OpenSees Days 2006

Practical implementation and packaging of SFSI models in OpenSees

SFSI modeling group

Oversight: Stewart, Krawinkler, Goulet

UCD group: Kutter, Gajan

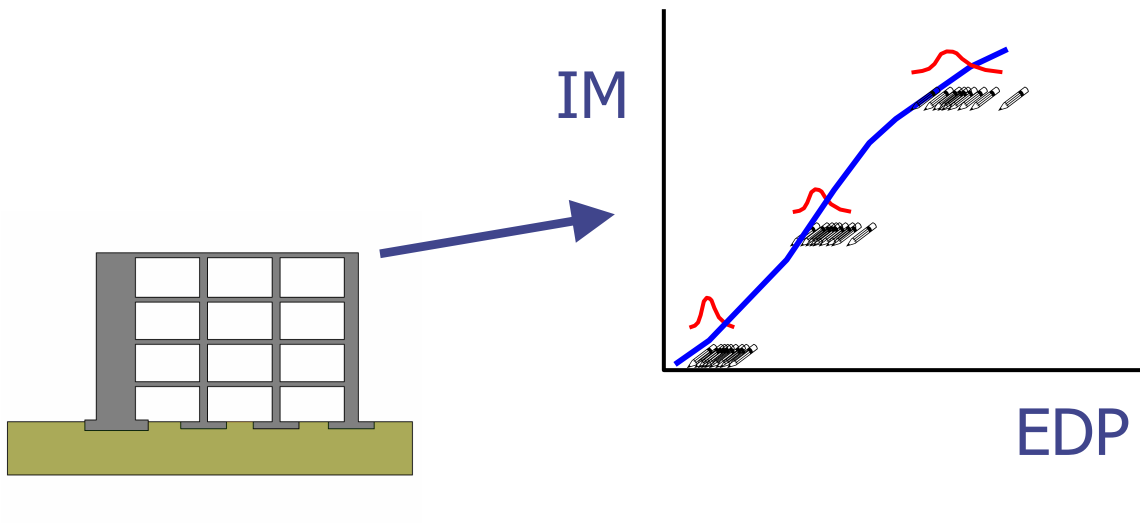
UCI group: Hutchinson, Raychowdhury

UCLA group: Taciroglu, Tehrani

Presented by Christine Goulet, PhD Candidate, UCLA

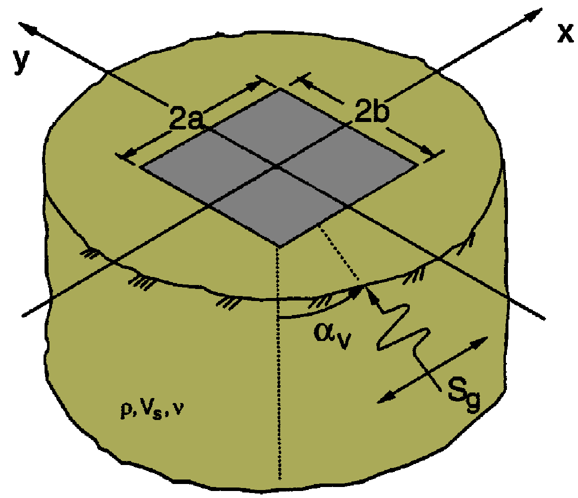
Outline

1. Overview of SFSI Mechanisms
2. SFSI Group Objectives
3. Overview of the different models (UCD, UCI, UCLA)
4. Sensitivity studies and comparison of models
5. Example of results SFSI for a building structure
6. Remaining work

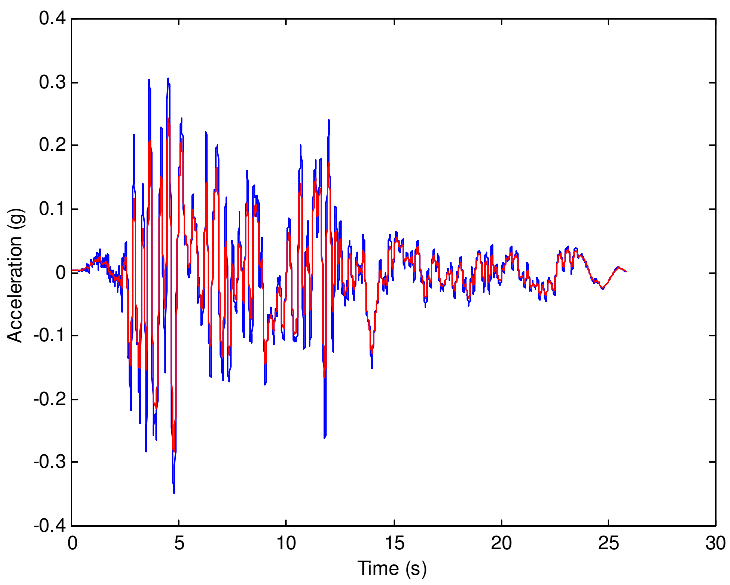


1. Kinematic SFSI – Transfer functions

- Contributions from:
  - Base-slab averaging
  - Foundation embedment



- Models exist
  - Result is FIM / FFM transfer function



Source: Veletsos et al. (1997)

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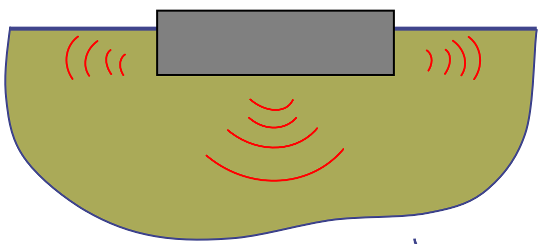
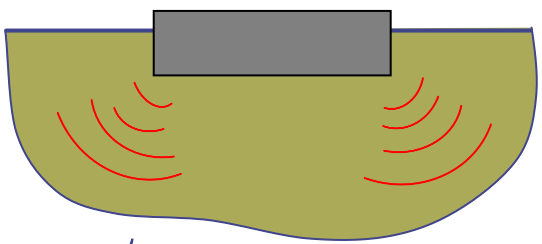
1. Inertial SFSI – OpenSees models

- Mechanisms at foundation level:

  - Translation, base shear

  - Rotation, moment

The foundation acts as a source of waves
⬇
Dissipation of energy
⬇
Radiation damping

Vibrations in soil
⬇
Hysteretic damping

1. Why bother? Are SFSI effects important?

- Yes, for stiff, short period structures, the effects can be important.

- Field data shows:
  - Foundation damping ratios up to ~ 10-20%
  - Period lengthening up to ~ 1.5
  - FIM/FFM Sa's at low period as low as ~ 0.5

Source: J. Stewart

2. SFSI Group Objectives

Packaging of tools and models through:

- Development of clear parameter selection protocols (physical, empirical, non-physical)
- Sensitivity studies of results to empirical and non-physical parameters
- Improvement of consistency of results between codes
- Improvement of numerical stability
- Preparation of documentation, OpenSees implementation

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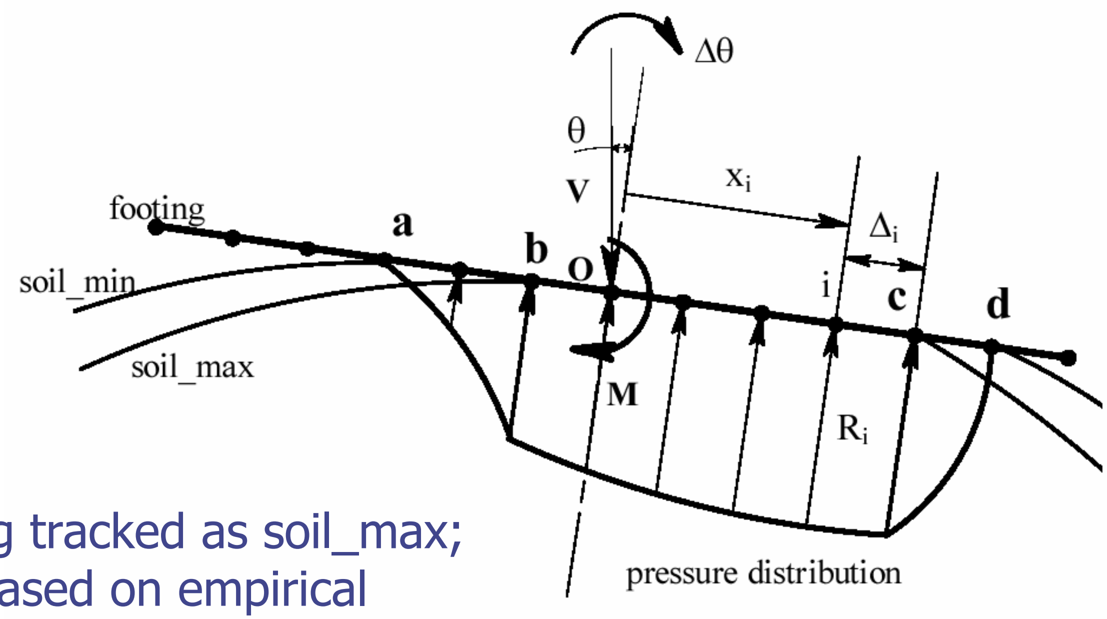
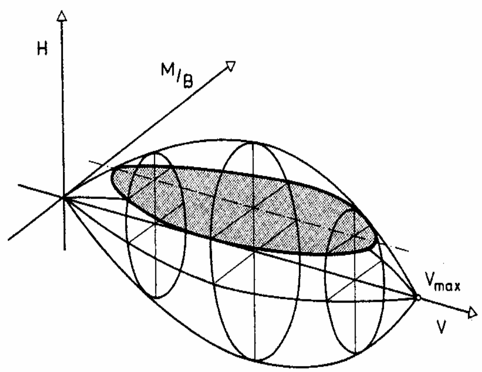
3.1 UCD Model

- Macro-elements
- For prescribed sliding displacement (u), rotation (θ), and settlement (s), calculates
    - Base shear (H)
    - Moment (M)
    - Axial Force (V)



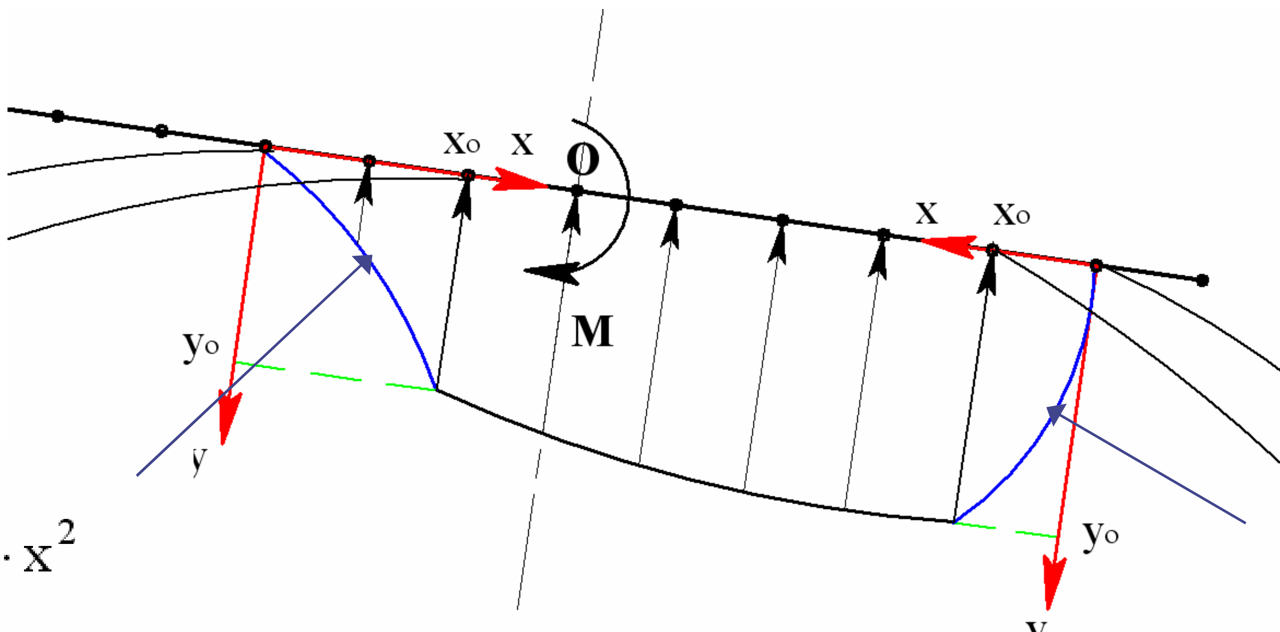
- Curved surface beneath footing tracked as soil_max; soil_min is function soil_max based on empirical relations
- Central area with soil_max: σ=soil_max*K_z < V_{max}
- Outside central area: empirical parabolic transition to zero stress
- H-M-V responses coupled through capacity surface



3.1 UCD Model

Parameters:

- Physical
  - Bearing capacity, V_{max}
  - Shear modulus and Poisson's ratio (to establish K_z, K_H)
- Empirical: Rebound factor, R_v
- Hard-wired into code:
  - Bounding surface parameters (6)
  - Parabolic shape parameters (2)
  - Flow rule parameters (1)

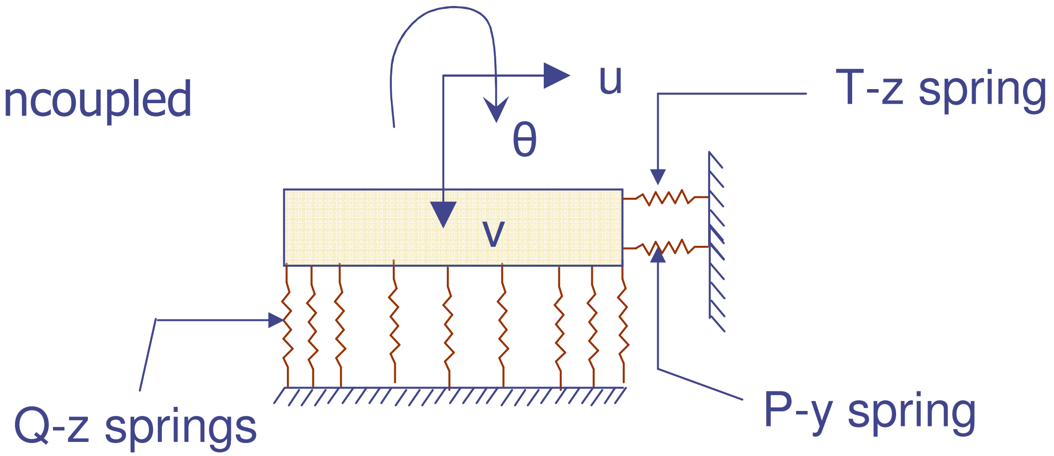


$$y = \left(\frac{y_o}{x_o^{\,2}} \right) \cdot x^2$$

$$y = \left(\frac{y_o}{x_o^{\,0.5}} \right) \cdot x^{0.5}$$

3.2 UCI Model

- Series of individual springs
- For applied H-M-V, ensemble of springs calculates:
    - Sliding displacement
    - Rotation
    - Settlement
- Shear-vertical responses uncoupled

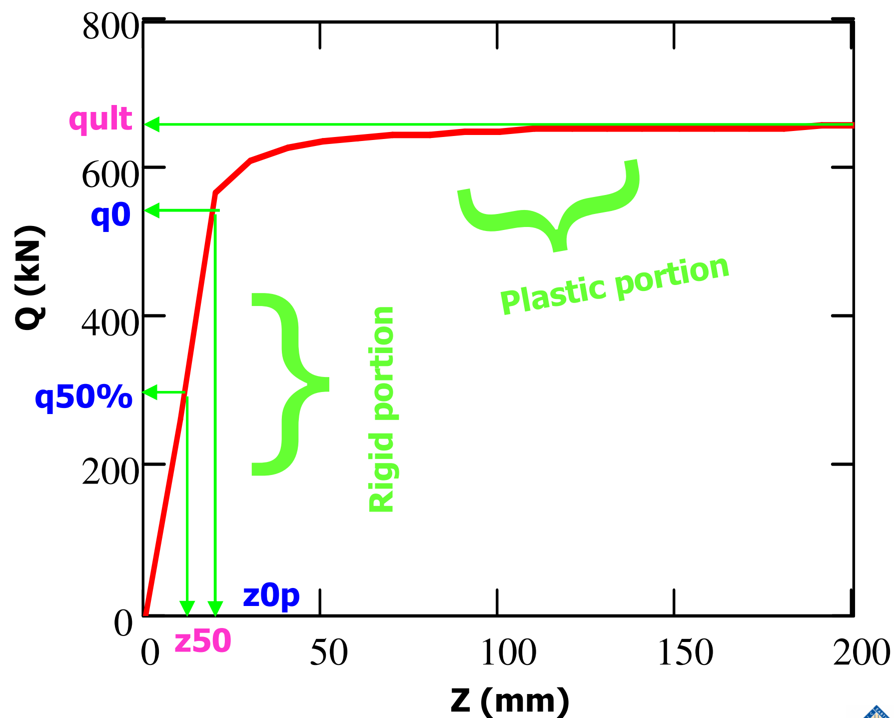


- Vertical response from non-linear Qz springs
- Horizontal is a combination of
    - Nonlinear Py for passive earth pressures
    - Nonlinear Tz for base sliding
- Mesh generator being implemented by UCI group
- All springs based on Boulanger et al., 2000

3.2 UCI Model

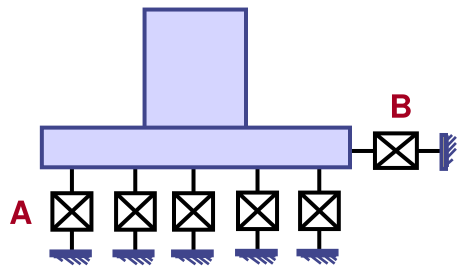
Parameters:

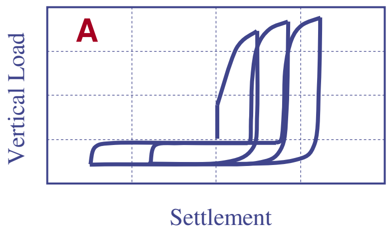
- Physical parameters
  - Ultimate capacity (e.g, Q_{ult})
  - Initial elastic stiffness (e.g., K_z)
- Other parameters
  - C_r – defines load where plastic deformation begins (e.g., $C_r = q_0/q_{ult}$)
  - z_{50}, n, c – parameters defining shape of plastic deformation curve
  - Gap cohesion, closure

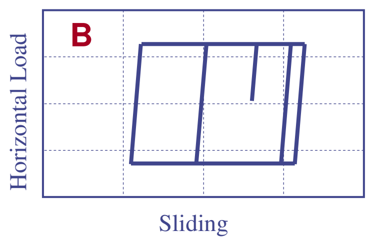


3.3 UCLA model

- Series of individual springs
- For applied H-M-V, ensemble of springs calculates:
    - Sliding displacement
    - Rotation
    - Settlement
- Shear-vertical responses to be coupled





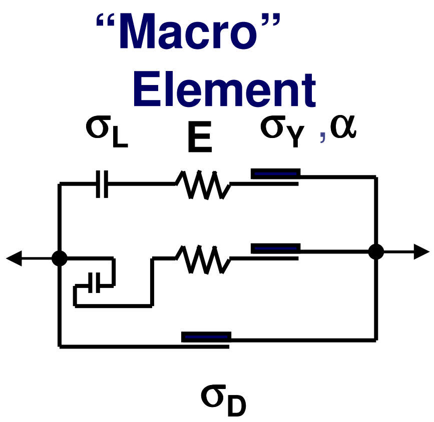


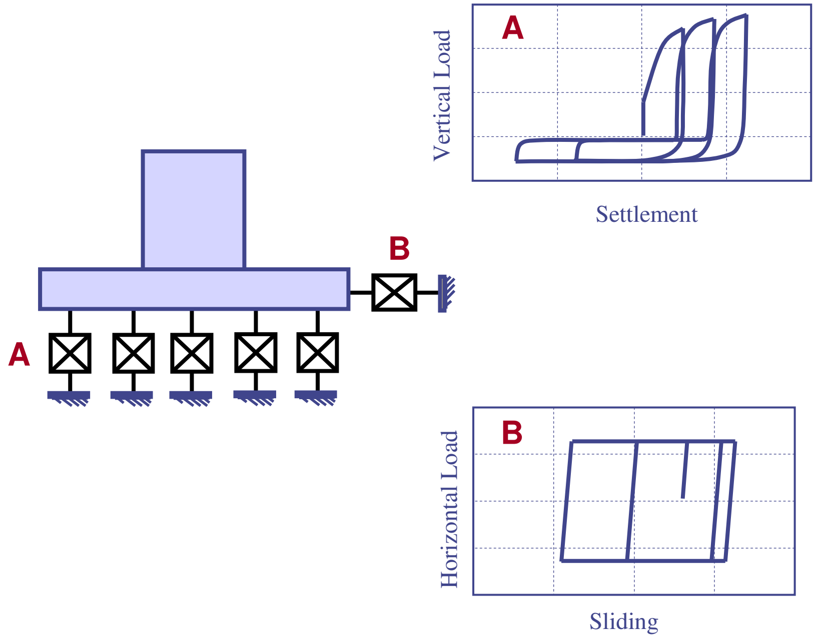
- Vertical response from non-linear Qz springs
- Horizontal response from Tz (base sliding)
- All springs based on Taciroglu et al. (2006) and Orakcal et al. (2006)

3.3 UCLA model

Parameters:

- "Physical" parameters
    - Stiffness (E)
    - Capacity (σ_y)
- Empirical parameters
    - Shape of nonlinear backbone curve
    - Parameter that controls cohesion and closure of gap elements





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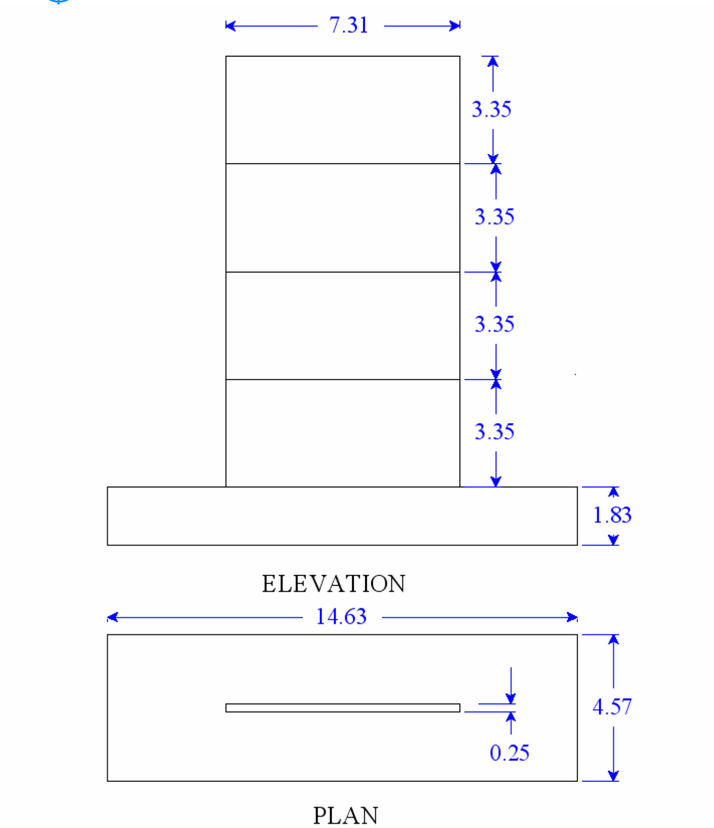
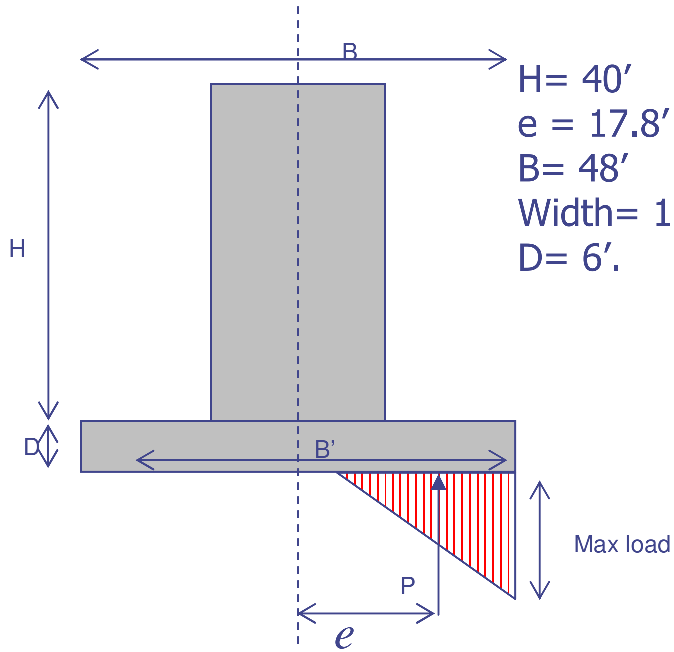
4. Comparison of models as they are

- UCD: Single macro element simulates the whole foundation’s response, response coupled in x and y directions.
- UCI: Combination of springs and dampers are grouped for footings or larger foundation. Response is uncoupled in x and y directions.
- UCLA: Similar to UCI in principle, but with coupled response.
- So far, none of these models are fully implemented in OpenSees, although the Qz, Tz, Py springs are available as zero-length elements.

4. Sensitivity studies, examples





H= 40′
e = 17.8′
B= 48′
Width= 15′,
D= 6′.

Soil: OC clay with constant Su
Su= 1.1 ksf
Corresponding Gmax= 550 ksf

Loading protocol:

1. Ramped static-cyclic test with displacement control,
   Final displacement = 18″
2. Ground motion (Loma Prieta 1989 WVC270)
   - 2.1 Scaled to 50 % in 50 yrs hazard
   - 2.2 Scaled to 10 % in 50 yrs hazard
   - 2.3 Scaled to 2 % in 50 yrs hazard

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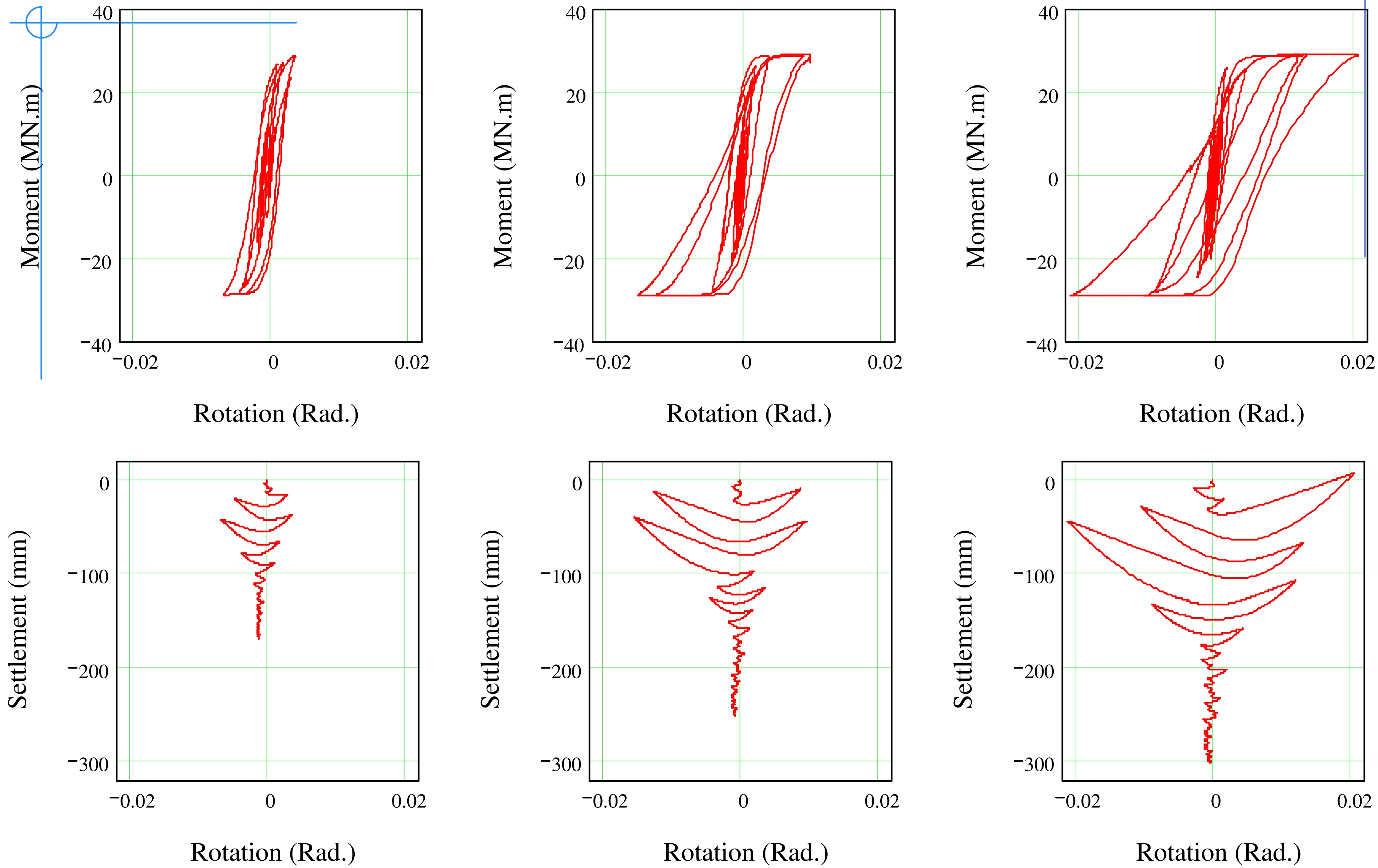
4. UCD - Fixed horizontal displacements



Small shake **Medium shake** **Big shake**

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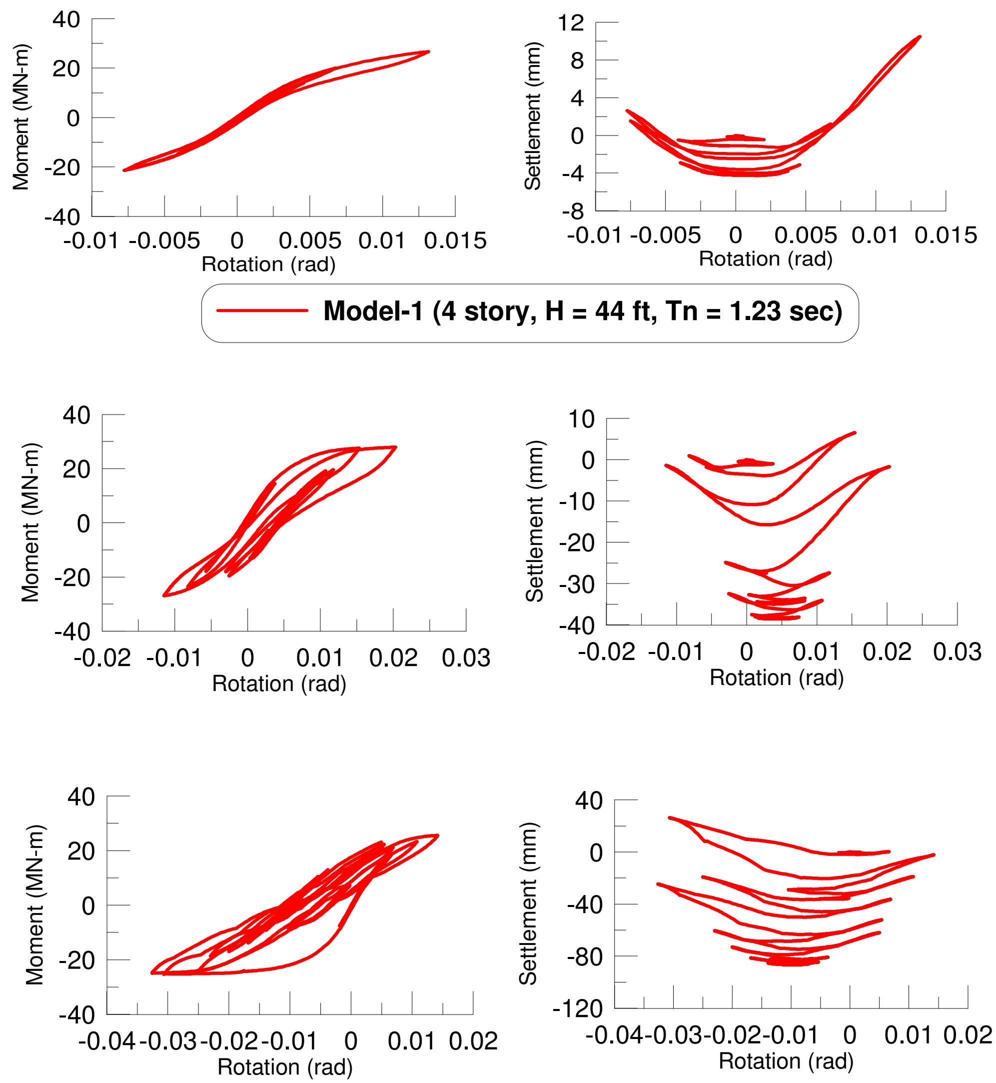
4. UCI - Fixed horizontal displacements



small

medium

big

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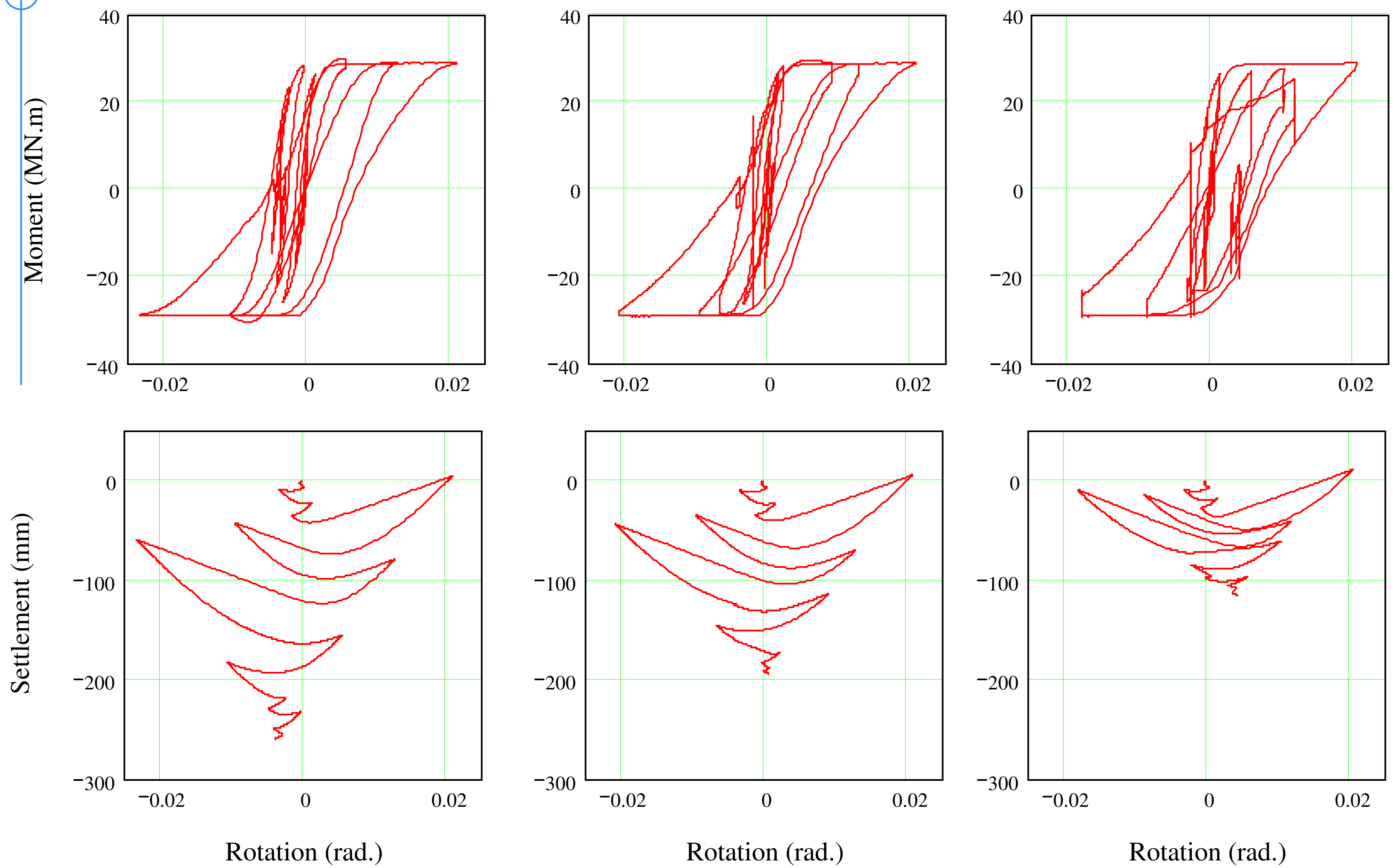
4. UCD Group, Rv parameter sensitivity



Rv = 0.01

Rv = 0.1

Rv = 0.5

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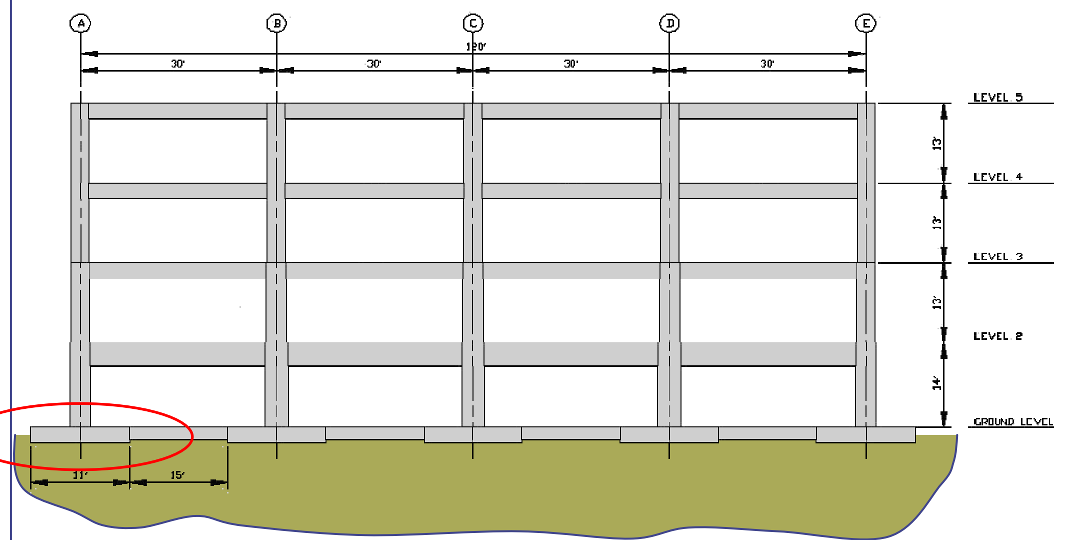
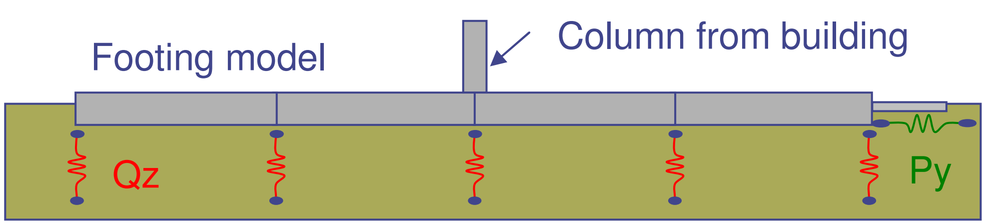
5. Simulation results with a 4 story RC Frame building (PEER Benchmark)



Building: RC 4 story frame building

- "Benchmark Building": typical office building
- 4 x 6 bays
- T_1= 1s

Haselton et al. (2006)



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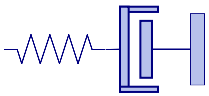
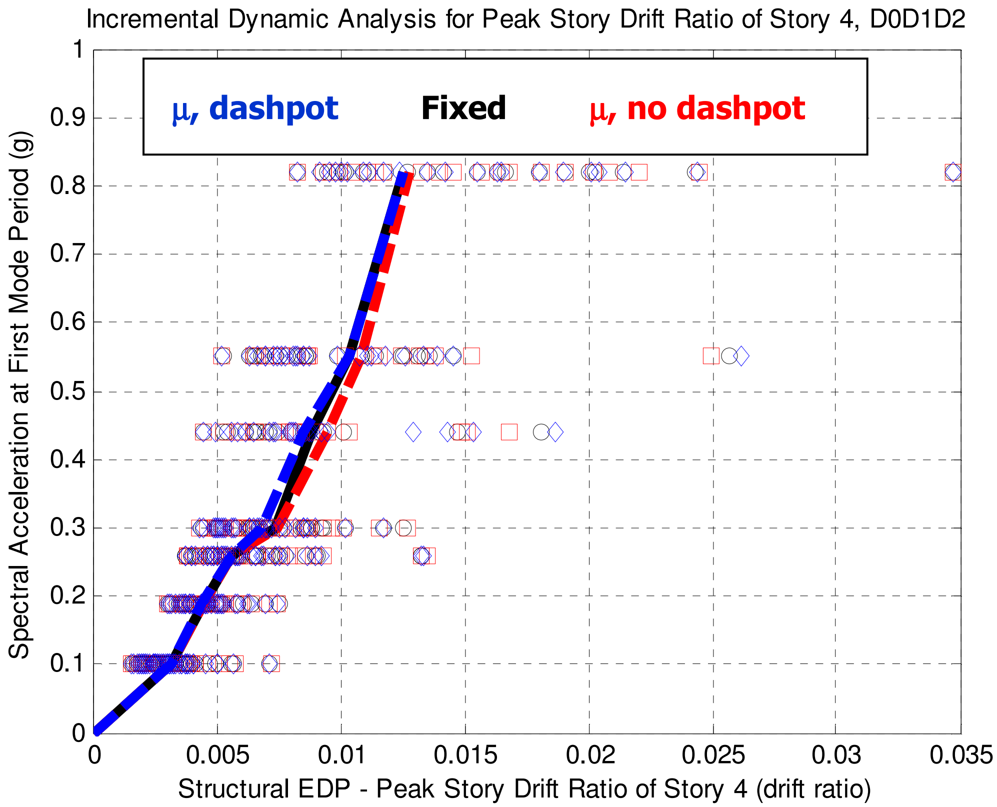
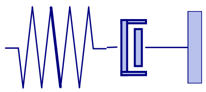
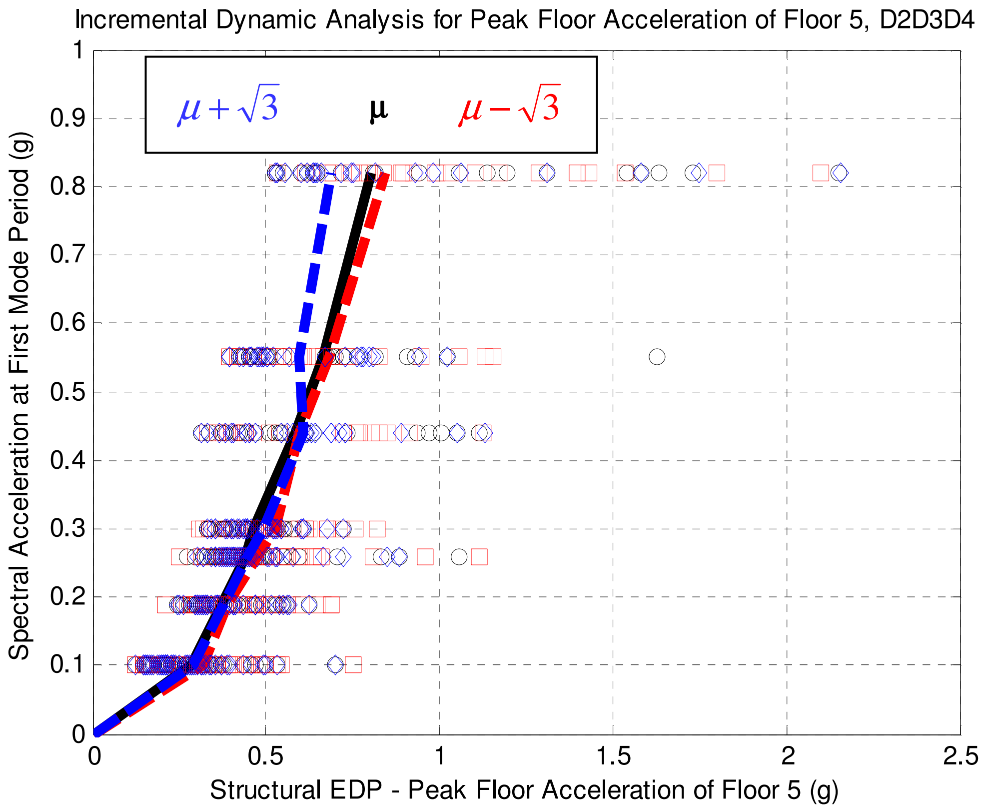


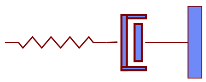


Fixed based and flexible base with effect of viscous damping

5. Simulation results with a 4 story RC Frame building (PEER Benchmark)







Varying spring stiffness properties

Based on ϕ variability

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5. Simulation results with a 4 story RC Frame building (PEER Benchmark)

Results are consistent with what we expected: long period, flexible structure, not much inertial effects.

It took time and it was quite laborious to assemble Qz and Py springs. UCI tools will be useful.

Convergence issues arose. It is not clear at this point why this was the case.

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6. Remaining Work

- Identify ranges of parameters and complete sensitivity studies across those ranges
- Simulations for non-fixed horizontal conditions
- Complete the investigation to explain the discrepancies for settlement estimates
- Sensitivities for additional structures
- Numerical stability issues
- Packaging in OpenSees as simple elements, preparation of clear guidelines for users
- Retest the elements with a stiffer realistic building structure

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