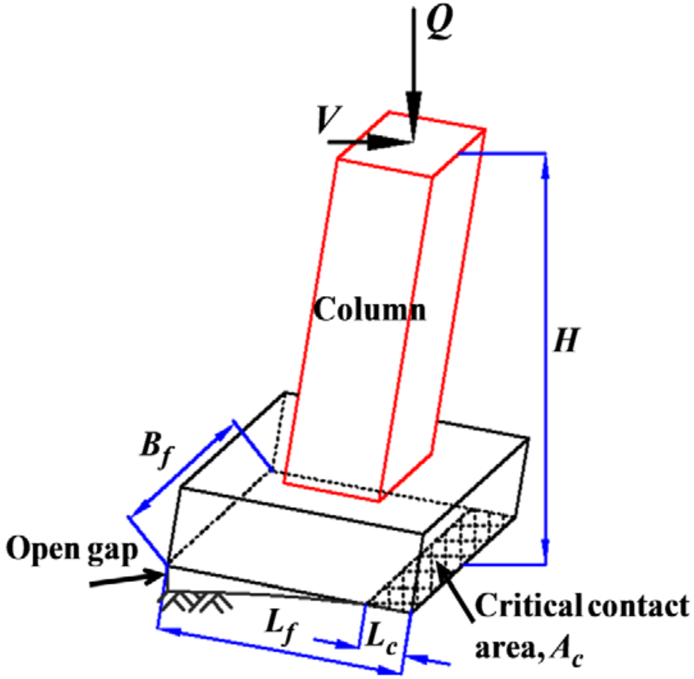
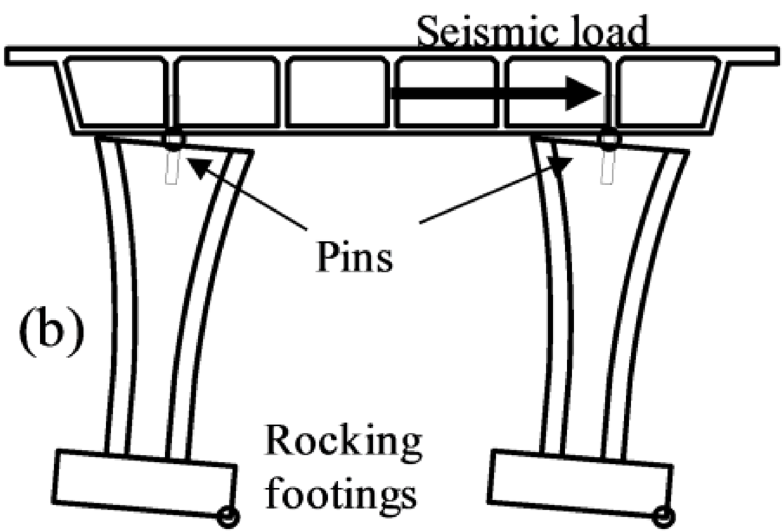


Last Hurdles for Implementation of Rocking Foundations for Bridges



Bruce Kutter
Sashi Kunnath
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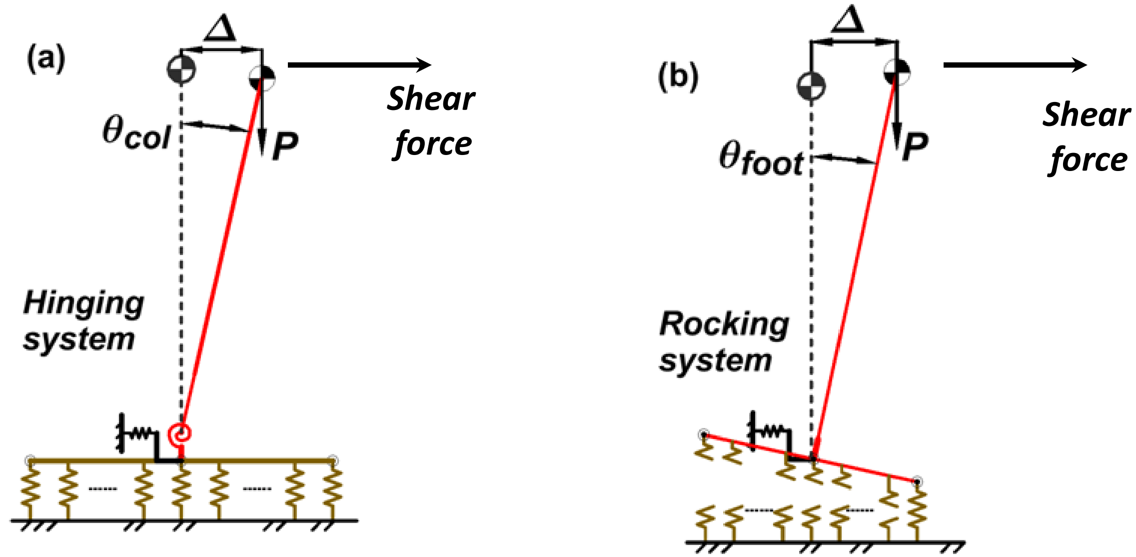
Ideas for today

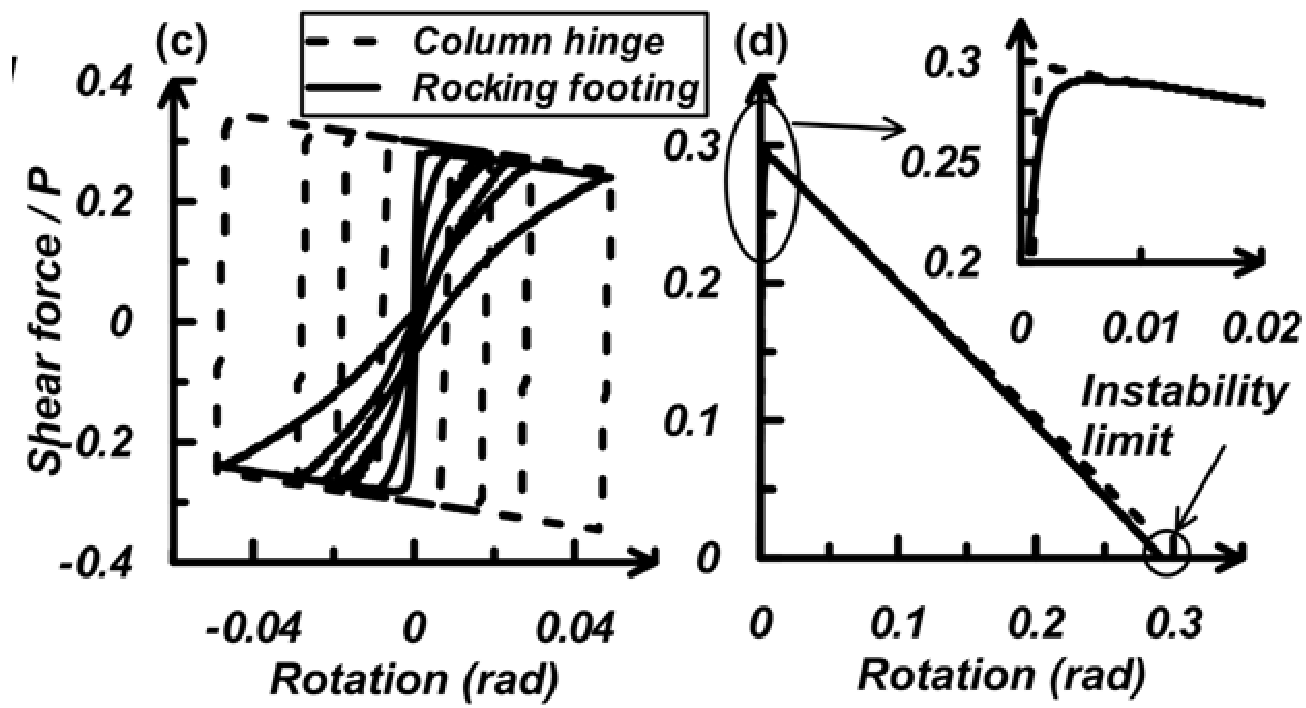
- Correct misconceptions about analysis and stability of rocking and hinging systems
  - No need to analyze rocking systems as if they are fundamentally different from hinging systems
  - IDA and fragility curves show rocking systems are superior to conventional hinging systems. (Deng et al. 2011, Spectra)
- Energy dissipation and recentering
- Design implementation
  - ASCE 41 – component action tables for rocking foundations
  - DDBD (Direct Displacement-Based Design)

Opensees models – large deformations (corotational transformation)

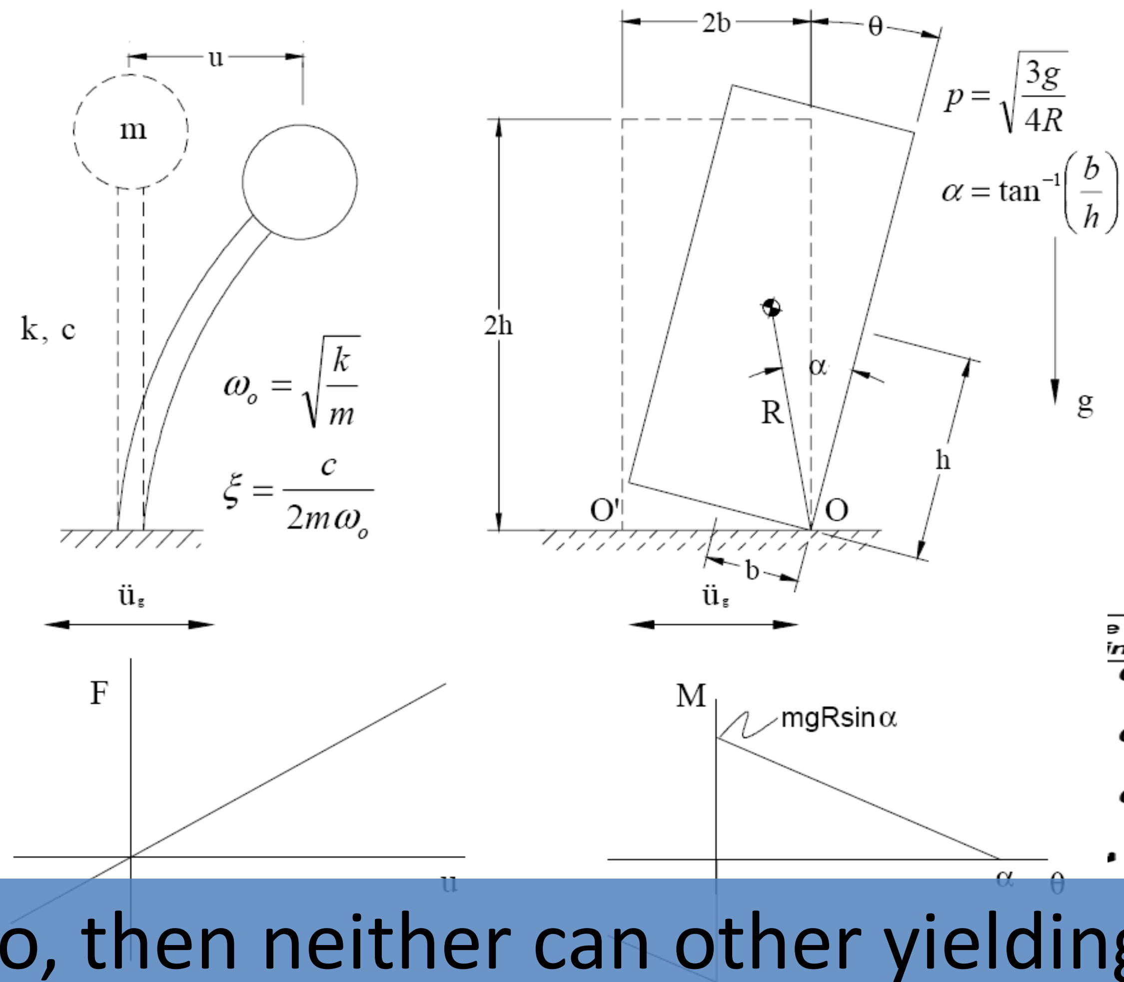
(Lijun Deng's work)

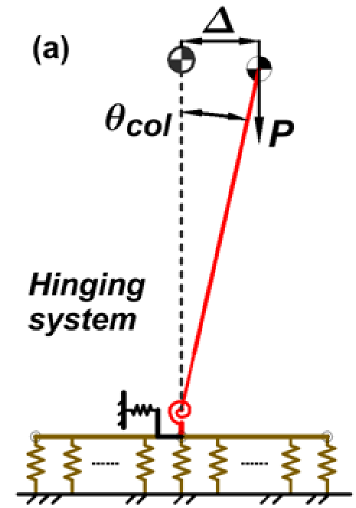


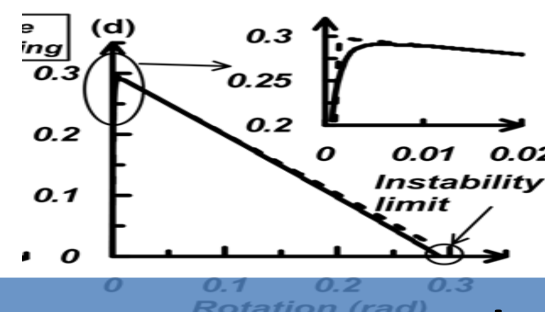
Pushover curves for rocking and hinging systems,
Cr = Cy = 0.3



Makris and Kostantinidis (2001) – *"rocking structures cannot be replaced by "equivalent" single-degree-of-freedom-oscillators"*







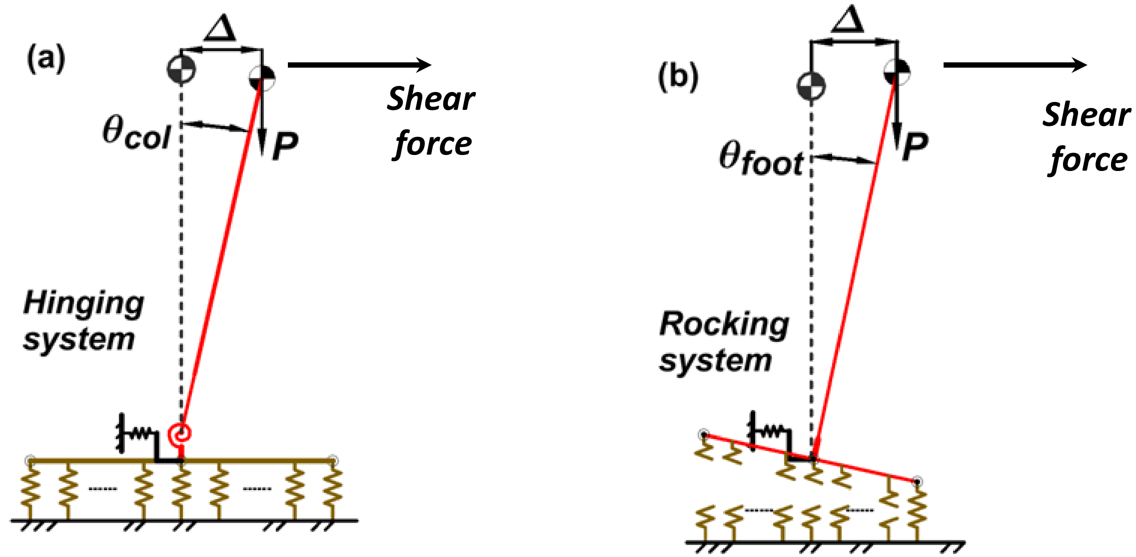
If so, then neither can other yielding systems with significant axial load

Hurdle 1 - mistaken notion that rocking behavior is fundamentally different from hinging behavior.

- Both have a well defined capacity and stiffness.
- Pushover curves are very similar
- The rotation required to cause instability (i.e., the rotation at which the $P\text{-}\Delta$ moment is equal to the moment capacity) is approximately equal to the minimum of C_r or C_y. So, if $C_r = C_y$, the rotation to cause instability is the same for rocking and hinging systems.
- The one important difference is the benefit of re-centering associated with rocking.

OpenSees models – large deformations (corotational transformation)

(Lijun Deng's work)



Pushover curves for rocking and hinging systems,

Cr = Cy = 0.3

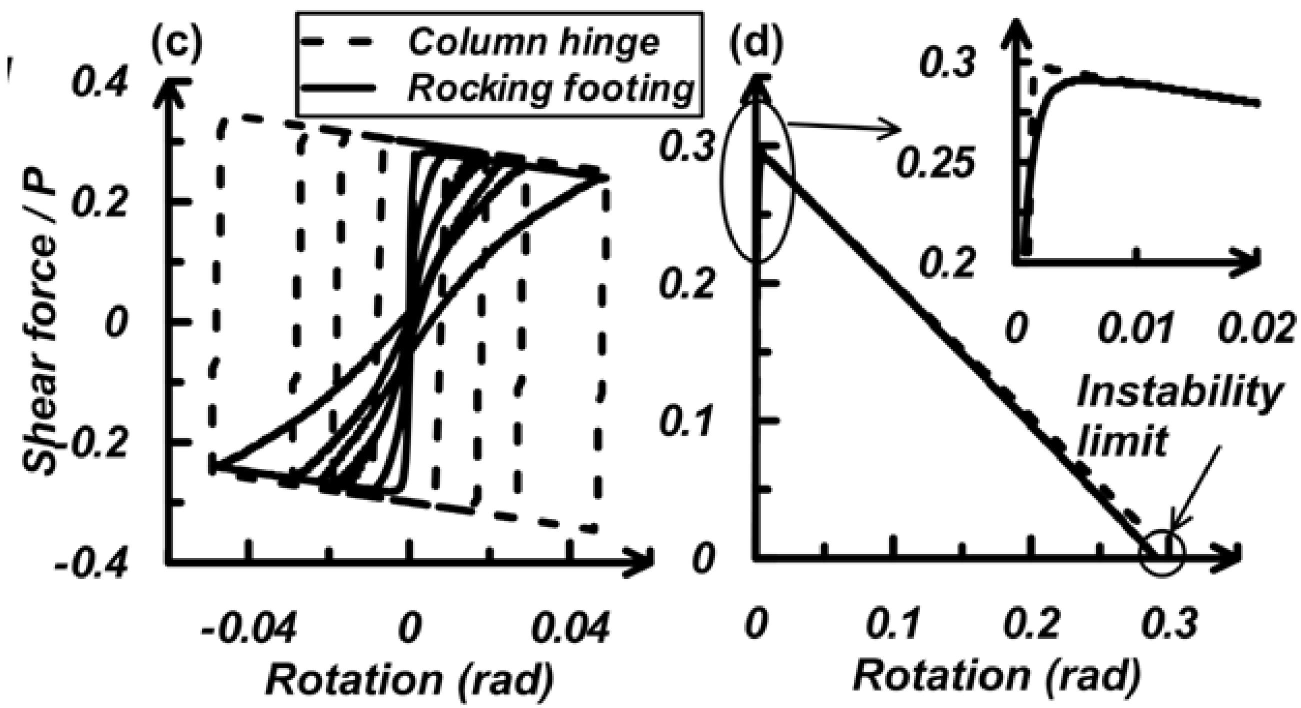


Table 1. Values for parametric studies

H_c (m)	Period, T_1 (s)	C_y	C_r	$K_{\theta C} / K_R$	L_f (m)	Remarks
Short: 3	0.3	0.3	0.4	1.0	2.64	Hinging-column system
	0.3	0.4	0.3	2.0	1.92	Rocking-foundation system
	0.5	0.3	0.4	1.0	2.64	Hinging-column system
	0.5	0.4	0.3	2.0	1.92	Rocking-foundation system
Tall: 10	0.5	0.3	0.4	1/4	8.82	Hinging-column system
	0.5	0.4	0.3	1/1.5	6.17	Rocking-foundation system
	1.0	0.3	0.4	1/4	8.82	Hinging-column system
	1.0	0.4	0.3	1/1.5	6.17	Rocking-foundation system

$C_y = M_{c\_col}/(P\ H_c)$: base shear coefficient to initiate column yielding

$C_r = M_{c\_foot}/(P\ H_c)$: base shear coefficient to initiate footing rocking

$K_{\theta C} / K_R$: elastic stiffness of the column / elastic stiffness of footing

40 pulse-like and 40 broadband motions from PEER database (Baker)

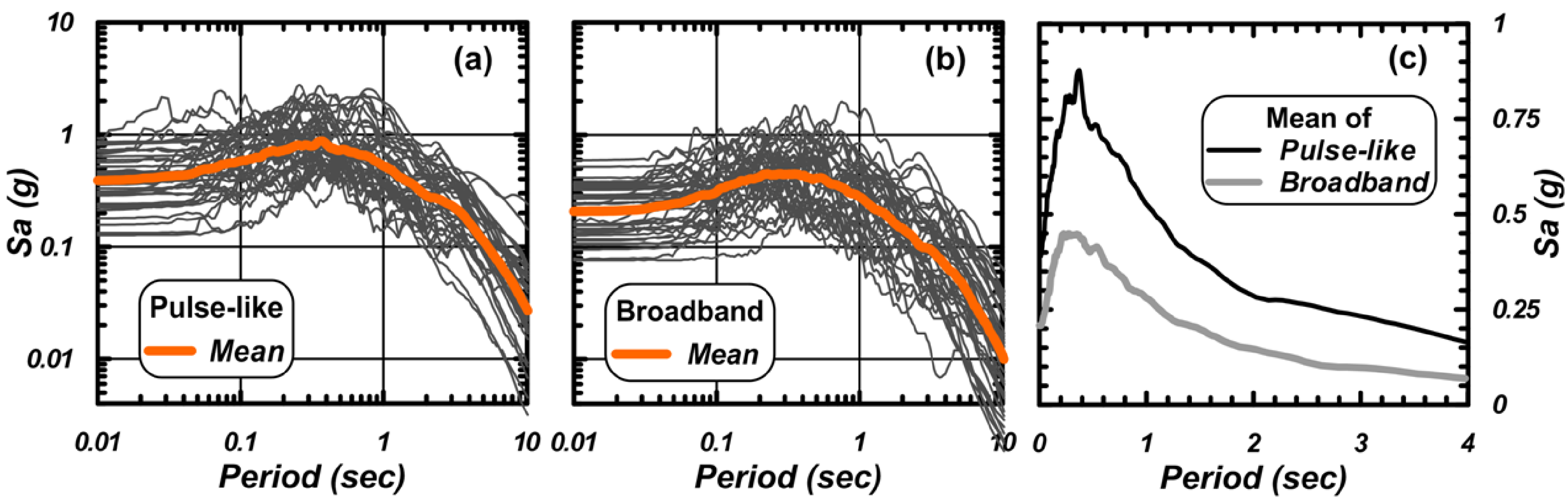
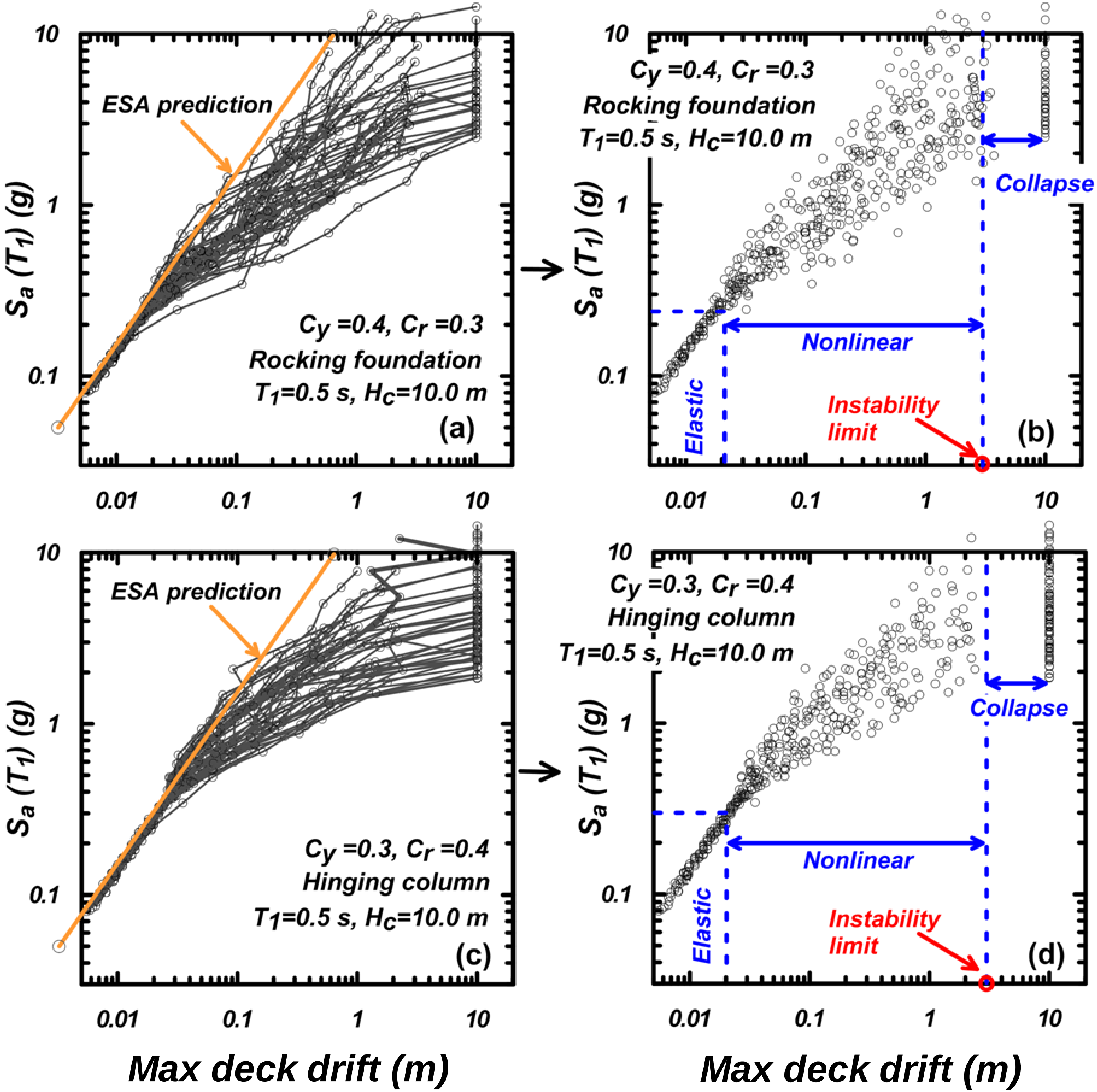
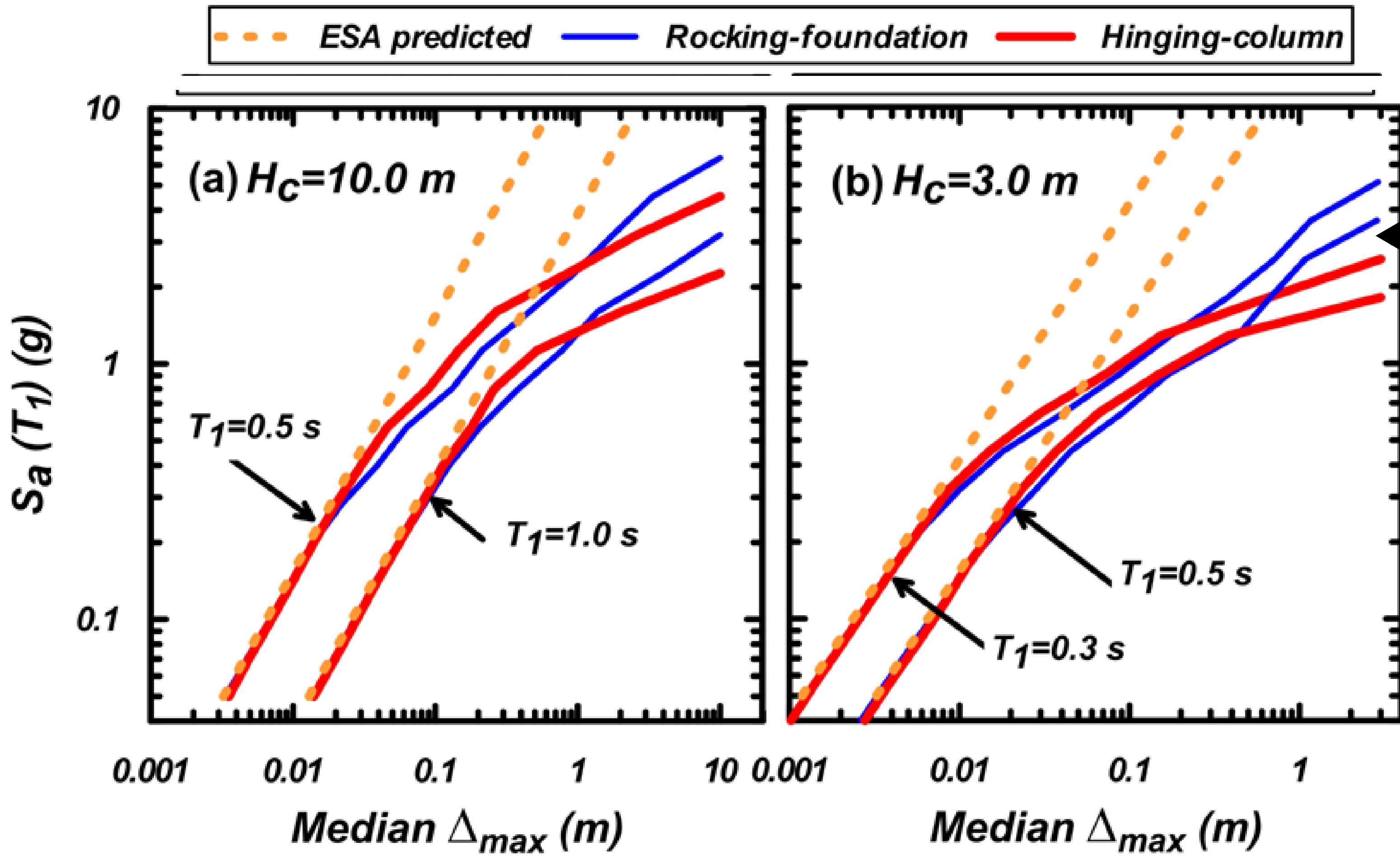


Figure 3. Spectral accelerations of unscaled ground motions: (a) 40 pulse-like motions, (b) 40 broadband motions at soil site recorded in earthquakes of Magnitude=7 and Distance=10 km, and (c) a comparison of mean spectra of two types of motions in linear scale.



ESA prediction
C_y =0.4, C_r =0.3
Rocking foundation
T_1=0.5 s, H_c=10.0 m
(a)
S_a (T_1) (g)
Nonlinear
Collapse
Elastic
Instability limit
(b)
C_y =0.3, C_r =0.4
Hinging column
(c)
(d)
Max deck drift (m)

Median deck drift from IDA
Min(Cy or Cr) = 0.3



Rocking system is more stable

Figure 10. Spectral acceleration at the elastic system period vs. median maximum deck drifts for all the systems in this study. For rocking systems C_r=0.3; for hinging column systems C_y=0.3.

Hurdle 2 - mistaken notion that conventional methods for predicting drift demand are not appropriate for rocking systems.

- We show that response-spectrum-based approaches are equally appropriate (or equally inappropriate) for rocking and hinging systems.

Residual deck drift from IDA
Min(Cy or Cr) = 0.3

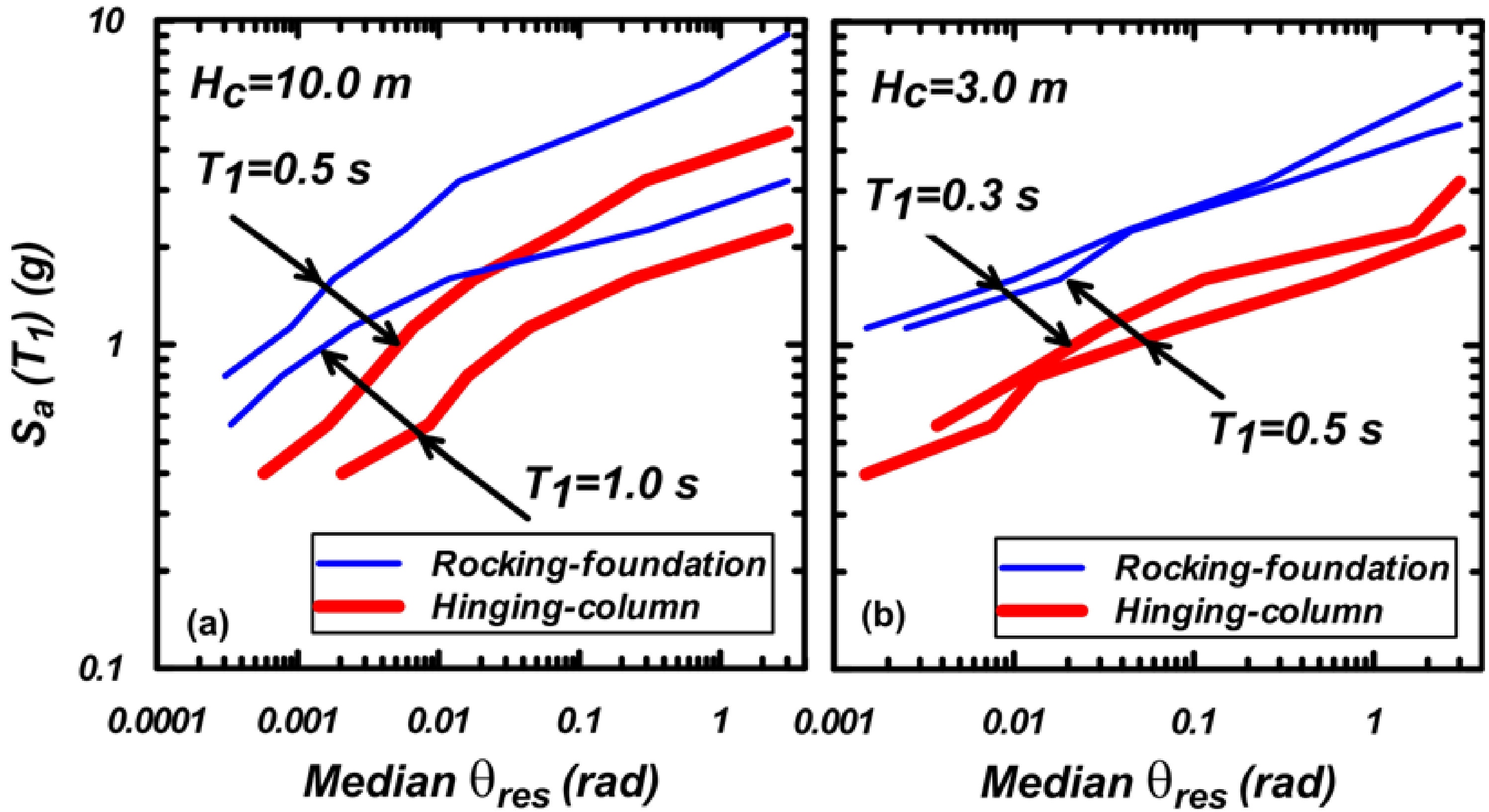


Figure 11. Spectral acceleration at elastic period of systems vs. median residual drift ratio (Δ_{res} / H_c): (a) tall column bridges; and (b) short column bridges. The approach to obtain the median maximum drift of the deck illustrated in Figure 9 was employed here to obtain the median residual drift ratio of the deck.

Comparison of performance in broadband and pulse-like motions

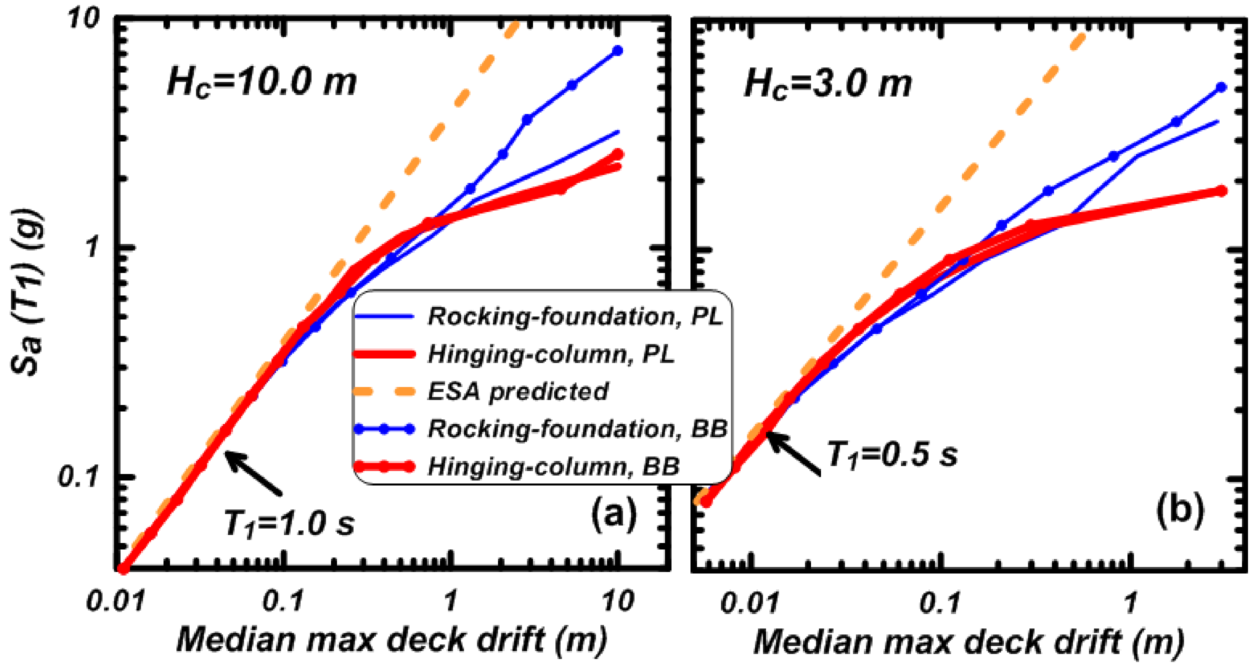
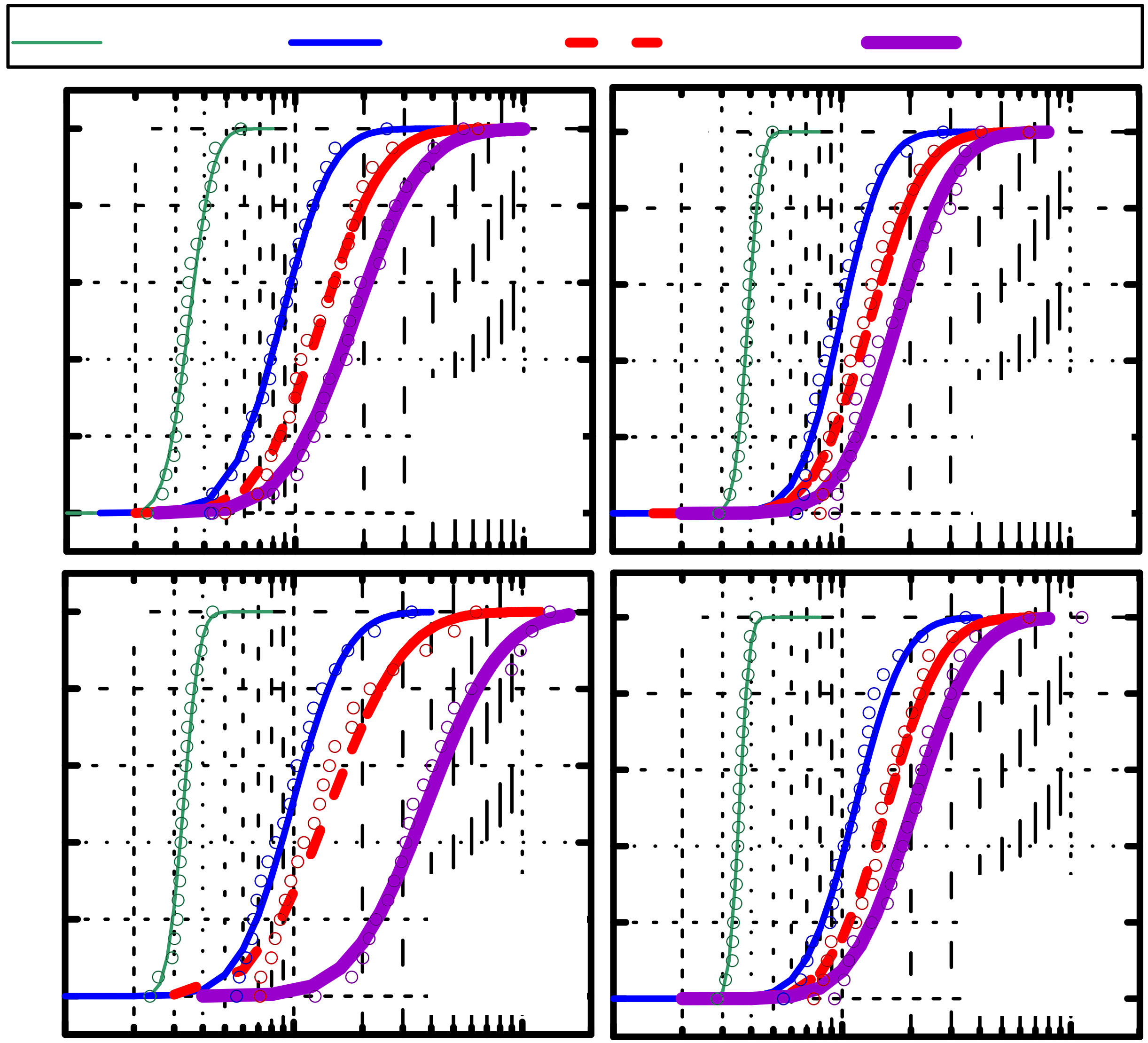


Figure 13. Comparison of median maximum drift of deck of rocking and hinging systems subject to pulse-like and broadband motion suite: (a) H_c=10.0 m, T_1=1.0 s; (b) H_c =3.0 m, T_1=0.5 s. Legend notations: PL= pulse-like motions; BB= Broadband motions.

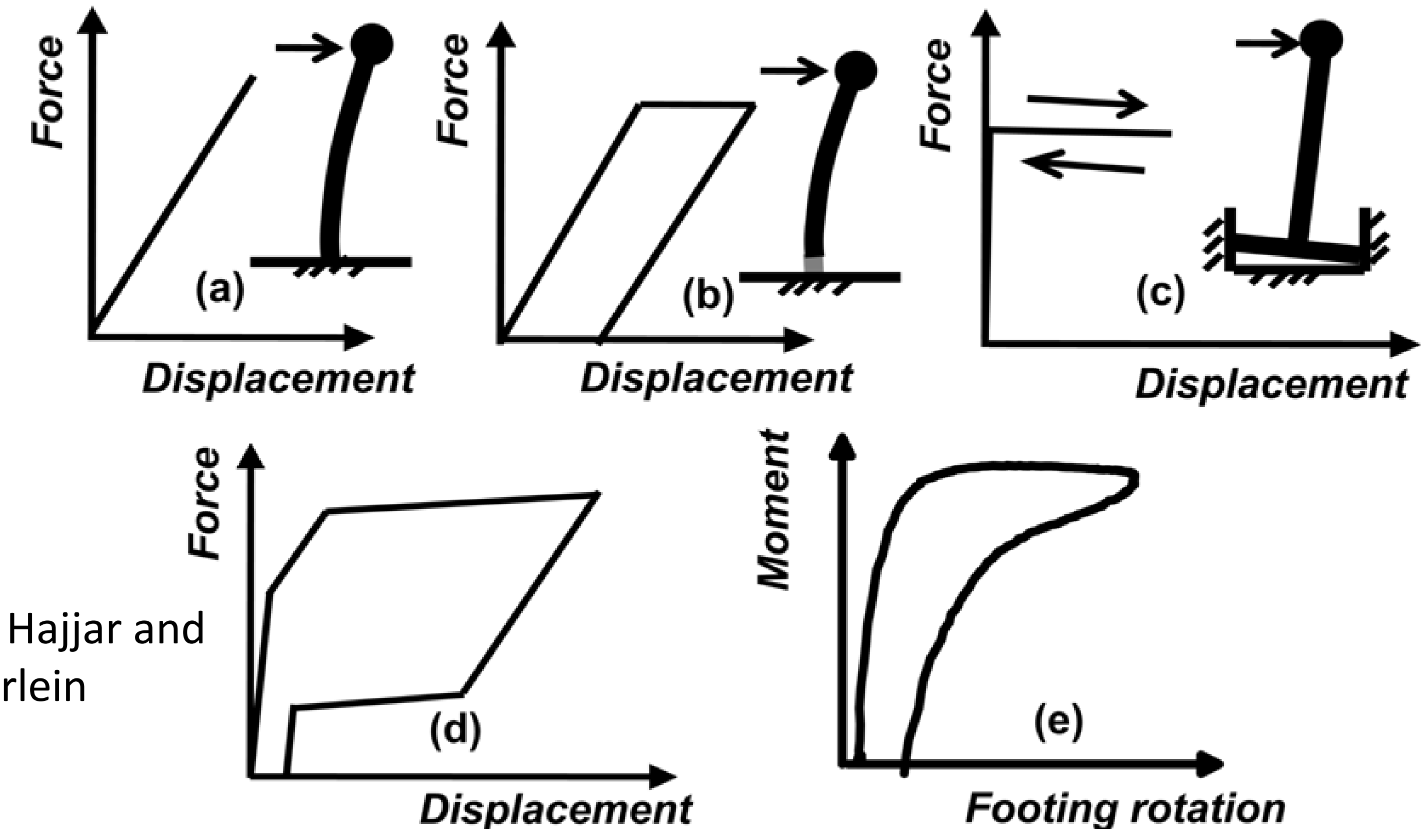
Fragility Curves – pulse like motions



Hurdle 3– misconception that a rocking system is less stable than a hinging system

- For the analyses presented, rocking systems are more stable than hinging systems.
  - It all comes down to the hysteresis curve
    - Capacity
    - Stiffness
    - Damping
    - Recentering
  - Rocking systems have recentering

The difference in behavior comes down to the shape of the hysteresis curve.

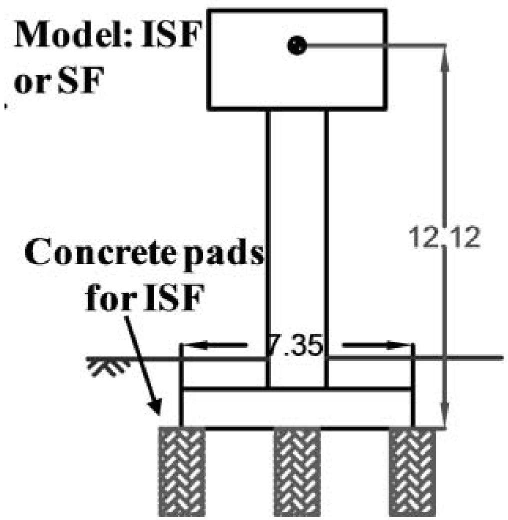


e.g., Hajjar and Deierlein

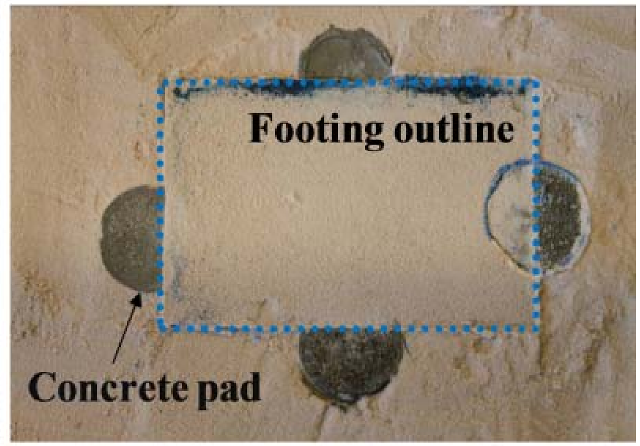
Figure 13. Load-displacement hysteresis for different energy-dissipating devices: (a) an elastic column, (b) an elastic-perfectly-plastic column, (c) a rocking footing on a rigid ground (with zero hysteretic and radiation damping), (d) a controlled rocking building system [33], and (e) experimental data from a rocking-foundation model with L_f/L_c=30.2.

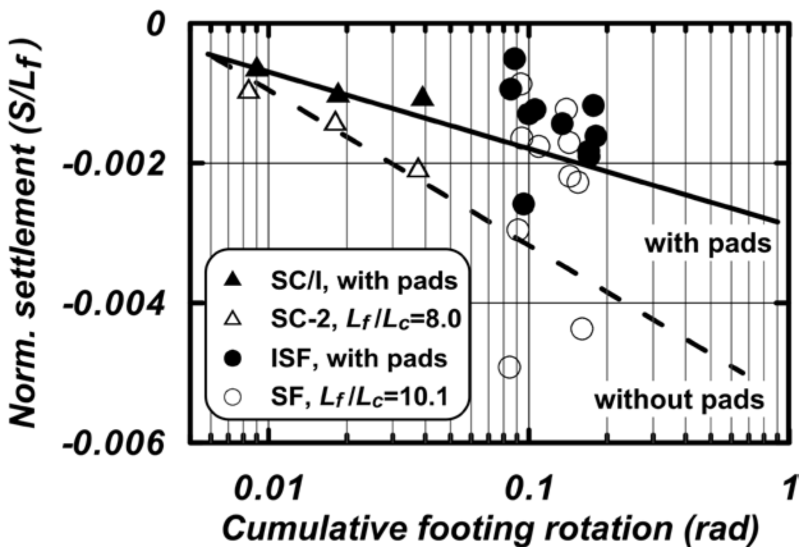
Other Hurdles – rocking may not be appropriate for poor soils without improvement

(b)

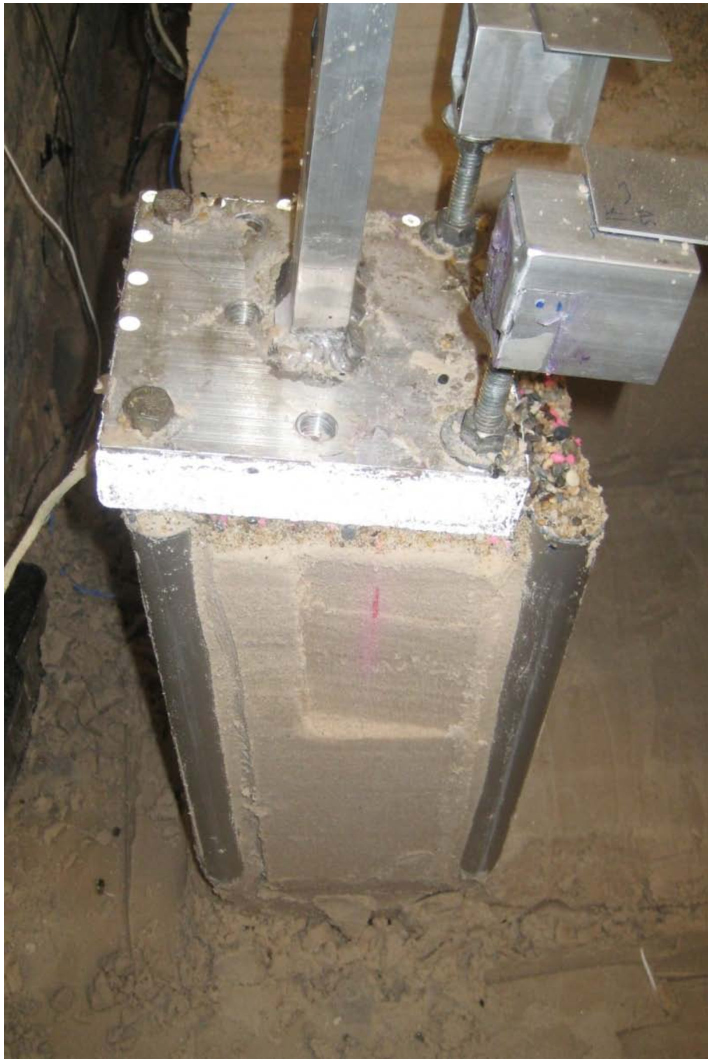


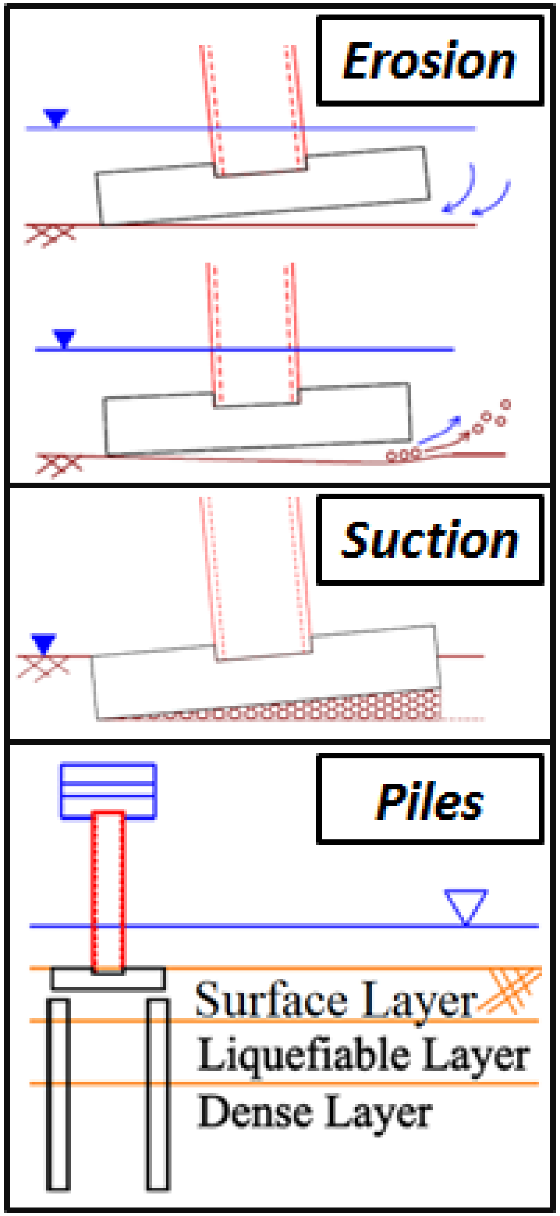
(c)





Rocking on liquefiable soils with and without piles (Allmond et al. 2010)





Other Hurdles

- Lack of design methods – partly solved by showing that conventional methods also apply to rocking systems.
  - ASCE-41 work
    - Credit Mark Moore, ZFA, among others
    - Developing Component Action Tables for Rocking systems
  - DDBD
    - Need to carefully characterize the damping and stiffness properties of the hysteresis loop.

ASCE 41 – Rehabilitation of Existing Buildings component action tables

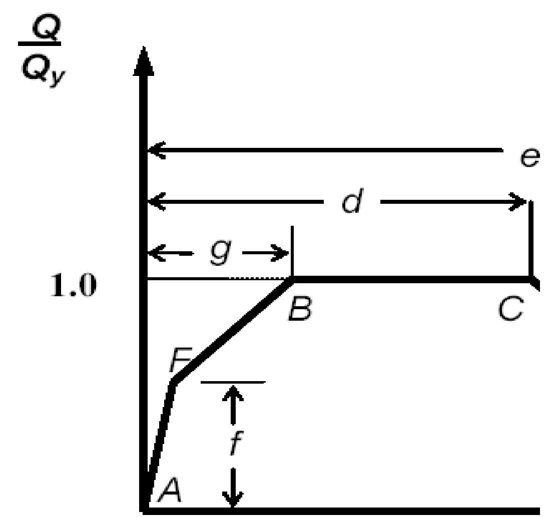
Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures

Shallow foundation rocking/overturning

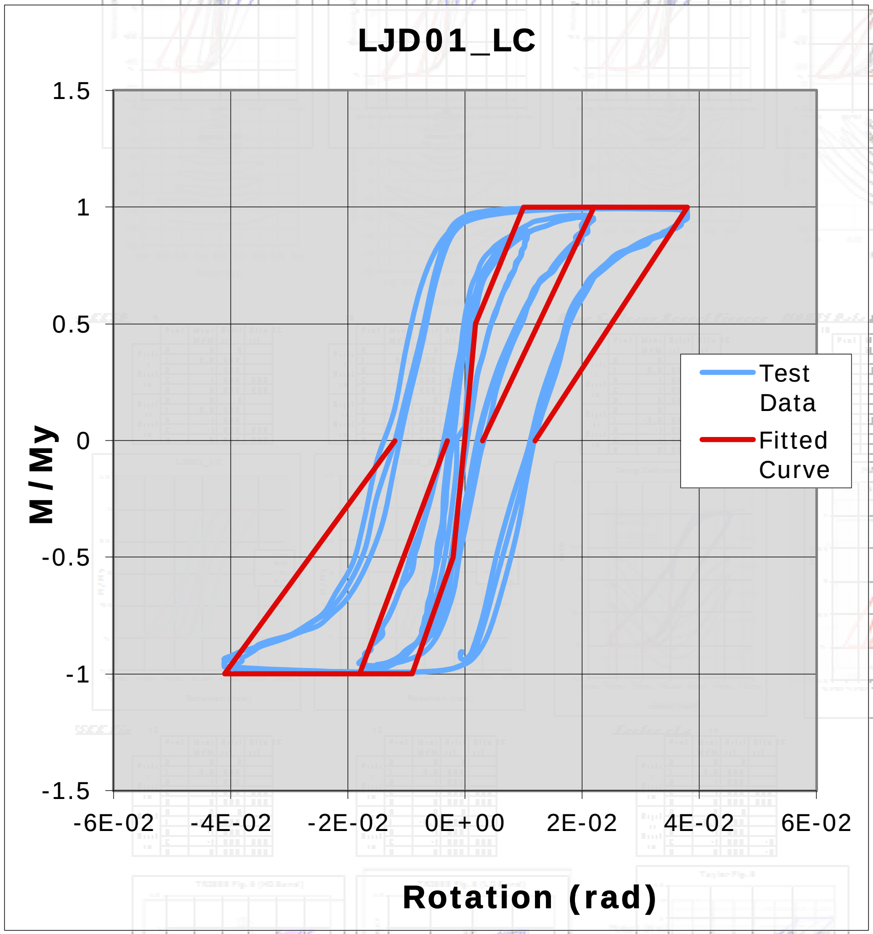
Condition 1. Rocking dominates over sliding: (M/V)/Lf >1

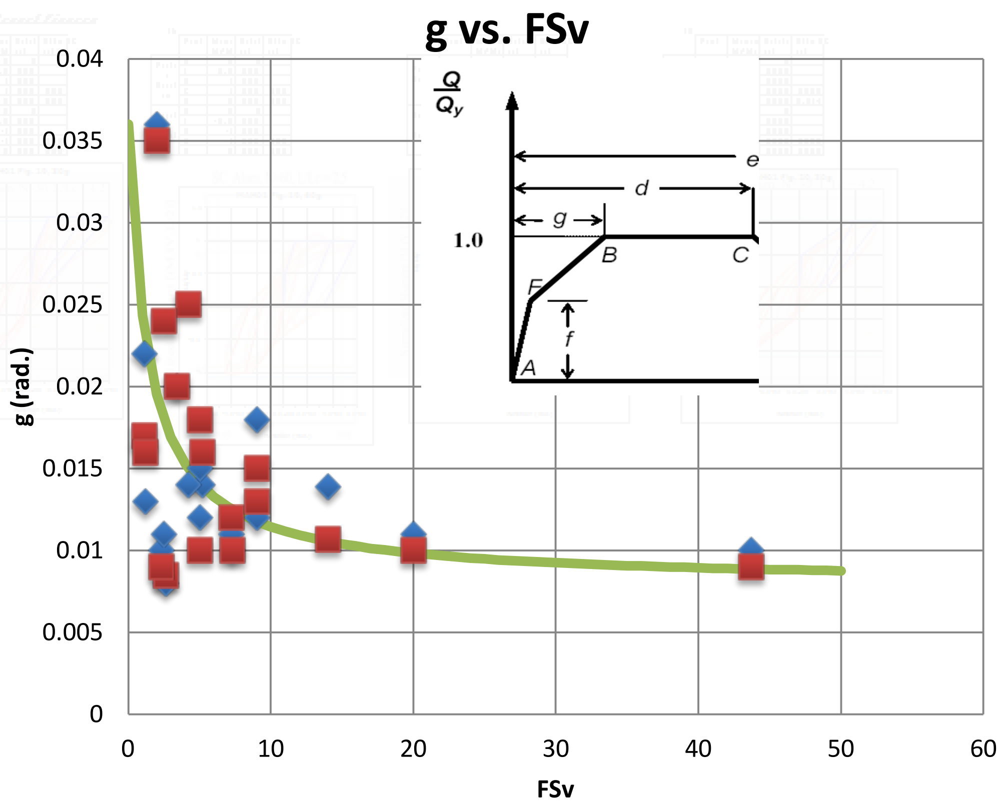
B	C	D	E	F	G	H	I	J	K
	Footing Shape		Rigidity Index?	Footing Rotation Angle (radians)		Elastic strength ratio	Total Footing Rotation Angle (based on the assumption that allowable storey drift >1%) (radians)		
Lc/tf	(Bf/Bm)	Bf/Lc	Ir	g	d	f	IO	LS	CP
0.01	Rectangle (1)	10 or more		0.005	0.1	0.33	0.02	0.08	0.1
0.3	Rectangle (1)			0.01	0.1	0.5	0.015	0.08	0.1
1	Rectangle (1)			0.02	0.1	0.67	0	0	0
0.01	Rectangle (1)	3		0.005	0.1	0.33	0.02	0.08	0.1
0.3	Rectangle (1)	3		0.01	0.1	0.5	0.011	0.0675	0.085
1	Rectangle (1)	3		0.02	0.1	0.67	0	0	0
0.01	Rectangle (1)	1 or less		0.005	0.1	0.33			
0.3	Rectangle (1)	1 or less		0.01	0.1	0.5			
1	Rectangle (1)	1 or less		0.02	0.1	0.67			
0.01	I-shape (5)	10 or more		0.003	0.1	0.5			
0.3	I-shape (5)	10 or more		[illegible]	0.1	0.5			
1	I-shape (5)	10 or more		0.01	0.1	0.5			
<0.01	I-shape (5)	3							
0.1	I-shape (5)	3							
0.4	I-shape (5)	3							
<0.01	I-shape (5)	1 or less							
0.1	I-shape (5)	1 or less							
0.3	I-shape (5)	1 or less							

Not final values



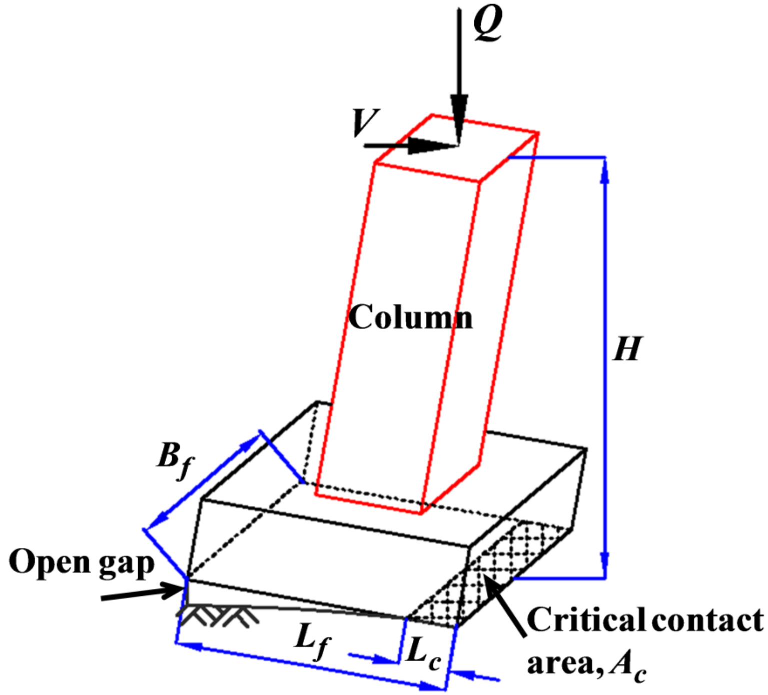
Characterizing backbone and hysteresis loops for ASCE 41 and DDBD (Ken Johnson)

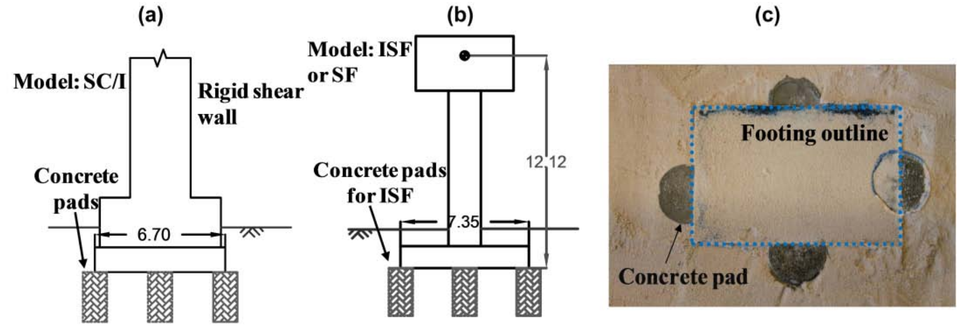


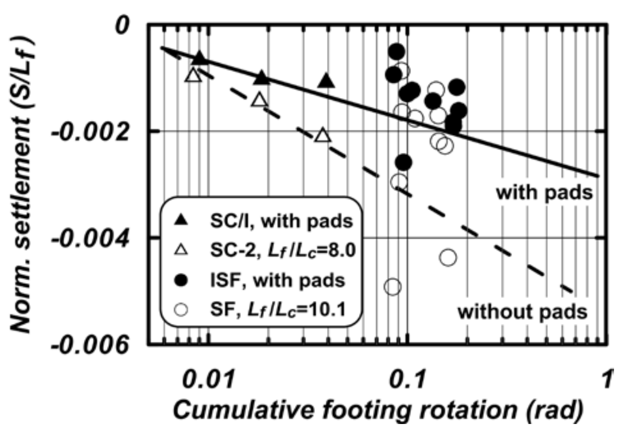


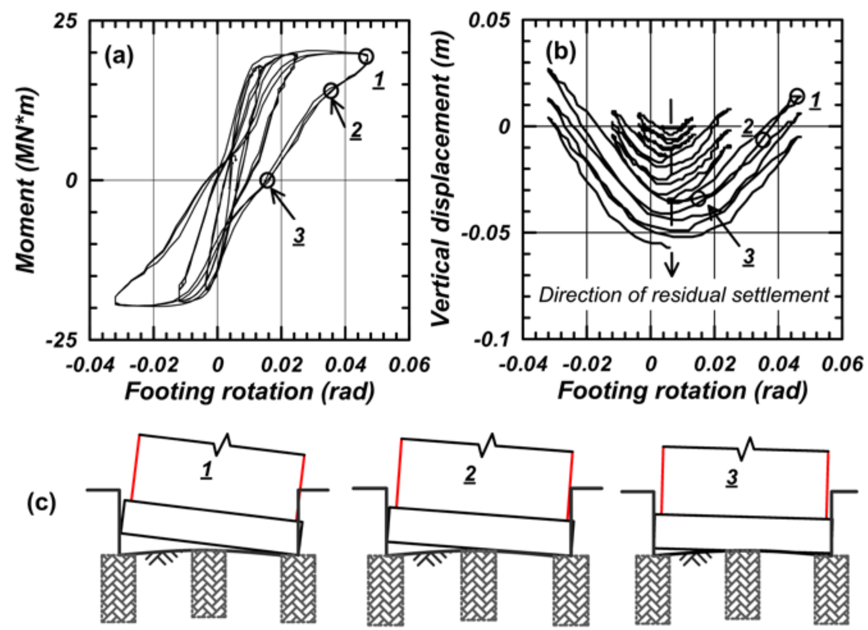
Conclusions

- Corrected misconceptions about analysis and stability of rocking and hinging systems
  - No need to analyze rocking systems as if they are fundamentally different from hinging systems
  - IDA and fragility curves show rocking systems are superior to conventional hinging systems. (Deng et al. 2011, Spectra)
- Energy dissipation and recentering are important
- Ground improvement can be used to allow rocking in poor soils (piles or concrete pads)
- Design implementation
  - ASCE 41 – component action tables for rocking foundations
  - DDBD (Direct Displacement-Based Design)

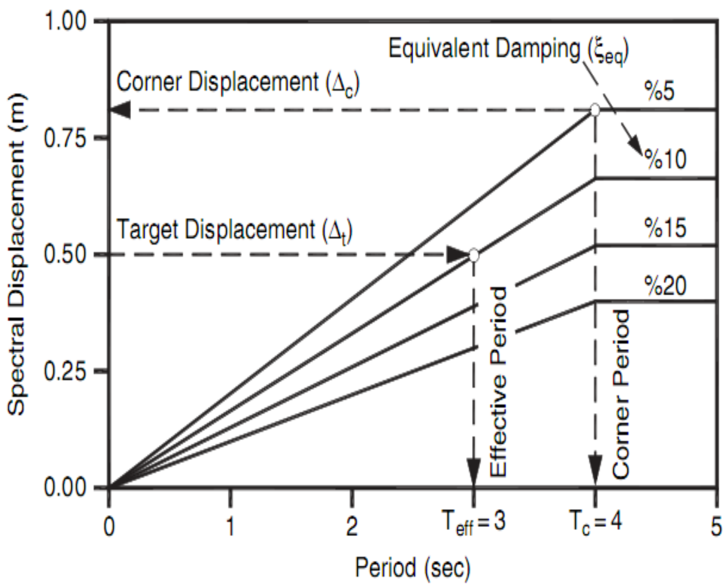

Q
V
Column
H
B_f
Open gap
L_f
L_c
Critical contact area, A_c


(a)
(b)
(c)
Model: SC/I
Rigid shear wall
Concrete pads
6.70
Model: ISF or SF
Concrete pads for ISF
7.35
12.12
Footing outline
Concrete pad


Norm. settlement (S/L_f)
Cumulative footing rotation (rad)
0
-0.002
-0.004
-0.006
0.01
0.1
1
with pads
without pads
SC/I, with pads
SC-2, L_f/L_c=8.0
ISF, with pads
SF, L_f/L_c=10.1


(a)
Moment (MN*m)
25
0
-25
Footing rotation (rad)
-0.04 -0.02 0 0.02 0.04 0.06
1
2
3
(b)
Vertical displacement (m)
0.05
0
-0.05
-0.1
Direction of residual settlement
Footing rotation (rad)
-0.04 -0.02 0 0.02 0.04 0.06
(c)
1
2
3

Direct Displacement Based Design



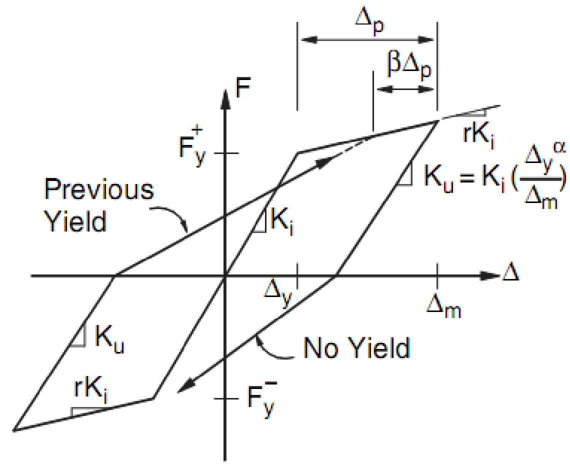


Figure 4. The hysteresis of Takeda Fat model