Seismic Performance Evaluation of Bridges with Foundations Designed to Uplift

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Acknowledgments

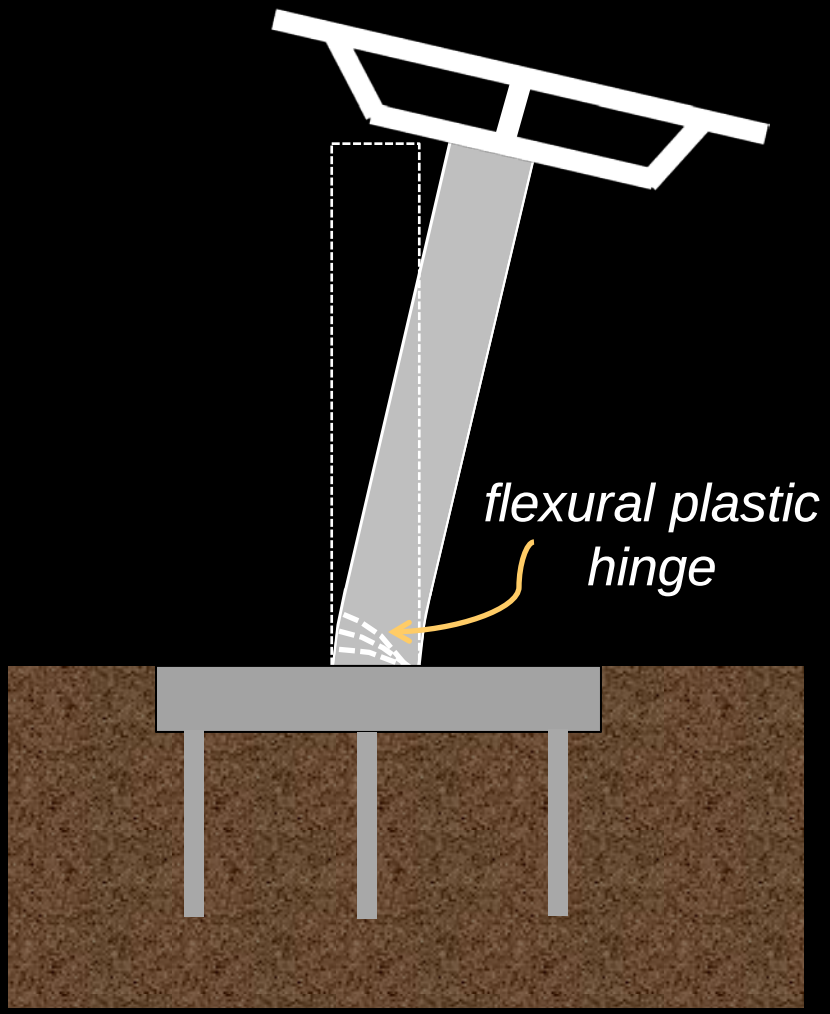
Pacific Earthquake Engineering Research (PEER) Center for funding this work through the Transportation Research Program

2 Questions

1. Can foundation rocking be considered as an alternative seismic design method of bridges resulting in reduced: i) post-earthquake damage, ii) required repairs, and iii) loss of function ?

2. Probabilistic seismic performance evaluation ?

Fixed-Base Design



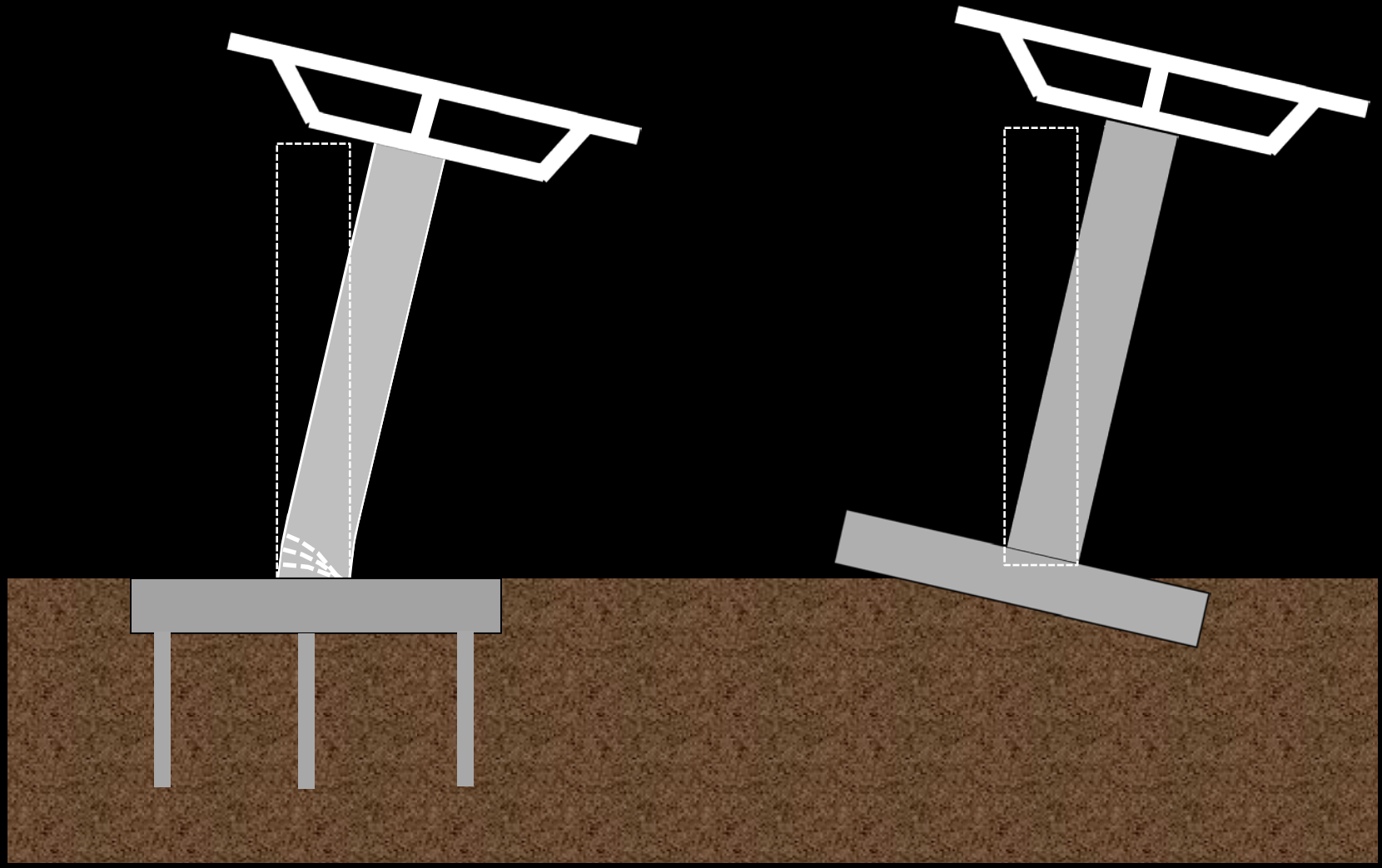
*Susceptible to significant post-earthquake **damage** and permanent lateral deformations that:*

- *Impair traffic flow*
- *Necessitate costly and time consuming repairs*

Design Using Rocking Shallow Foundations

“Fixed” base pier

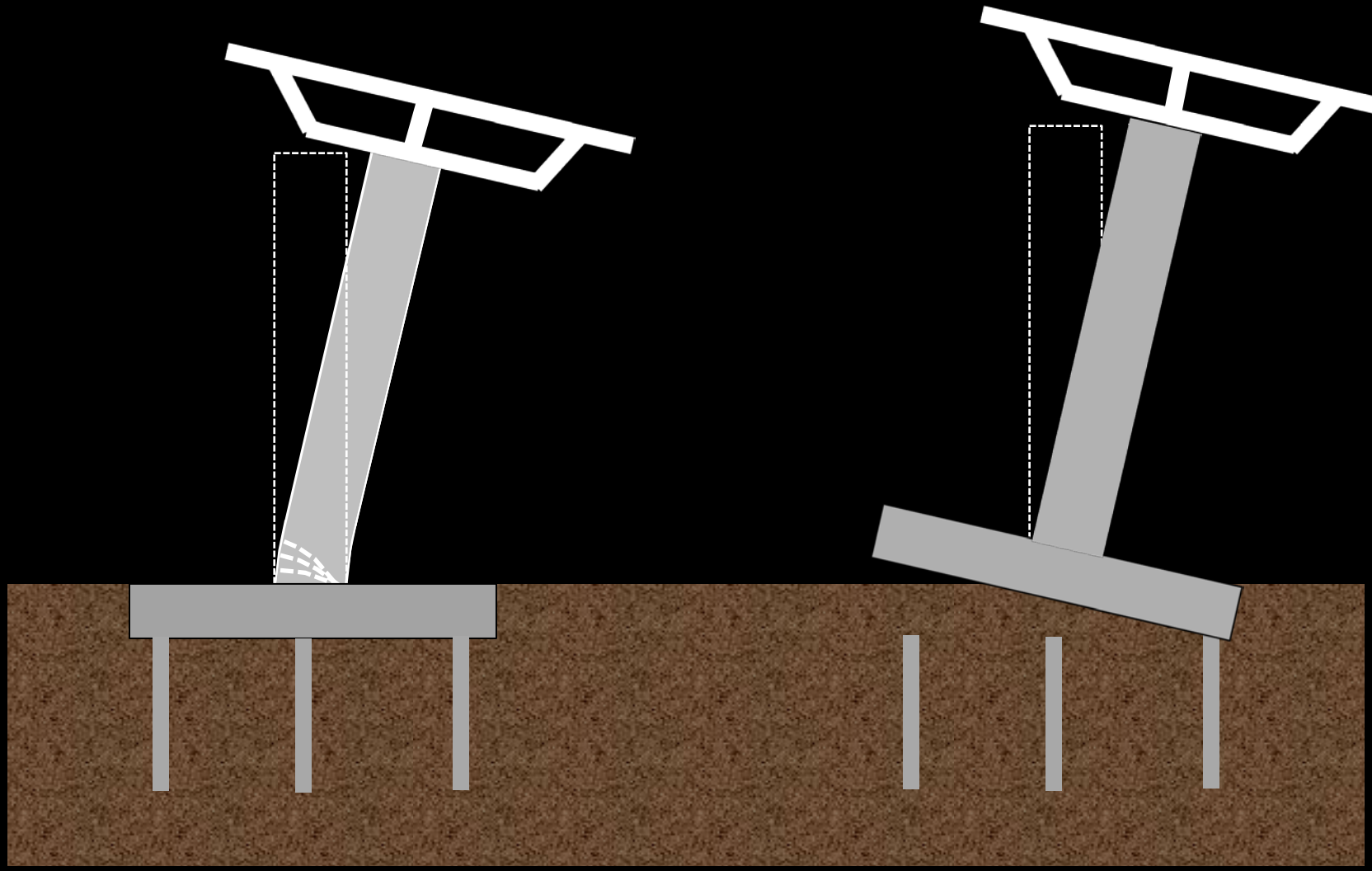
*Pier on **rocking** shallow foundation*



Design Using Rocking Pile Foundations

Fixed-base pier

Pier on rocking pile foundation



Numerical Case Studies

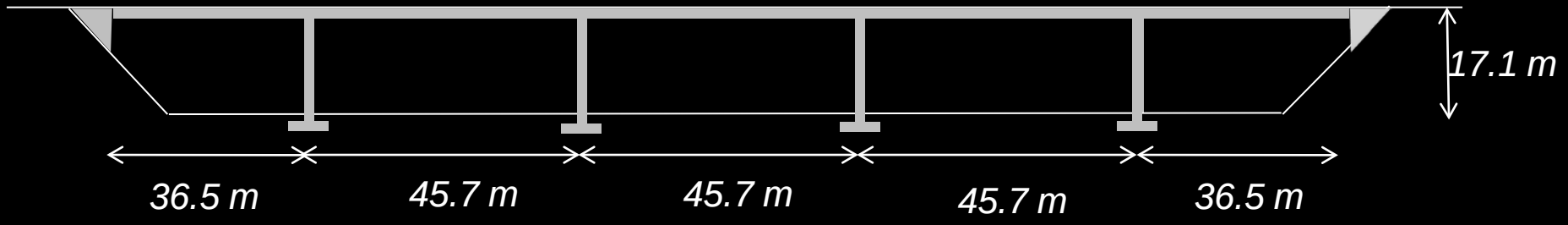
Two archetype bridges are designed with:

i) fixed base piers

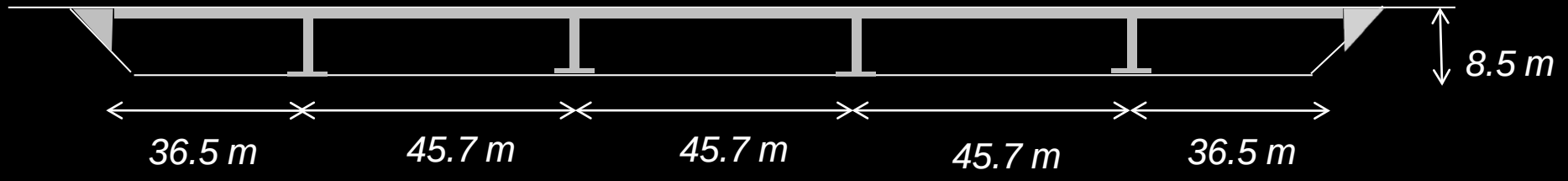
ii) rocking foundations

- *Cast in place box girder*
- *Single column bents*

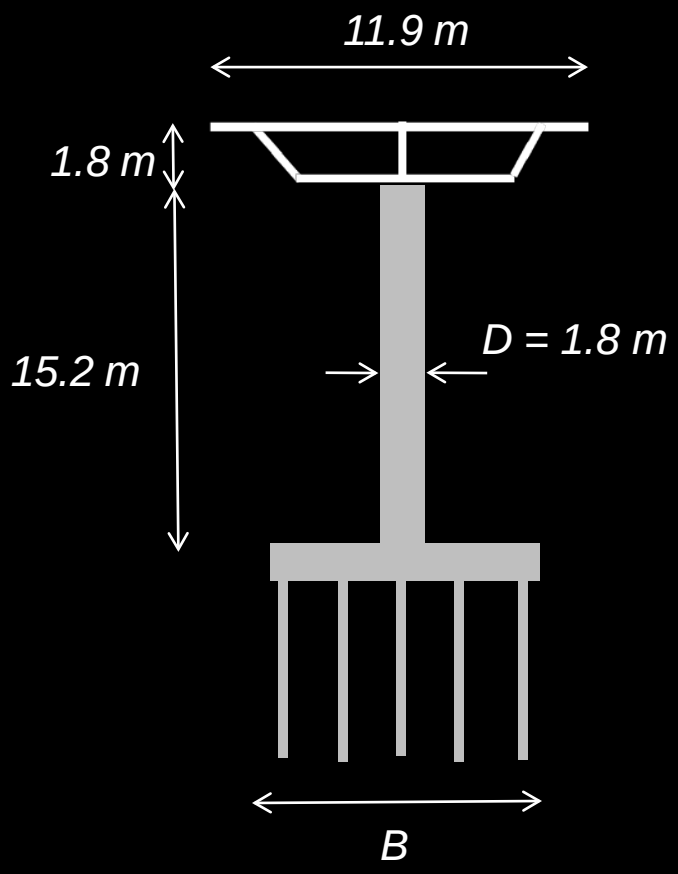
Archetype 1 - Tall Overpass

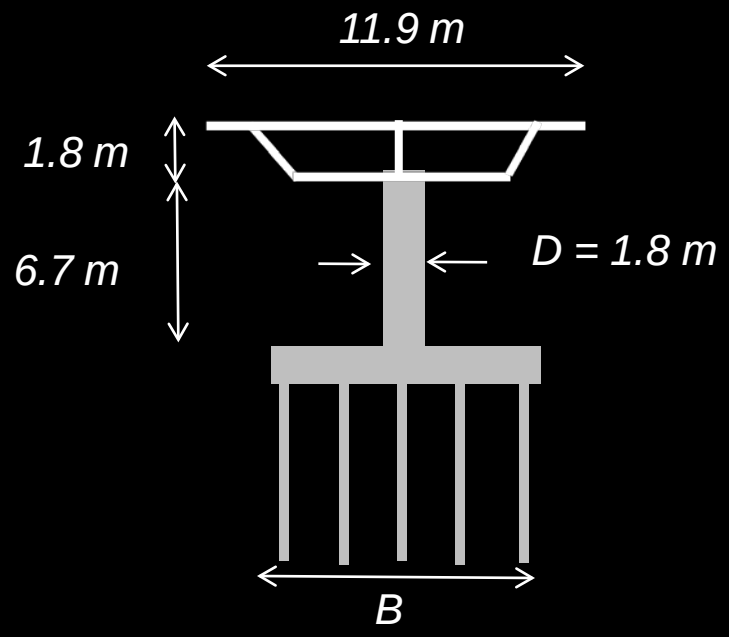


Archetype 2 – Short Overpass



Fixed-Base Designs

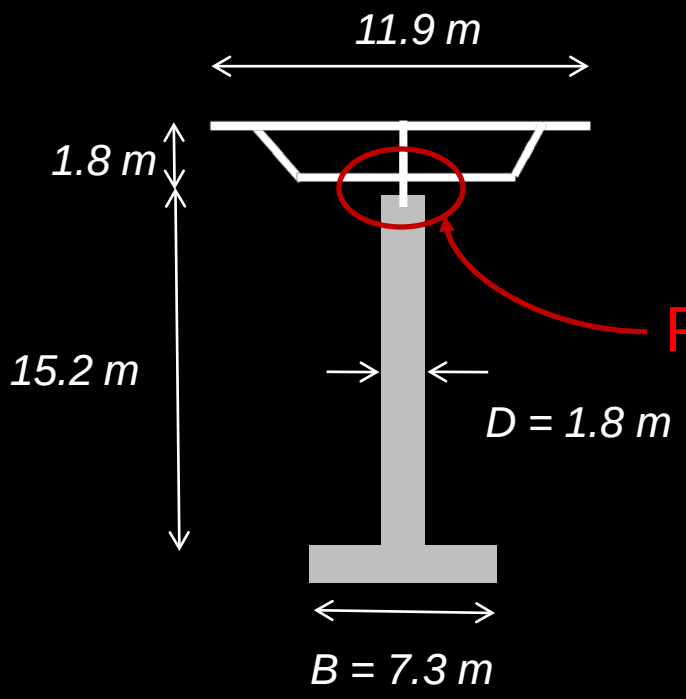




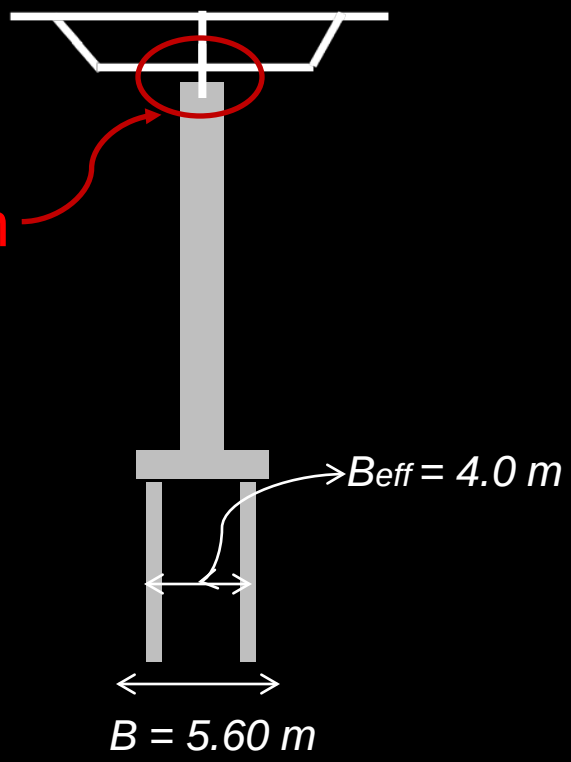
- Column axial load ratio $N / f_c' A_g = 0.1$
- Longitudinal steel ratio $\rho_l = 2\%$

Designs Using Rocking Foundations

Rocking on Soil



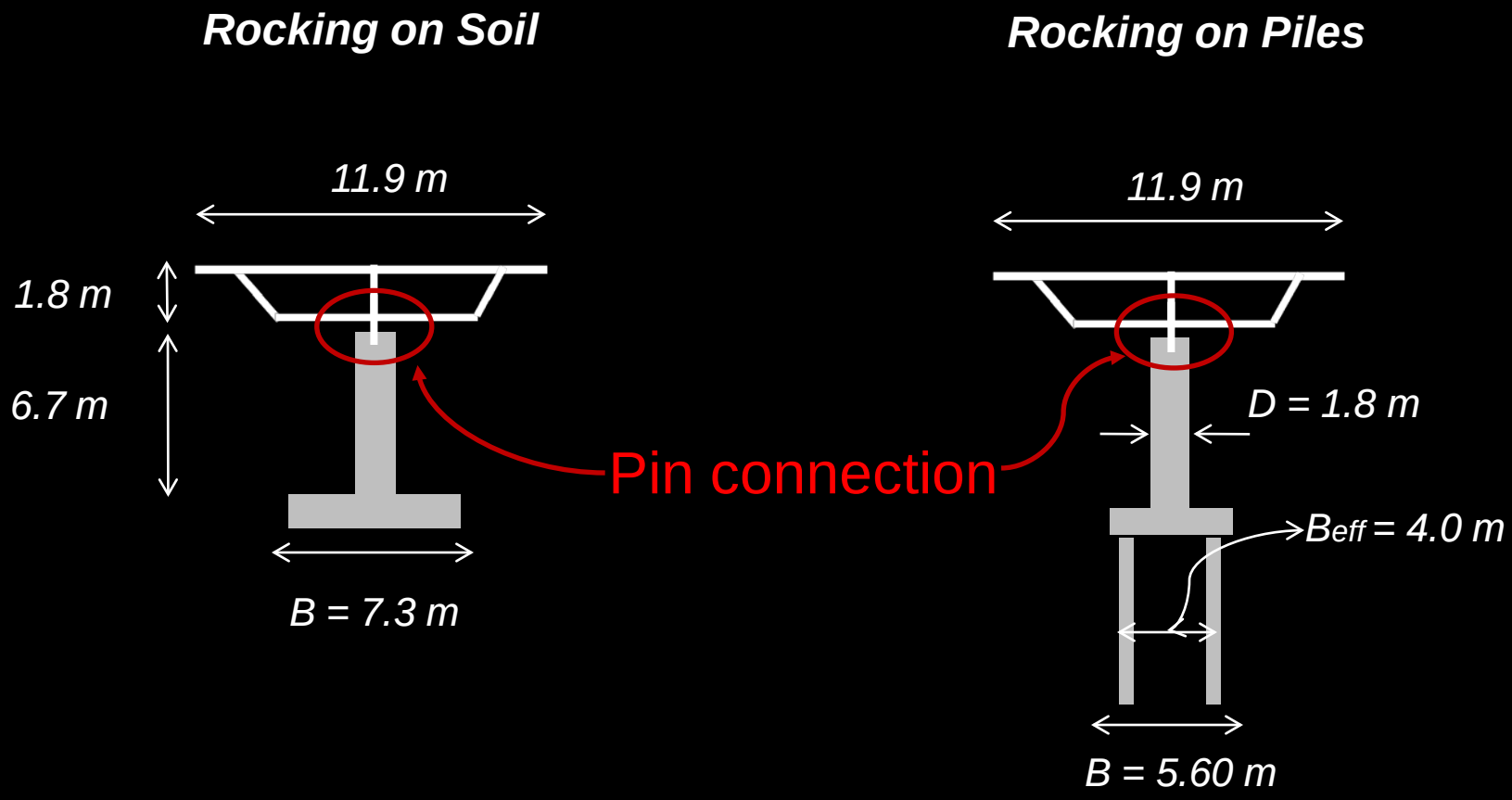
Rocking on Piles



- Soil Ultimate stress σ_u = 0.6 MPa
- $FS_v = A\sigma_u / N = 5.4$

Longitudinal steel ratio ρ_l = 3%

Designs Using Rocking Foundations

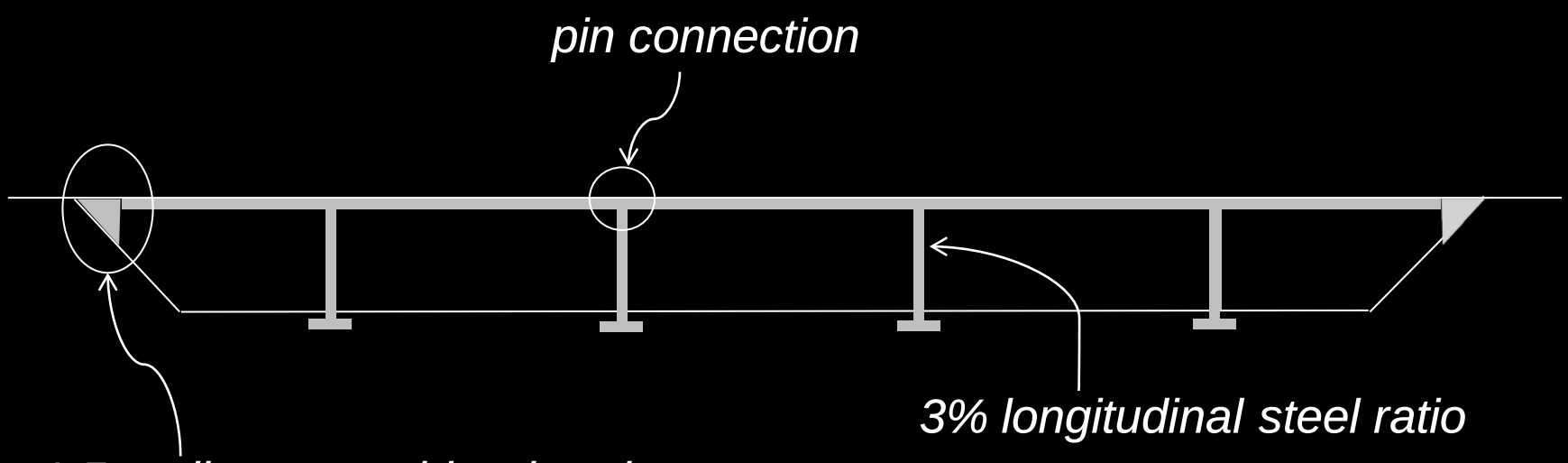


- Soil Ultimate stress σ_u = 0.6 MPa
- $FS_v = A\sigma_u / N = 5.4$

Longitudinal steel ratio ρ_l = 3%

Bridge with Rocking Foundations

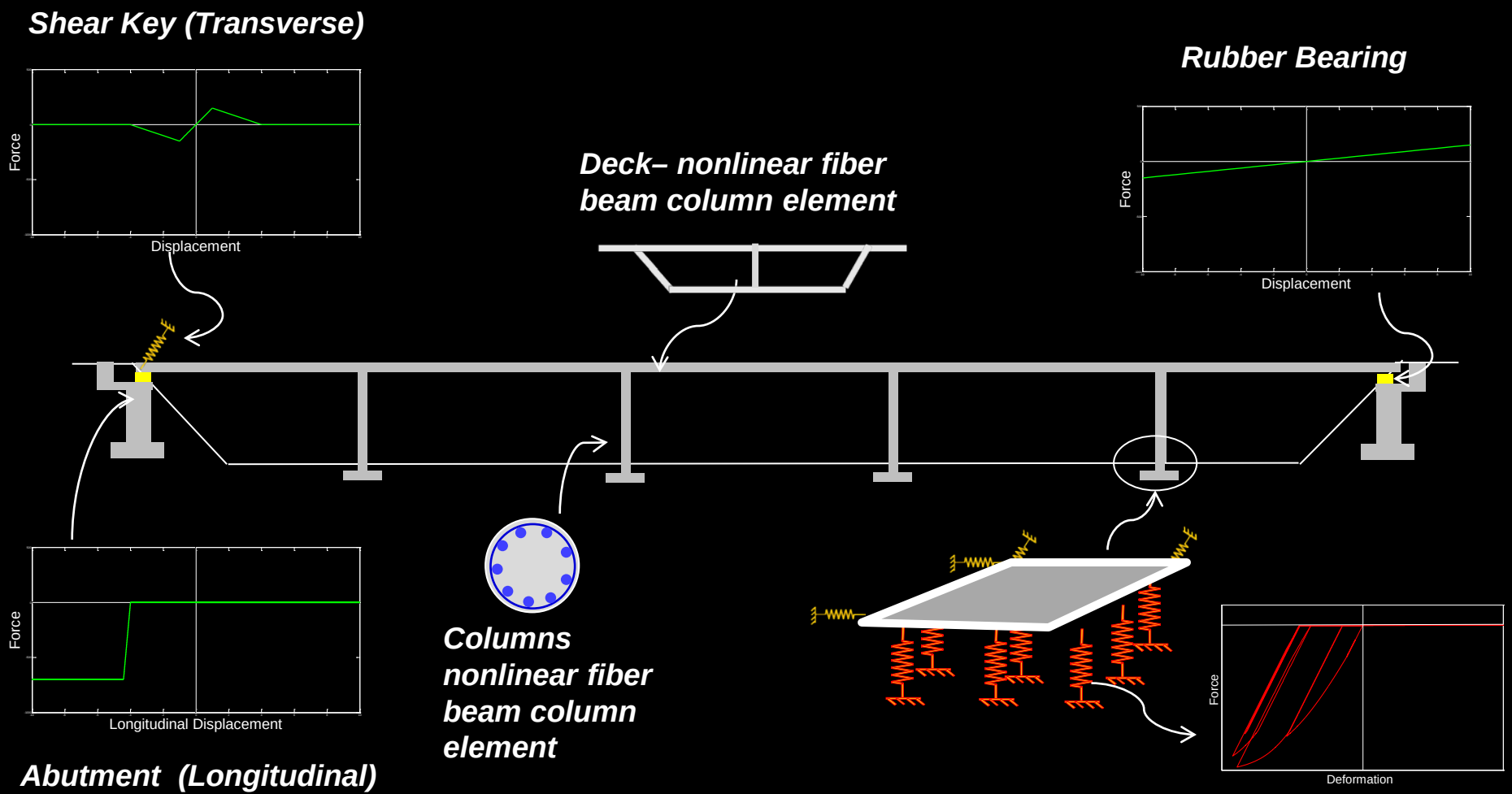
Design Modifications (in comparison with fixed-base)



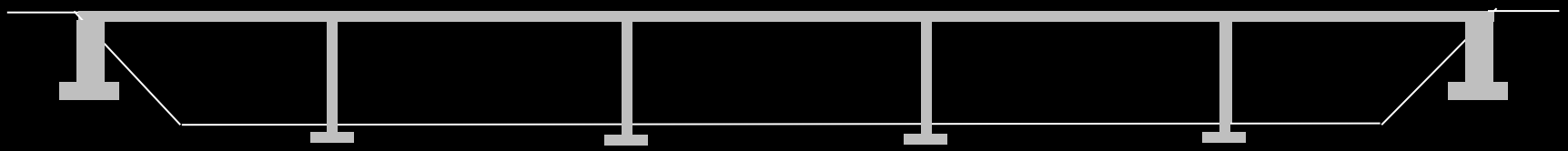
- *1.5 m diameter rubber bearings*
(0.20 m in fixed-base bridge)

- *60 cm gap in joint seal assembly*
(10 cm in fixed-base bridge)

3-D Modeling of Bridges in OPENSEES

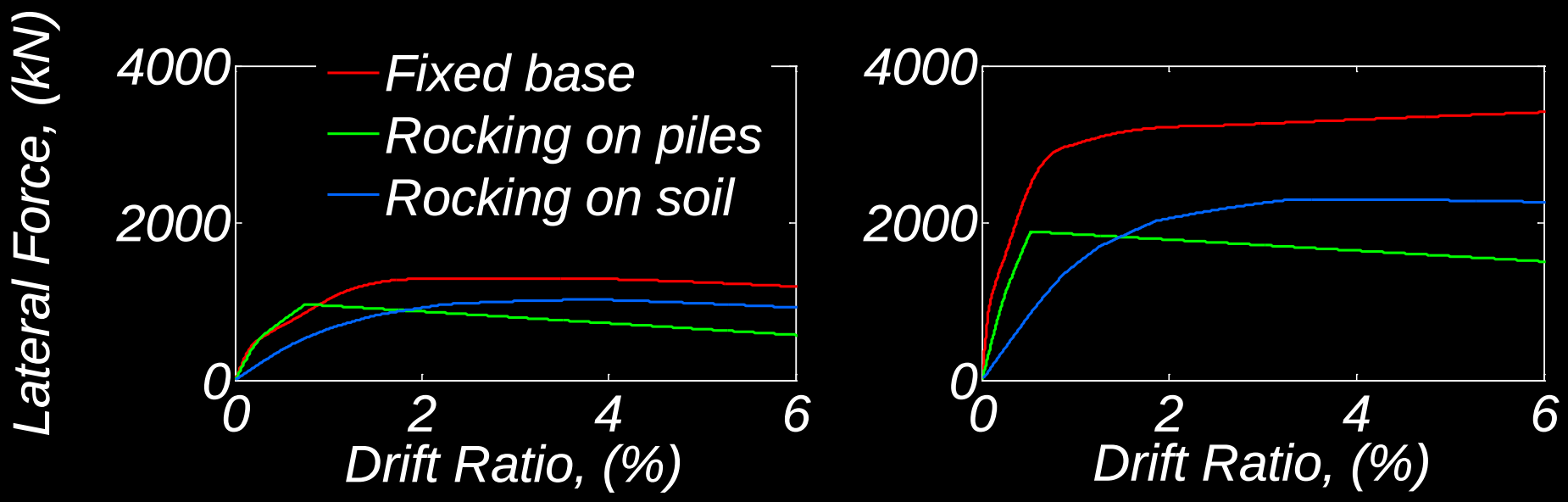


Bridge Models – Mode Periods

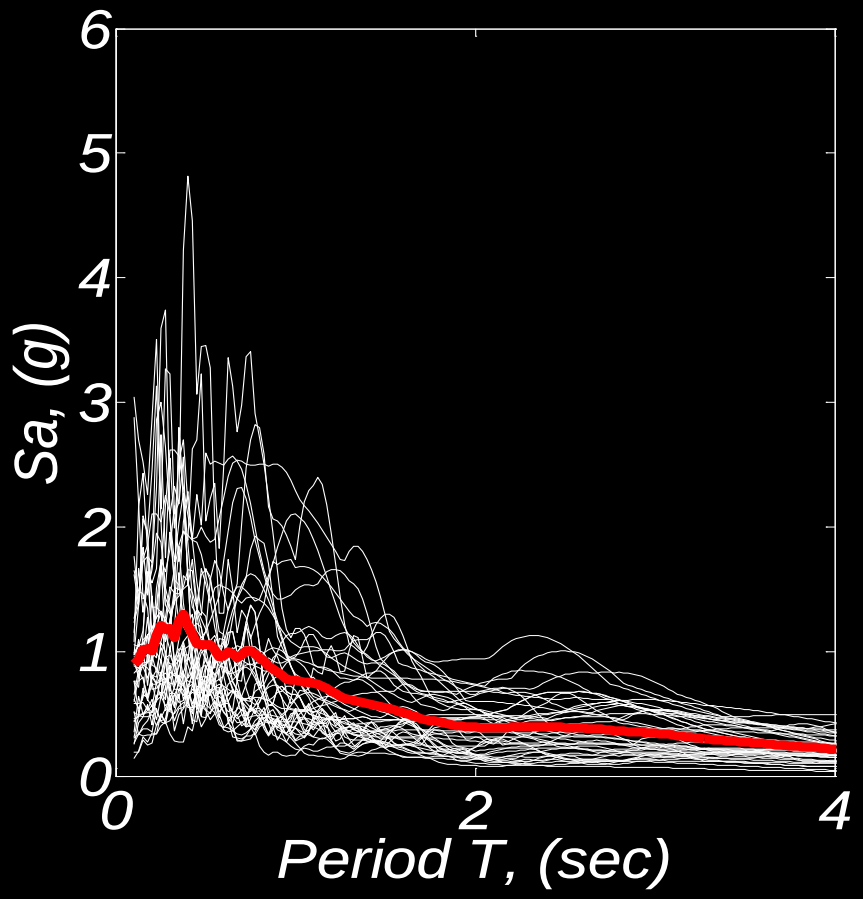


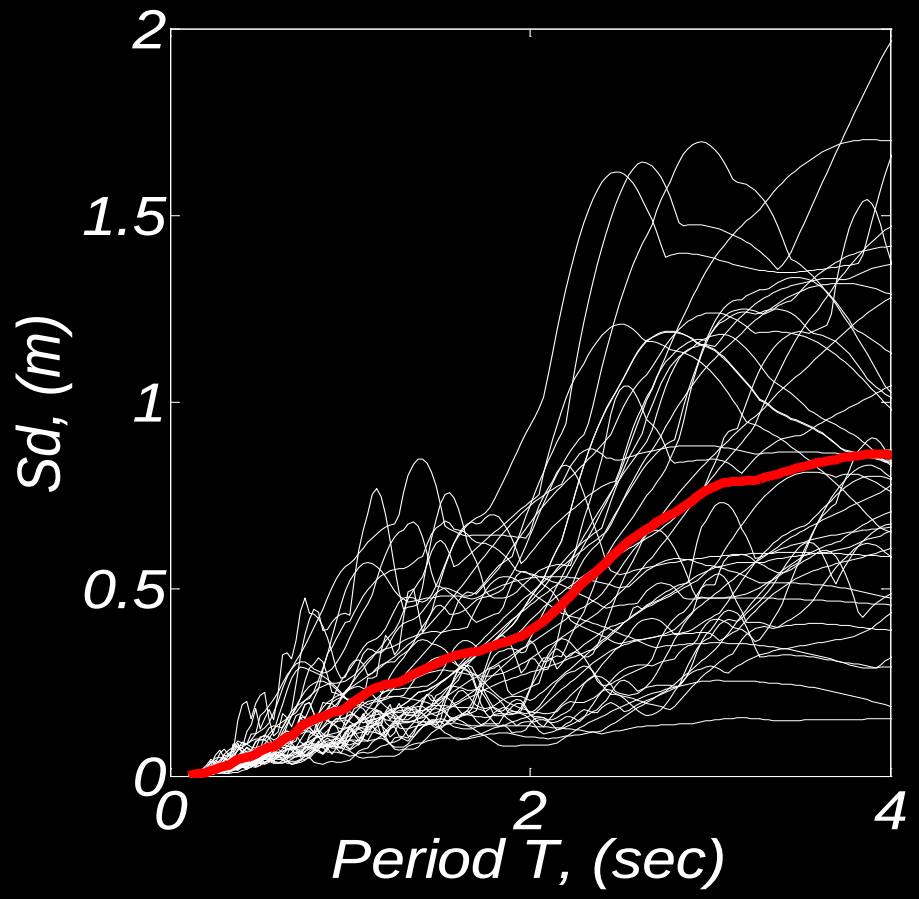
	Fixed Base	Rocking on Piles	Rocking on Soil
TALL			
1st mode, T_1 (sec)	1.2	2.2	2.4
2nd mode, T_2 (sec)	0.9	1.9	2.0
SHORT			
1st mode, T_1 (sec)	0.7	2.2	2.2
2nd mode, T_2 (sec)	0.7	1.8	1.9

Monotonic Behavior – Individual Pier



Ground Motions – Response Spectra 2% Damping



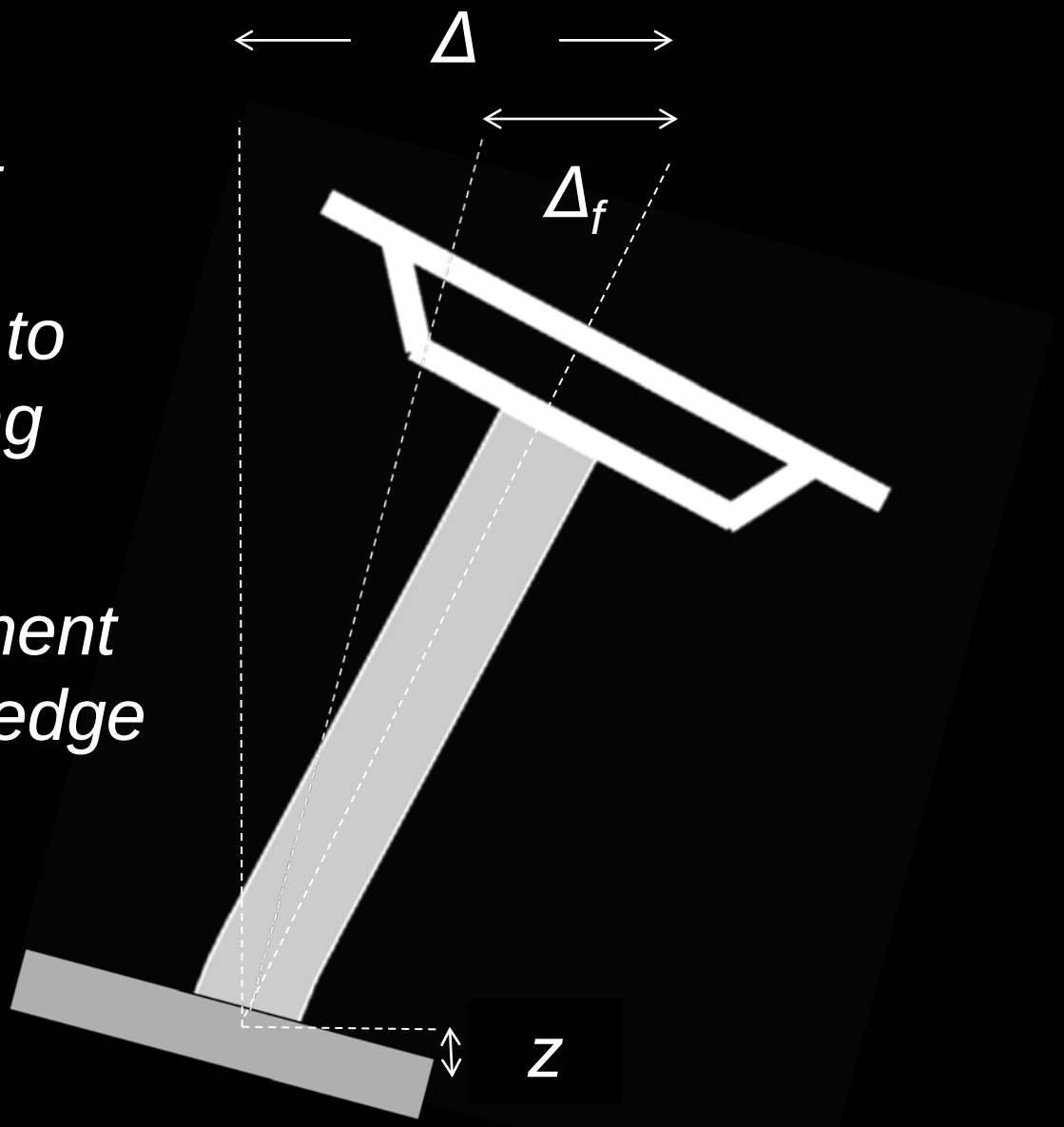


Computed Response of Bridge Column

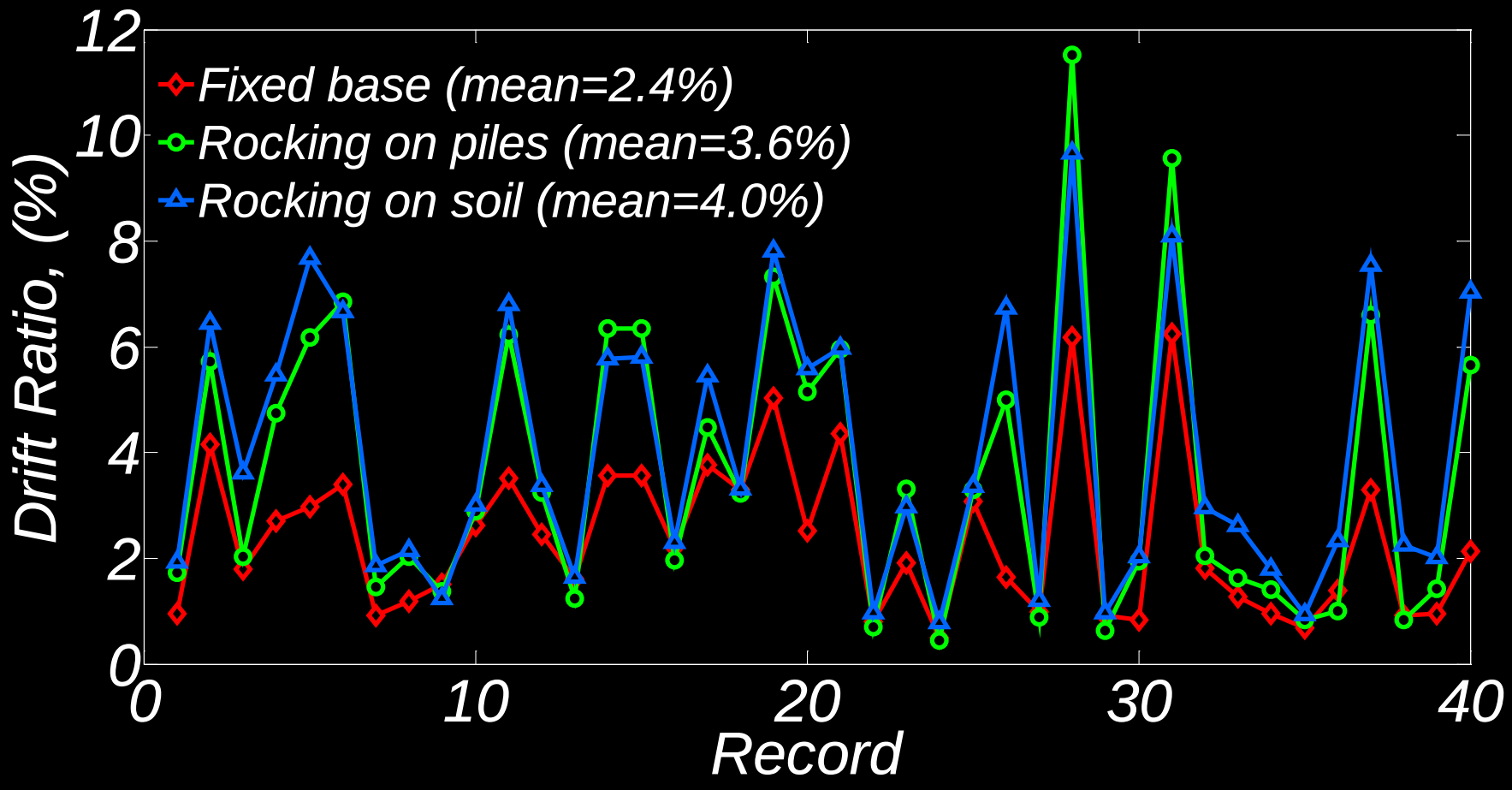
Δ: total drift

Δ_f: drift due to pier bending

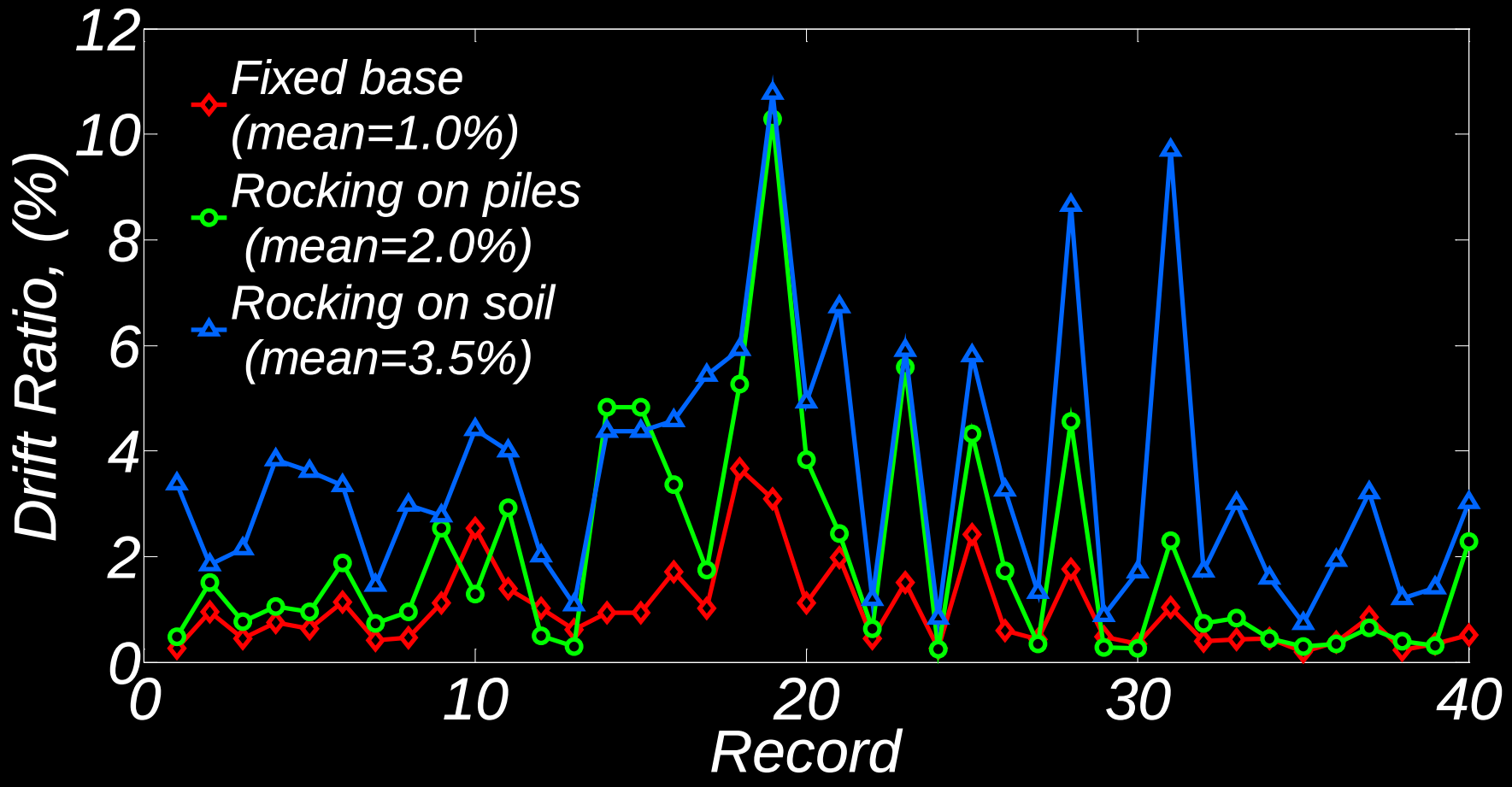
z: soil settlement at foundation edge



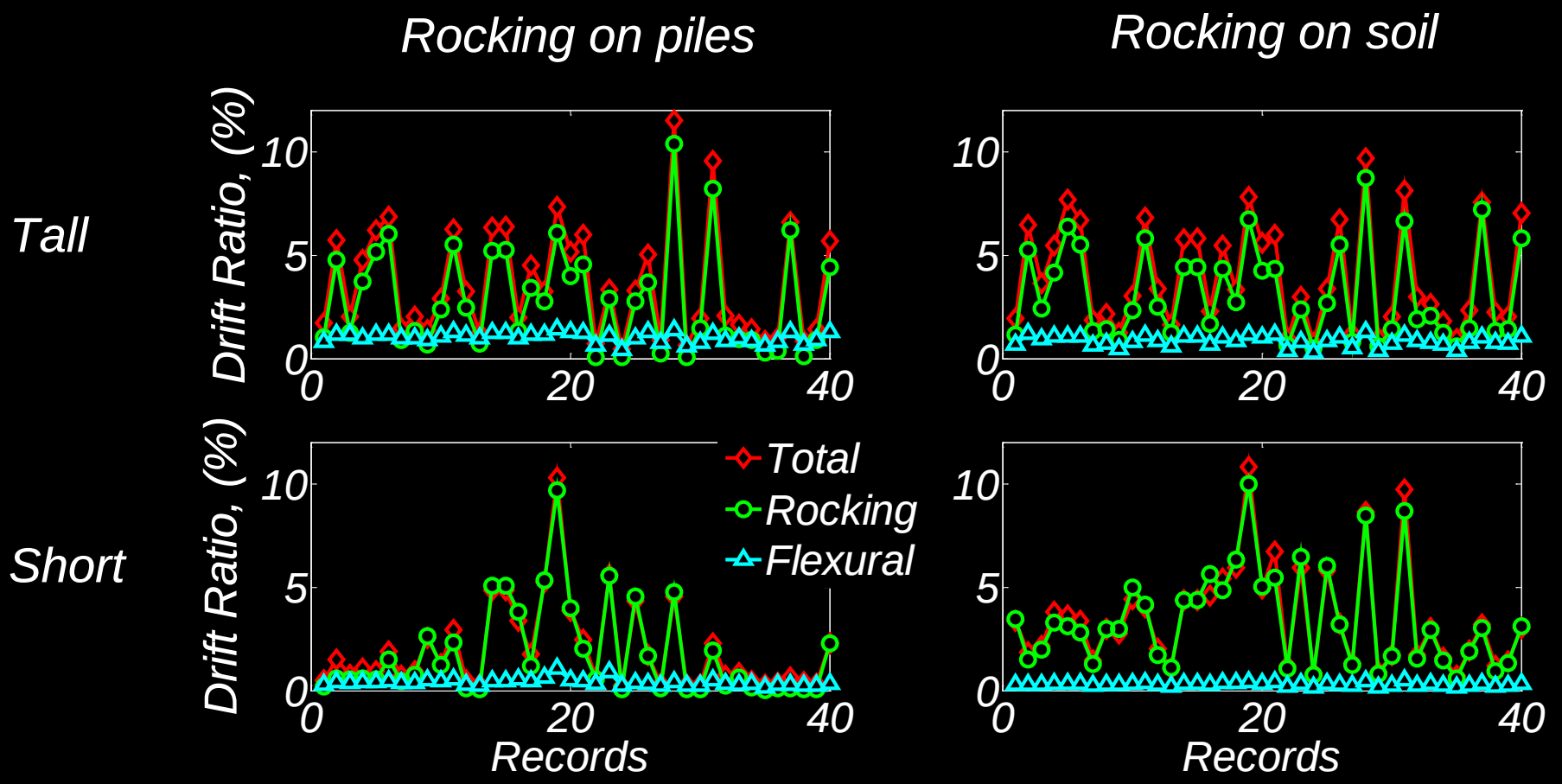
Tall Bridge Response - Total drift ratio



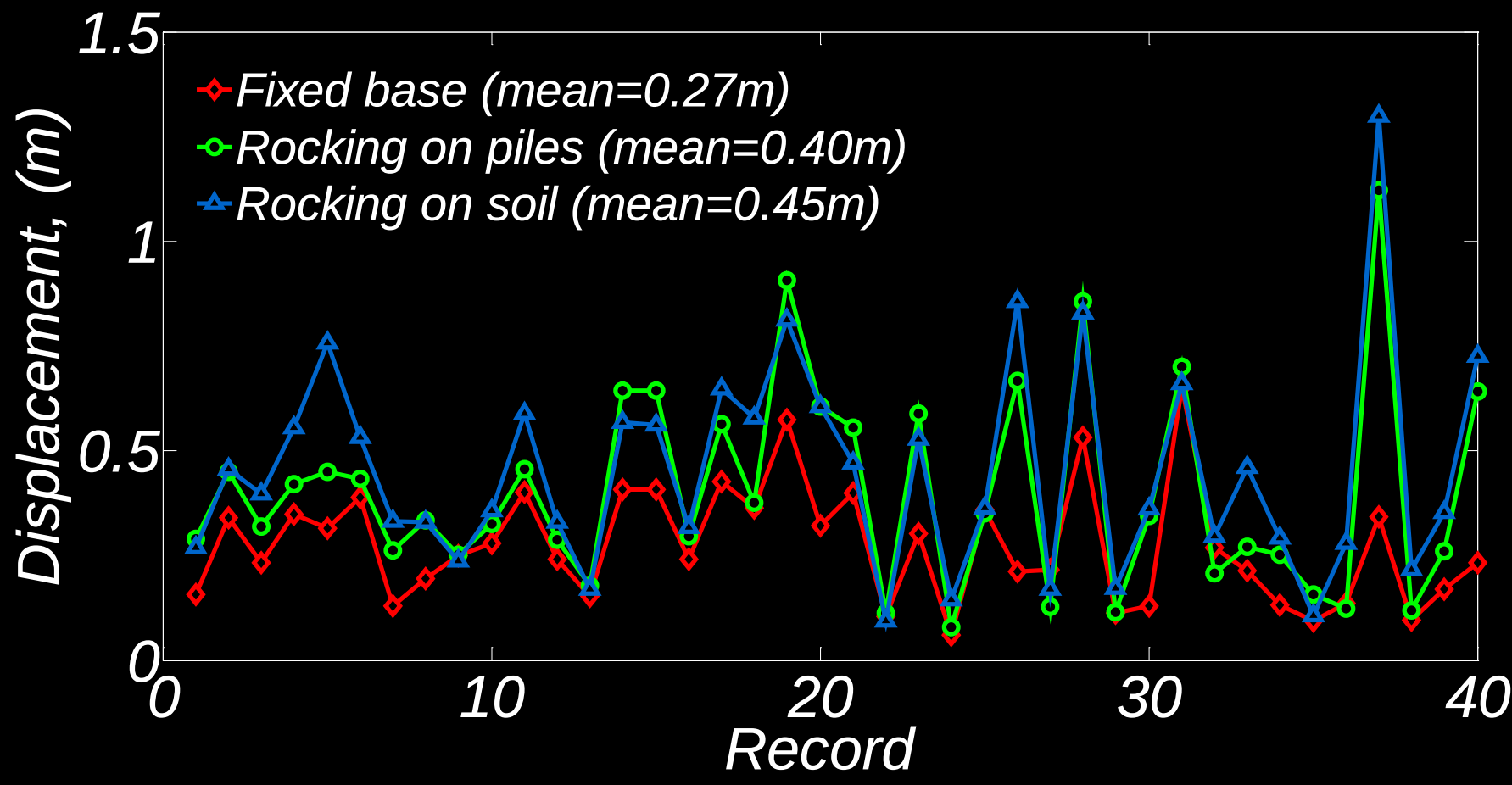
Short Bridge Response - Total drift ratio



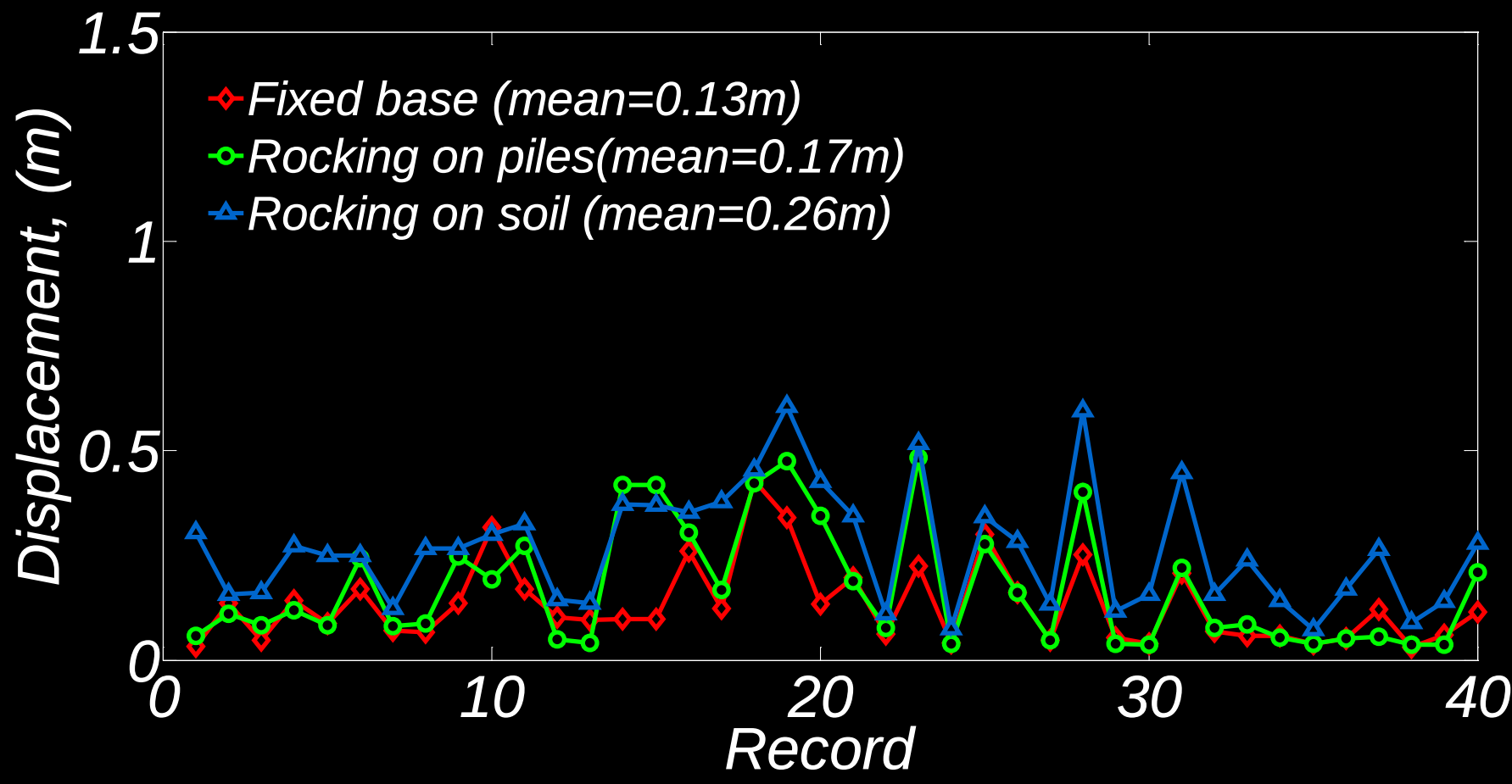
Bridge Response - drift ratio disaggregation



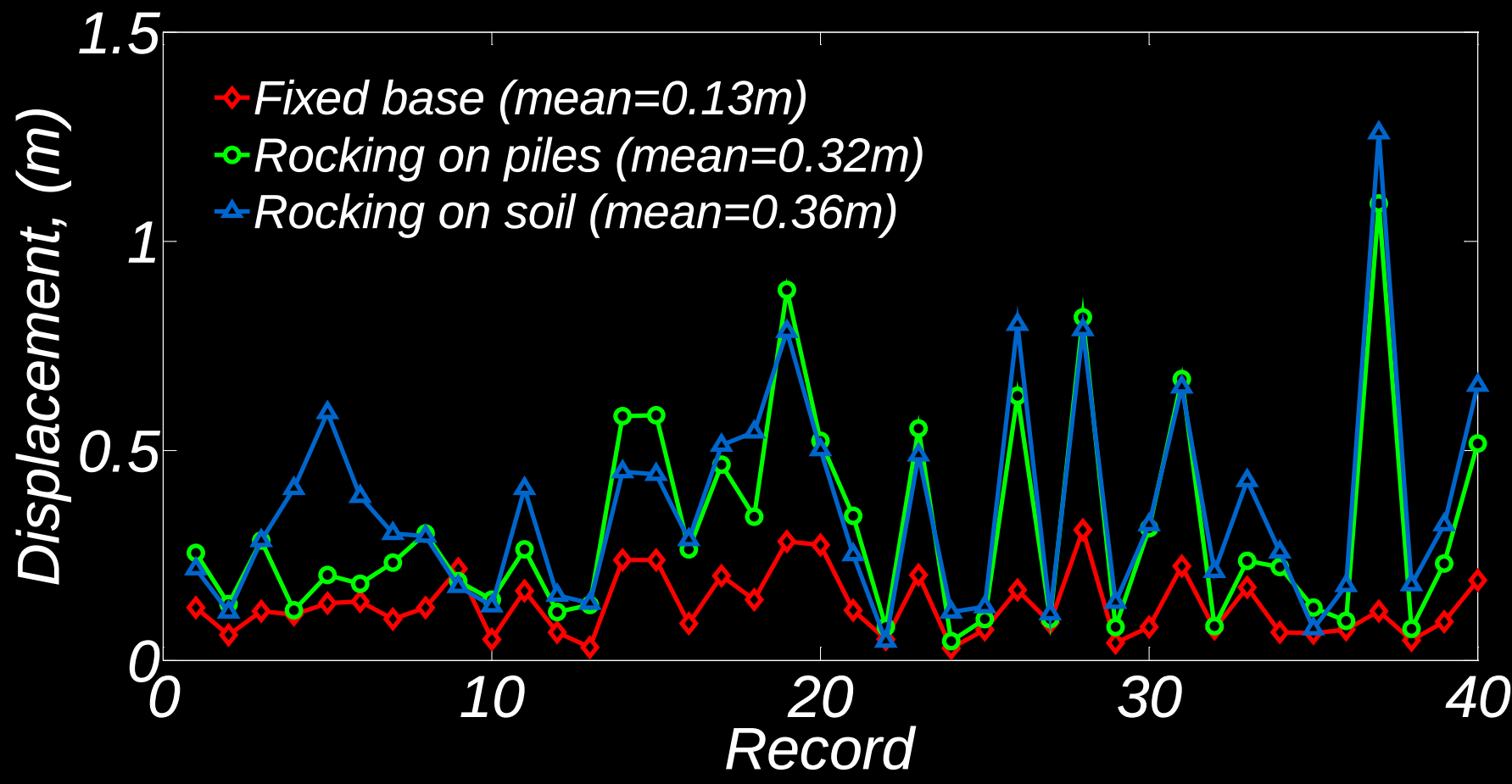
Tall Bridge Response – Bearings



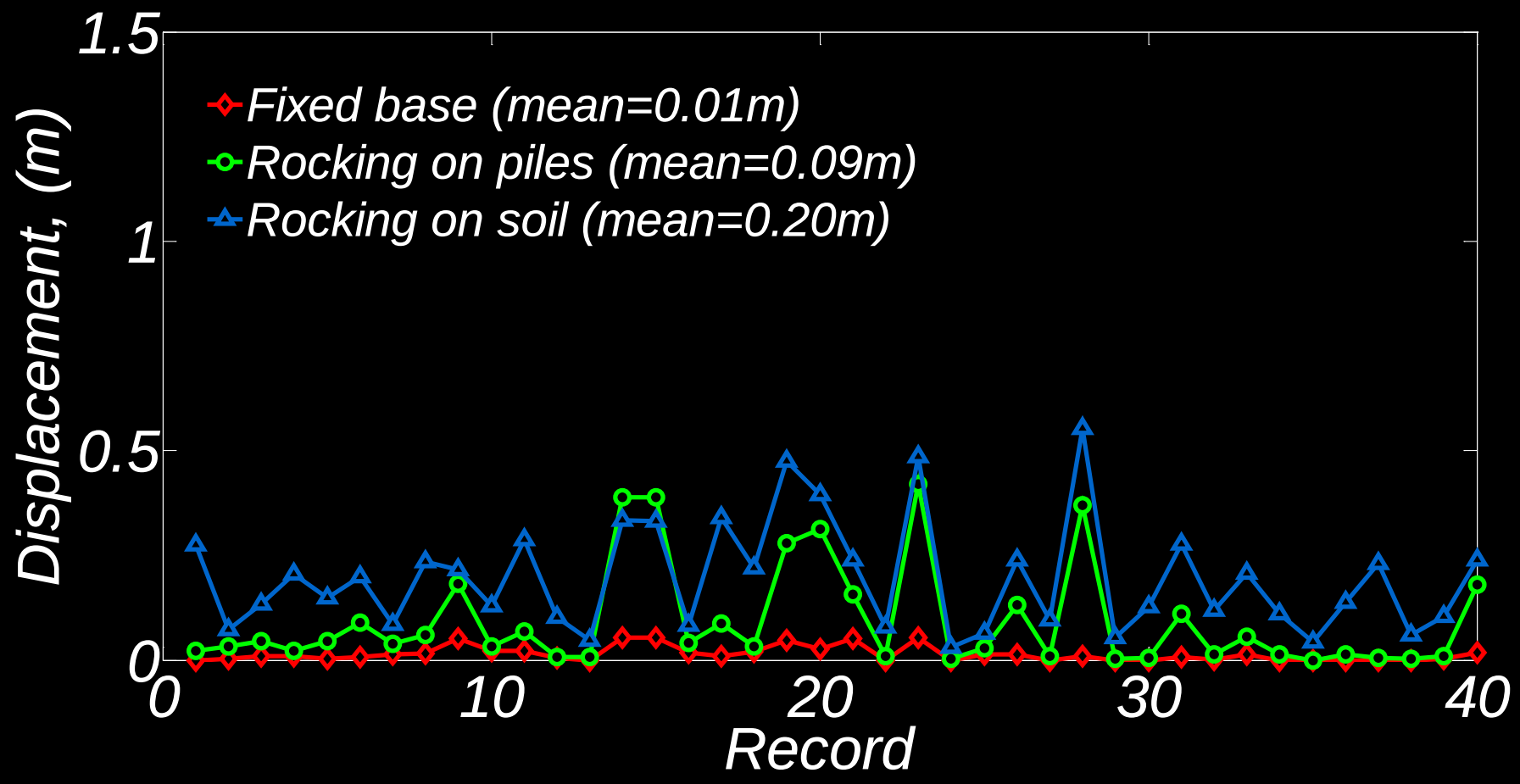
Short Bridge Response – Bearings



Tall Bridge Response
Longitudinal Displacement



Short Bridge Response
Longitudinal Displacement



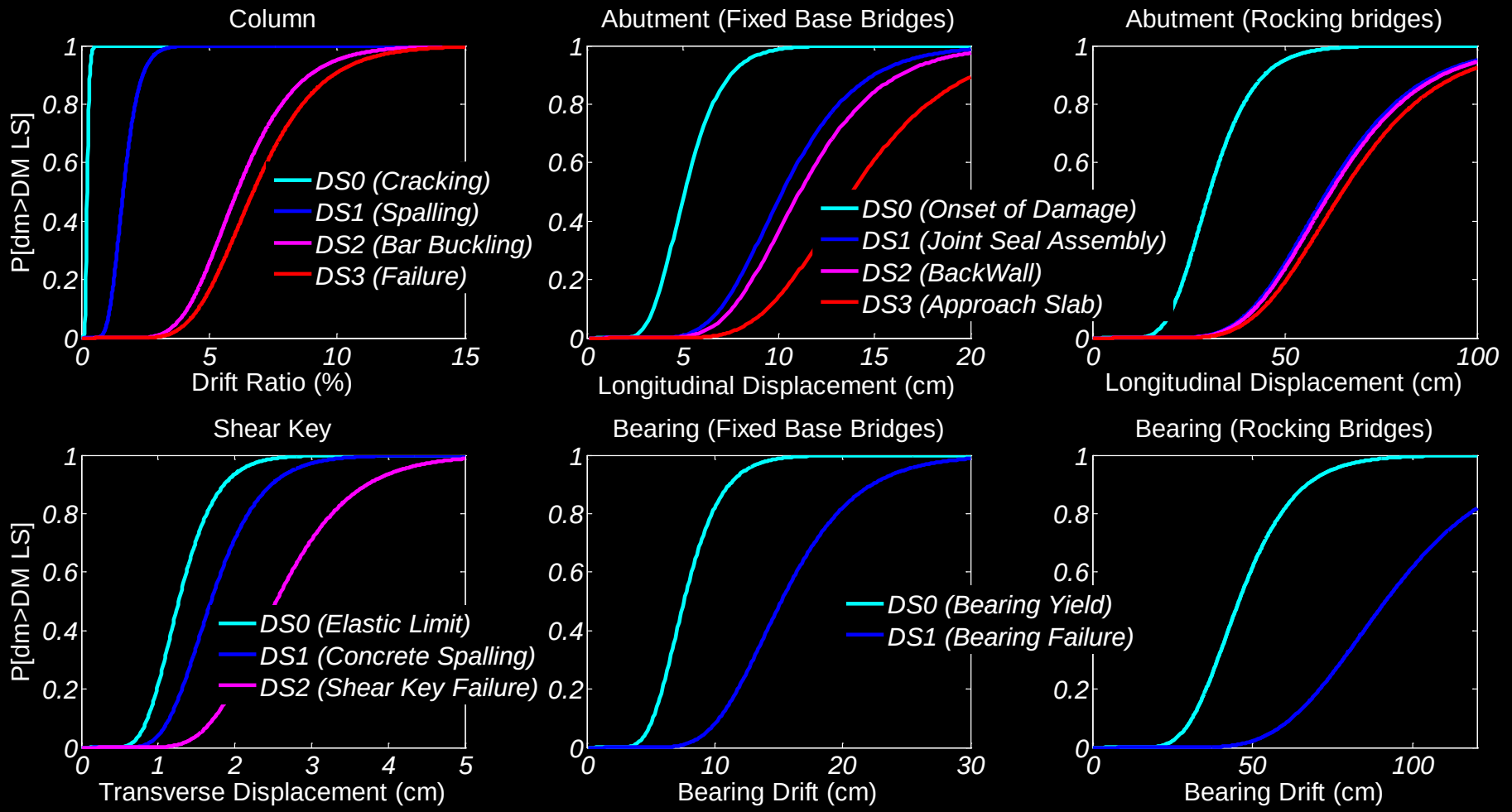
Probabilistic Performance Based Earthquake Evaluation (PBEE)

The PEER methodology and the framework of Mackie et al. (2008) was used for the PBEE comparison of the fixed base and the rocking designs.

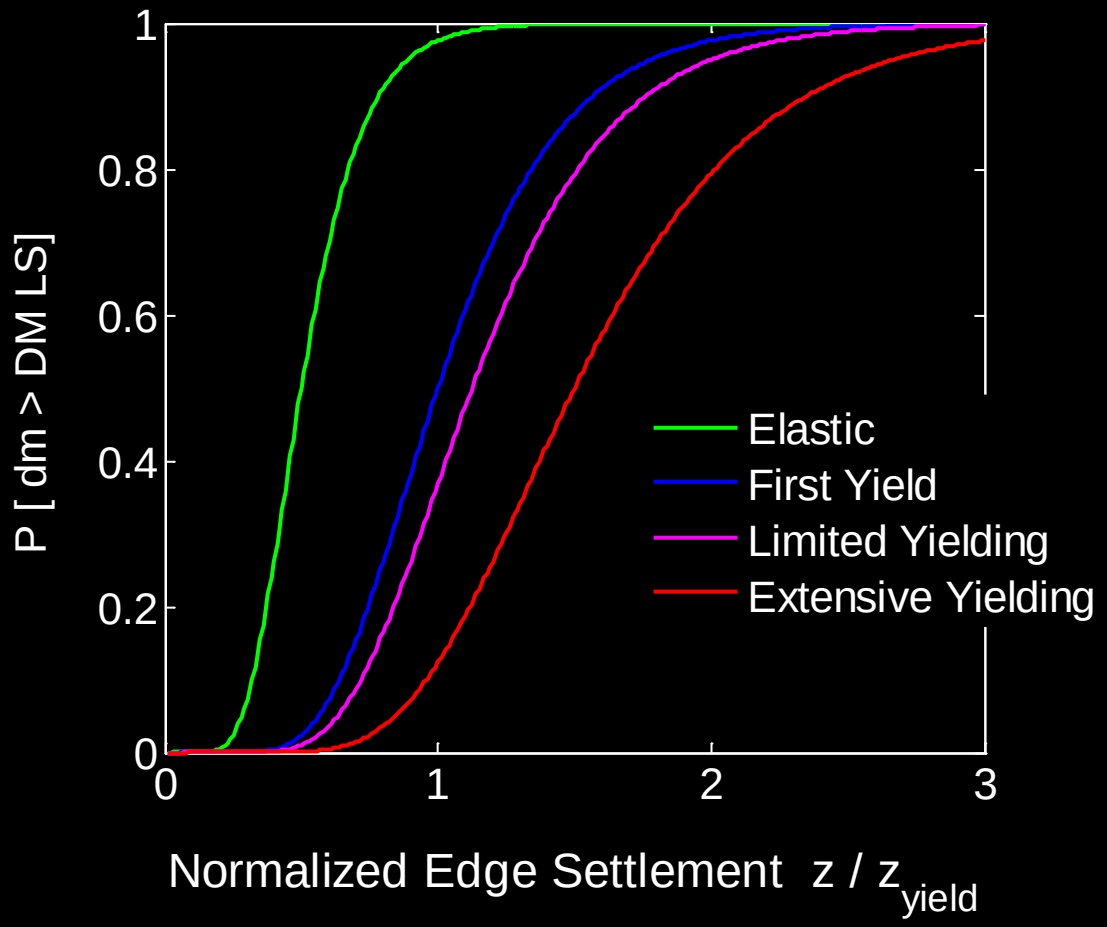
- ***Ground Motion Intensity Measures [Sa (T_1)]***
- ***Engineering Demand Parameters (e.g. Pier Drift)***
- ***Damage in Bridge Components***
- ***Repair Cost of Bridge System***

A damage model and repair cost estimation were developed for rocking on soil foundations

PBEE Evaluation – Damage Models (Mackie et al. 2008)



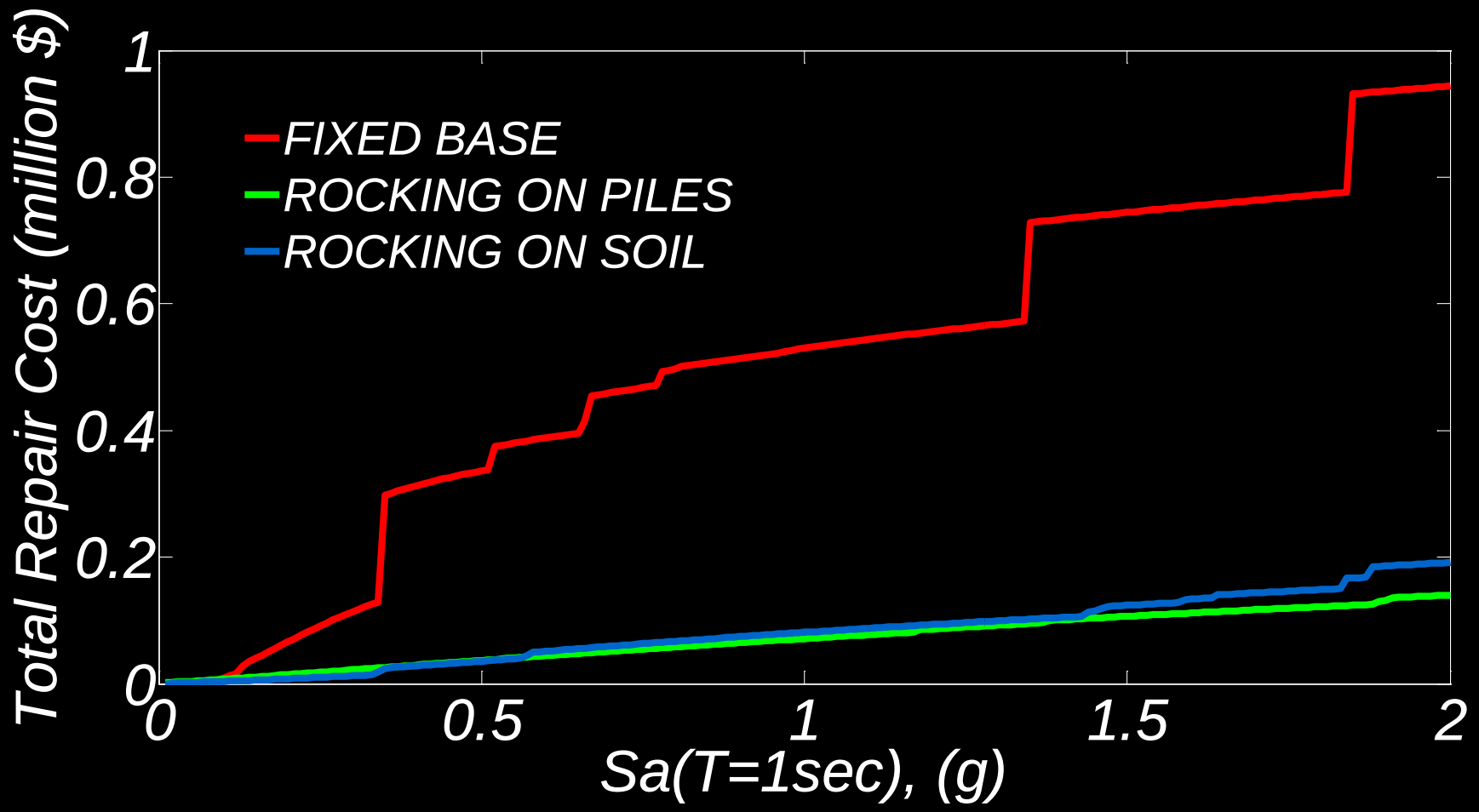
PBEE Evaluation
Foundation Damage Model



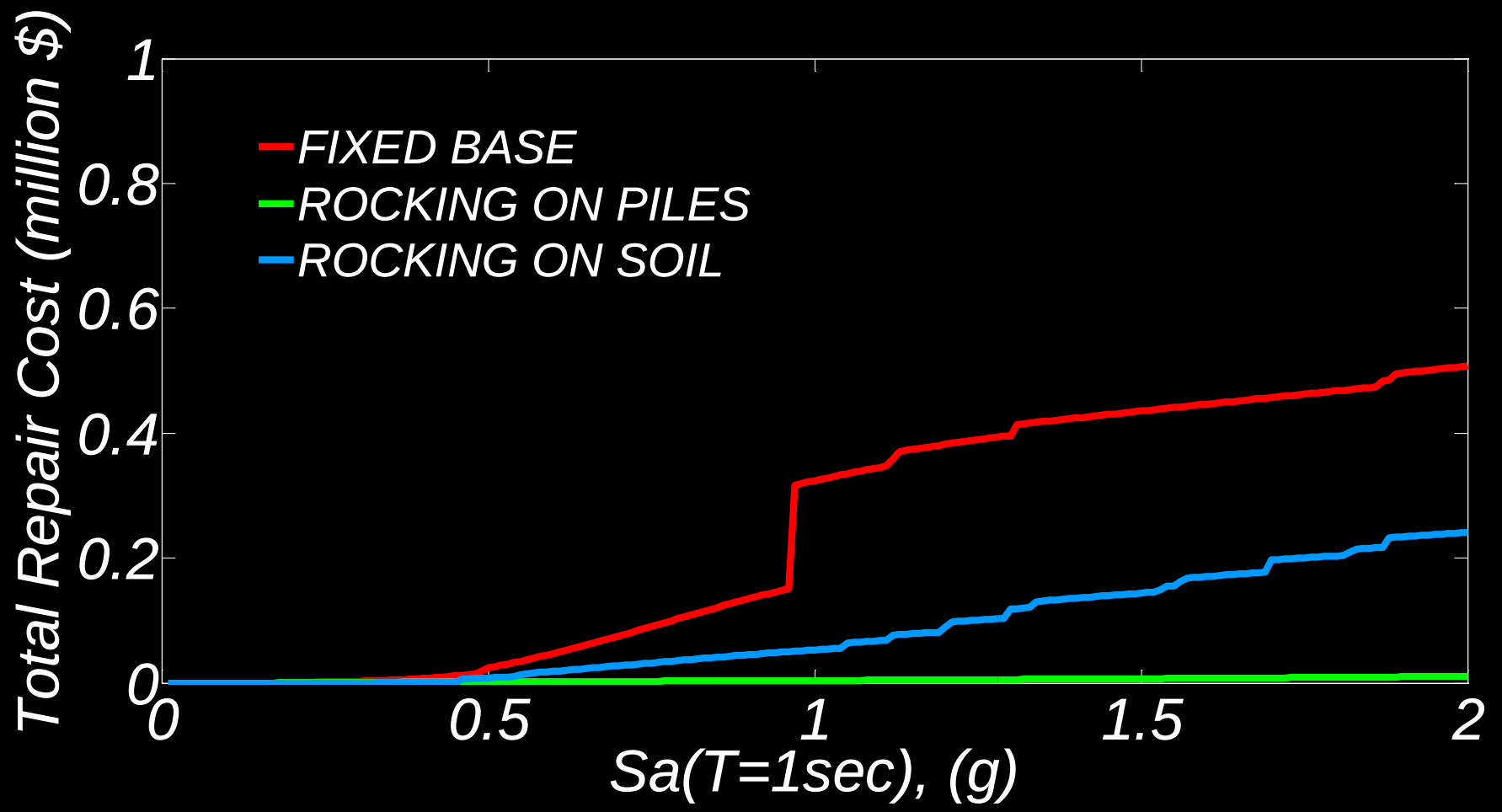
Damage States - Median Costs ($)

		FIXED BASE	ROCKING ON PILES	ROCKING ON SOIL
COLUMNS	CRACKING	0	0	0
	SPALLING	49800	49800	49800
	BAR BUCKLING	113700	113700	113700
	FAILURE	542600	542600	542600
ABUTMENT	ONSET OF DAMAGE	0	0	0
	JOINT SEAL ASSEMBLY	21200	125000	125000
	BACK WALL	34300	138100	138100
	APPROACH SLAB	181100	284900	284900
BEARINGS	YIELD	0	0	0
	FAILURE	93400	133900	133900
SHEAR KEYS	ELASTIC	0	0	0
	CONCRETE SPALLING	5200	5200	5200
	FAILURE	51200	51200	51200
FOUNDATION	ELASTIC	N/A	N/A	15500
	FIRST YIELD	N/A	N/A	29100
	LIMITED YIELDING	N/A	N/A	62900
	EXTENSIVE YIELDING	N/A	N/A	100500

PBEE Tall Bridge – Median Repair Cost

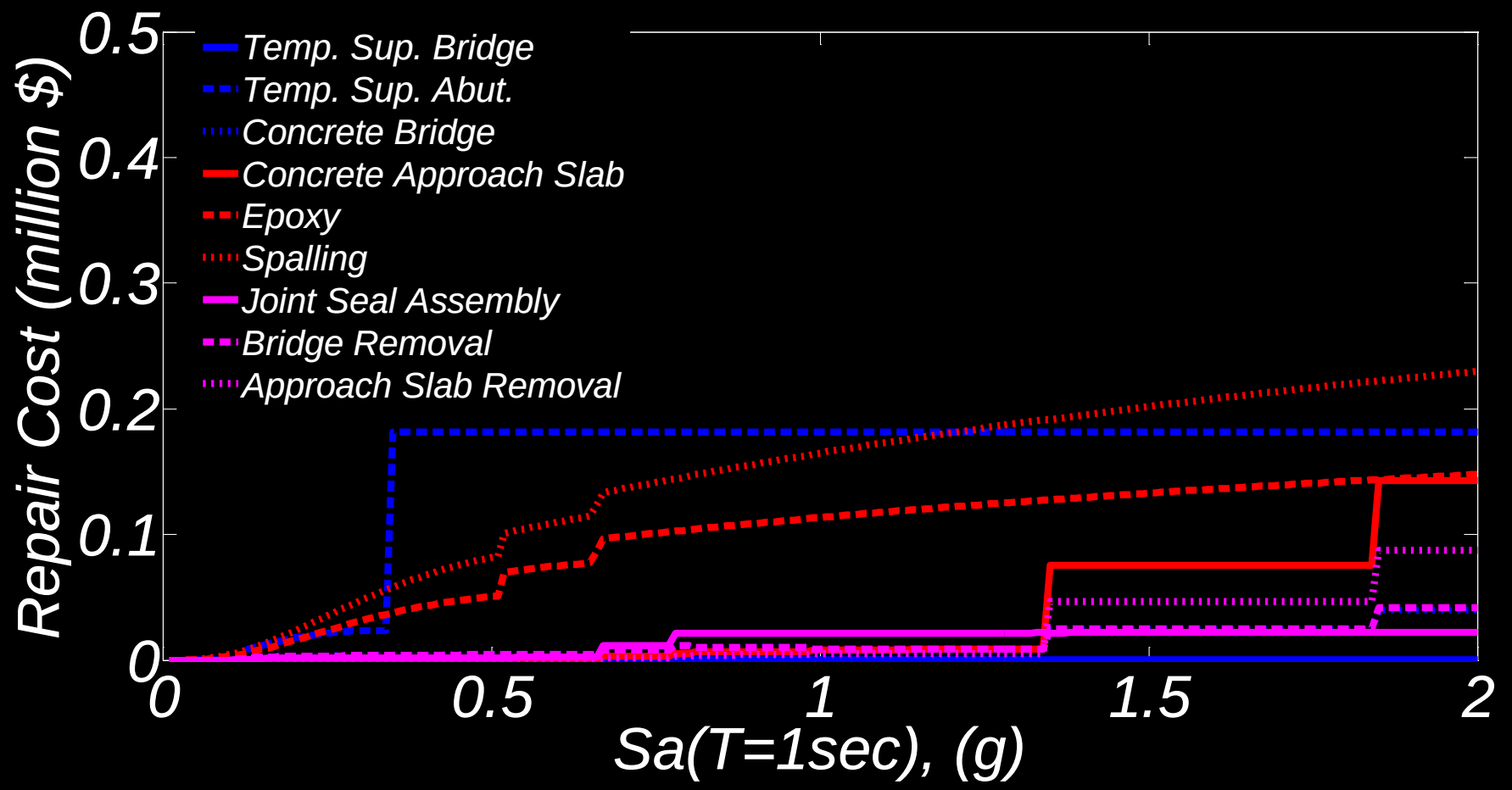


PBEE Short Bridge – Median Repair Cost



PBEE – Disaggregation of Cost

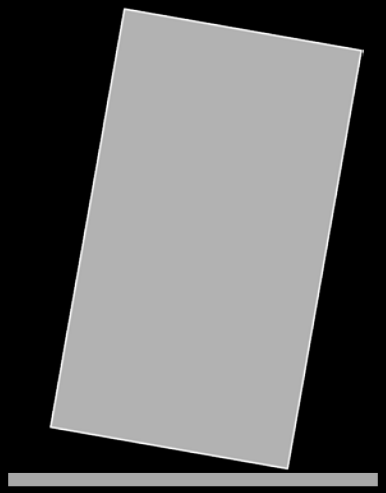
FIXED BASE -TALL



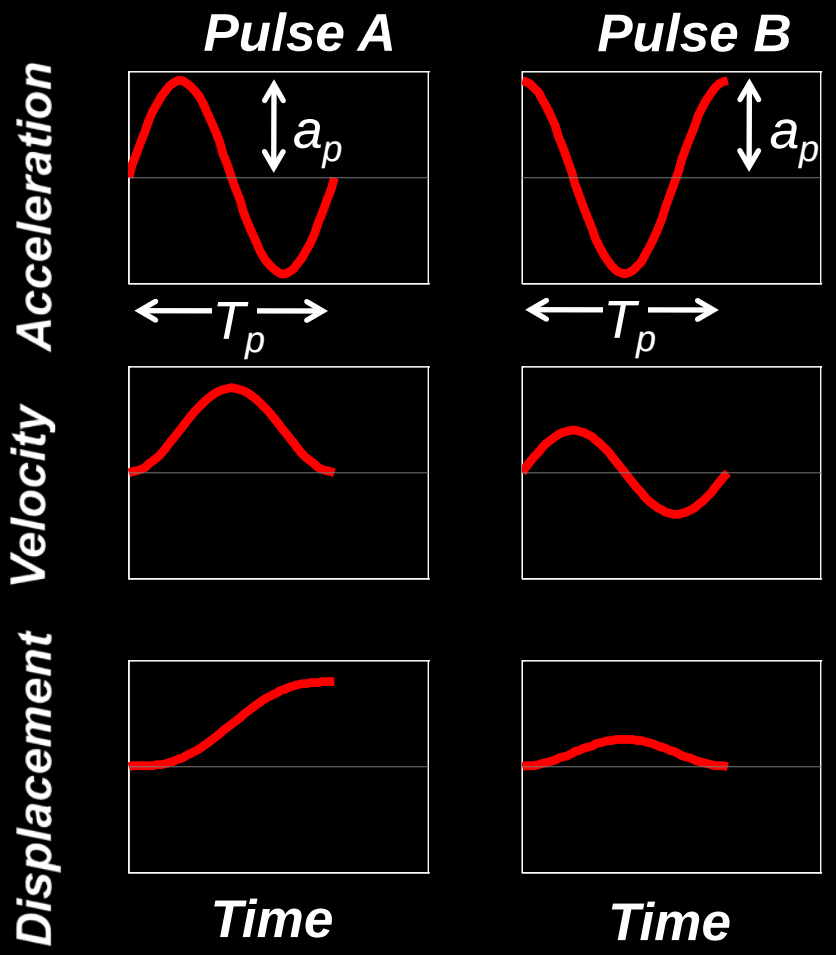
END

Ground motion characteristics that may lead to overturn ?

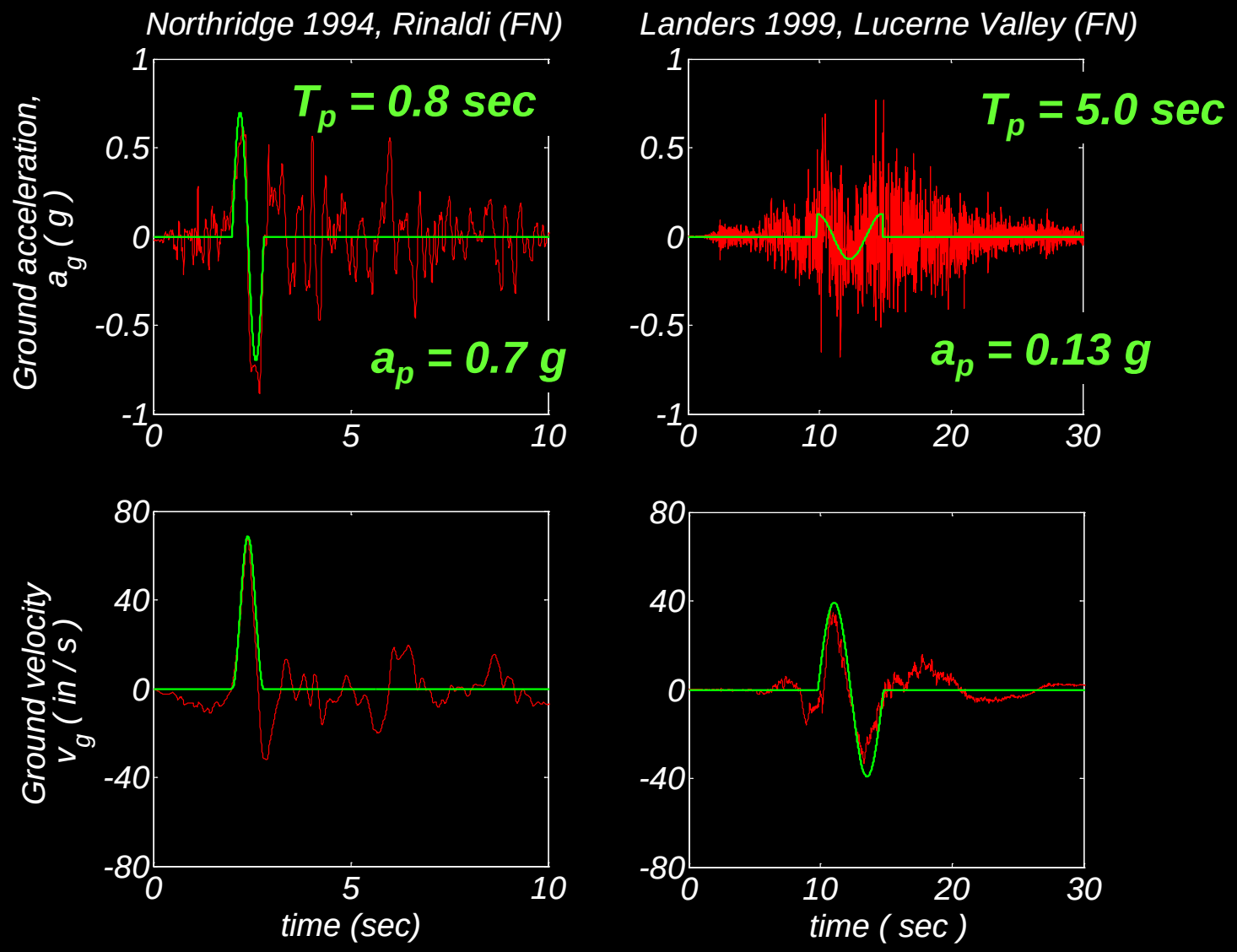
Ground motions with strong pulses (especially low frequency) that result in significant nonlinear displacement demand



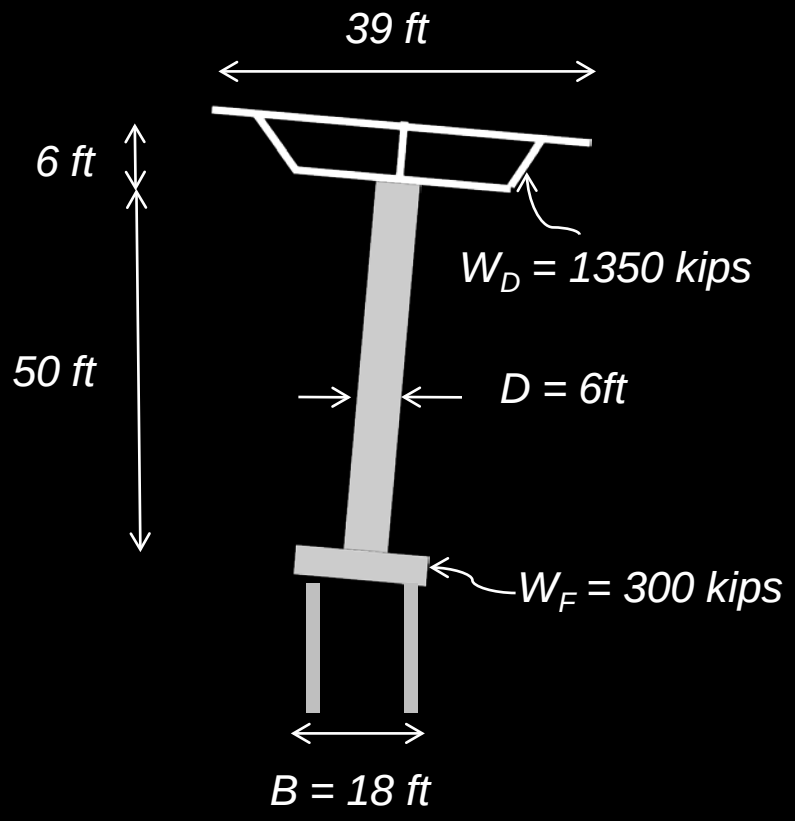
Rocking response of rigid block on rigid base to pulse-type excitation
Zhang and Makris (2001)

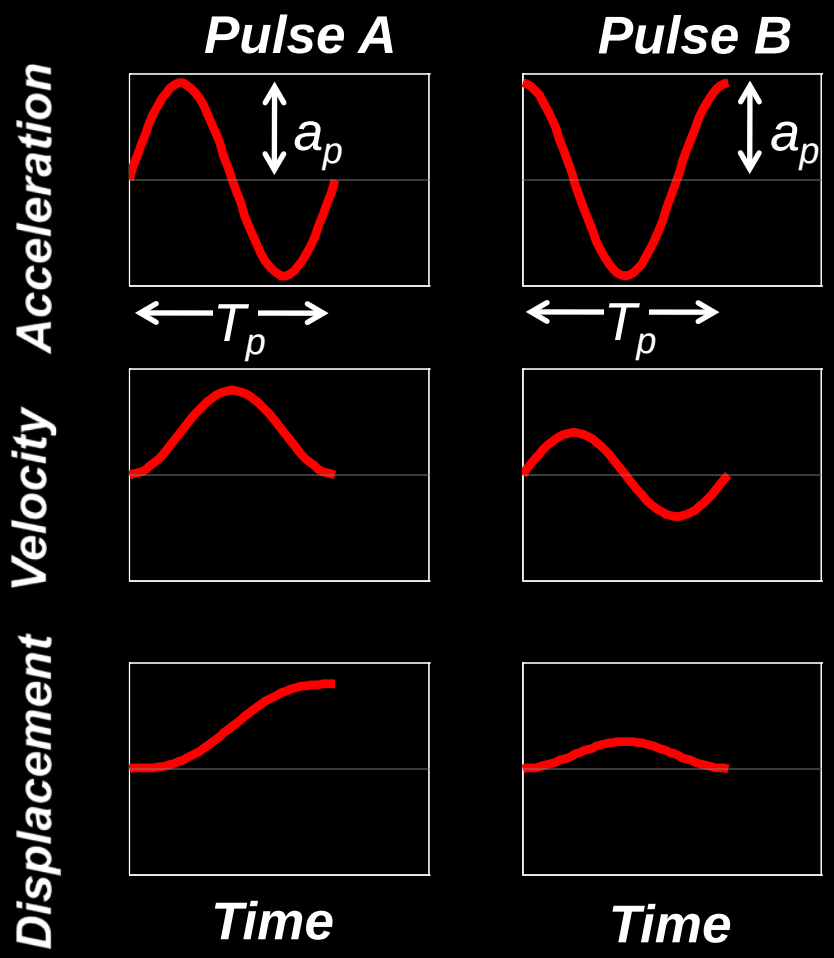


Near Fault Ground Motions and their representation using Trigonometric Pulses



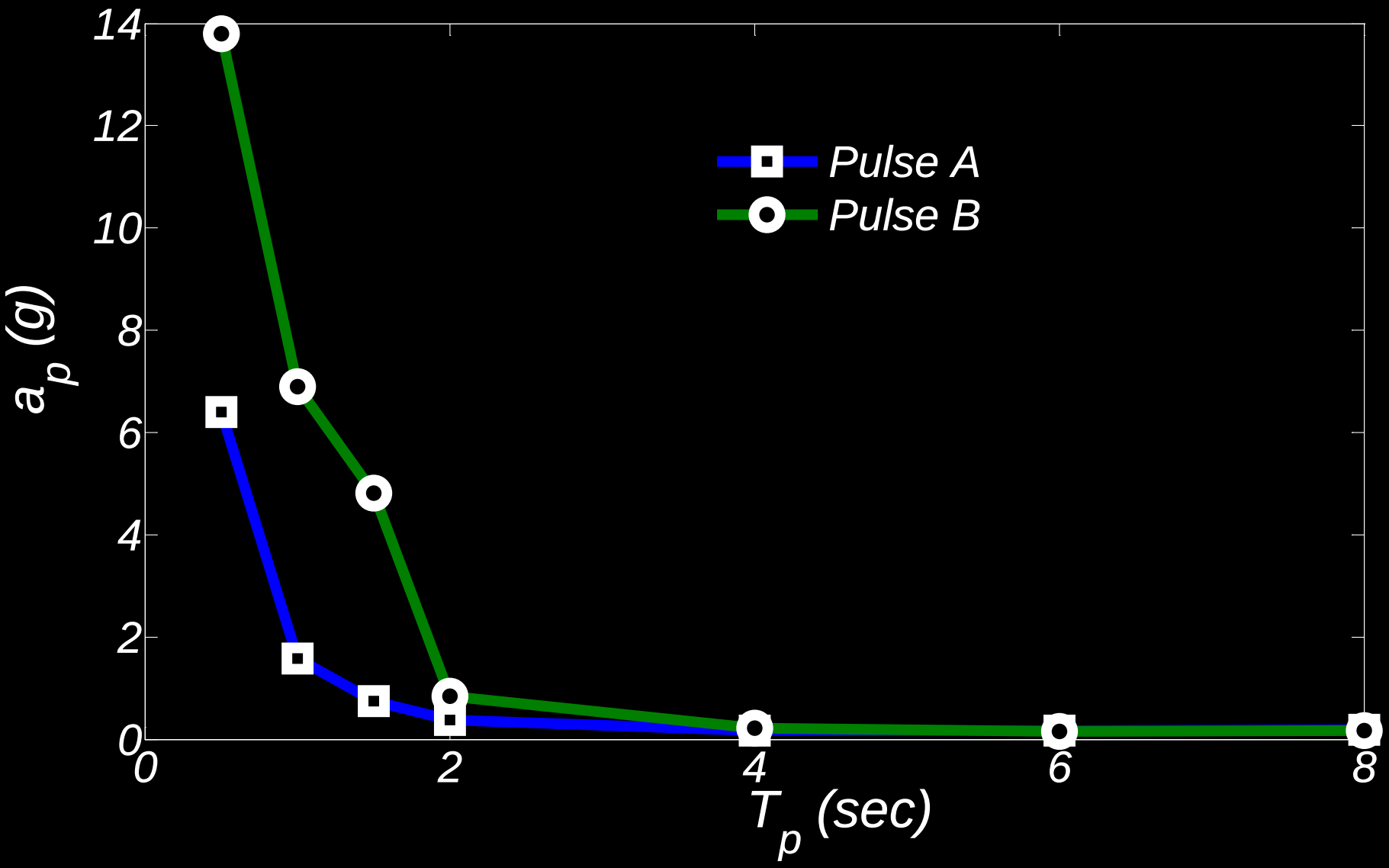
Conditions that may lead to overturn



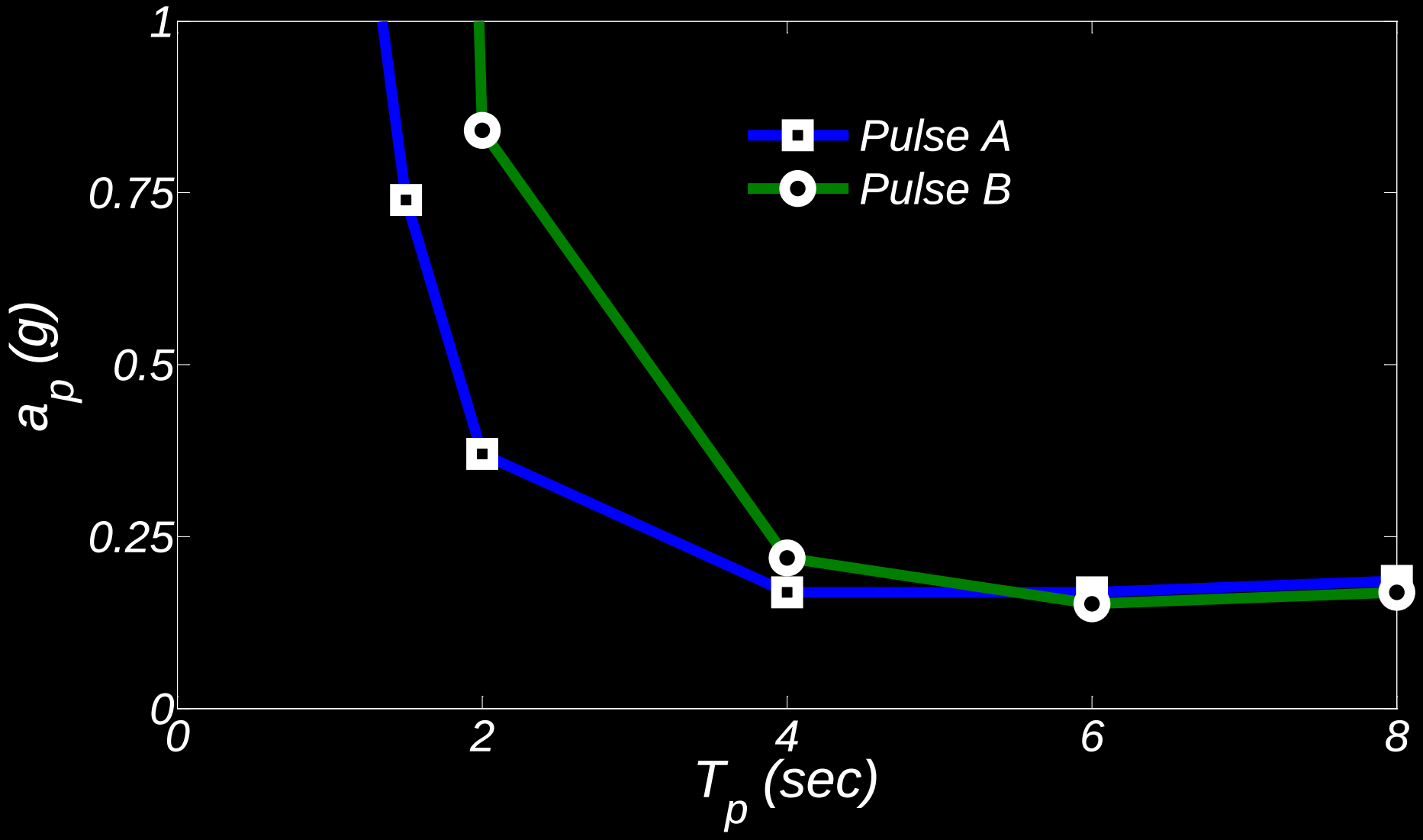


Minimum a_p at different T_p that results in overturn ?

Conditions that may lead to overturn



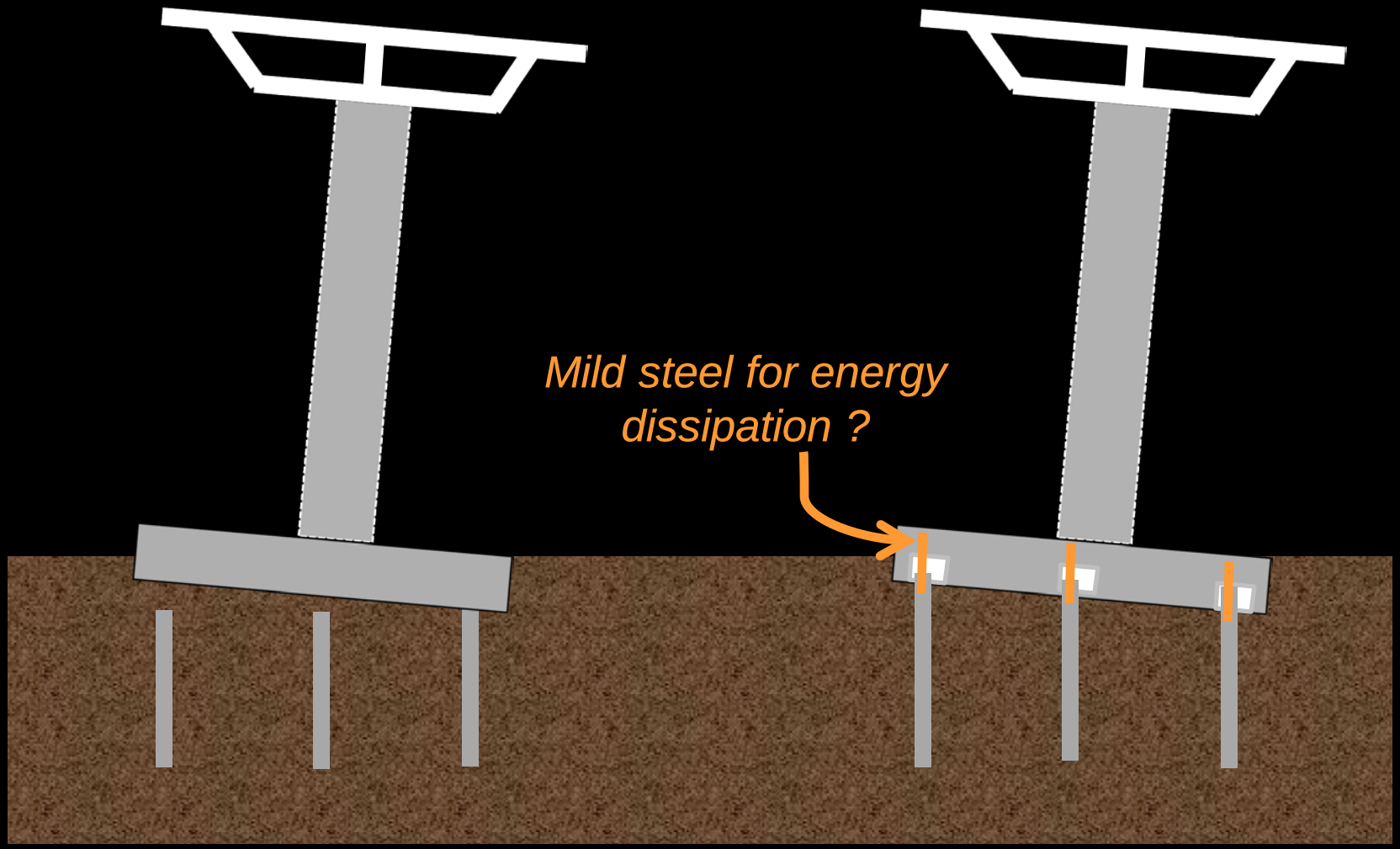
Conditions that may lead to overturn



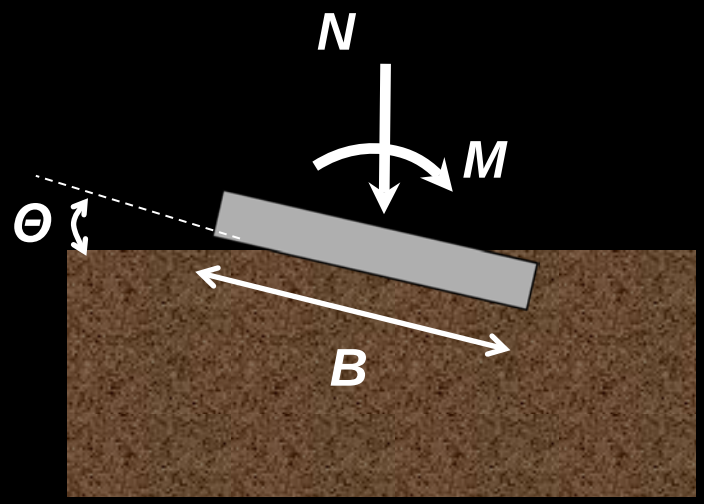
Design Using Rocking Pile-Caps

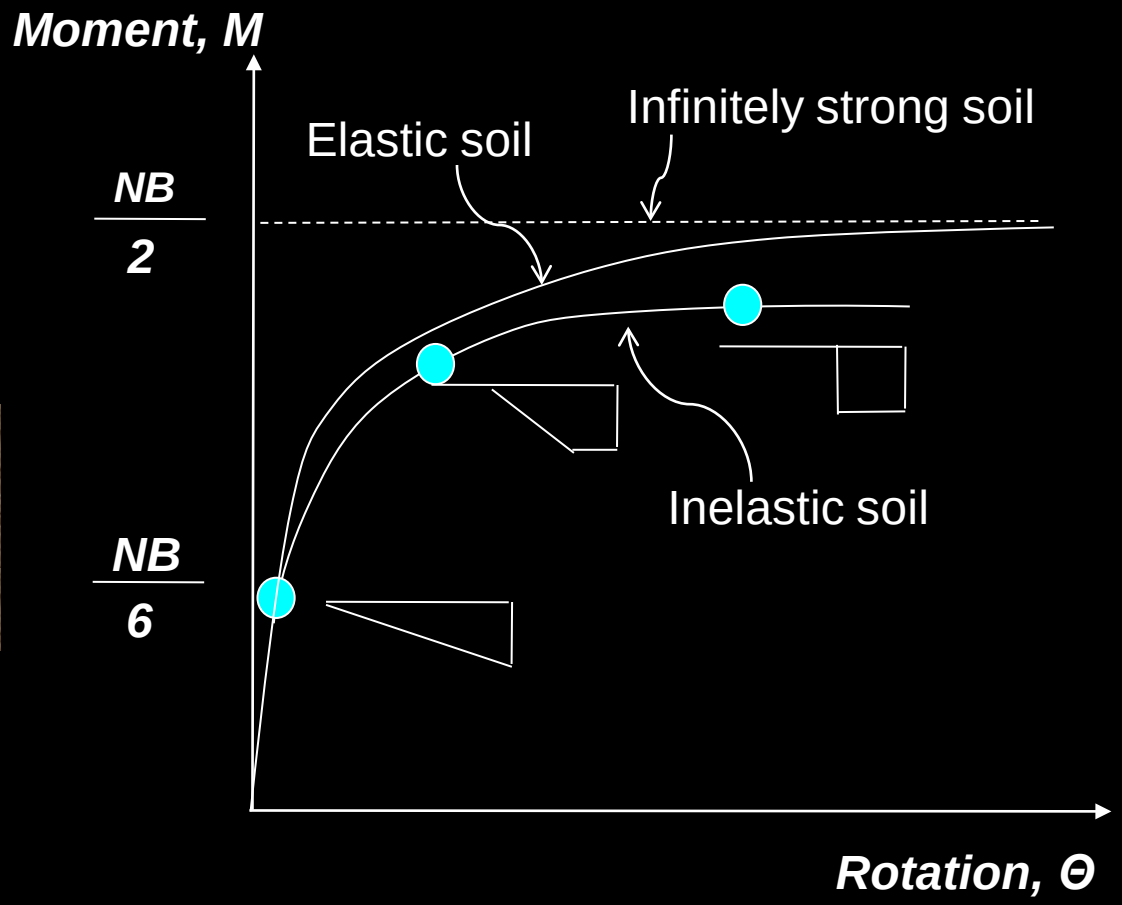
Pile-cap simply supported on piles

Pile-cap with sockets

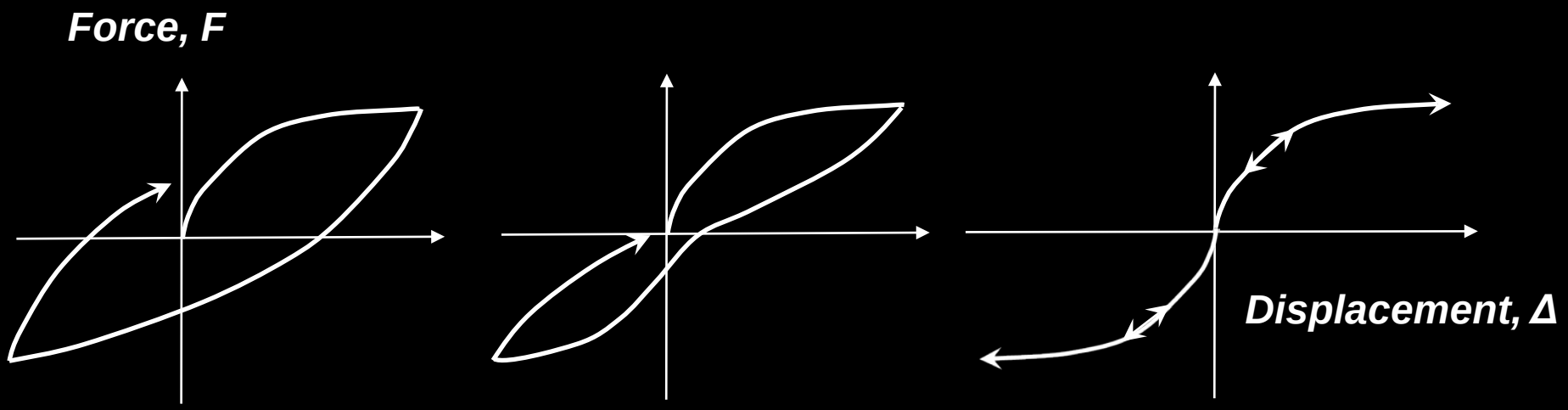


Rocking Foundations - Nonlinear Behavior





Nonlinear Behavior Characteristics



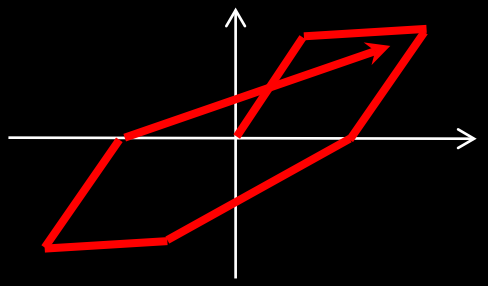
Fixed*-base or shallow foundation with *extensive soil inelasticity

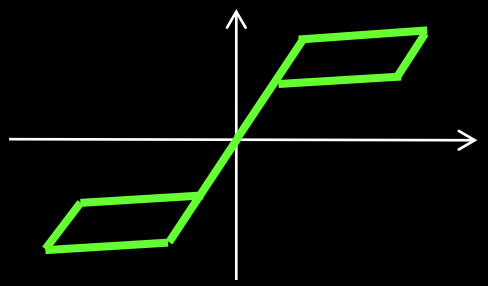
Shallow foundation with *limited soil inelasticity

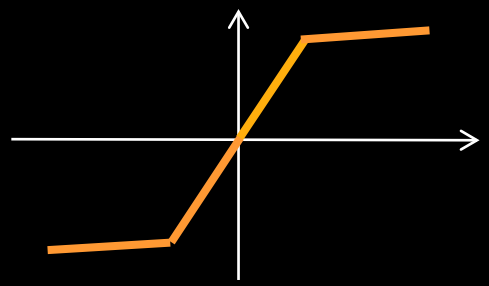
Rocking pile-cap or shallow foundation on *elastic soil

SDOF Nonlinear Displacement Response

Mean results of 40 near-fault ground motions



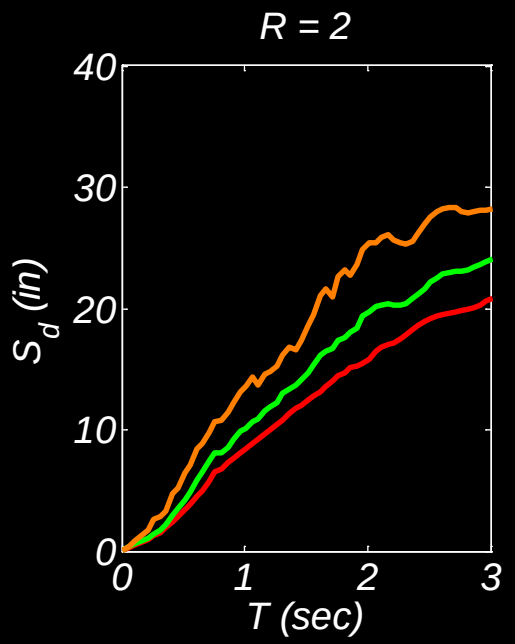


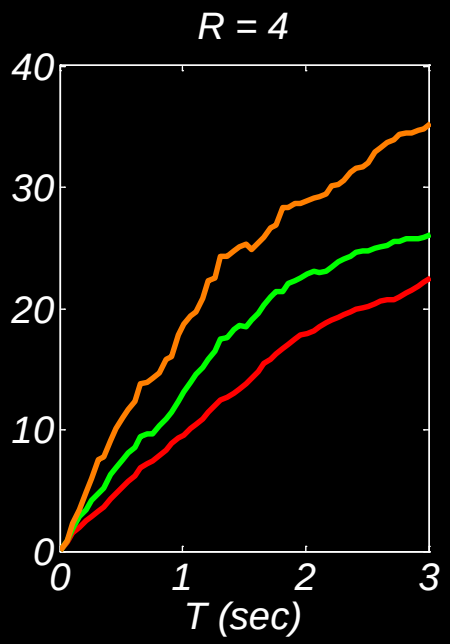


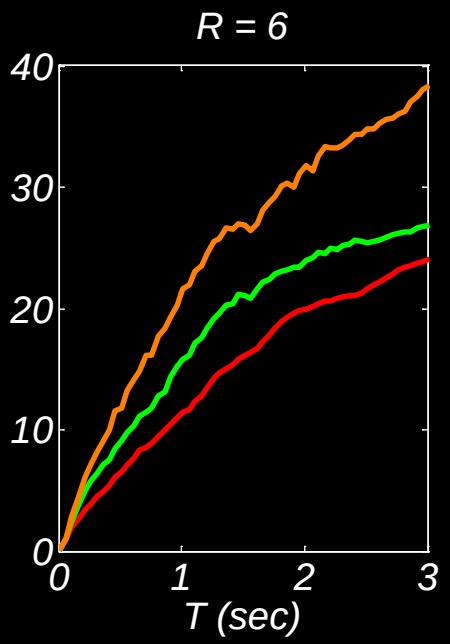
Clough

Flag

Nonlinear Elastic







INITIAL COST

FIXED BASE

- *Large foundations and piles*

ROCKING FOUNDATIONS

- *Smaller foundations and piles*
- *Larger rubber bearings*
- *Larger joint seal assembly*
- *Larger reinforcing steel ratio*

Monotonic Behavior – Individual Pier