Model Design and Dynamic Similitude (1g/Large Scale Testing)

Seismic Response of MSE Bridge Abutments

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Acknowledgements

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  - Caltrans
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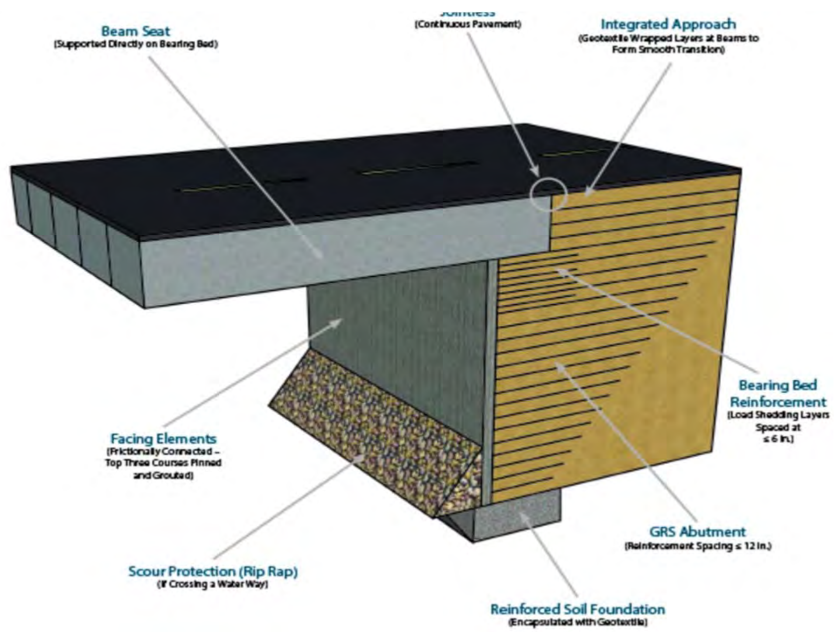
- Project team:
  - Prof. Yewei Zheng, Old Dominion University
  - Prof. Benson Shing, UCSD
  - Prof. Patrick Fox, Head of CEE at Penn State University



Seismic Response of MSE Bridge Abutments

Geosynthetics in transportation applications:

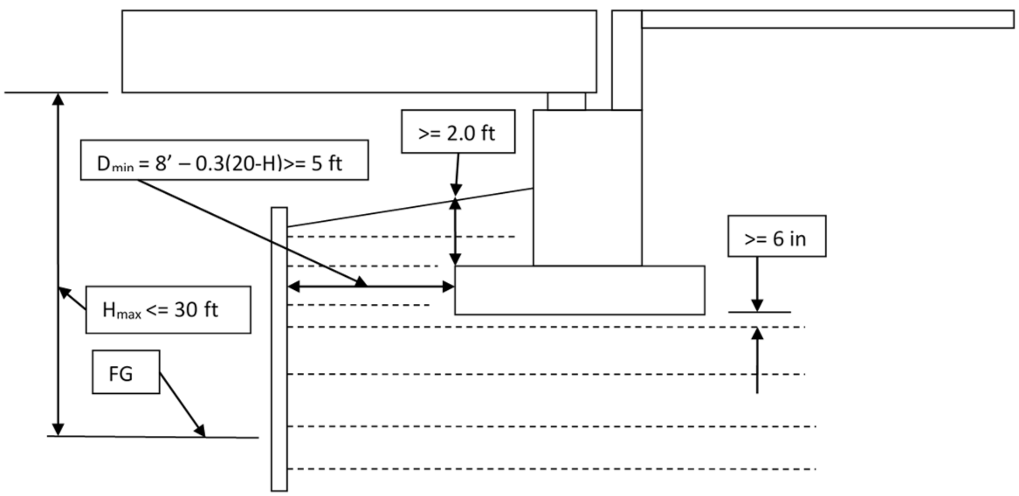
- Roadways
- Embankments
- Slopes
- Retaining walls
- **Bridge abutments**



MSE abutments have many advantages over pile-supported bridge abutments, including cost savings, easier and faster construction, and smoother transition

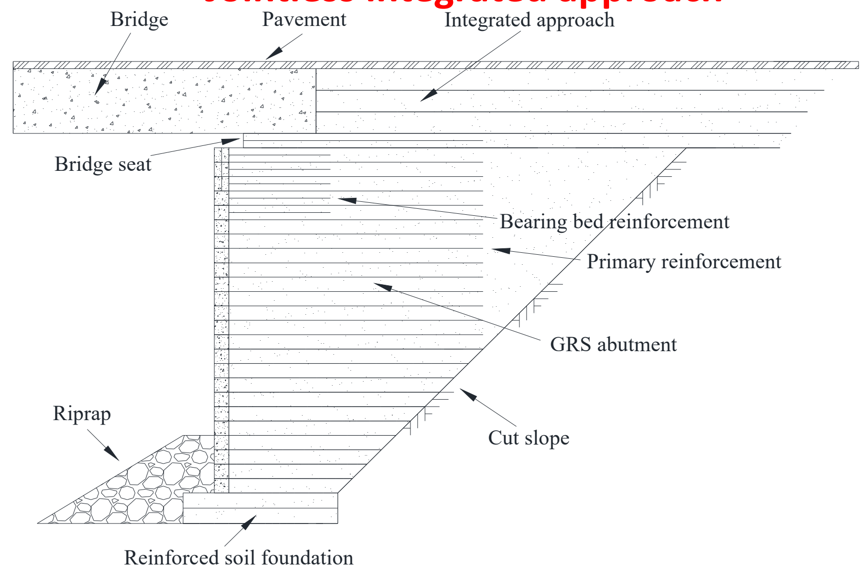
MSE Bridge Abutment vs. GRS-IBS

Bridge seat set back from facing with joint



MSE Bridge Abutment

Jointless integrated approach



GRS-IBS Abutment

- MSE: inextensible metallic reinforcements or extensible geosynthetic reinforcements embedded in compacted granular soil, and the reinforcement spacing and length is designed assuming that they are tie-backs
- GRS: closely-spaced geosynthetic reinforcements (≤ 12 in) embedded in compacted granular soil in order to form a GRS composite material

Research Motivation

MSE bridge abutments have been widely used in US, but there are concerns regarding the seismic performance, like in California:

- Geotechnical: backfill settlements and facing displacements
- Structural: bridge deck and seat movements, impact force between bridge deck and seat, and interaction between bridge superstructure and abutment

MSE wall performance in Maule Earthquake, Chile

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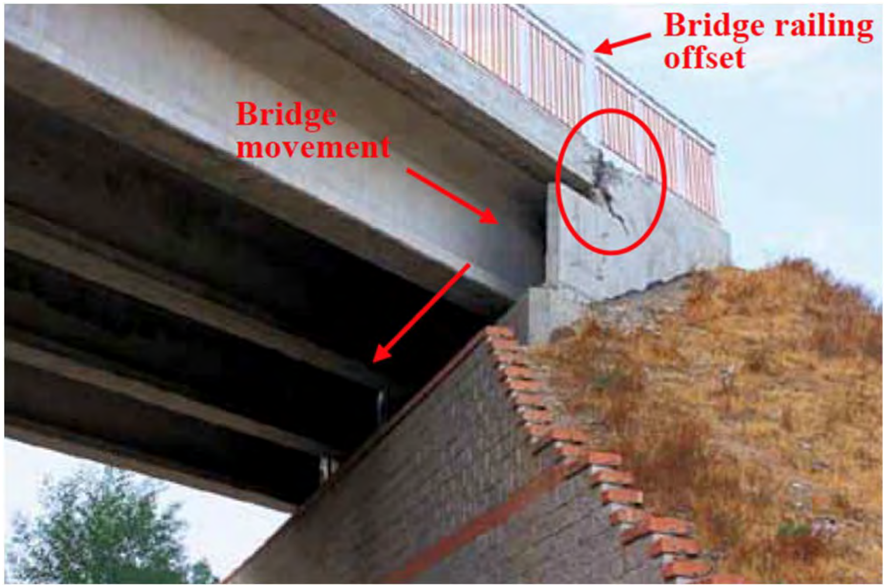
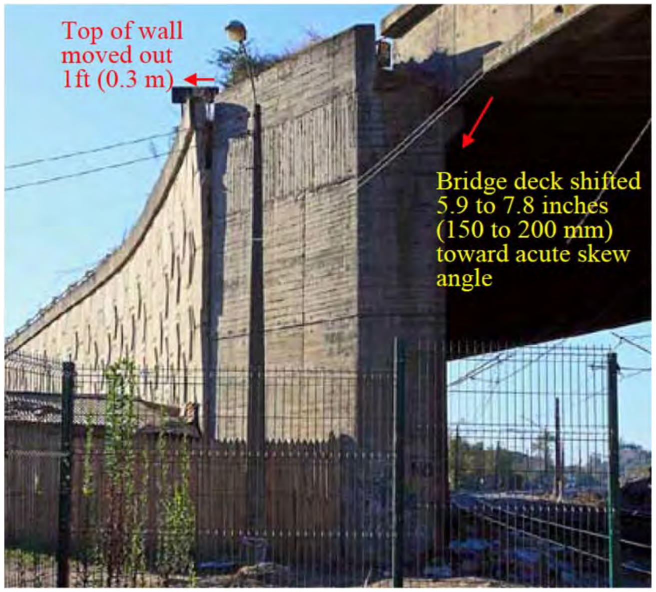


MSE bridge abutment performance in Maule Earthquake, Chile



Project Objectives

- ***Bridge seat movement and rocking*** – bridge seat may rock or translate in different directions during shaking, leading to interactions with the bridge deck and upper wall backfill;
- ***Volumetric compression of the backfill soils*** – seismic shaking can induce compression of reinforced soil backfill under the bridge surcharge or approach slab loads, and this compression may result in differential settlement between the bridge and approach slab;
- ***Bridge beam impact forces on the bridge seat and impacts on retained fill*** – seismic shaking can cause relative movement between the bridge deck and bridge seat, result in impact forces that may damage the bridge seat or cause the formation of a passive wedge in the retained backfill behind the bridge seat;
- ***Transverse vs. longitudinal seismic behavior*** – to investigate the 3D behavior of the wall during one-dimensional shaking in different directions, in particular the movement of the bridge seat;
- ***Design details (reinforcement spacing, reinforcement stiffness, reinforcement type)*** – the different tests performed in this study having different configurations and reinforcement types will help understand the impact of these details on the seismic performance of the MSE bridge abutment, and the effect of these design variables need to be investigated;
- ***Wall face displacements during static and seismic loading*** – it is important to understand the facing displacements after shaking as they may lead to serviceability or maintenance problems;
- ***Reinforcement strains during static and seismic loading*** – to investigate the tensile forces developed during shaking and check the design assumptions for internal stability design

Literature Review – MSE Wall Seismic Performance

- El-Emam and Bathurst (2004, 2005, 2007) performed a series of shake table tests on reduced-scale MSE walls with a full-height rigid facing panel
- Ling et al. (2005, 2012) conducted full-scale shake table tests on MSE walls with battered modular block facing using fine sand and silty sand as backfill soils
- Yen et al. (2011) found that a MSE abutment performed well from post-earthquake reconnaissance for 2010 Maule Earthquake
- Helwany et al. (2012) conducted large-scale shaking table tests on a GRS abutment and found that it could sustain sinusoidal motions with an acceleration amplitude up to 1g without significant distress

Motivation for Using 1g Shake Table Testing

- Shake table testing has been successfully to investigate the seismic performance of MSE walls:
  - MSE walls/slopes with no surcharge (El-Emam and Bathurst 2004, 2005, 2007; Ling et al. 2005, 2012; Tatsuoka et al. 2009, 2012)
  - Shake table testing has been used to evaluate MSE walls with a surcharge load to simulate a bridge abutment (Helwany et al. 2012)
- Can use actual (or similar) materials used in the field (backfill soil, geosynthetic reinforcements, facing blocks, reinforced concrete)
- Can use similar construction techniques
- Can evaluate actual construction details
- Can evaluate interaction between abutment and bridge deck
- Can incorporate instrumentation on reinforcements

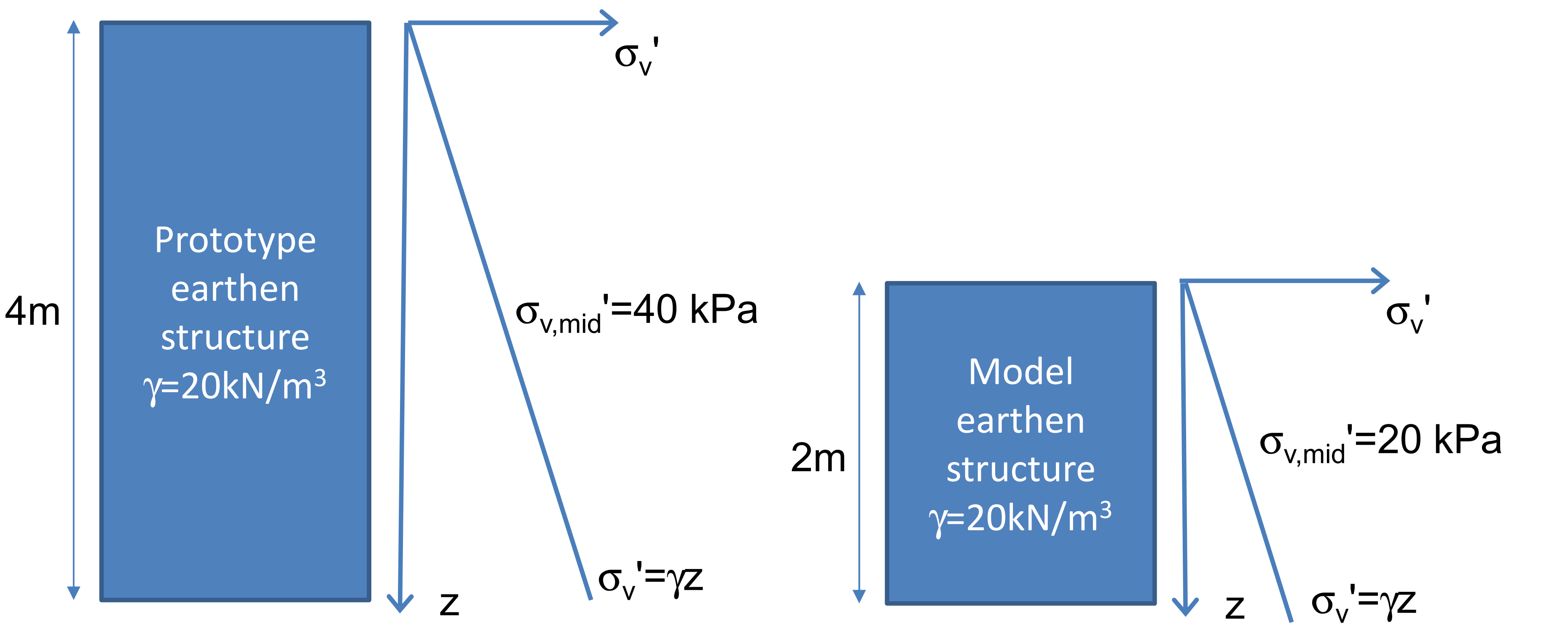
UCSD Shake Table

UCSD South Powell Structural Lab Shake Table:

- Dimensions: 10 ft. x 16 ft.
- Shaking DOF: 1D in N-S direction
- Maximum gravity load: 80 kips
- Dynamic stroke: $\pm$ 6 in.
- Dynamic capacity: 90 kips

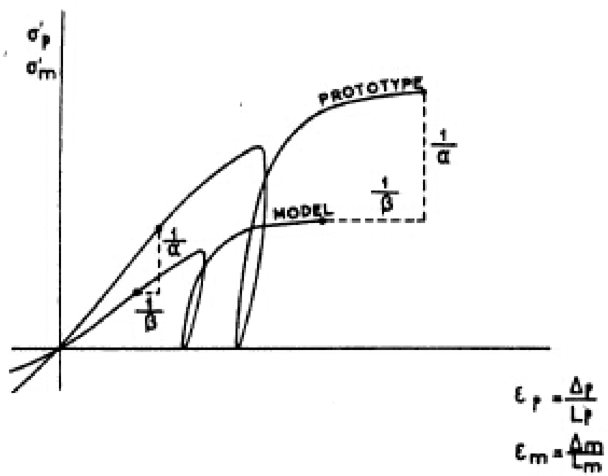
Need for Scaling in Reduced Scale 1g Tests

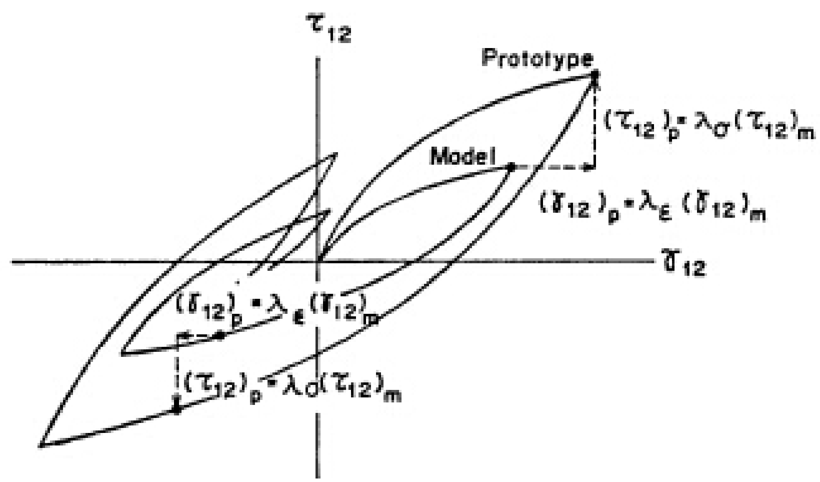
- When testing a model at 1g with a geometry that is N times smaller than a prototype, the self-weight is still proportional to the height of the soil layer
- The effective stresses in a model will be reduced proportional to the geometric scaling



Need for Scaling in Reduced Scale 1g Tests

- Shear strength and stiffness of soils depend on the effective stress
  - Shear strength is typically linearly related to the effective stress
  - Stiffness is nonlinearly related to the effective stress
- The stress-strain curve may change as a function of effective stress (peak values may not occur at the same strain)
- Scaling relationships are thus required to design a reduced scale model so that results can be extrapolated from model to prototype





Monotonic and cyclic stress-strain relationships for model and prototype
(Rocha 1957; Roscoe 1968)

1*g* Similitude Relationships

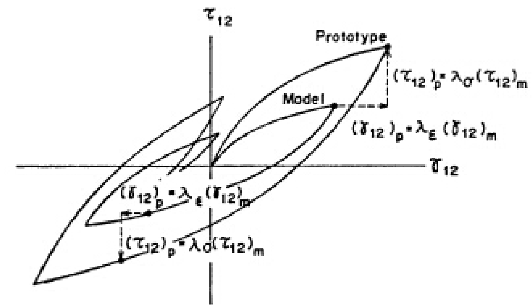
- Appropriate similitude relationships are needed for the design of reduced-scale model so that experimental results from reduced scale 1*g* shaking table tests can be extrapolated to full-scale conditions
- Most widely used set of 1*g* similitude relationships - **Iai (1989)**
  - Basis: equilibrium and mass balance of soil, structures, and pore water
  - Assumption: scaled stress-strain relationships for soil are independent of confining stress if appropriate scaling factors are selected
  - Three independent scaling factors:
    - Geometry scaling factor λ – most important for reduce scale model design
    - Density scaling factor λ_ρ – typically assumed to be 1 for the same soil
    - Strain scaling factor λ_ε – can be determined using shear wave velocity measurements, typically assumed to be 1
  - Applicability: applicable to deformation analysis prior to failure, not applicable to the ultimate state of stability due to large deformations or loss of soil contact

1*g* Similitude Relationships

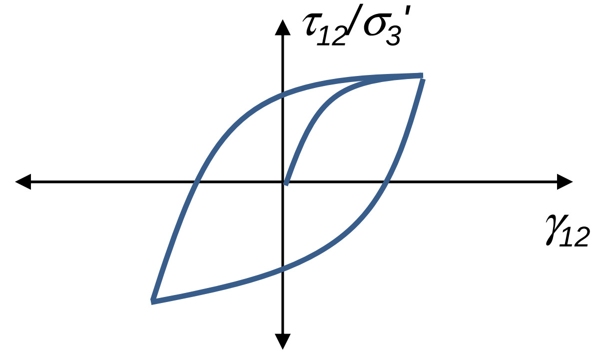
Similitude relationships (Iai 1989)

Variable	Scaling factor	$\lambda_\rho = 1$, $\lambda_\varepsilon = 1$	$\lambda = 2$
Length	λ	λ	2
Density	λ_ρ	1	1
Strain	λ_ε	1	1
Mass	$\lambda^3\lambda_\rho$	λ^3	8
Acceleration	1	1	1
Velocity	$(\lambda\lambda_\varepsilon)^{1/2}$	$\lambda^{1/2}$	1.414
Stress	$\lambda\lambda_\rho$	λ	2
Modulus	$\lambda\lambda_\rho/\lambda_\varepsilon$	λ	2
Stiffness	$\lambda^2\lambda_\rho/\lambda_\varepsilon$	λ^2	4
Force	$\lambda^3\lambda_\rho$	λ^3	8
Time	$(\lambda\lambda_\varepsilon)^{1/2}$	$\lambda^{1/2}$	1.414
Frequency	$(\lambda\lambda_\varepsilon)^{-1/2}$	$\lambda^{-1/2}$	0.707

Goal: Choose soil conditions to have a similar normalized stress-strain response in model and prototype for $\lambda_\varepsilon = 1$



Original stress-strain relationships for soil in the model and prototype (Rocha 1957)



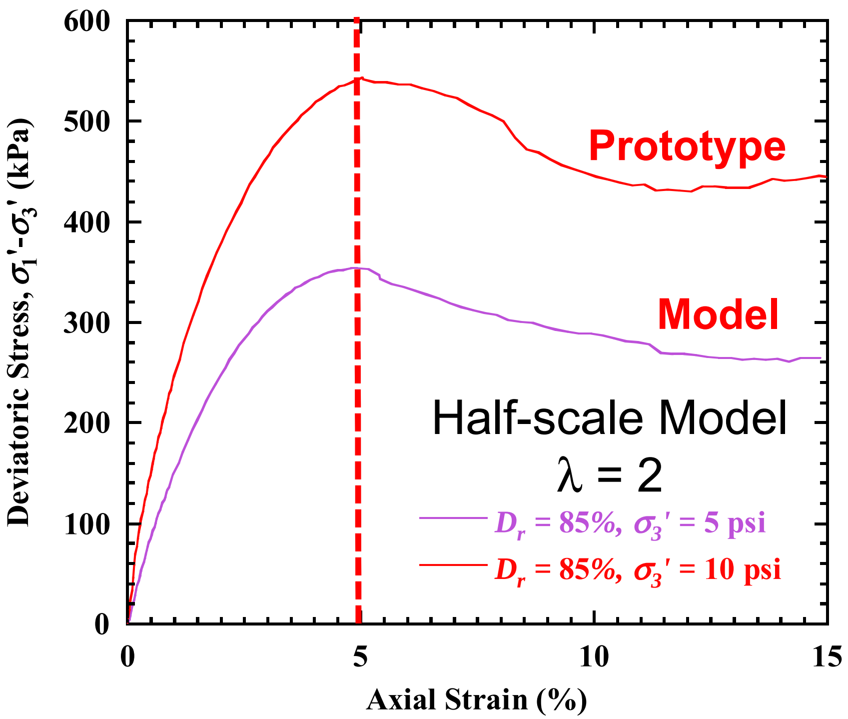
Normalized stress-strain relationships for soil in the model and prototype for λ_ε=1

Selection of Compaction Conditions

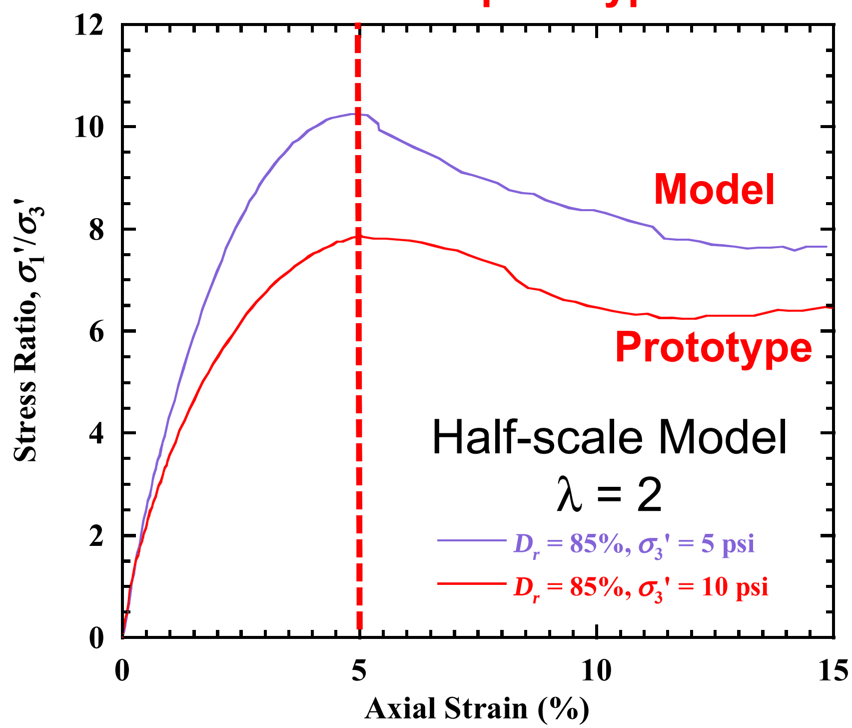
- Typical relative density (D_r) for prototype structures = 85% (RC = 96%)

Peak stresses occur at approximately same axial strain (5%), which indicates that the assumption of $\lambda_\varepsilon = 1$ is valid

However, due to the nonlinear effects of confining stress on shear strength and stiffness, the normalized curves are not similar for model and prototype for same D_r



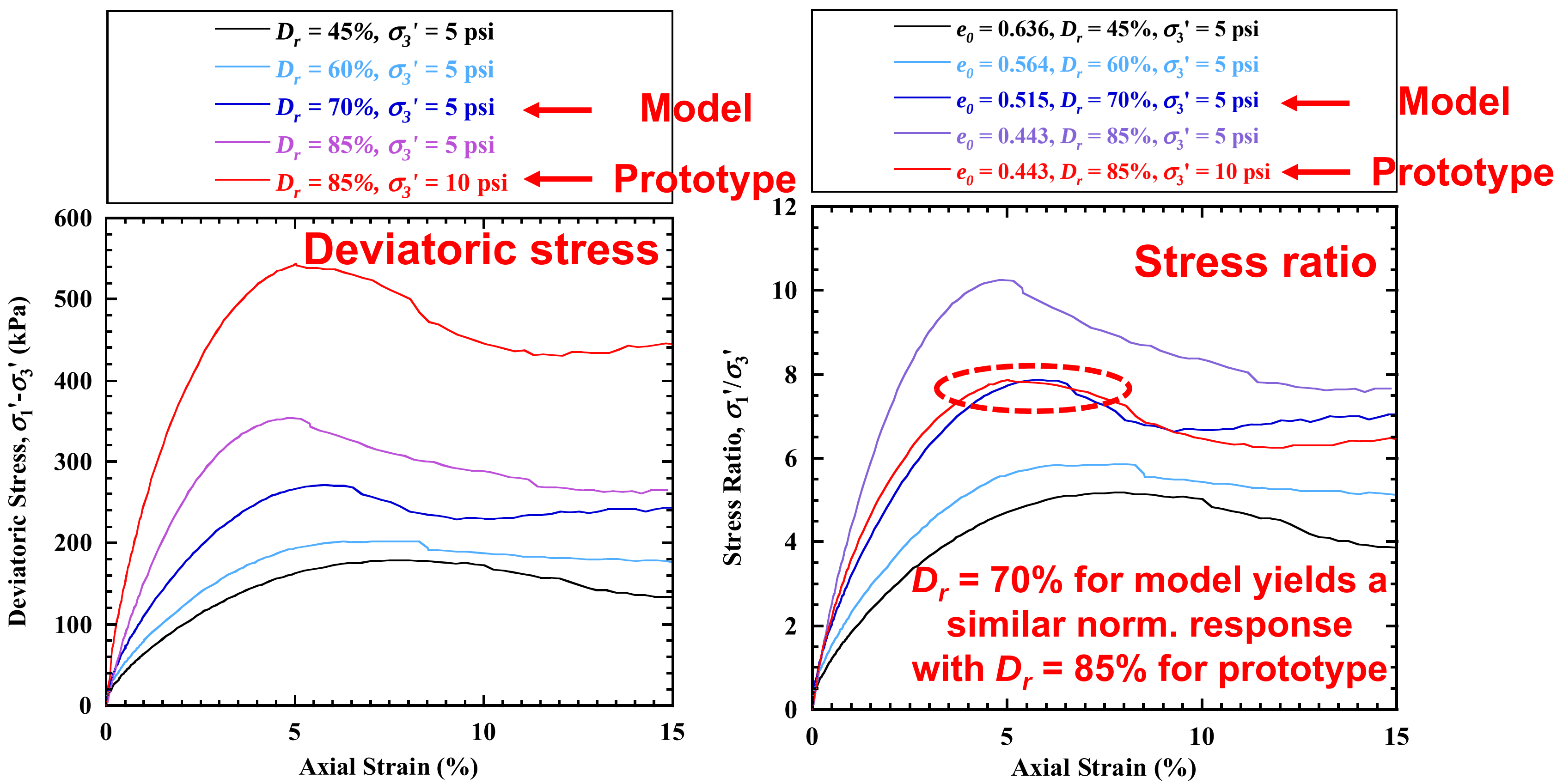
Deviator stress



Stress ratio

Selection of Compaction Conditions

- Typical relative density (D_r) for prototype structures = 85% (RC = 96%)
- Target relative density (D_r) for model specimens = **70%** (RC = 92%)



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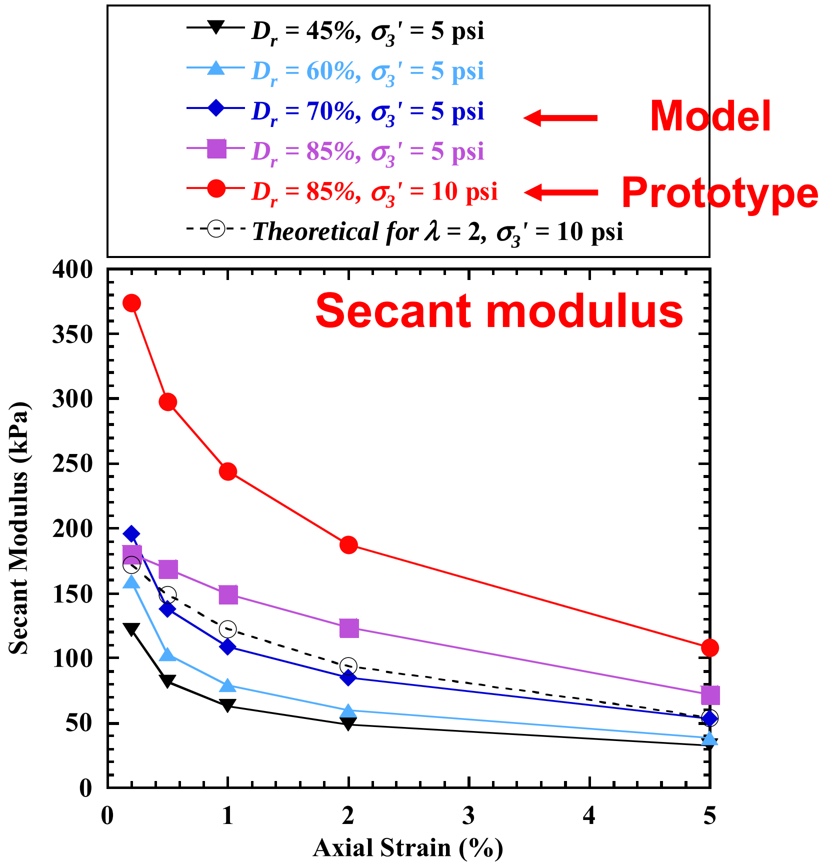
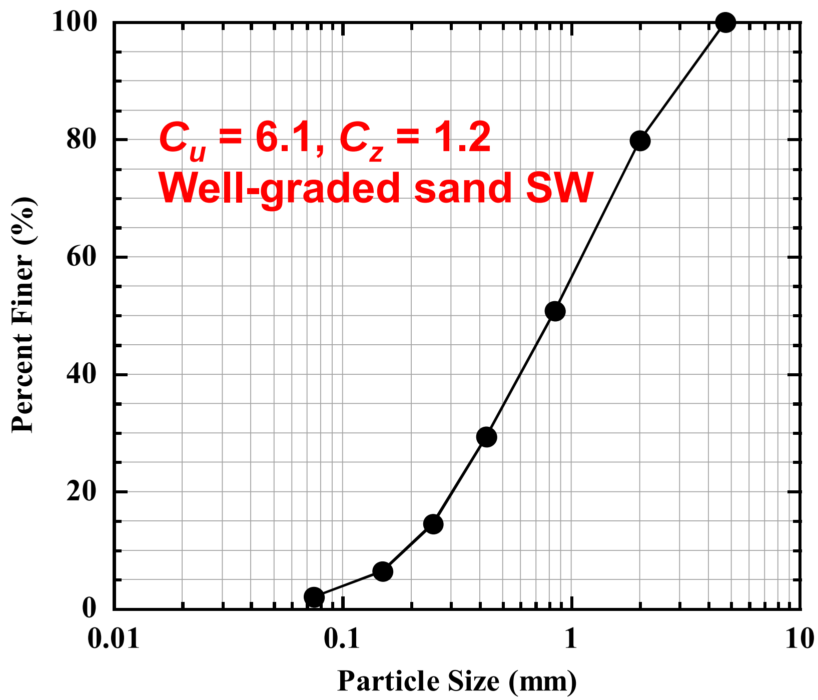


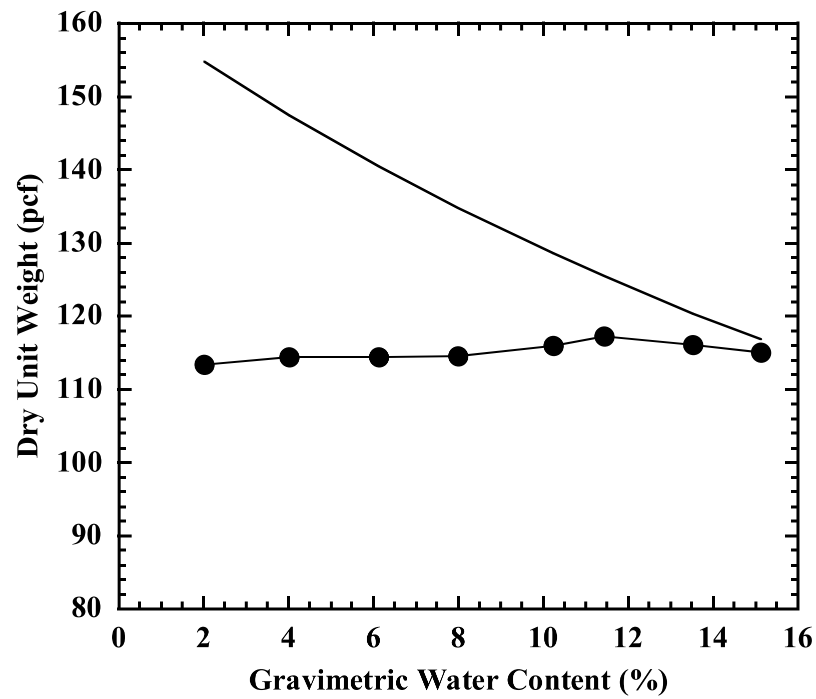
Theoretically-scaled secant modulus as a function of strain is consistent with the target relative density

Total unit weights for w_c = 5% are close for both prototype and model relative densities for this soil:
γ = 113 pcf for D_r = 70%
γ = 119 pcf for D_r = 85%
So assumption of λ_ρ = 1 is reasonable

Backfill Soil

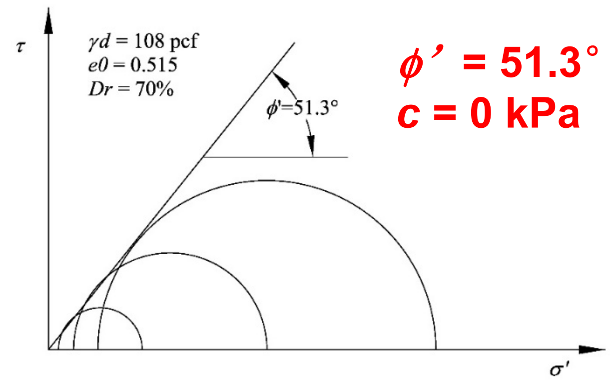
- Sieve analysis – Gradation curve
- Standard Proctor compaction curve (not sensitive



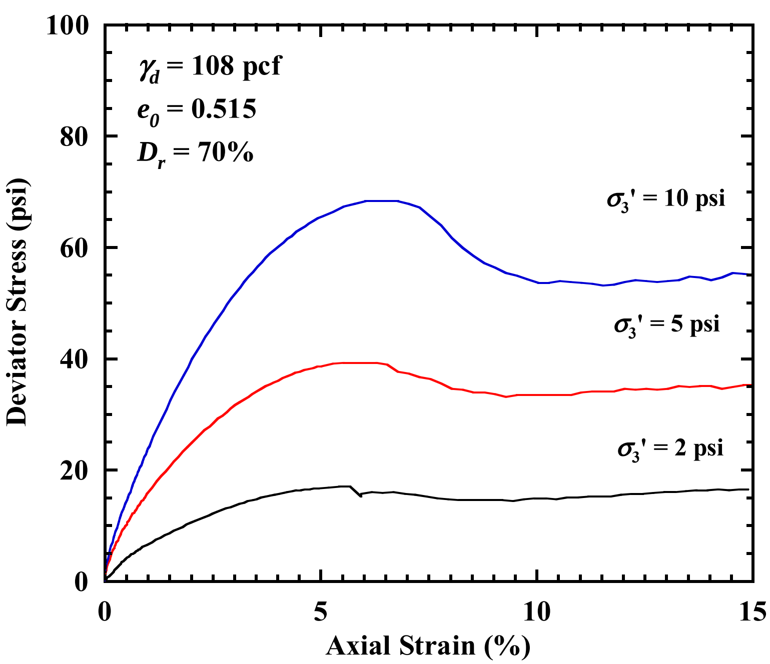


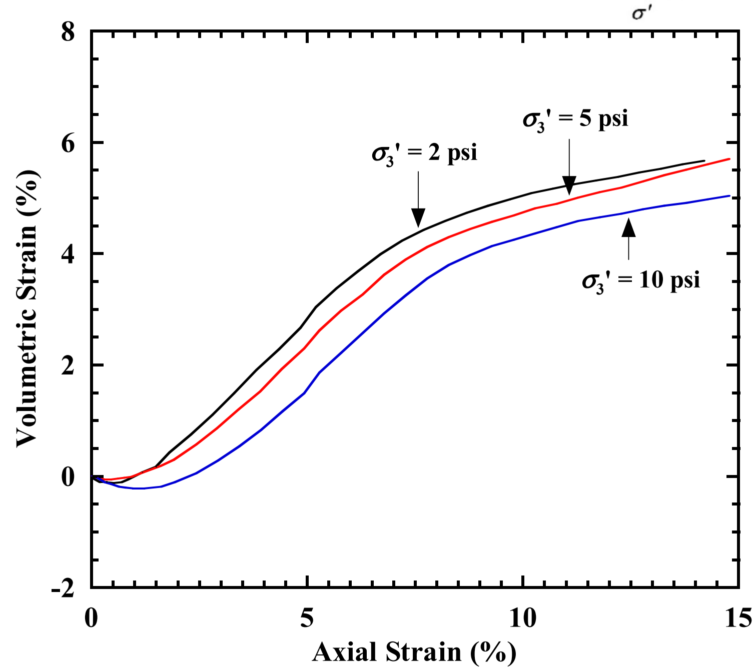
Backfill Soil

- Shear strength and volumetric behavior for D_r = 70%



ϕ' = 51.3°
c = 0 kPa



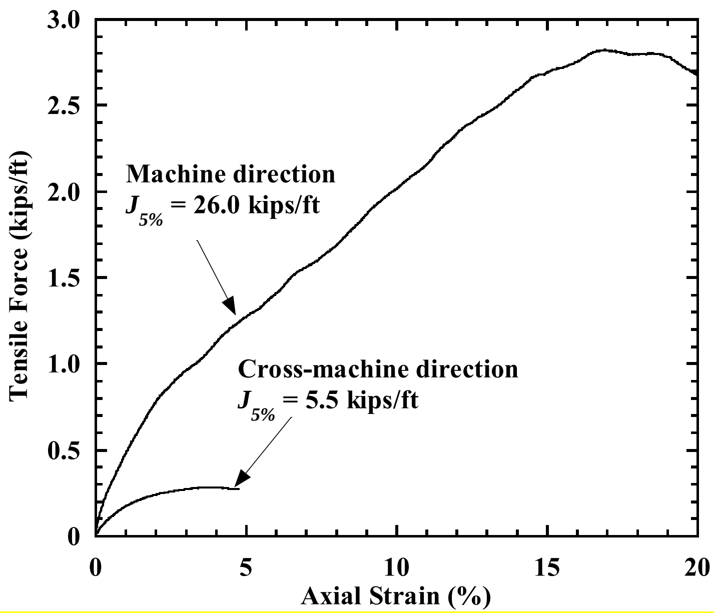


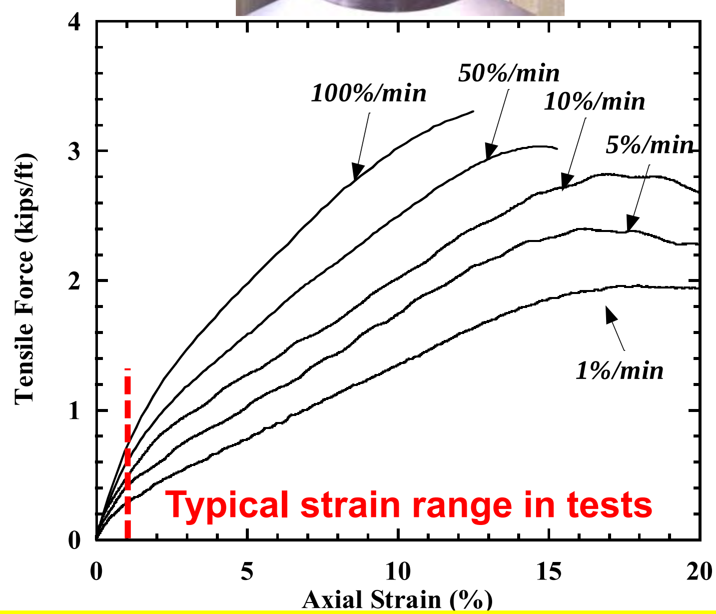
Geogrid Reinforcement

Prototype: Tensar UX 1700

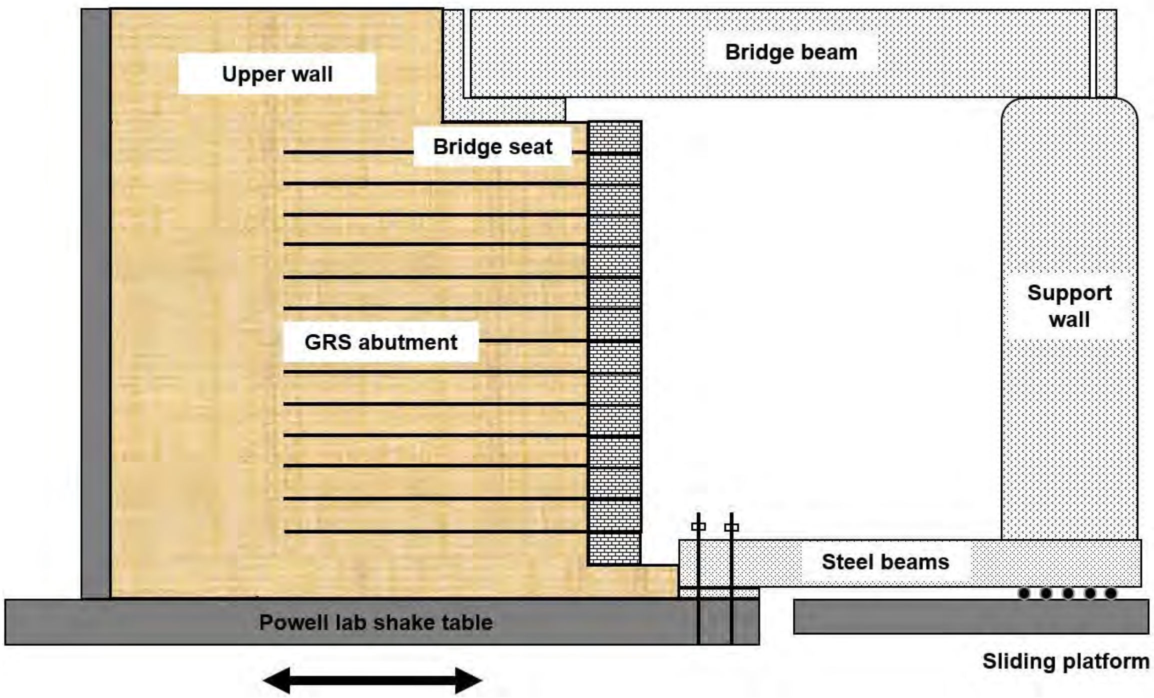
Model: Tensar LH 800

- Index stiffness = 26 kips/ft
- Stiffness scaling factor = 4





Target Prototype and Model Design



Model geometry scaling for λ =2

	Prototype	Model
Wall height (ft)	14	7
Bridge seat thickness (in)	12	6
Clearance height (ft)	15	7.5
Wall length (ft)	15.6	7.8
Wall width (ft)	14	7
Bridge width (ft)	6	3

Block scaling

	Prototype	Model
Product	-	Keystone
Dimensions (L x W x H)	24 in x 12 in x 12 in	12 in x 10 in x 6 in

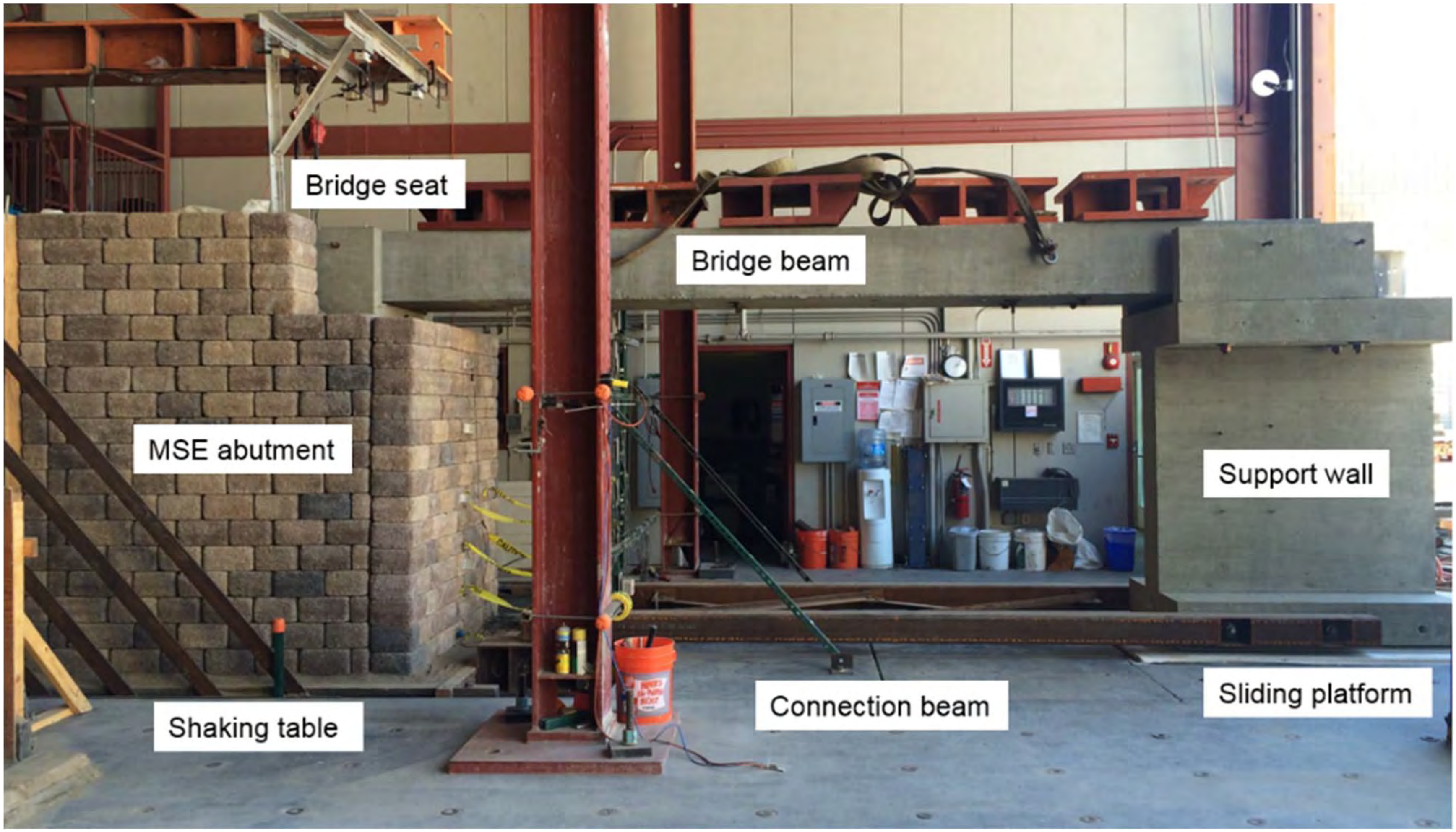
Reinforcement scaling

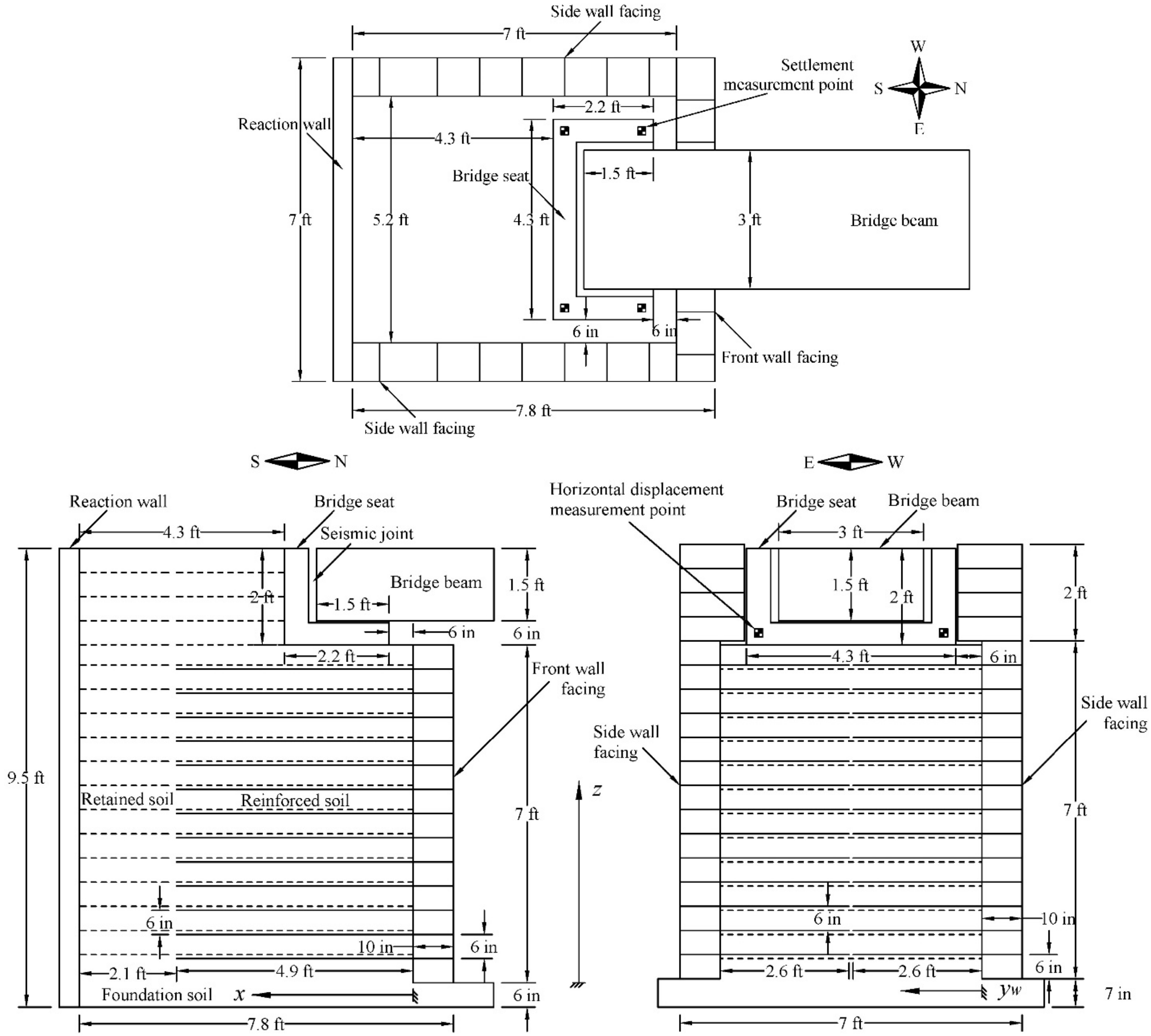
	Prototype	Model
Product	UX1700	LH800
Stiffness (kips/ft)	100	26

Testing Plan

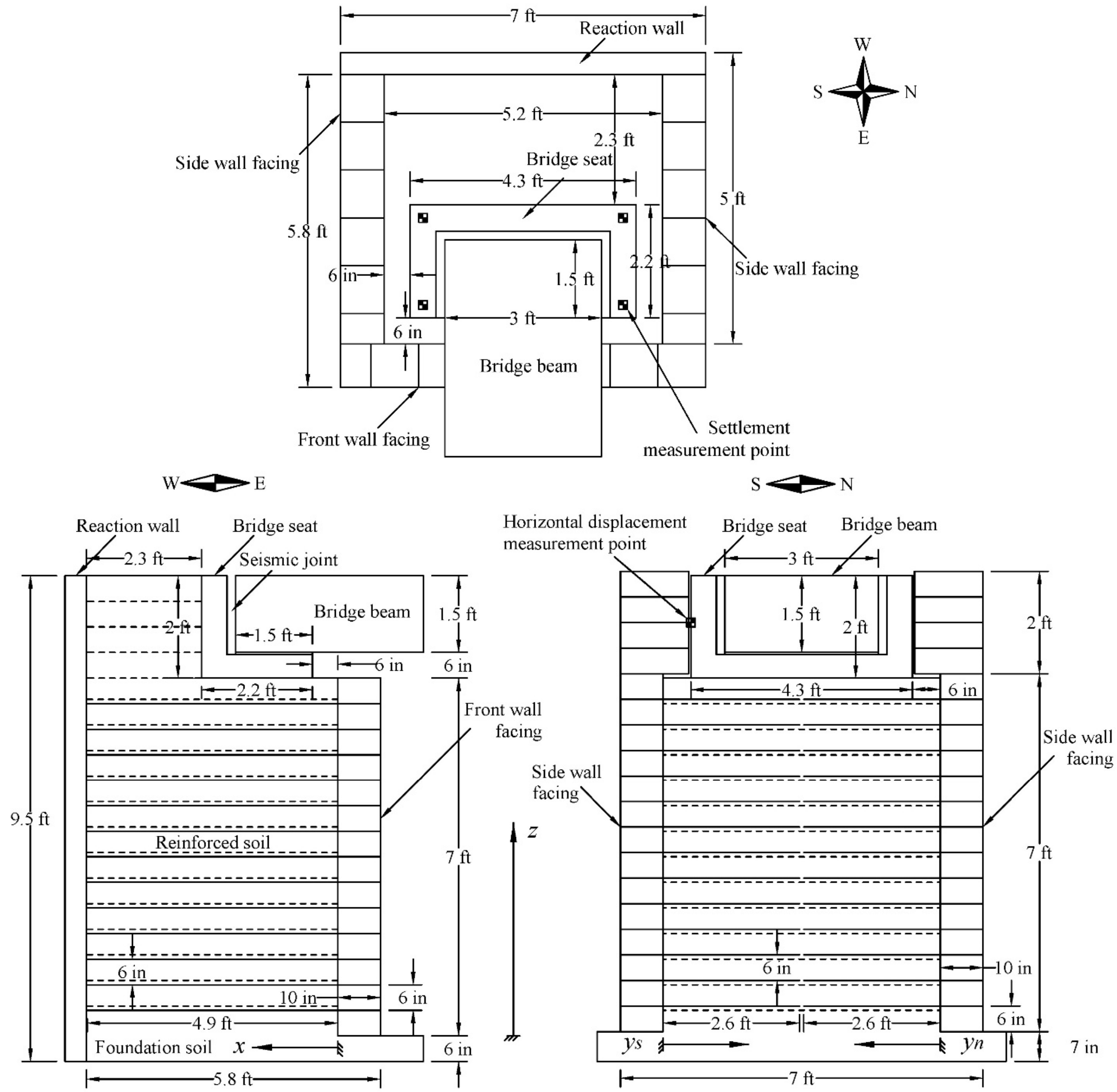
Test No.	Variable	Bridge Surcharge Stress (psf)	Reinforcement Spacing (in)	Reinforcement Stiffness (kips/ft)	Shaking Direction
1	Baseline	1380	6	26	Longitudinal
2	Bridge Surcharge Stress	900	6	26	Longitudinal
3	Geogrid Reinforcement Spacing	1380	12	26	Longitudinal
4	Geogrid Reinforcement Stiffness	1380	6	13	Longitudinal
5	Steel mesh Reinforcement	1380	6	330	Longitudinal
6	Shaking Direction	1380	6	26	Transverse

Longitudinal Test Configuration

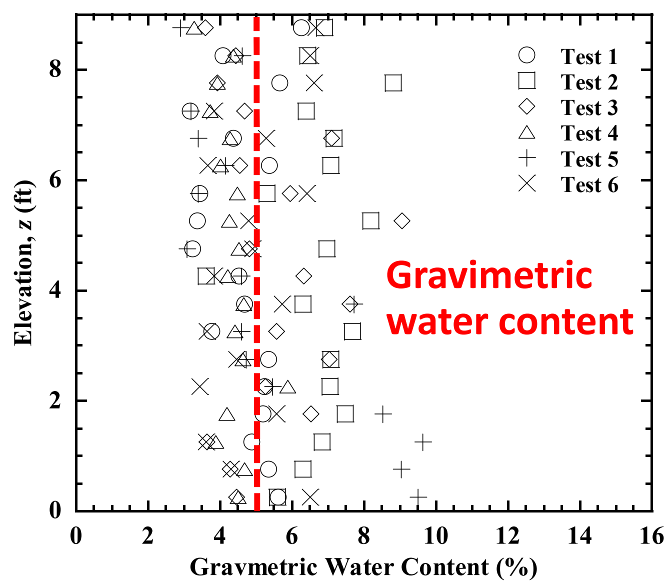


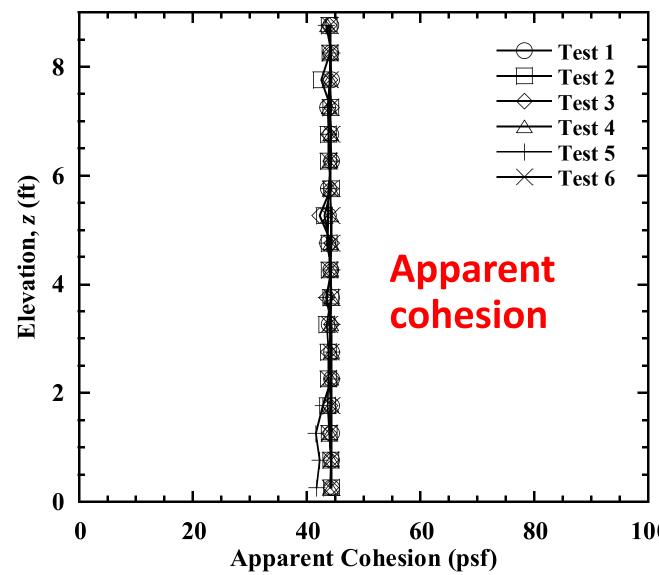

Side wall facing
7 ft
Settlement measurement point
W
S
N
E
2.2 ft
Reaction wall
4.3 ft
1.5 ft
Bridge seat
7 ft
5.2 ft
4.3 ft
3 ft
Bridge beam
6 in
6 in
Front wall facing
7.8 ft
Side wall facing
S
N
E
W
Horizontal displacement measurement point
Reaction wall
Bridge seat
Bridge seat
Bridge beam
4.3 ft
Seismic joint
3 ft
Bridge beam
2 ft
1.5 ft
1.5 ft
2 ft
2 ft
1.5 ft
6 in
6 in
2.2 ft
4.3 ft
6 in
Front wall facing
Side wall facing
9.5 ft
Side wall facing
z
Retained soil
Reinforced soil
7 ft
7 ft
6 in
6 in
10 in
6 in
10 in
6 in
2.1 ft
4.9 ft
2.6 ft
2.6 ft
Foundation soil
x
6 in
yw
7 in
7.8 ft
7 ft

Transverse Test Configuration


7 ft
Reaction wall
W
S
N
E
5.2 ft
2.3 ft
Bridge seat
4.3 ft
Side wall facing
5 ft
5.8 ft
6 in
2.2 ft
1.5 ft
Side wall facing
3 ft
6 in
Bridge beam
Front wall facing
Settlement
measurement point
W
E
S
N
Reaction wall
Bridge seat
2.3 ft
Seismic joint
Bridge beam
2 ft
1.5 ft
1.5 ft
6 in
6 in
2.2 ft
Front wall
facing
9.5 ft
Reinforced soil
7 ft
6 in
10 in
6 in
4.9 ft
Foundation soil
x
6 in
5.8 ft
Horizontal displacement
measurement point
Bridge seat
Bridge beam
3 ft
1.5 ft
2 ft
2 ft
4.3 ft
6 in
Side wall
facing
Side wall
facing
z
7 ft
6 in
10 in
6 in
2.6 ft
2.6 ft
ys
yn
7 in
7 ft

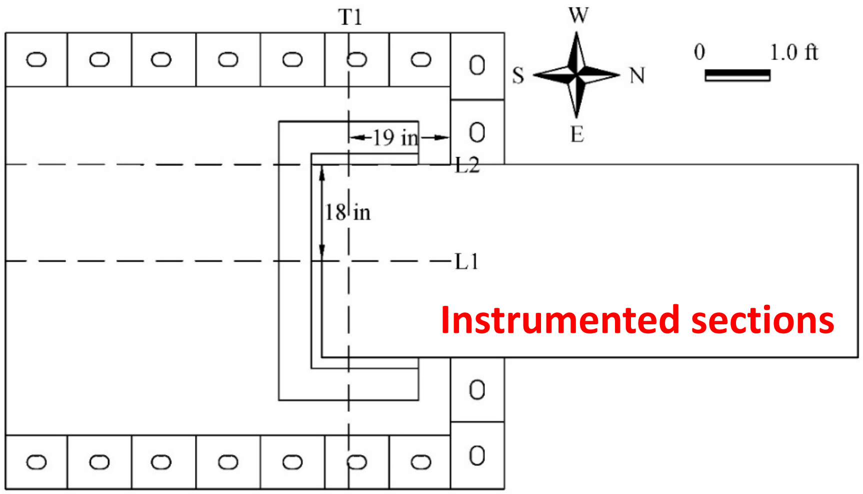
Construction Data

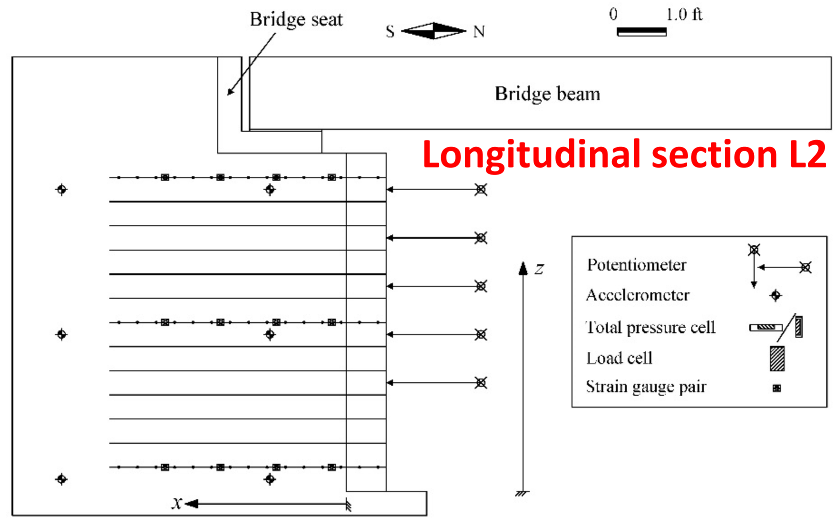


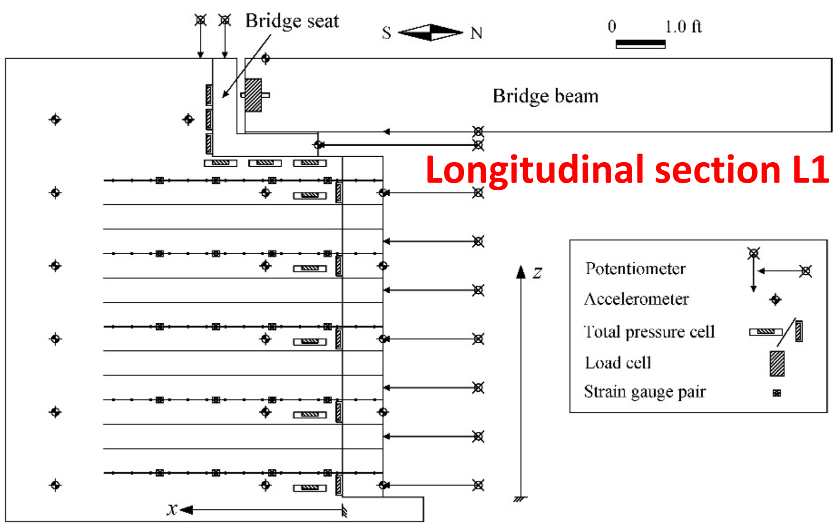


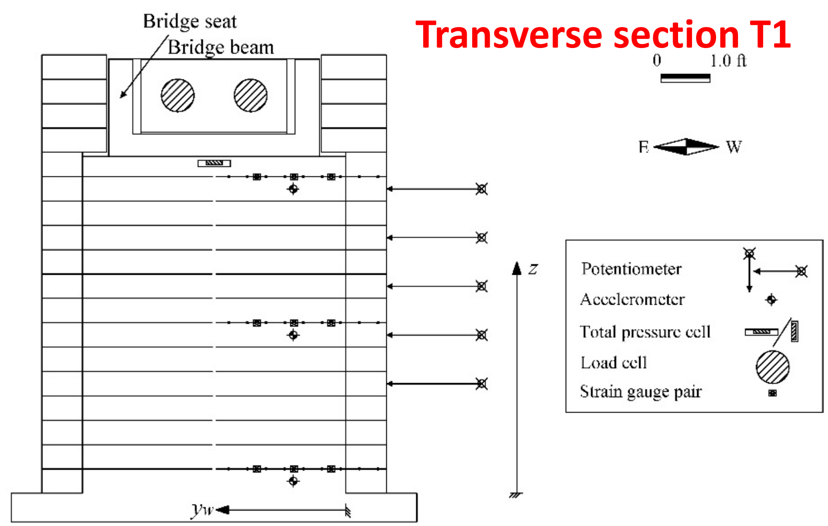
Test No.	1	2	3	4	5	6	Target
Average dry unit weight (pcf)	105.4	108.7	108.6	106.5	105.3	107.8	16.9
Average relative density (%)	64	73	73	67	64	65	70
Average water content (%)	4.7	6.7	5.5	4.3	5.5	5.0	5.0

Instrumentation - Longitudinal Test





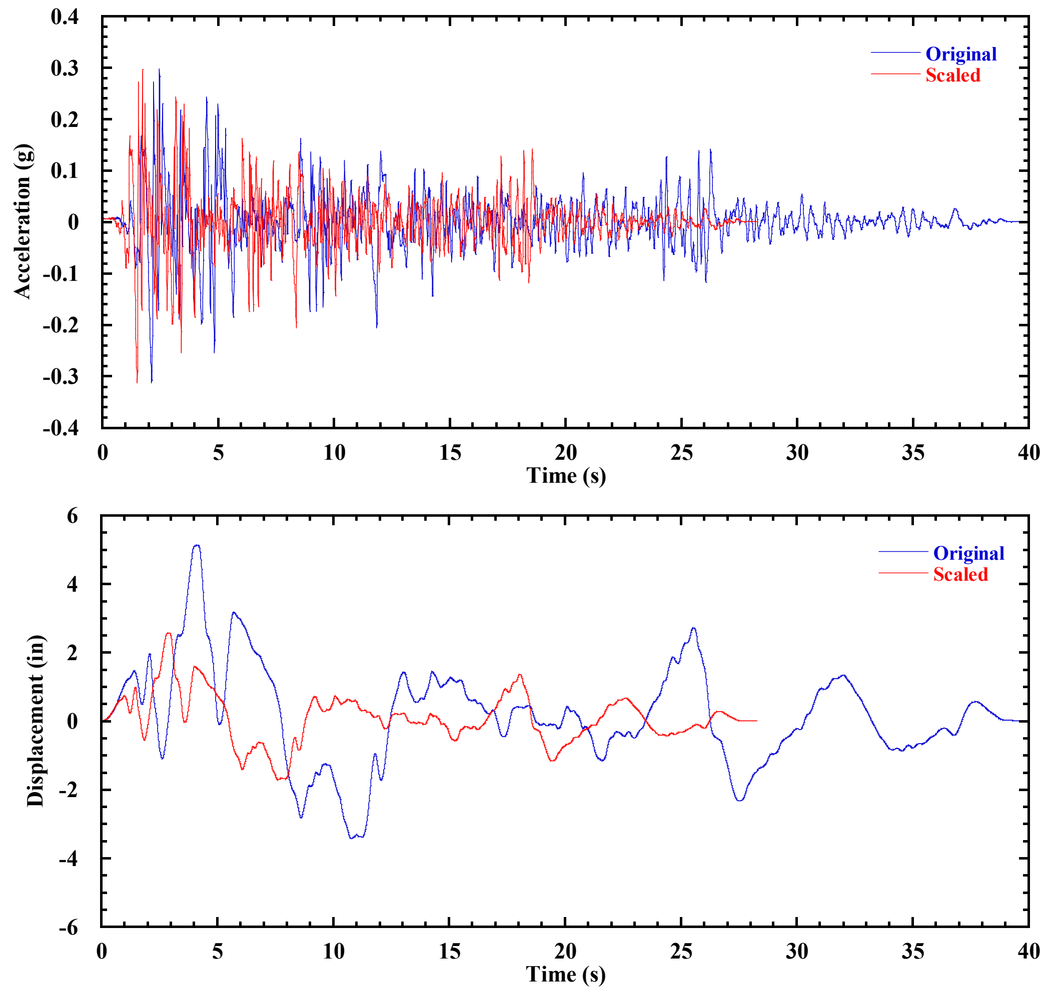




Scaling of Earthquake Motions

For a ½ scale model:

- Frequency of motion is increased by √2, which shortens the duration
- Acceleration amplitude stays the same as the original motion
- Displacement amplitude is scaled by 1/2

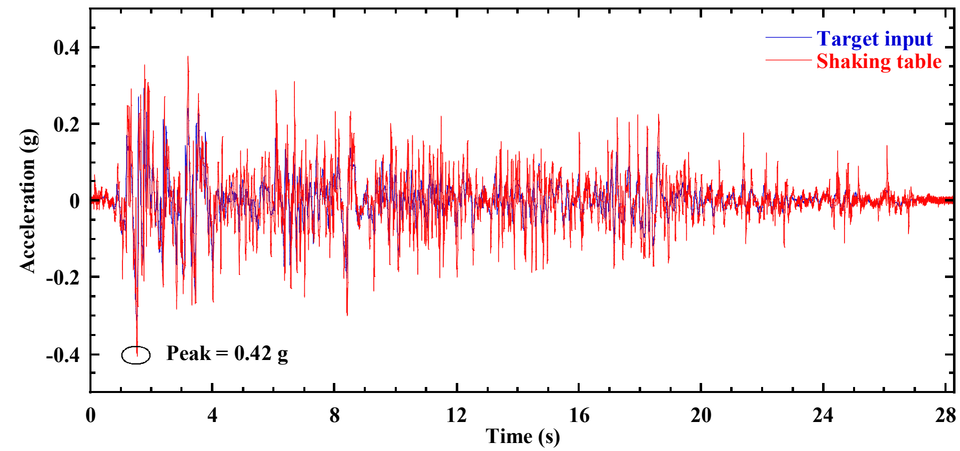


Imperial Valley Motion

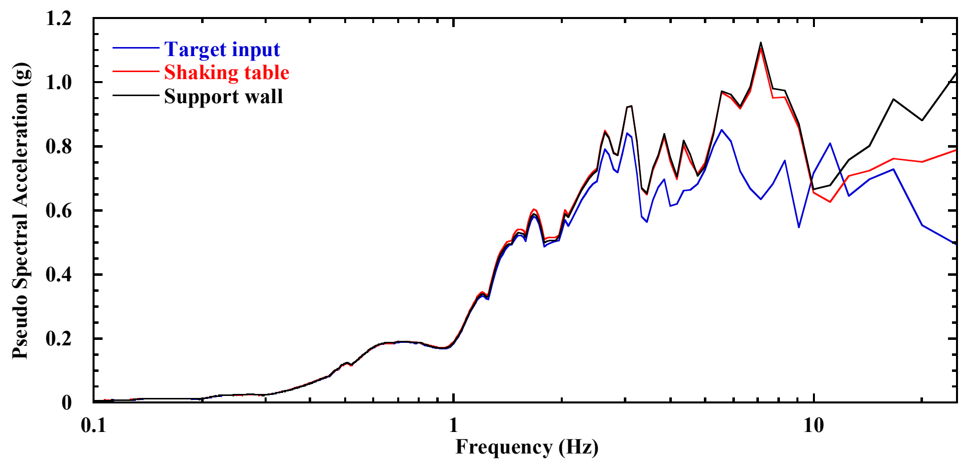
Input Motions

Shaking event	Motion	PGA (g)	PGD (in)
1	**White Noise**	**0.10**	**0.11**
2	**1940 Imperial Valley**	**0.31**	**2.57**
3	**White Noise**	**0.10**	**0.11**
4	**2010 Maule**	**0.40**	**4.25**
5	**White Noise**	**0.10**	**0.11**
6	**1994 Northridge***	**0.58**	**3.49**
7	**White Noise**	**0.10**	**0.11**
8	***Sin @ 0.5 Hz***	***0.05***	***1.97***
9	***Sin @ 1 Hz***	***0.10***	***0.98***
10	***Sin @ 2 Hz***	***0.20***	***0.49***
11	***Sin @ 5 Hz***	***0.25***	***0.10***
12	***White Noise***	***0.10***	***0.11***

Longitudinal Testing System



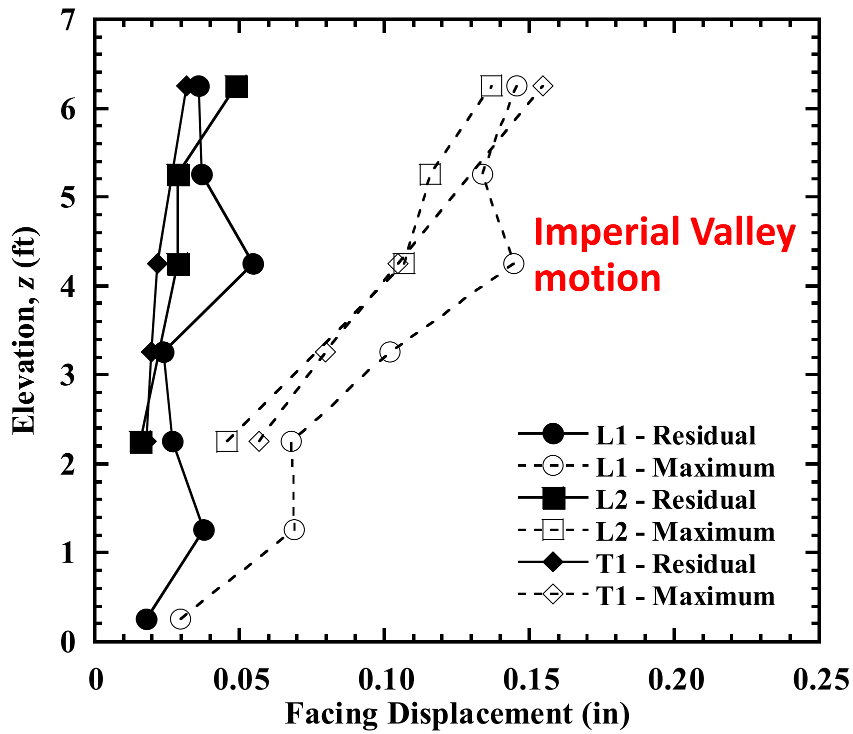
Imperial Valley Earthquake Acceleration Time History

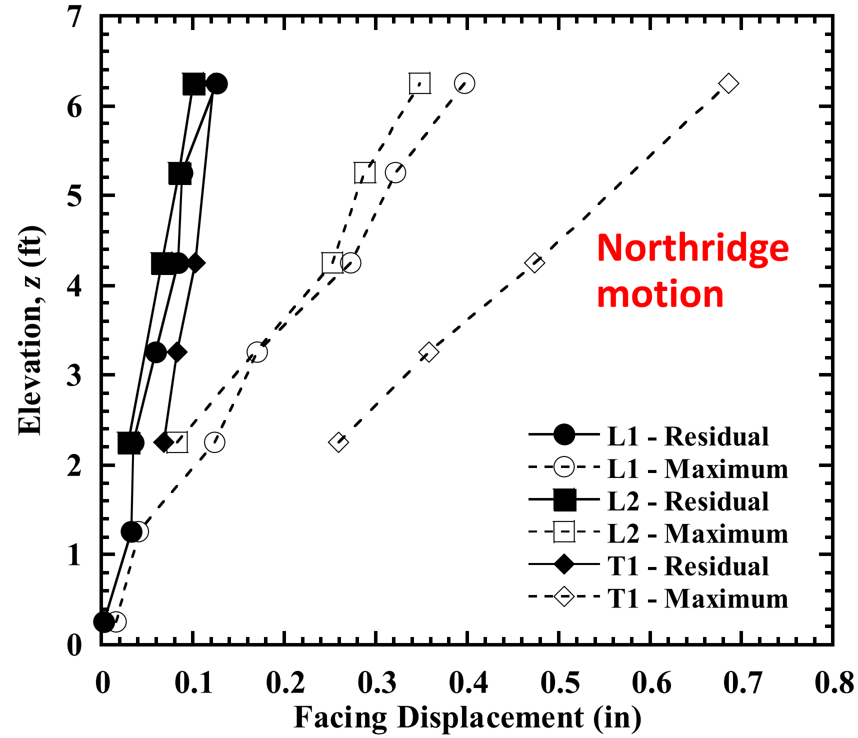


Response Spectra

- Measured displacement time histories for the shaking table, reaction wall, and support wall are identical with the target input displacement time history
- Actual shaking table acceleration time history in general matches well with the target input accelerations
- Actual pseudo-spectral accelerations for the shaking table agree reasonably well with the target values

Facing Displacements

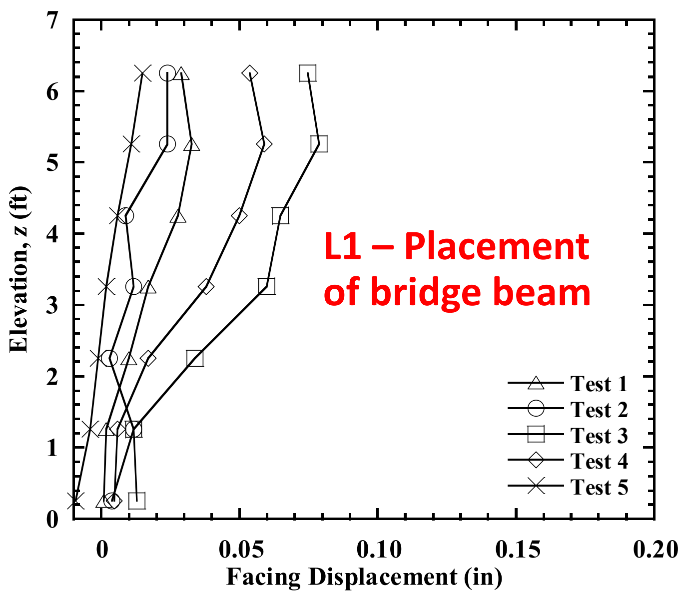


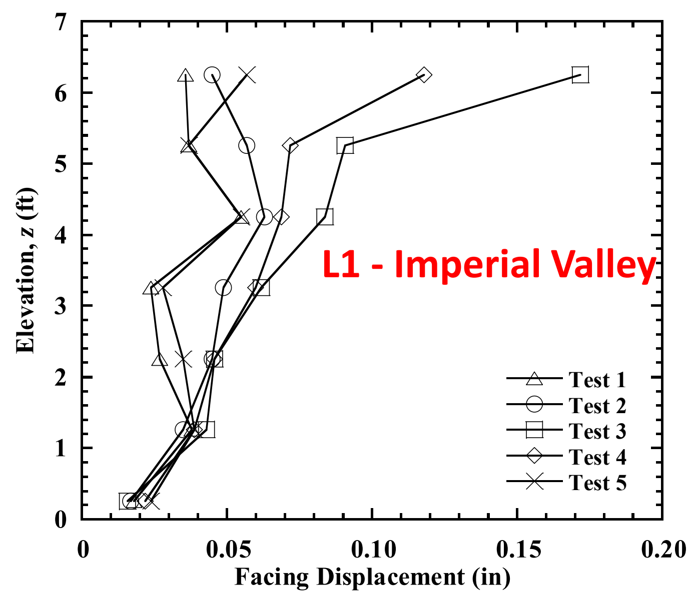


- Seismic displacements at the top are larger than the bottom
- Residual displacements are generally small (max 0.14 in for the Northridge motion)
- Longitudinal shaking resulted in displacements in transverse direction

Facing Displacements

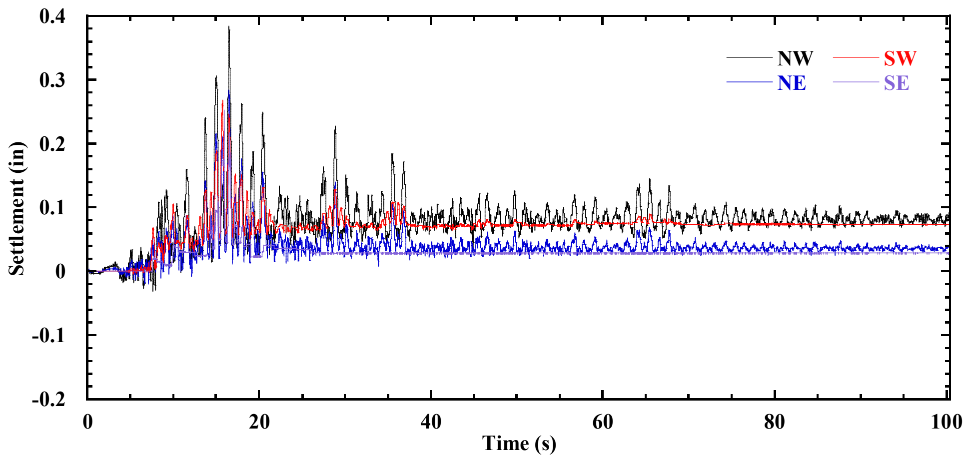
Test No.	1	2	3	4	5
Description	Baseline	Reduced Bridge Load	Increased Reinforcement Spacing	Reduced Reinforcement Stiffness	Steel Reinforcement





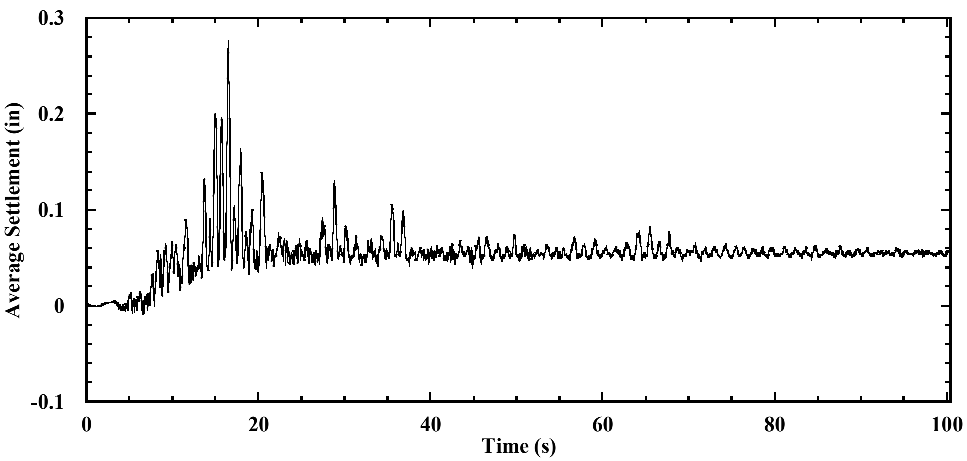
- Reinforcement spacing and stiffness have the most significant effects
- Greater bridge load resulted in larger displacements under static loading, but smaller residual displacements from seismic loading

Bridge Seat Settlements



Bridge Seat Settlement Measurements at Corners

Bridge Seat Instrumentation

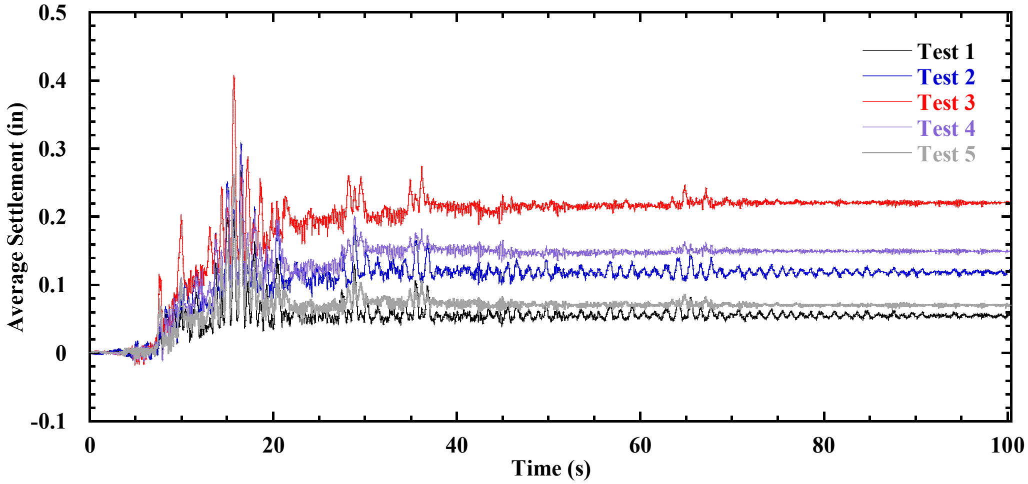


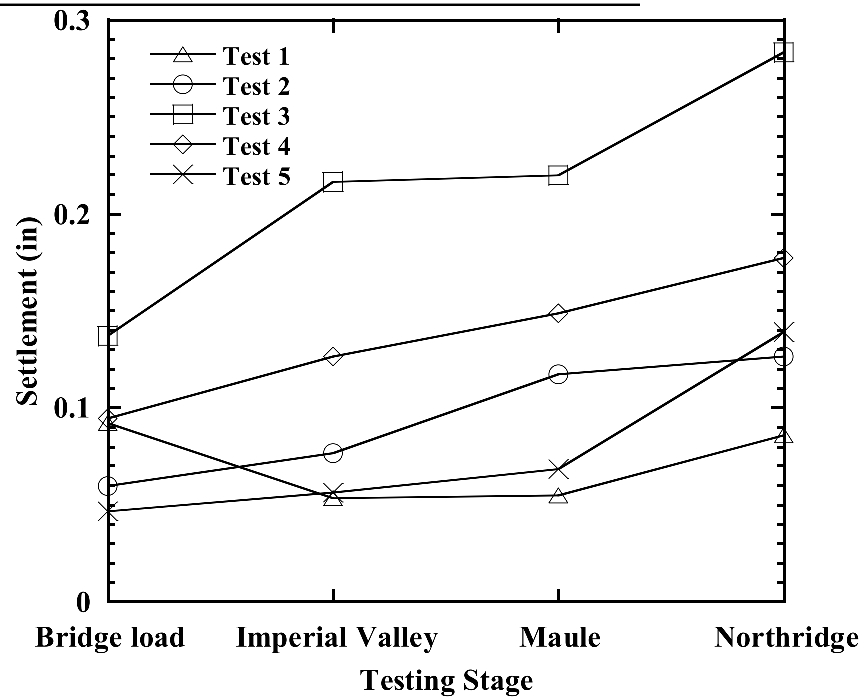
Average Bridge Seat Settlement

- Maximum dynamic settlement is 0.28 in, and residual settlement is 0.06 in, corresponding to a vertical strain of 0.07%
- This residual settlement would not be expected to cause significant damage

Bridge Seat Settlements

Test No.	1	2	3	4	5
Description	Baseline	Reduced Bridge Load	Increased Reinforcement Spacing	Reduced Reinforcement Stiffness	Steel Reinforcement

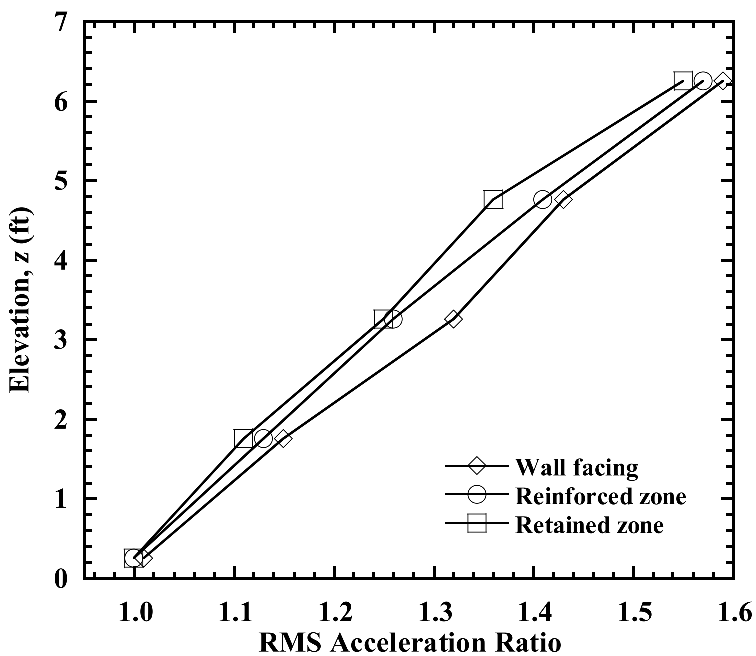


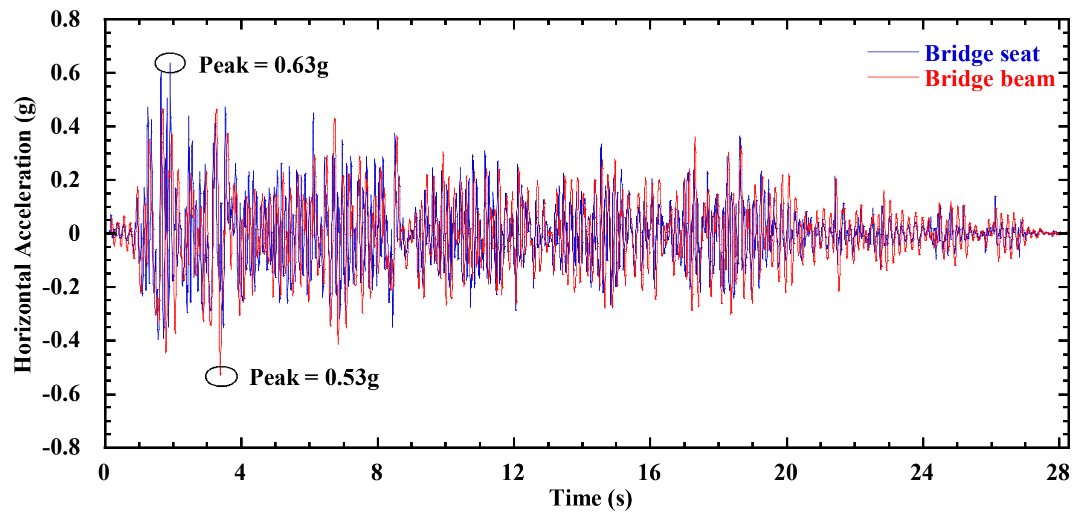


- Reinforcement spacing and stiffness have the most significant effects
- Greater bridge load resulted in larger settlements for static loading, but smaller settlements for seismic loading

Acceleration Responses

Accelerations for the Imperial Valley motion in Test 1



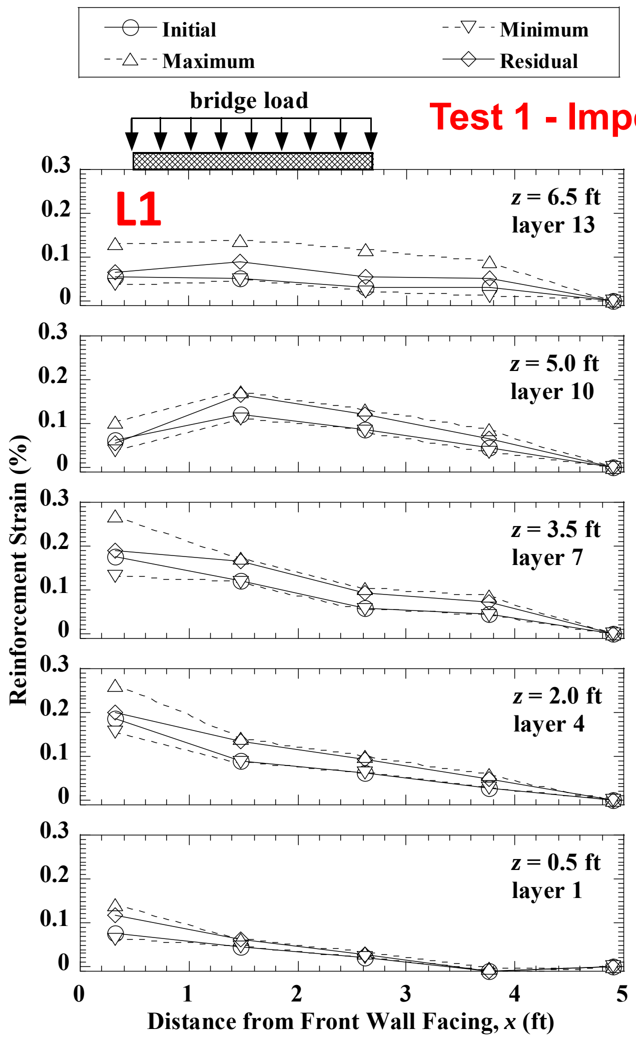


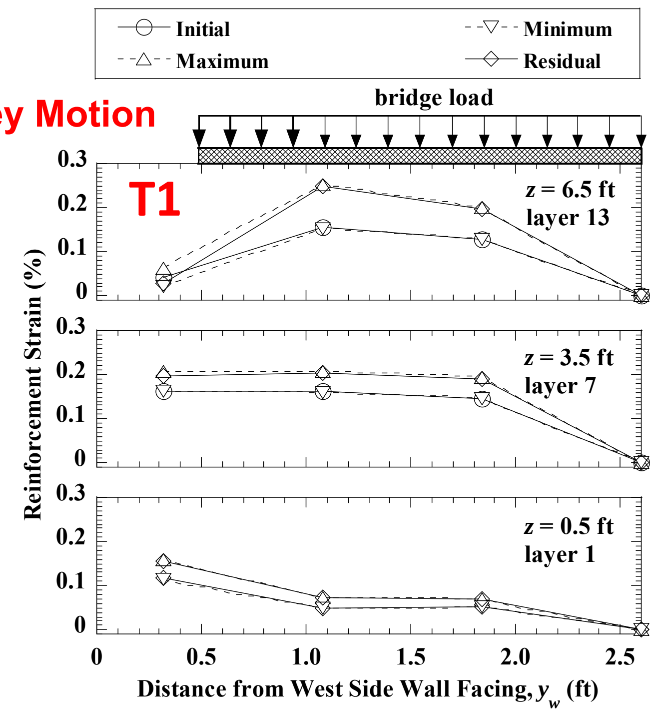
Amplification ratio = 1.60 for bridge seat
Amplification ratio = 1.80 for bridge beam

- Acceleration amplification increases with elevation in the MSE bridge abutment
- Amplification ratios increase from retained zone to reinforced zone to wall facing
- Amplification ratio for bridge beam is larger than bridge seat

Reinforcement Strains

Test 1 - Imperial Valley Motion

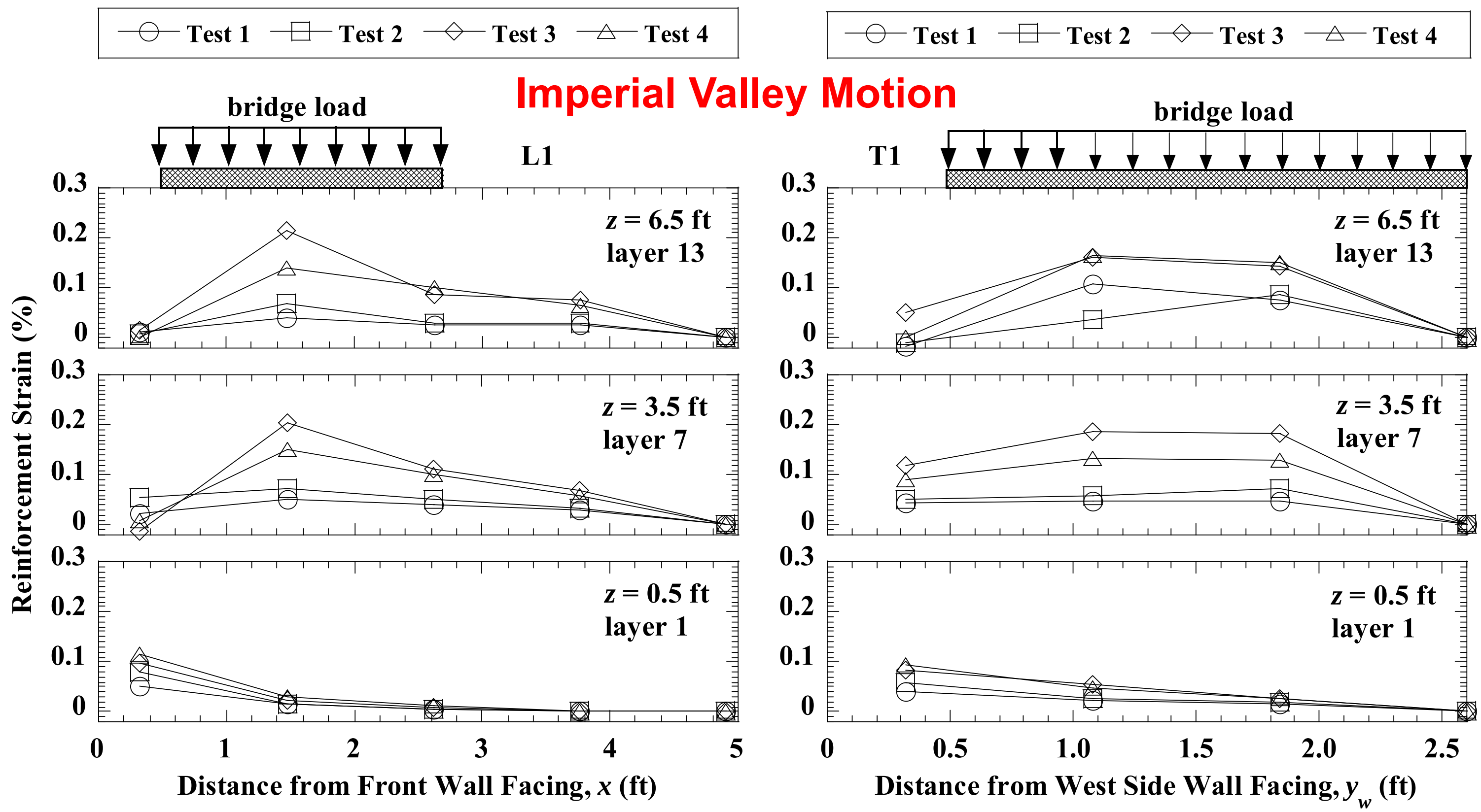




- Max strains are small and far from the ultimate capacity of the geogrids
- Location of max strains under the bridge seat in upper layers and near connections in lower layers
- Longitudinal shaking resulted in strains in the transverse direction

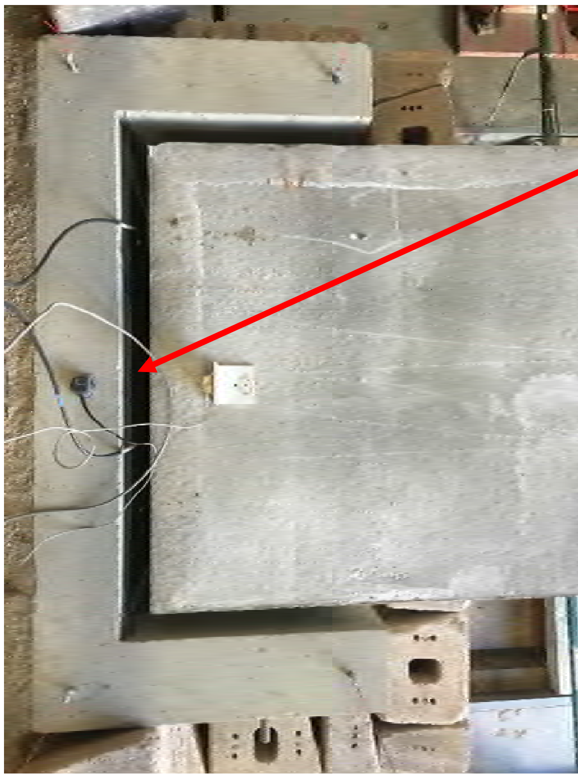
Reinforcement Strains

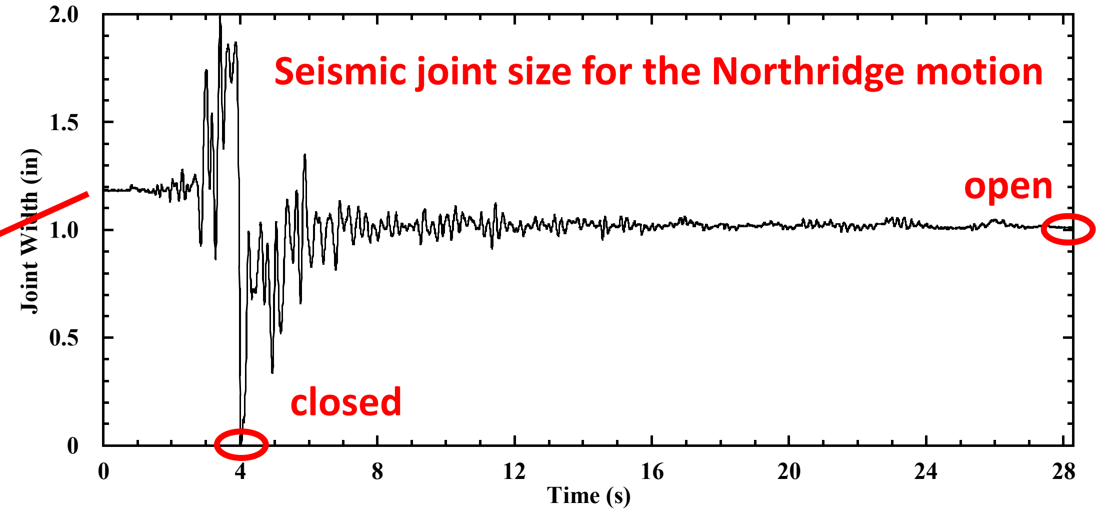
Incremental residual reinforcement strains

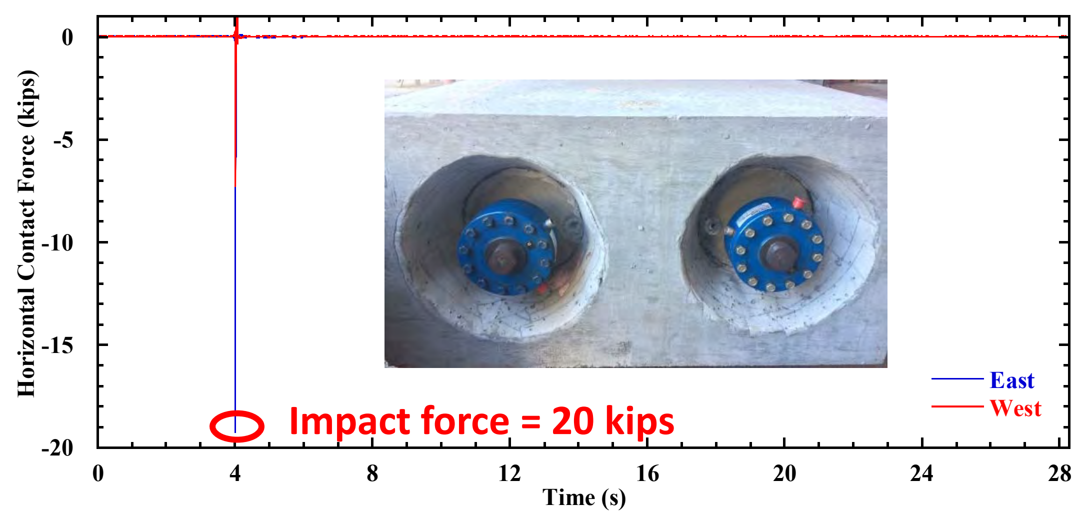


- Reinforcement spacing and stiffness have the most significant effects
- Greater bridge load results in larger reinforcement strains

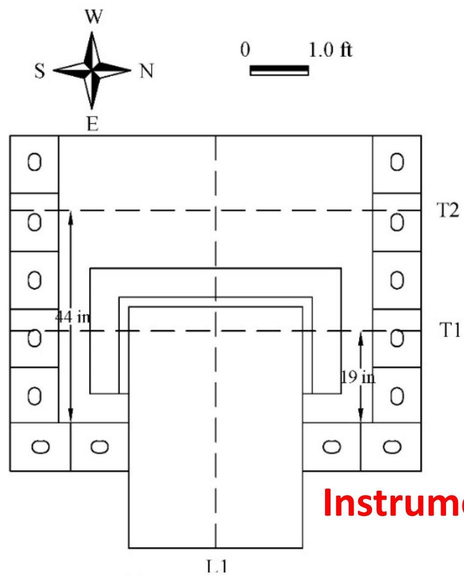
Contact Forces



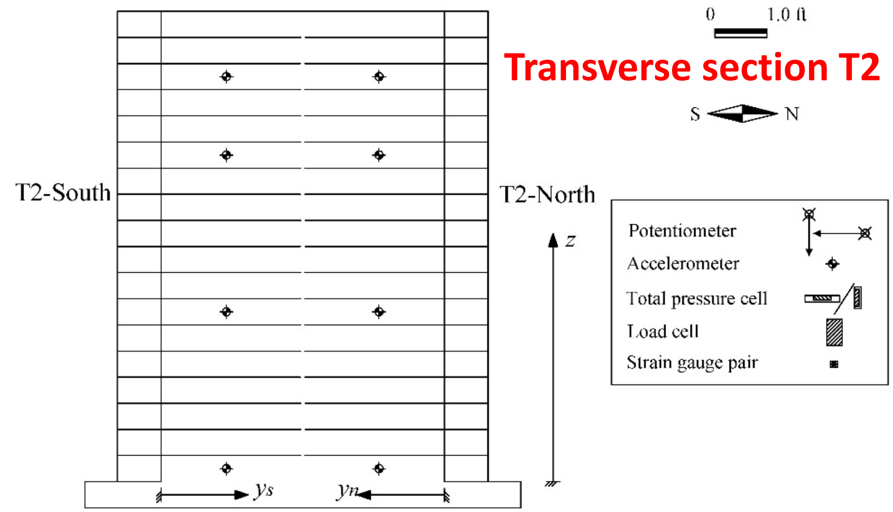




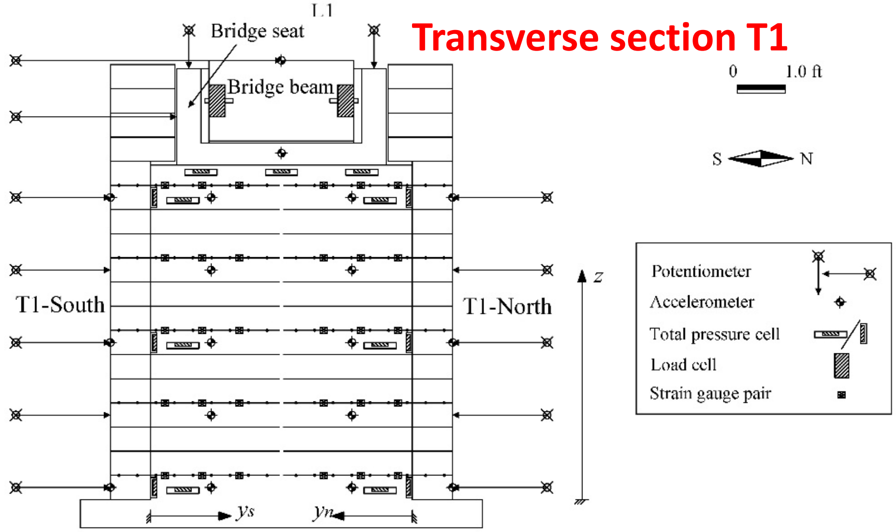
Instrumentation - Transverse Test



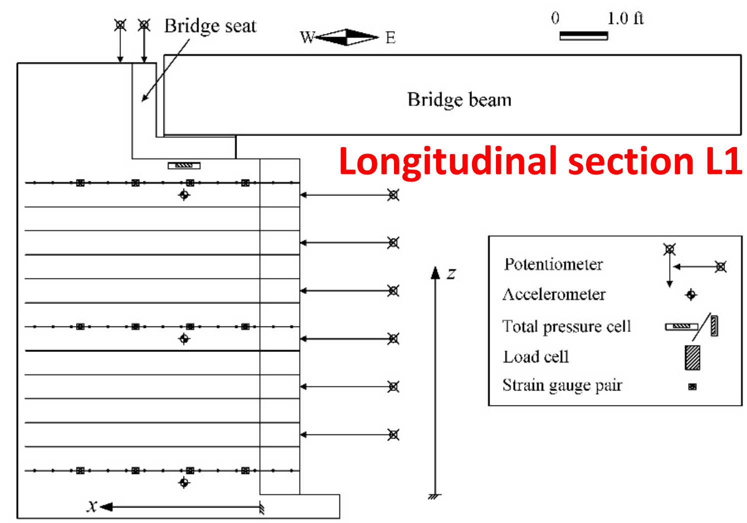
Instrumented sections



Transverse section T2

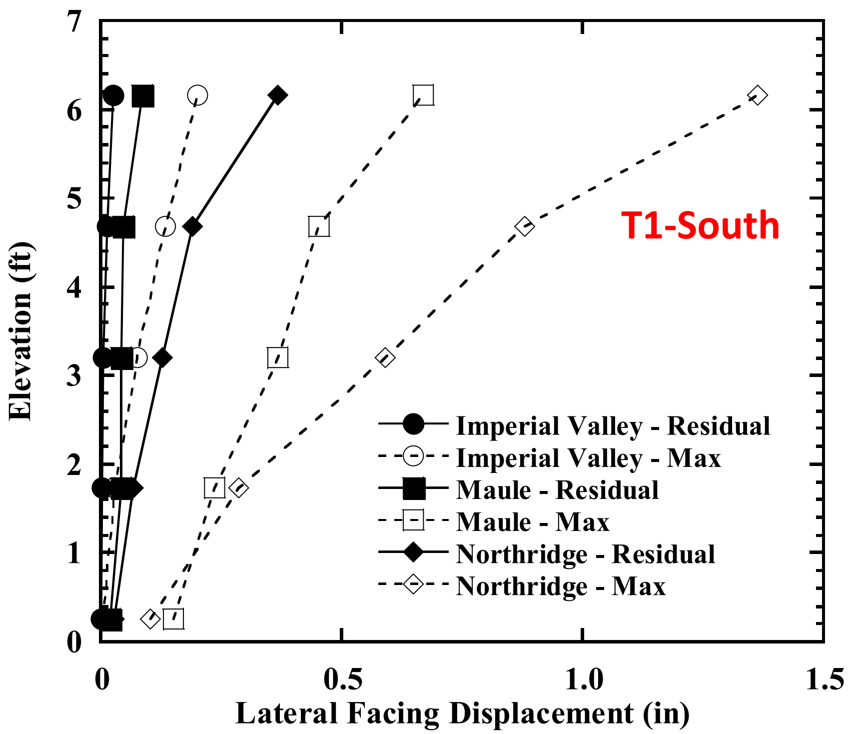


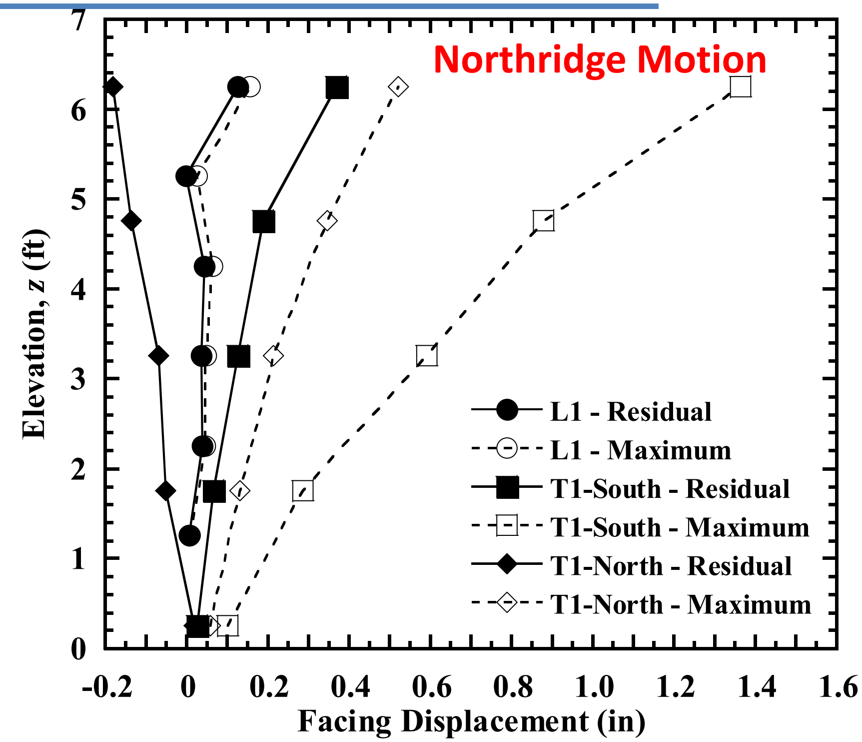
Transverse section T1



Longitudinal section L1

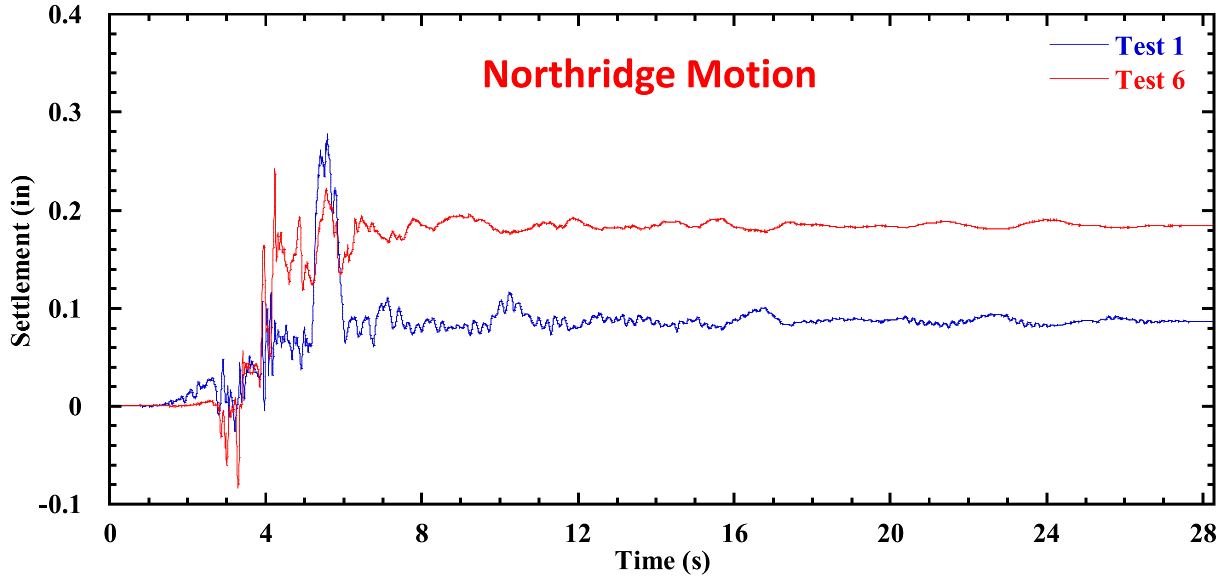
Facing Displacements





- Seismic-induced maximum facing displacements are much larger for the Northridge motion than the other two motions, but most of the displacements were recovered after shaking
- T1-South had outward displacements, whereas T1-North had inward displacements
- Transverse shaking resulted in displacements in longitudinal direction

Bridge Seat Settlements

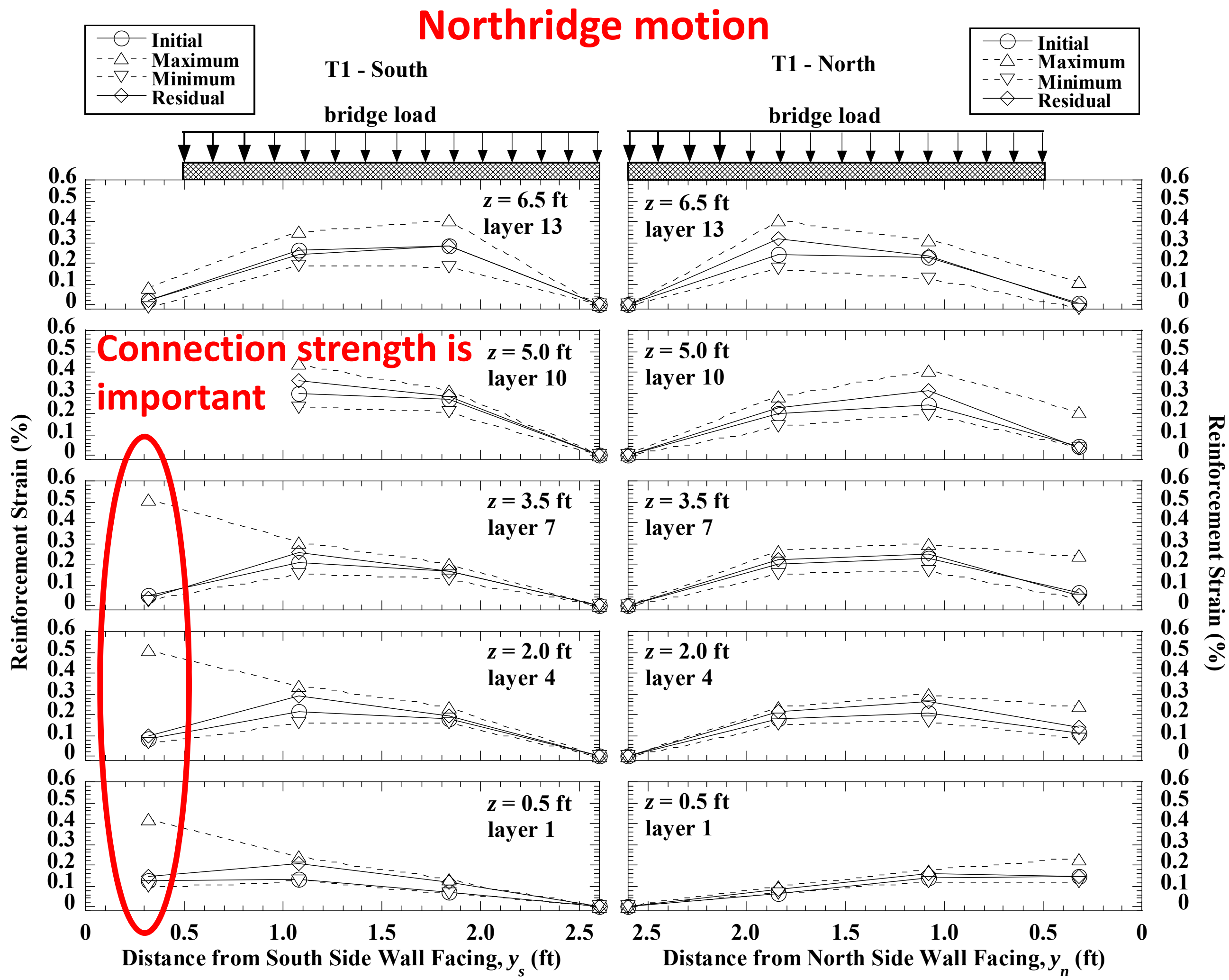


Average incremental residual bridge seat settlement (model scale)

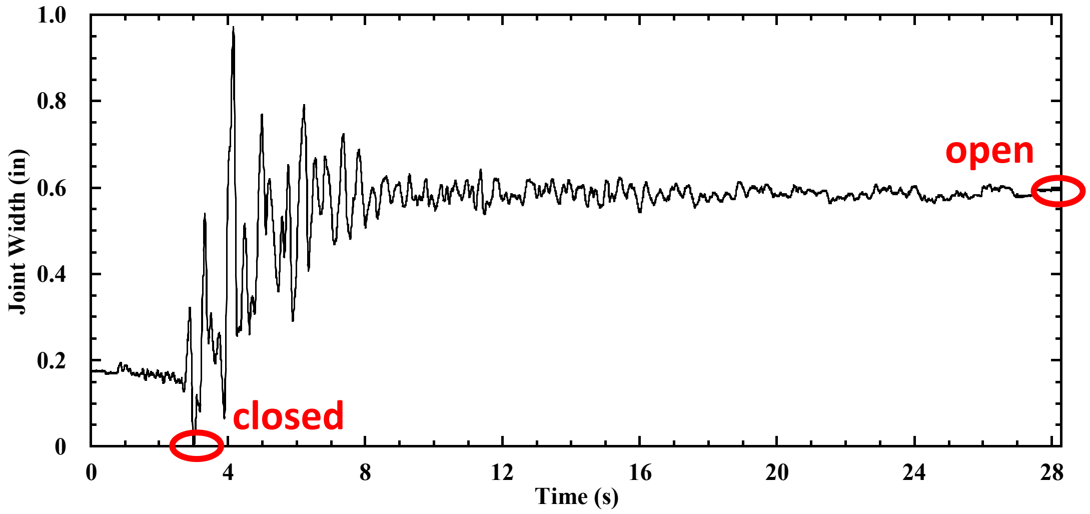
Shaking Direction	Imperial Valley (in)	Maule (in)	Northridge (in)
Longitudinal	**0.06**	**0.06**	**0.09**
Transverse	**0.10**	**0.19**	**0.19**

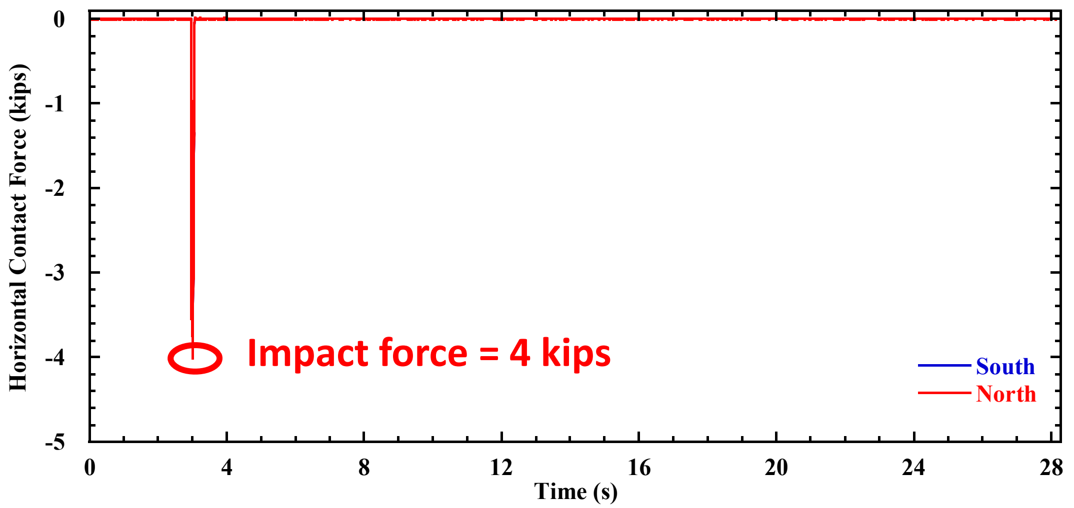
Transverse > Longitudinal

Reinforcement Strains



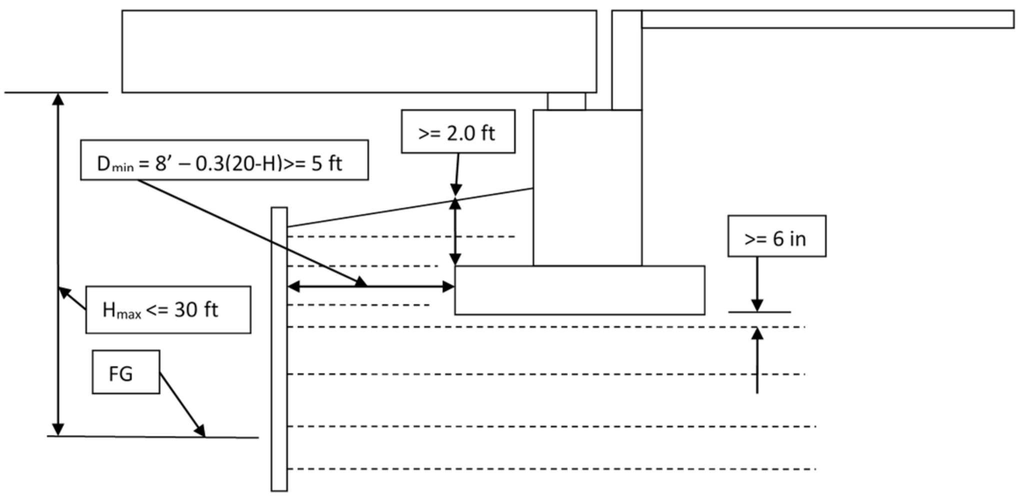
Contact Forces





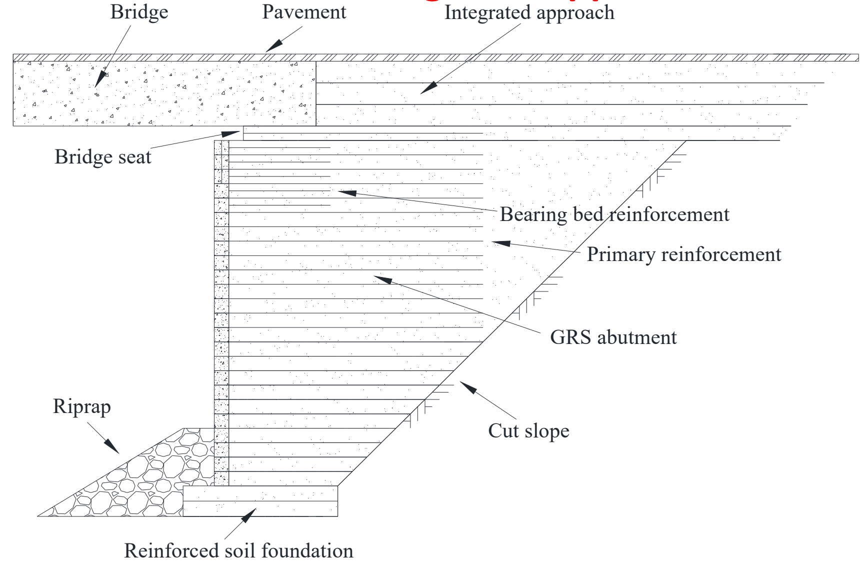
Future Testing on LHPOST

Bridge seat with joint



MSE Bridge Abutment

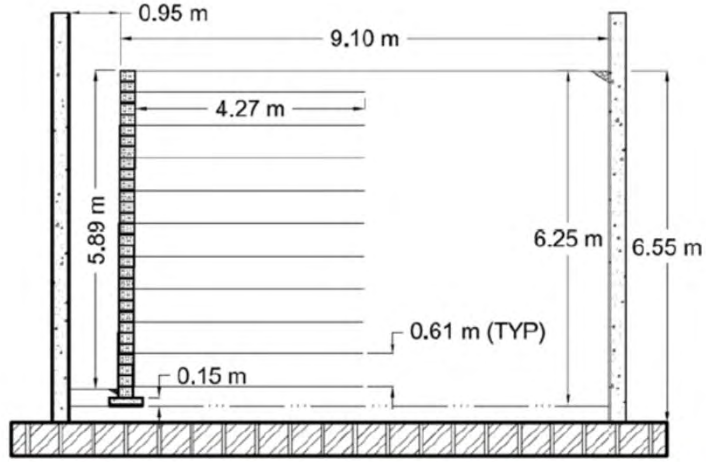
Jointless integrated approach



GRS-IBS Abutment

- Compare the response of actual bridge abutment designs using full-scale models
  - Caltrans-approved MSE bridge abutment (footing embedded in GRS mass with setback)
  - FHWA GRS-IBS abutment (bridge beam resting on GRS mass)
- No similitude required, can use actual construction materials, can use representative geometry of field-scale system

Future Testing on LHPOST: Plane-Strain Container



Conclusions

- MSE bridge abutment seismic/residual displacements are small and are not expected to cause significant damage to bridge superstructures
  - Seismic longitudinal residual bridge seat settlements range from 0.06 to 0.28 in.
  - Seismic longitudinal residual lateral facing displacements range from 0.05 to 0.17 in.
- Main take-aways:
  - Reducing reinforcement spacing and increasing reinforcement stiffness are the most effective means to reduce static and seismic abutment deformations
  - Greater bridge load results in larger deformations for static loading, but smaller deformations for seismic loading, which is attributed to the larger soil stiffness under greater bridge load
- Seismic residual bridge seat settlements due to transverse shaking are larger than for the longitudinal shaking
- Overall, the MSE bridge abutments show good seismic performance in terms of facing displacements and bridge seat movements
- The limitation of available shaking table size/capacity in the Powell lab had some effects which can be alleviated with numerical simulations and full-scale testing

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- Zheng, Y., McCartney, J.S., Shing, P.B., and Fox, P.J. (2018). "Half-scale transverse shaking table test of a geosynthetic reinforced soil bridge abutment." Geosynthetics International. 10.1680/jgein.18.00019.
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- Zheng, Y., Fox, P.J., Shing, P.B., and McCartney, J.S. "Physical model tests on half-scale geosynthetic reinforced soil bridge abutments. II: Dynamic loading." Journal of Geotechnical and Geoenvironmental Engineering. In review.