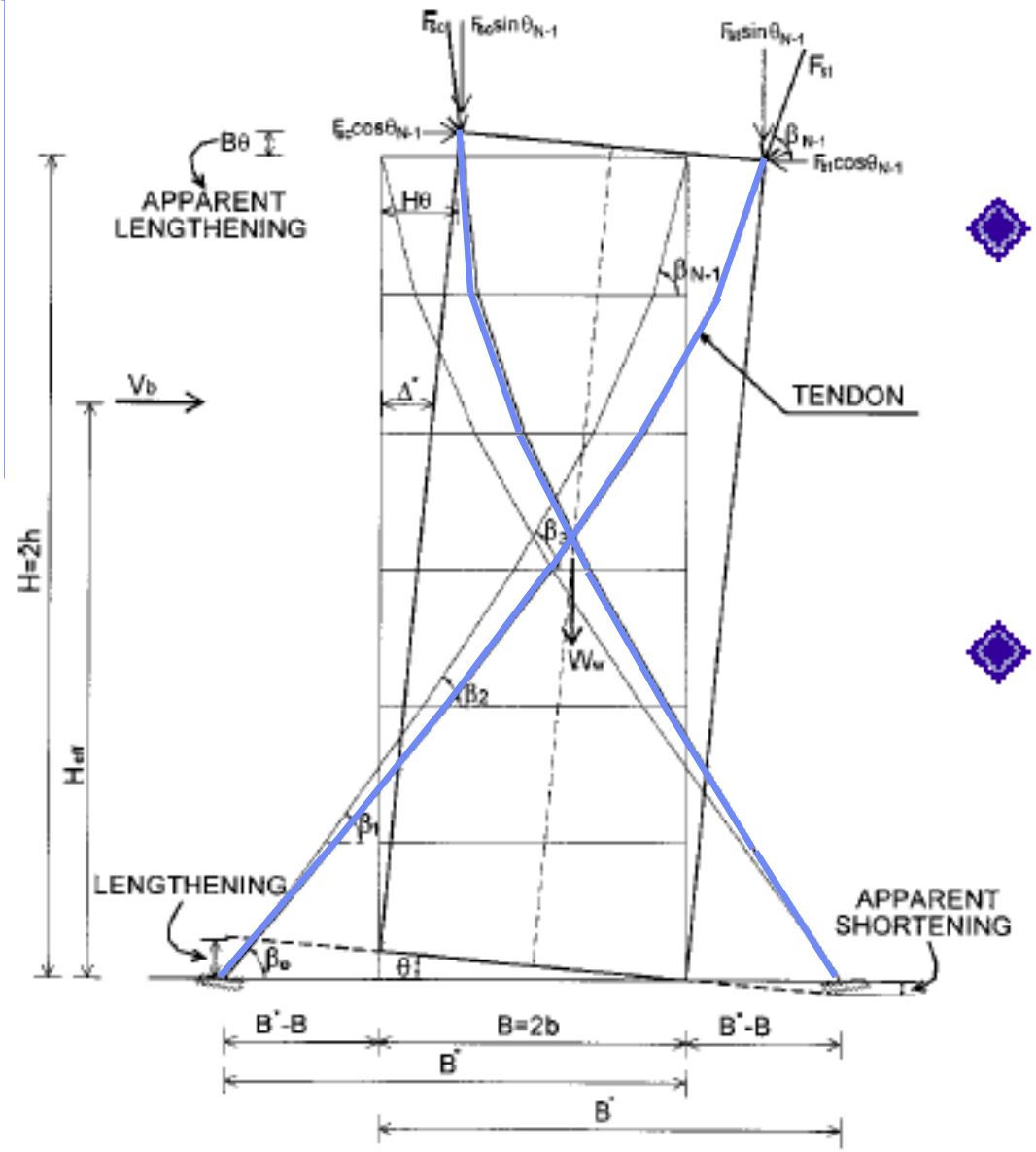
- Rocking also generates impact energy that is transferred back to structure
- Development of simple method to predict maximum displacement due to rocking

Priestley et al. (1978)

Rocking: Structural Solutions

- Filiatrault et al. (1992), Anderson (2003)
- Kurama et al. (1999), Priestley et al. (1999)
- Taghdi et al. (2000)
- Holden et al. (2003)
- Bonelli and Holmberg (2004)
- Marko et al. (2004)
- Ajrab et al. (2004)
- Toranzo-Dianderas et al. (2004)

e.g. Draped Tendons

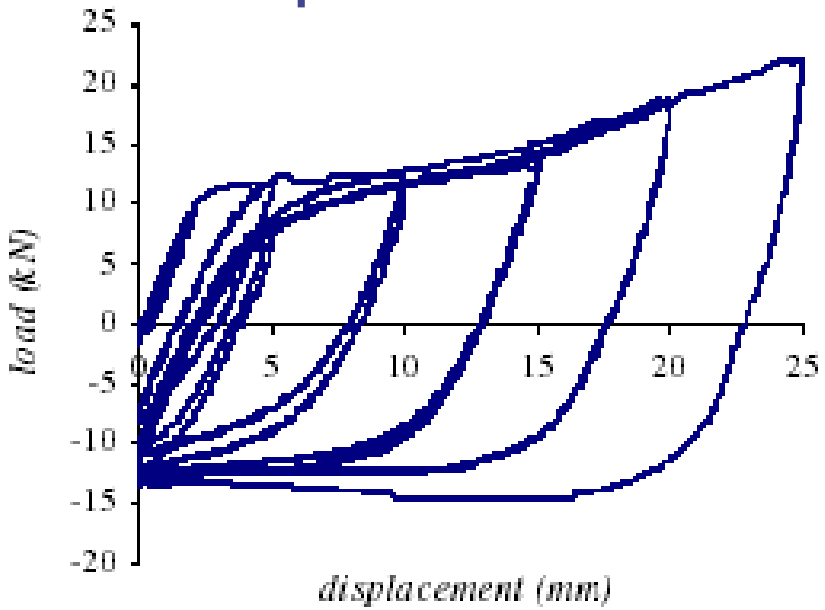


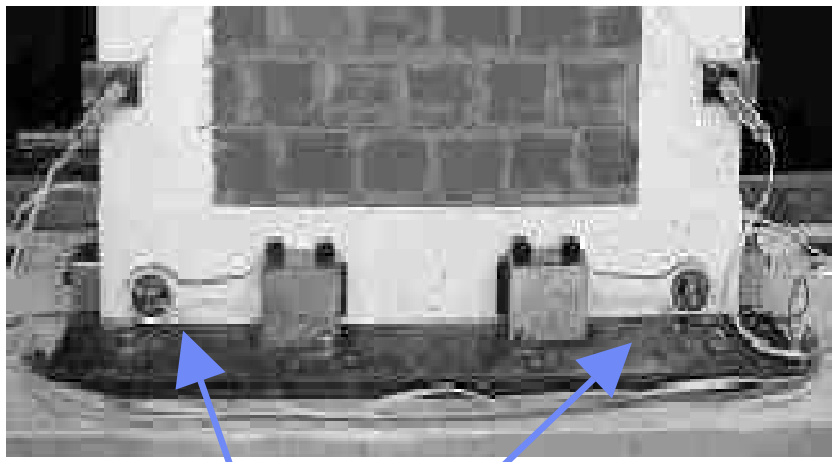
- Wall remains protected from damage while tendons yield
- Energy dissipated through tendons

Ajrab et al. (2004)

e.g. Mechanical Base Dampers

- Shake table tests on ¼-scale masonry wall model
- Dampers provided local energy dissipation directly at base ends of wall
- Little to no damage observed in wall with base dampers





Steel dampers

Toranzo-Dianderas et al. (2004)

Key Ideas: Foundations

- Soil-foundation interface can provide the key features of:
  - Rocking can provide valuable dissipation of energy during seismic loading (due to bearing capacity mobilization)
  - Re-centering can reduce deformation demands (due to gap formation and closing)

Simulations - Previous Work

- SDOF & MDOF systems w/ lumped masses
- Rigid, 2-element, Winkler system of springs
- Linear-elastic springs

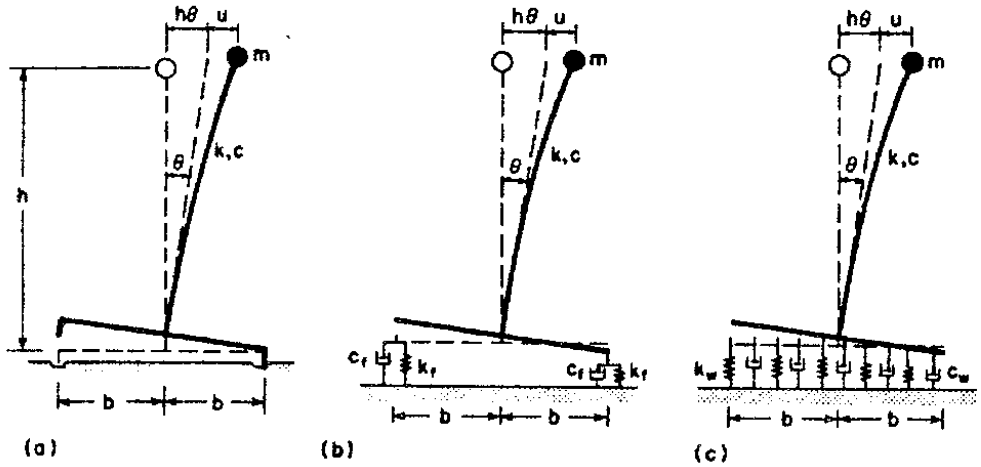


Figure 1. Structure Supported on Three Different Foundation Soil Idealizations: (a) Rigid Foundation; (b) Two-Element Foundation; (c) Winkler Foundation

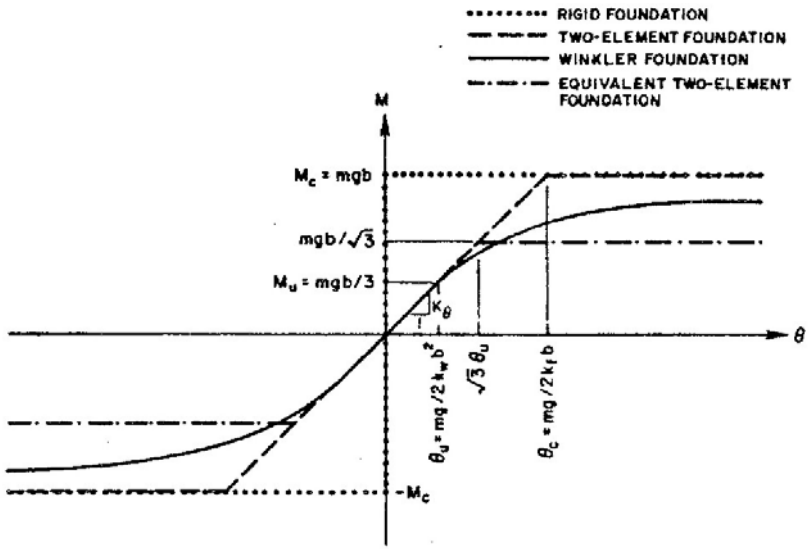
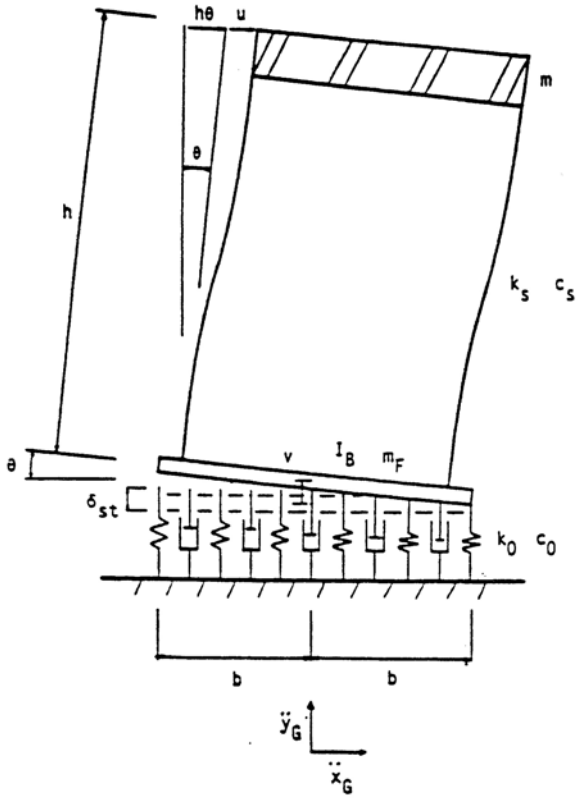


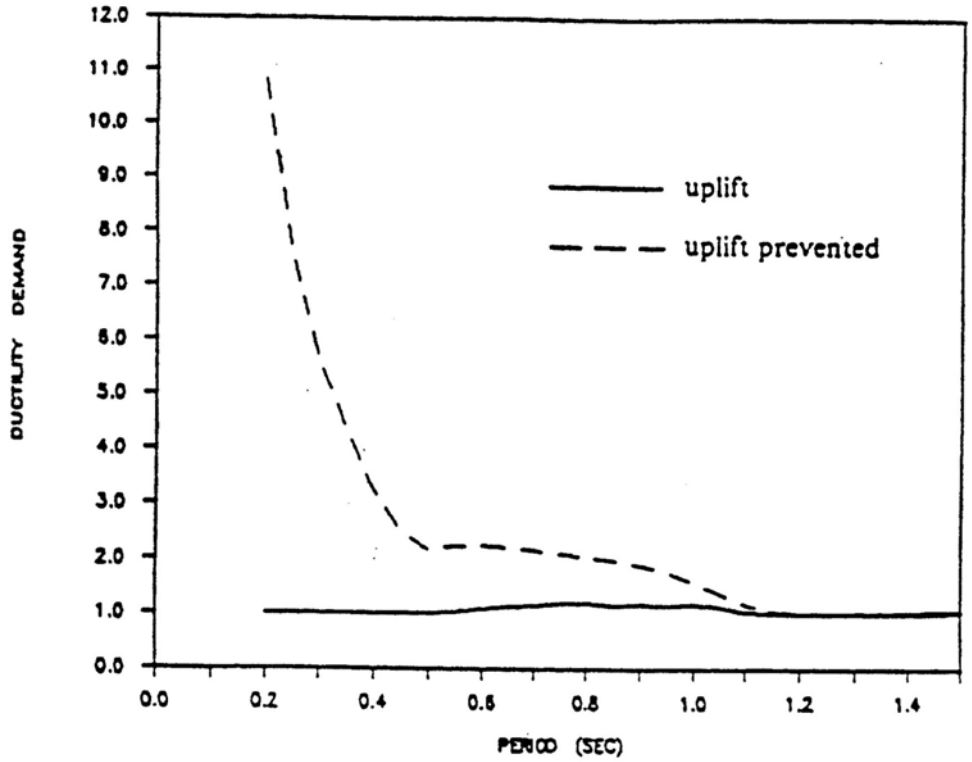
Figure 2. Moment-Rotation Relations for Unbonded Foundation Mat Supported on Different Foundation Soil Idealizations

Chopra & Yim; Yim and Chopra (1985)

Simulations - Previous Work

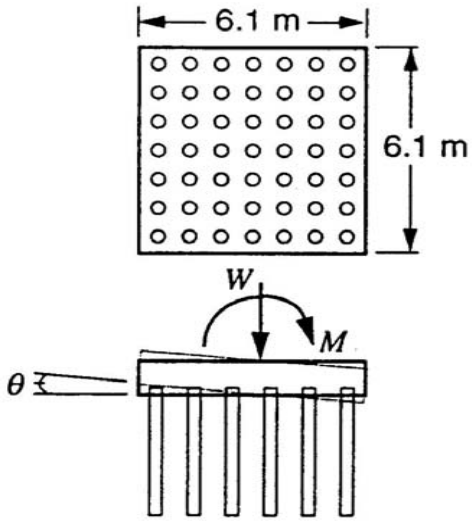
- Elastic Winkler springs below nonlinear (degrading) shear wall structure
- Two different GM types (long duration & short impulsive motion)



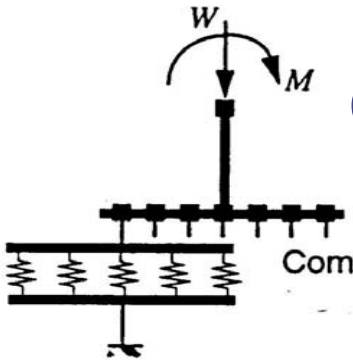


Nakaki & Hart (1987)

Simulations – Previous Work



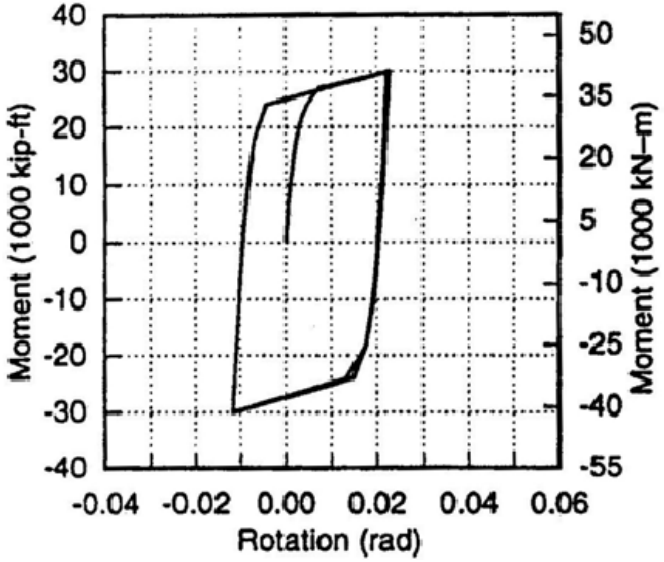
a) Pile group

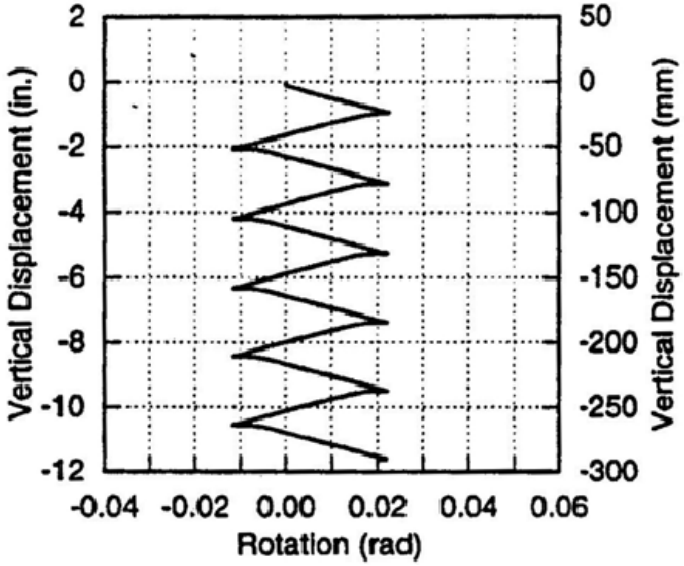


Composite spring model

b) Composite spring model

- Application to Bridge modeling
- Composite of parallel springs
- Combined w/ nonlinear column behavior





Fenves (1997)

“Big Picture” Question

- Under what conditions should foundation rocking be avoided, allowed, or encouraged in building design?
  - Need methods to quantify the benefits (e.g. structural demand reduction, energy available at footing)
  - Need methods to quantify the consequences (e.g. permanent and cyclic settlement, rotations)

Research Program

- Physical Model Testing
  - 1-g experiments (Bartlett, Weissing, Negro)
  - Centrifuge experiments
    - Wall-foundation; 8 series of tests (Gajan, Rosebrook, Kutter): KRR and SSG series
    - Building-Foundation; 1 series/two bldg-fnds (Chang, Thomas): JMT series
- Numerical Modeling
  - Macro-element modeling (UCD)
  - Winkler-based modeling (UCSD)

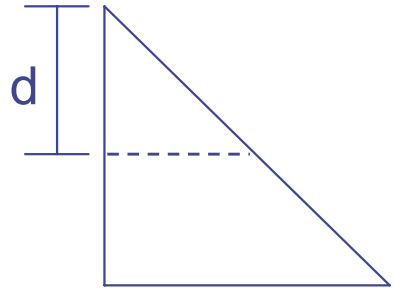
Centrifuge (UC Davis)



Center for Geotechnical Modeling at UC Davis: 9.1-m radius centrifuge

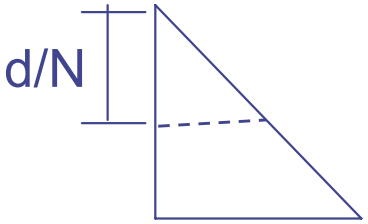
Scaling in centrifuge:

Prototype



$\sigma = \rho . g . d$

Model (N-g)

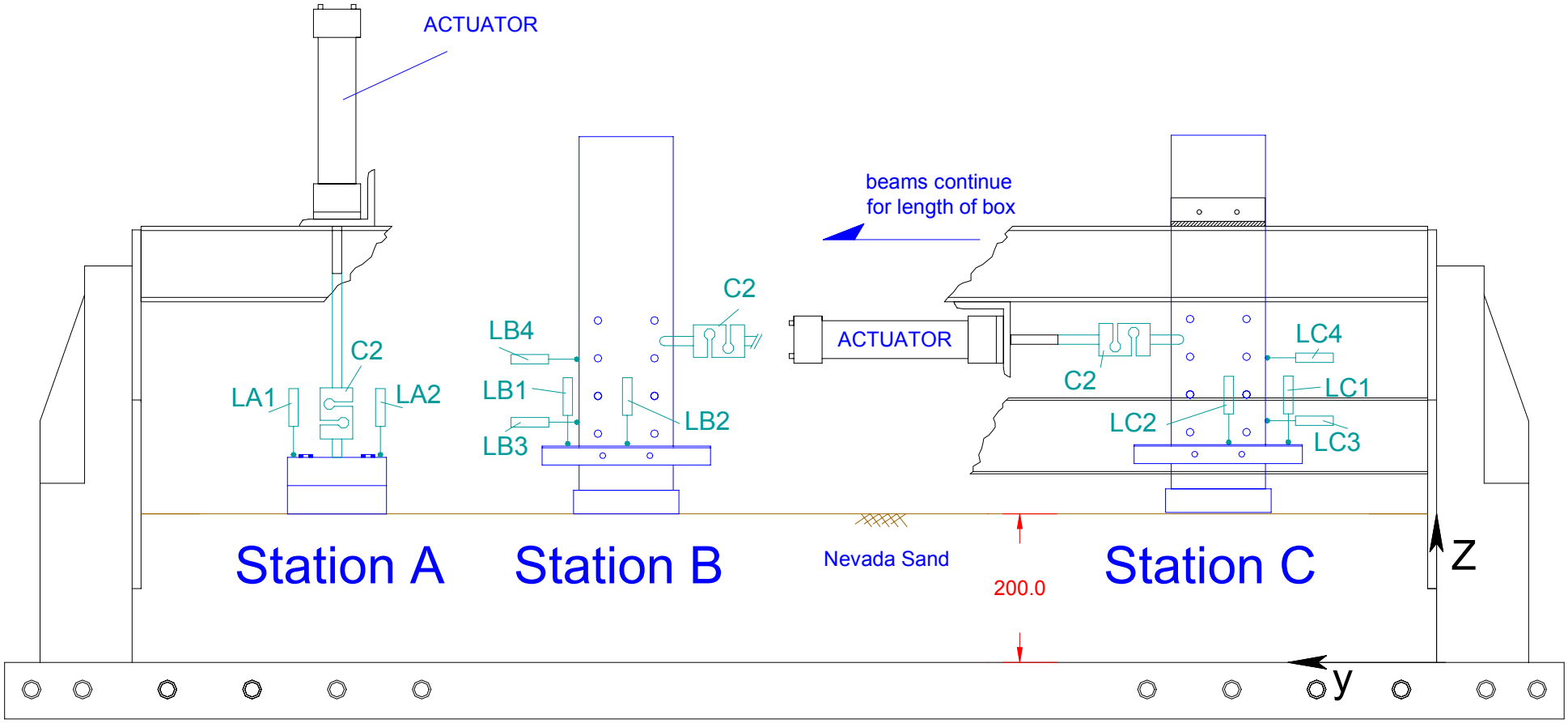


$\sigma = \rho . (N.g) . d/N$
$= \rho . g . d$

Our tests: N=20

$L_m = (1/20) * L_p$; $\sigma_m = \sigma_p$

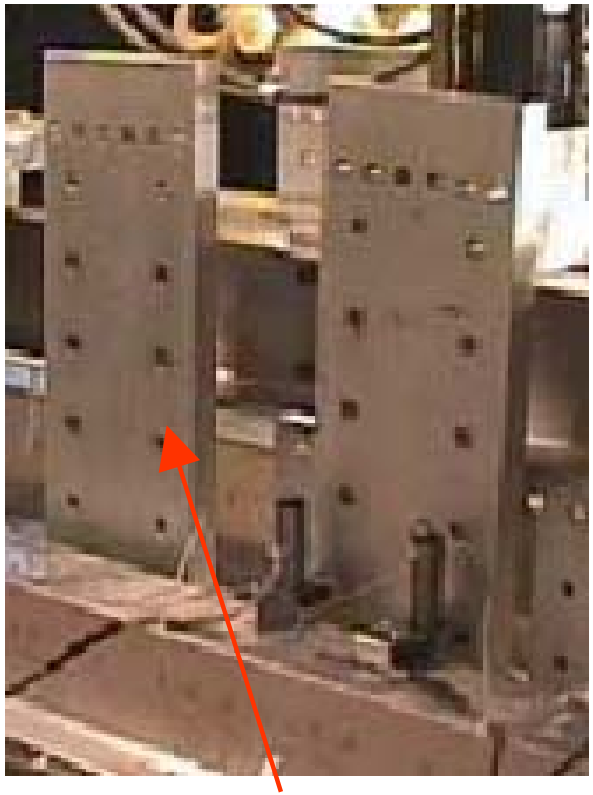
Wall-Foundation Experiments



KRR and SSG Series experiments

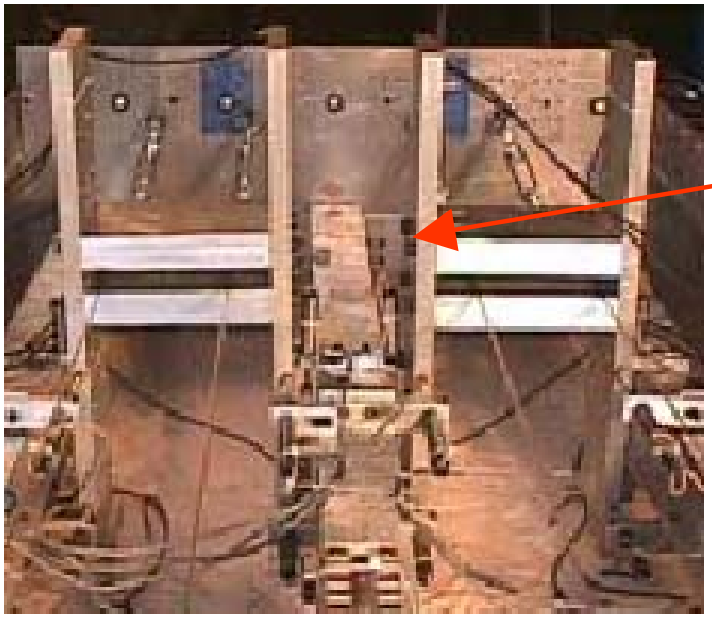
Rosebrook & Kutter (2002) and Gajan et al. (2003)

Wall-Foundation Experiments



Planar wall-footing model

- Tests on clay and sand
- Varying embedment (0, B, 3B)
- Model wall-footing systems with various precompression loads ("FSv = 3-15")

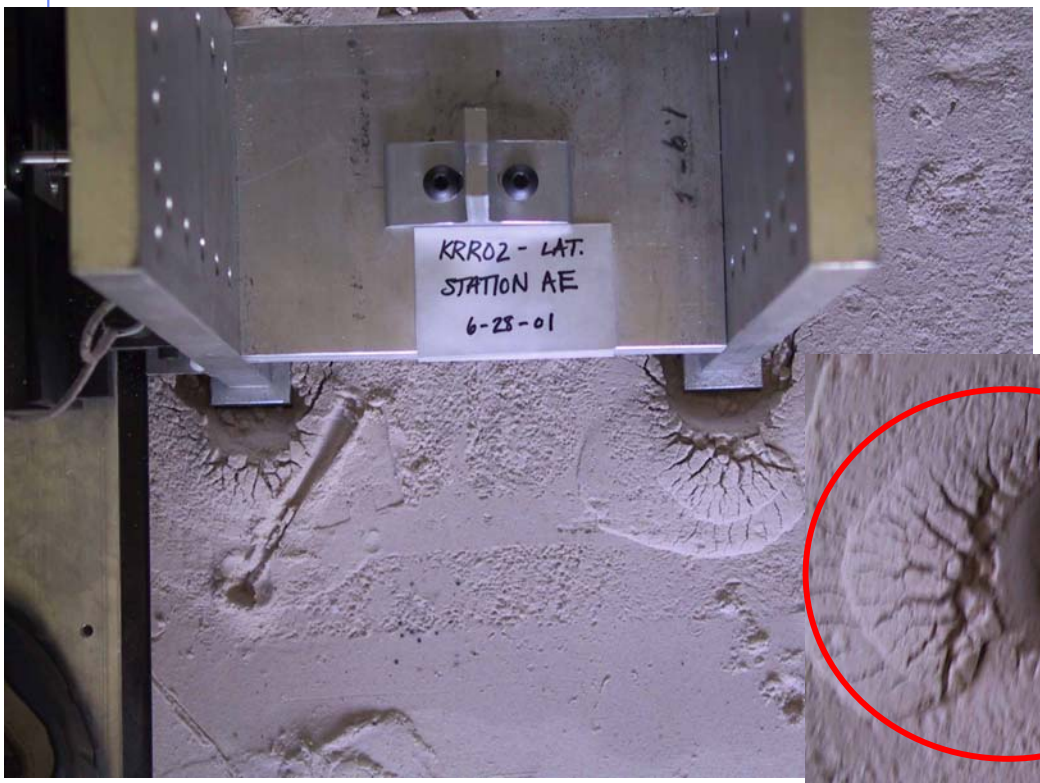


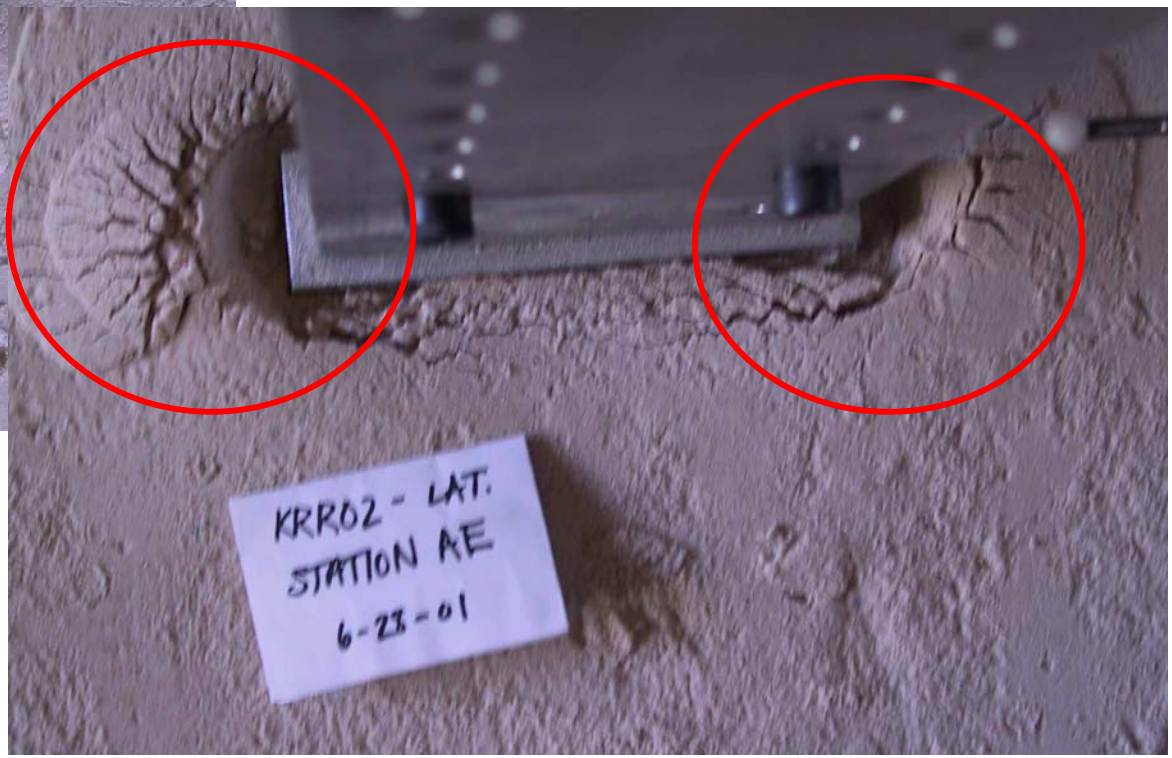
Two wall-footing models loaded in parallel

A word about definitions...

- Classical terminology in Geotech Eng: Factor of Safety
  - ...against ...<bearing, overturning, sliding> failure
  - e.g. FSv, FSot, FSs
  - But...there is little association with “safety” in this definition
- Effectively analogous to axial stress in a column: eg 10%f’cAg
- We’ll refer to this as a degree of pre-compression eg Qult/Qapplied (Qu/Qa)
  - Defined for any mode (axial, shear, moment)

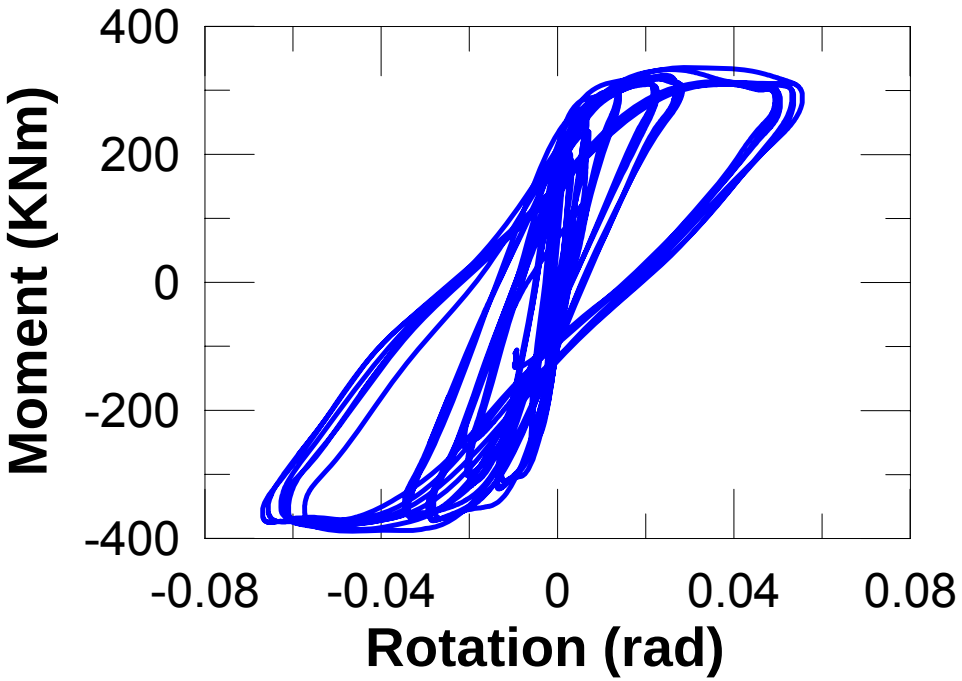
Physical Observations

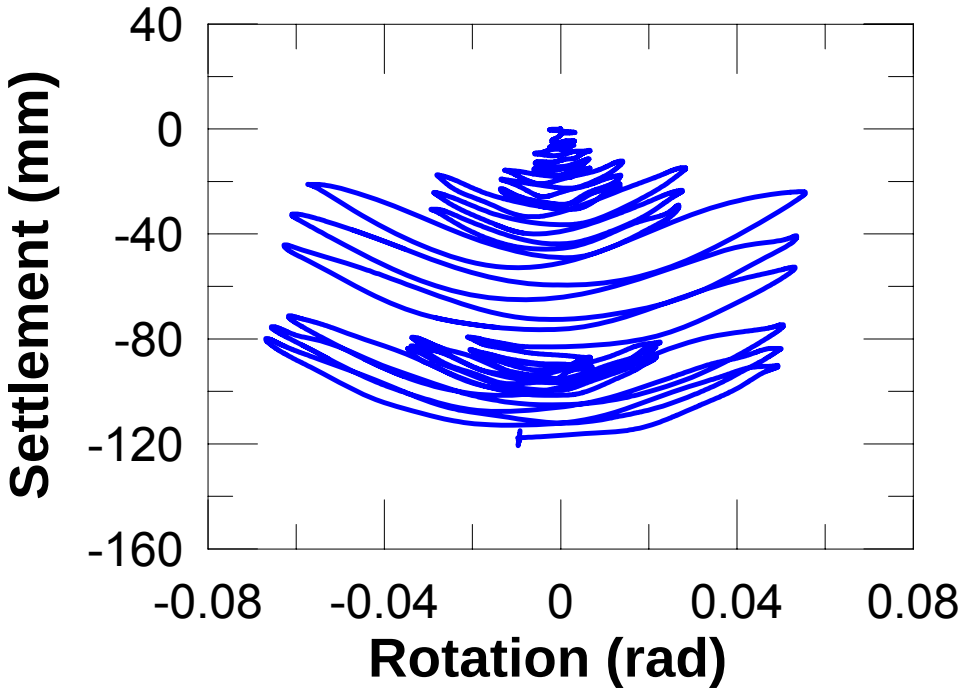




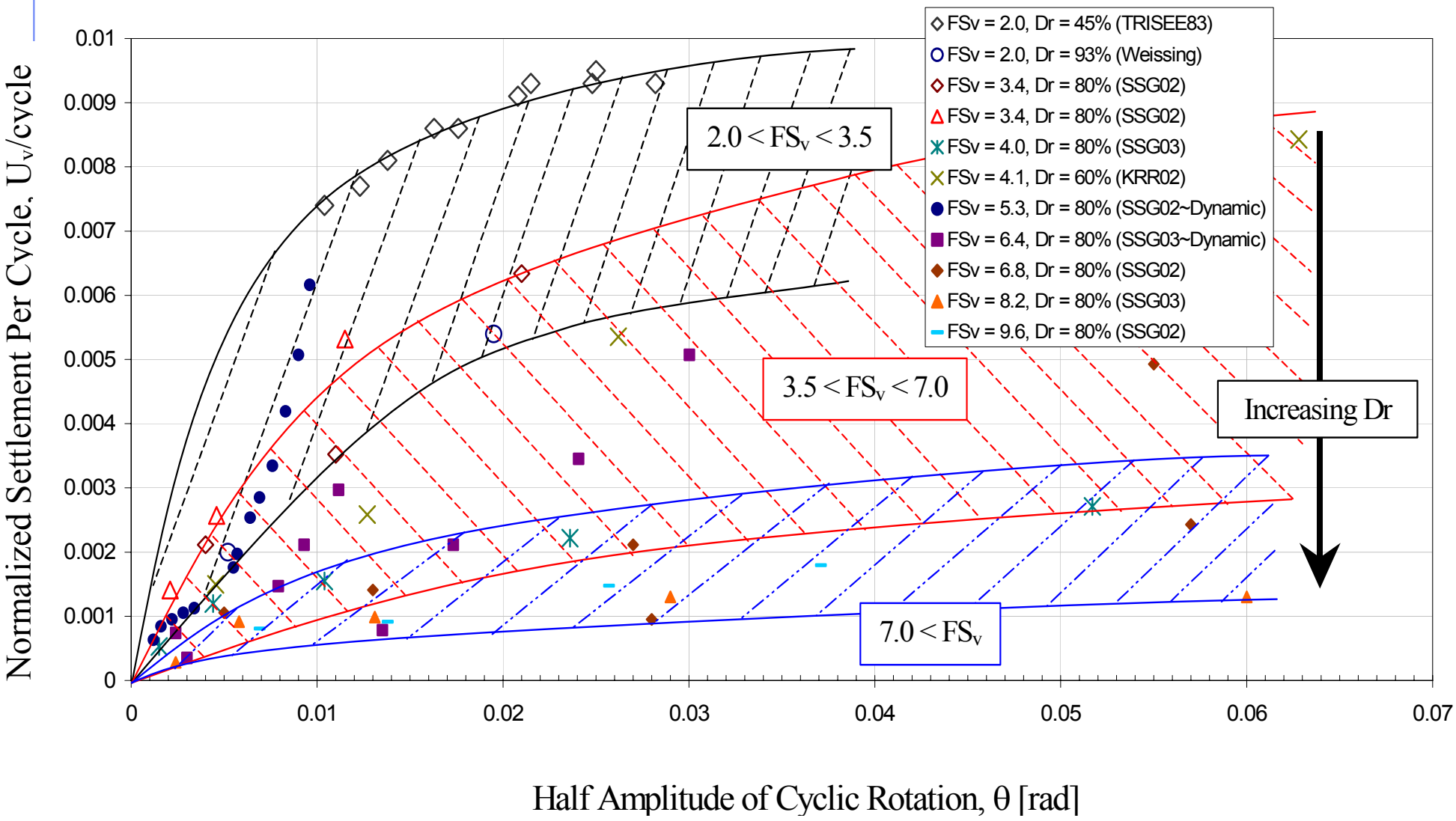
Findings: Footing Response

- Moment-rotation plots show good energy dissipation but result in settlement
- K_θ and s = f(soil type, soil density, footing size, aspect ratio, D_f , Qu/Qa, loading)

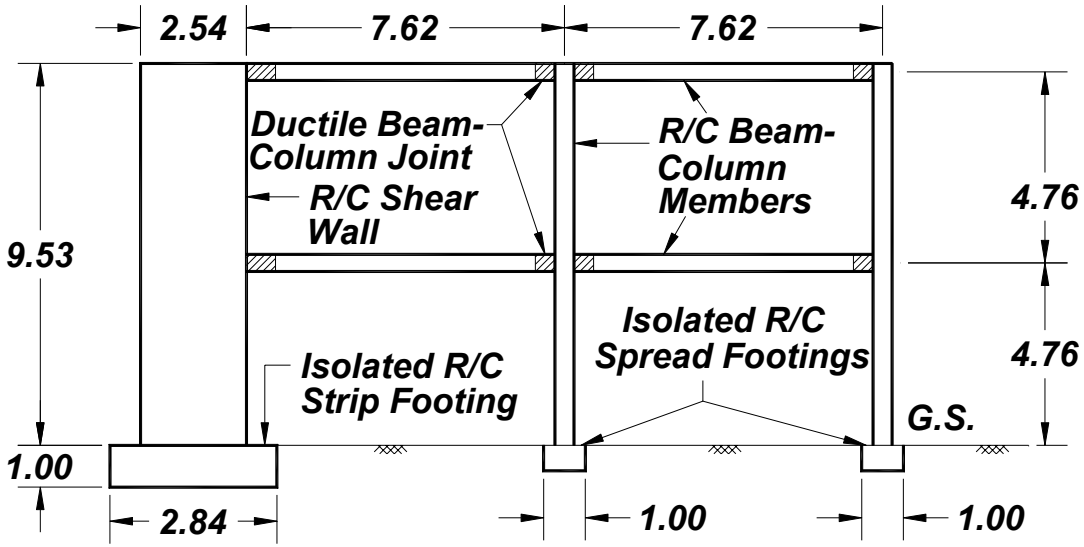




Findings: Settlement-Rotation

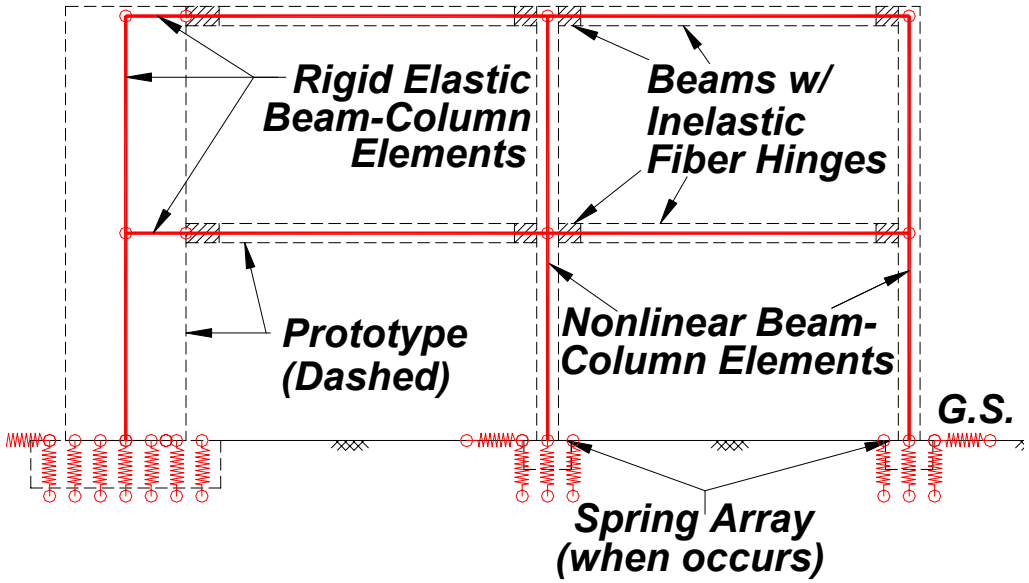


Building-Foundation Tests



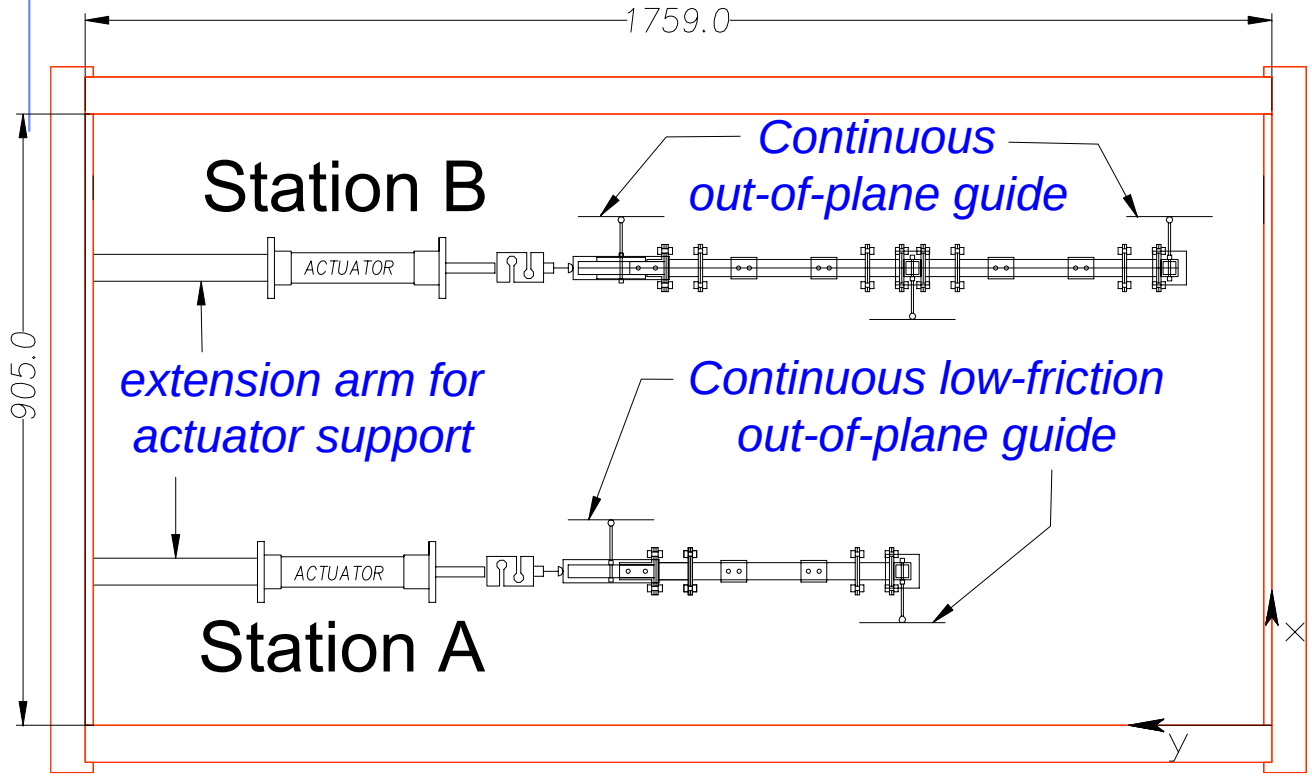
Prototype R/C Structure (units in meters) Target Tn ~ 0.5s; (Qu/Qa)govern = 5

Idealized Finite Element Model



Building-Foundation Tests

- Slow cyclic lateral loading (inertial input)
- Dynamic loading (base excitation)
- Earthquake loading (base excitation)

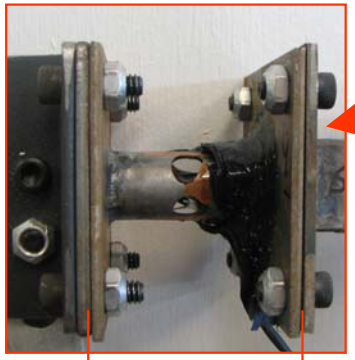


Plan view of Soil Box

D_r=85% dense dry sand

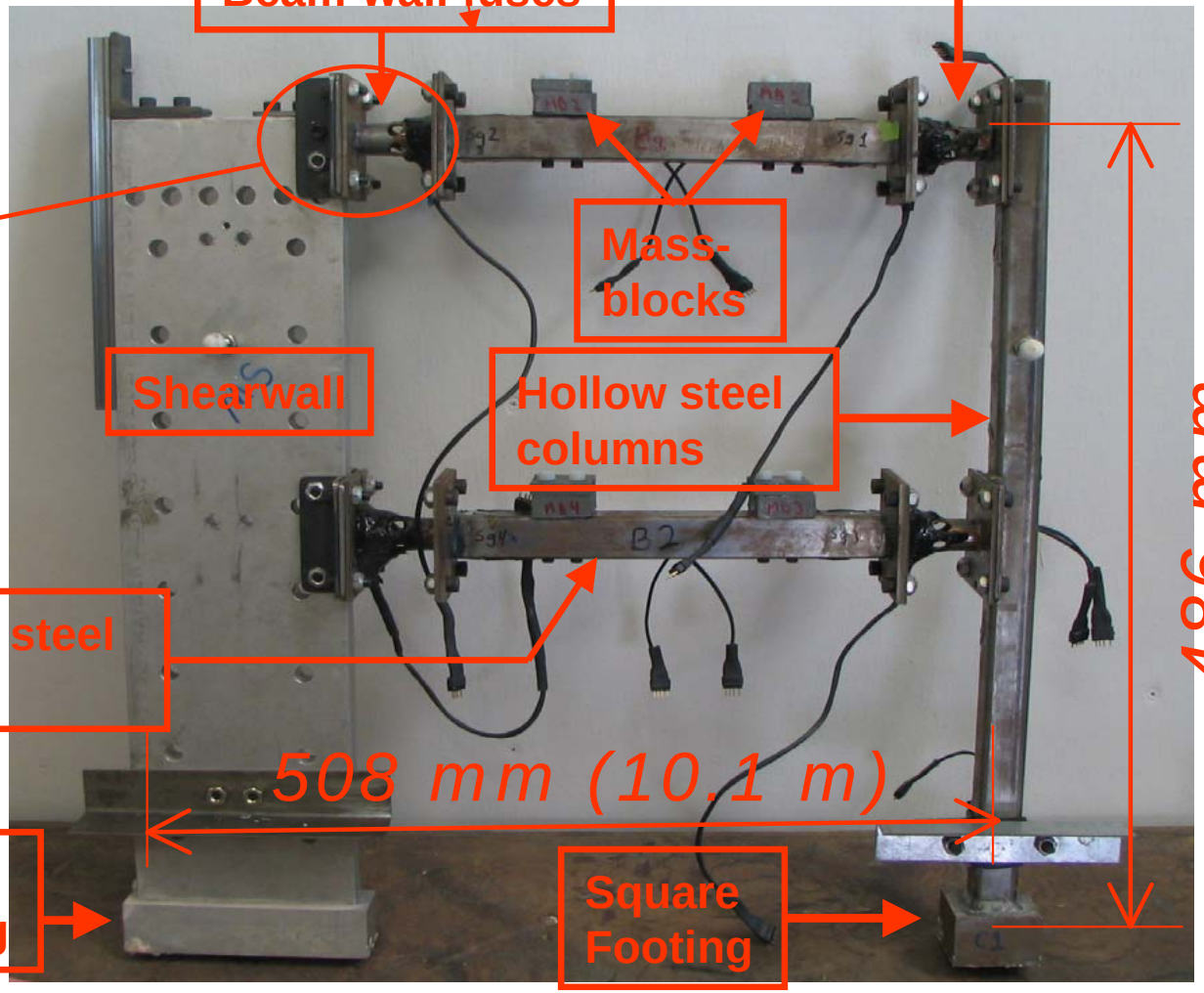
One Bay Model

Ductile fuse: full bridge configuration of 4 strain gages

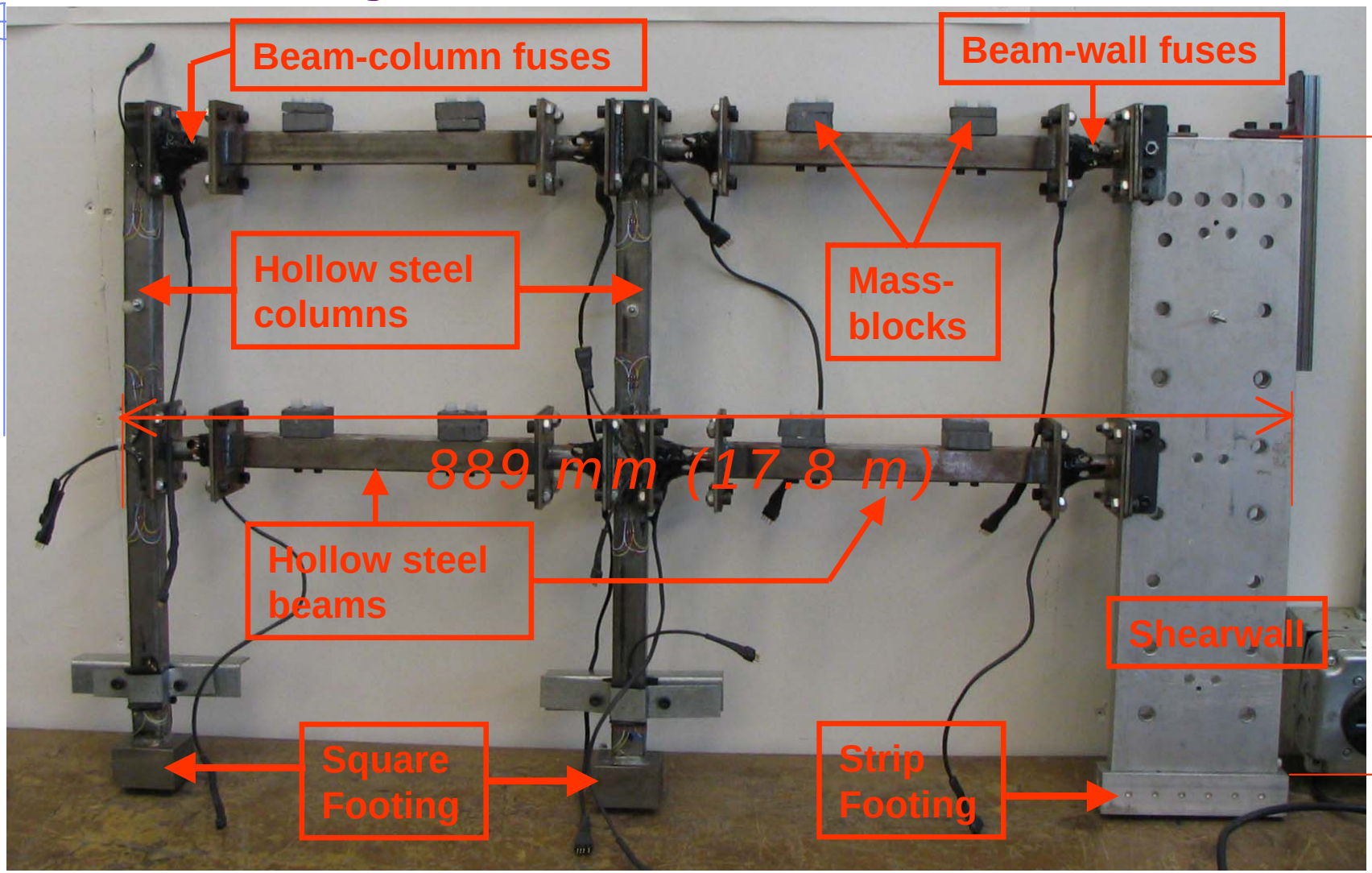


51 mm

0.1 L_{beam}

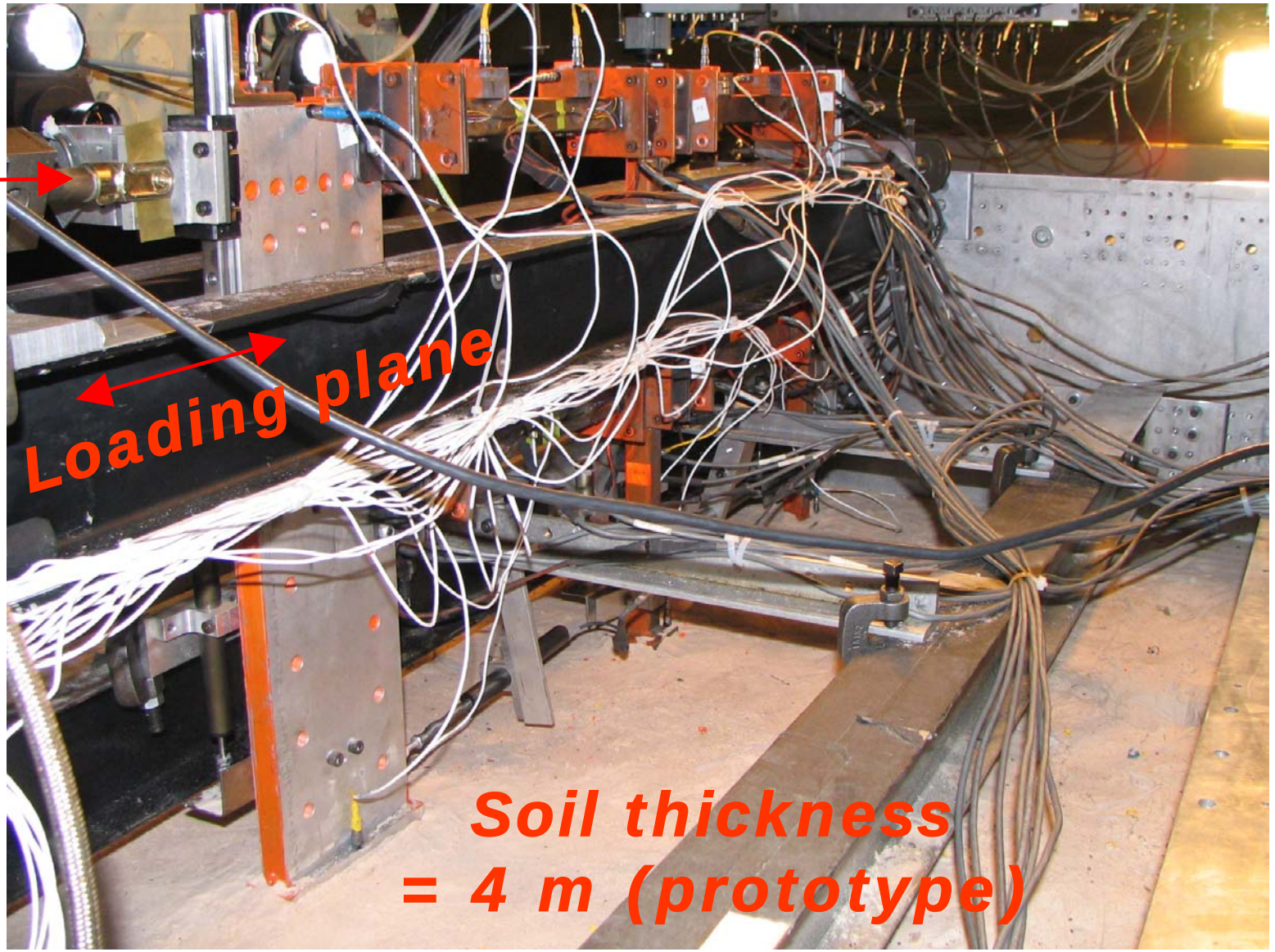


Two Bay Model



Instr: load cell, strain gages, accelerometers, linear pots

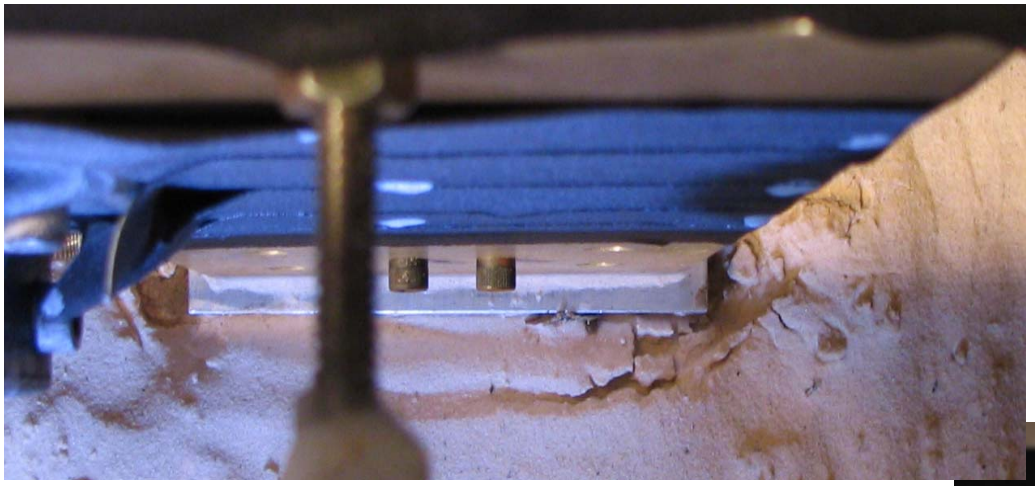
Two Bay in Centrifuge

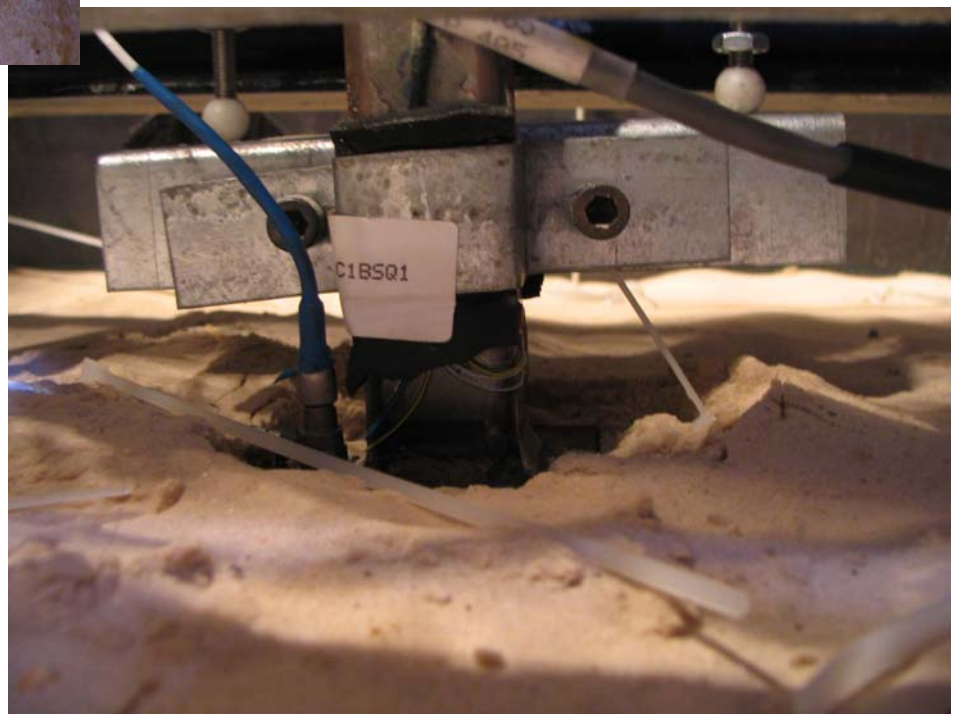


One Bay Testing Summary

Name	Ave Max Disp/ Drift Ratio (%)	Name	Base acc (g)
HSC1	19 mm / 0.20 %	D1	0.09 g
HSC2	17 mm / 0.18 %	D2	0.20 g
HSC3	12 mm / 0.13 %	D3	0.65 g
HSC4	28 mm / 0.29 %	D4	0.93 g
HSC5	55 mm / 0.58 %		
HSC6	116 mm / 1.22 %		
HSC7	240 mm / 2.52 %		
HSC8	396 mm / 4.16 %		

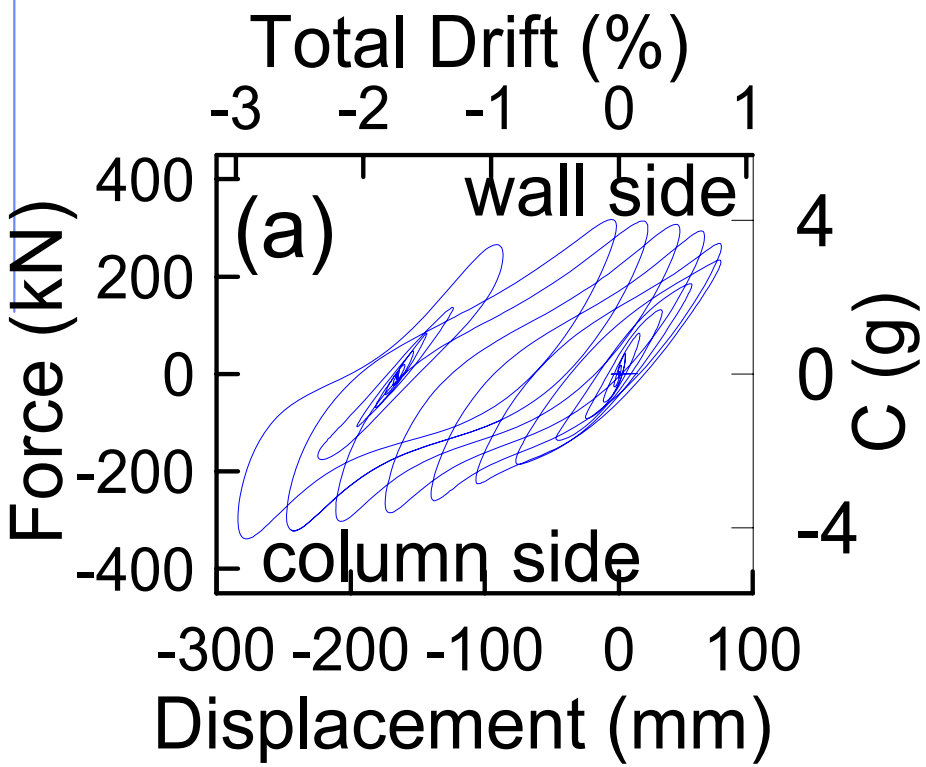
Physical Observations



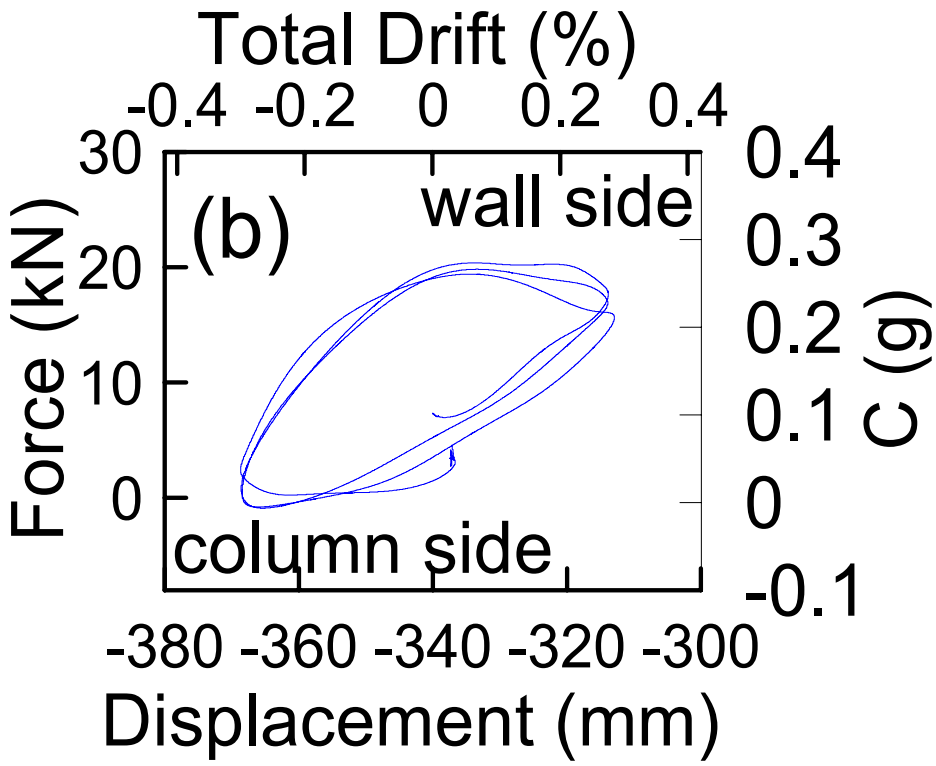


Findings: Global Response

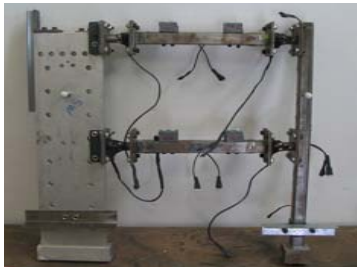
Test D3
PA = 0.65g



Test HSC4
γ = 0.3%



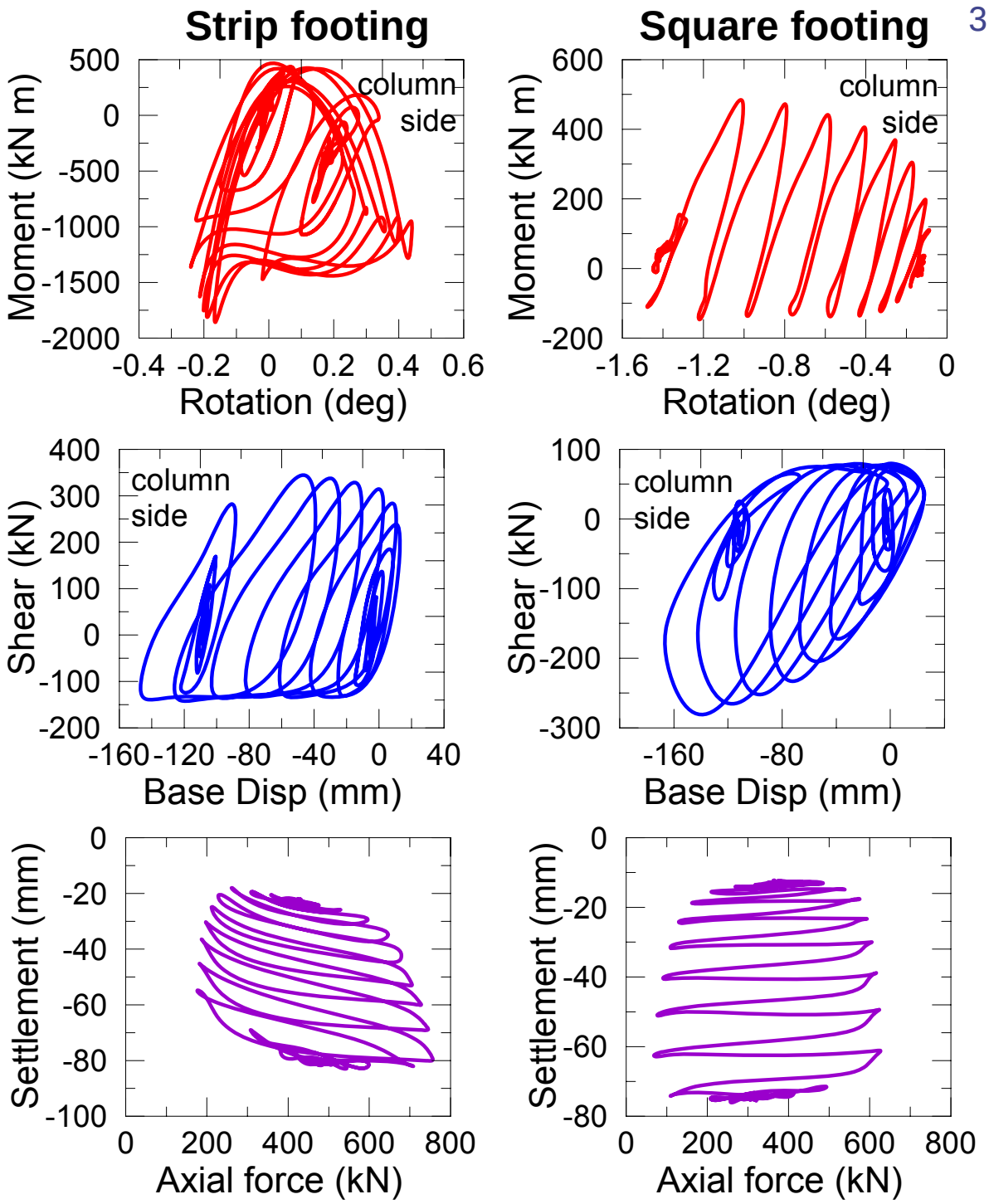
One-bay Model



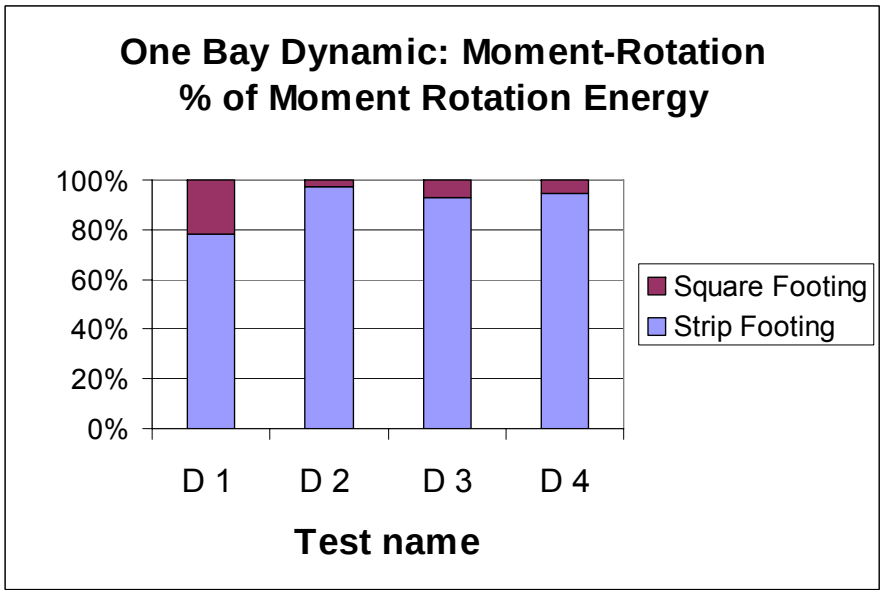
Findings: Footing Response

Test D3
PA = 0.65g

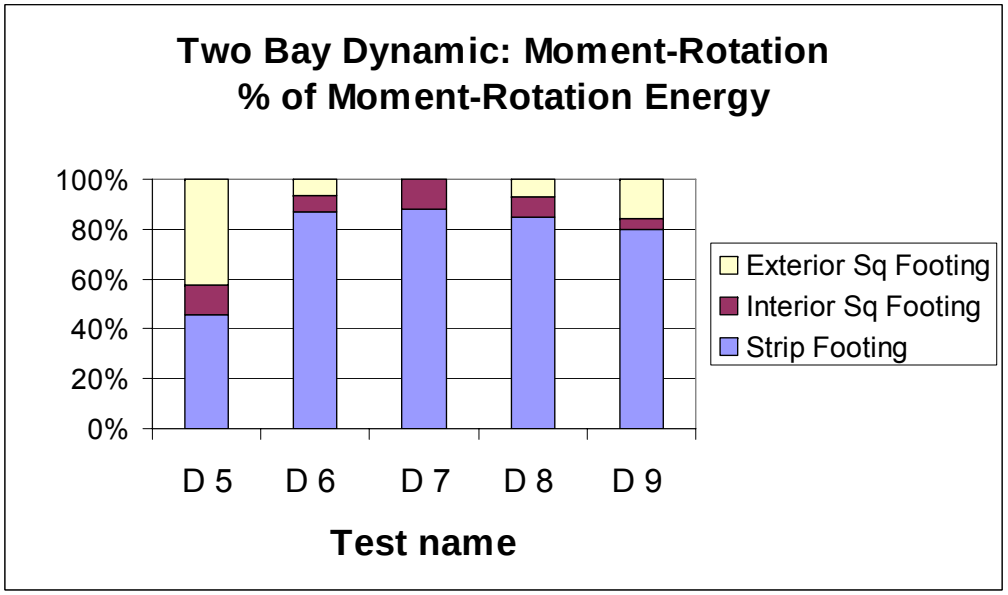
One-bay Model



Findings: Energy Dissipation



One-bay Model

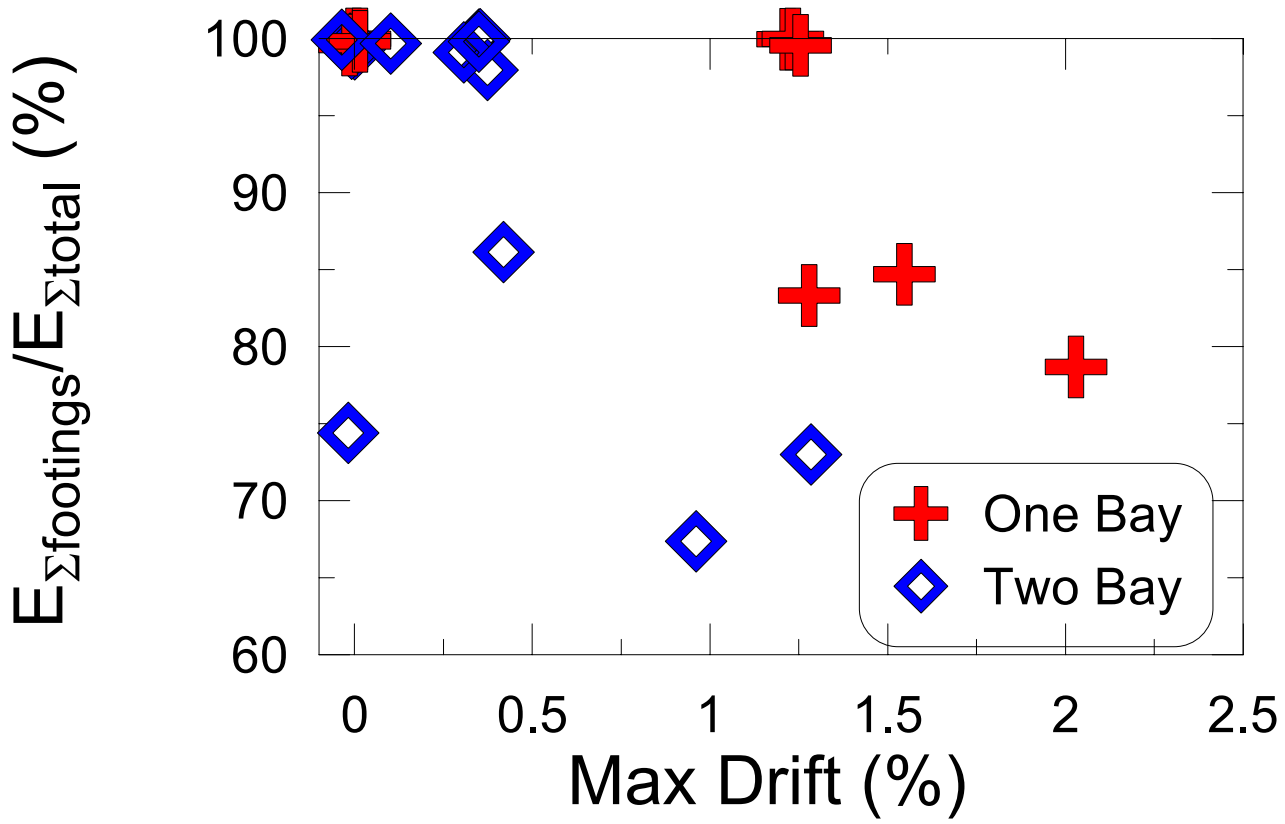


Two-bay Model

Findings: Energy Dissipation

$$E_{\sum footings} = E_{M-\theta} + E_{V-v} + E_{Q-s} \qquad (1)$$

$$E_{\sum total} = E_{\sum footings} + E_{\sum joints(M-\theta)} \qquad (2)$$



Summary of Physical Model Tests

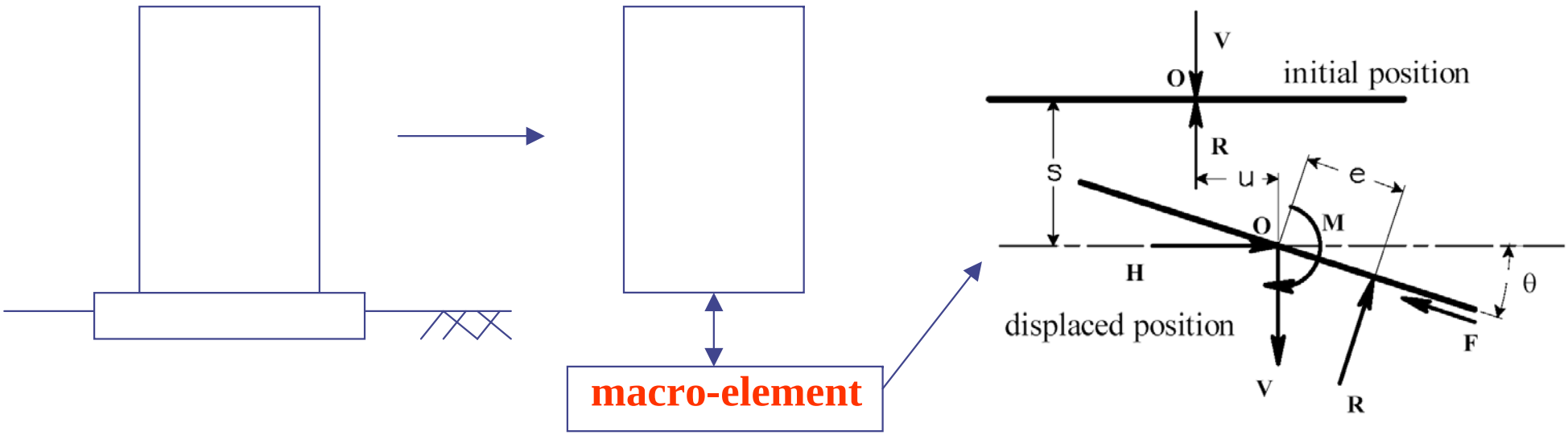
- Previous (1g) and recent centrifuge tests substantiate and assist in quantifying the benefits and consequences of rocking shallow foundations; for the subset of structure-foundation models
- Provide a robust set of data for calibration of numerical models

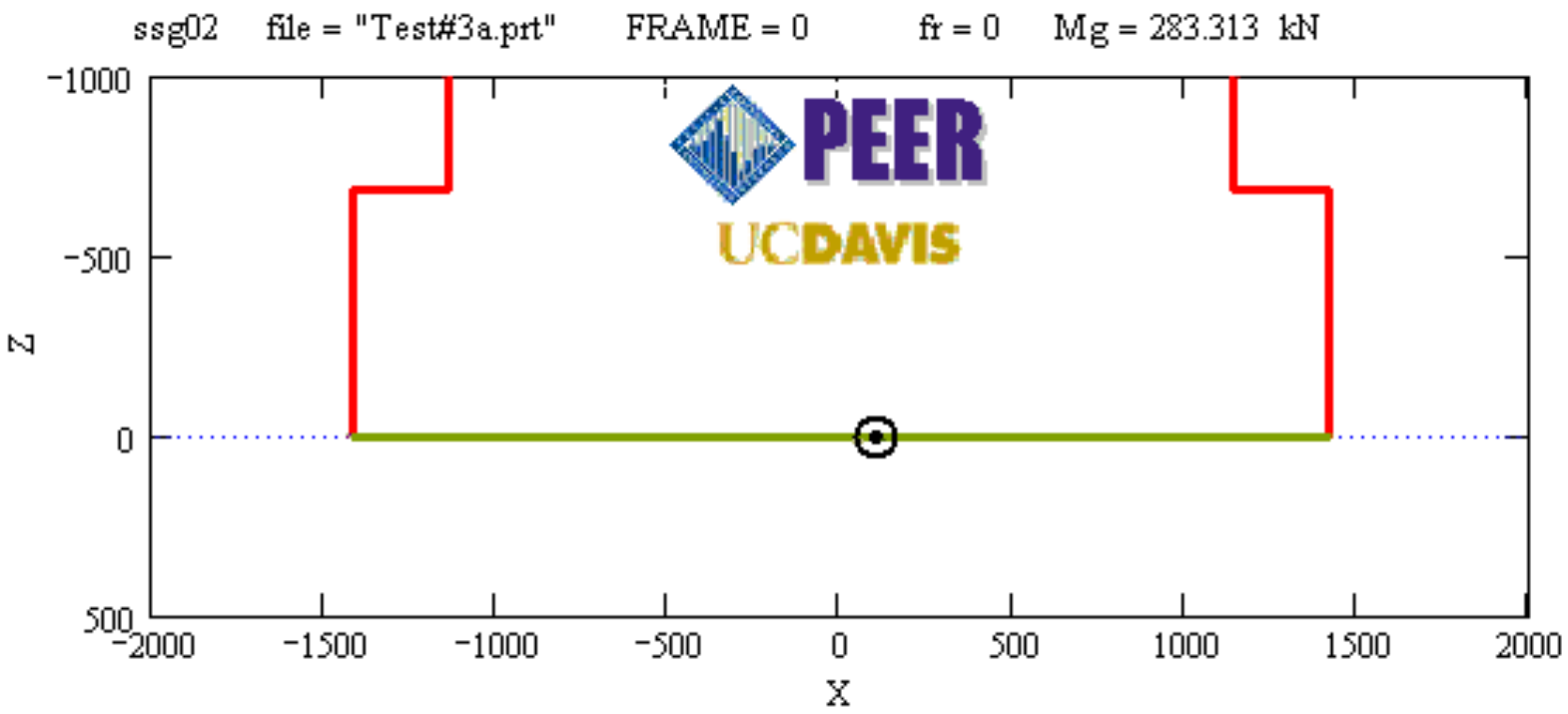
Numerical Modeling

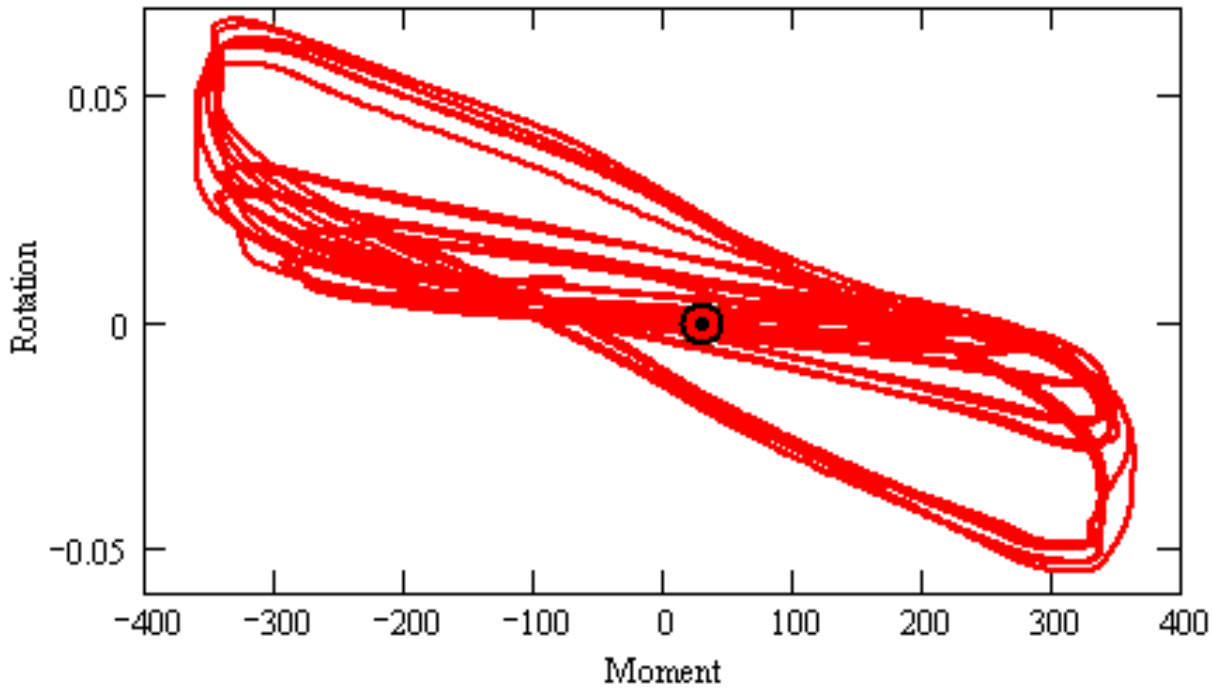
- Macro-element modeling (UCD)
- Winkler-based (design-oriented) modeling (UCSD)
- All modeling conducted in OpenSEES (PEER developed platform)
- Sensitivity Studies & Model comparisons

Macro-element Model

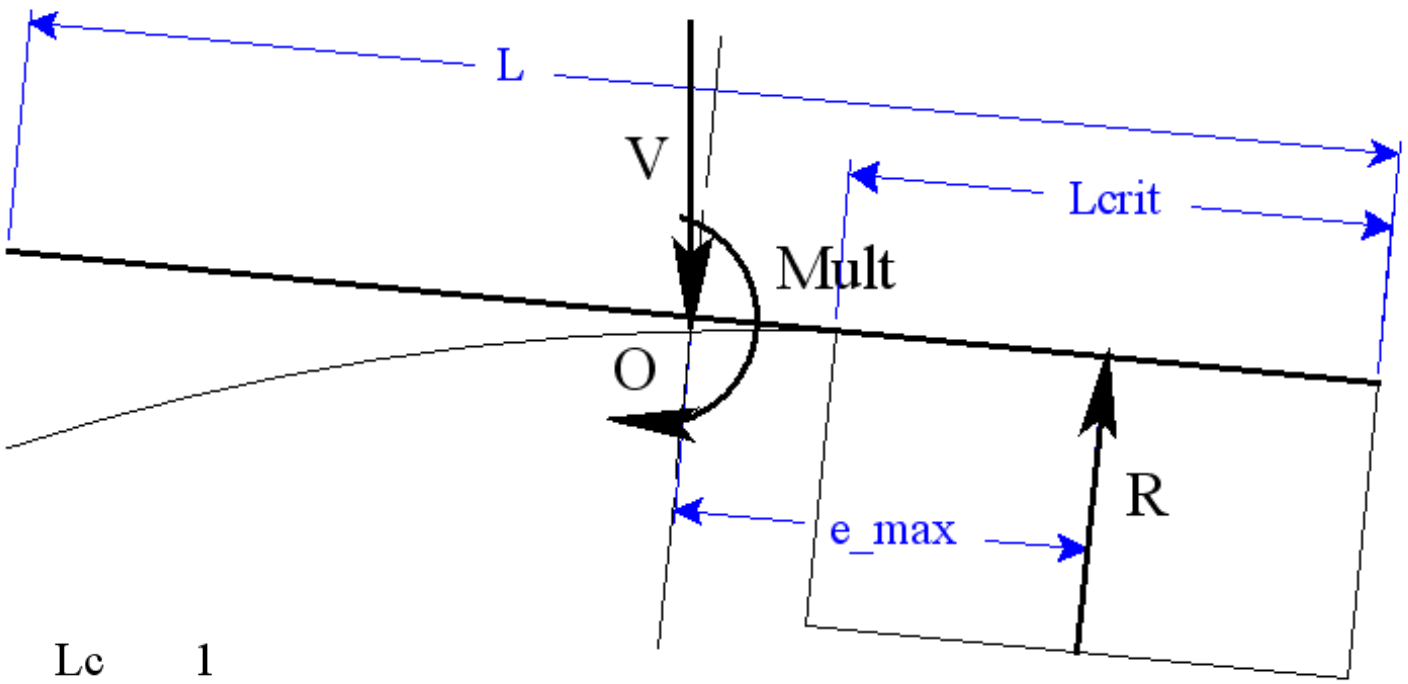
- Considers foundation and surrounding soil as a single macro-element
- Constitutive model that relates the forces (V, H, M) and displacements (s, u, θ) acting at the base center point of the footing




ssg02 file = "Test#3a.prt" FRAME = 0 fr = 0 Mg = 283.313 kN
-1000
-500
0
500
Z
-2000
-1500
-1000
-500
0
500
1000
1500
2000
X


0.05
0
-0.05
Rotation
-400
-300
-200
-100
0
100
200
300
400
Moment

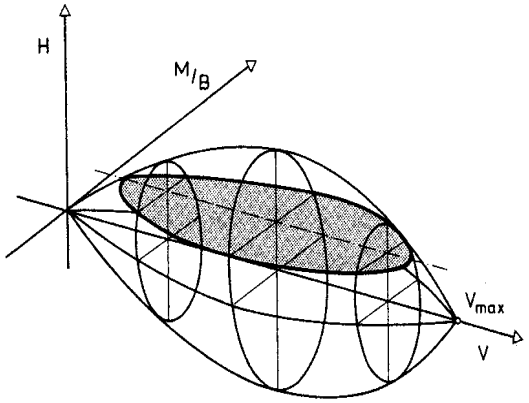
Macro-Element Model



$$\frac{Lc}{L} = \frac{1}{FS_V}$$

$$M_{ult} = \frac{V \cdot L}{2} \cdot \left[1 - \frac{Lc}{L}\right]$$

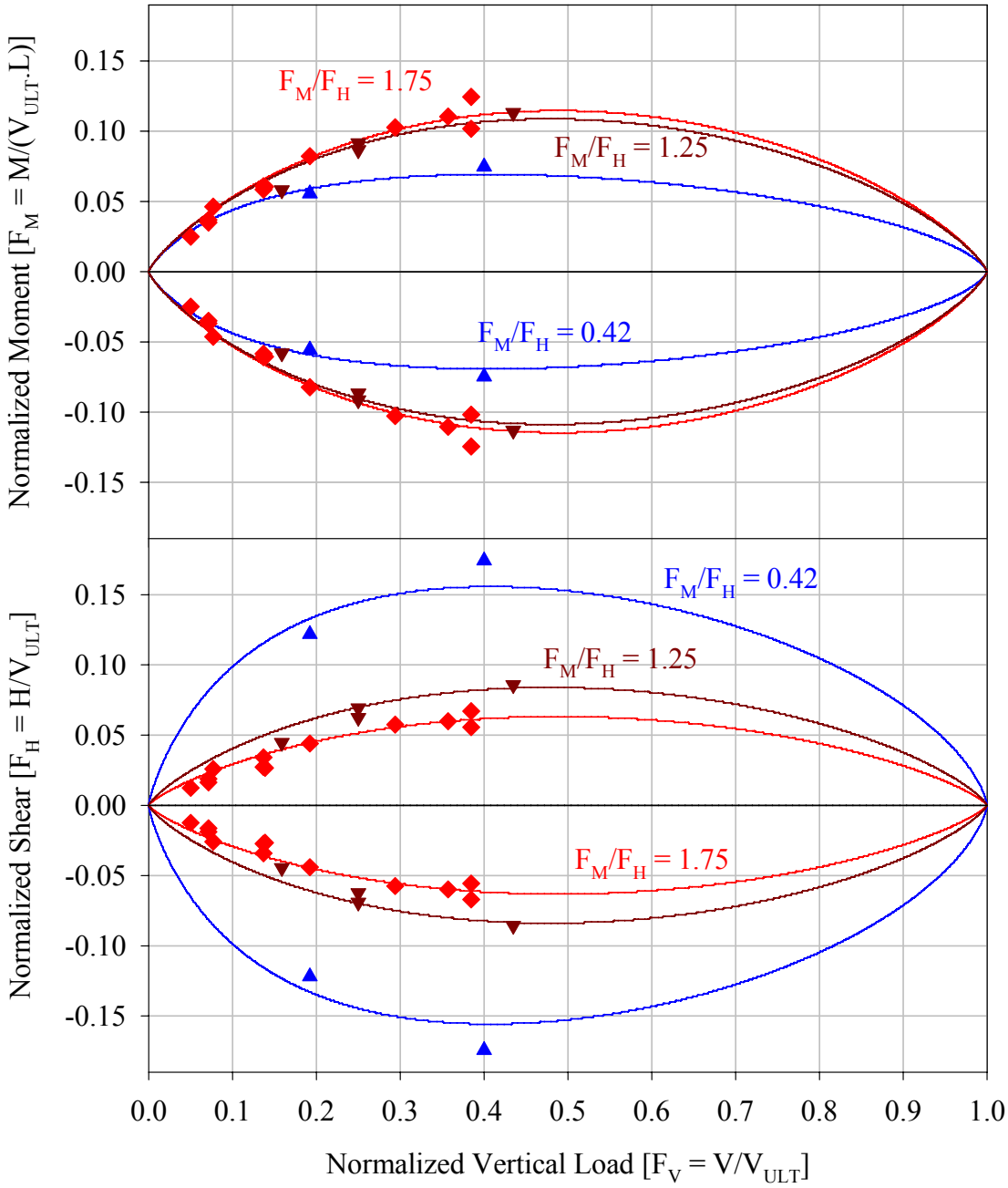
Failure Envelopes



Cremer et al. (2001)

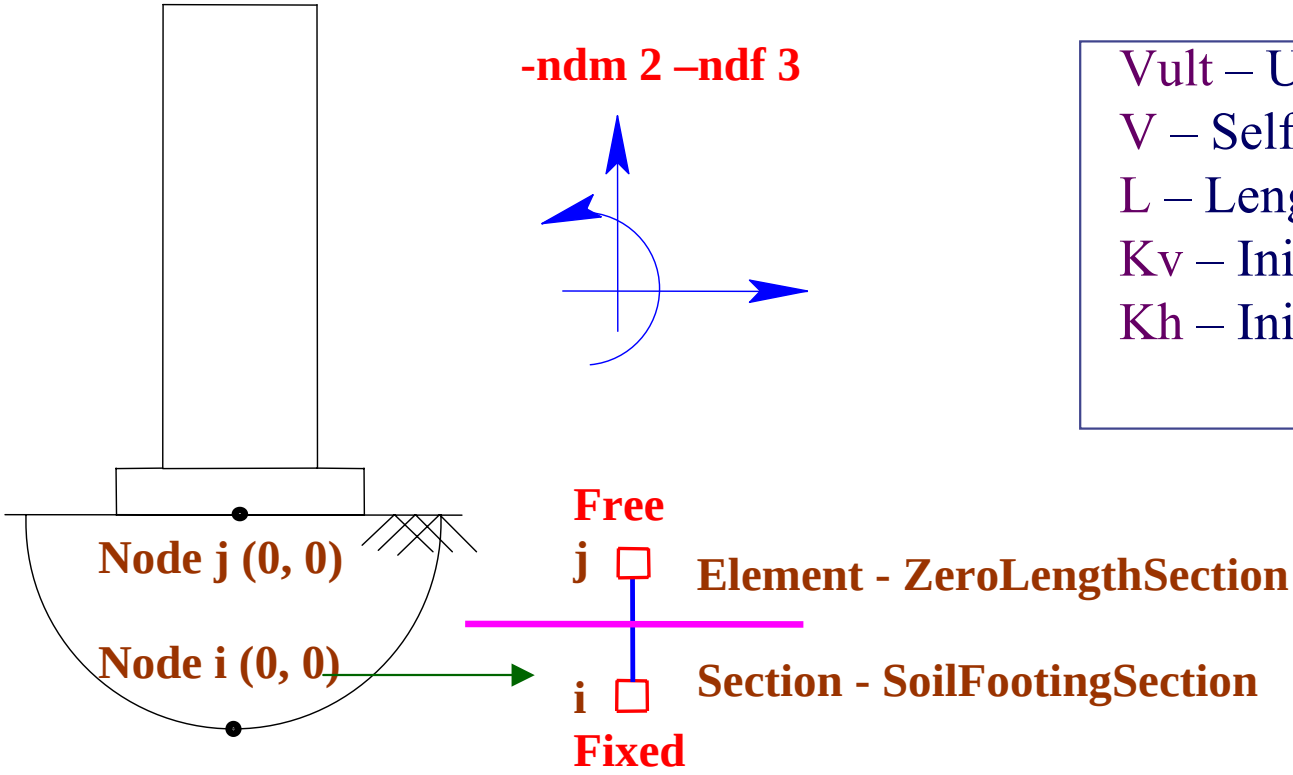
Houlsby and Cassidy (2002)

Nova and Montrasio (1991)



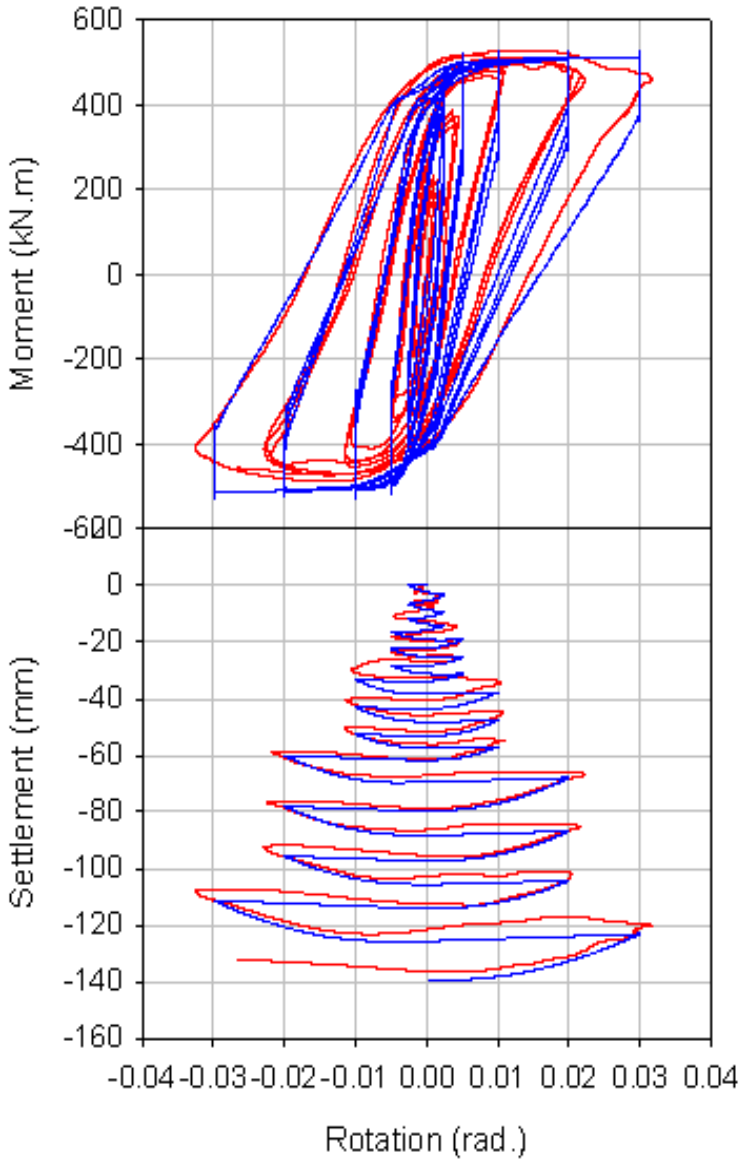
OpenSEES Implementation

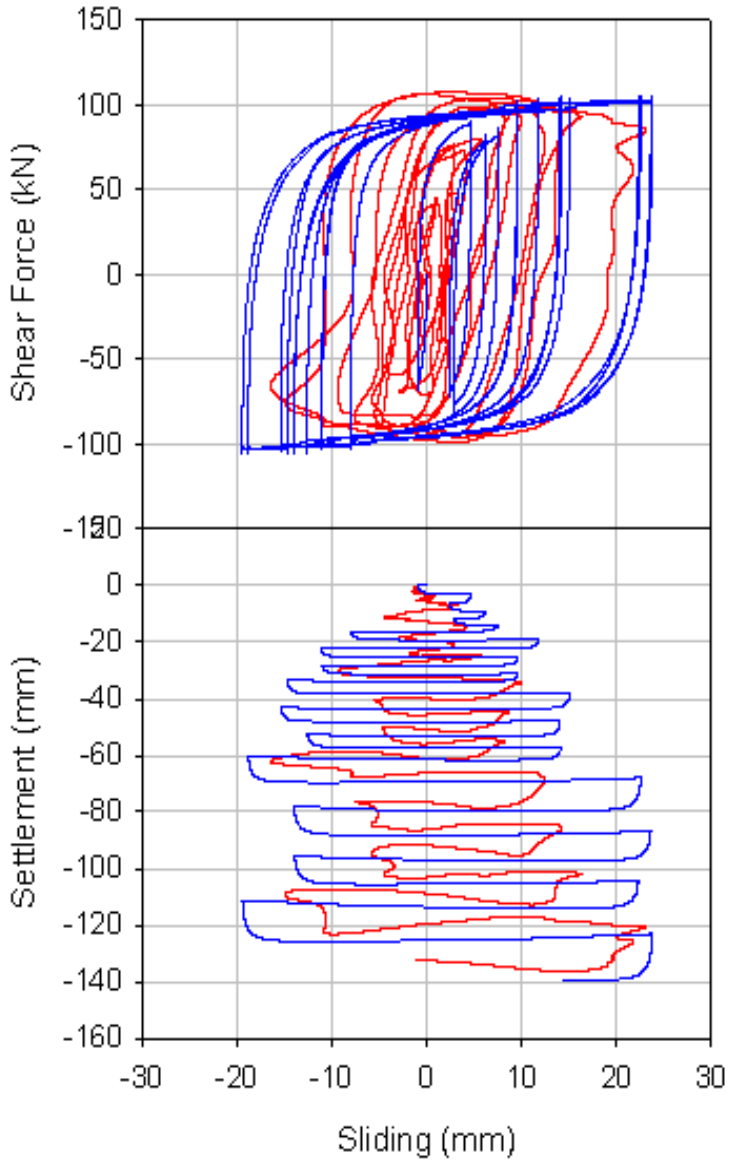
section SoilFootingSection -secID -FS -Vult -L -Kv -Kh -deltaL
element ZeroLengthSection -eleID -iNode -jNode -secID <-orientation>



Vult – Ultimate vertical load
V – Self weight of the structure
L – Length of the footing
Kv – Initial vertical stiffness
Kh – Initial horizontal stiffness

Experimental-Numerical Comparison

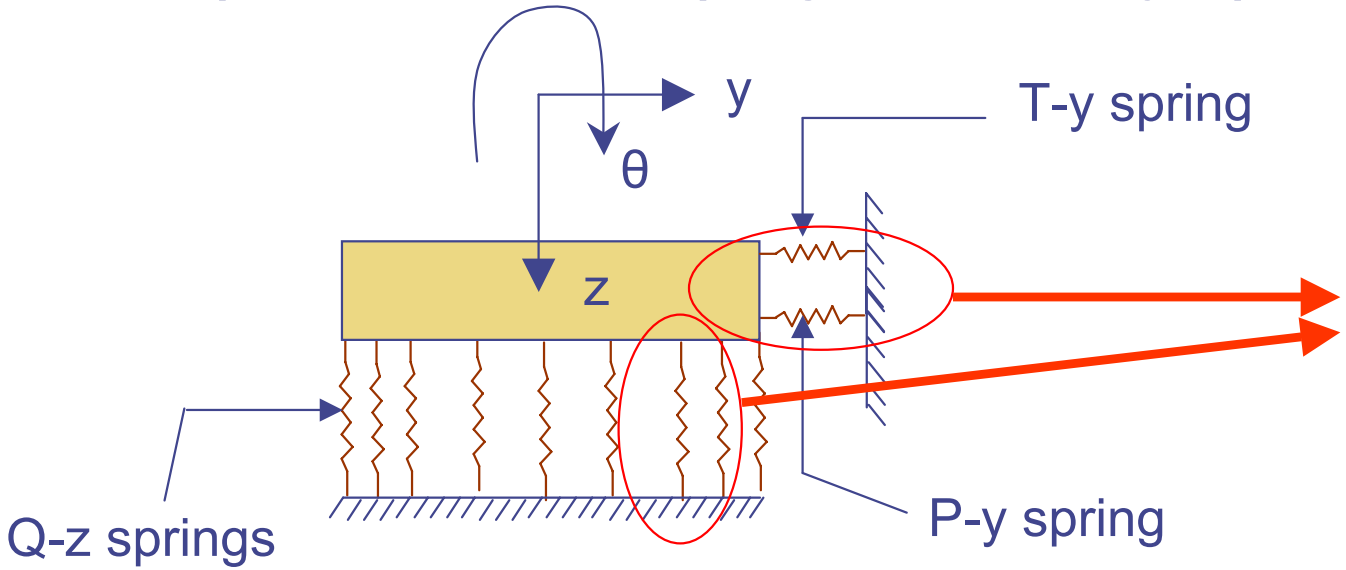


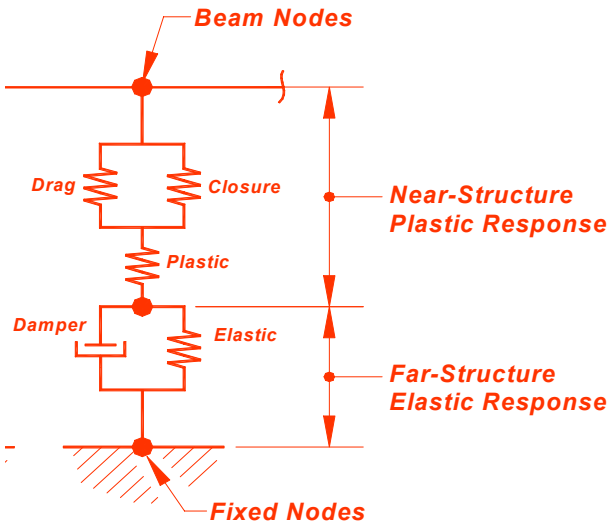


(Qu/Qa = 2.5)

Winkler-based Model

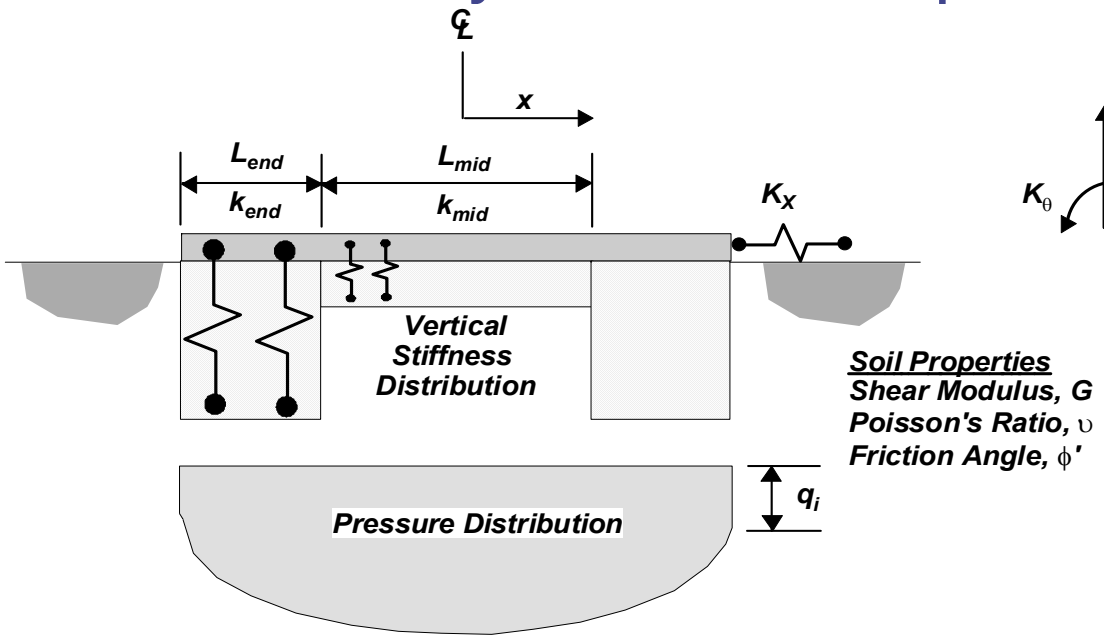
- Series of individual uncoupled springs
- For applied H-M-V, ensemble of springs calculates:
  - Sliding displacement
  - Rotation
  - Settlement
- Shear-vertical responses uncoupled
- Gap, closure, damping defined by springs in series

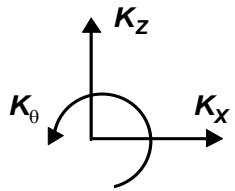




Winkler-based Model

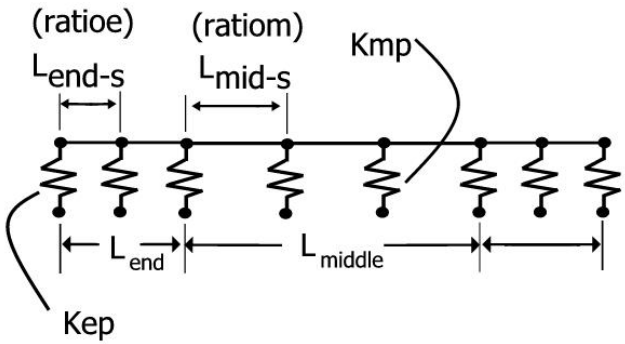
- Vertical resistance from non-linear Qz springs
- Horizontal resistance is a combination of
  - Nonlinear Py for passive earth pressures
  - Nonlinear Ty for base sliding
- Mesh generator implementation
- All springs based on Boulanger et al., 2000
- Previously calibrated to pile test data





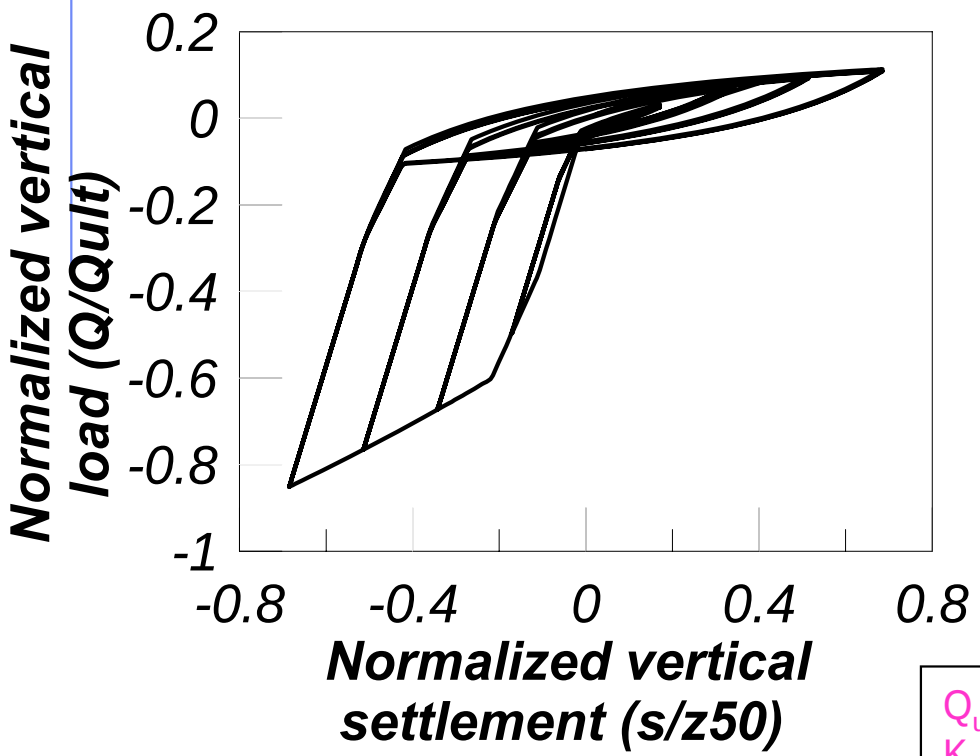
Soil Properties
Shear Modulus, G
Poisson's Ratio, υ
Friction Angle, ϕ'

Variable Lateral Springs Spacing



Winkler-based Model: q-z

- Vertical nonlinear springs; providing vertical and rocking resistance (aka “q-z” in pile analysis, for tip resistance)



Elastic portion:

q0= 2. Cr. qult

q0= load at the start of the plastic loading cycle

Plastic portion:

$$q = q_{ult} - (q_{ult} - q_o)\left(\frac{c \cdot z_{50}}{c \cdot z_{50} + \left|z - z_{op}\right|}\right)^n$$

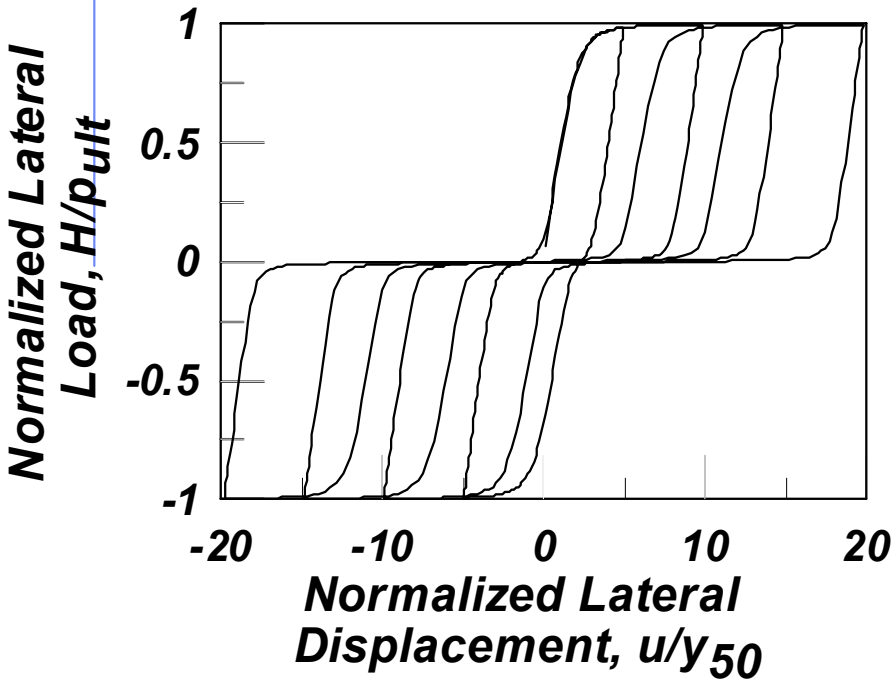
Q_{ult} = ultimate bearing capacity
K_{el} = initial elastic stiffness (vertical)
z50 = displacement at 50% of Q_{ult}
} **- User Inputs**

n, c, Cr = parameters defining the shape of the Q-z curve in plastic region - hard-coded in the material model

Cr = q/qult when plastic yielding first occurs in virgin loading

Winkler-based Model: p-y

- Horizontal nonlinear springs; accounting for passive resistance in front of the embedded footing (aka “p-y” in pile analysis, also lateral resistance)



Elastic portion:

p0= 2. Cr. pult

p0= load at the start of the plastic loading cycle

Plastic portion:

$$p = p_{ult} - (p_{ult} - p_o)\left(\frac{c \cdot y_{50}}{c \cdot y_{50} + |y - y_{op}|}\right)^n$$

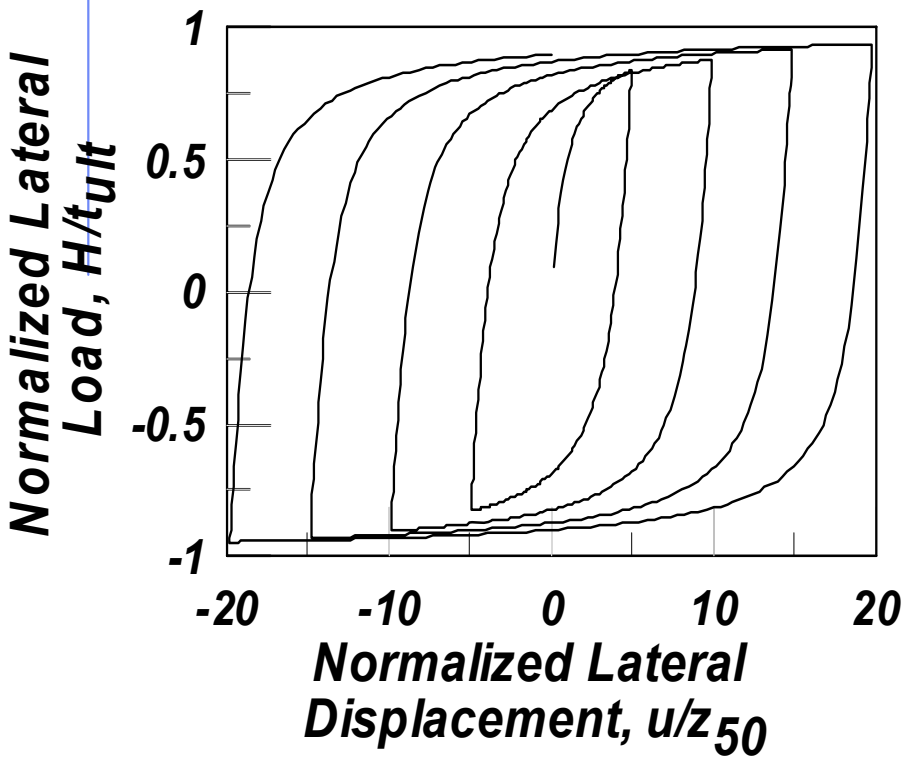
P_{ult} = ultimate bearing capacity
K_{el} = initial elastic stiffness (vertical)
z50 = displacement at 50% of P_{ult}
} **- User Inputs**

n, c, Cr = parameters defining the shape of the P-y curve in plastic region - hard-coded in the material model

Cr = p/pult when plastic yielding first occurs in virgin loading

Winkler-based Model: t-y

- Horizontal nonlinear springs; accounting for frictional resistance between footing and soil (aka “t-z” in pile analysis, skin resistance)



Elastic portion:

t0= 2. Cr. tult

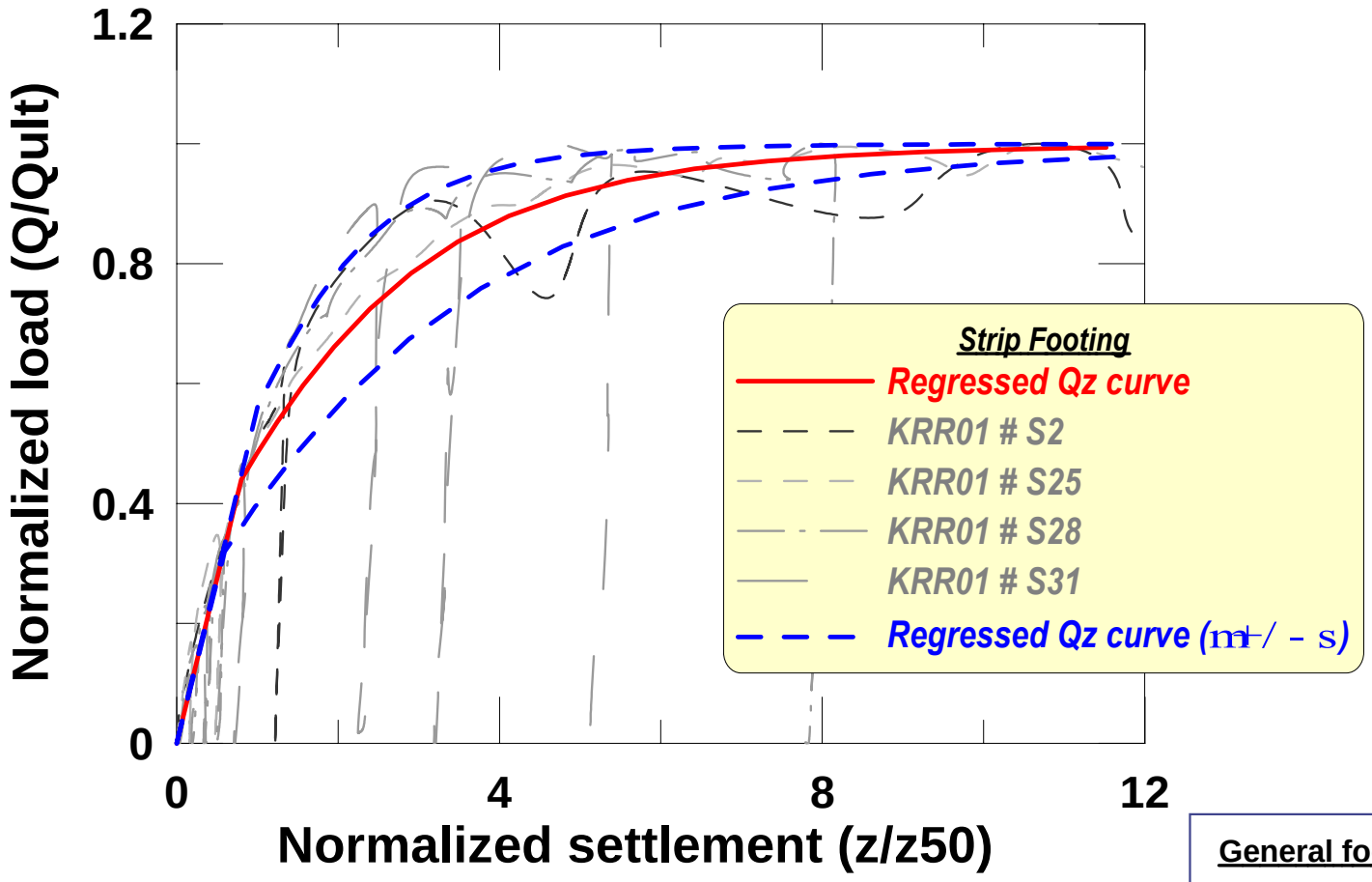
t0= load at the start of the plastic loading cycle

Plastic portion:

$$t = t_{ult} - (t_{ult} - t_o)\left(\frac{c \cdot y_{50}}{c \cdot y_{50} + \left|y - y_{op}\right|}\right)^n$$

t_{ult} = ultimate lateral capacity (friction)
K_{el} = initial elastic stiffness (lateral)
y50 = displacement at 50% of t_{ult}
n, c, Cr = parameters defining the shape of the T-y curve in plastic region - hard-coded in the material model

Mechanistic Calibration; eg q-z



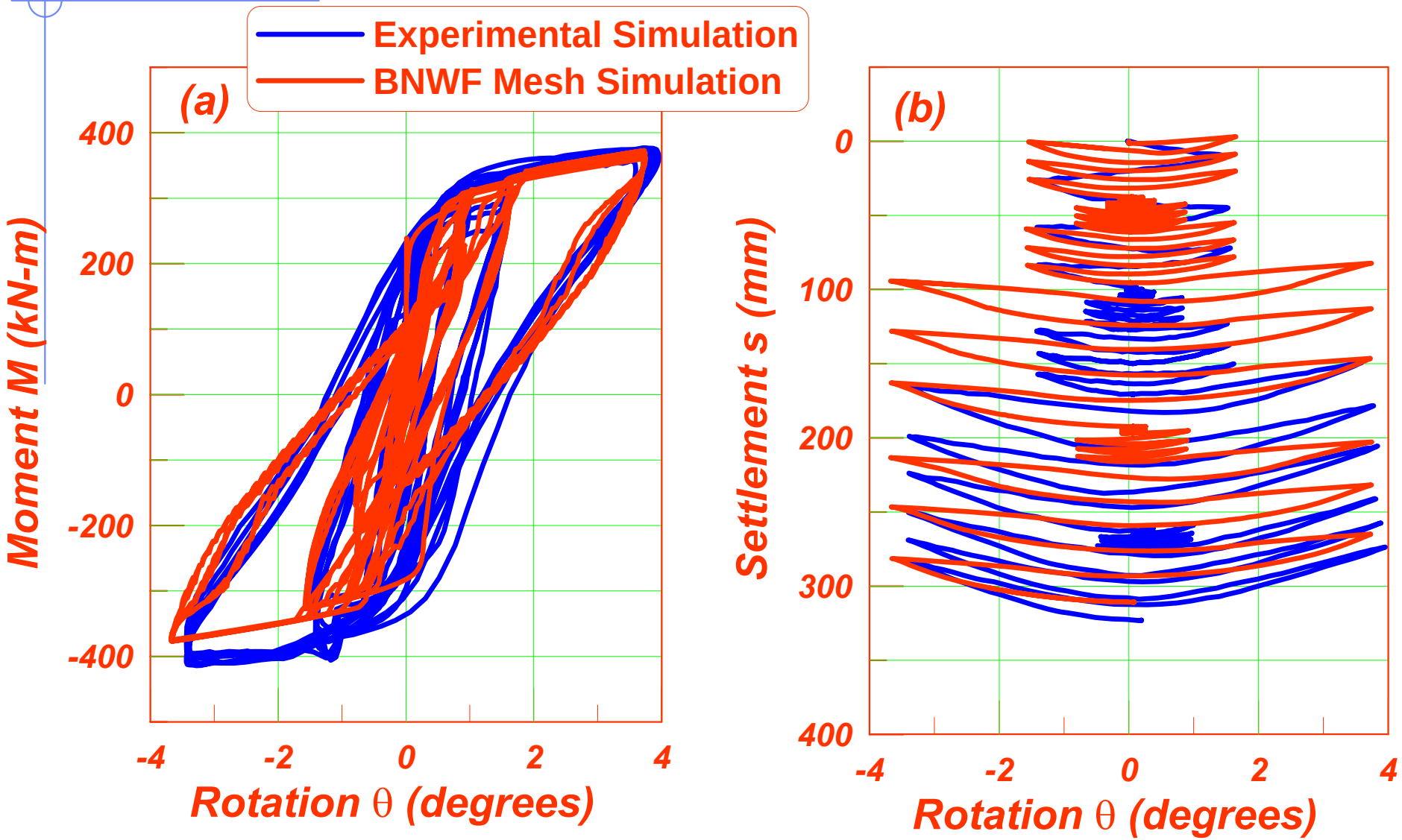
General soil condition

- Medium to dense sand (D_r = 55-80%)
- phi= 33-40^0
- Water content = 0-5%

General footing condition

Strip	Square
Centrifuge tests	Full-scale tests
L/B = 3.5-6.6	B = 1-3m
Df = 0-0.3m	Df = 0.7-0.9m
FSv = 2-3.8	FSv = 2-2.3

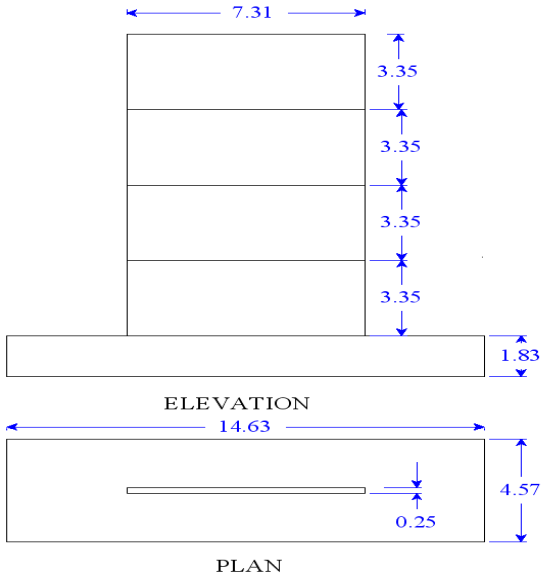
Experimental-Numerical Comparison



Sand, Qu/Qa=3.0, ϕ' = 38, Dr = 60%

Comparison of Models

- 3 different wall-footing prototypes
- Range of EQ motions & static cyclic input
- Resting on OC clay
- Tn (fixed-base) ~ 0.2-0.8 sec
- Tn (flexible-base) ~ 0.4-1.3 sec



Model	Height (m)	Stories	Mass @ floor x 10^5 (kg)	Total weight on the footing (MN)	Factor of safety (FS_v)	T_n (fixed base) (sec)	T_n (flex base/no sliding) (sec)	T_n (flex base/ sliding) (sec)
1	14.4	4	3.75	5.78	3.13	0.44	0.84	0.98
2	6.4	1	6.46	3.78	4.79	0.21	0.40	0.58
3	23	5	2.72	6.94	2.61	0.76	1.29	1.42

Comparison of Models

- Physical parameters used in the study

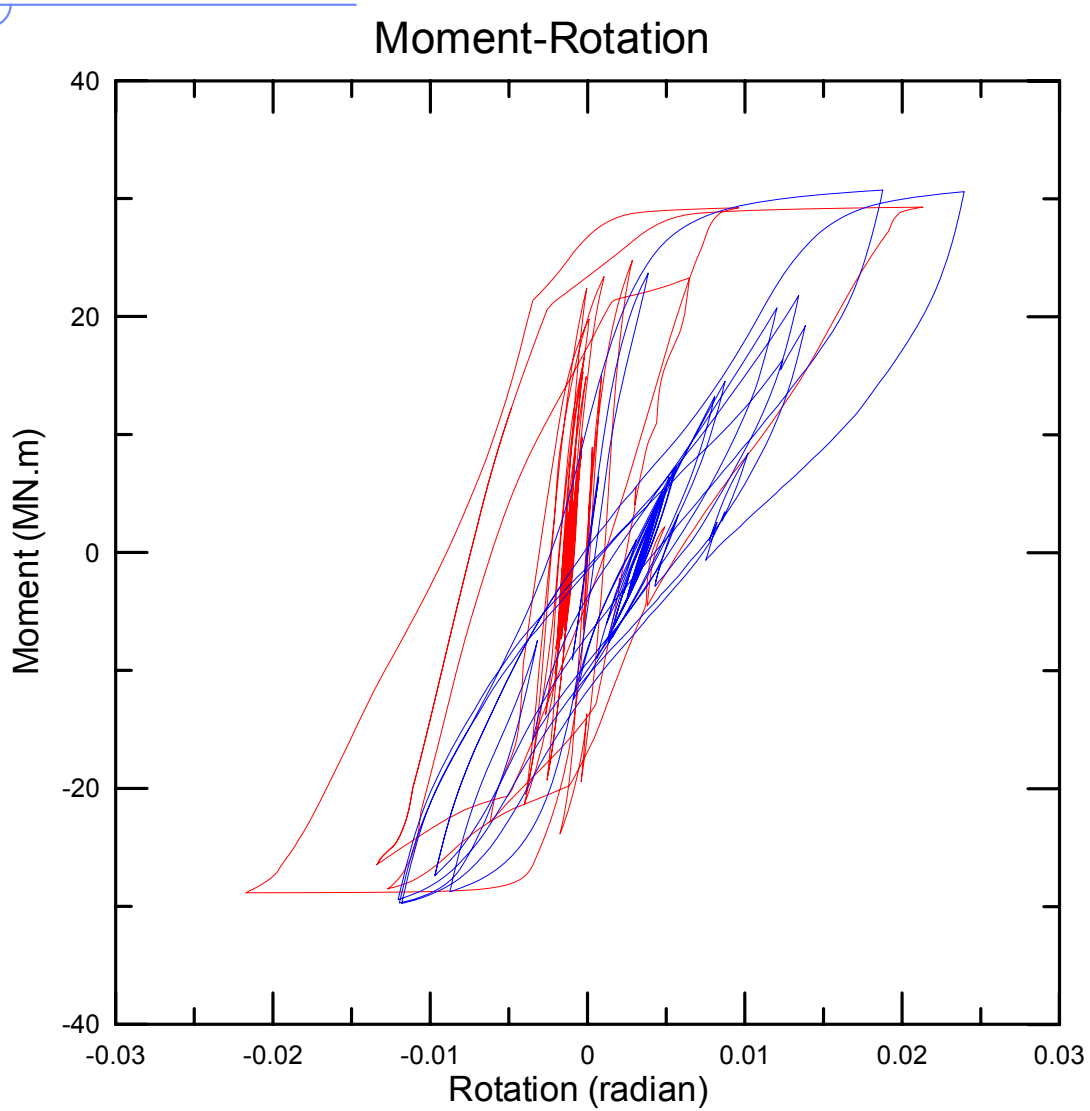
Basic and Given parameters

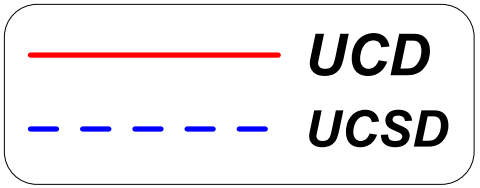
- c_u = 52.67 kPa, $\phi = 0^0$
- ν = 0.5, G_{max} = 26.33 MN/m^2
- Rayleigh damping = 5% (first two modes)
- Radiation damping = 5%

Derived parameters

- Bearing capacity, Q_{ult} = 18.11 MN (from *Terzaghi, 1943*)
- Shear Capacity, V_{ult} = 3.32 MN (V_{ult}=c*Lf*Bf)
- Vertical stiffness, Kv = 814 MN/m (from *Gazetas, 1991*)
- Horizontal stiffness, kx = 750 MN/m (from *Gazetas, 1991*)

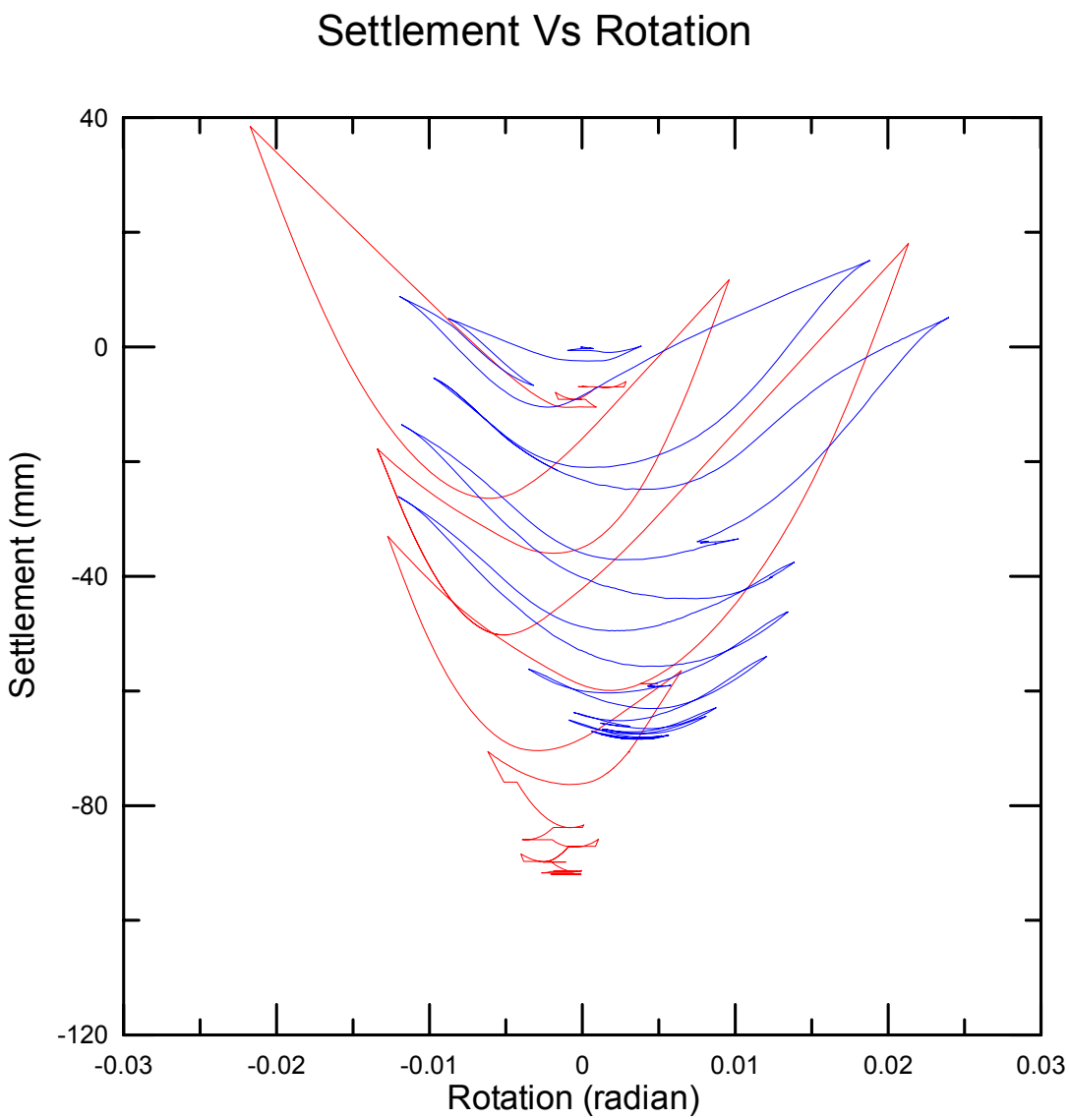
M-θ (Model 1: Tn(fb) = .44s)

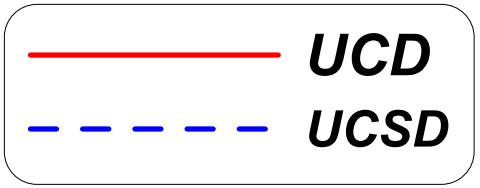




2% in 50 Year Motion

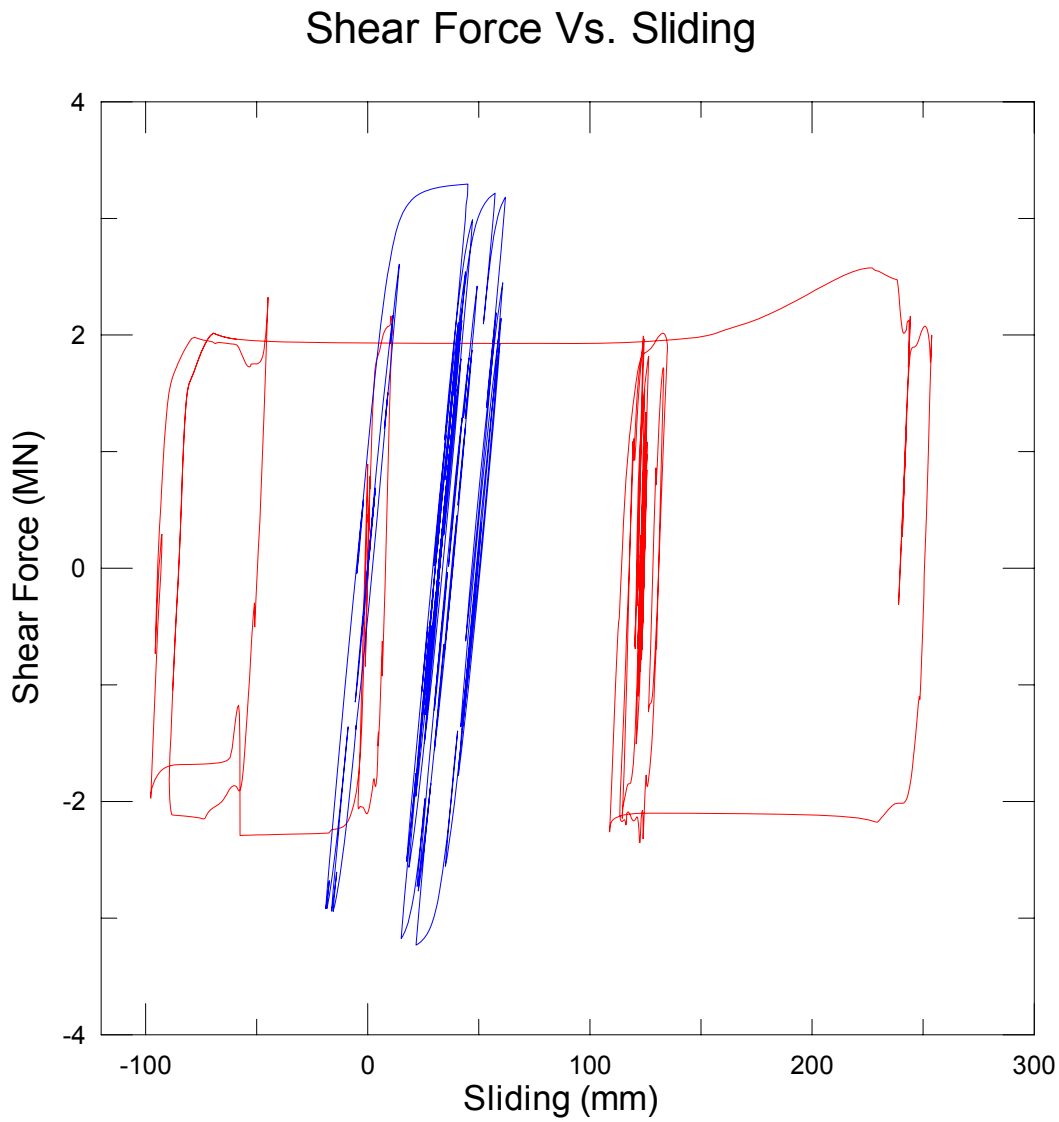
S-θ (Model 1: Tn(fb) = .44s)





2% in 50 Year Motion

V-v (Model 1: Tn(fb) = .44s)

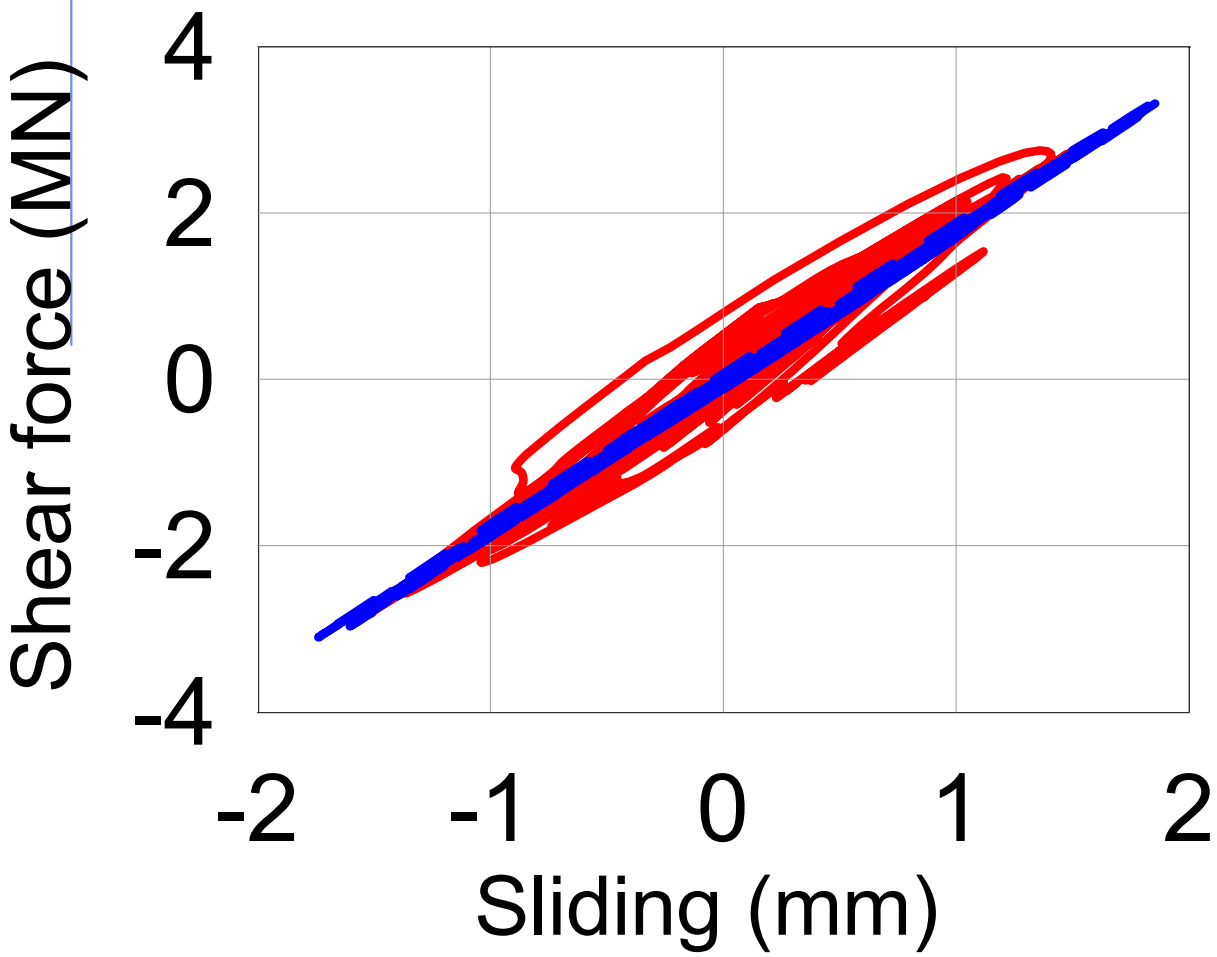


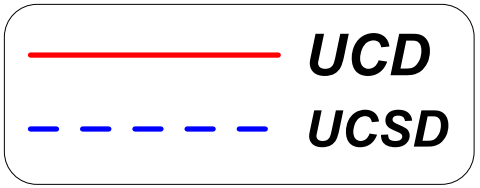
2% in 50 Year Motion

Revisit Shear Resistance Modeling

- Vu (old)= 3.32 MN; Vu (new)= 26 MN
- Kx (old)= 750 MN/m; Kx (new)= 1815 MN/m
- Tn (model1)= 0.98s; Tn (model1)= 0.95s
- Tn (model2)= 0.58s; Tn (model2)= 0.54s
- Tn (model3)= 1.42s; Tn (model3)= 1.35s

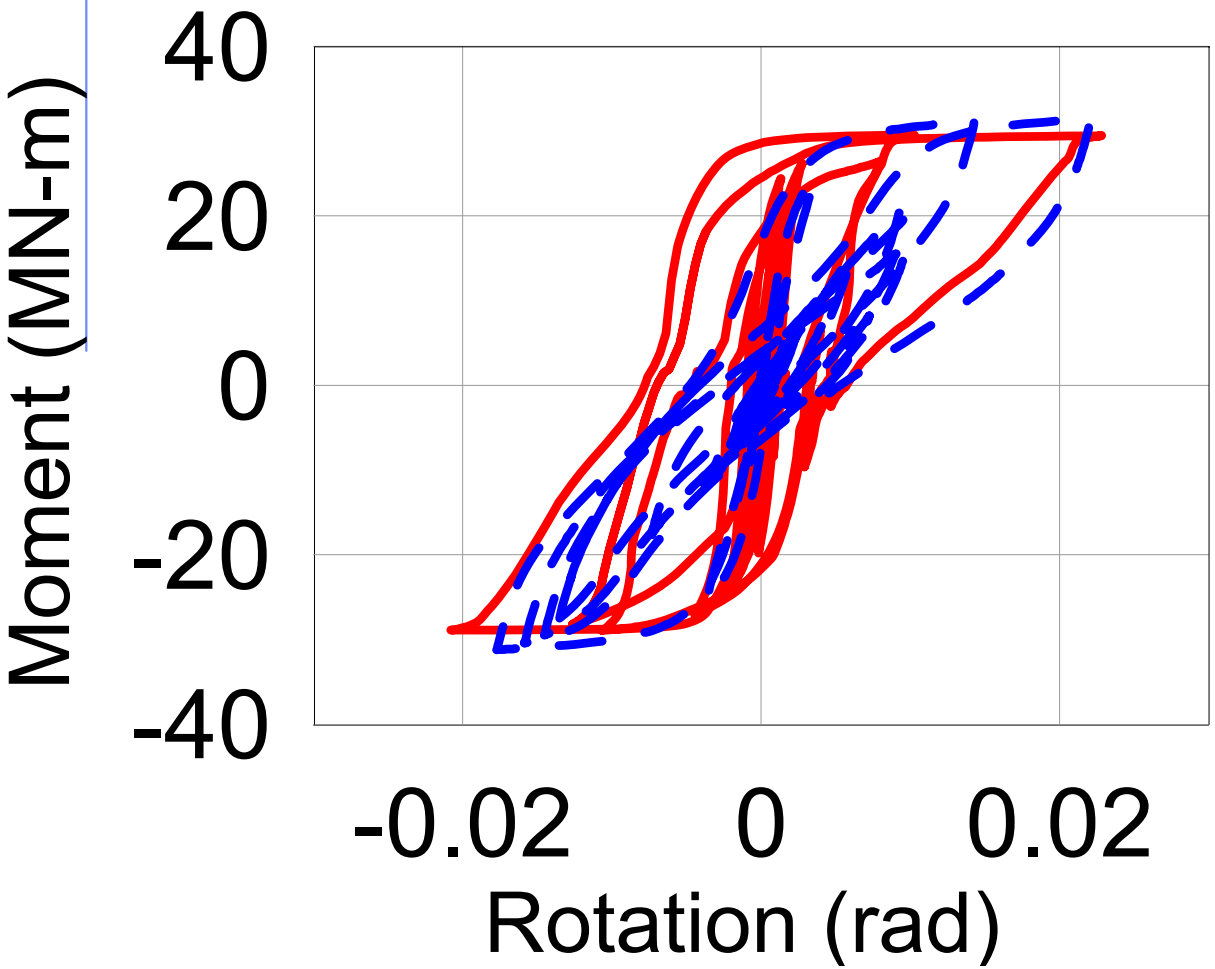
V-v (Model 1: Tn(fb) = .44s)

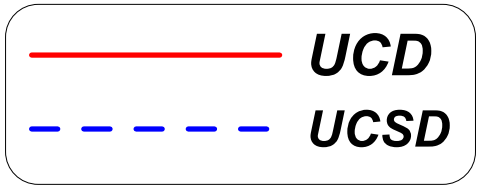




2% in 50 Year Motion

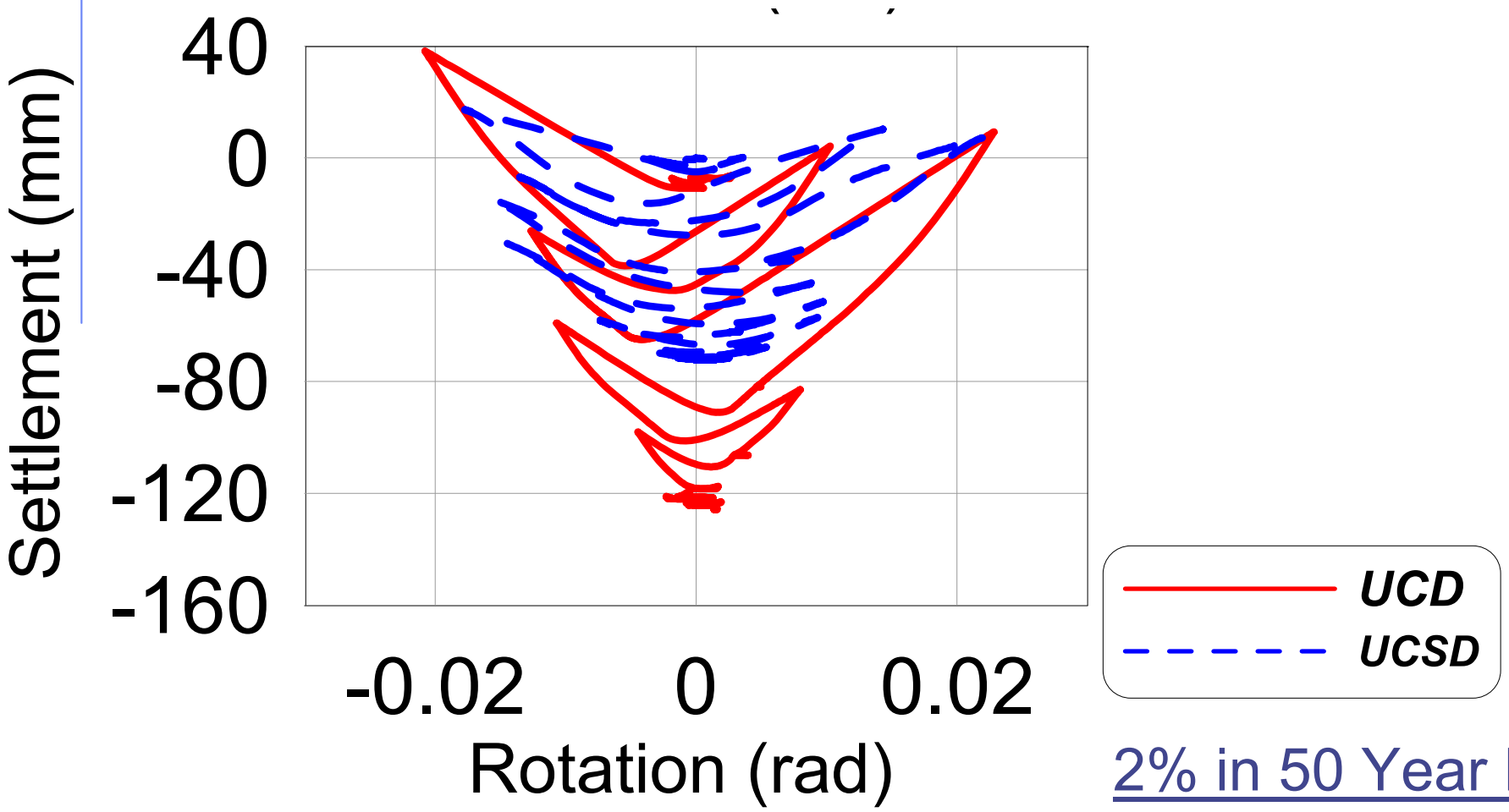
M-θ (Model 1: Tn(fb) = .44s)





2% in 50 Year Motion

S-θ (Model 1: Tn(fb) = .44s)



2% in 50 Year Motion

Discussion

- Positive comparative points
  - Initial stiffnesses and general shape of M-θ response reasonably comparable
  - Initial settlement response and shape of settlement response, particularly in higher amplitude earlier cycles reasonably comparable
- Physical Differences
  - Shear-moment coupling
    - Results in reduction of shear capacity at given moment; which is not captured in a Winkler-based model
    - Differences more pronounced for lower M/V ratio wall-foundation model
  - Settlement estimations under low amplitude shaking are challenging to capture accurately; variations in s between models can be on the order of 2-3x

Outcomes

- We hope to propagate this new knowledge and these new tools into practice as they are refined and become more readily available:
  - All data reports available on-line: cgm.engr.ucdavis.edu
  - OpenSEES implementation and examples of various foundation elements use will be complete by Fall 2007
- Findings from this work will help us:
  - Improve nonlinear static procedures
  - Improve accuracy of our nonlinear dynamic analyses capabilities
  - Provide improved confidence in the use of the foundation as an energy dissipative system

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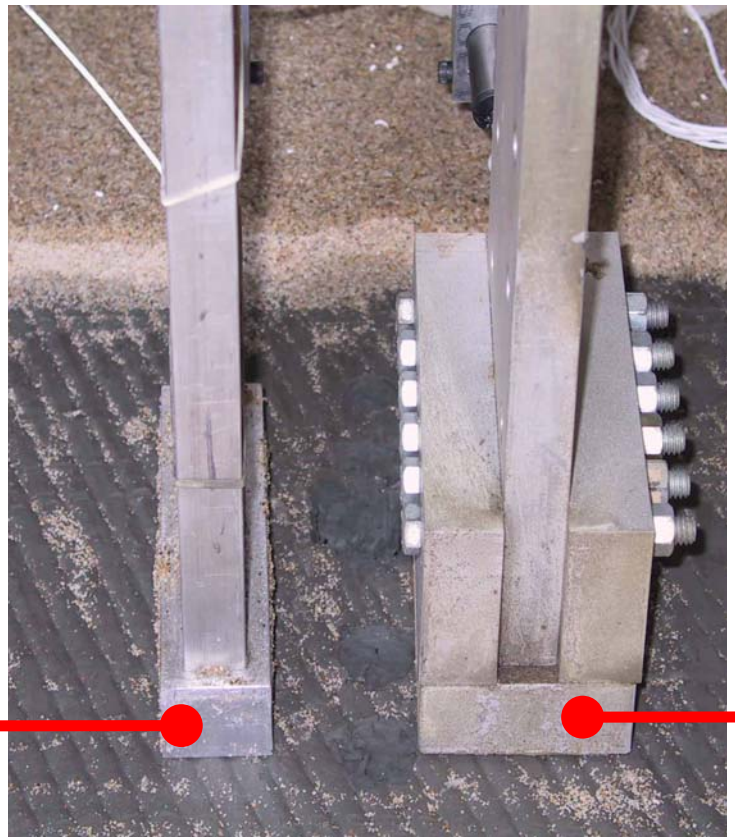
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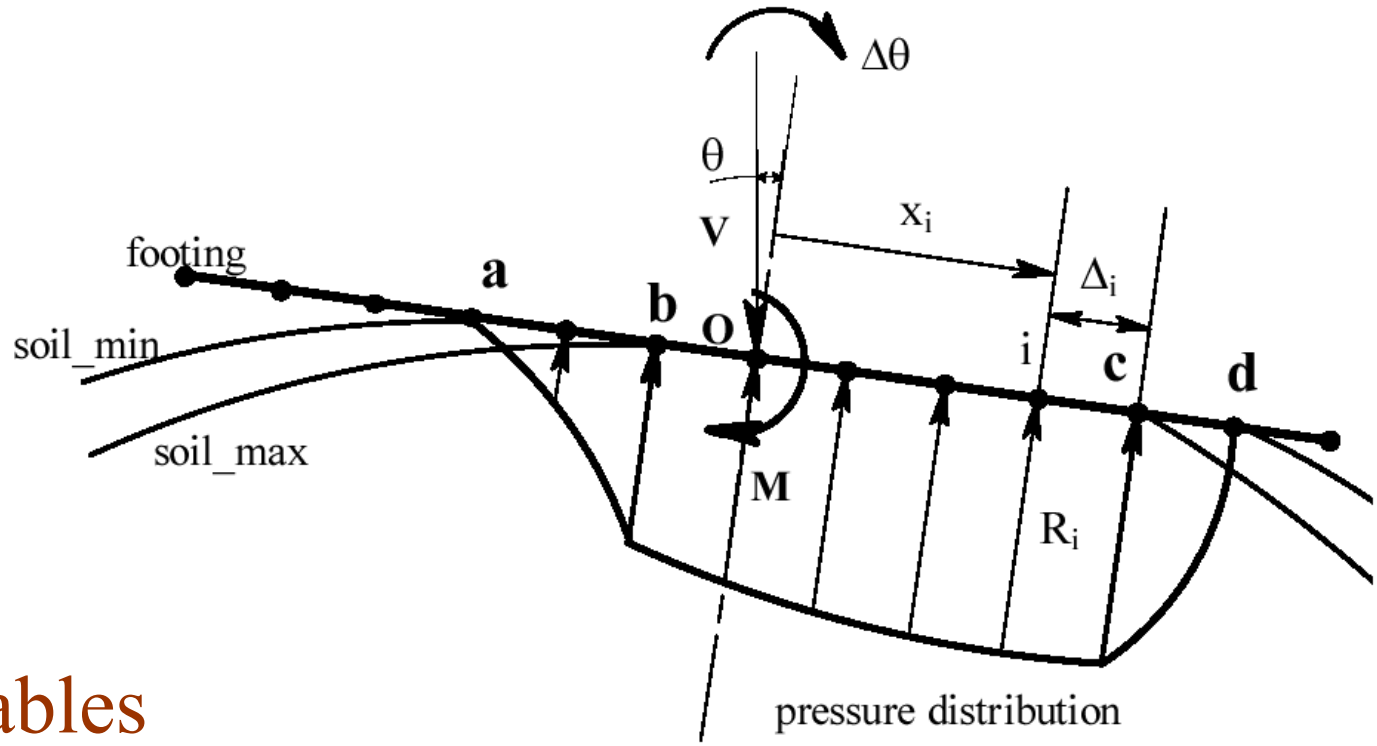
Wall-Foundation Experiments



Small footing

Large footing

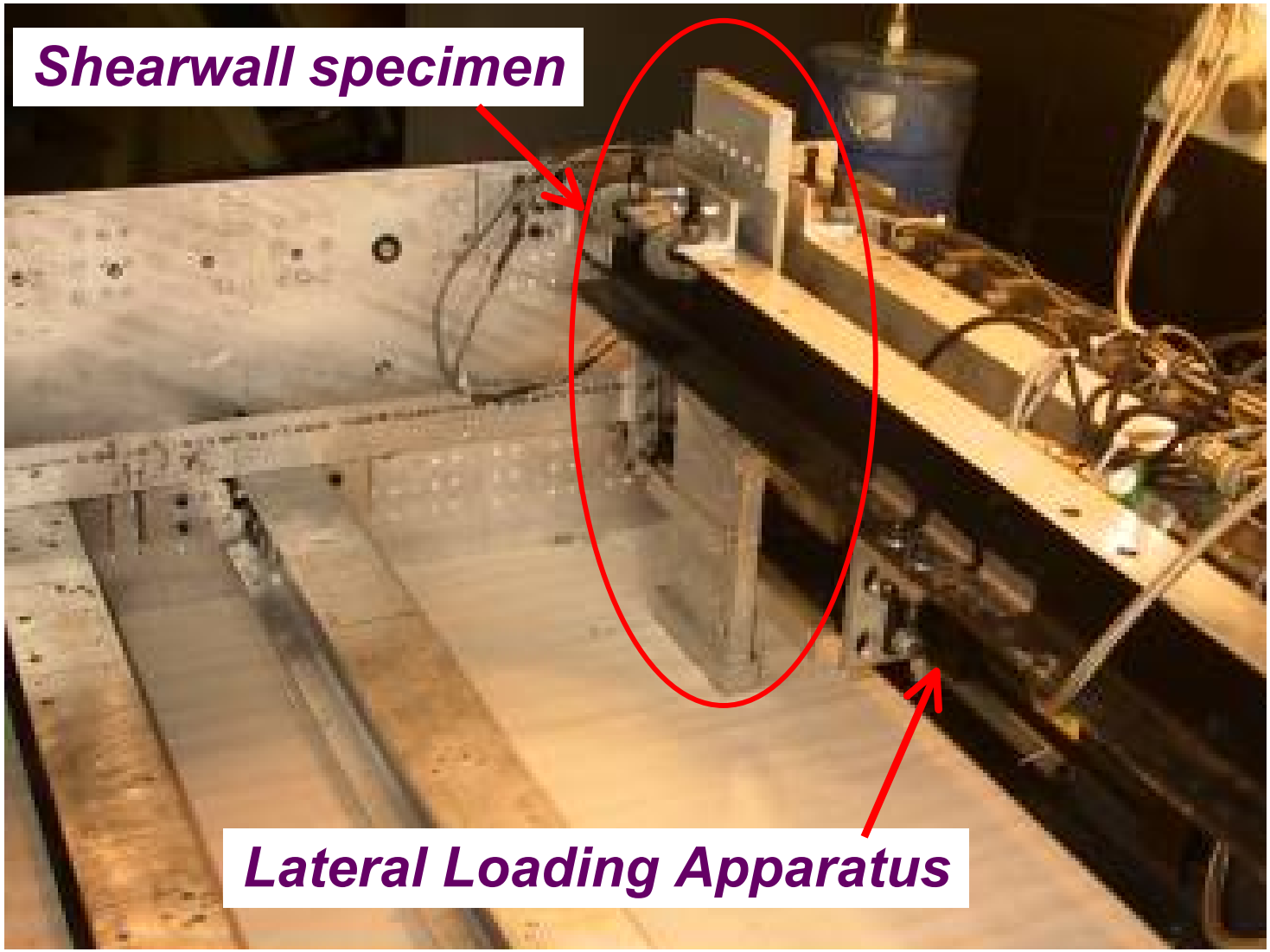
Macro-Element Model



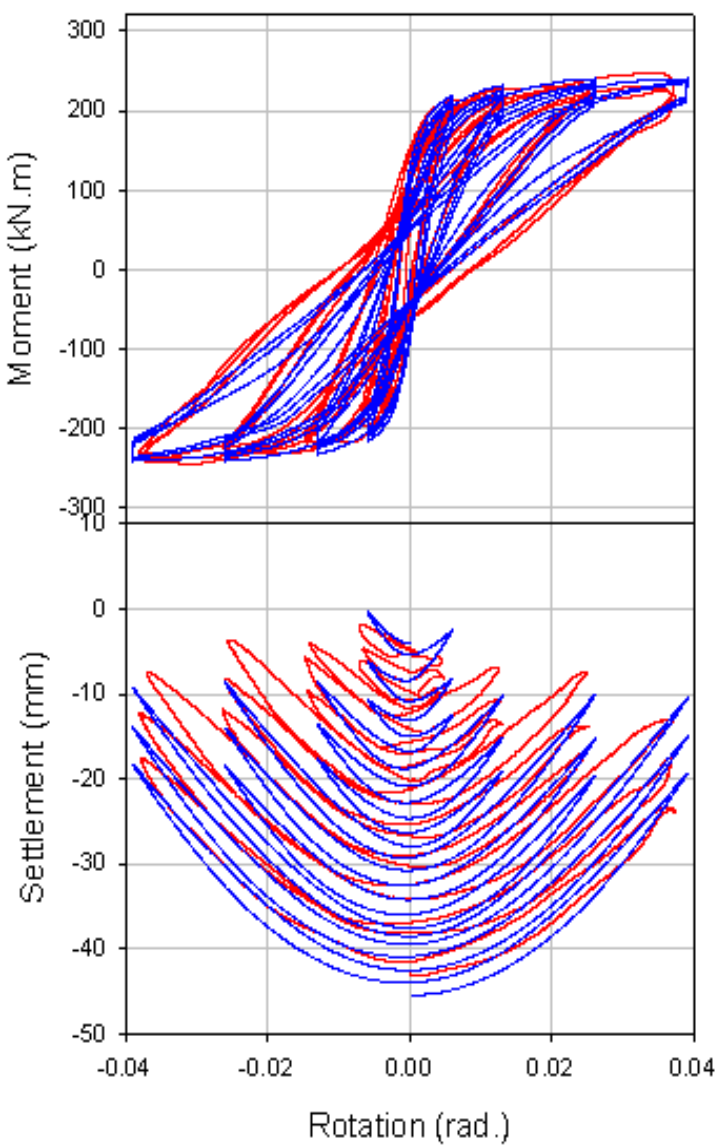
Internal variables

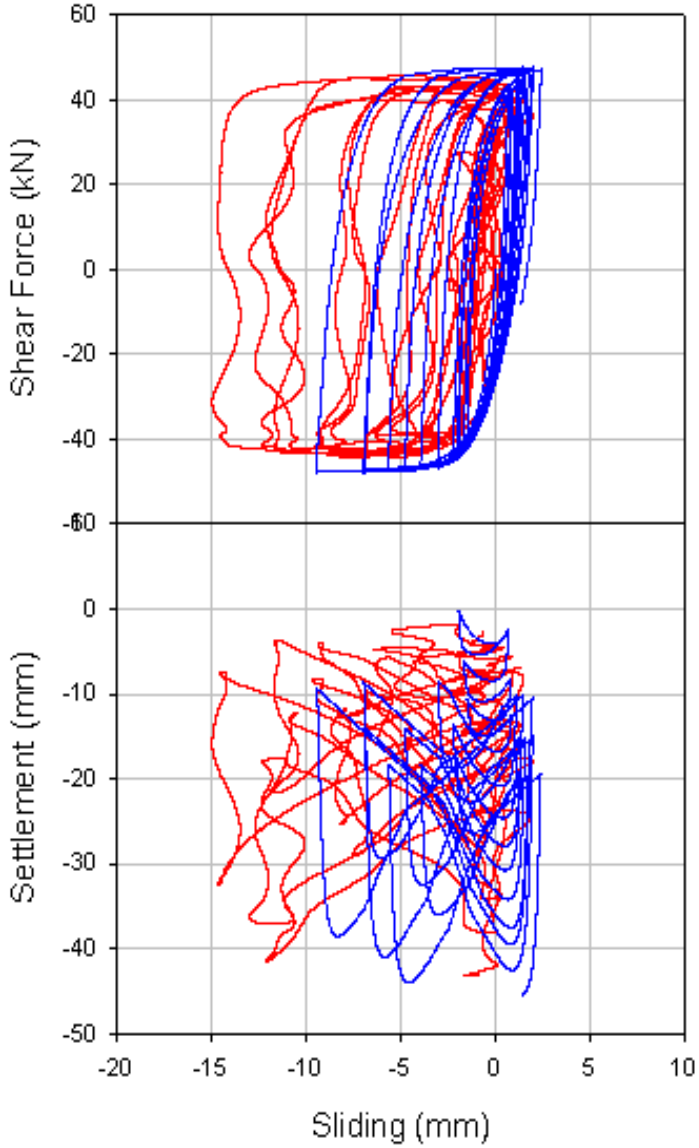
- Footing location
- Current soil surface location (soil_min)
- Maximum past settlement (soil_max)
- Current bearing pressure
- Maximum past pressure experienced

Wall-Foundation Experiments



Experimental-Numerical Comparison



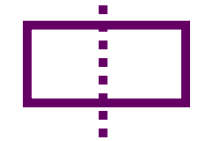


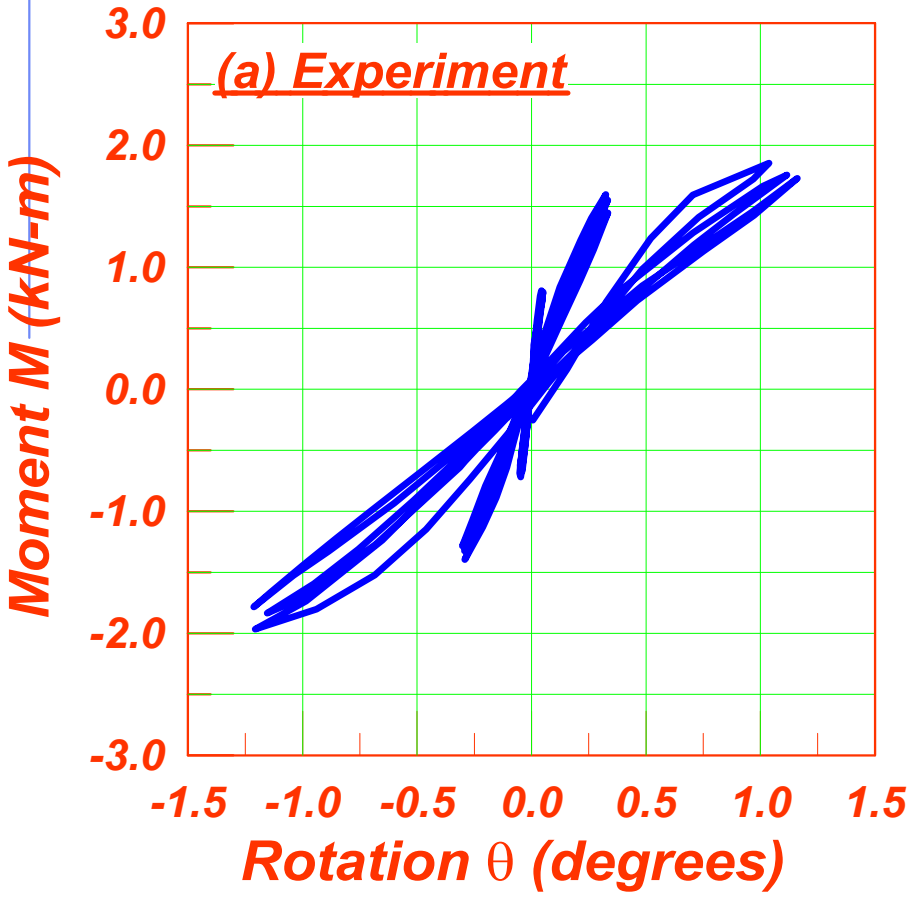
(Qu/Qa = 7.5)

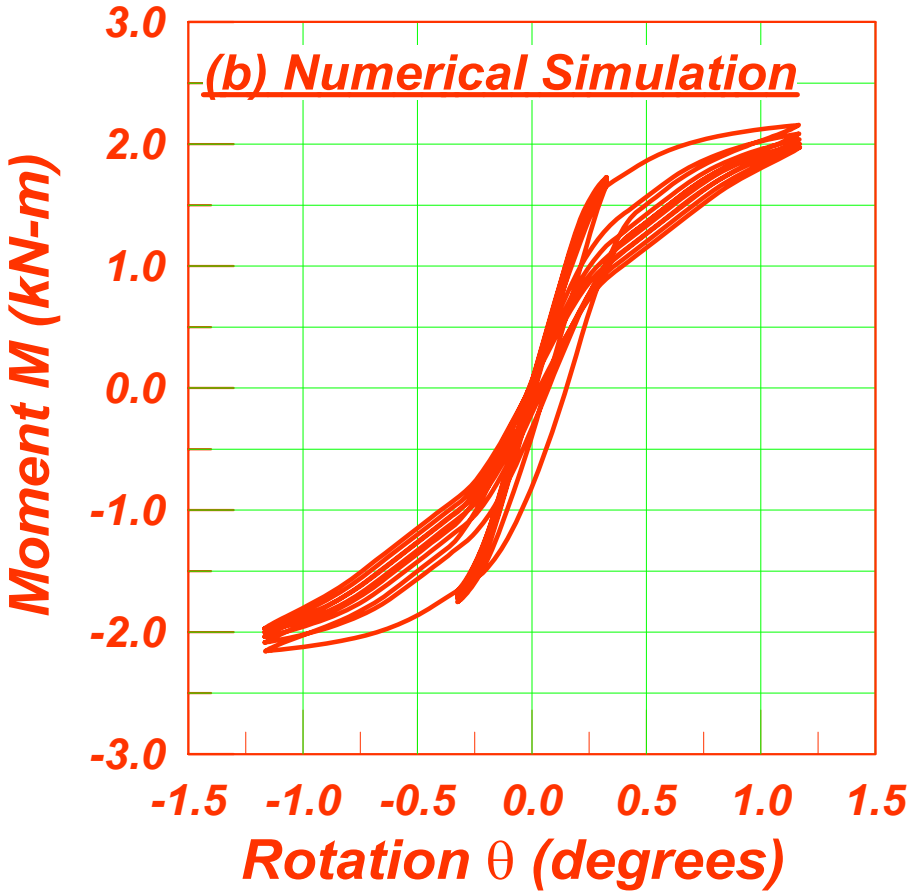
Experimental-Numerical Comparison

Taylor et al (1980); 1-g tests

Type A Footings:
Strong Axis Rocking



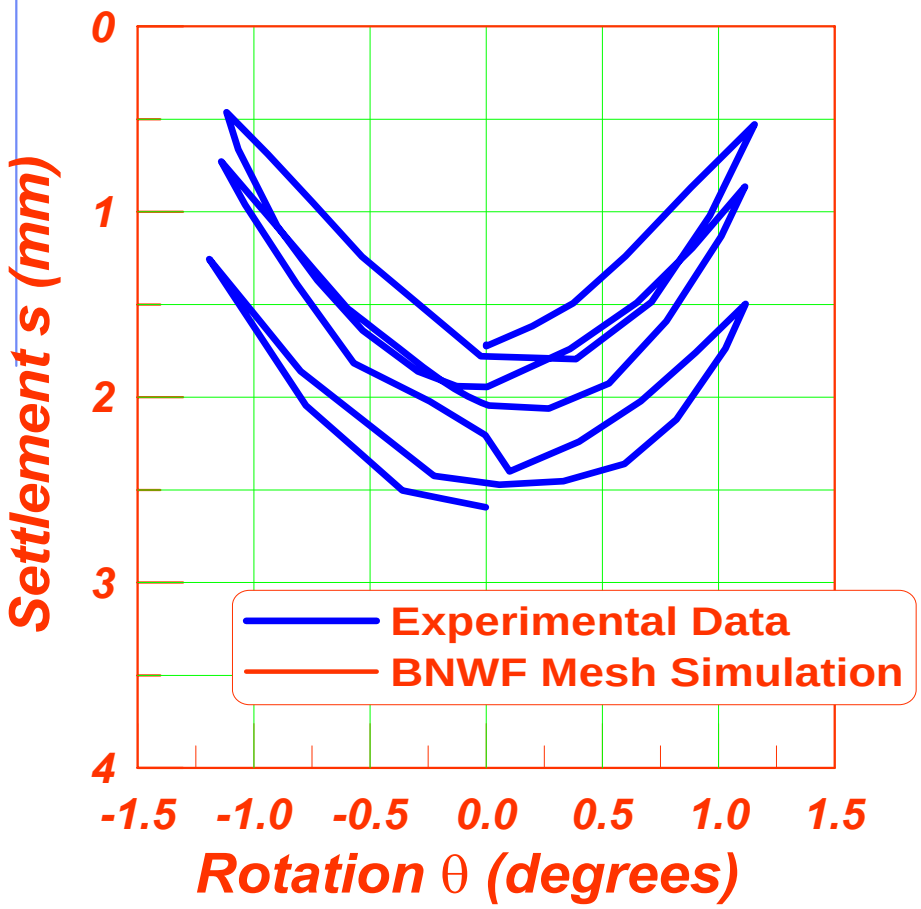




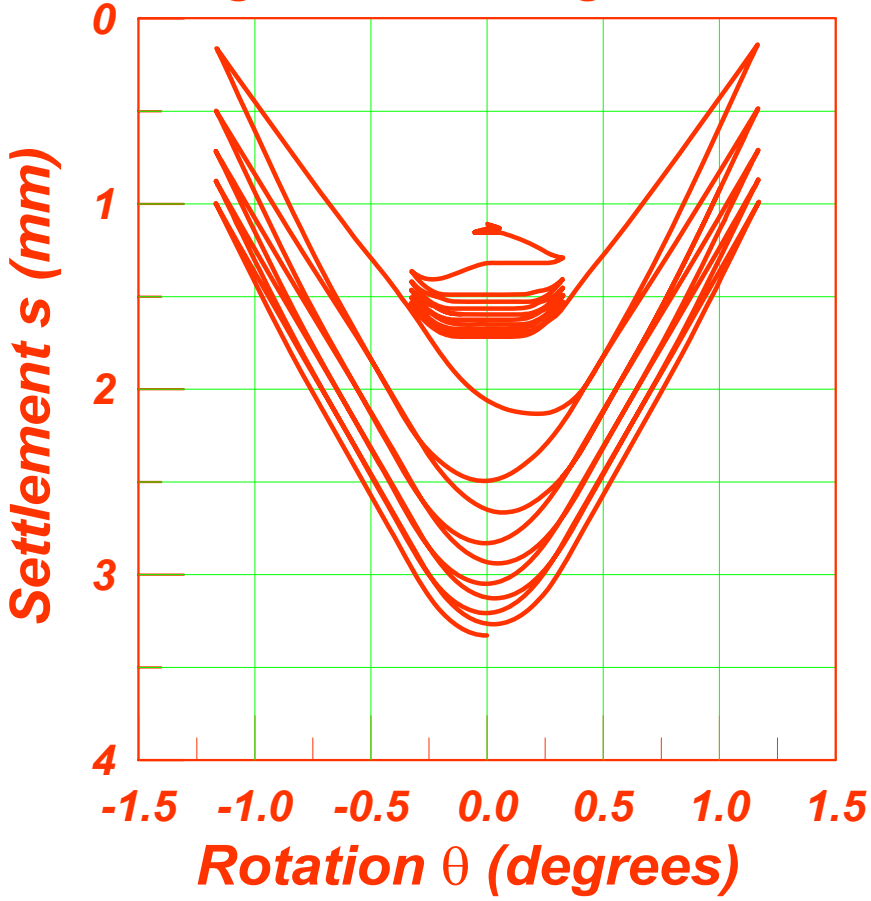
One-g, Clay, cu = 49 kPa, ϕ' = 0

Experimental-Numerical Comparison

Taylor et al (1980); 1-g tests



Type A Footings:
Strong Axis Rocking



One-g, Clay, cu = 49 kPa, $\underline{\phi}$' = 0