Experiments and Design Recommendations for Single Column Rocking Bridge Piers

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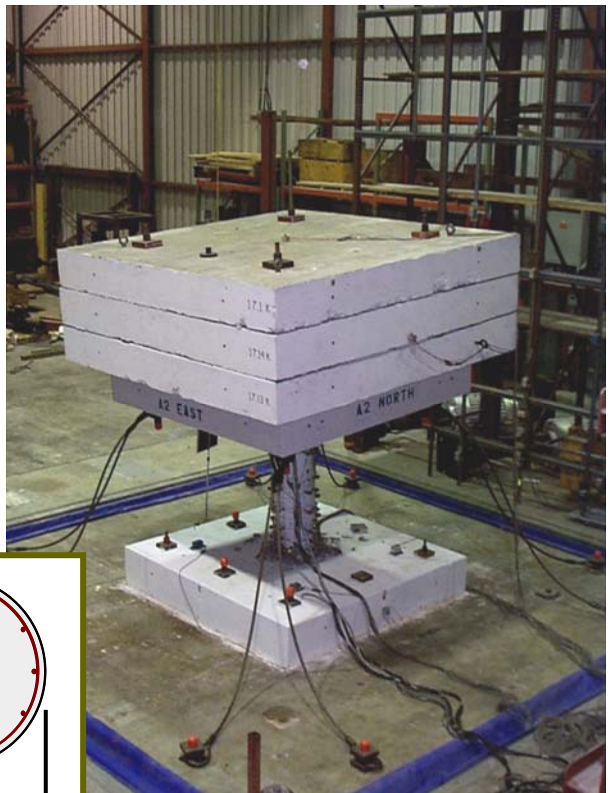
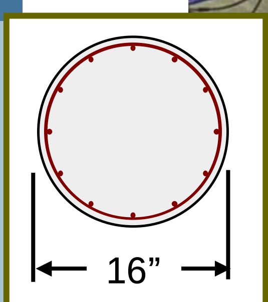
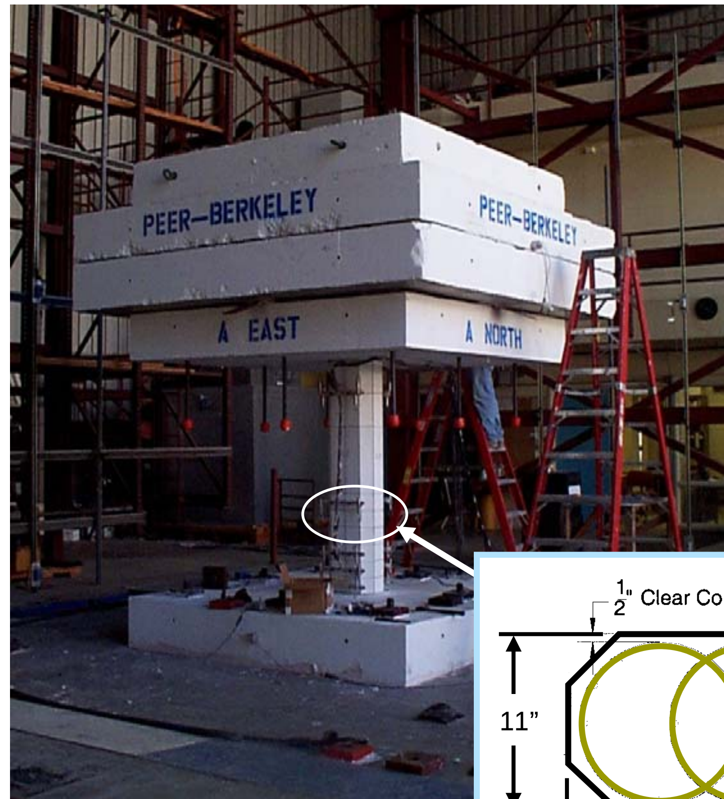
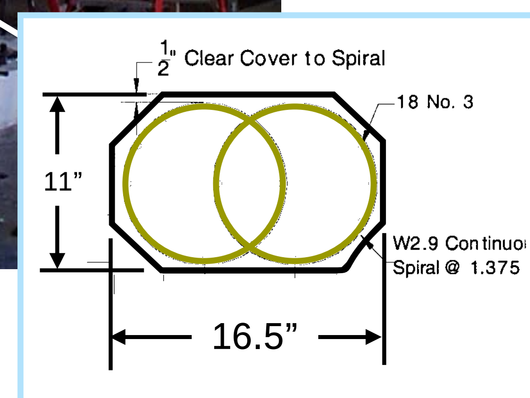
Many bridge column tests: Improve understanding and numerical models





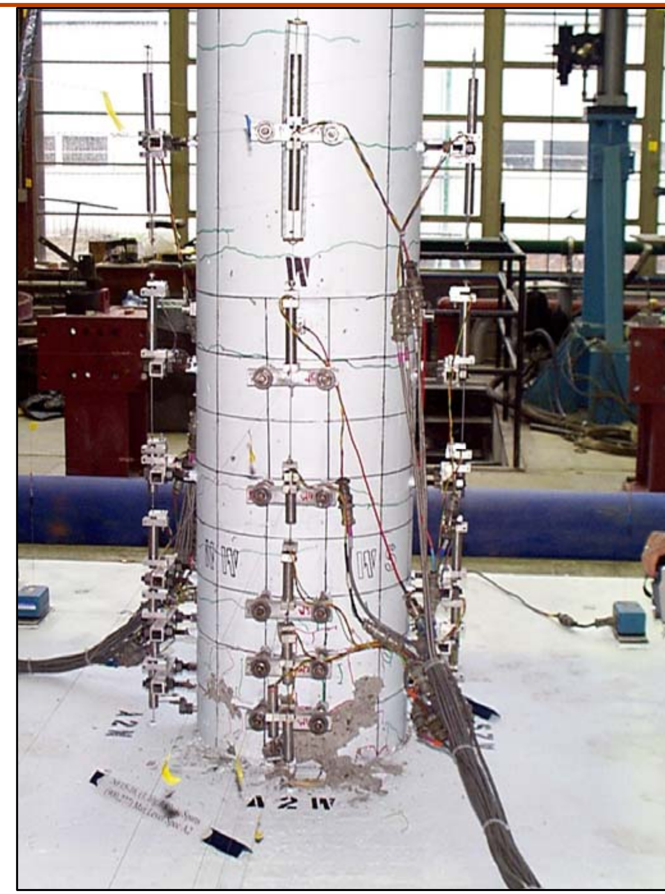




Unidirectional and multidirectional shaking

- Intense near-fault motions
- Subduction zone motions

Recent focus on bridge systems



After First Maximum Level Event (μ=6)

Modern SDC-compliant columns behave quite well:

- Under design level excitations have moderate spalling of cover
- Ductile behavior under rare events
  →buckling and fracture of rebar
  →occasional geometric instability

But...

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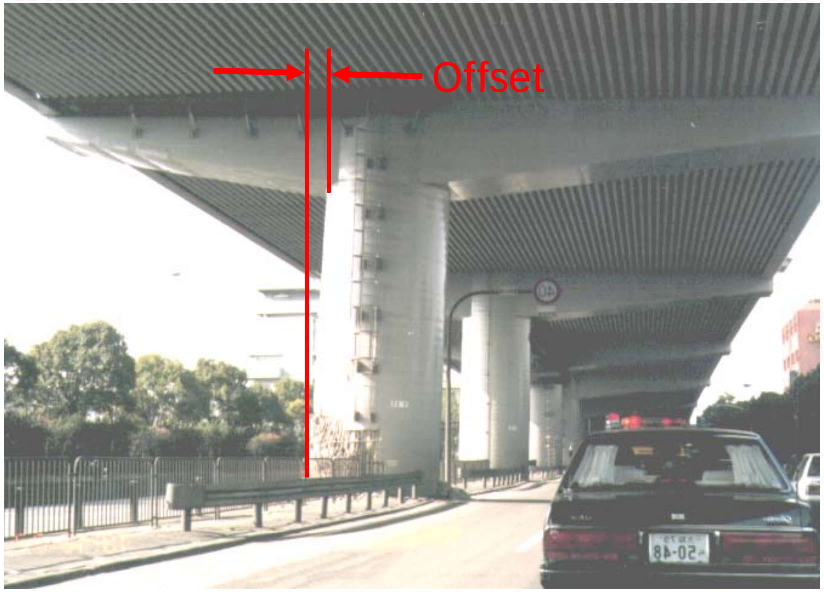
Be careful what you ask for…

Ductile systems may have large residual displacements

About 100 columns with a tilt of more than 1.75% drift were demolished after 1995 Kobe Earthquake although they did not collapse



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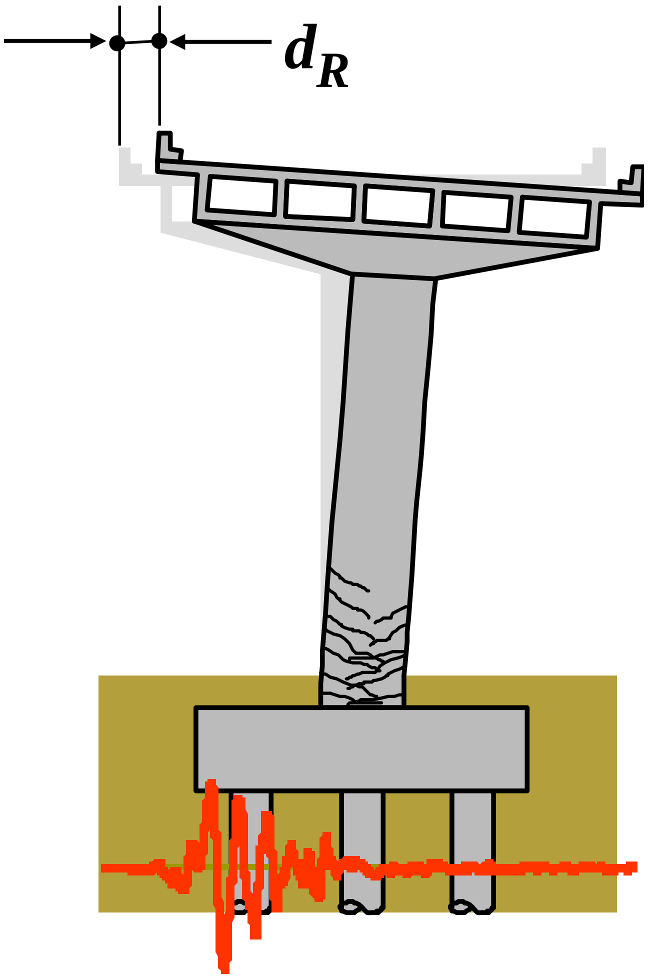
Residual Displacements



Japanese Design Specifications for Highway Bridges

Explicit design criteria

$$d_R \leq d_{Ra} = 1\%\ \text{drift}$$

$$d_R = C_R(\mu_r - 1)(1 - r)d_y$$

Applied to some typical SDC Columns

Aspect Ratio	μ_{design}	d_R %
4	5.7	1.9
6	5.2	2.6
8	4.9	3.2

For continued operation, or to minimize residual displacements, we need to design for much higher forces:

- ➔ Stronger foundations
- ➔ Stronger decks
- ➔ More costly

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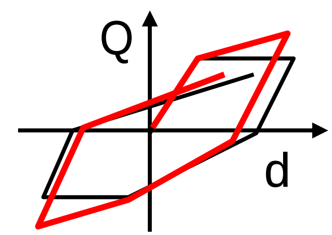
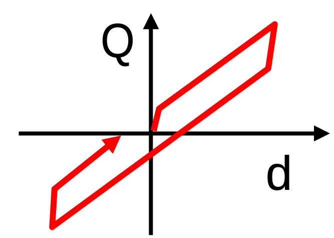
Reducing residual displacements

- Increased post-yield stiffness
  - Unbonded high strength steel added to normal mild steel reinforcement (Iemura et al)



- Seismic isolation
  - Many isolation and supplemental energy dissipation devices (numerous investigators)

Caltrans-supported tests of single and Multiple span bridge systems (Mahin, Fenves & Makris)



Current PEER research effort underway

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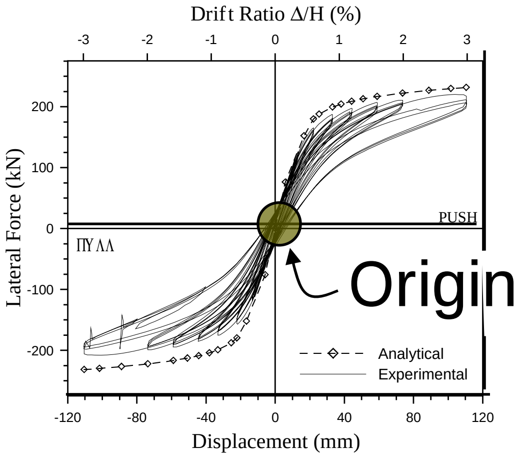
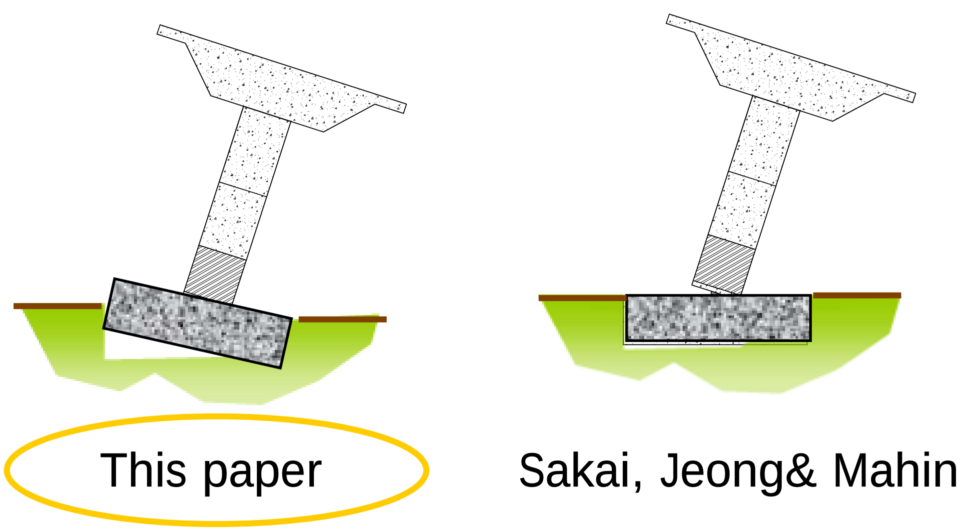
Reducing residual displacements

- Origin-oriented hysteretic loops
  - Post-tensioned precast columns for rapid construction (Priestley, Mander, Billington, Sanders, etc.)
  - Partially prestressed RC columns (Park, Zatar, Ikeda, Mahin & Sakai, etc.)
  - Rocking foundations (Fenves, Hutchinson, Kawashima, Mahin, Yim, etc.)





Rocking / Uplifting Foundations

UC Berkeley and *UC Davis*

Mahin, *Kutter, and Jeremic*

Analyses, plus shaking table and centrifuge tests to develop and validate simplified methods for design and analysis of shallow spread footings allowed to rock on competent soil

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

For soils where spread footings are feasible, engineers often find that footing width needs to be increased, or anchored using piles, so a plastic hinge can develop in column

- → Earthquake experience suggests foundation uplift can be an effective earthquake resistant mechanism
- → Significant amounts of research confirms this

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Literature Review

- Housner, G.W. (1963). “The Behavior of Inverted Pendulum Structures During Earthquakes.” *Bulletin of the Seismological Society of America,* SSA 52(2).
- Chopra, A. K. and Yim, C., (1983). “Simplified Earthquake Analysis of Structures with Foundation Uplift.” *Structural Engr.,* ASCE, Vol. 111, No. 4, April 1985.
- Priestley NMJ, Seible F and Calvi GM (1996). *Seismic design and retrofit of bridges,* John Wiley, 1996.
- Alameddine, F., and Imbsen, R.A., (2002). “Rocking of Bridge Piers Under Earthquake Loading.” Proceedings of the Third National Seismic Conference & Workshop on Bridges and Highways.
- Kawashima, K. and Hosoiri, K. (2003). “Rocking Response of Bridge Columns on Direct Foundations,” *Proceedings,* Symposium on Concrete Structures in Seismic Regions, Paper No. 118, FIB, Athens.
- WINROCK: Computer program to estimate displacement of bridge piers allowed to rock on their foundations, Caltrans (Version 1.1.2 – 5/25/05)
- Sakellaraki, D., Watanabe, G. and Kawashima, K. (2005). “Experimental Rocking Response of Direct Foundations of Bridges, *Proceedings,* ”2nd Int. Conf. on Urban Earthquake Engineering, March 7-8, 2005, Tokyo Inst. of Technology, Tokyo, Japan.
- Konstantinidis, D. and Makris, N. 92009), “Experimental and analytical studies on the response of freestanding laboratory equipment to earthquake shaking,” *Earthquake Engng Struct. Dyn.* 2009; **38**:827-848.

But....

Concept is still not used

→ Lack of demonstration that mechanism works for bridge-like structures

→ Absence of sufficiently simple but general guidelines for application in design

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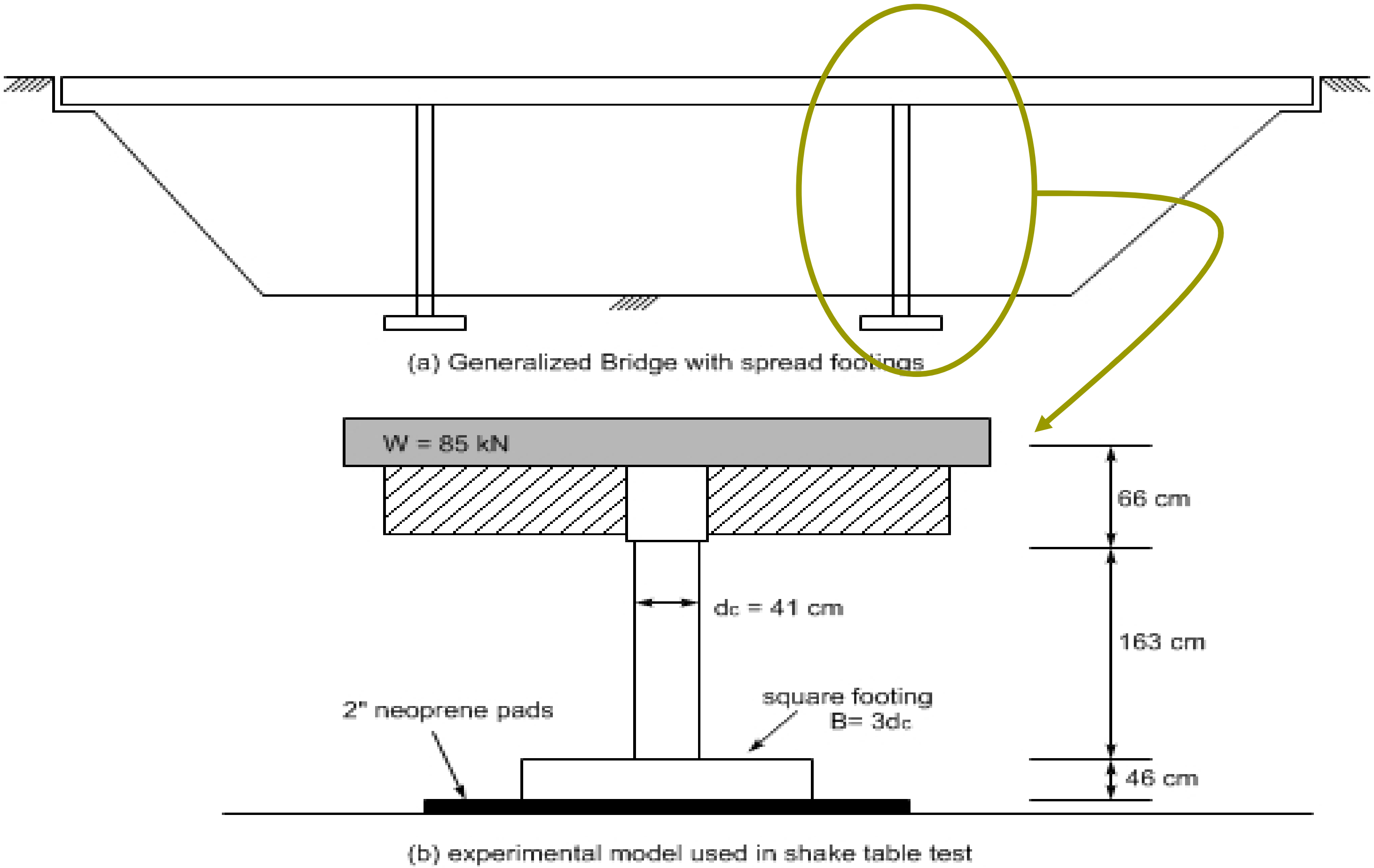
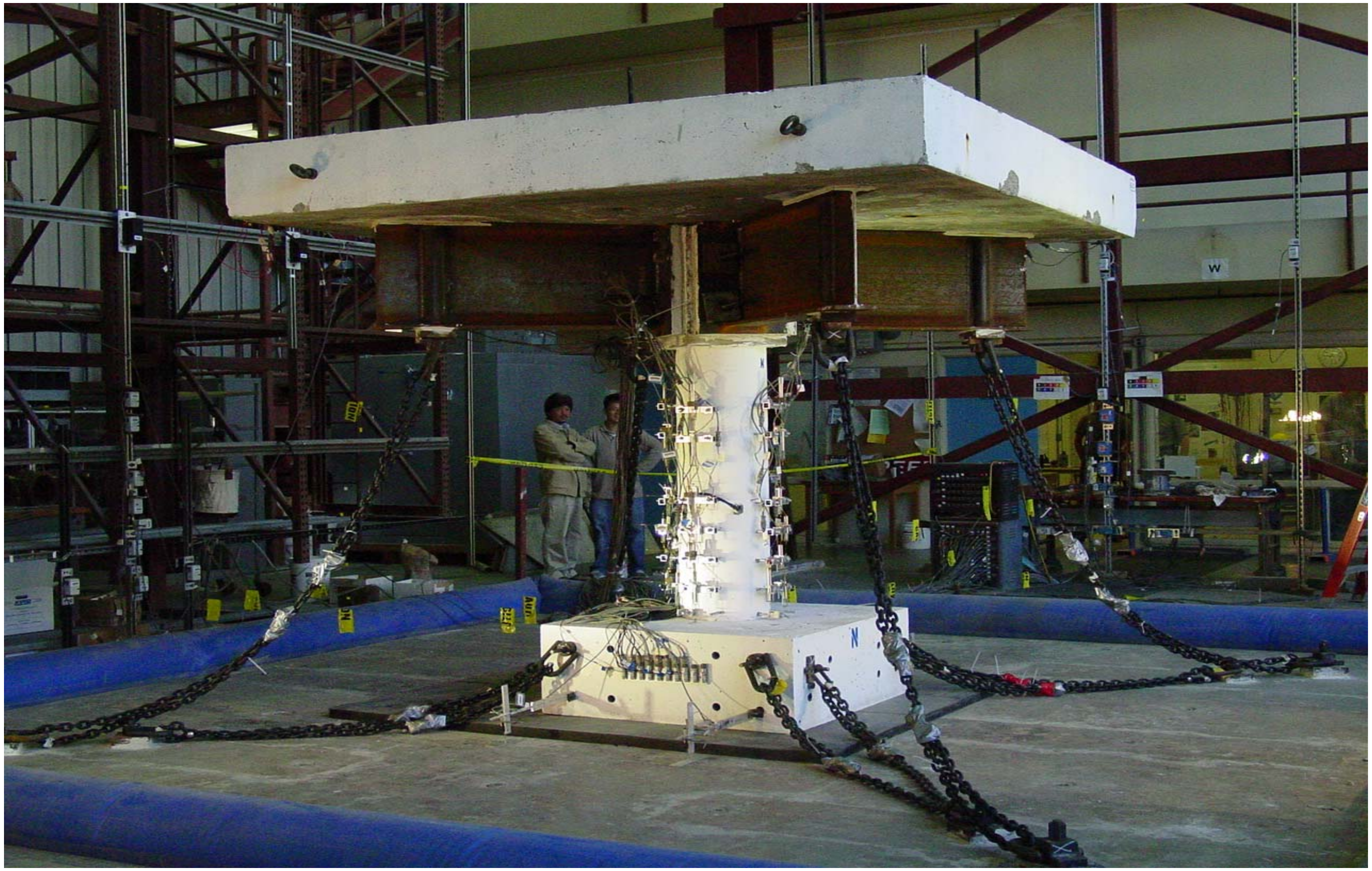
Test Concept



Shaking Table Tests



UC Berkeley Earthquake Simulator

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Test matrix

Test Group	**A** *Los Gatos*	**B** *Los Gatos*	**C** *Tabas*	**D** *Tabas*	**E** *Los Gatos*	**F** *Tabas*
1) 1D – X 2) 1D – Y 3) 2D – X, Y 4) 2D – X, Z 5) 3D – X, Y, Z	10% original record	35% original record	11% original record	40% original record	35% original record *Period shift* $dt=\sqrt{2}*dt_o$	50% original record

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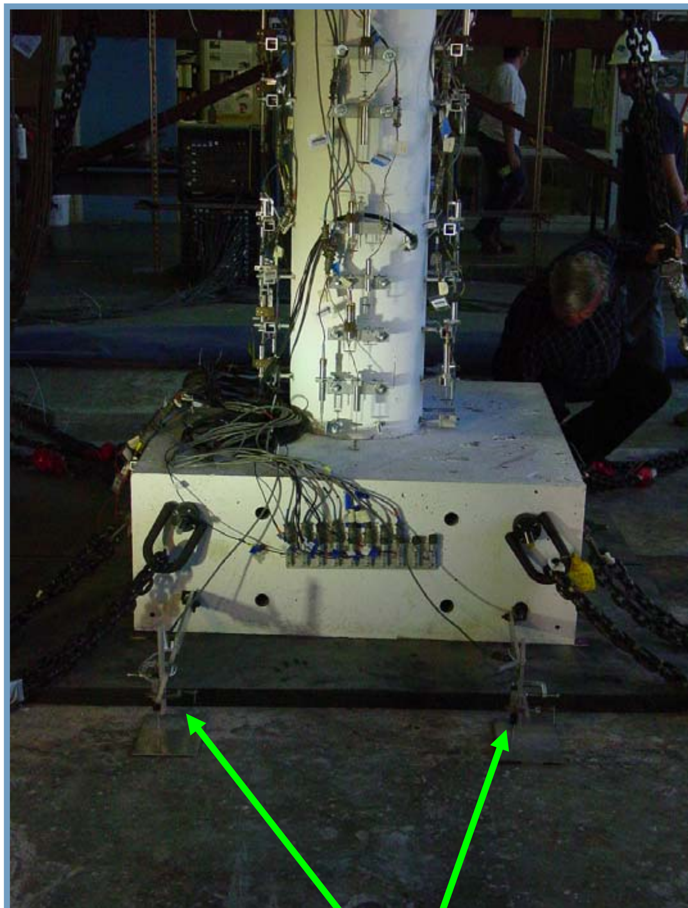
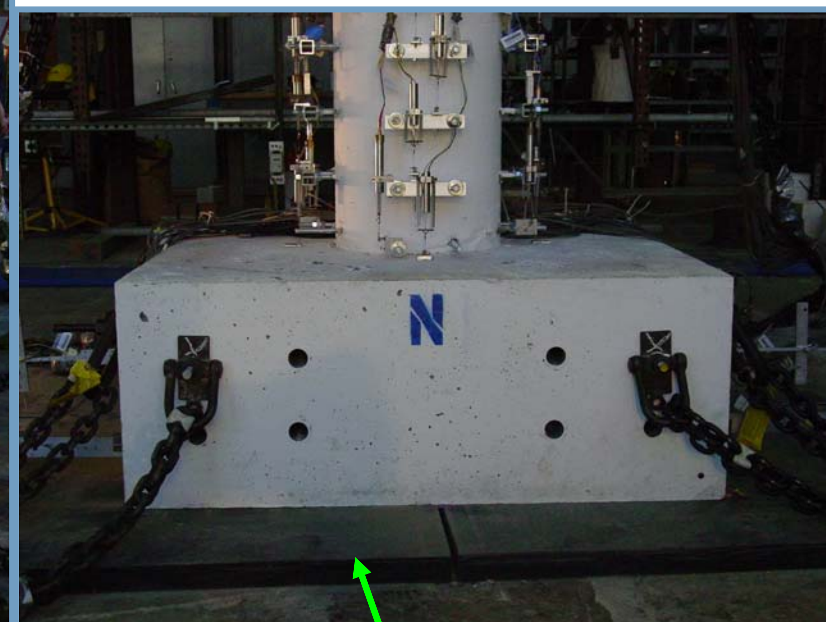
Footing & Neoprene Pad Details





Neoprene pads

Uplift measurements

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Shake Table Test Movies

QuickTime™ and a
MPEG-4 Video decompressor
are needed to see this picture.

QuickTime™ and a
MPEG-4 Video decompressor
are needed to see this picture.

Y Component - Los Gatos

X+Y Component Los Gatos

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Base Rocking Detail

QuickTime™ and a
MPEG-4 Video decompressor
are needed to see this picture.

X+Y+Z Components - Los Gatos

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MPEG-4 Video decompressor
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MPEG-4 Video decompressor
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Note twisting of footing about vertical axis

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Experimental Results: Typical test

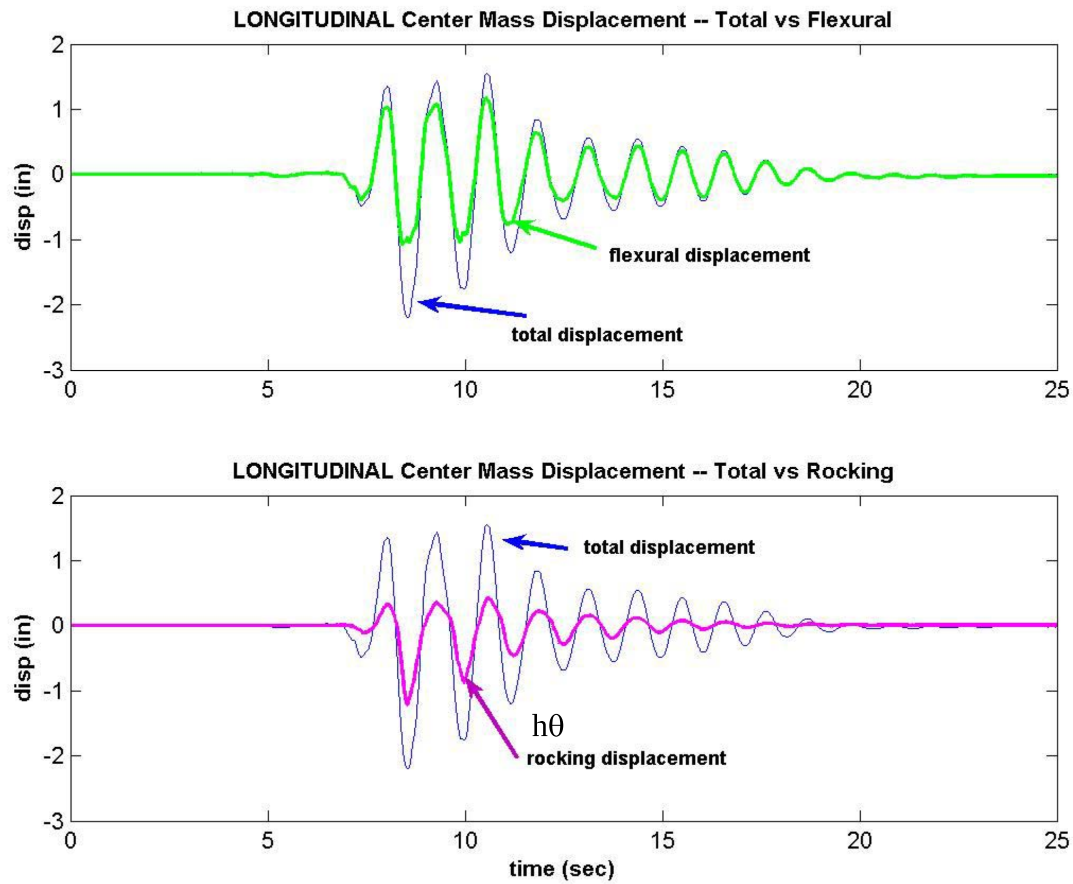
Center of Mass Displacement

$$u_{total} = \Delta u + h\theta$$

1989 Loma Prieta (Los Gatos)

<u>Excitation Level:</u>

- μ=2 *fixed base design*
- No yielding for rocking system



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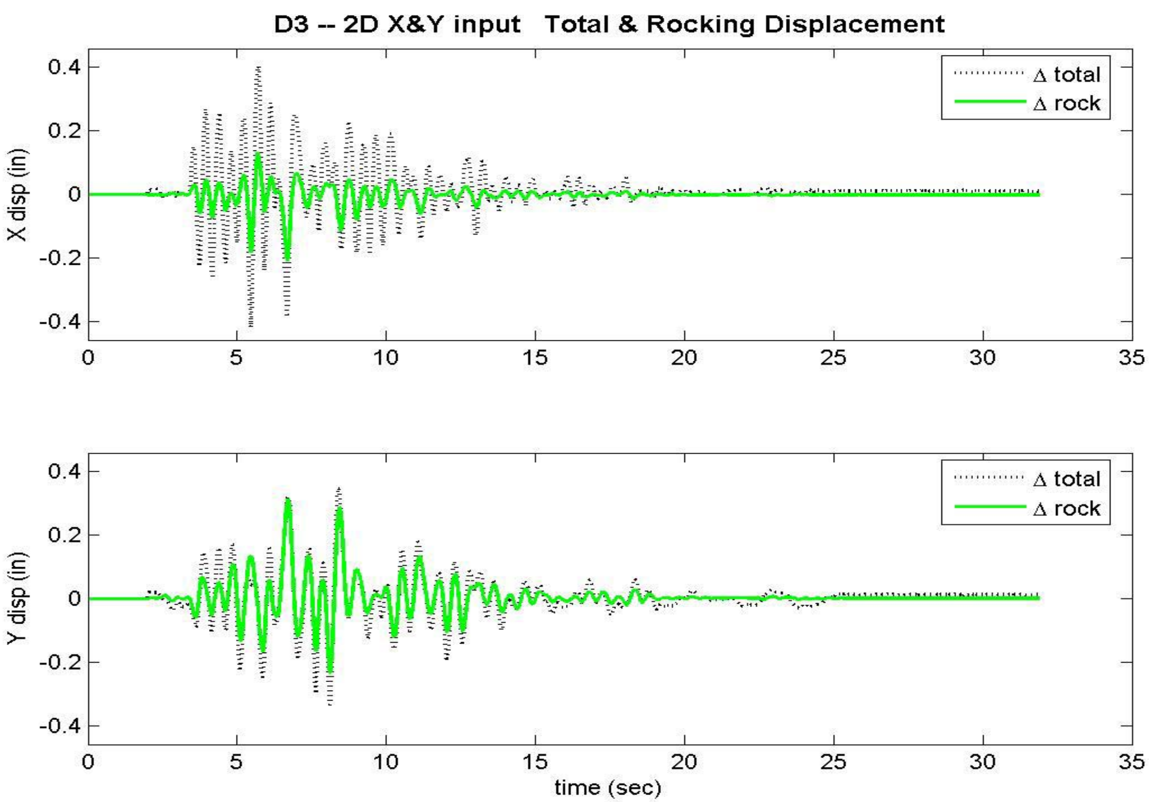
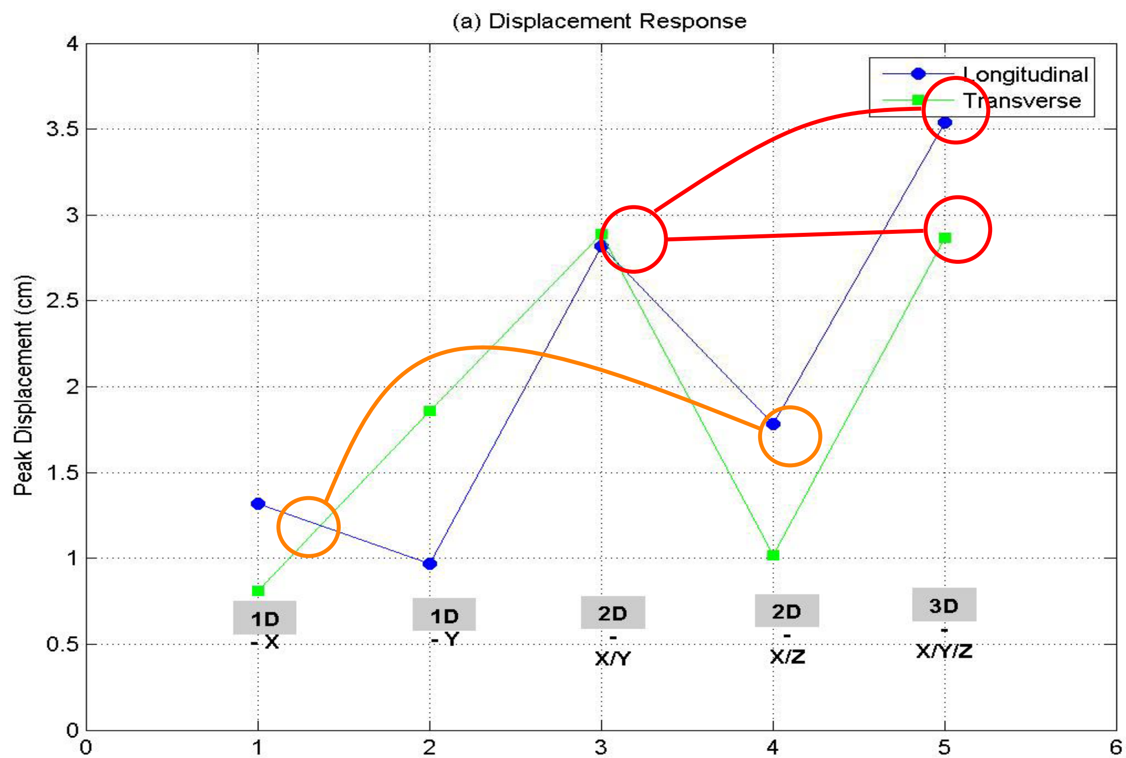
Experimental Data
Tabas 2D X+Y input (D group)



Peak Displacements for 5 Los Gatos Record Inputs (B group)



Can a column uplift then yield?

Footing increased to $3D_C$ x $5D_c$

Rocking only for low and moderate excitations

Rocking any yielding for large excitation

YES

So still generally need ductile detailing

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Experimental Results: Typical test

Center of Mass Displacement

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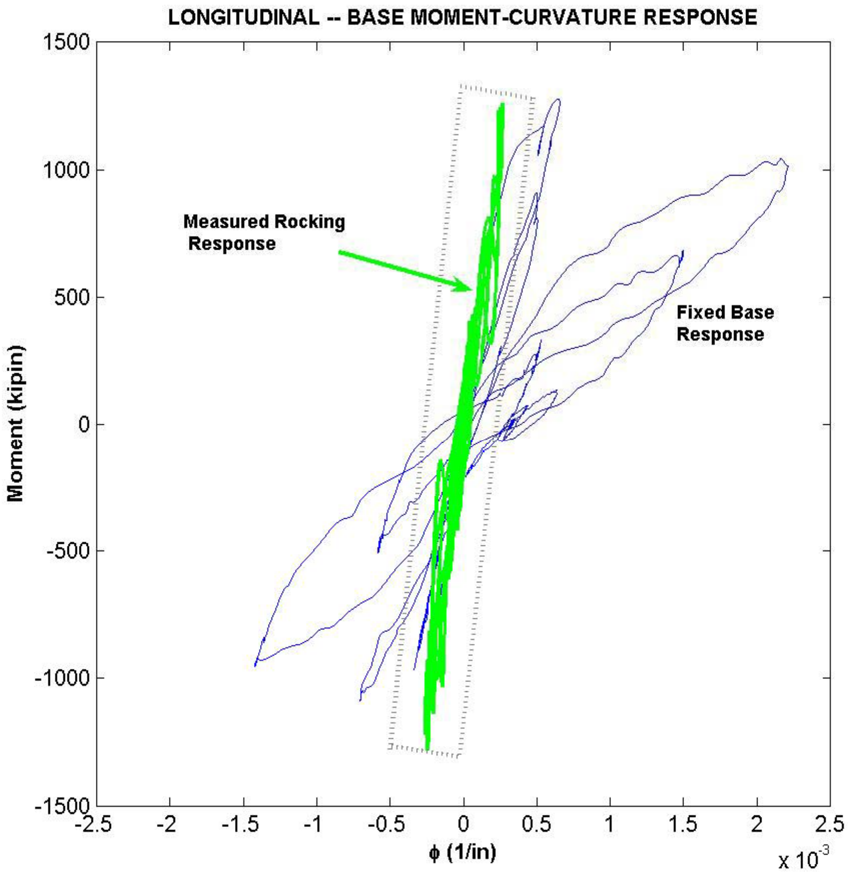
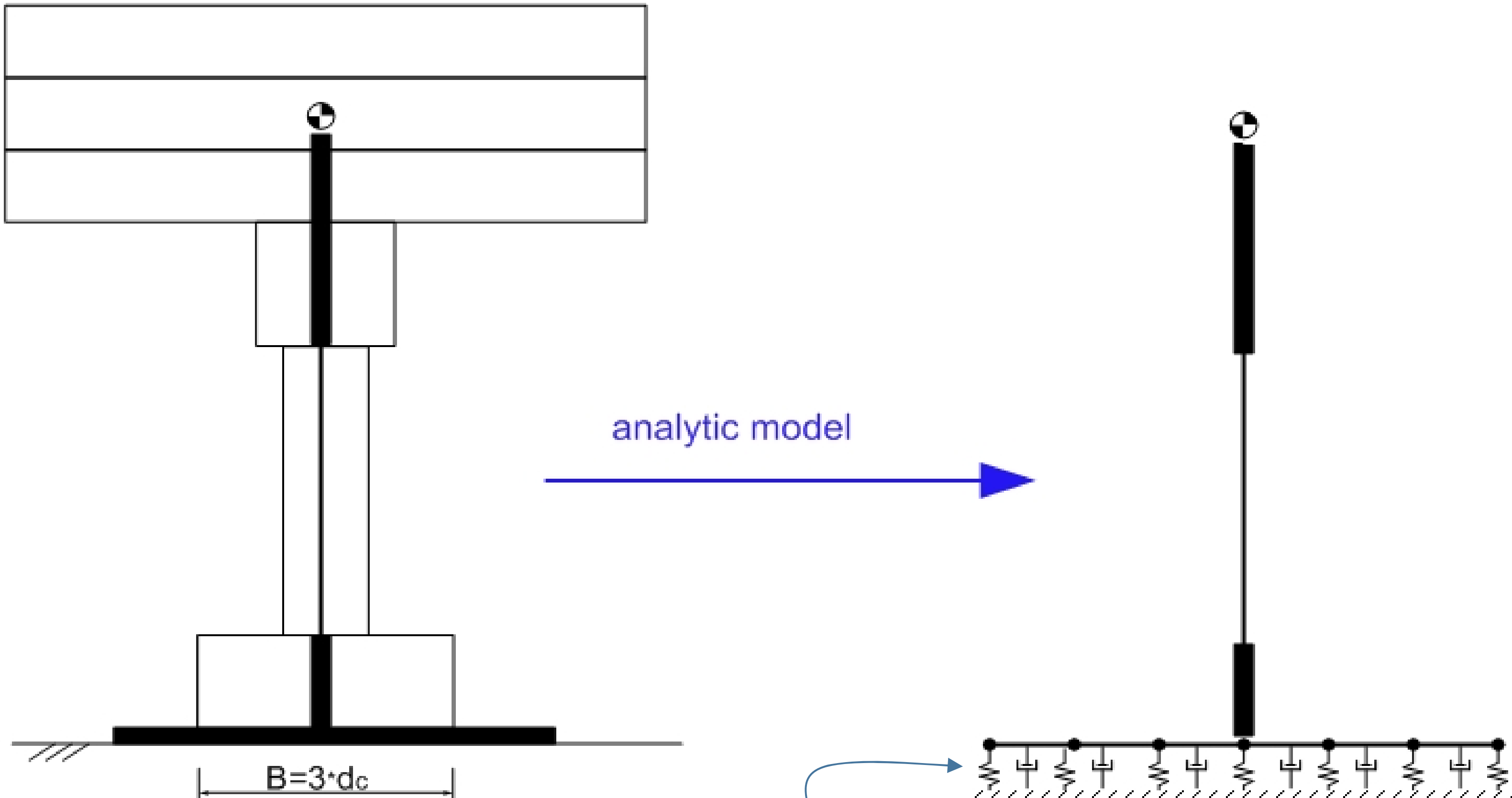
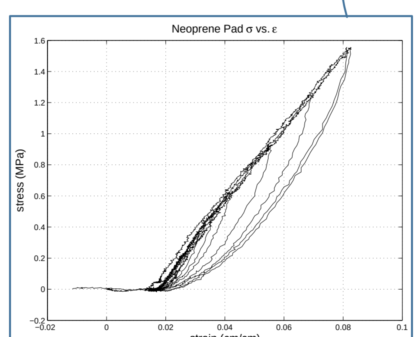


Analytic Model



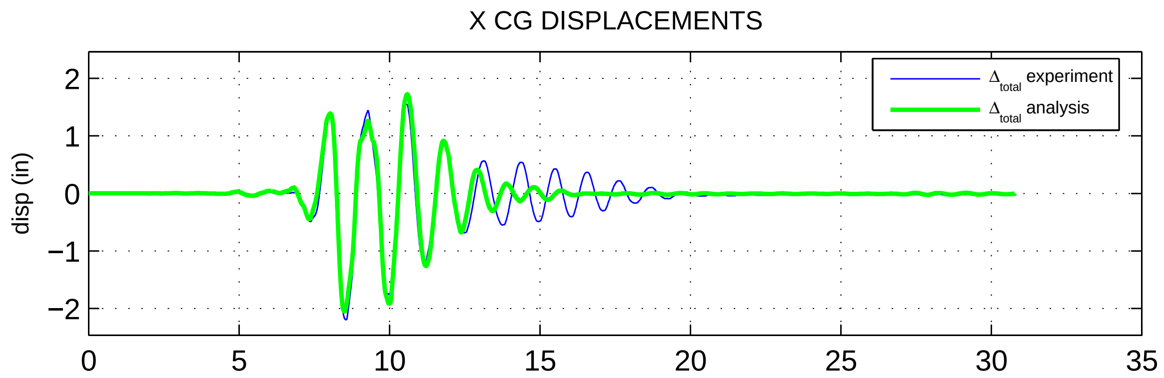


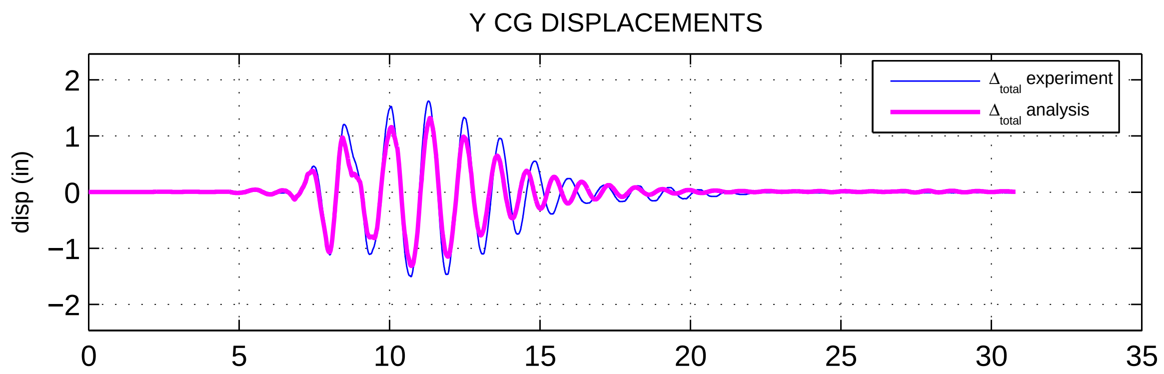
Beam on nonlinear Winkler-spring/dashpot foundation

Elastomeric Pad Properties

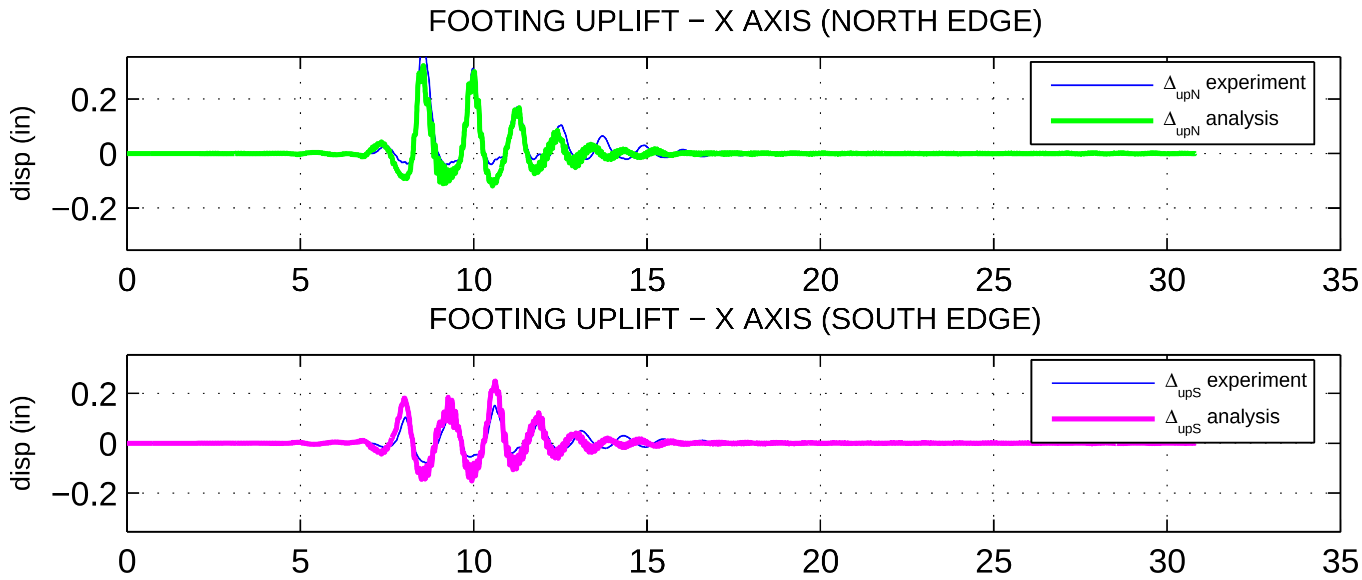
Validation of Analytic Model

global displacements

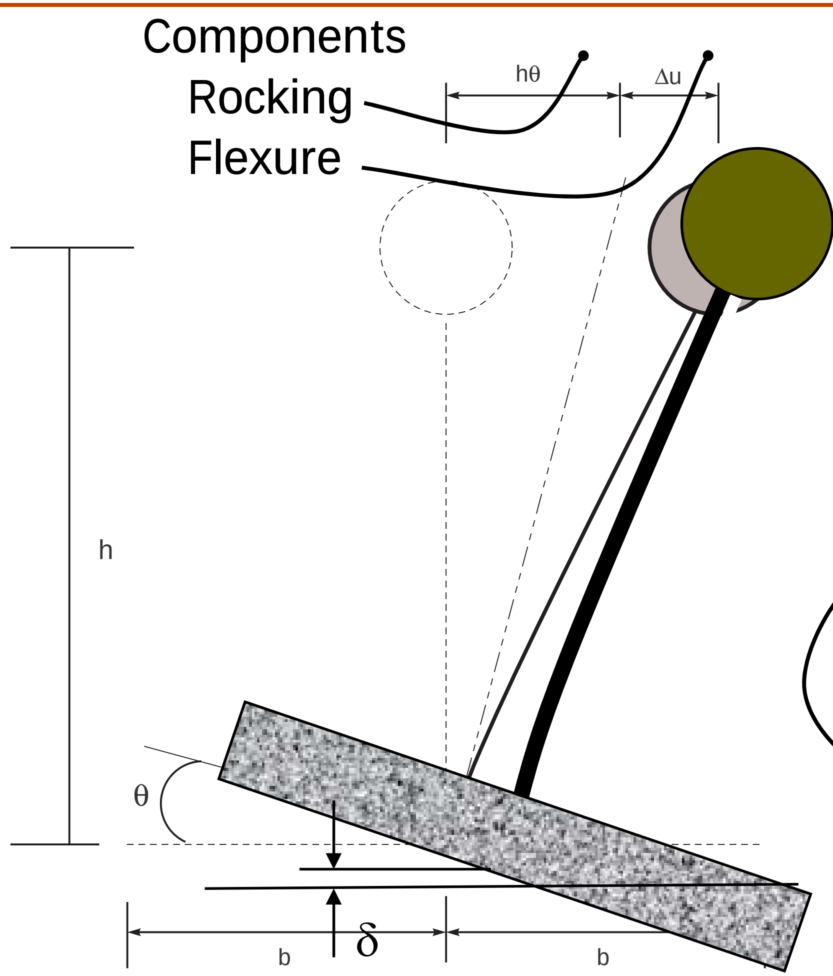


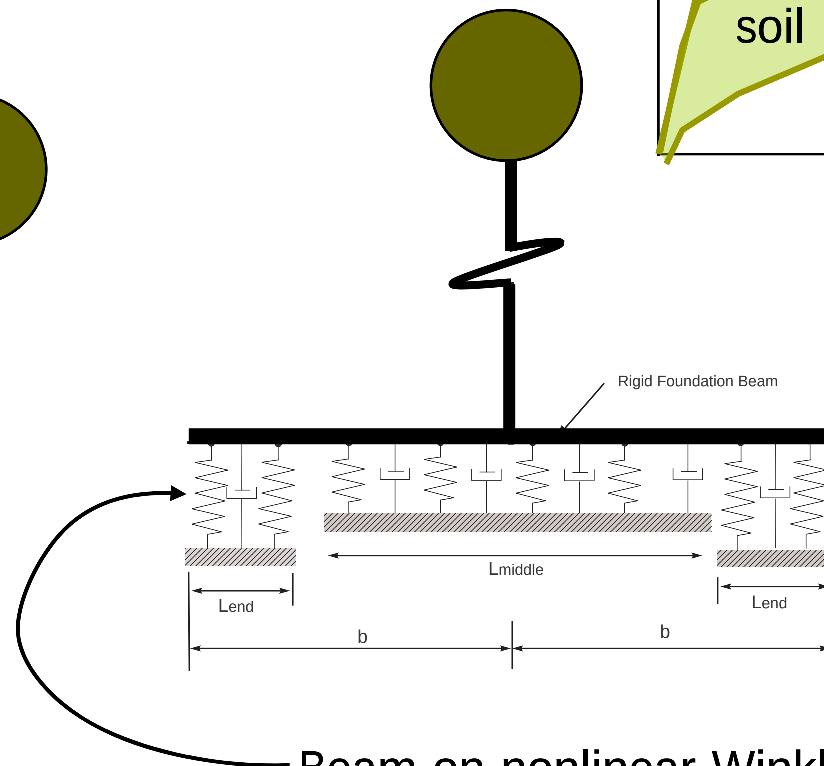


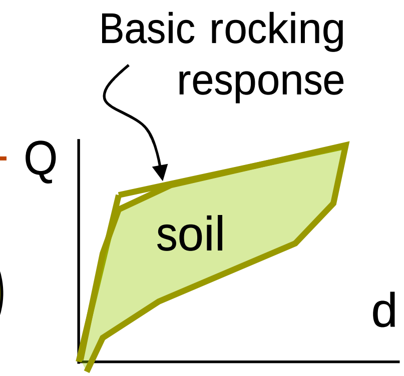
Validation of Analytic Model
footing uplift



Rocking Bridge on Soil







Beam on nonlinear Winkler-spring/dashpot foundation model (extended to 3D based on Hutchenson & Kutter)

Initial Parametric Analyses on Rocking of Bridge Piers

Parameters include:

- Column Height (L)
- Column Diameter (D_c)
- Footing Width/Length
- Soil Strength (FS: Gravity Factor of Safety)
- Soil Model Type
  - Elastic Perfectly Plastic Springs
  - QZ Simple Soil Spring/Dashpots
- Ground Motions
  - X, Y, X+Y, X+V, Y+V, X+Y+V
  - Suites with 10% and 2% in 50yr probability of exceedence for Los Angeles (firm ground)
- Column Strength (Ductility of reference fixed base column)

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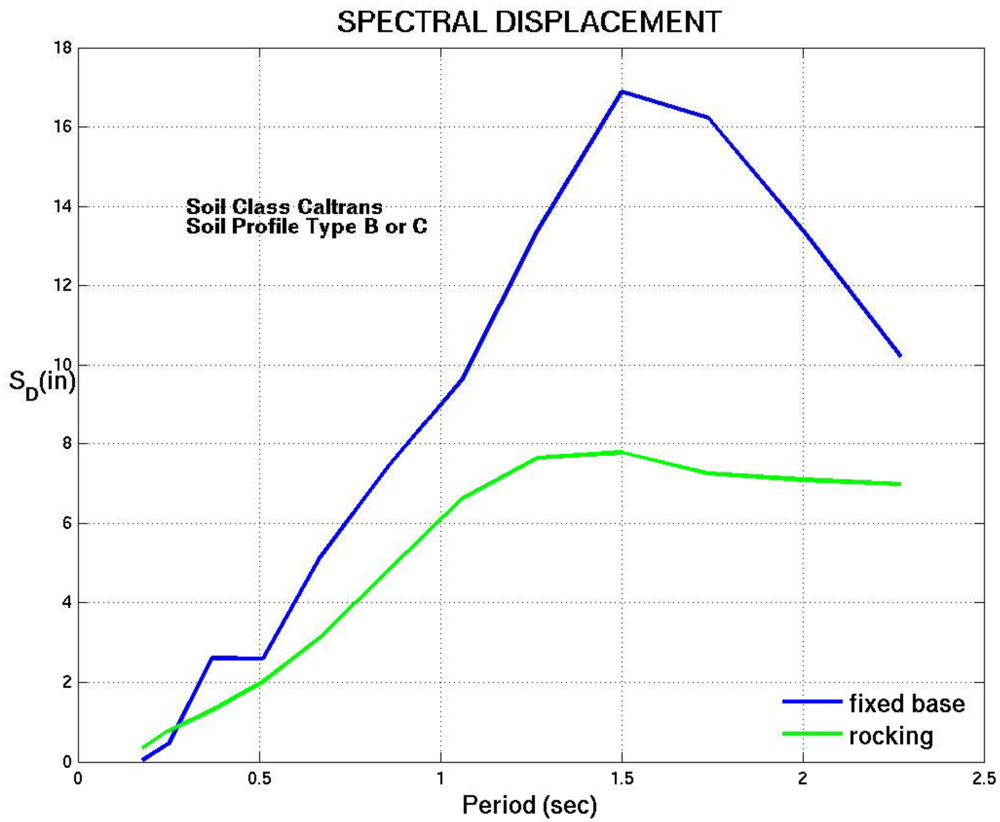
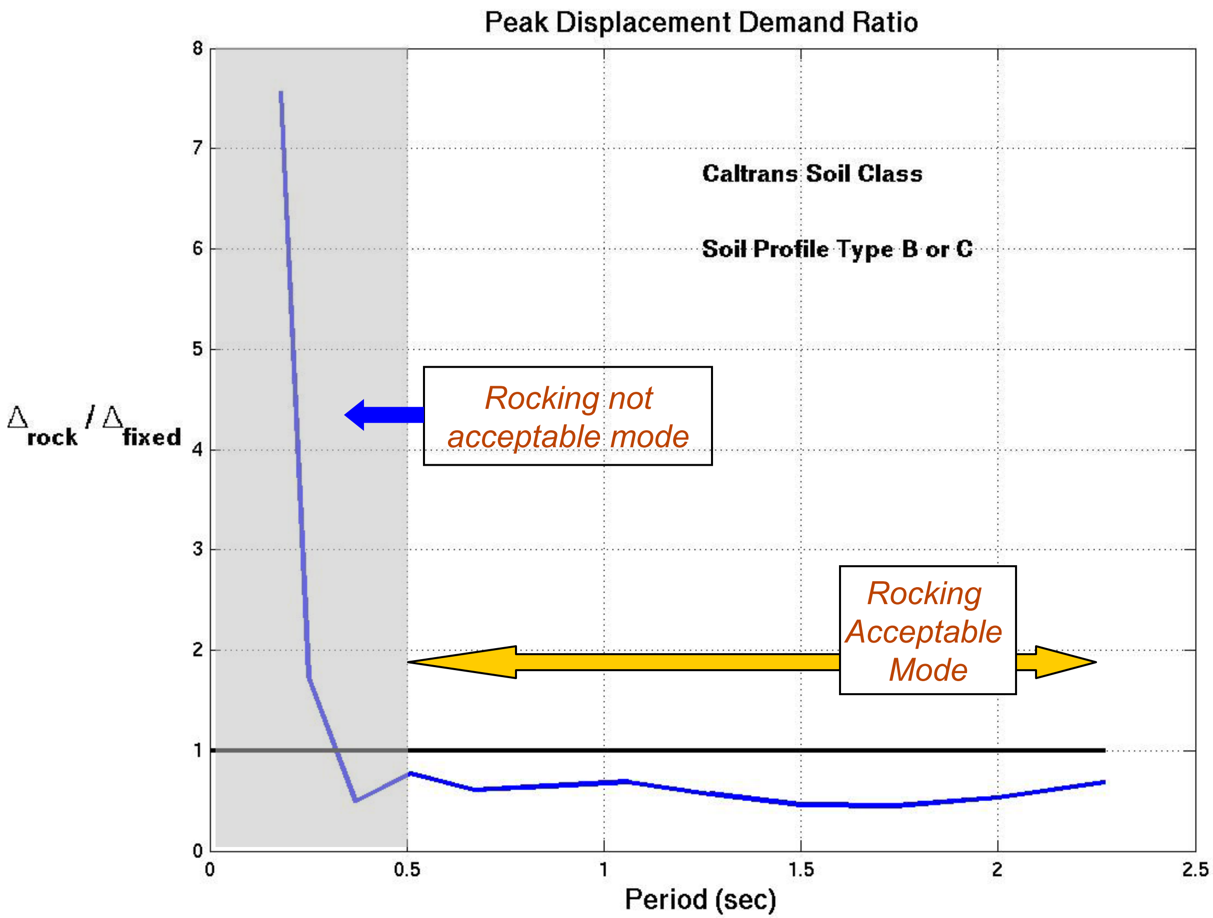
Rocking System Characteristics
Spectral Displacement



Rocking System Characteristics



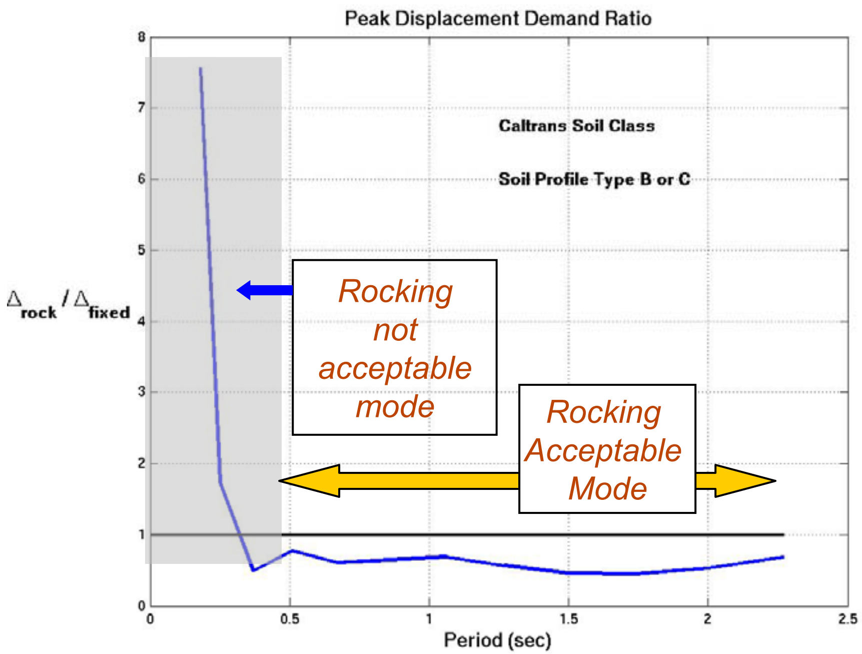
Observations from experiments

- Rocking does not produce global instability for tested configurations
- Plastic hinging can occur following rocking without fixity condition at base
- Rocking mechanism reduces flexural displacement demands for smaller than typical footing dimensions for competent soil conditions

Observations from analytical studies

Analytical investigation of the rocking behavior of spread footings supporting bridge piers:

- Confirms that rocking can provide a viable means of resisting earthquake effects for many bridges
- Peak displacements were similar to or smaller than would be expected for a comparable elastic or yielding system for moderate and long periods.
- Rocking columns expected to have less flexural damage, and overall to re-center
- More research needed to validate design guidelines



Thank

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