Construction and Long-Term Performance of Transportation Infrastructure Constructed Using EPS Geofoam on Soft Soil Sites in Salt Lake Valley, Utah

S. Bartlett, E. Lawton, C. Farnsworth, D. Negussey, A. Stuedlein, M. Perry

THE UNIVERSITY OF UTAH

Objectives (UDOT contract)

- Monitor the long-term performance of geofoam embankments and compare its settlement performance with other embankment systems.
    - Measure the differential settlement in MSE wall transition zones.
    - Measure the vertical stress distribution that develops in the geofoam embankment.
    - Measure the vertical and horizontal stress that develops in a typical bridge abutment.
- Develop and calibrate a numerical model (FLAC) for predicting the vertical and horizontal static stress distribution in the geofoam mass for the instrumented embankment and abutment areas.
- Use the FLAC model to predict the seismic response and sliding stability of typical geofoam configurations.
- Evaluate the possible magnitude of the vertical stress transfer that is occurring to the tilt-up panel wall at 3500 South using FLAC.
- Measure the temperature profile in the pavement section.

Objectives

- **Long Term Monitoring**
  - Construction Settlement
  - Post-Construction Settlement
  - Transition Zones
  - Settlement Performance Comparison
- Assessment and Modeling of Performance Data
  - Settlement
  - Pressure Distribution
    - Vertical
    - Horizontal
  - Connections and Panel Walls
- Seismic Design
- General Design

UDOT Reports

- Bartlett, S.F., Lawton, E.C., Farnsworth, C.B., and Newman, M.P., 2011,"Design and Evaluation of Geofoam Embankment for the I-15 Reconstruction Project, Salt Lake City, Utah, Prepared for the Utah Department of Transportation Research Division, Report No. UT-???, Oct. 2011, 184 p.

- Bartlett, S.F. and Farnsworth, C.B., 2004. "Monitoring and Modeling of Innovative Foundation Treatment and Embankment Construction Used on the I-15 Reconstruction Project, Project Management Plan and Instrument Installation Report," UDOT Research Report No. UT-04.19, 202 p.

- Farnsworth, C. B. and Bartlett, S. F. (2008). "Evaluation of Rapid Construction and Settlement of Embankment Systems on Soft Foundation Soils." *UDOT Research Report No. UT-08.05*, Utah Department of Transportation, Salt Lake City, Utah.

Papers

•Farnsworth C. F., Bartlett S. F., Negussey, D. and Stuedlein A. 2008, "Construction and Post-Construction Settlement Performance of Innovative Embankment Systems, I-15 Reconstruction Project, Salt Lake City, Utah," Journal of Geotechnical and Geoenvironmental Engineering, ASCE (Vol. 134 pp. 289-301).

• Newman, M. P., Bartlett S. F., Lawton, E. C., 2010, "Numerical Modeling of Geofoam Embankments," Journal of Geotechnical and Geoenvironmental Engineering, ASCE, February 2010, pp. 290-298.

• Bartlett, S. F. and Lawton E. C., 2008, "Evaluating the Seismic Stability and Performance of Freestanding Geofoam Embankment," 6th National Seismic Conference on Bridges and Highways, Charleston, S.C., July 27th – 30th 2008, 17 p.

• Bartlett, S. F., Negussey, D., Farnsworth, C. B., and Stuedlein, A., 2011, "Construction and Long-Term Performance of Transportation Infrastructure Constructed Using EPS Geofoam on Soft Soil Sites in Salt Lake Valley, Utah," EPS 2011 Geofoam Blocks in Construction Applications, Oslo Norway.

Papers (cont.)

- Bartlett, S. F., Trandafir, A. C., Lawton E. C. and Lingwall, B. N., 2011, "Applications of EPS Geofoam in Design and Construction of Earthquake Resilient Infrastructure," EPS 2011 Geofoam Blocks in Construction Applications, Oslo Norway.

- Bartlett S. F., Farnsworth, C., Negussey, D., and Stuedlein, A. W., 2001, "Instrumentation and Long-Term Monitoring of Geofoam Embankments, I-15 Reconstruction Project, Salt Lake City, Utah," EPS Geofoam 2001, 3rd International Conference, Dec. 10th to 12th, 2001, Salt Lake City, Utah, 23 p.

- Negussey, D., Stuedlin, A. W., Bartlett, S. F., Farnsworth, C., "Performance of Geofoam Embankment at 100 South, I-15 Reconstruction Project, Salt Lake City, Utah," EPS Geofoam 2001, 3rd International Conference, Dec. 10th to 12th, 2001, Salt Lake City, Utah, 22 p.

Primary Uses of Geofoam on the I-15 Project

- Reduce Settlement to Protect Buried Utilities
- Improve Slope Stability of Embankments
- Rapid Construction in Time Critical Areas

EPS Density

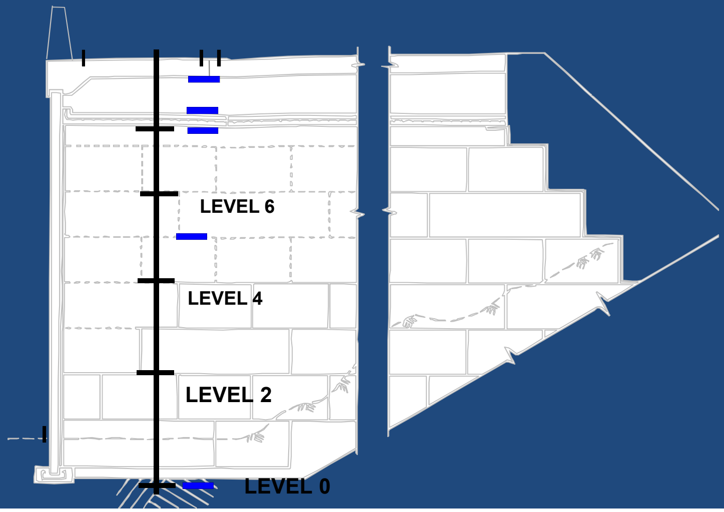
Property	ASTM Test C 578	Type XI	Type I	Type VIII*	Type II	Type IX
Nominal Density (kg/m^3)	C303 / D 1622	12	16	20	24	32
Minimum Density (kg/m^3)	C303 / D 1622	11	15	18	22	29

*** Type VIII was used for I-15 Reconstruction**

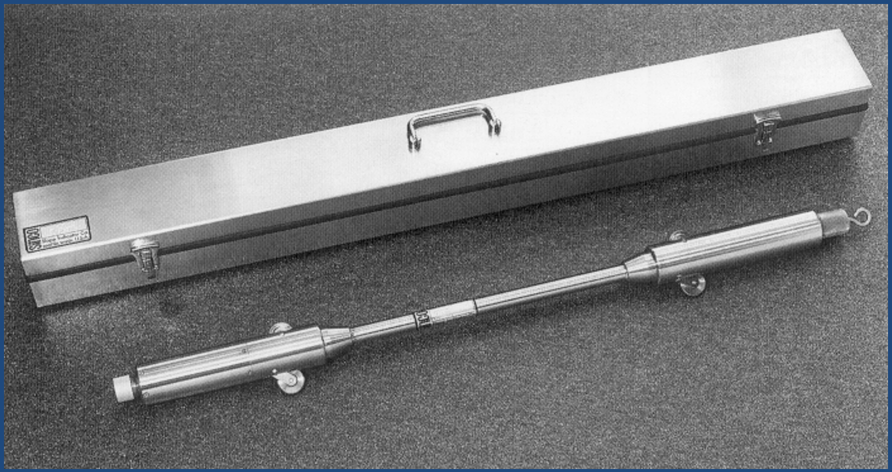
Objectives

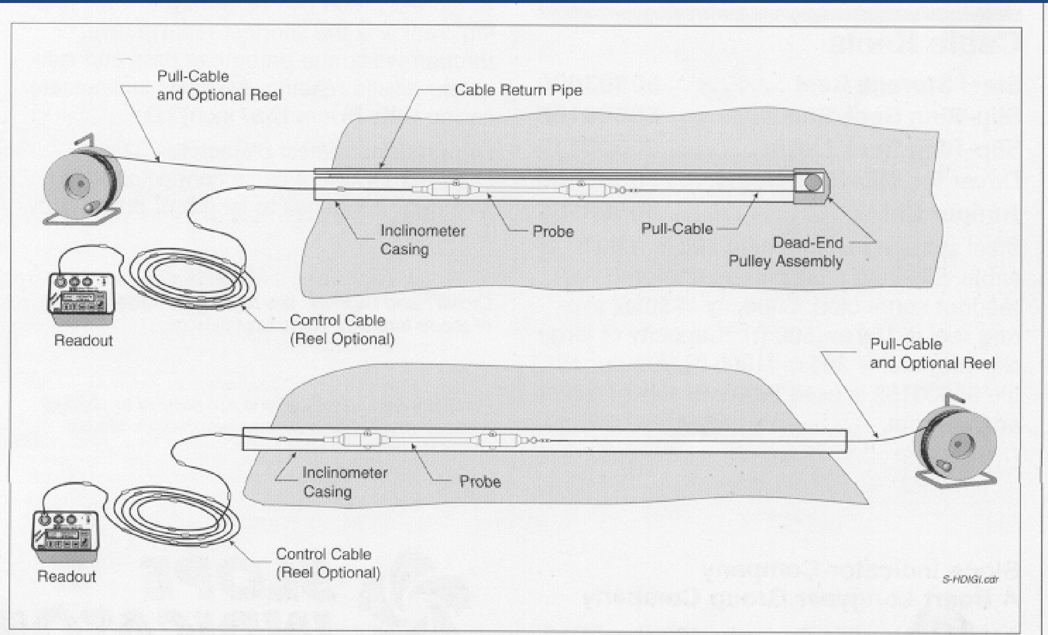
- **Long Term Monitoring**
  - Construction Settlement
  - Post-Construction Settlement
  - Transition Zones
  - Settlement Performance Comparison
- Assessment and Modeling of Performance Data
  - Settlement
  - Pressure Distribution
    - Vertical
    - Horizontal
  - Connections and Panel Walls
- Seismic Design
- General Design

Geotechnical Instrumentation



Geotechnical Instrumentation

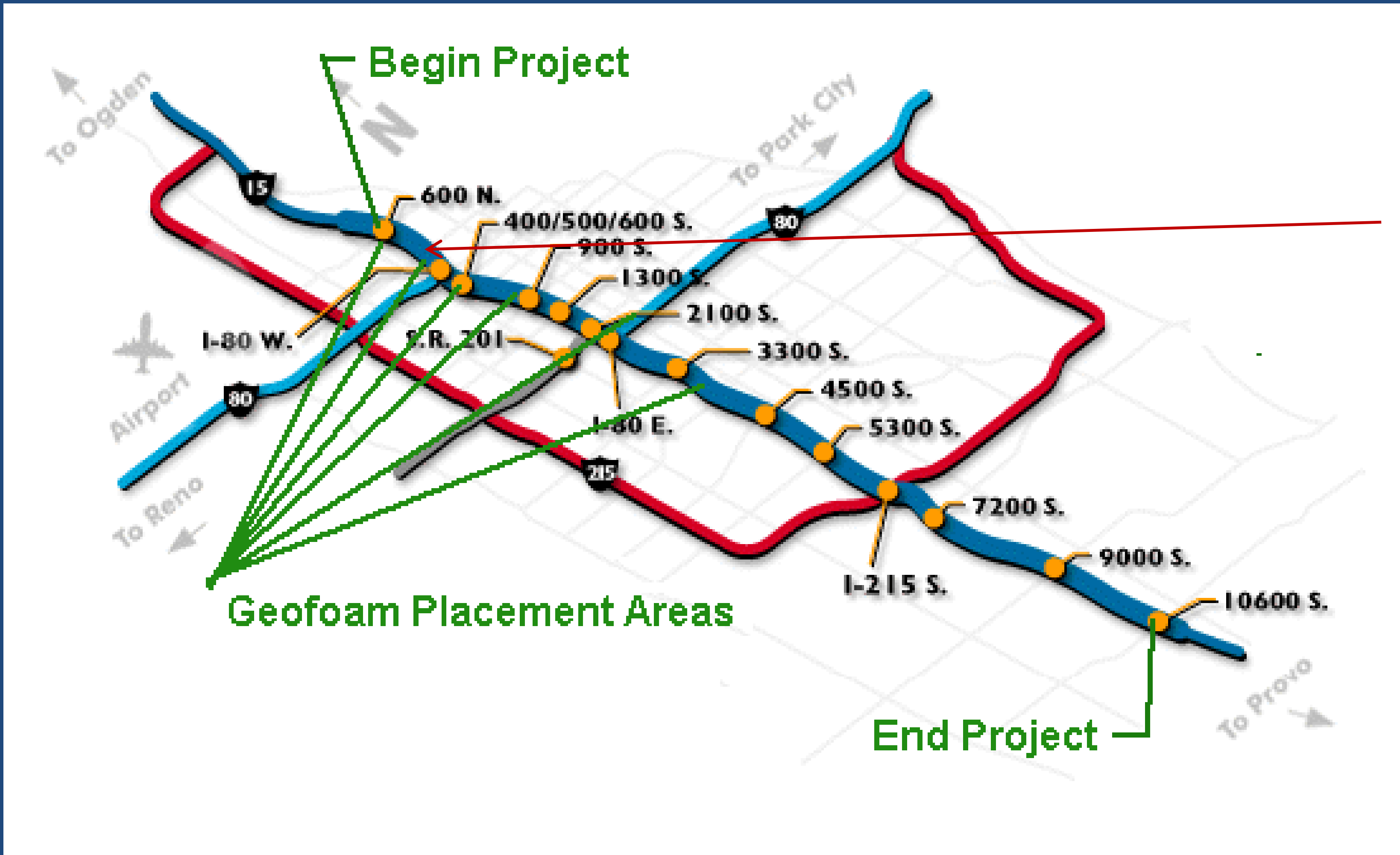




Horizontal Inclinometer Systems, with and without dead-end pulley assembly

Geotechnical Instrumentation
Surveying

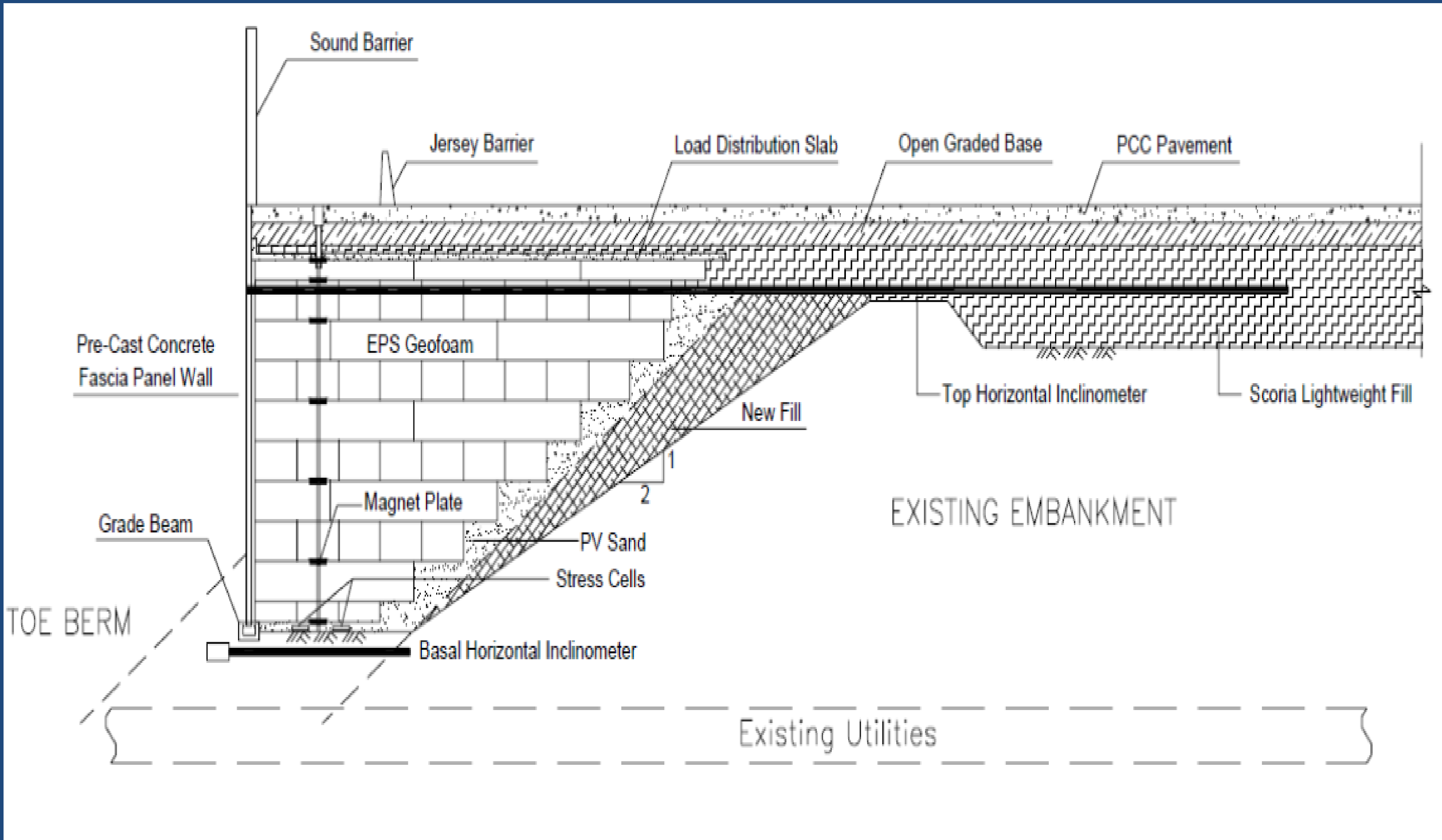
Geofoam Placement Areas



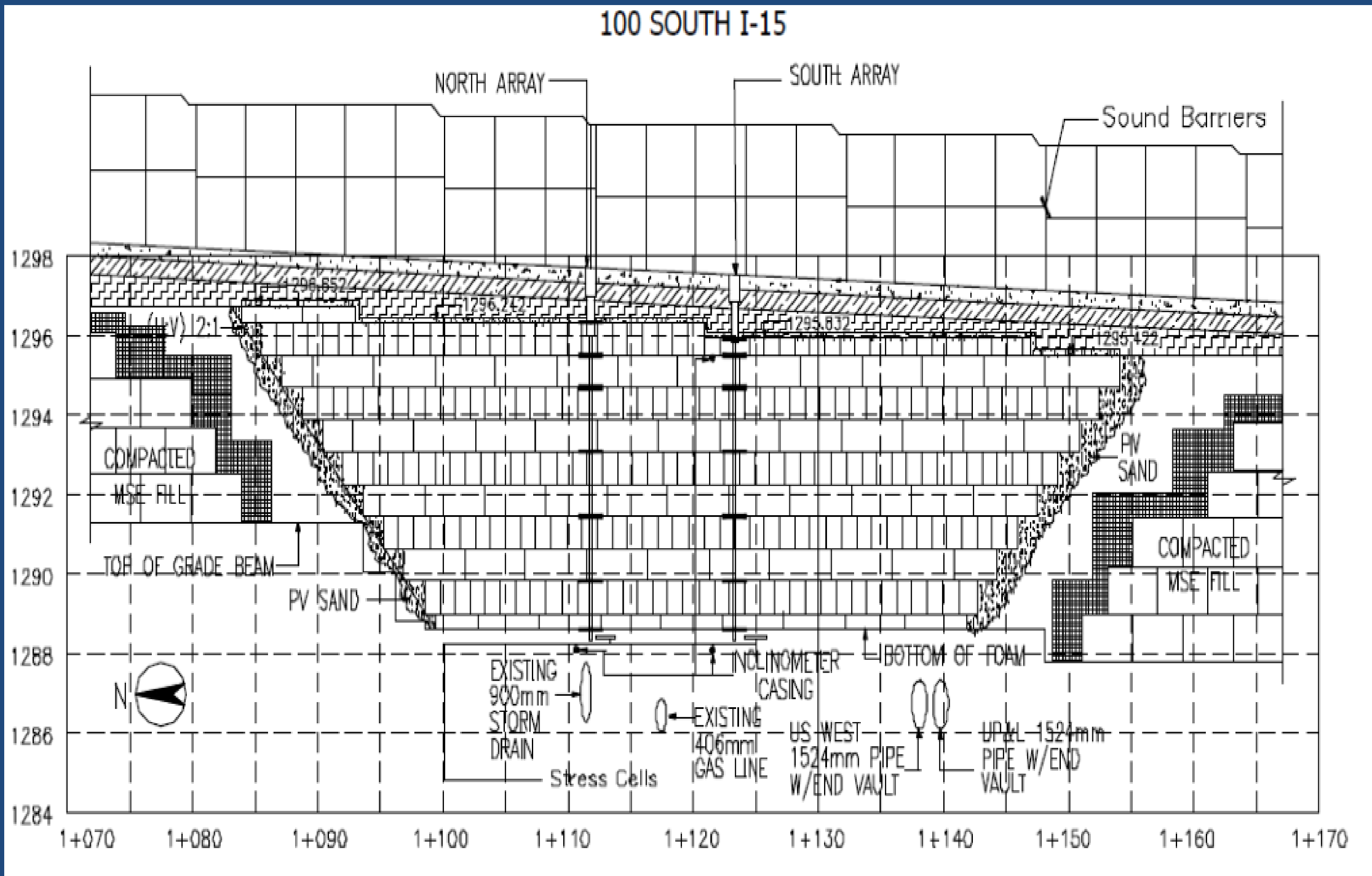
- 500 N
- 100 S
- 400 S
- 900 S
- 1300 S
- State St
- 2100 S
- 3300 S

100 South Array (Construction)

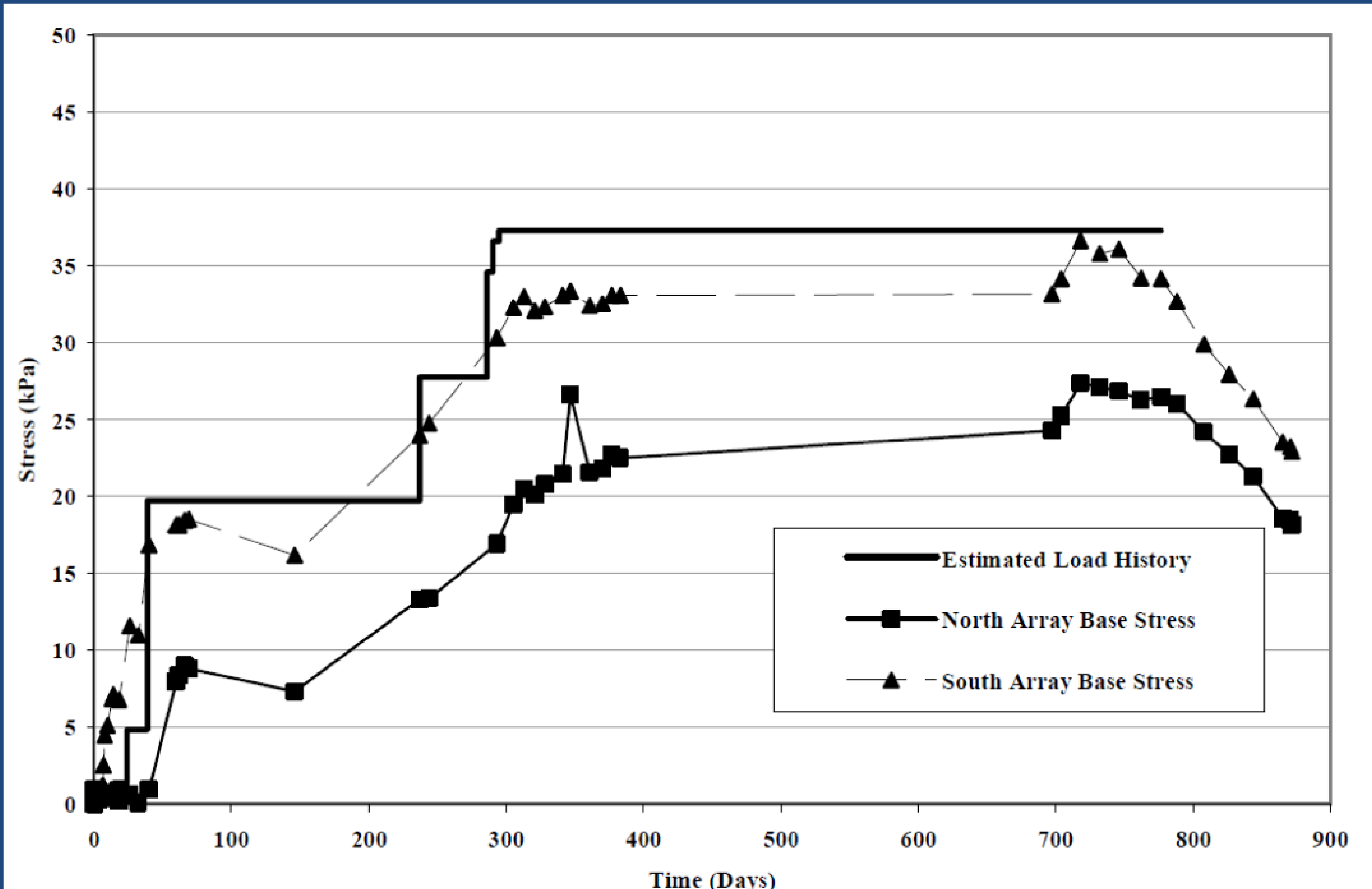
100 South Array (cross-section view)



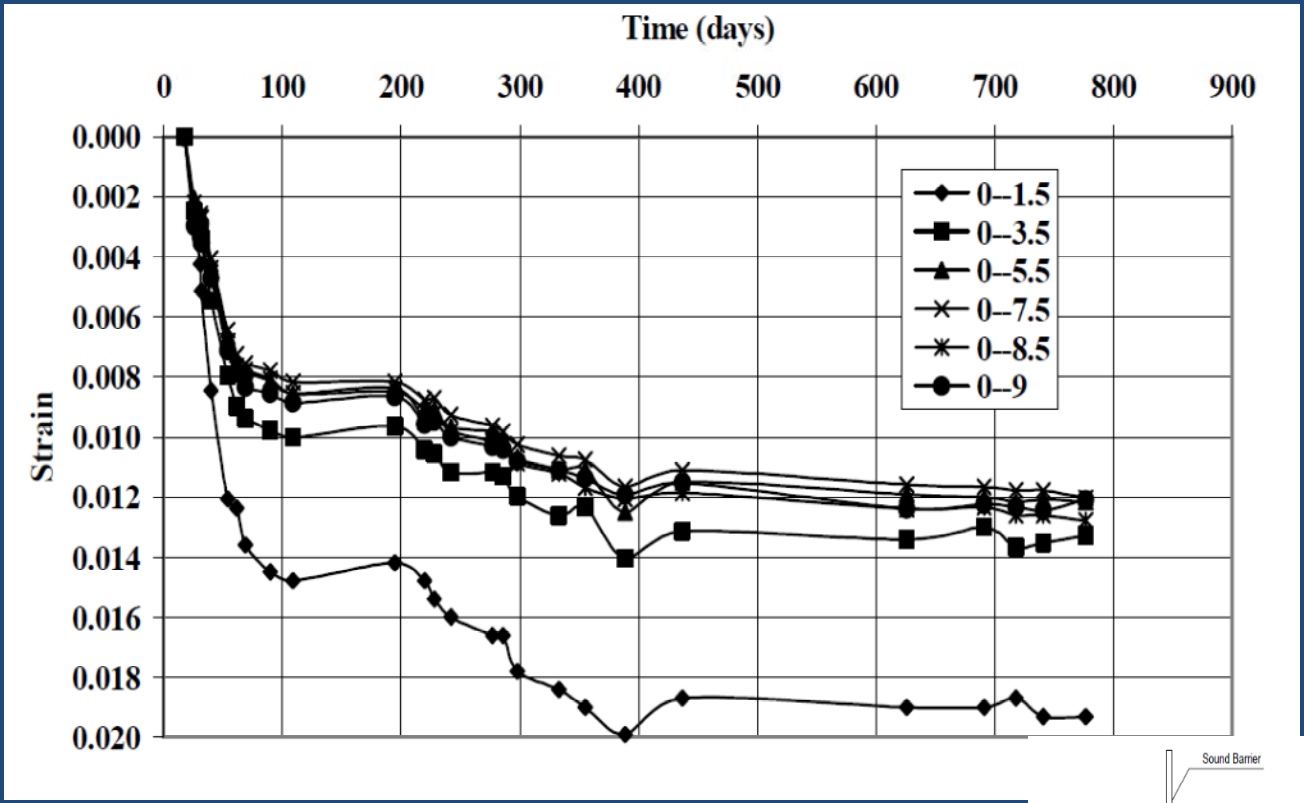
100 South Array (profile view)

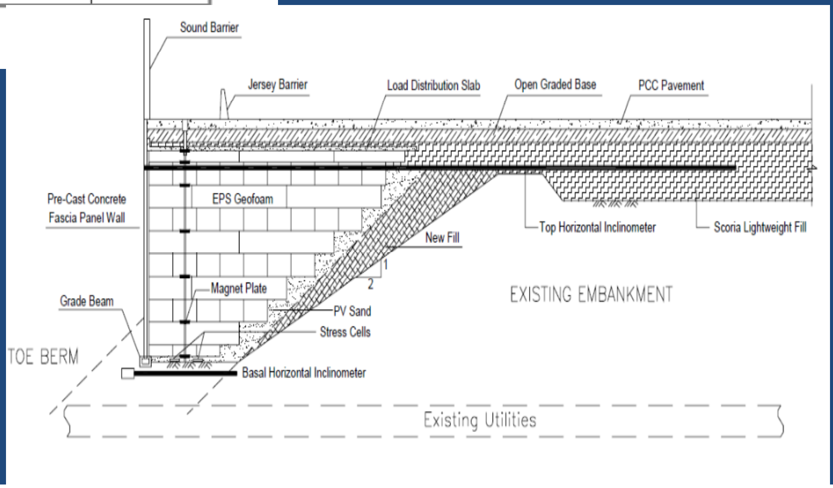


100 South Array
(Load and Pressure Cells)

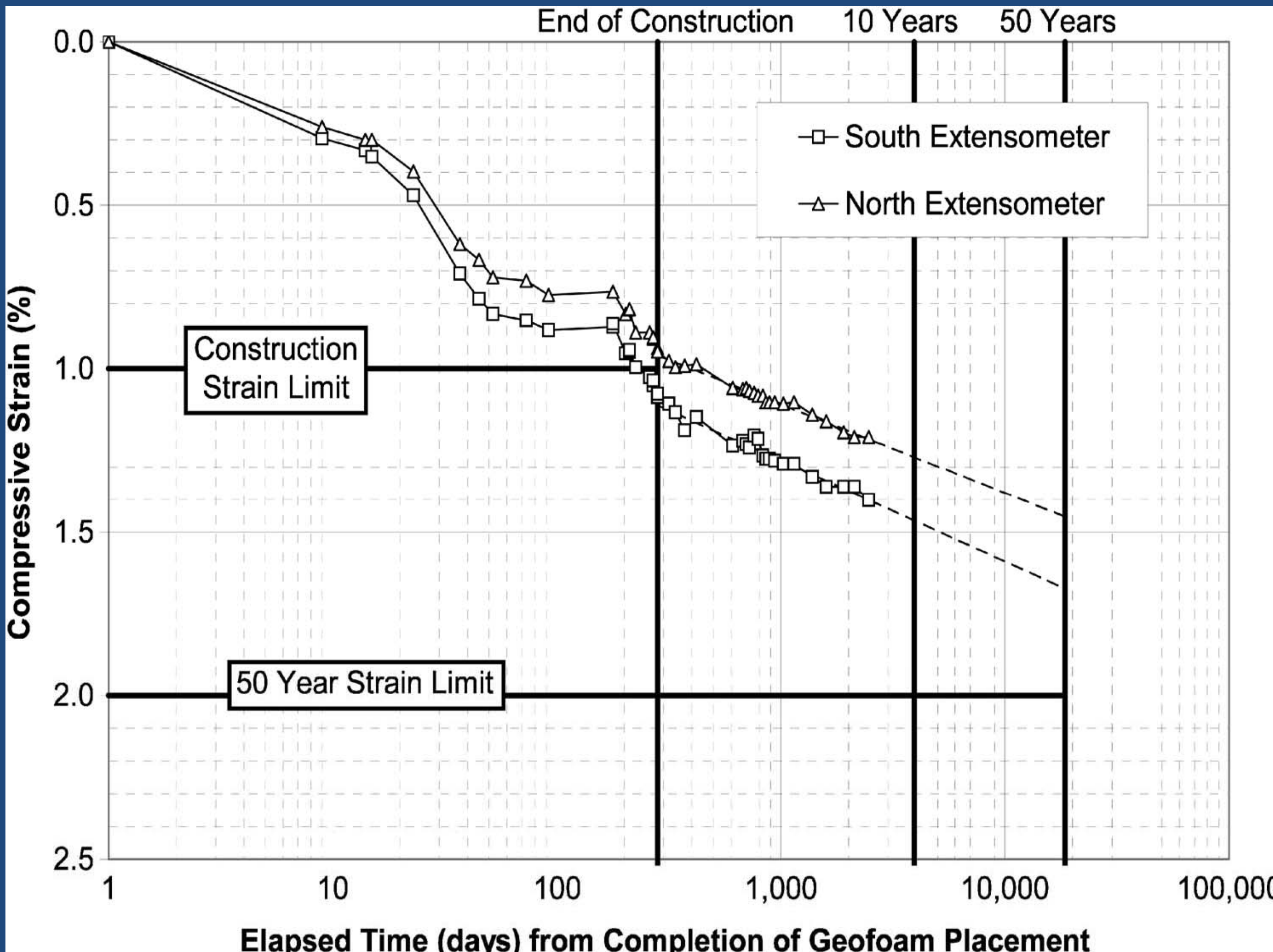


100 South Array (Vertical Strain)

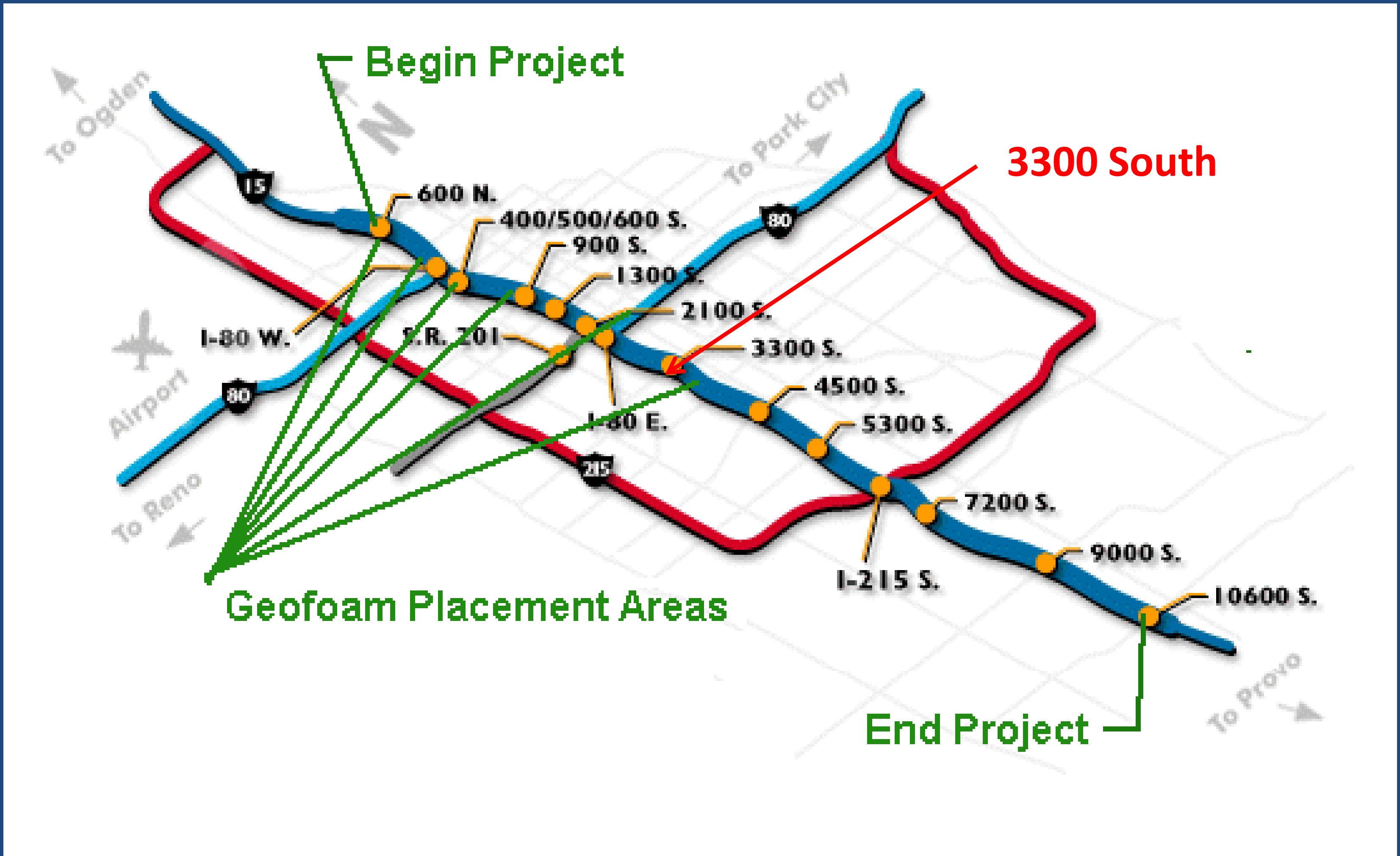




100 South Array
(Creep Settlment)



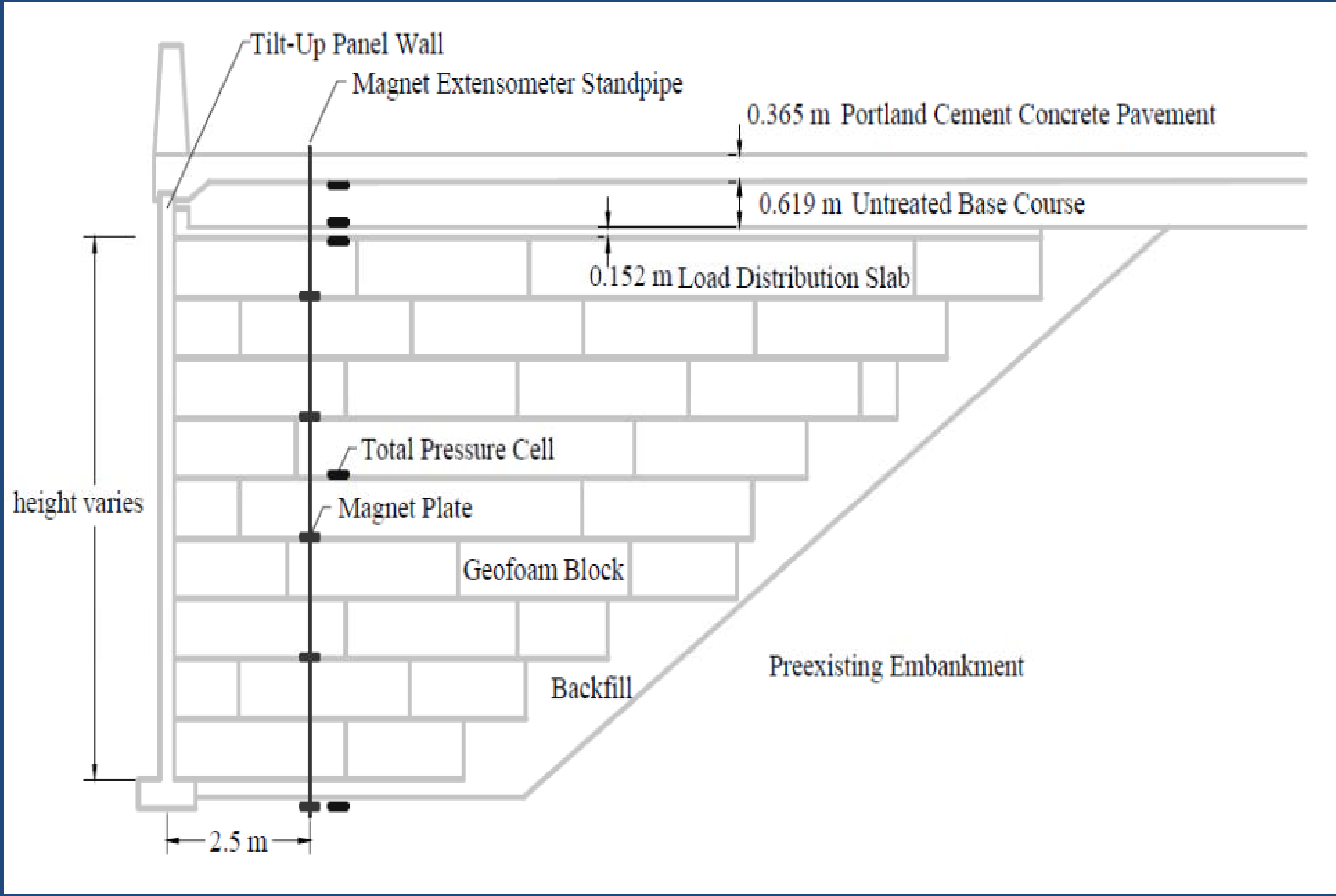
3300 South Instrumentation Array



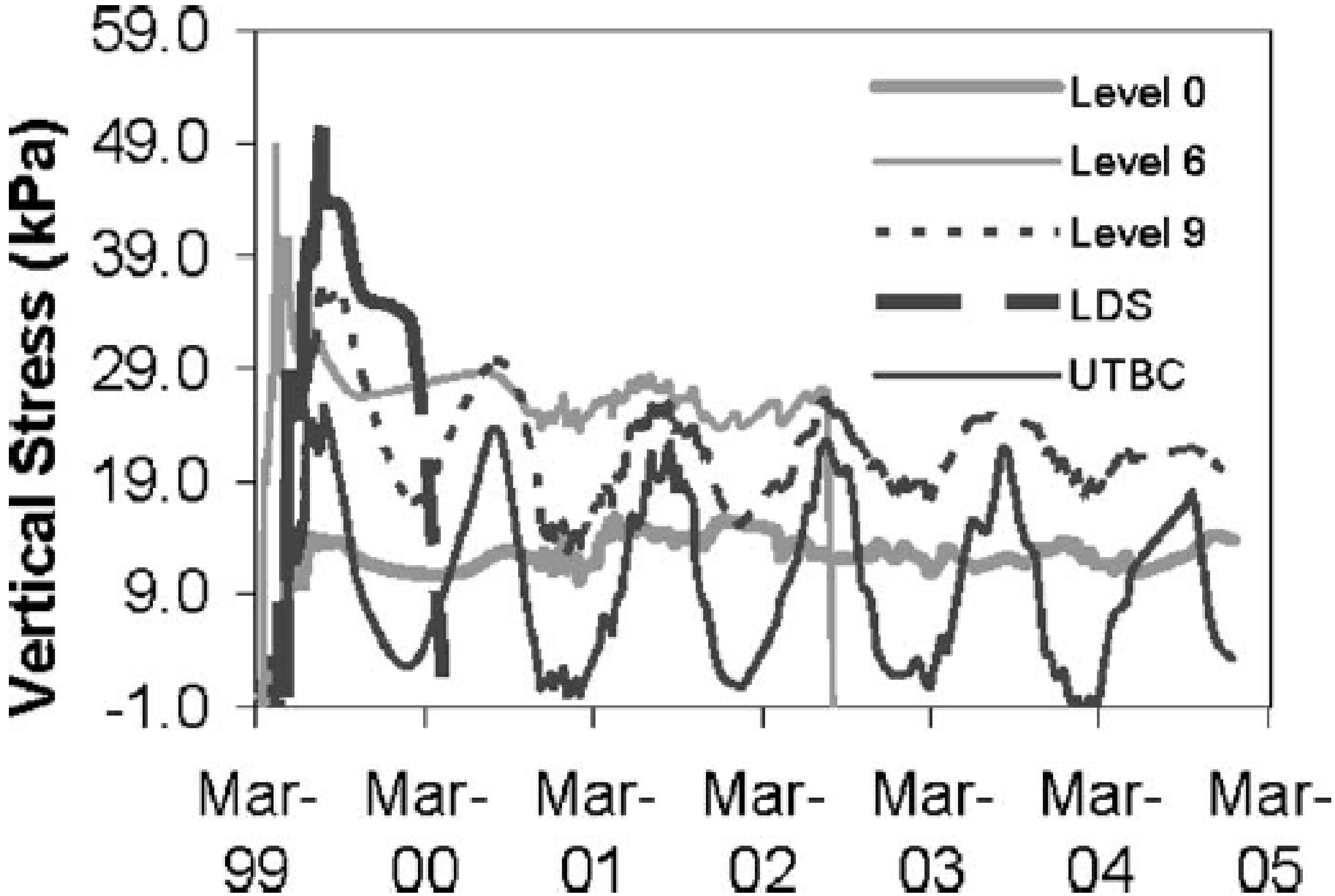
- 500 N
- 100 S
- 400 S
- 900 S
- 1300 S
- State St
- 2100 S
- 3300 S

3300 South Array
(Construction)

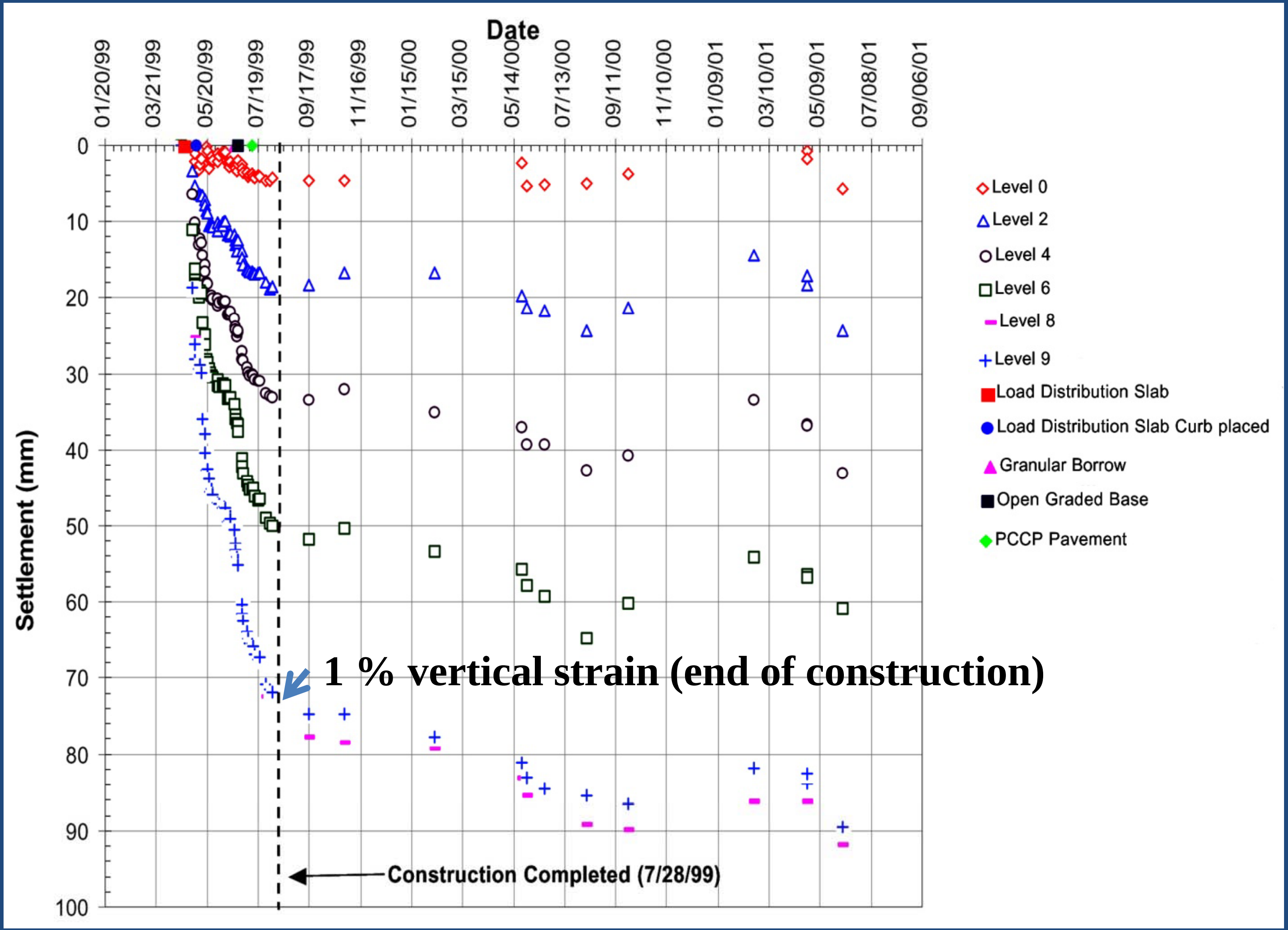
3300 South Geofoam Array (Cross-Sectional View)



3300 South Array
(Load and Pressure Cells)

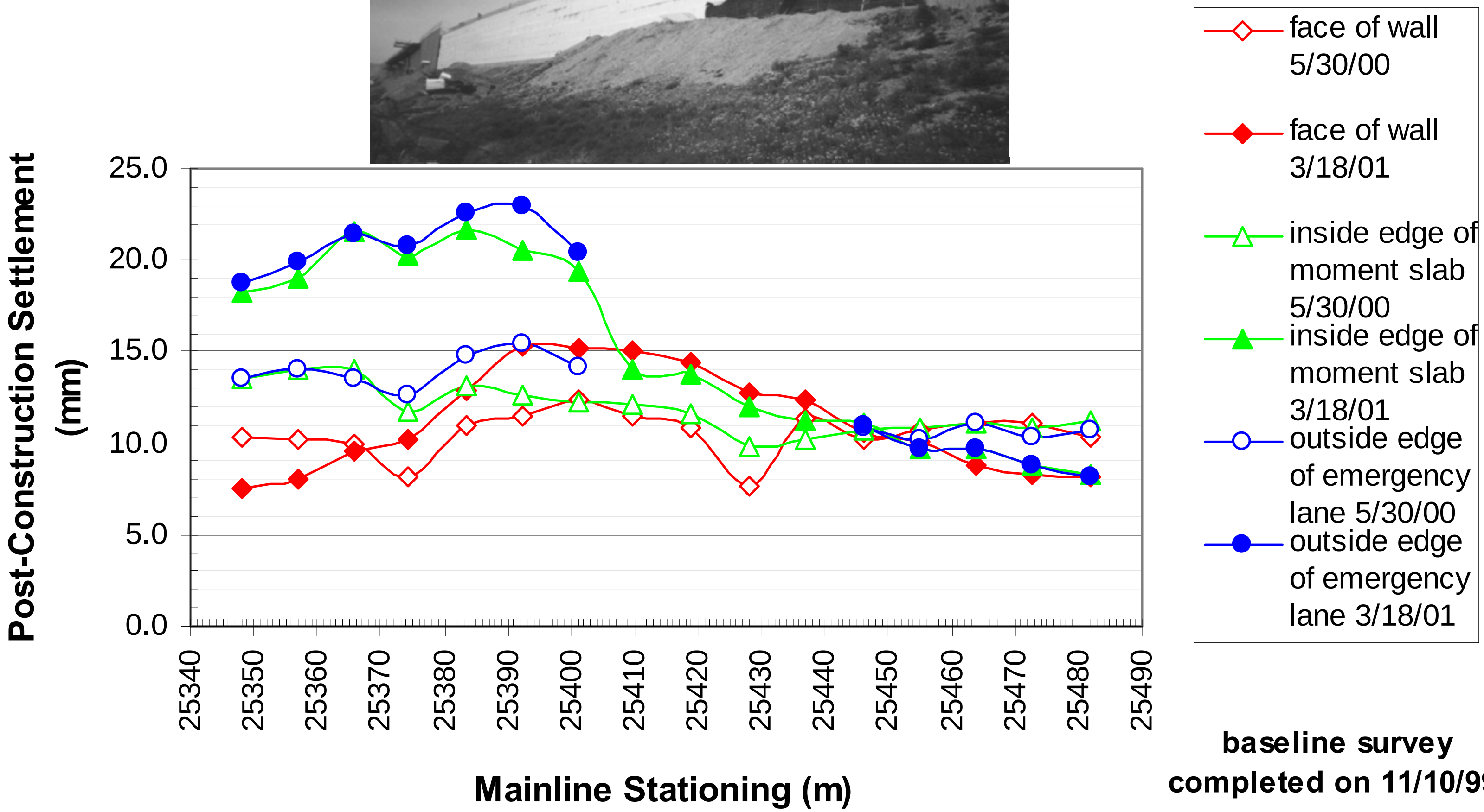


3300 South Array (Vertical Settlement / Strain)



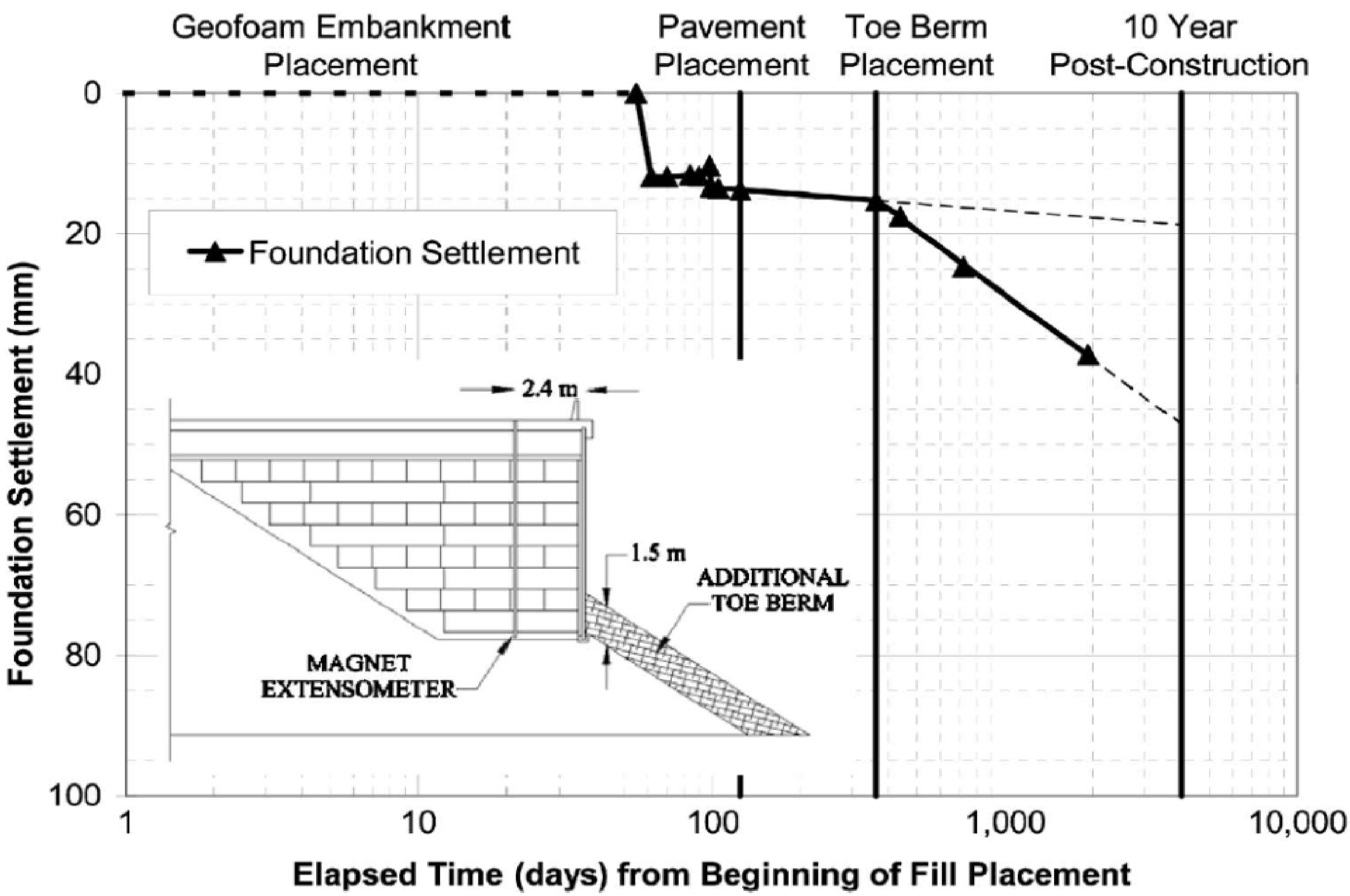
3300 South Array
(Settlement in Transition Zones)

Transition slope
3.5 H : 1 V

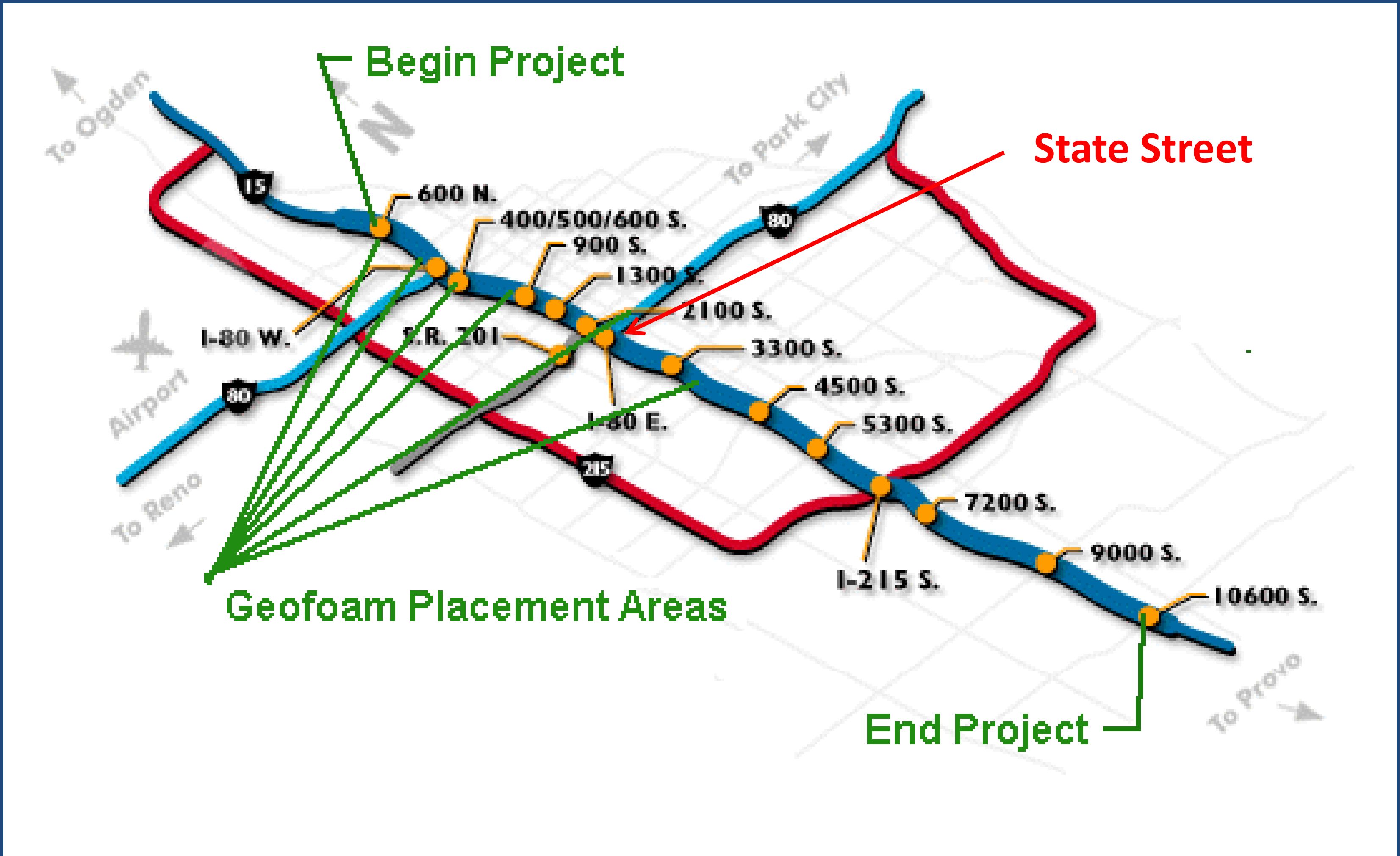


baseline survey completed on 11/10/99.

3300 South Array (Creep Settlement)



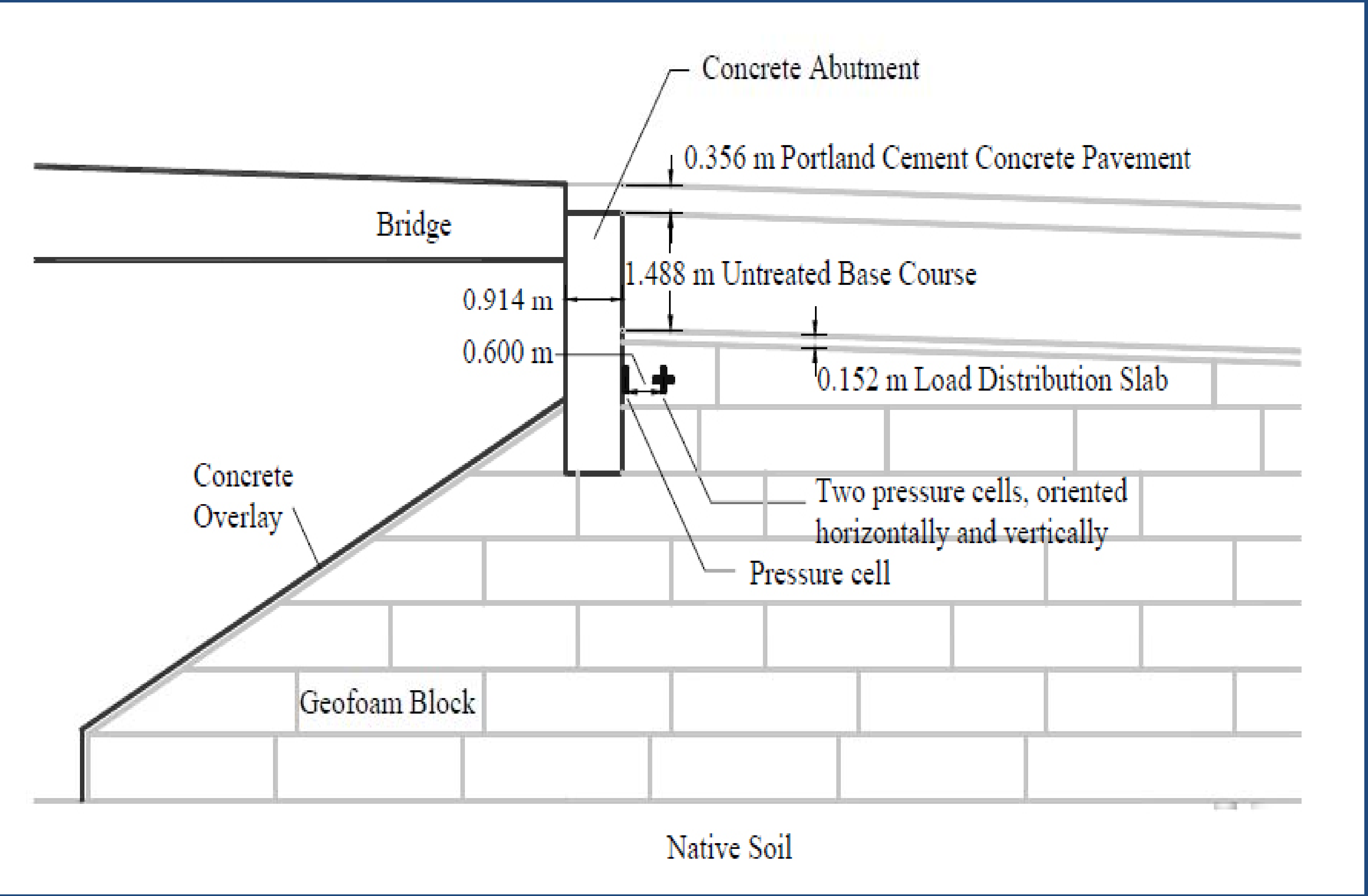
State Street Instumentation



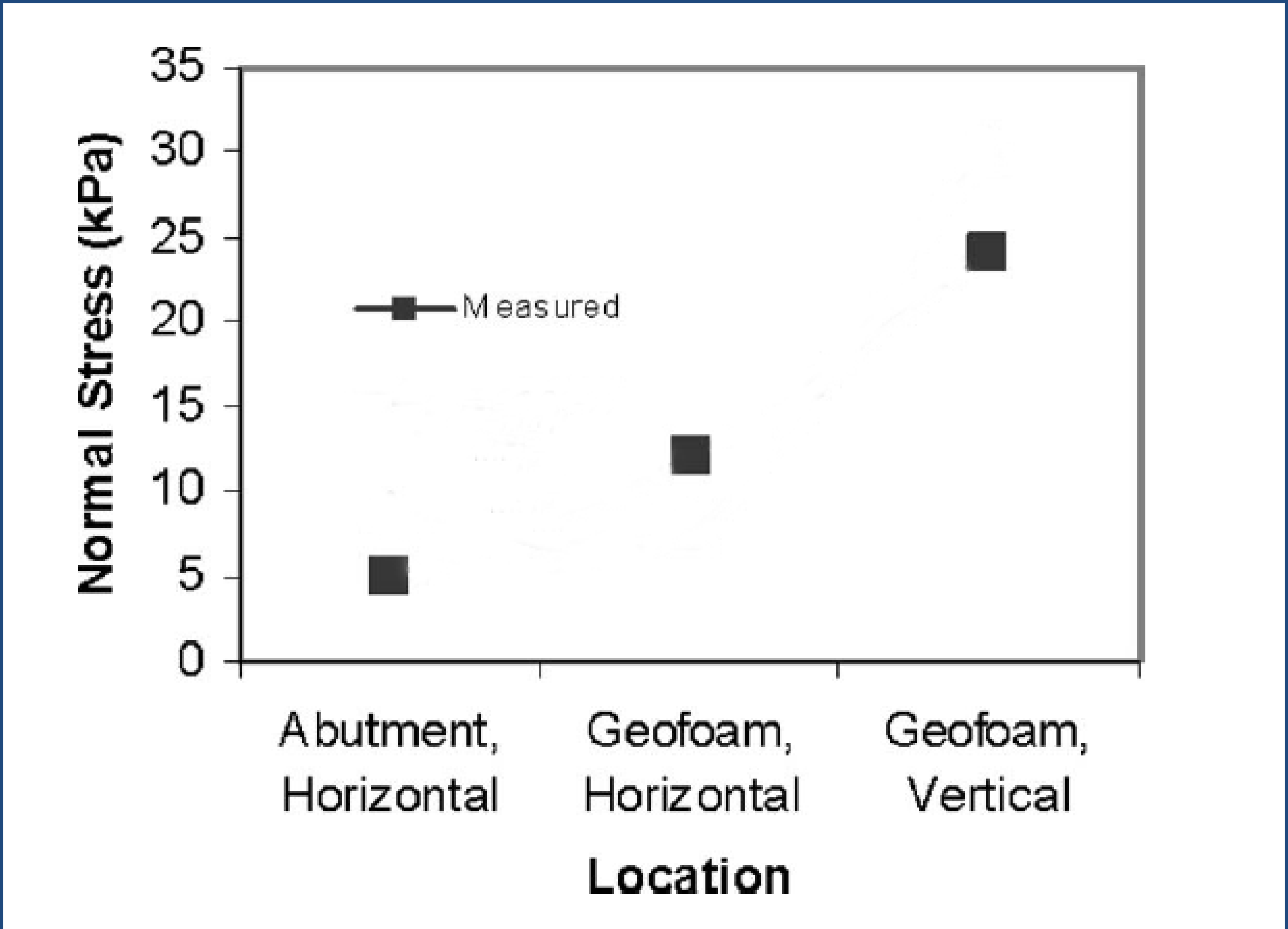
- 500 N
- 100 S
- 400 S
- 900 S
- 1300 S
- State St
- 2100 S
- 3300 S

State Street Construction

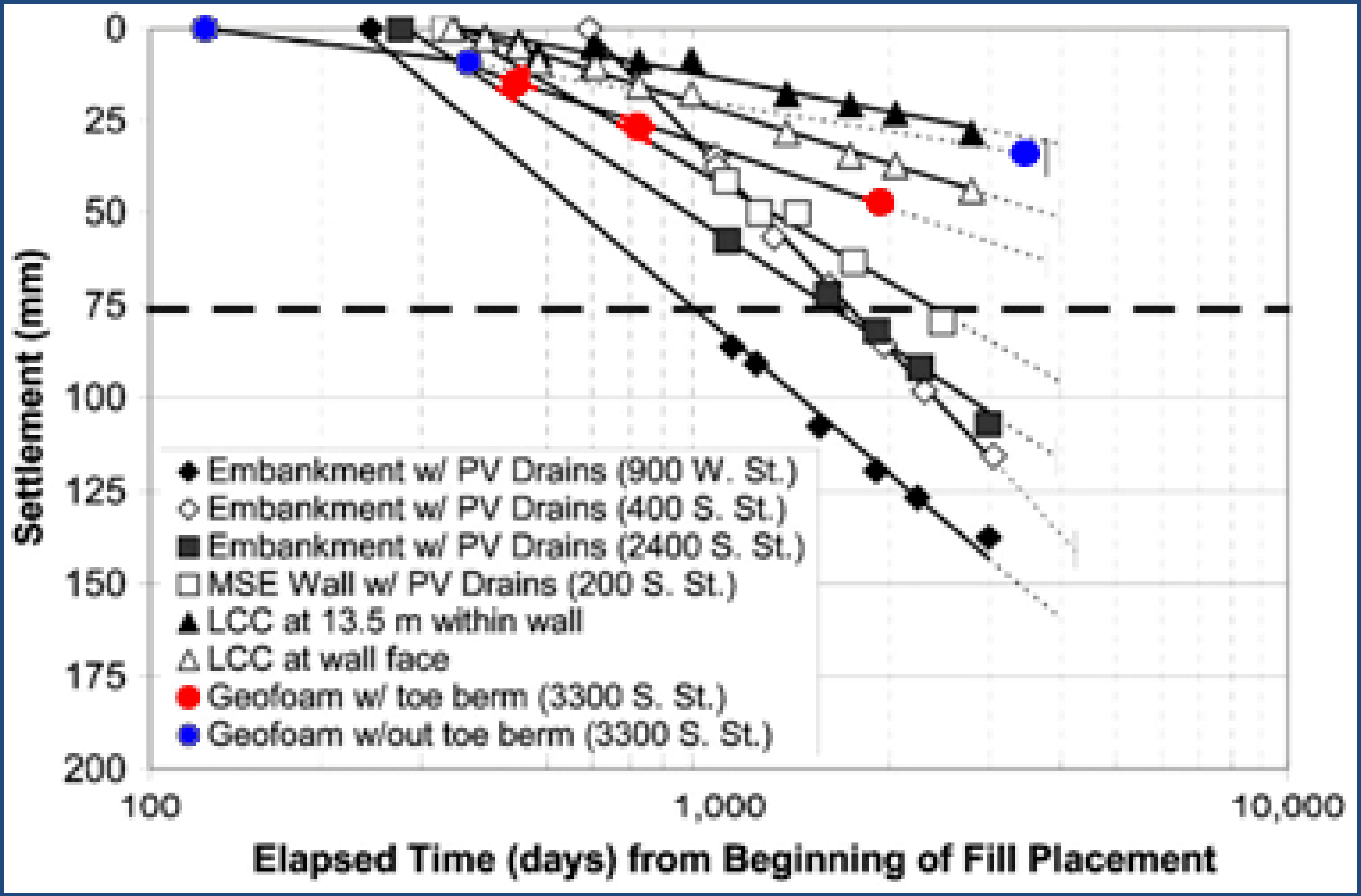
State Street Array



State Street Array
(Pressure Cells Measurements)



Geotechnologies’ Settlement Performance



Conclusions

• EPS geofoam exhibited the best overall settlement performance of the I-15 geotechnologies

• Compression, seating and inter-block gap closure of EPS produced about 1 percent vertical deformation during construction loading.

• Vertical pressure levels are in reasonable agreement with allowable design limits of about 30 kPa.

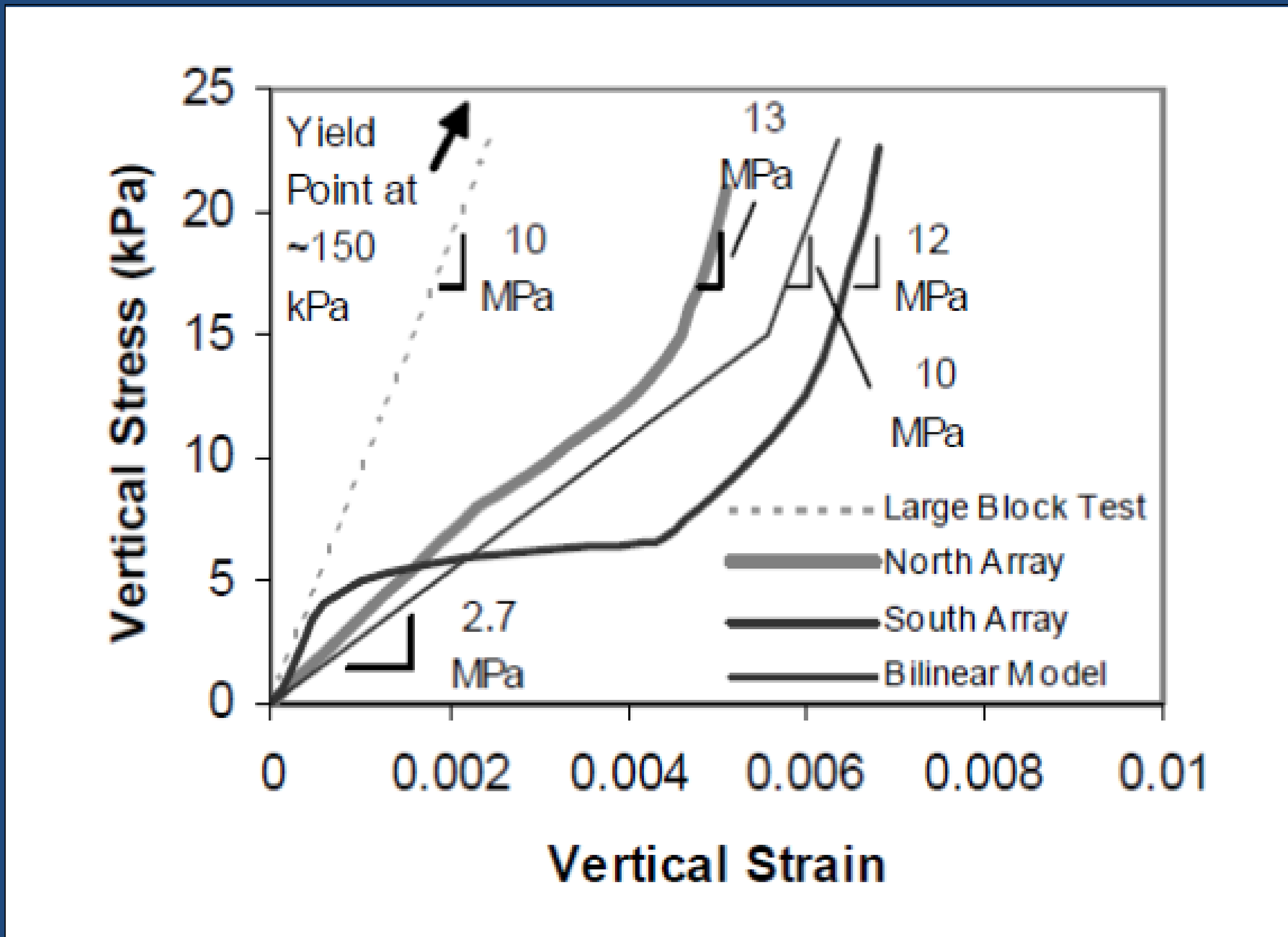
•I-15 EPS embankment has undergone about 0.2 to 0.4 percent creep deformation in a 10-year post construction period.

•The 10-year design criterion has been met and the 50-year design criterion of 1.5 percent total strain will most likely be met.

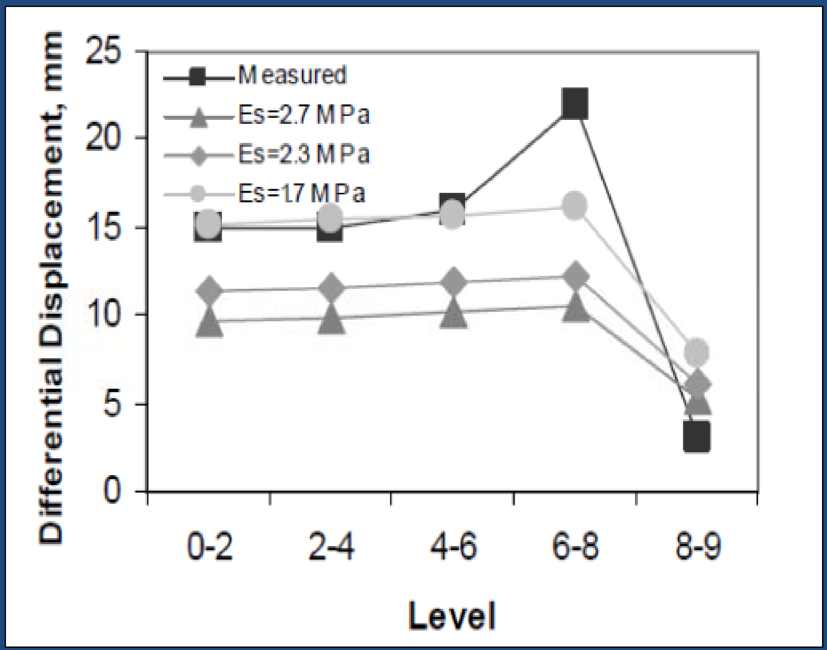
Objectives

- **Long Term Monitoring**
  - Construction Settlement
  - Post-Construction Settlement
  - Transition Zones
  - Settlement Performance Comparison
- **Assessment and Modeling of Performance Data**
  - Settlement
  - Pressure Distribution
    - Vertical
    - Horizontal
  - Connections and Panel Walls
- Seismic Design
- General Design

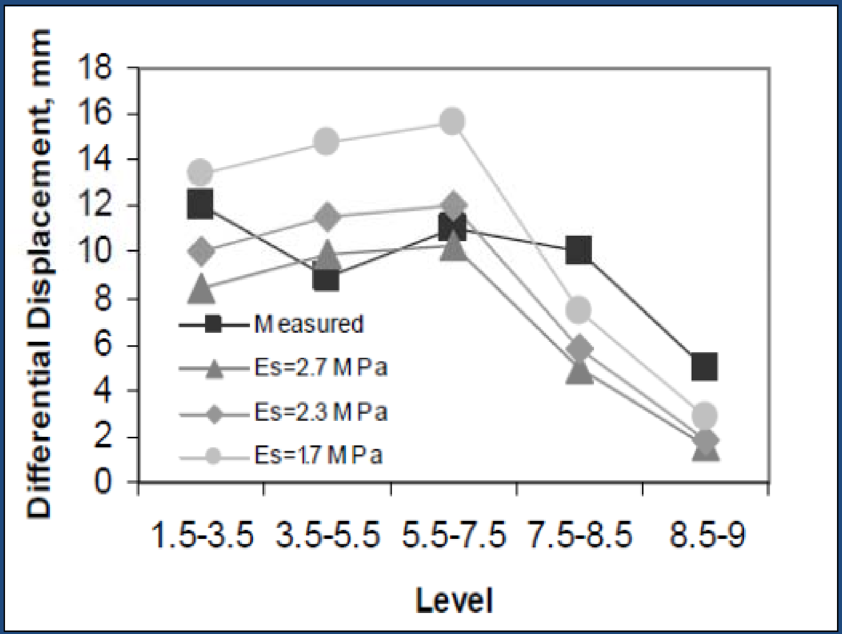
Bi-linear Settlement Model



Modeling of Vertical Displacement with EPS Embankment

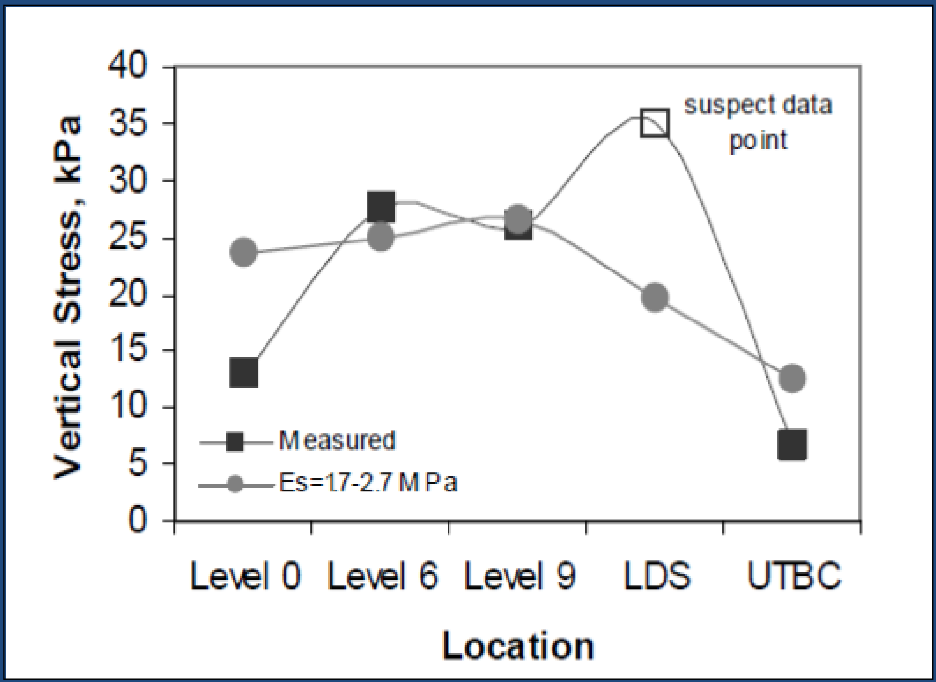


3300 South



100 South

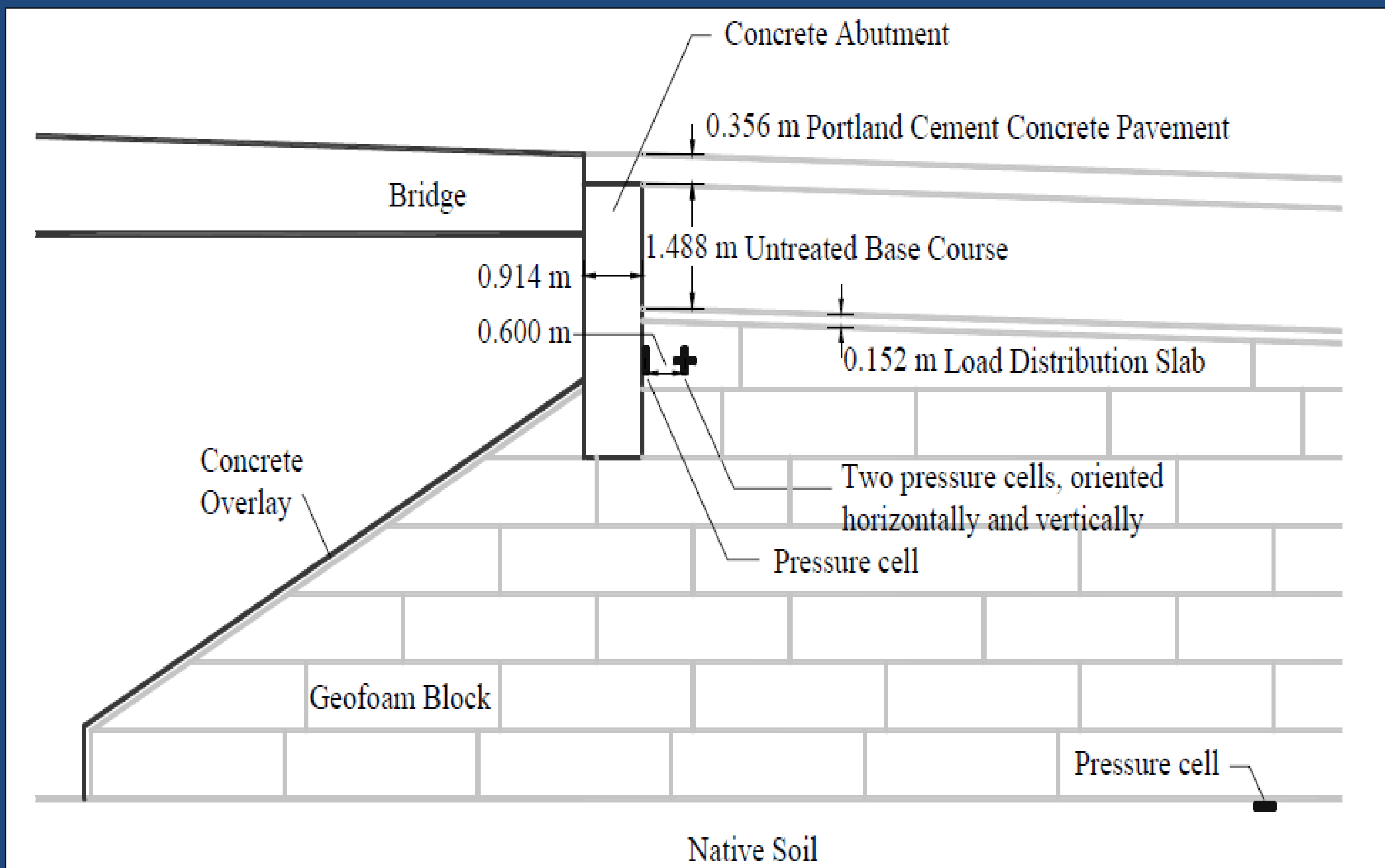
Modeling of Vertical Pressure



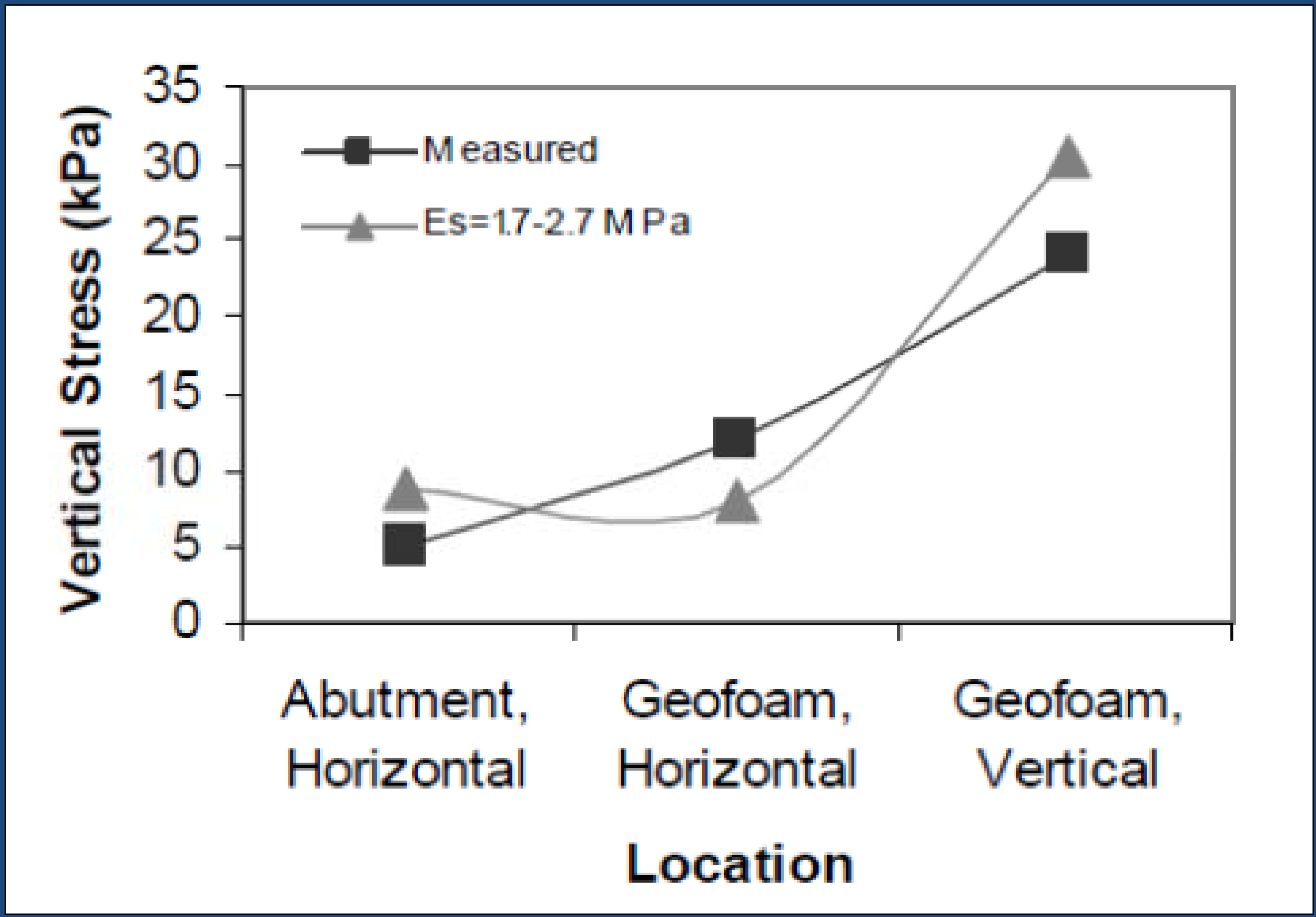
3300 South

100 South
(No pressure cells in EPS)

Modeling of Horizontal Stresses (State Street Array)

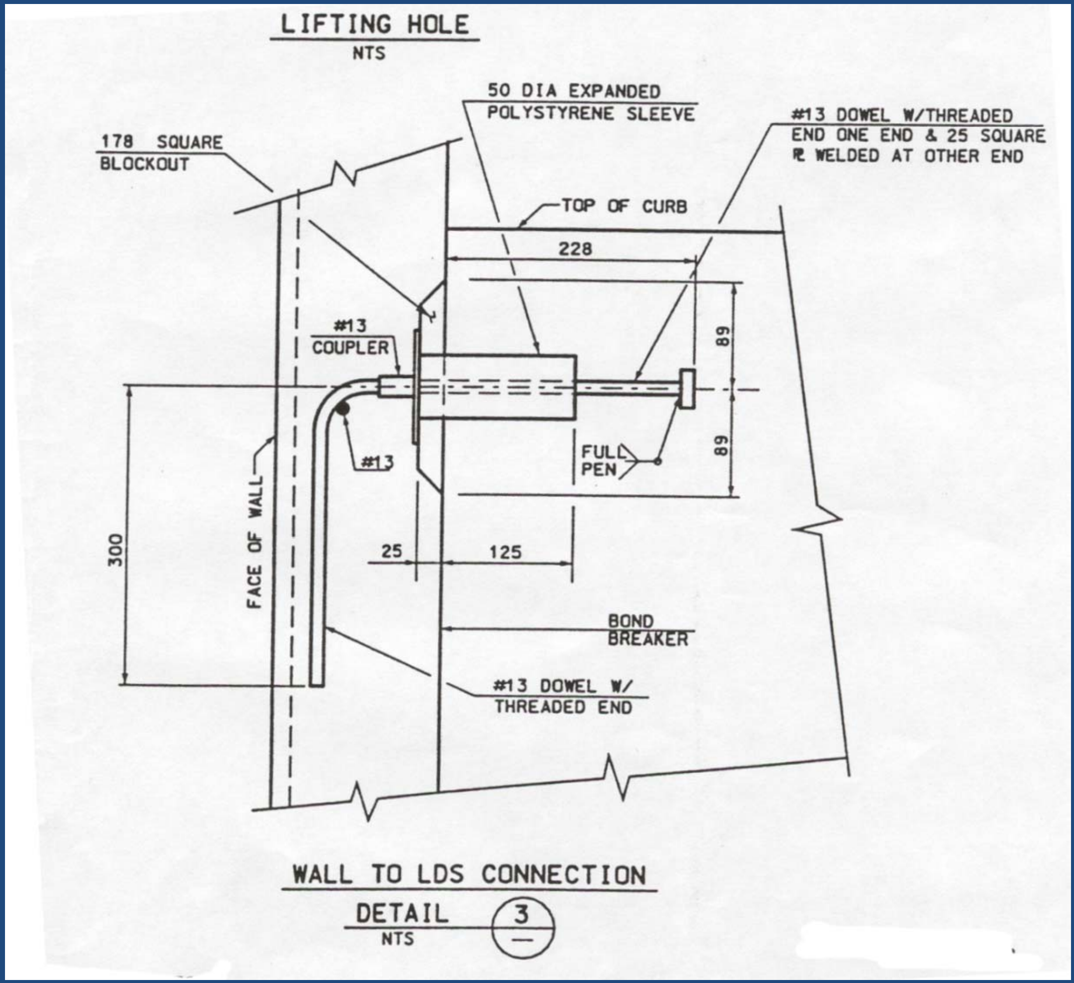


Modeling of Horizontal Stresses



State Street Array

Connections



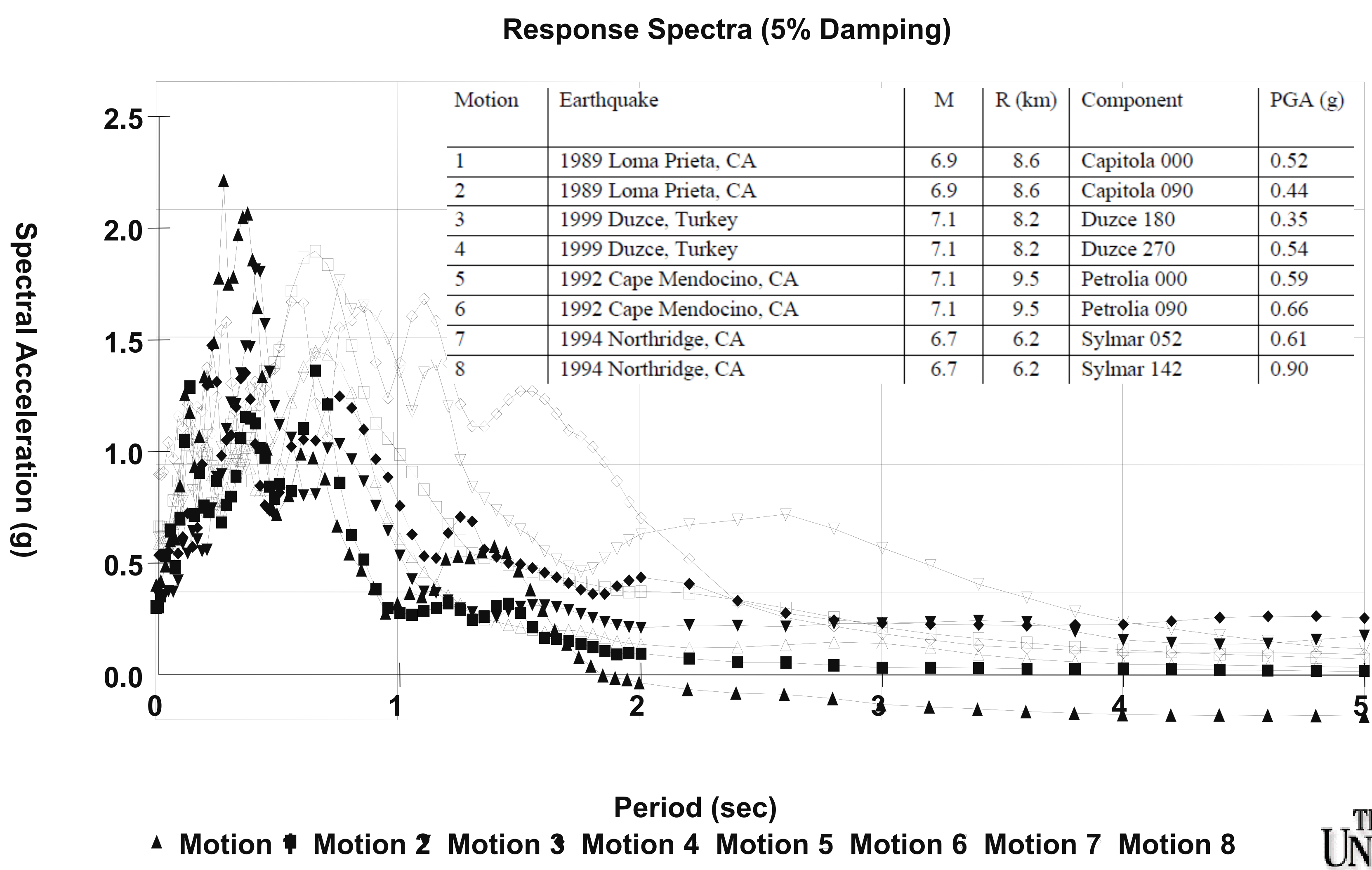
Damaged Connection

- Approximately 1% loading strain can be expected.
- Strain due to seating of untrimmed block and elastic compression.
- Damaged connection was later repaired by dowels.
- Rigid connect should be avoided.

Objectives

- **Long Term Monitoring**
  - Construction Settlement
  - Post-Construction Settlement
  - Transition Zones
  - Settlement Performance Comparison
- **Assessment and Modeling of Performance Data**
  - Settlement
  - Pressure Distribution
    - Vertical
    - Horizontal
  - Connections and Panel Walls
- **Seismic Design**
- General Design

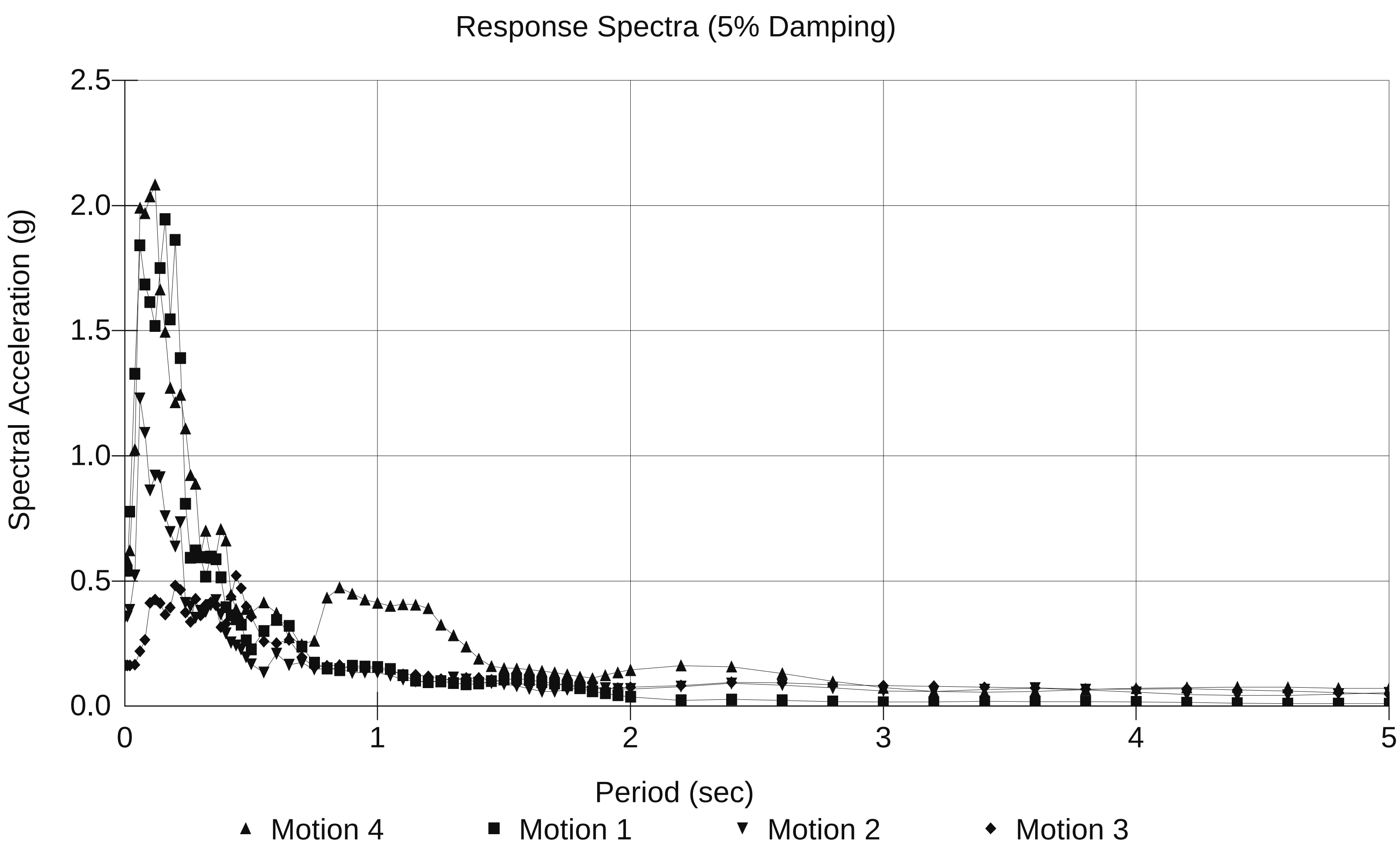
Horizontal Acceleration Response Spectra



Motion	Earthquake	M	R (km)	Component	PGA (g)
1	1989 Loma Prieta, CA	6.9	8.6	Capitola 000	0.52
2	1989 Loma Prieta, CA	6.9	8.6	Capitola 090	0.44
3	1999 Duzce, Turkey	7.1	8.2	Duzce 180	0.35
4	1999 Duzce, Turkey	7.1	8.2	Duzce 270	0.54
5	1992 Cape Mendocino, CA	7.1	9.5	Petrolia 000	0.59
6	1992 Cape Mendocino, CA	7.1	9.5	Petrolia 090	0.66
7	1994 Northridge, CA	6.7	6.2	Sylmar 052	0.61
8	1994 Northridge, CA	6.7	6.2	Sylmar 142	0.90

THE UNIVERSITY OF UTAH

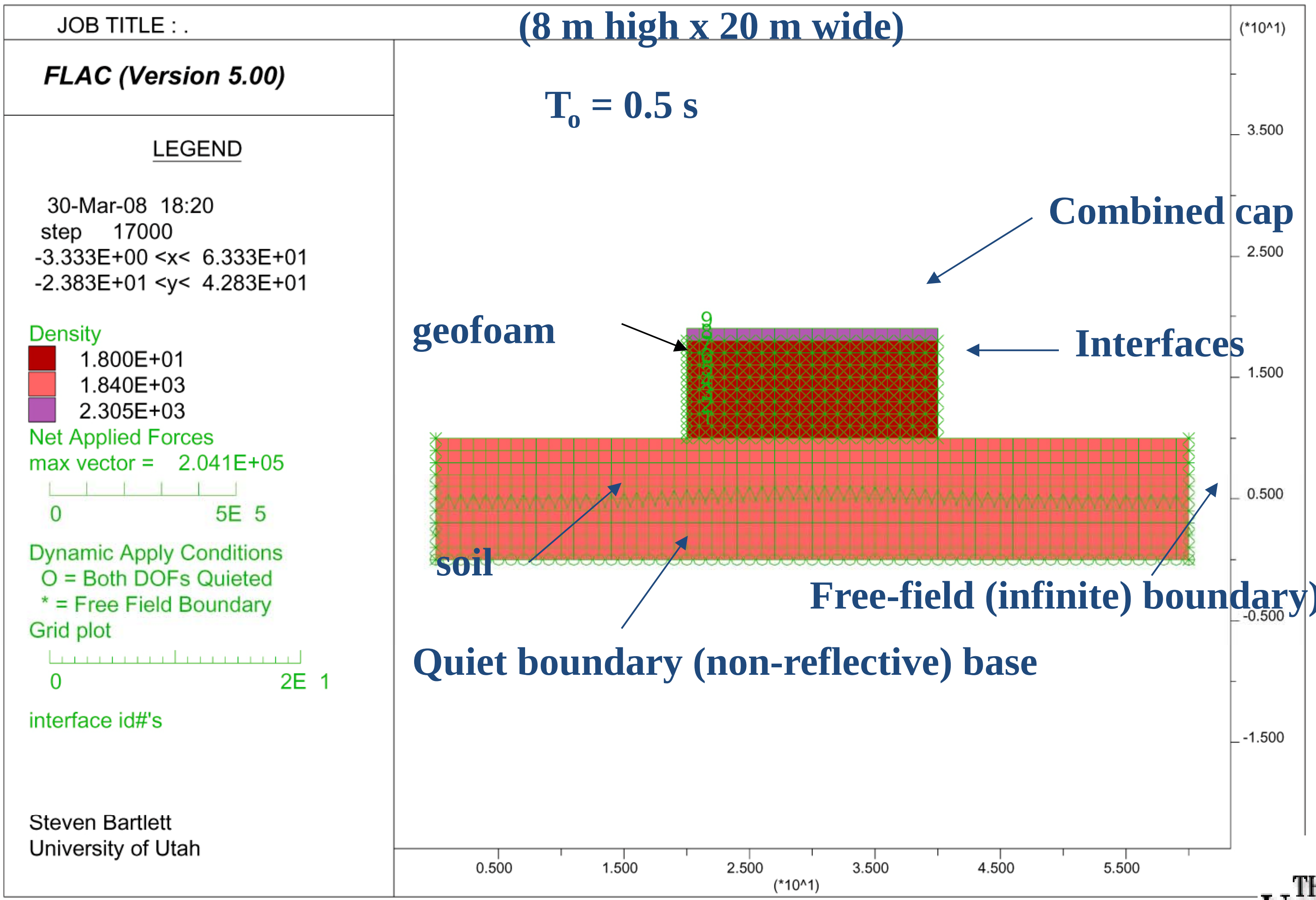
Vertical Acceleration Response Spectra



Numerical Modeling Approach

- FLAC (Fast Lagrangian Analysis of Continua)
  - 2D or 3D
  - Explicit Finite Difference Method
  - Large Strain Mode
    - Sliding and Separation at Nodal Interfaces
  - Nonlinear Modeling capability
    - Elasto-Plastic Model w/ Mohr-Coulomb Failure Criteria and Plastic Post-Yield Behavior
    - Hysteretic damping

Sliding Evaluations



Elastic Properties for Sliding Evaluations

Material Type	Layer No.	ρ (kg/m^3)[4]	E (MPa)[5]	ν[6]	K (MPa)[7]	G (MPa)[8]
Foundation Soil	1-10	1840	174	0.4	290.0	62.1
Geofoam	11-18	18	10	0.103	4.2	4.5
UTBC[1]	19	2241	570	0.35	633	211
LDS[2] & PCCP[3]	19	2401	30000	0.18	15625	12712

[1] Untreated base course, [2] Load distribution slab, [3] Portland concrete cement pavement, [4] Mass density, [5] Initial Young's modulus, [6] Poisson's ratio, [7] Bulk modulus, [8] Shear modulus

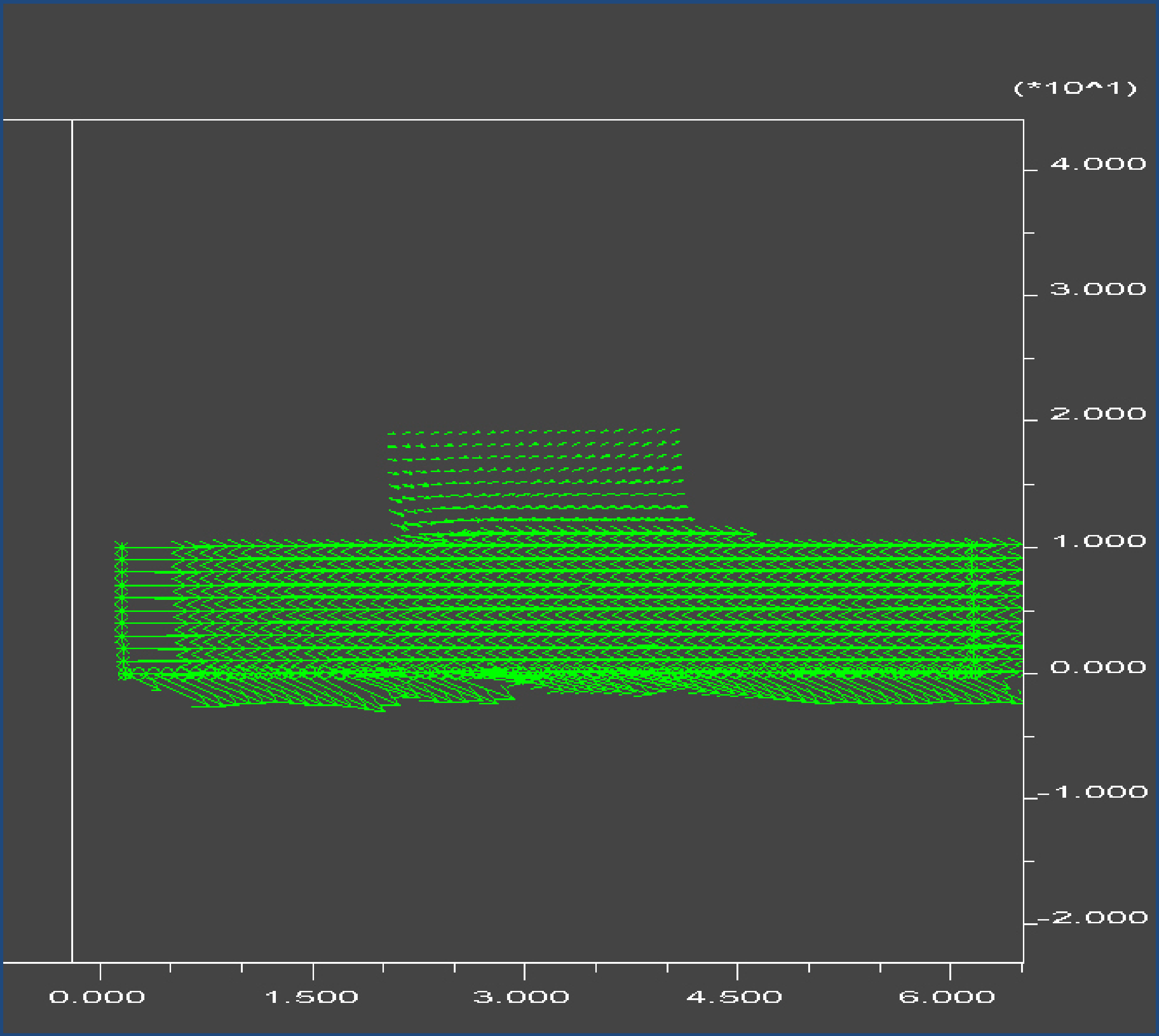
Interface Properties for Sliding Evaluations

Contact Surface	Interface number (bottom to top)	Normal and Shear Stiffness (k_n = k_s) (MPa)	Friction angle (degrees)
Geofoam-soil	1	102	31[1]
Geofoam-Geofoam	2-8	102	38
Geofoam-Lump Mass	9	102	38[2]

[1] A glued interface was used for interface 1 in FLAC because the geofoam is abutted against the panel wall footing and cannot slide. [2] Neglects any tensile or shear bonding that may develop between the top of geofoam and base of the load distribution slab.

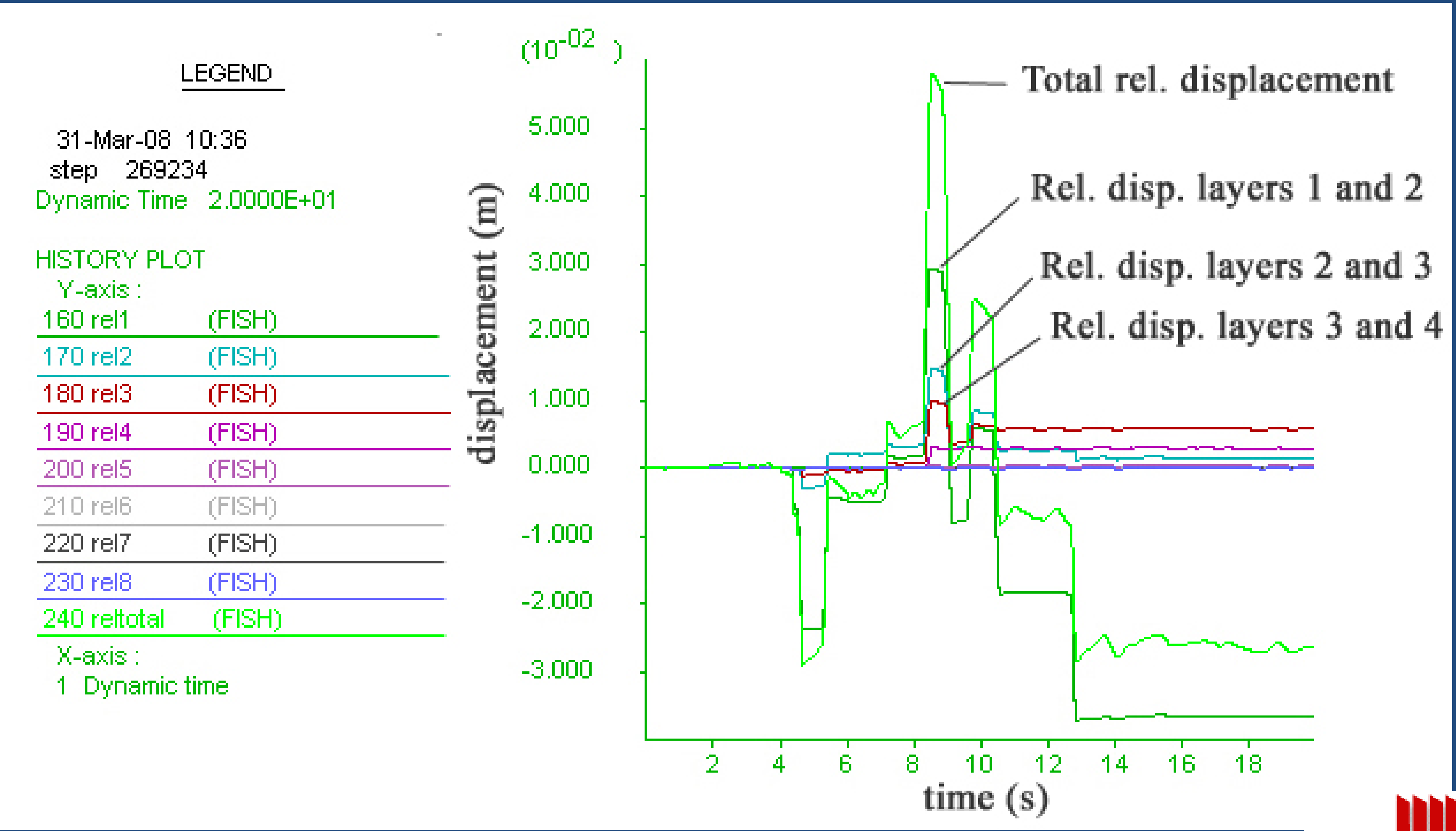
THE UNIVERSITY OF UTAH

Displacement Vectors from FLAC



Video

Relative and Total Sliding Displacement

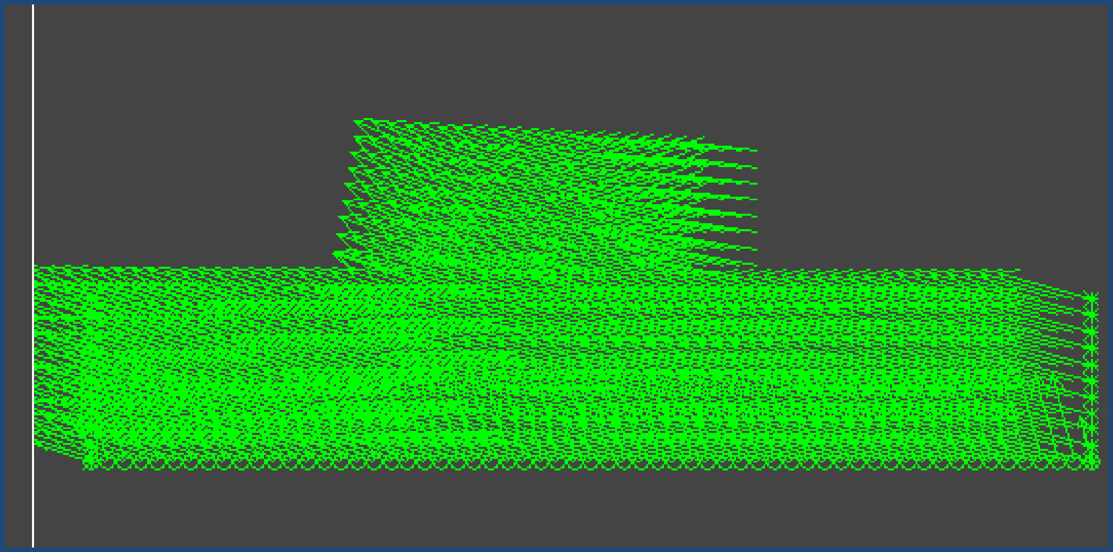


Sliding Displacement Summary

Case	Horizontal Motion	Vertical Motion	Displacement (m)
1a	1	Not applied	0.06
1b	1	1	0.06
2a	2	Not applied	0.01
2b	2	1	0.05
3a	3	Not applied	0.06
3b	3	2	0.06
4a	4	Not applied	1.3
4b	4	2	1.3
5a	5	Not applied	0.005
5b	5	3	0.01
6a	6	Not applied	0.05
6b	6	3	0.06
7a	7	Not applied	0.5
7b	7	4	0.6
8a	8	Not applied	0.6
8b	8	4	0.5

Shear Keys to Prevent Sliding

Rocking/Uplift and Sway Evaluations



Model Modifications

- interface nodes removed (no sliding between layers)
- overlying concrete was "bonded" to geofoam
- basal sliding prohibited
- M-C model with hysteretic damping including tensile, compression and shear properties specified
- both vertical and horizontal component present

THE UNIVERSITY OF UTAH

Rocking and Uplift Results

Case	Max. uplift (left corner) (m)	Max. uplift (right corner) (m)
1b	0.06	0.05
2b	0.02	0.04
3b	0.2	0.2
4b	0.2	? rotation due to tensile yielding
5b	0.01	0.01
6b	0.03	0.03
7b	? rotation due to tensile yielding	0.2
8b	0.25	0.25

THE UNIVERSITY OF UTAH

Sliding Calculations (simplified)

Table 17 Example interlayer sliding calculation

H =	8	m
Block thickness =	0.81	m
number of interfaces	9	
normal stress	25.36	kPa
interface friction	0.8	(geofoam - geofoam)
interface friction	0.6	(geofoam - soil)
geofoam shear strength	23	psi (EPS19 used in shear key)
geofoam shear strength	157.3	kPa

interface #	Horiz. Accel. (g)	mass (kg/m³)	inertial force (N/m³)	resisting sliding force (N/m³)	shear key coverage (%)	resisting force from key (N/m³)	FS sliding (w / key)
9	0.848	2585	21497	19073	6	9439	1.33
8	0.791	2585	20064	19478	4	6293	1.28
7	0.735	2585	18631	19681	3	4720	1.31
6	0.678	2585	17198	19884	2	3146	1.34
5	0.622	2585	15765	20087	1	1573	1.37
4	0.565	2585	14332	20290	0	0	1.42
3	0.509	2585	12898	20290	0	0	1.57
2	0.452	2585	11465	20290	0	0	1.77
1	0.396	2585	10032	20290	0	0	2.02
0	0.339	2585	8599	15217	0	0	1.77

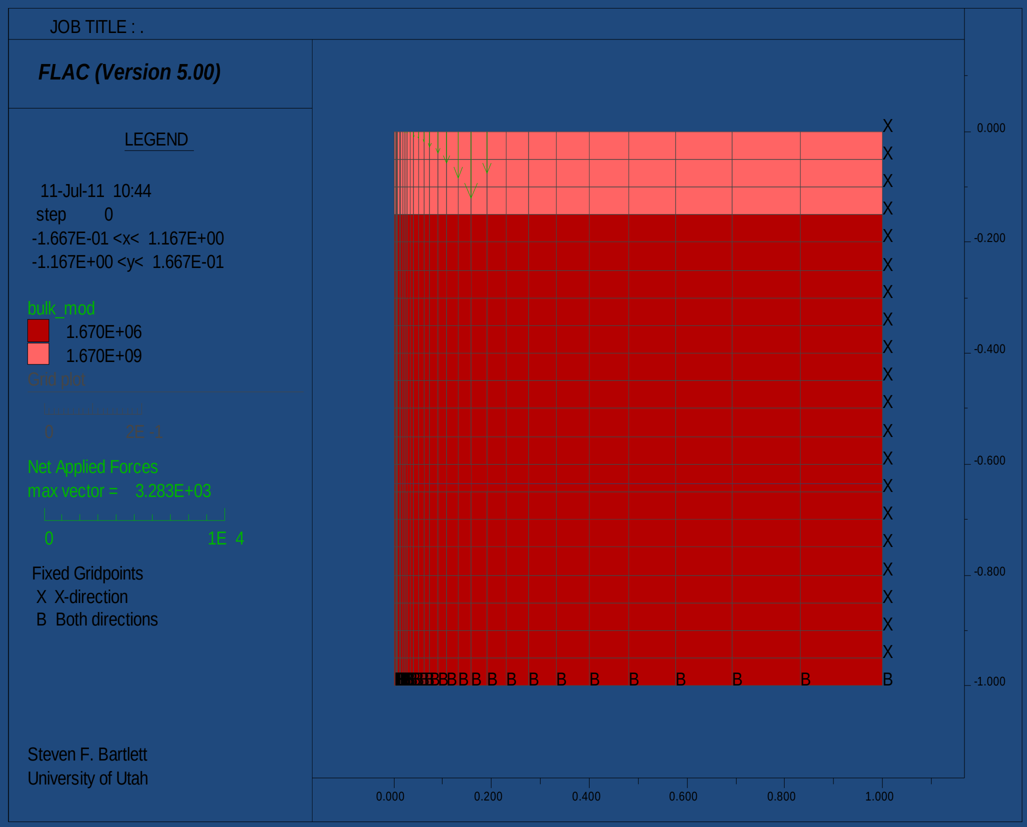
Conclusions

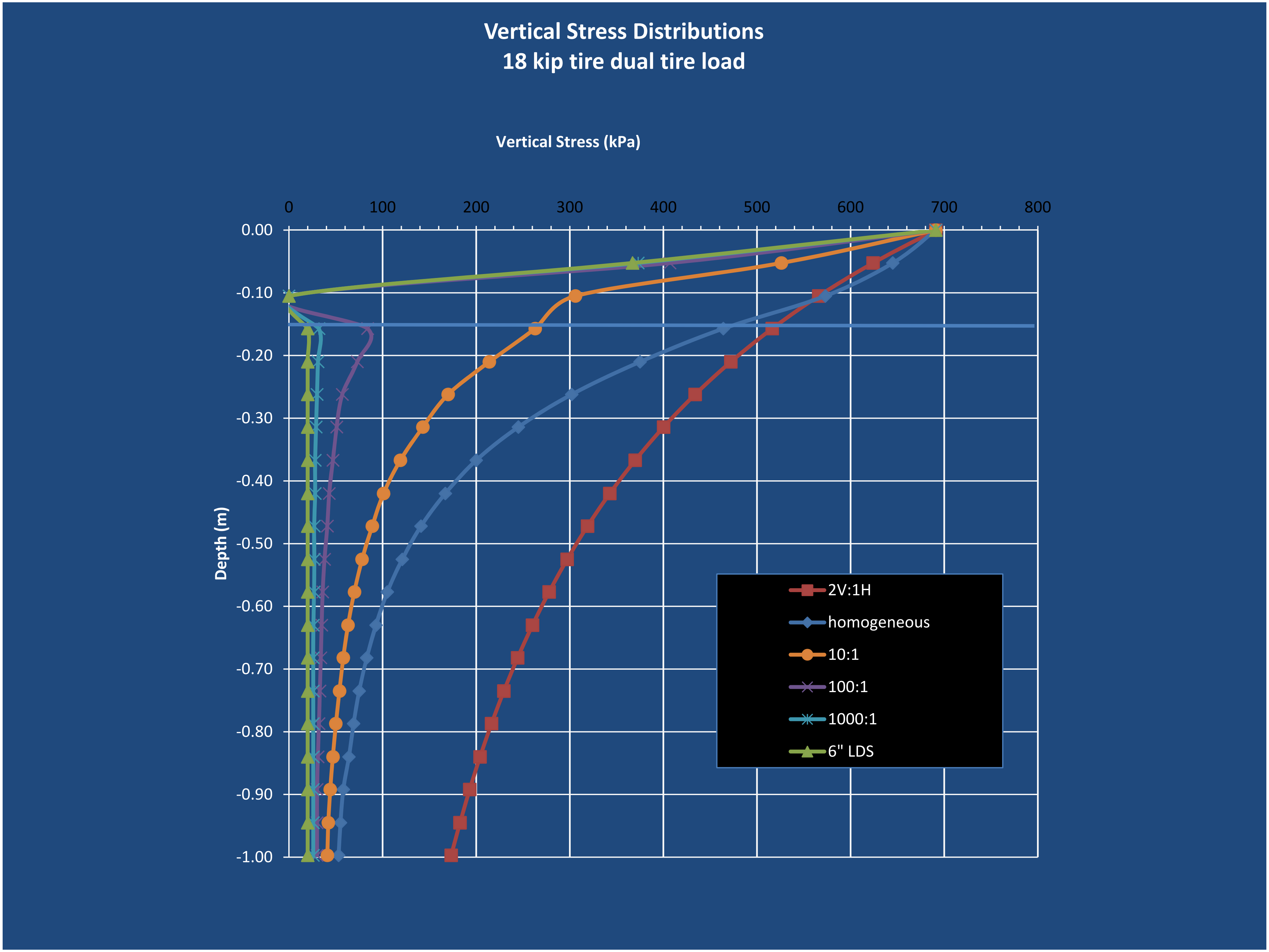
- Modeling offers insight into dynamic behavior of EPS embankments subjected to large, nearby earthquake and can be used for design and improving construction practices.
- Interlayer sliding is possible for large, near source earthquakes and is sensitive to long-period pulses in the input motion.
- Shear keys can be employed to prevent such sliding.
- Rocking and uplift do not appear to governing failure modes.
- Yielding (tension) appears to be possible in some basal layers, if sliding is prohibited.

Objectives

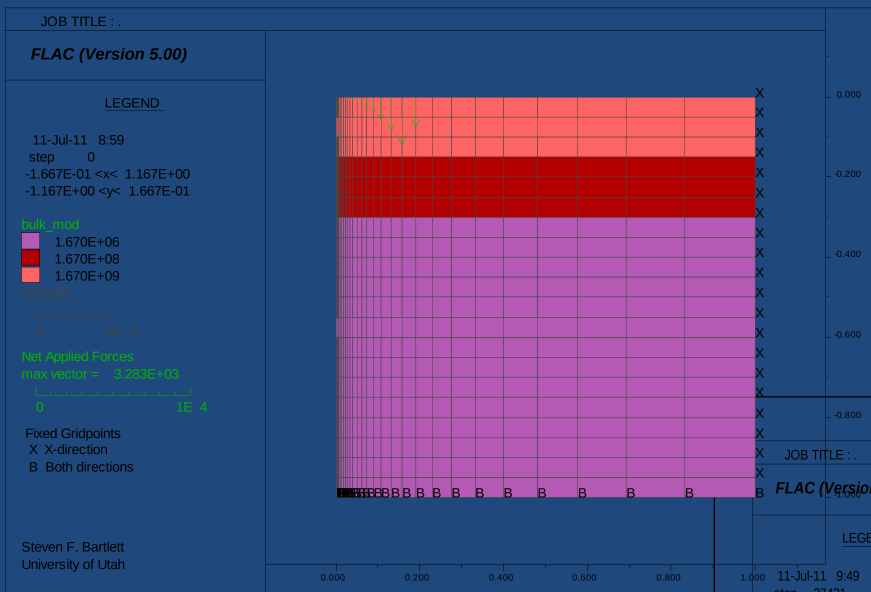
- **Long Term Monitoring**
  - Construction Settlement
  - Post-Construction Settlement
  - Transition Zones
  - Settlement Performance Comparison
- **Assessment and Modeling of Performance Data**
  - Settlement
  - Pressure Distribution
    - Vertical
    - Horizontal
  - Connections and Panel Walls
- Seismic Design
- **General Design - Allowable Stress in EPS**

2 Layer Model

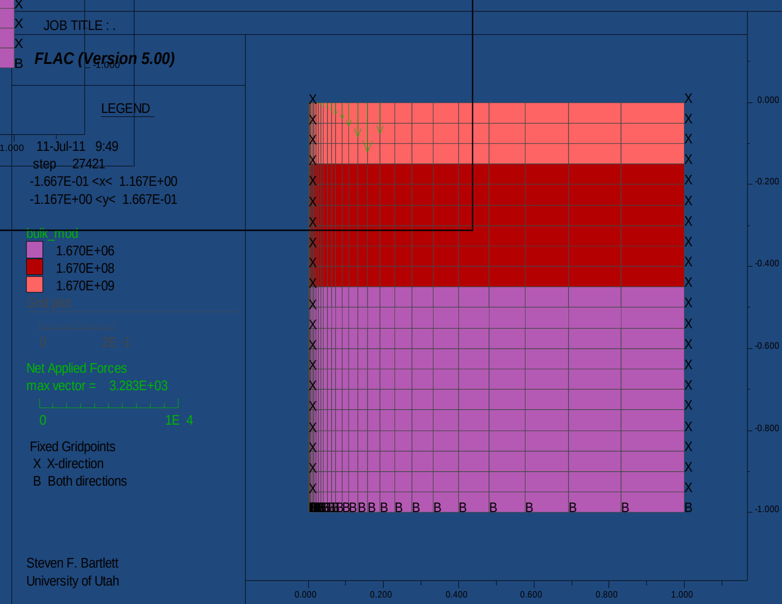



Vertical Stress Distributions
18 kip tire dual tire load
Vertical Stress (kPa)
0
100
200
300
400
500
600
700
800
Depth (m)
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
-0.60
-0.70
-0.80
-0.90
-1.00
2V:1H
homogeneous
10:1
100:1
1000:1
6" LDS

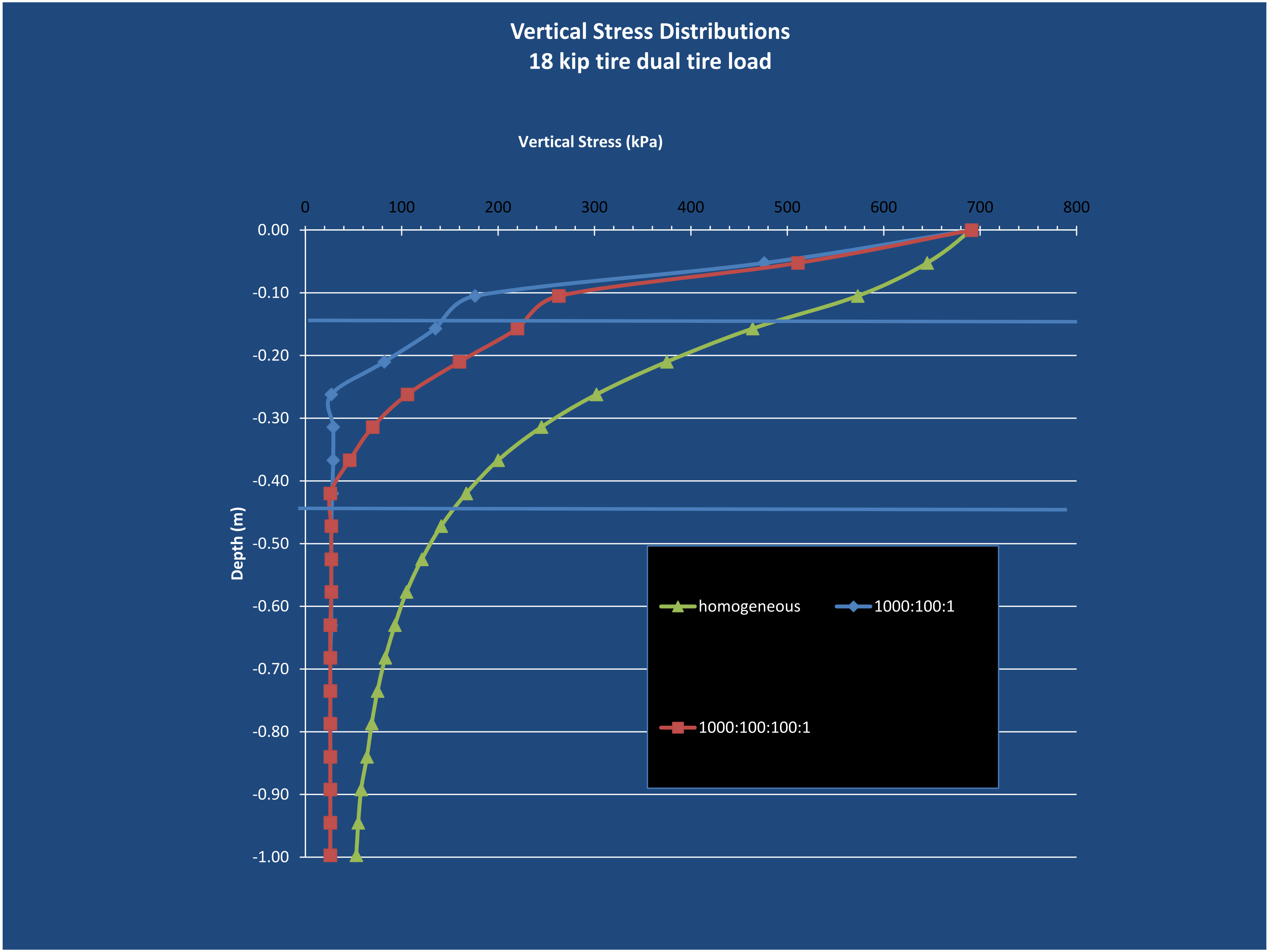
3 Layer Model



Thin base



Base with CLSM



Vertical Stress Distributions
18 kip tire dual tire load
Vertical Stress (kPa)
0
100
200
300
400
500
600
700
800
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
-0.60
-0.70
-0.80
-0.90
-1.00
Depth (m)
homogeneous
1000:100:1
1000:100:100:1

General Design Conclusions

- Review of Current Design Methods for Allowable Stress in EPS
  - Japanese Practice
  - European Design Codes (2011)
  - NCHRP 529
- I-15 Design was done using Draft European Design Codes (1998)
  - Based on performance data, this methodology is acceptable
- Recommend a Combination of:
  - NCHRP 529 and European Design Codes (2011)
- Neither Code Fully Addresses Vertical Stress Distributions for Layered Systems with Load Distribution Slabs
  - Typical Vertical Stress Distributions from Numerical Modeling

Questions