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Shake Table Testing of GRS Bridge Abutments

Prof. John S. McCartney and Yewei Zheng

University of California San Diego

Department of Structural Engineering

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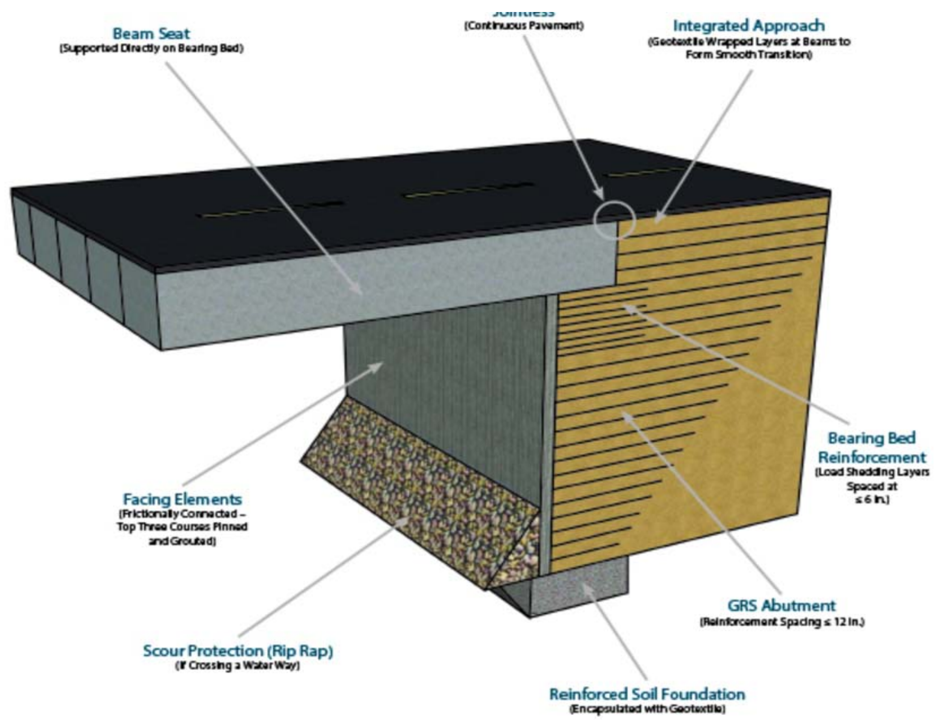
Presentation Overview

- Research Motivation
- Shaking Table Testing Program
  - Material Properties
  - Test Configuration
  - Construction
  - Instrumentation
  - Input Motions
- Test Results and Analysis
  - Longitudinal Tests
  - Transverse Test
- Conclusions and Future Work

GRS Bridge Abutments

<u>Geosynthetics in transportation application</u>

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

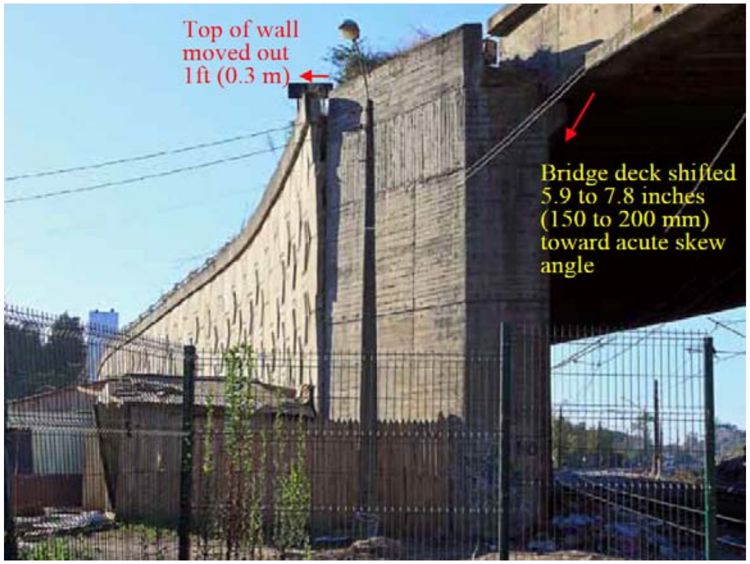


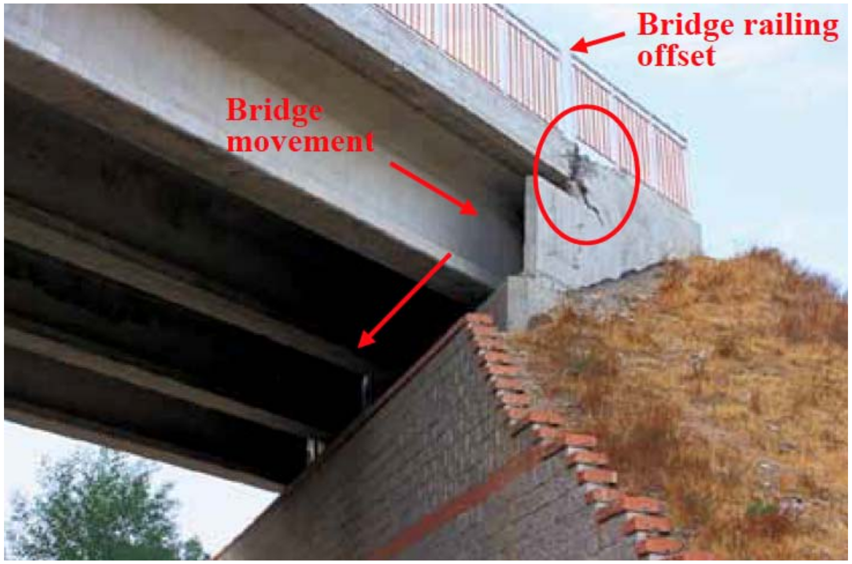
- GRS retaining walls as bridge abutments with bridge loads applied directly to the reinforced soil mass
- Many advantages, including lower cost, easier and faster construction, and smoother approach roadway transition

GRS Bridge Abutments

GRS bridge abutments have been widely used in US, but have not been adopted in California due to potential seismic issues:

- Geotechnical: backfill settlement and facing displacement
- Structural: bridge beam and seat movements, impact forces between bridge beam and seat, and interaction between bridge superstructure and GRS abutment





Post-earthquake investigations for the 2010 Maule earthquake, Chile (Yen et al. 2011)

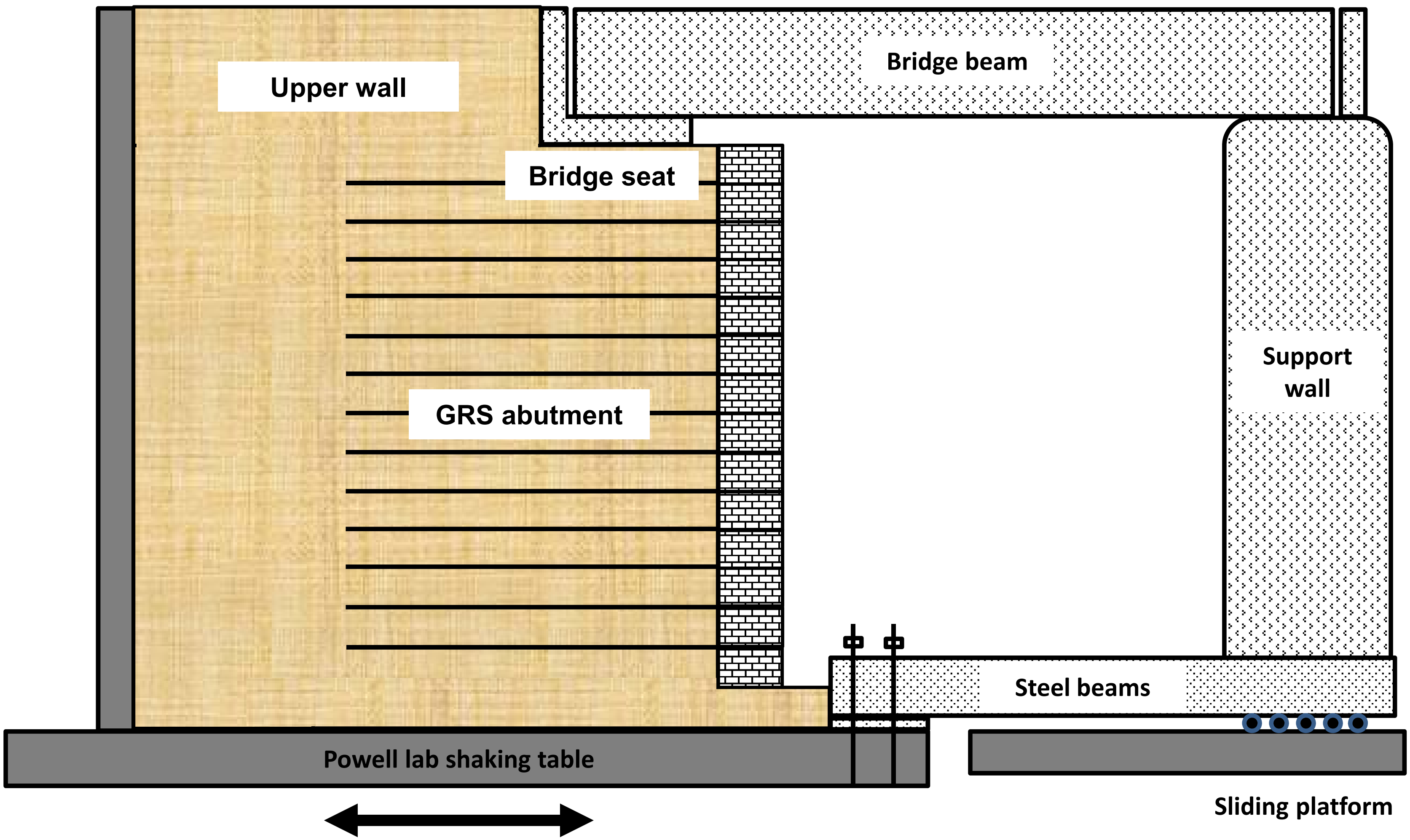
Shake Table Testing Program

Shaking table tests have been used successfully to investigate seismic performance of GRS structures (El-Emam and Bathurst 2004, 2005, 2007; Ling et al. 2005, 2012; Tatsuoka et al. 2012; Helwany et al. 2012)

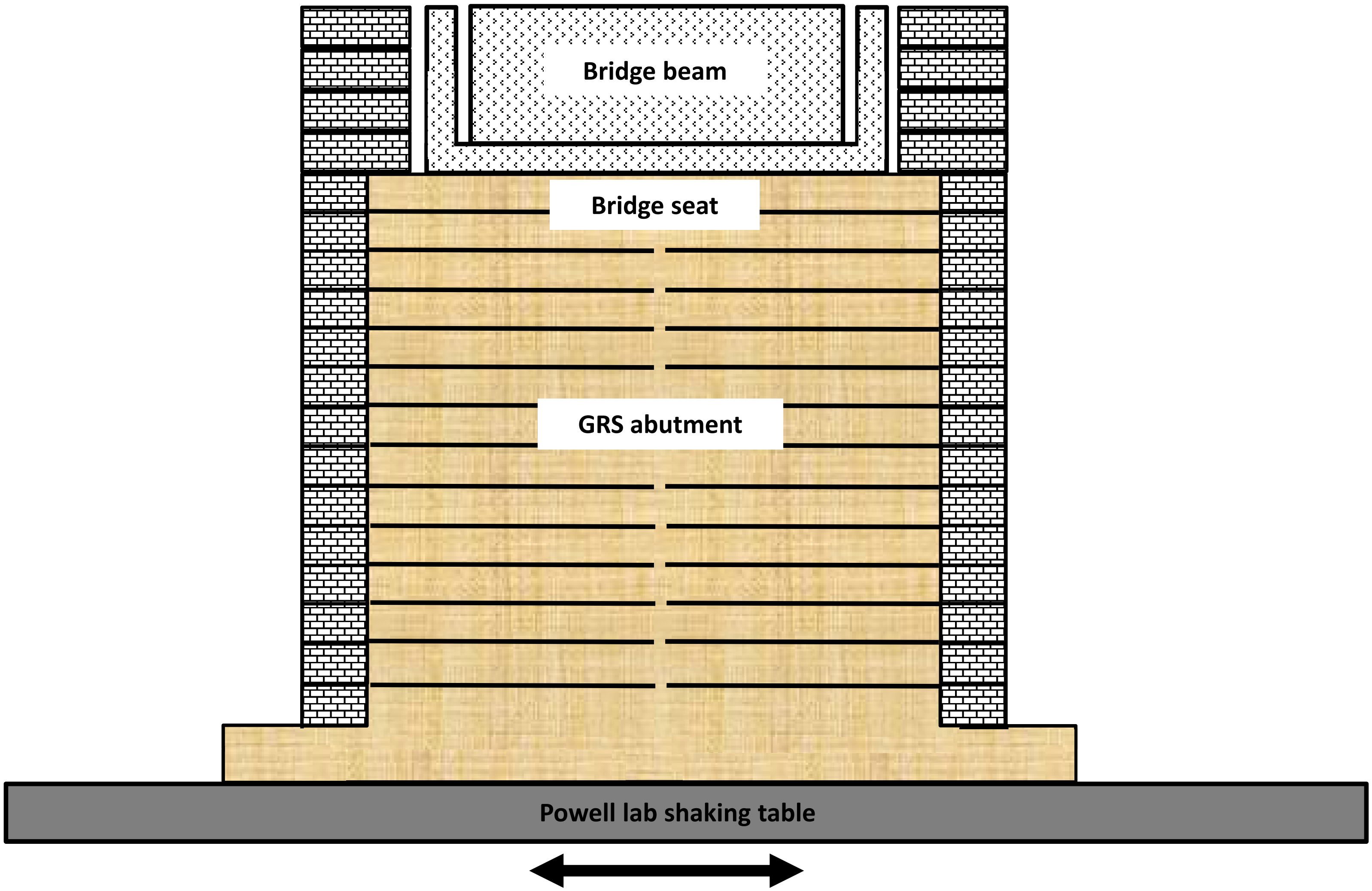
UCSD South Powell Structural Lab Shaking Table:

- Dimensions: 3 m x 5 m
- Shaking DOF: 1 D in N-S direction
- Maximum gravity load: 350 kN
- Dynamic stroke: ± 150 mm
- Dynamic capacity: 400 kN

Longitudinal Testing



Transverse Testing



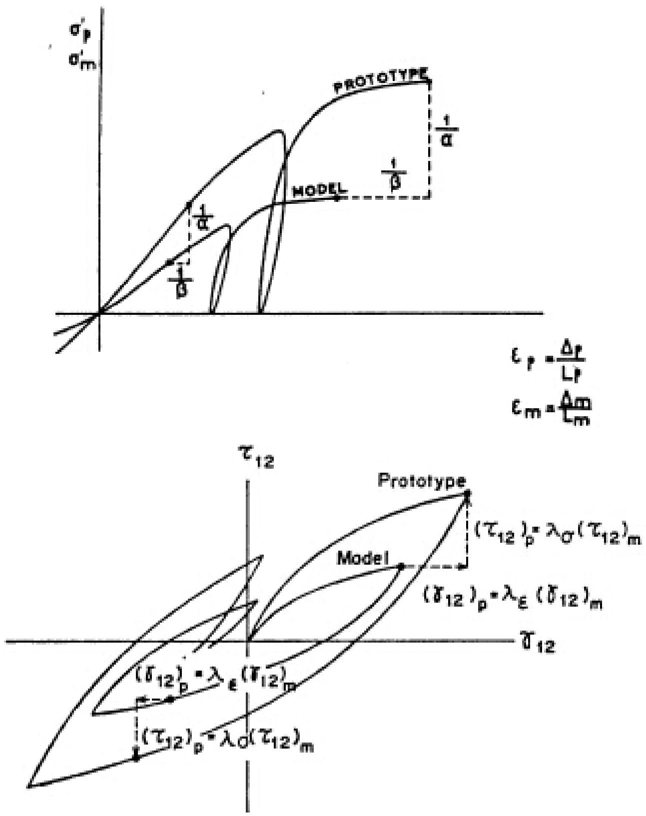
Similitude Relationships

Similitude for 1*g* shaking table tests (Iai 1989)

Variable	Theoretical scaling factor	Scaling factor for $\lambda = 2$
Length	λ	2
Material density	1	1
Strain	1	1
Mass	λ^3	8
Acceleration	1	1
Velocity	$\lambda^{1/2}$	1.414
Stress	λ	2
Modulus	λ	2
Stiffness	λ^2	4
Force	λ^3	8
Time	$\lambda^{1/2}$	1.414
Frequency	$\lambda^{-1/2}$	0.707

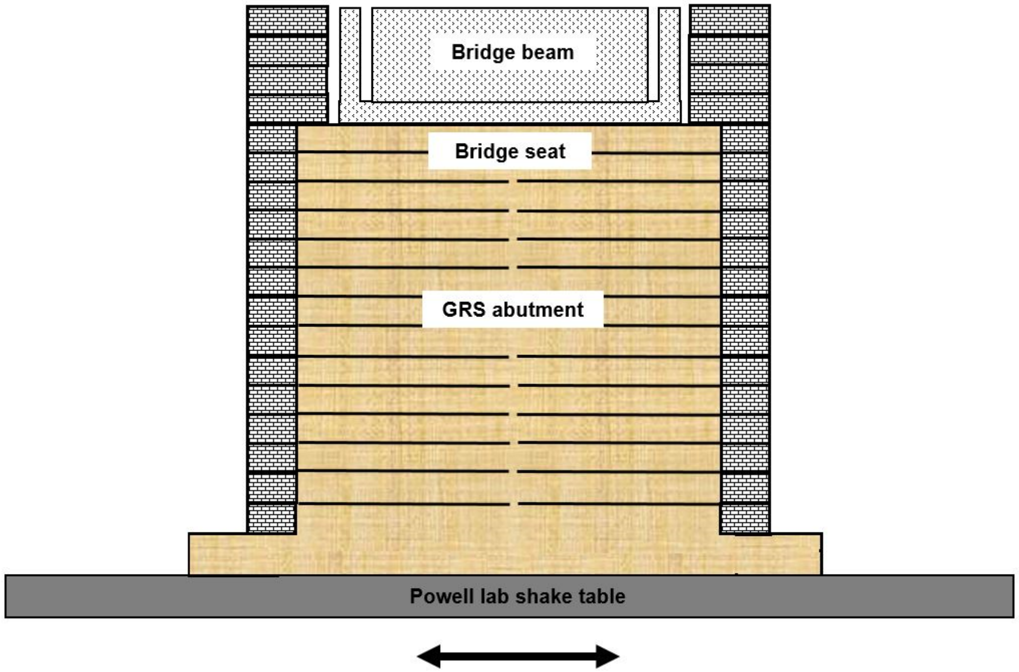
Model geometry, reinforcement stiffness, soil modulus, bridge load, and frequencies of earthquake motions were scaled

Goal: Similar response in model and prototype



Stress-strain relationships for model and prototype (Rocha 1957; Roscoe 1968)

Model Design



Model geometry scaling

	Prototype	Model
Wall height (m)	4.2	2.1
Bridge seat thickness (m)	0.3	0.15
Clearance height (m)	4.5	2.25
Wall length (m)	4.7	2.35
Wall width (m)	4.2	2.1
Bridge width (m)	1.8	0.9

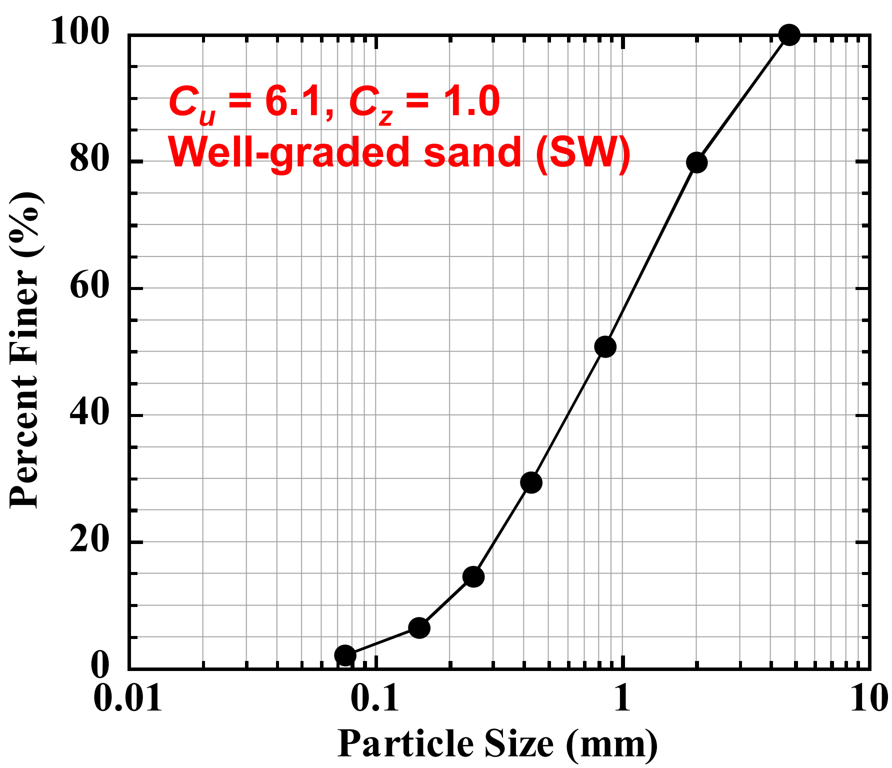
Block scaling

	Prototype	Model
Product	-	Keystone
Dimensions (L x W x H)	0.6 m x 0.5 m x 0.3 m	0.3 m x 0.25 m x 0.15 m

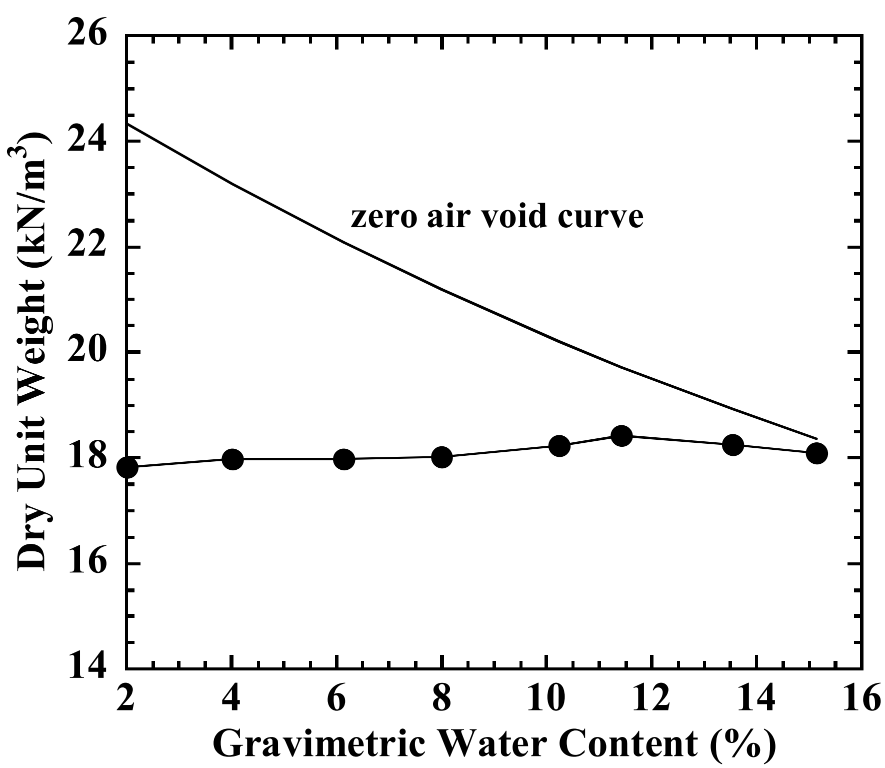
Reinforcement scaling

	Prototype	Model
Product	UX1700	LH800
Stiffness (kN/m)	1500	380

Backfill Soil



Gradation curve



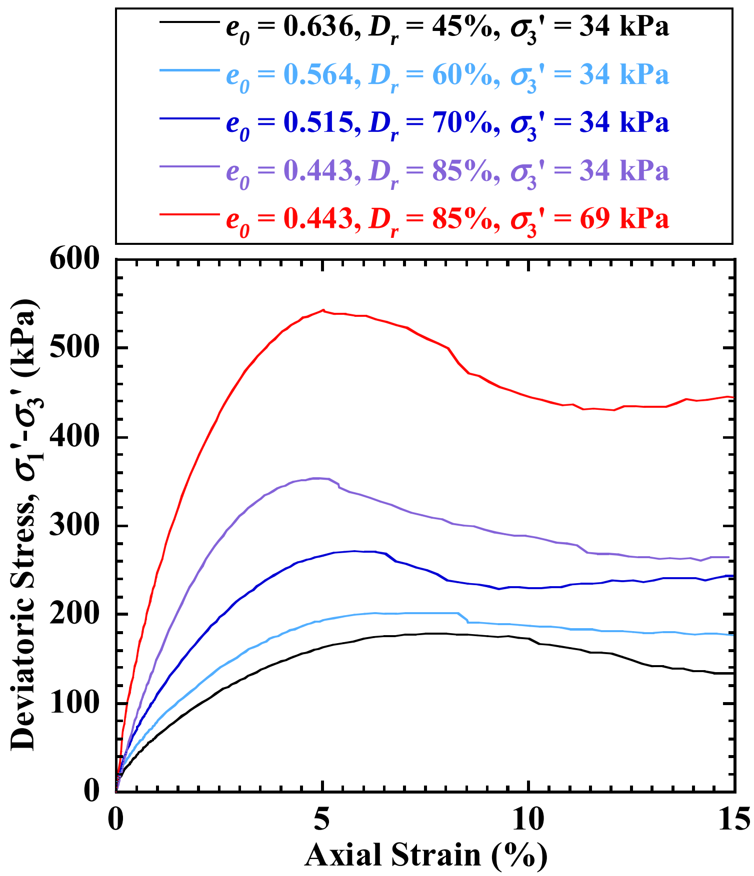
Compaction curve

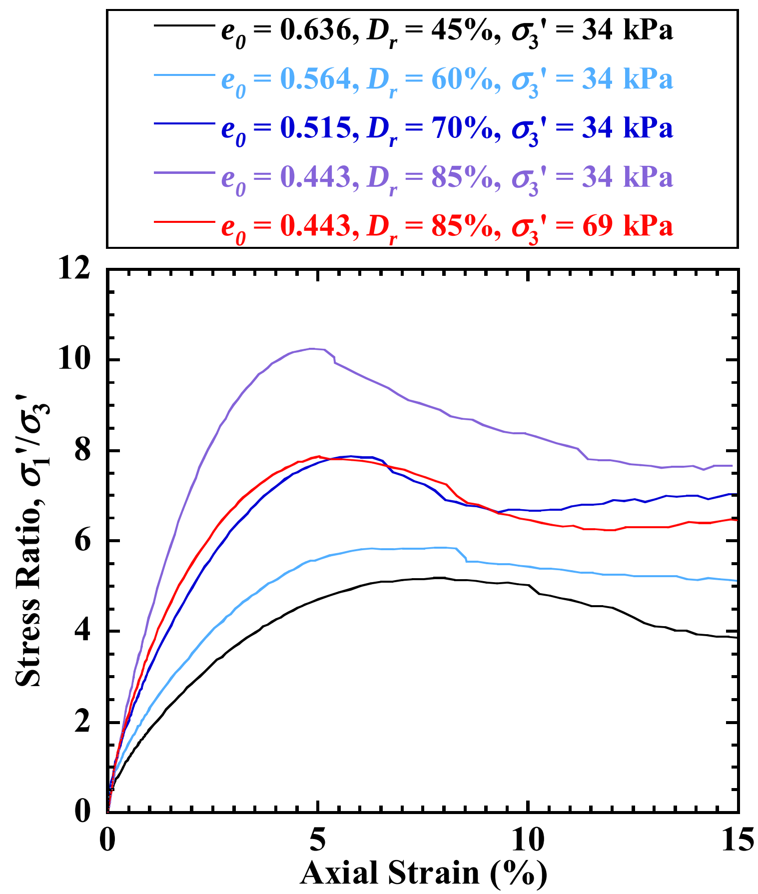
Backfill Soil Properties

Properties	Value
Specific gravity, G_s	2.61
Coefficient of uniformity, C_u	6.1
Coefficient of curvature, C_z	1.0
Maximum void ratio, e_{max}	0.853
Minimum void ratio, e_{min}	0.371
Peak friction angle, ϕ' (°)	51.3
van Genuchten (1980) SWRC model parameter, a_{vG} (kPa^{-1})	0.5
van Genuchten (1980) SWRC model parameter, N_{vG}	2.1
Drying curve volumetric water content at zero suction, θ_d	0.32
Wetting curve volumetric water content at zero suction, θ_w	0.20
Residual volumetric water content, θ_r	0

Selection of Compaction Conditions

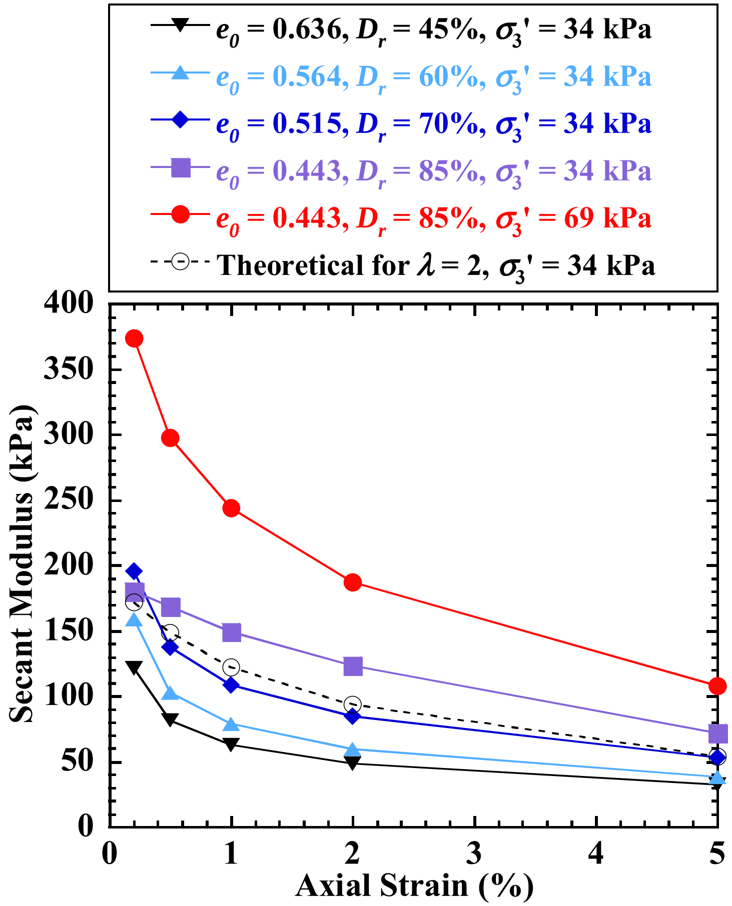
Target relative density (D_r) for prototype structures = 85% (96% standard relative compaction)

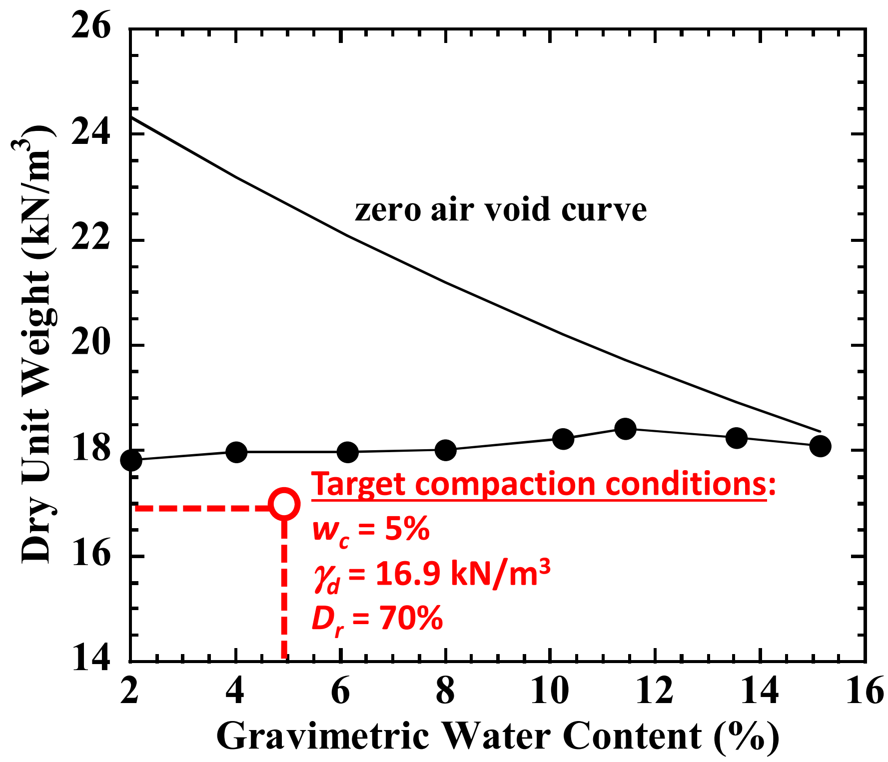




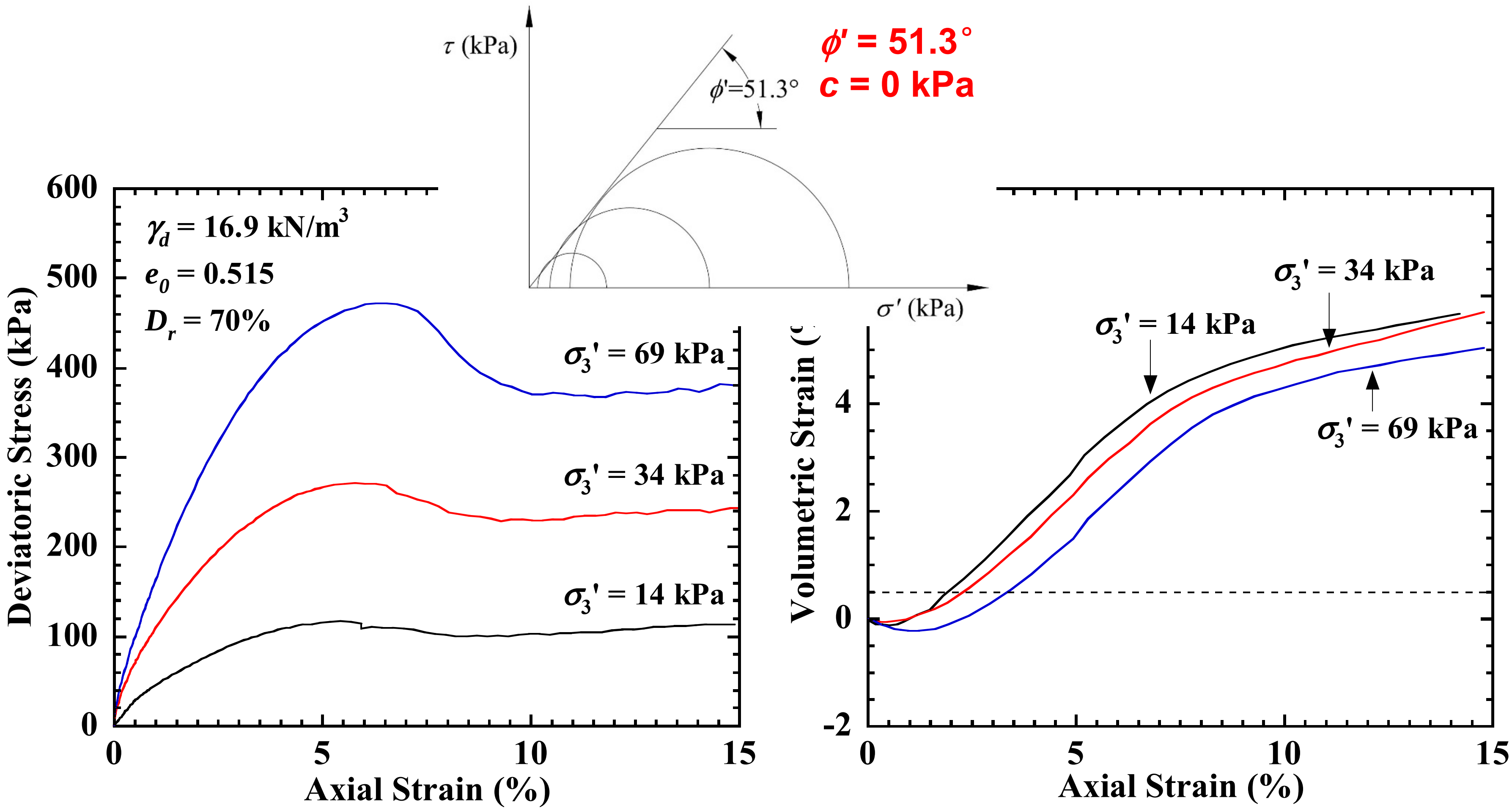
Selection of Compaction Conditions

Target relative density (D_r) for prototype structures = 85% (96% standard relative compaction)
Target relative density (D_r) for model specimens = 70% (92% standard relative compaction)





Backfill Soil



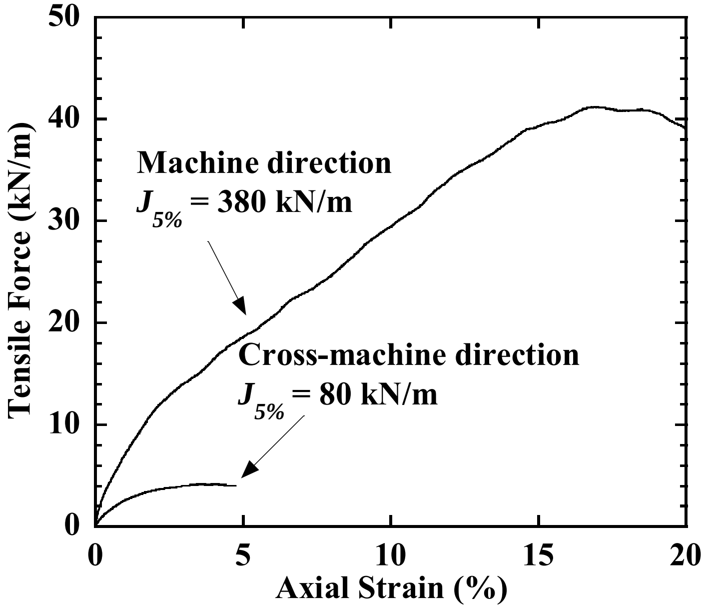
Triaxial test results for Dr = 70%

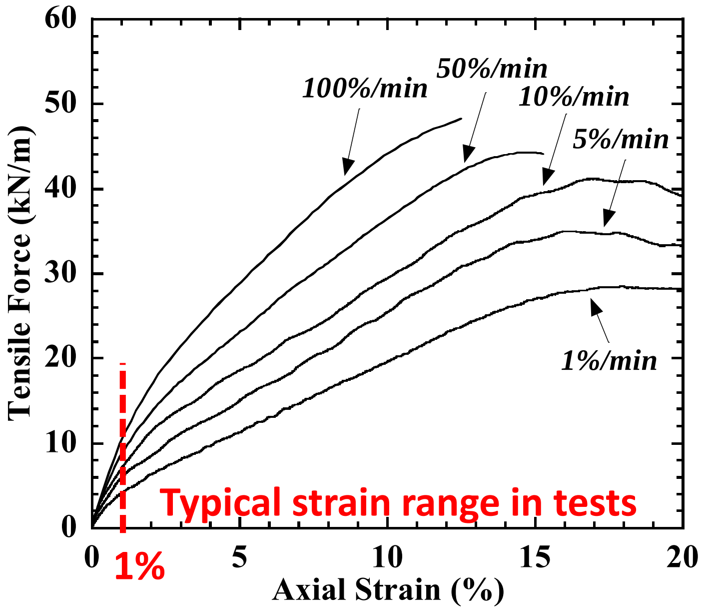
Geogrid Reinforcement

Prototype: Tensar UX 1700

Model: Tensar LH 800

- Index stiffness = 380 kN/m
- Stiffness scaling factor = 4



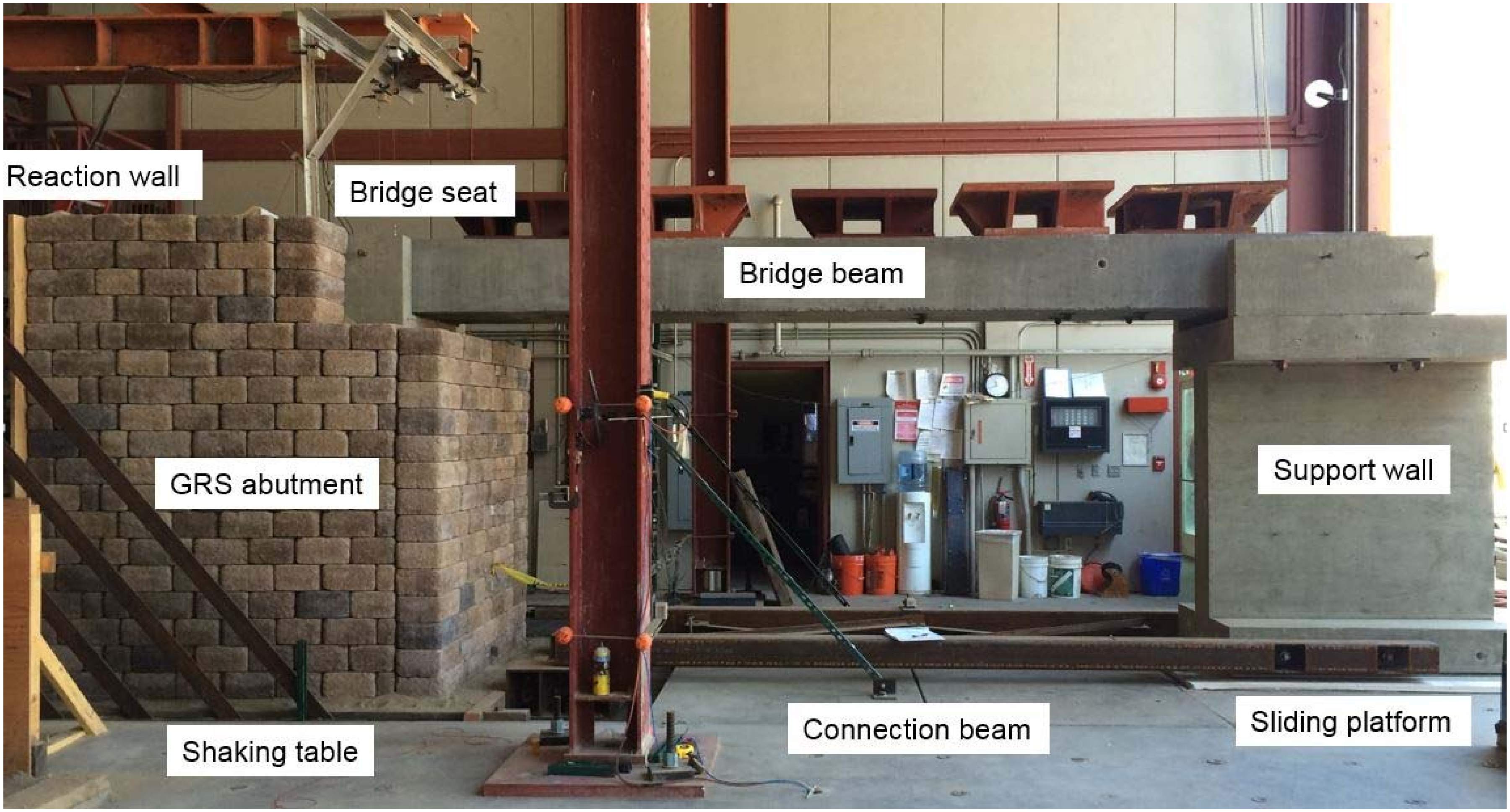


Shaking Table Testing Plan

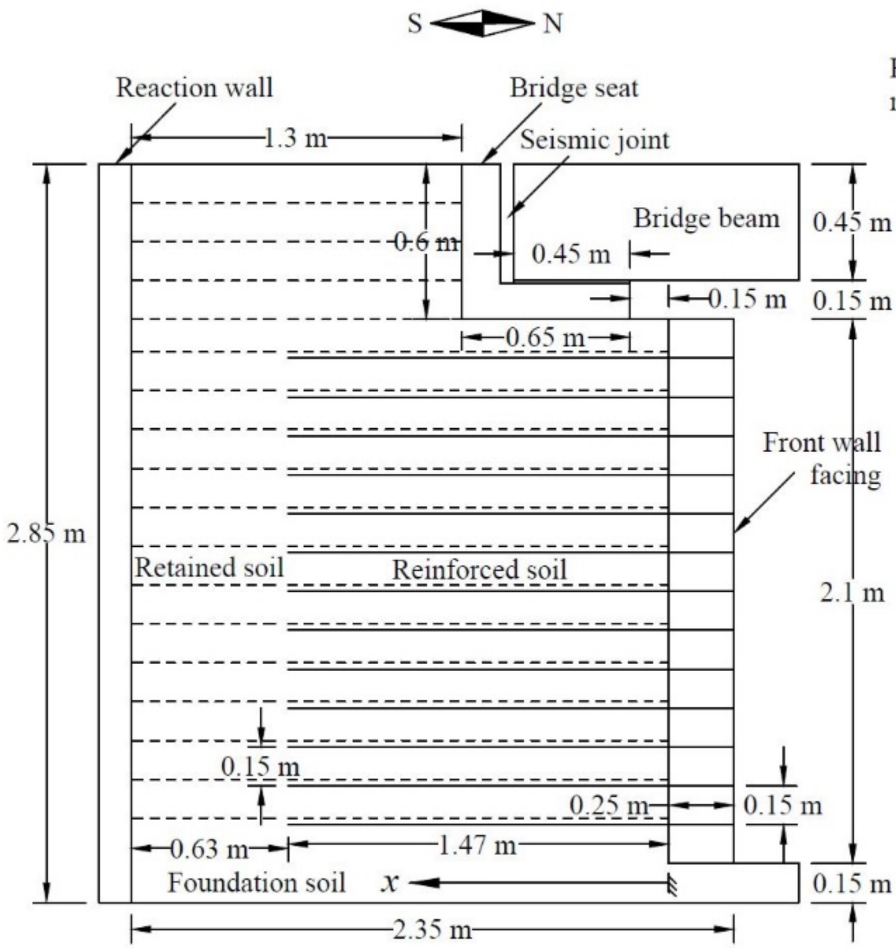
Test No.	1	2	3	4	5	6
Testing Purpose	Baseline	Reduced Bridge Load	Increased Reinforcement Spacing	Reduced Reinforcement Stiffness	Steel Welded Wire Mesh	Baseline
Bridge Stress (kPa)	66	43	66	66	66	66
Reinforcement Spacing (m)	0.15	0.15	0.30	0.15	0.15	0.15
Reinforcement Stiffness (kN/m)	380	380	380	190	4800	380
Shaking Direction	Long.	Long.	Long.	Long.	Long.	Trans.

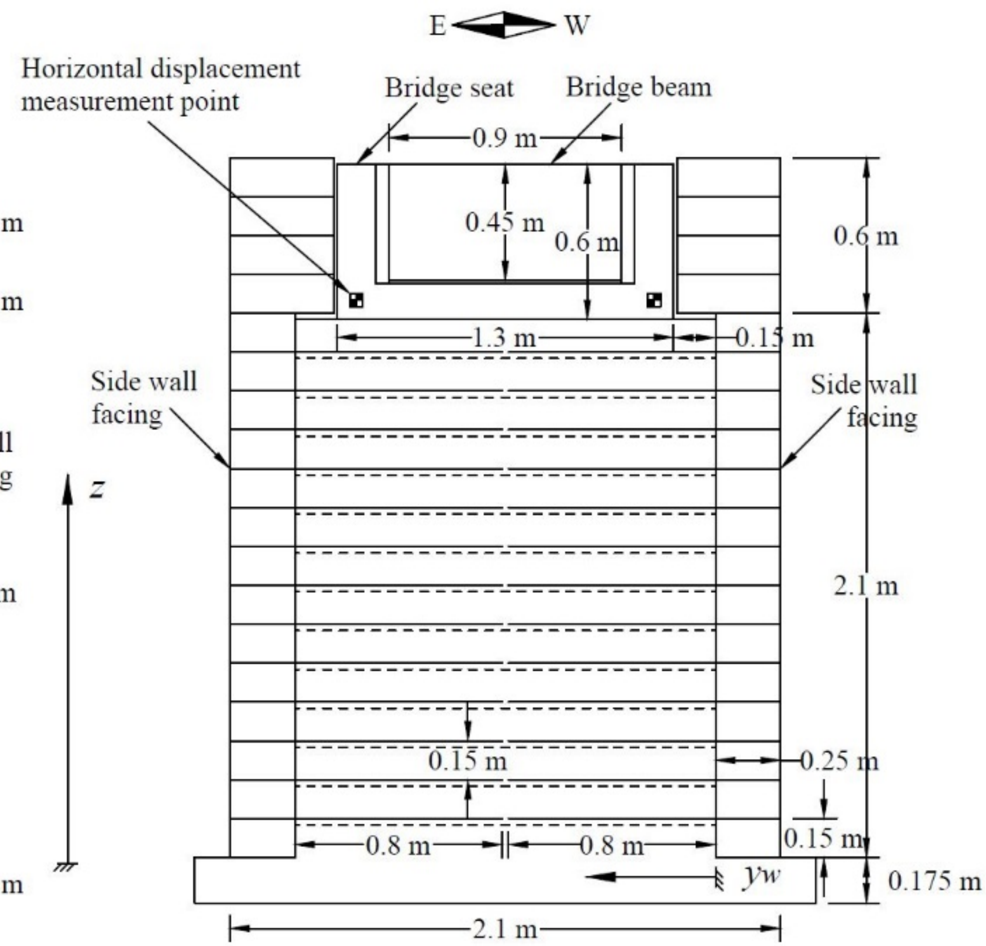
Construction

Longitudinal Test Configuration

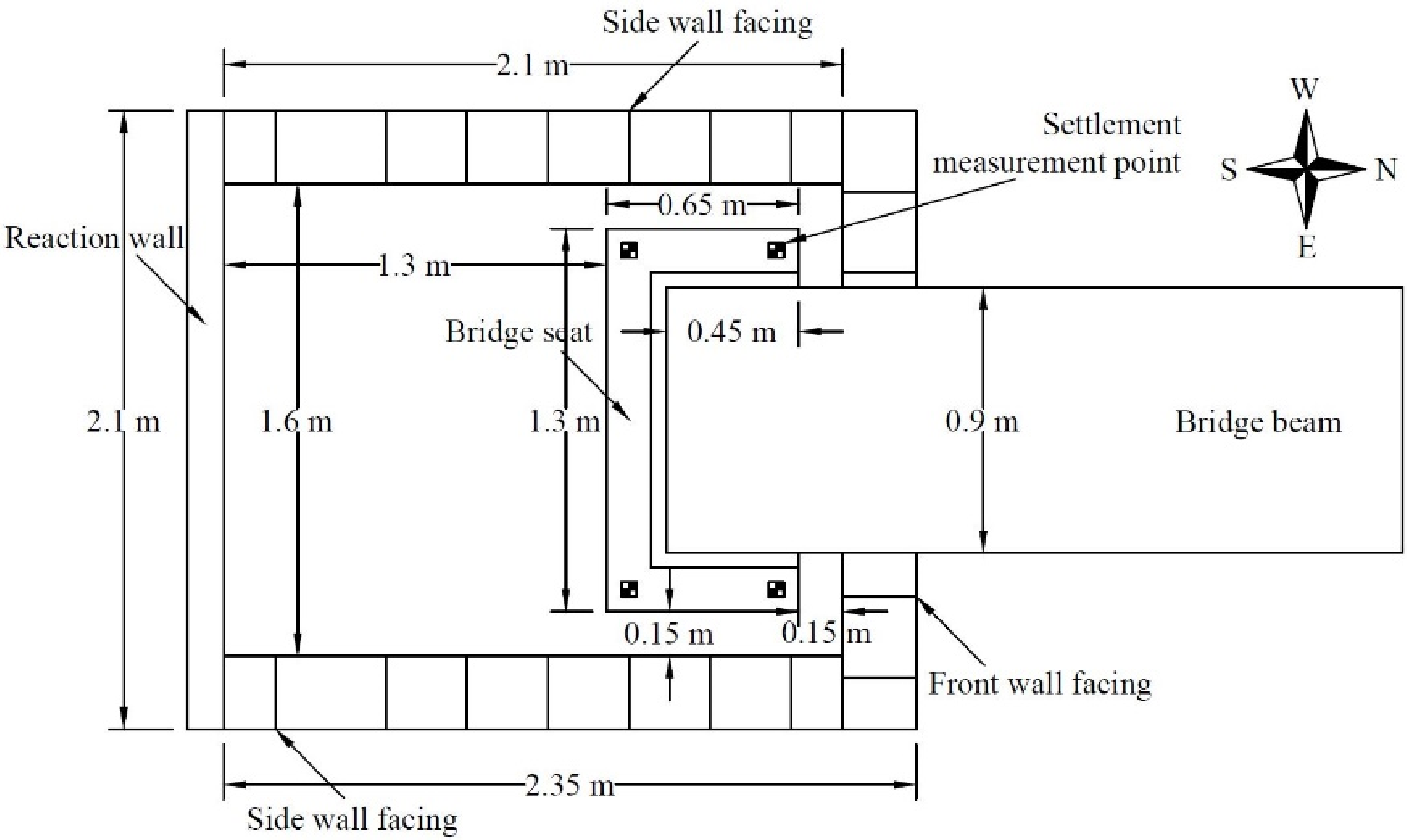


Longitudinal Model Geometry



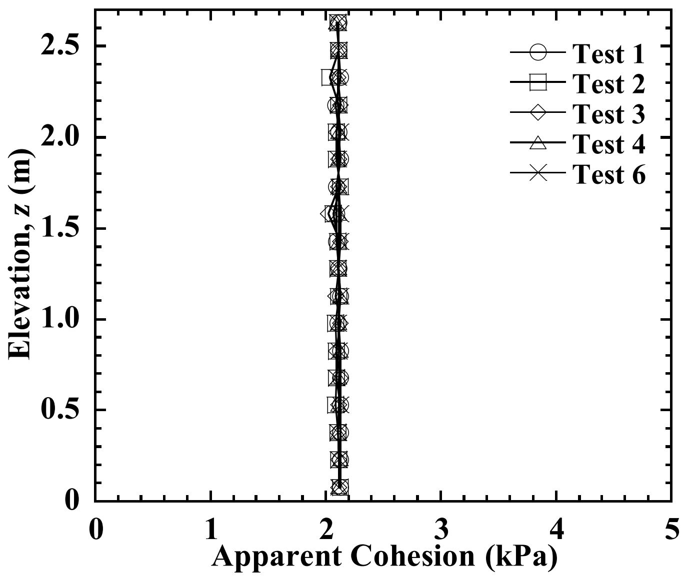


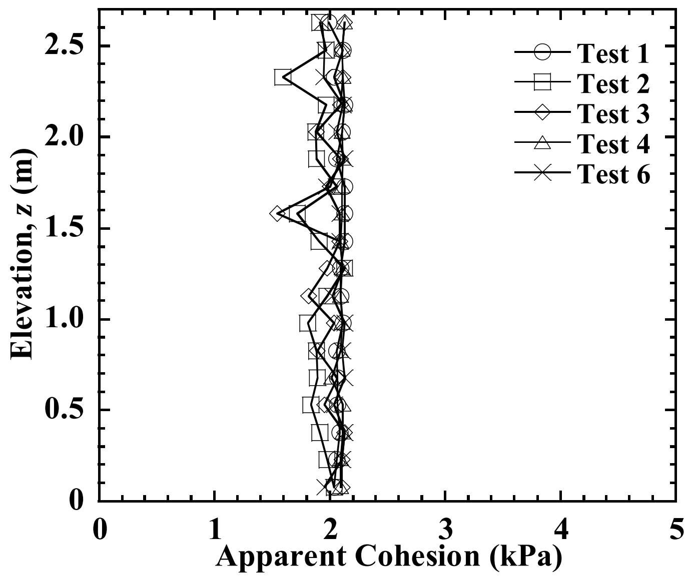
Longitudinal Model Geometry



Transverse Test Configuration

Construction





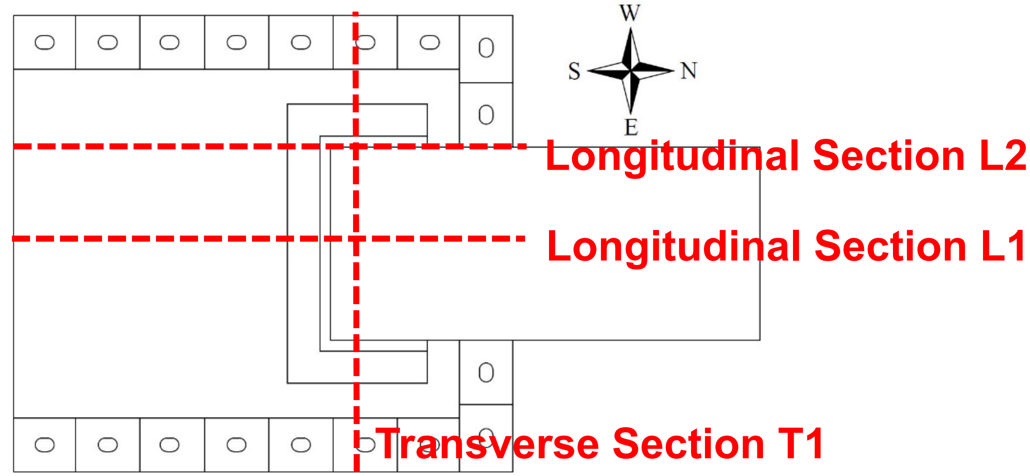
SWRC is needed for to estimate the apparent cohesion, but otherwise the material properties for saturated/dry soil can be used

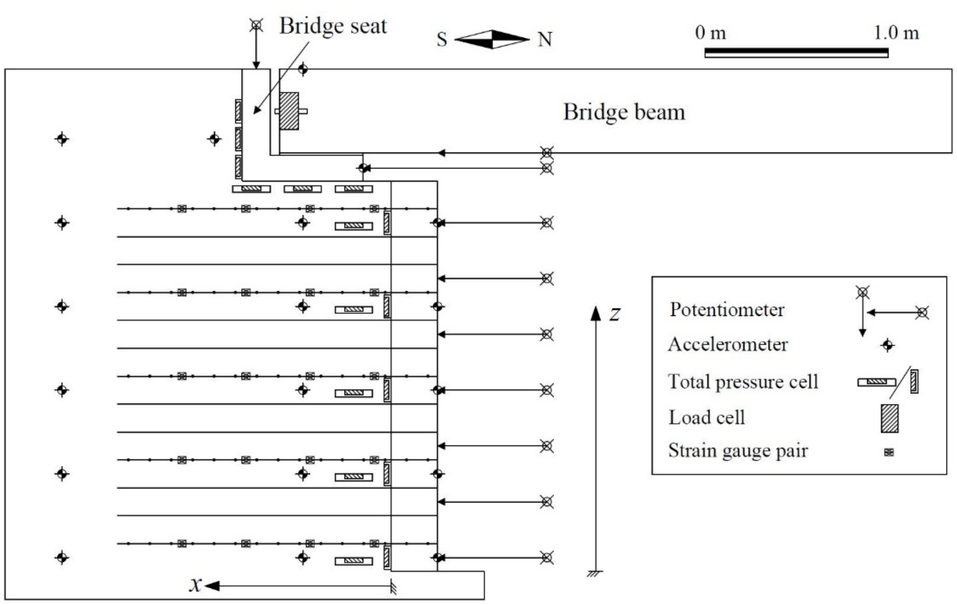
Test No.	1	2	3	4	6	Target
Average dry unit weight (kN/m³)	16.6	17.1	17.1	16.7	16.6	16.9
Average relative density (%)	64	73	73	67	65	70
Average water content (%)	4.7	6.7	5.5	4.3	5.0	5.0

Sensors

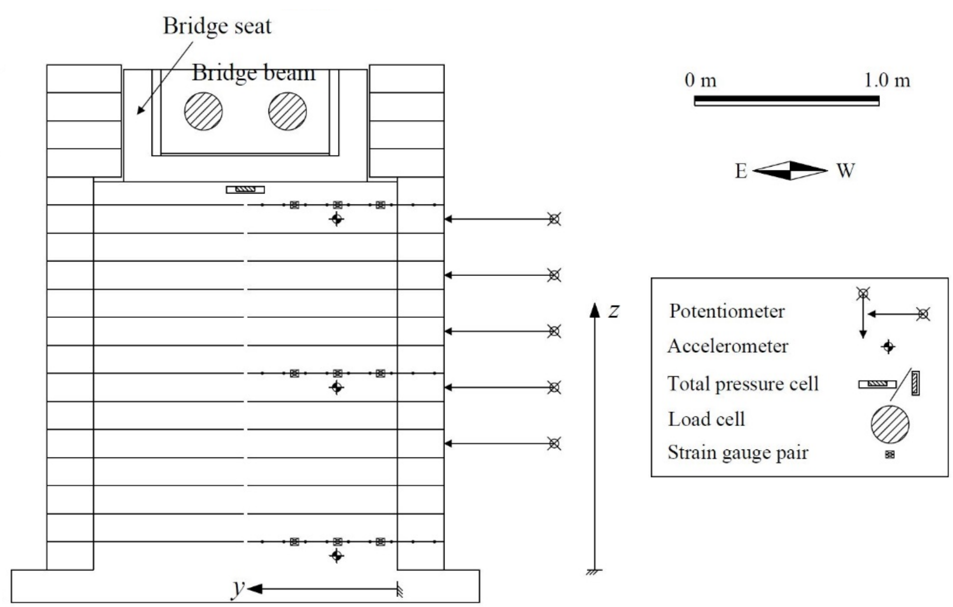
- Strain gauges
- String potentiometers
- Linear potentiometers
- Pressure cells
- Load cells
- Accelerometers
- Dielectric sensors

Longitudinal Test Instrumentation Plan





Longitudinal Section L1

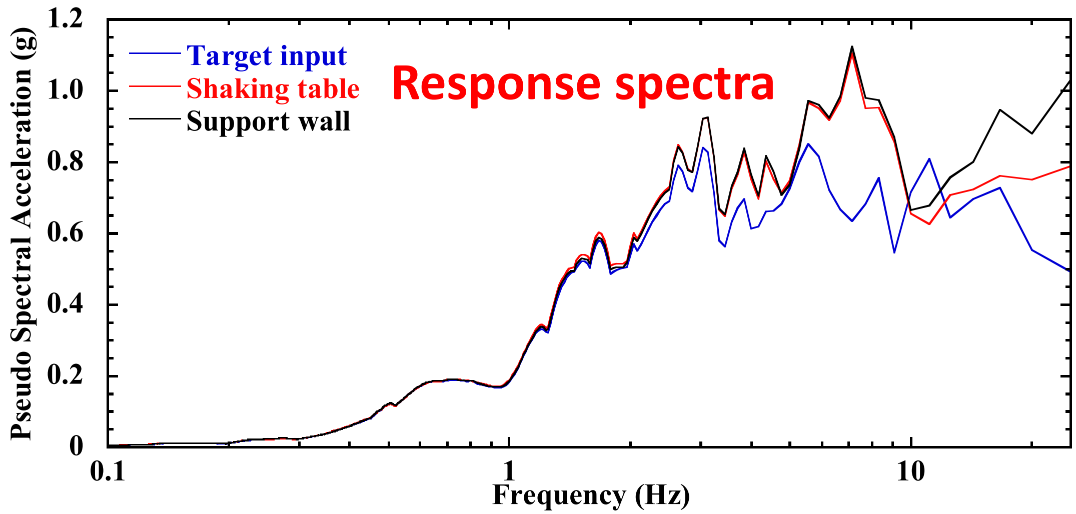


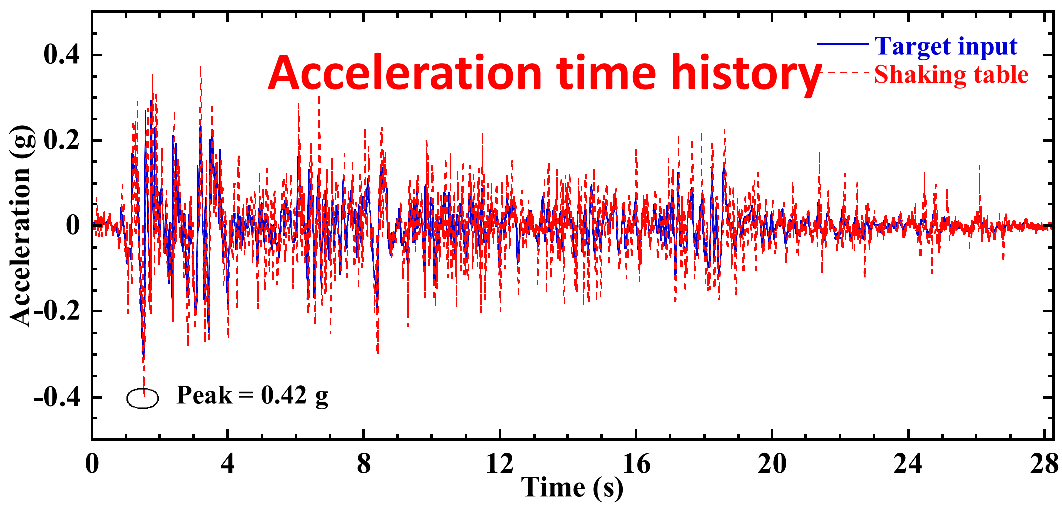
Transverse Section T1

Input Motions

Shaking event	Motion	PGA (g)	PGD (mm)
1	White Noise	0.10	-
2	1940 Imperial Valley	0.31	65
3	White Noise	0.10	-
4	2010 Maule	0.40	108
5	White Noise	0.10	-
6	1994 Northridge*	0.58	89
7	White Noise	0.10	-
8	Sin @ 0.5 Hz	0.05	50.0
9	Sin @ 1 Hz	0.10	25.0
10	Sin @ 2 Hz	0.20	12.5
11	Sin @ 5 Hz	0.25	2.5
12	White Noise	0.10	2.7

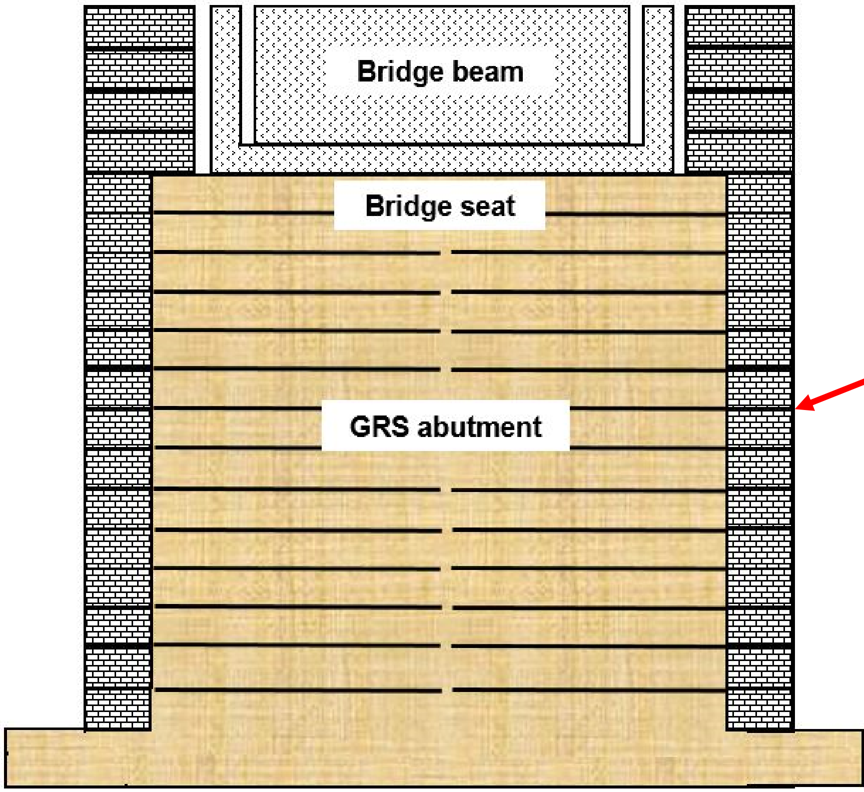
Testing System Performance

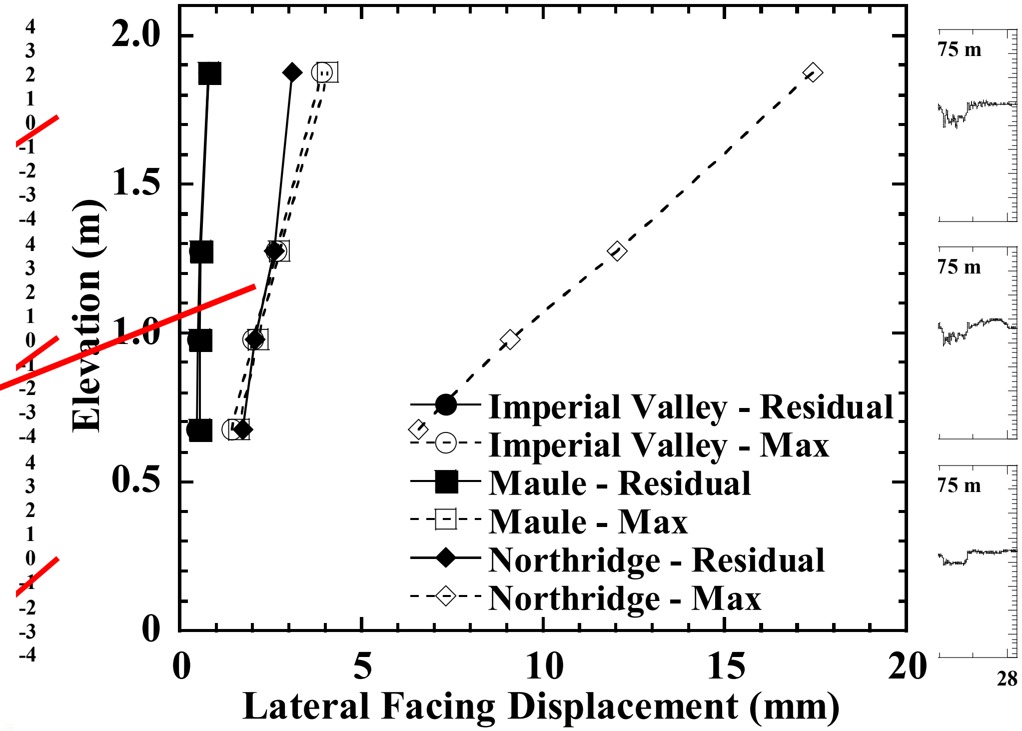




- The shaking table performed well in displacement-control mode for earthquake motions
- The steel connection beams and sliding platform successfully transmitted table motions to the base of the support wall
- The pseudo-spectral accelerations of the shaking table and target motion are in good agreement, which indicates that the shaking table adequately reproduced the salient characteristics of the target input motions

Facing Displacements (long.)



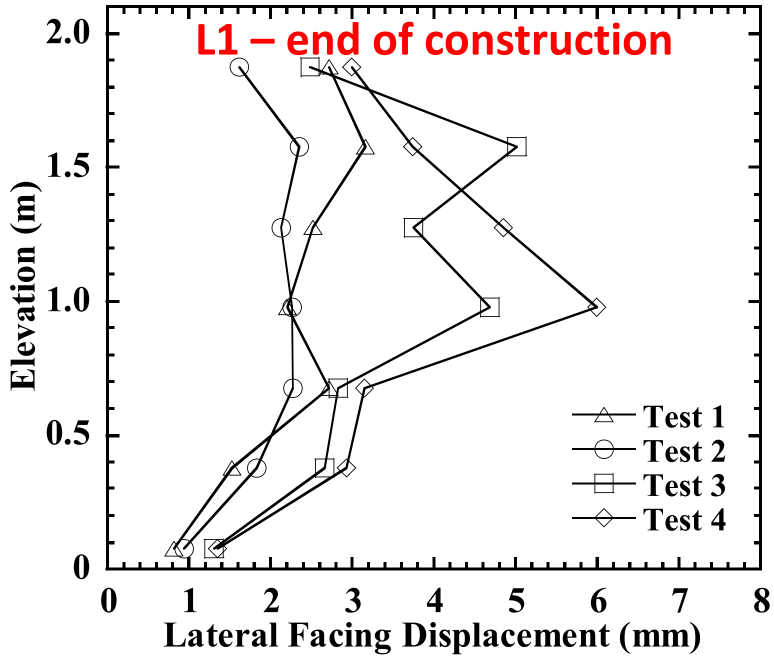


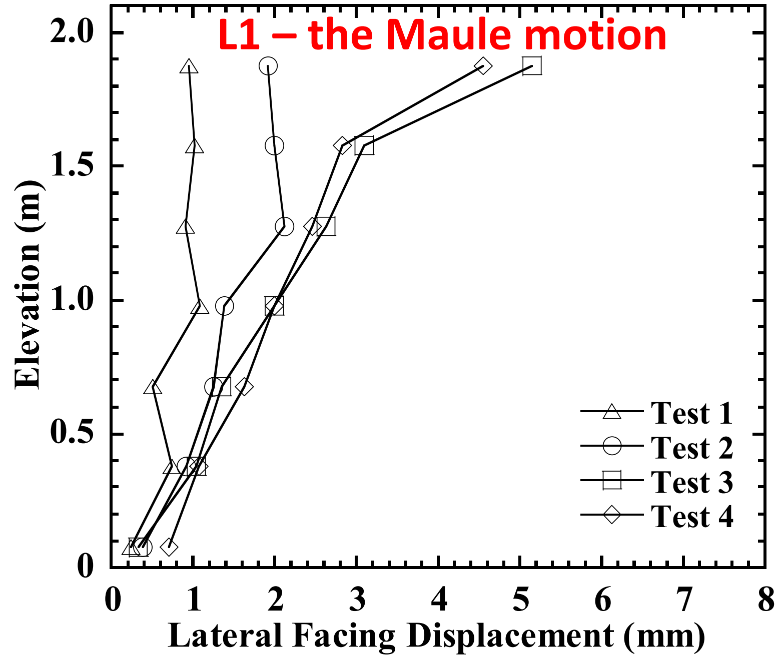
T1 lateral displacement profiles (mode scale) – Test 1

- Seismic displacements at the top are larger than the bottom
- Longitudinal shaking results in displacements in transverse direction

Facing Displacements (long.)

Test No.	1	2	3	4
Testing Purpose	Baseline	Reduced Bridge Load	Increased Reinforcement Spacing	Reduced Reinforcement Stiffness

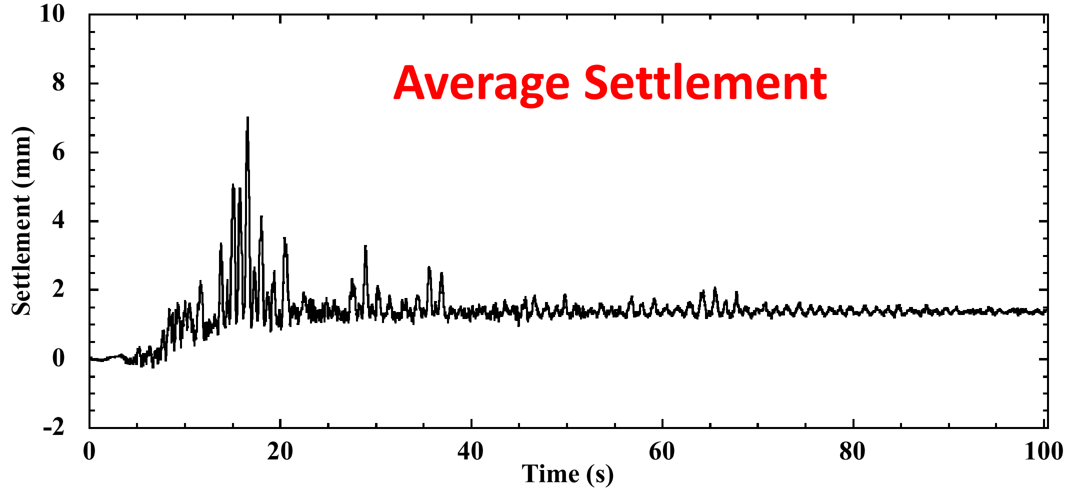




- Reinforcement spacing and stiffness have most significant effects
- Greater bridge load results in larger displacements for static loading, but smaller displacements for seismic loading

Bridge Seat Settlements for Test 1

Bridge seat instrumentation



Bridge seat settlements for the Maule motion (model scale) – Test 1

Average incremental bridge seat settlements (model scale) – Test 1

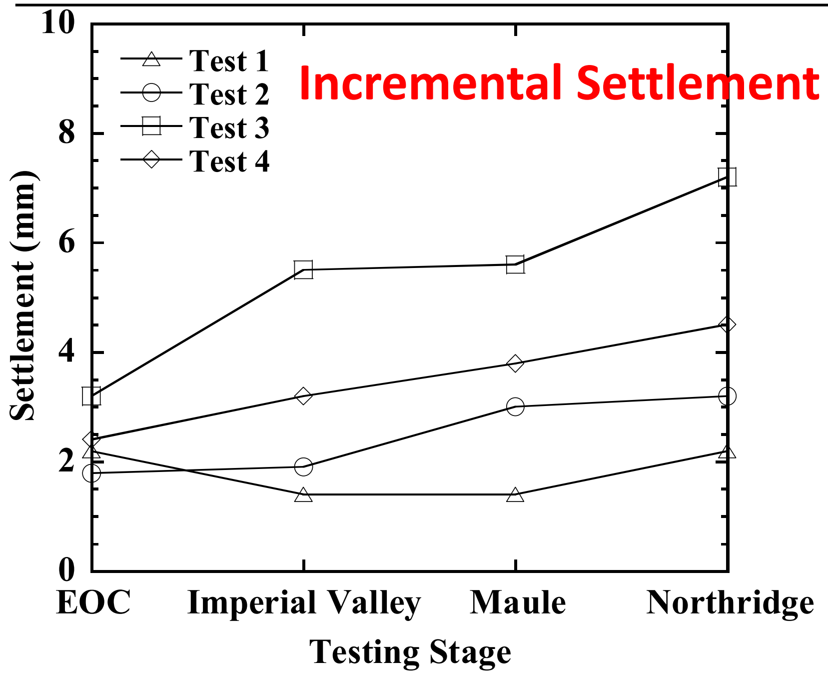
Earthquake motion	Max Settlement (mm)	Min Settlement (mm)	Residual Settlement (mm)
1940 Imperial Valley	3.1	-0.1	1.4
2010 Maule	7.0	-0.2	1.4
1994 Northridge	7.0	-0.7	2.2

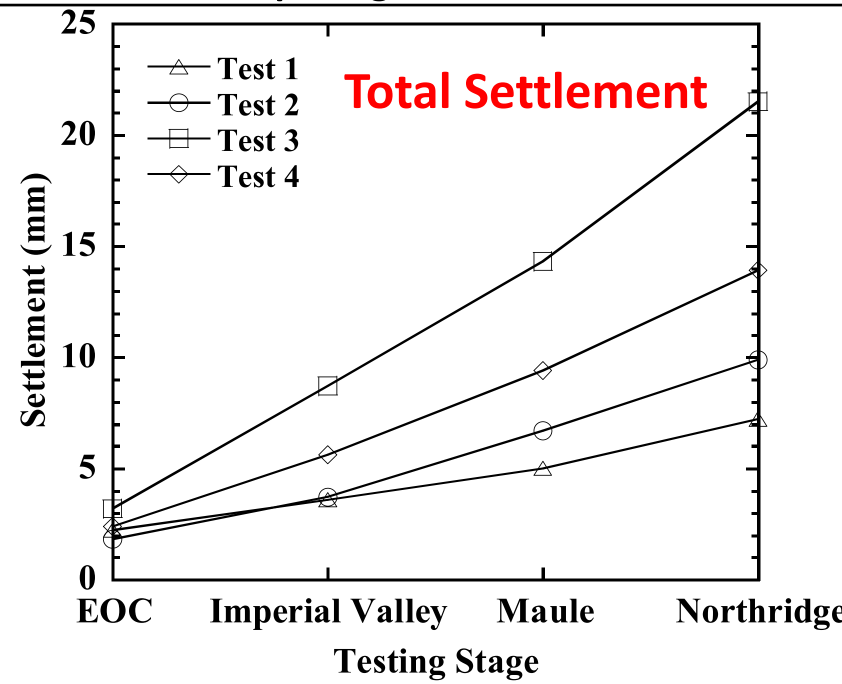
Vertical strain

0.1%

Bridge Seat Settlements (long.)

Test No.	1	2	3	4
Testing Purpose	Baseline	Reduced Bridge Load	Increased Reinforcement Spacing	Reduced Reinforcement Stiffness

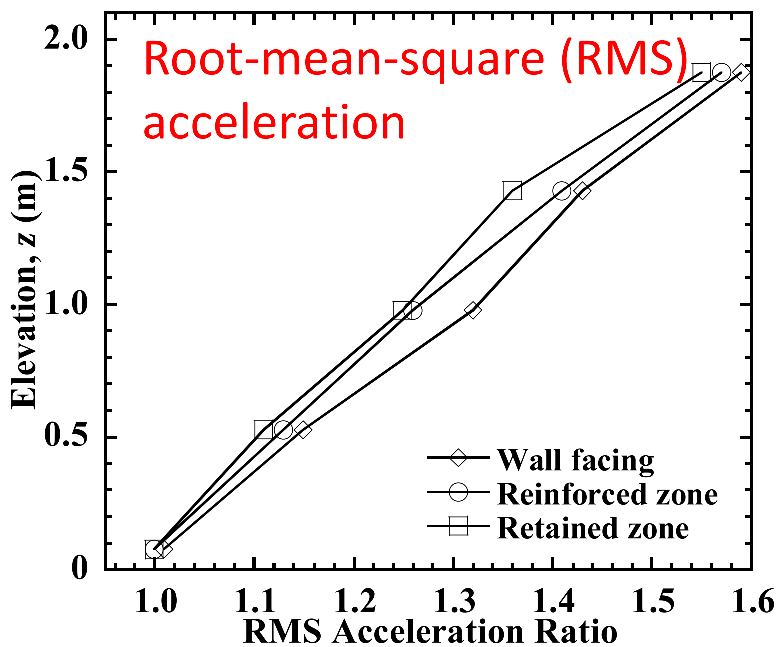


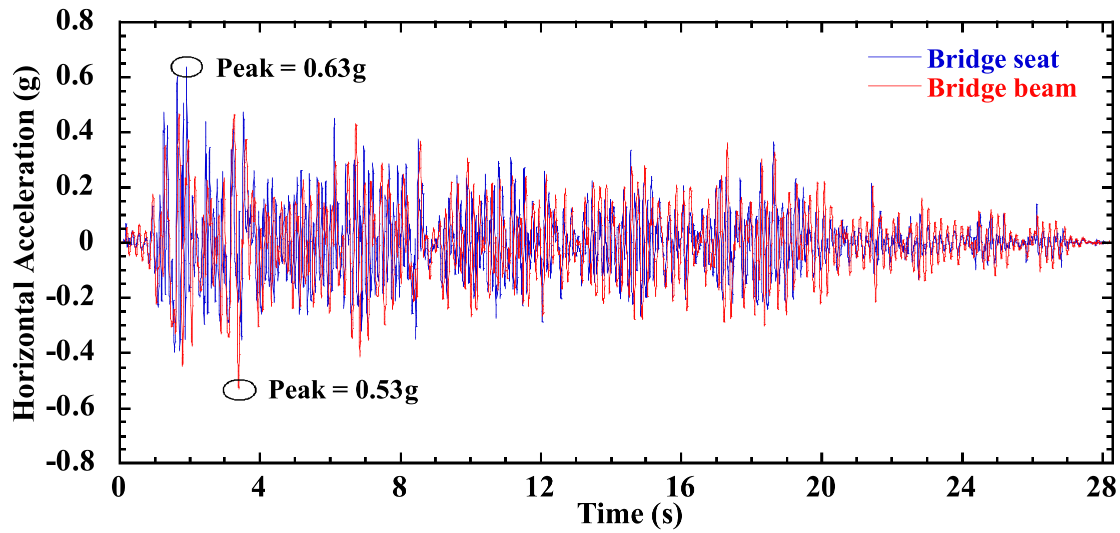


- Reinforcement spacing and stiffness have the most significant effects
- Greater bridge load results in larger settlements for static loading, but smaller settlements for seismic loading

Acceleration Amplification (long.)

Imperial Valley motion in Test 1

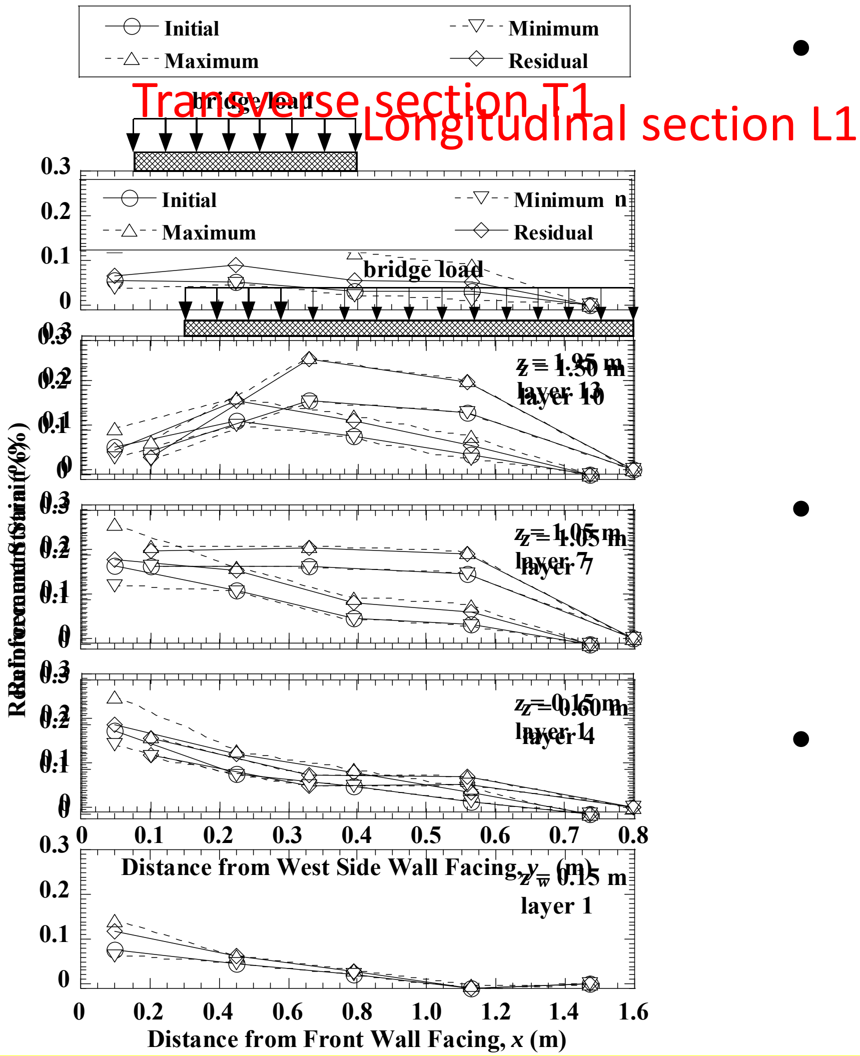




Amplification ratio = 1.6 for bridge seat
Amplification ratio = 1.8 for bridge beam

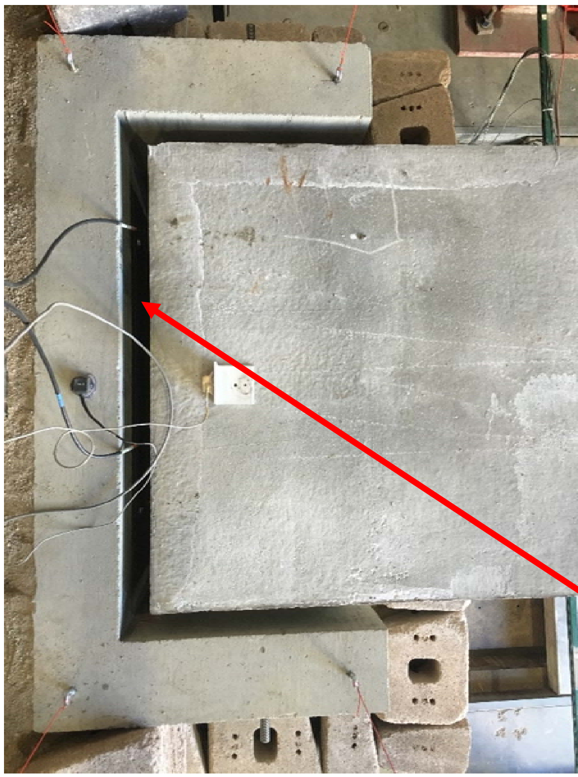
- Acceleration amplification increases with elevation in the GRS bridge abutment
- Amplification ratios increase from retained zone to reinforced zone to wall facing
- Amplification ratios for bridge beam are larger than bridge seat

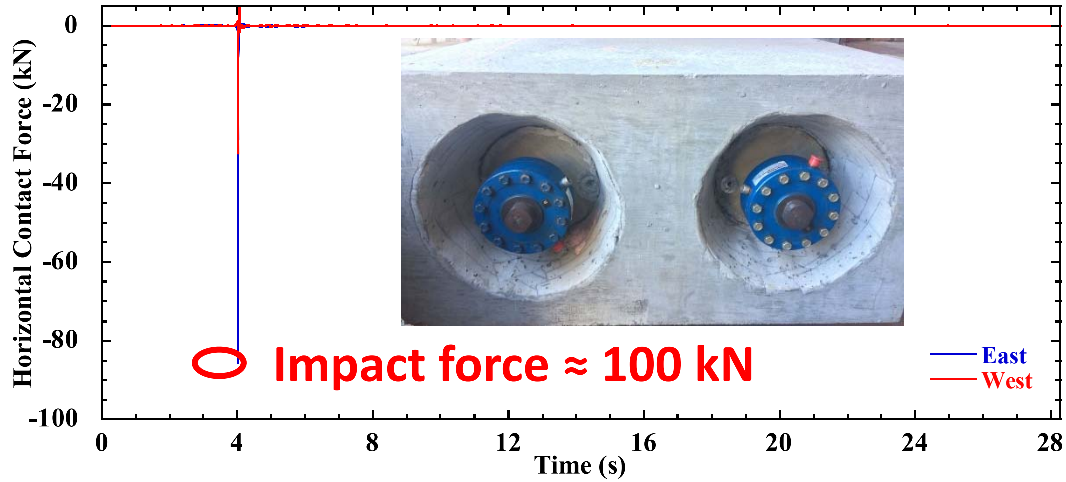
Reinforcement Strains (long.)



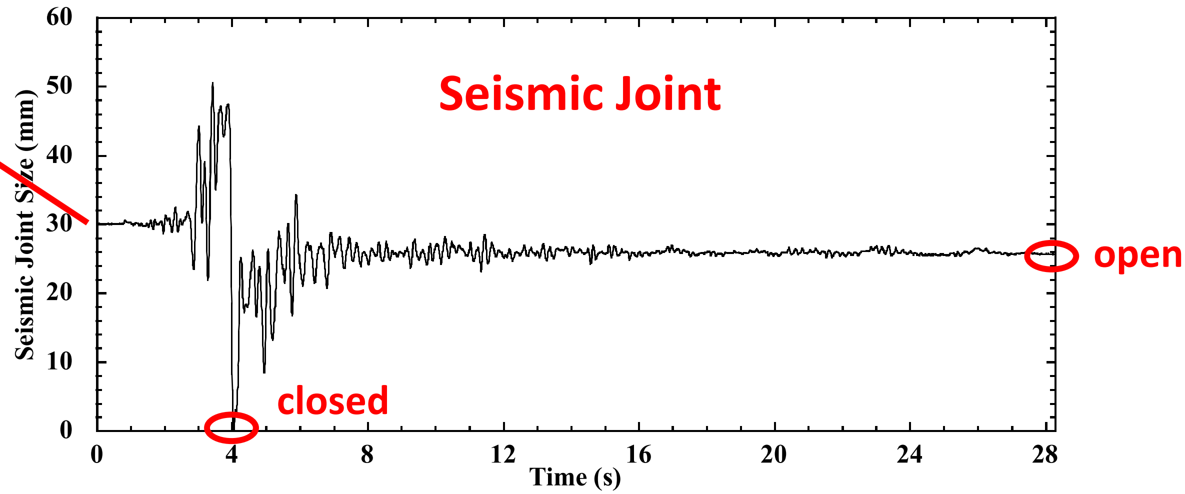
- The location of the seismic maximum reinforcement strain was observed to be under the bridge seat in the upper reinforcement layers, but was near the facing block connections in the lower layers.
- Residual strains under the bridge seat for the upper layers increased significantly
- Shaking in the longitudinal direction also caused increases in reinforcement strain in the transverse direction

Bridge Seat and Beam Interaction

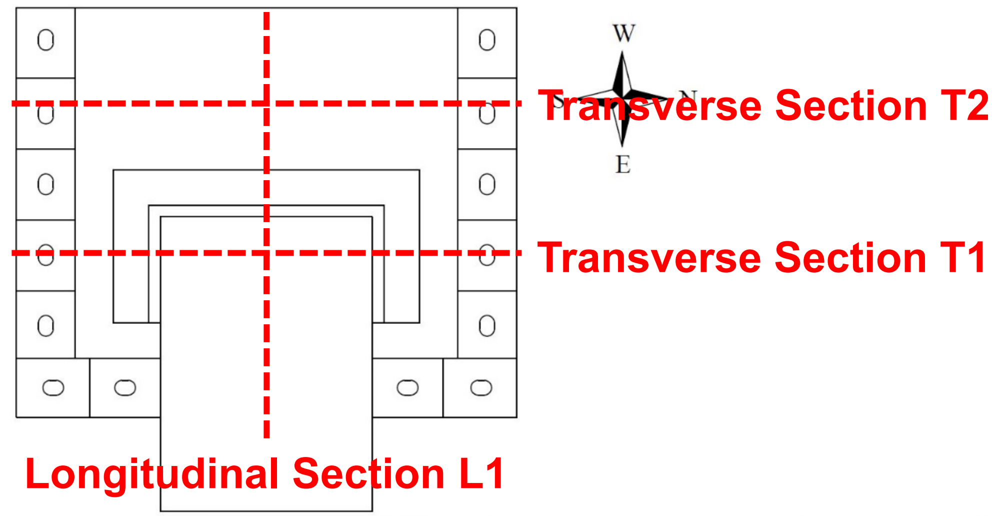


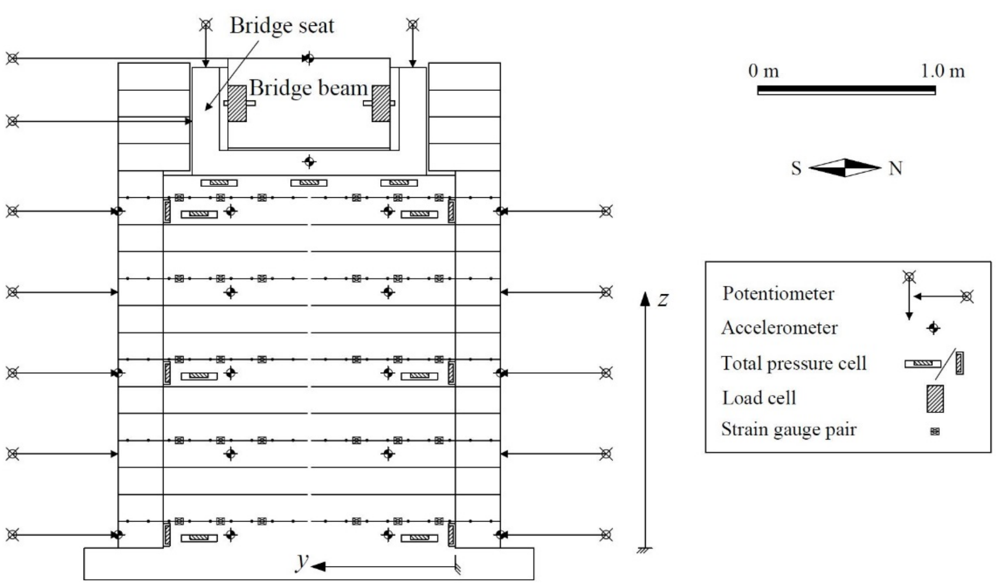


Impact force time history for the Northridge motion

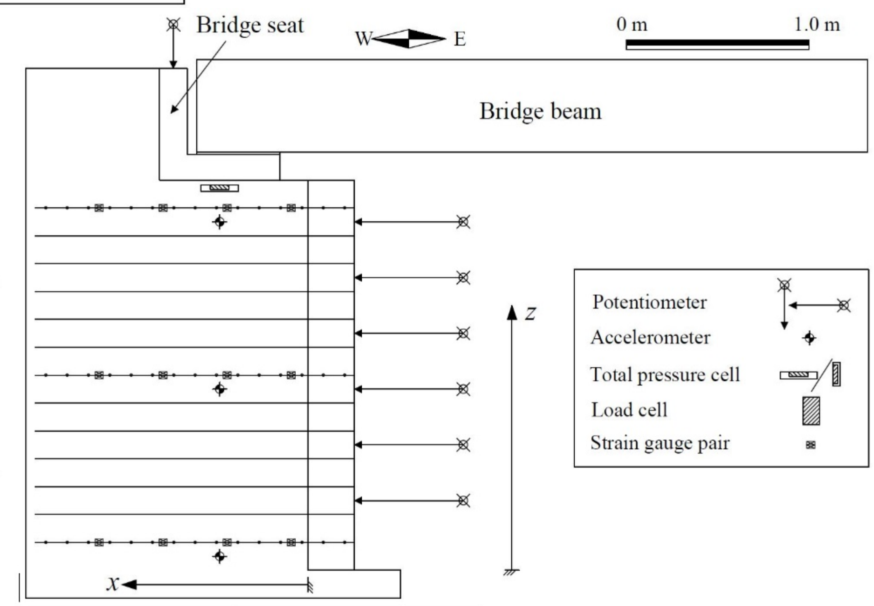


Transverse Test Instrumentation Plan



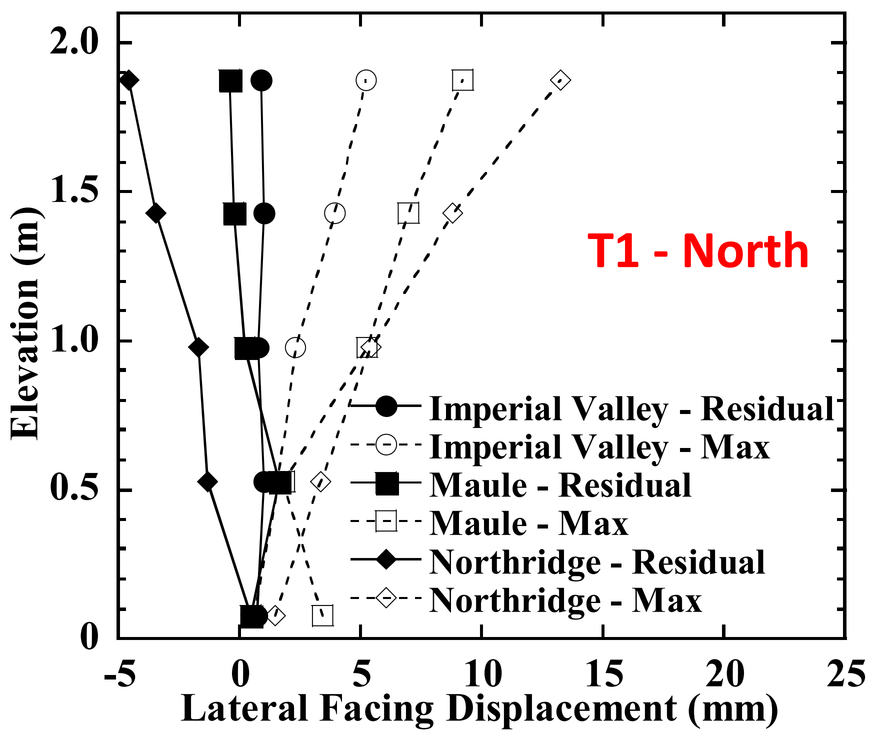


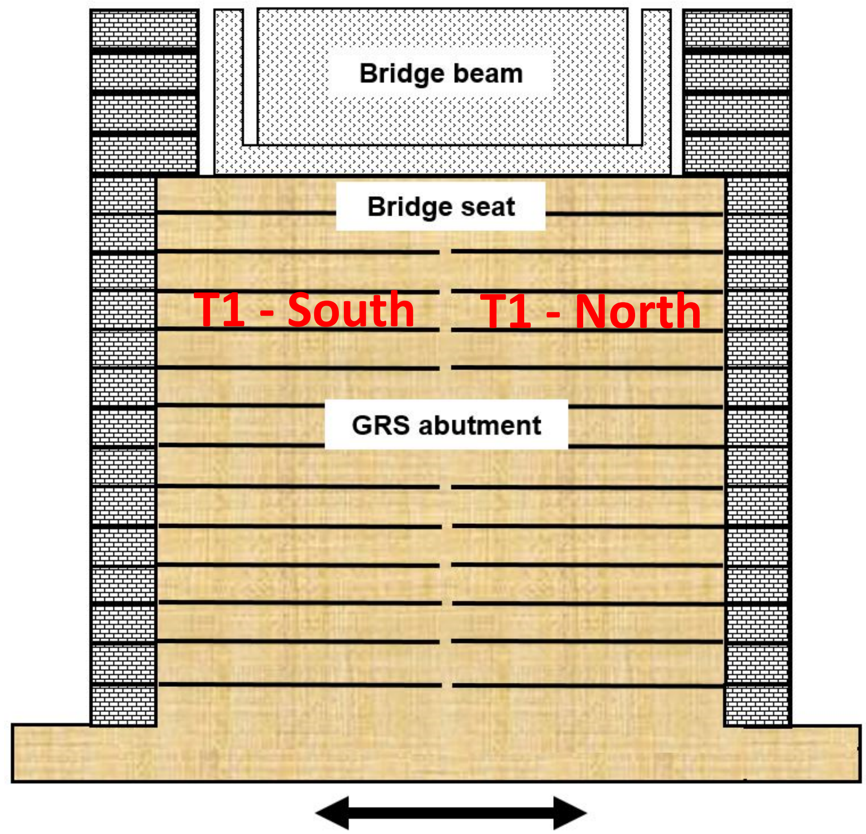
Transverse Section T1



Longitudinal Section L1

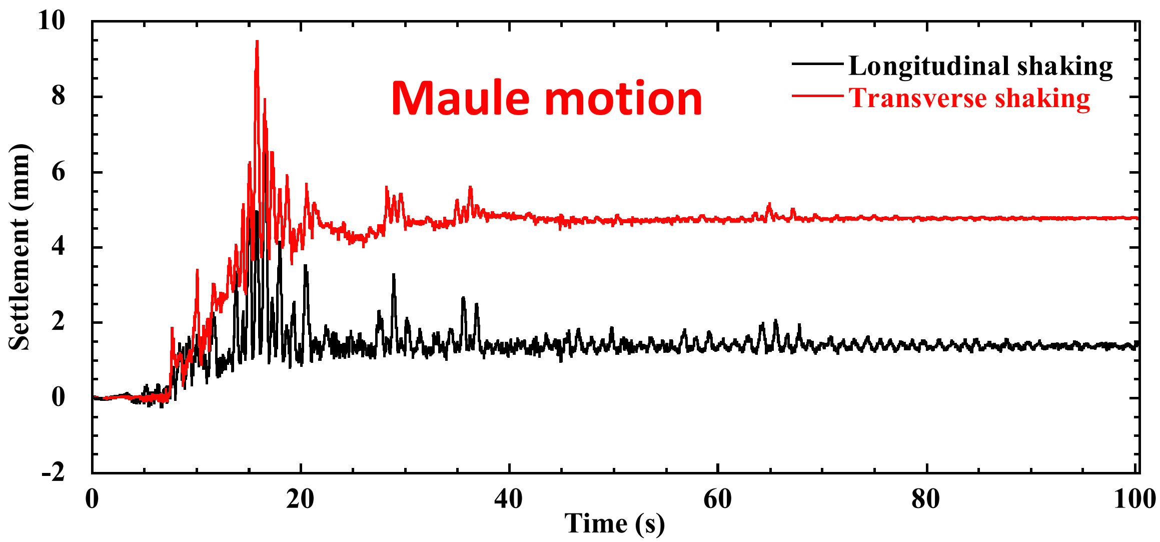
Facing Displacements (trans.)





- T1-South had outward residual displacements, whereas T1-North had inward residual displacements for the Northridge motion
- Transverse shaking results in displacements in longitudinal direction

Bridge Seat Settlements (trans.)



Average incremental bridge seat settlement time history (model scale)

Average incremental residual bridge seat settlement (model scale)

Shaking Direction	Imperial Valley (mm)	Maule (mm)	Northridge (mm)
Longitudinal	1.4	1.4	2.2
Transverse	2.5	4.8	4.7

Transverse shaking > Longitudinal shaking

Conclusions

- Incremental bridge seat settlements under seismic loading are relatively small for all tests (ranging from 1.5 mm to 7.0 mm), which would not be expected to cause significant damage to bridge structures
- Reducing reinforcement spacing and increasing reinforcement stiffness are the most effective means to reduce facing displacements and bridge seat settlements under seismic loading
- Greater bridge load resulted in larger deformations for static loading, but smaller deformations for seismic loading, which is attributed to the larger soil stiffness under greater bridge load
- Incremental 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 settlements

Ongoing Work

- FLAC 2D/3D numerical model validation for static and dynamic conditions
- Detailed investigations on the seismic design of GRS bridge abutments using validated numerical models
- The testing program performed in this study was limited by the size and payload capacity of the shaking table in the Powell Structural Lab, so full-scale testing on the NHERI shaking table will help to alleviate these effects
- Impact of unsaturated soil conditions on the seismic compression of backfill soils requires further investigations