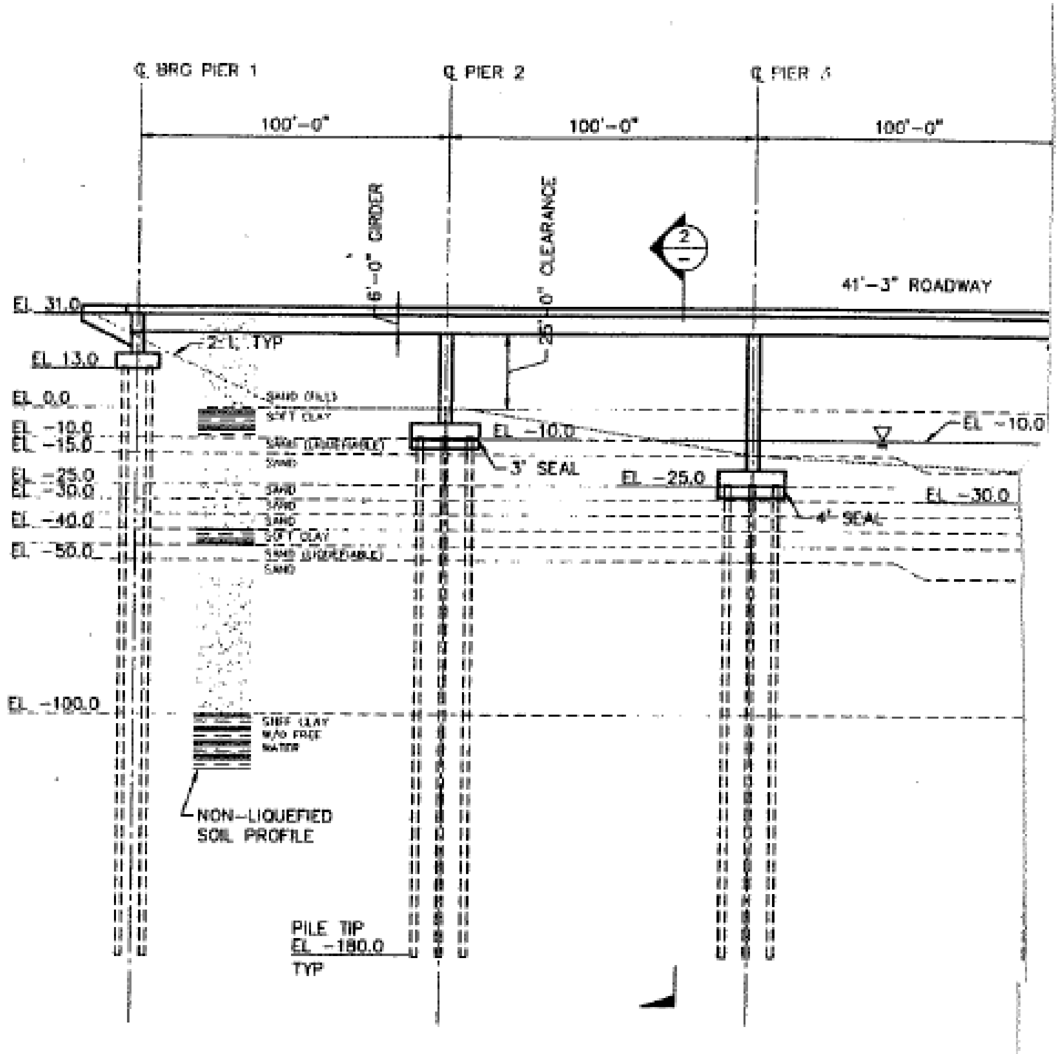
San Diego Regional Chapter

Workshop: **Liquefaction Evaluation, Mapping, Simulation and Mitigation**
September 12, 2014

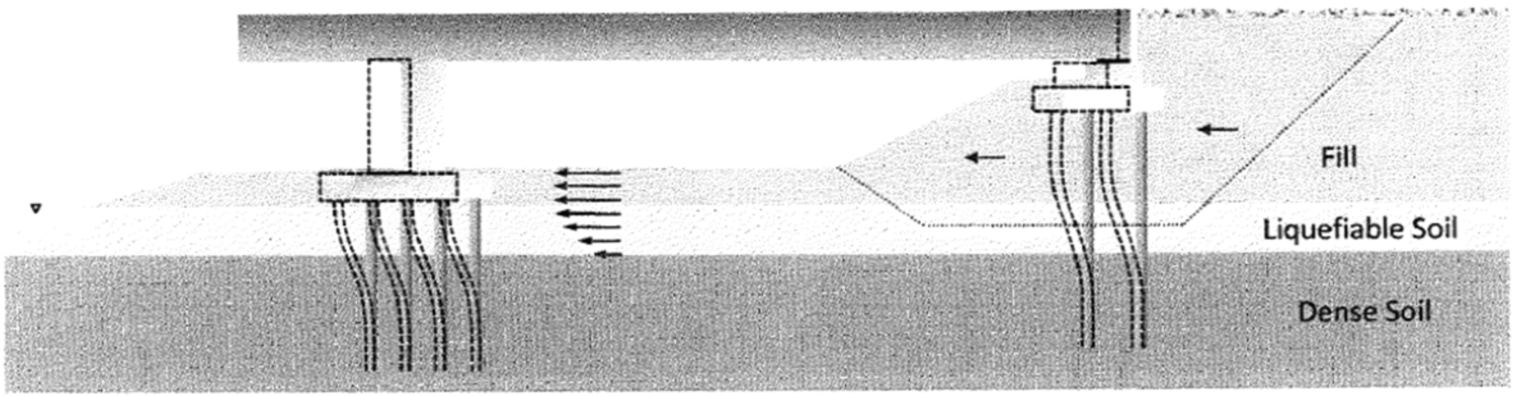
Seismic Response of Stratified Sites and Implications for Foundation Systems

Geoffrey R. Martin, Professor Emeritus, USC
&
Ahmed Elgamal, Professor, UCSD

Representative Stratified Site: Liquefaction Design Issues

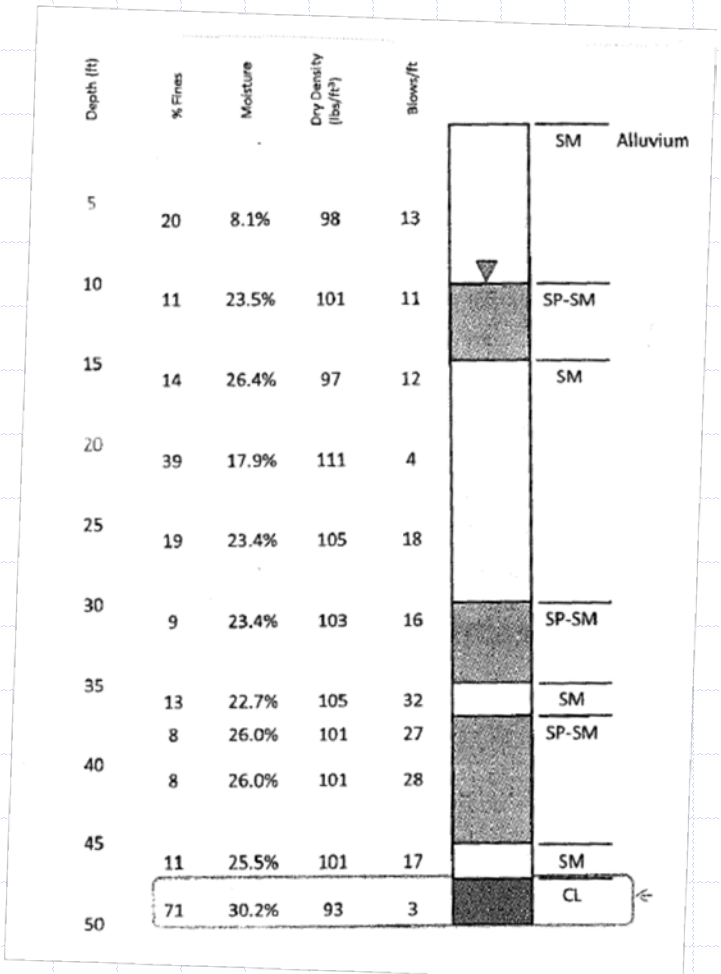


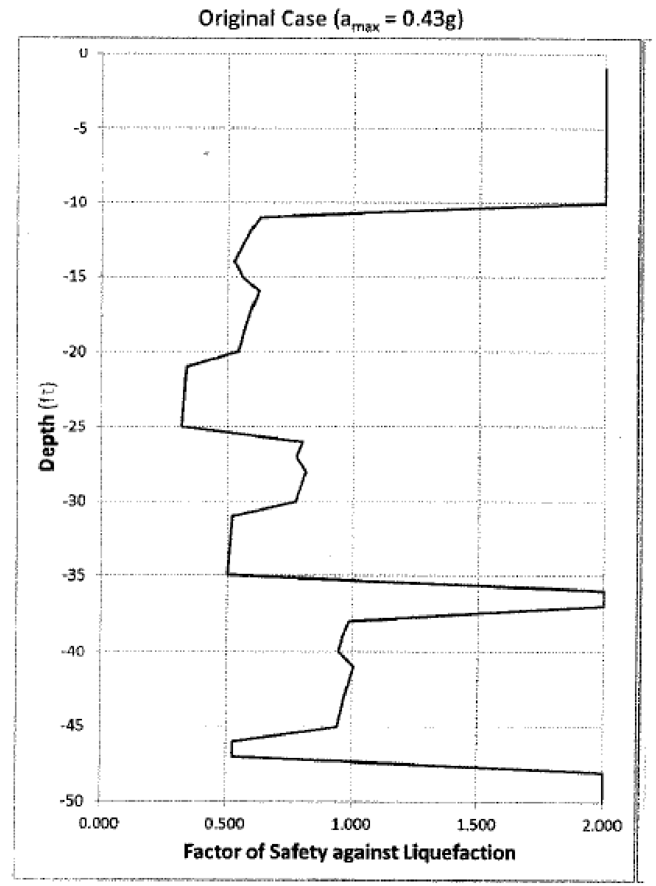
Bridges – Lateral Spread Design Issues



- Crust load–deformation behavior. How much deformation to reach ultimate passive pressure? Adjustments for non-plane strain behavior.
- Prediction of crust displacement.
- Potential restraining effect of the foundation.
- Potential restraining effect of the superstructure.
- Contribution of inertial loads to the foundation displacement demand.
- More specific performance criteria.

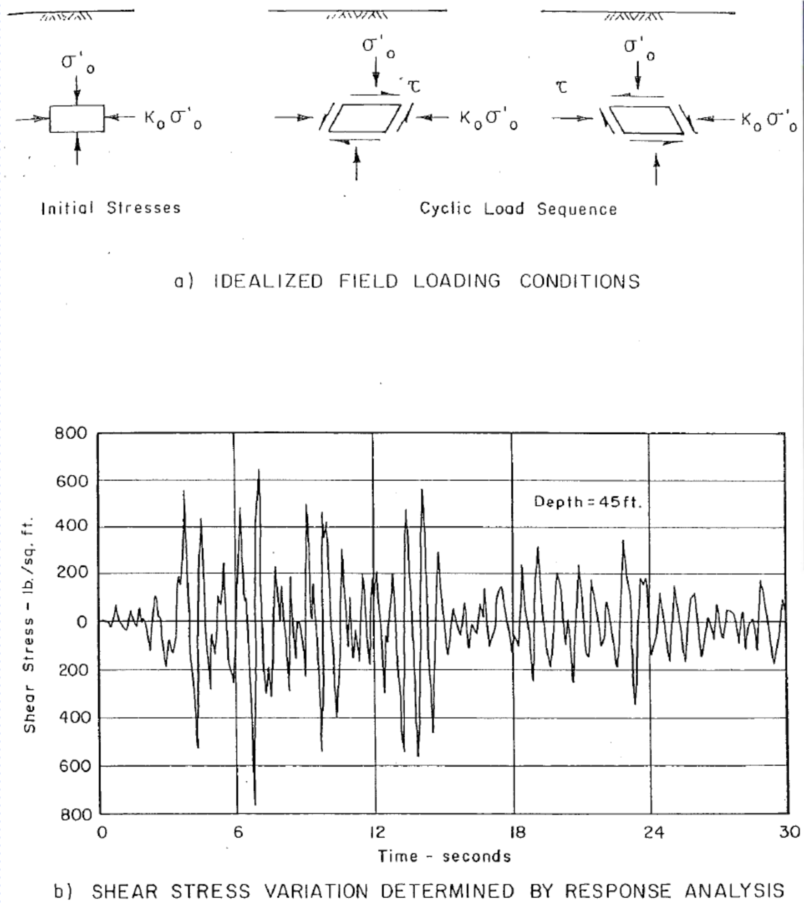
Stratified Sites: Variability of Triggering Factors of Safety

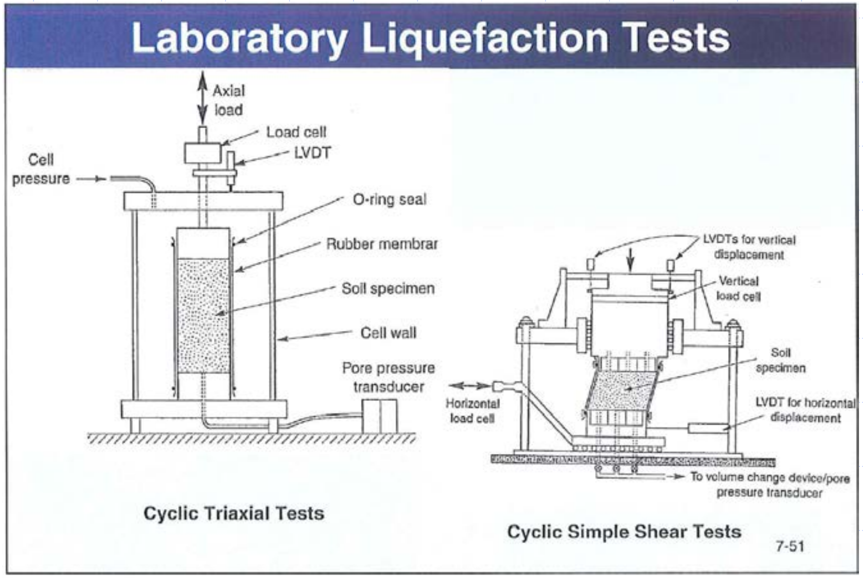




Historical Developments

- Laboratory Simulation of Seismic Loading



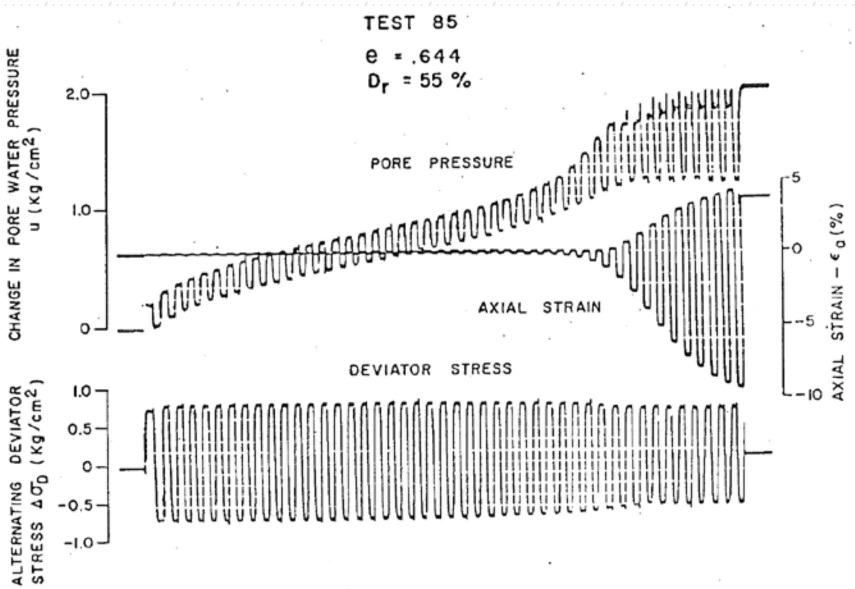


- Seed et al. / Finn et al.
  1960's / 1970's

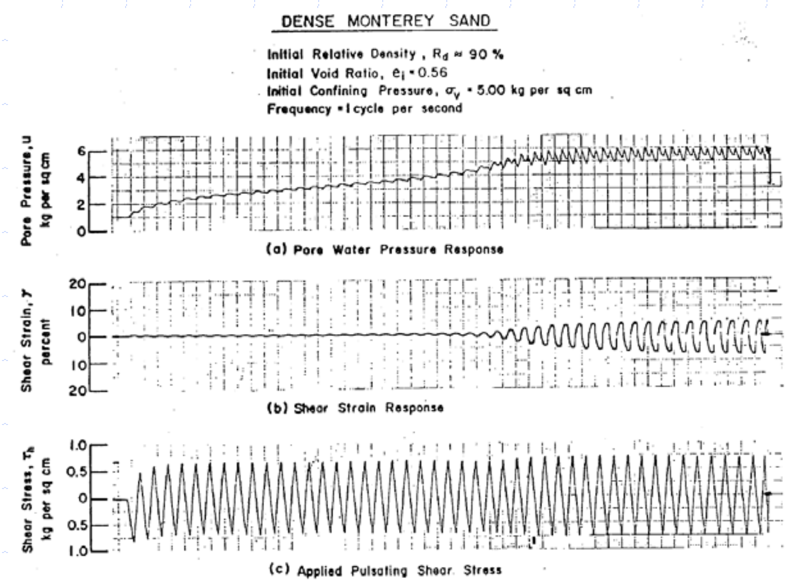
Cyclic Simple Shear Stress Induced by Seismic Loading

Historical Developments

- Laboratory Test Results

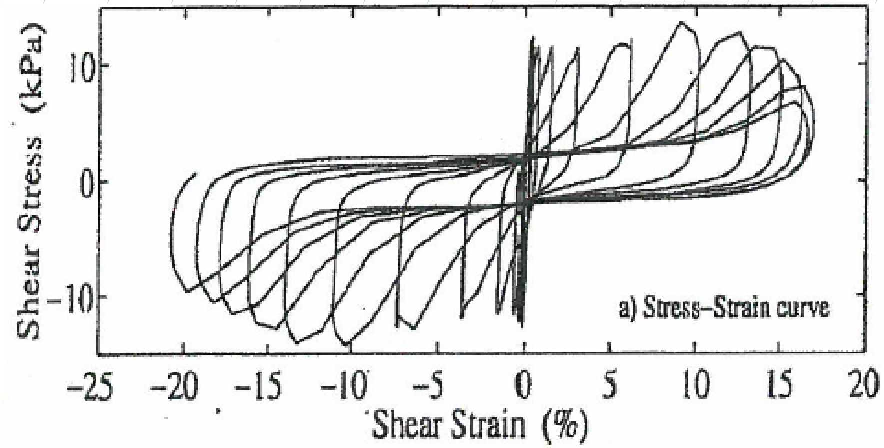


Representative/Cyclic Triaxial Test Results (Finn, 1971)

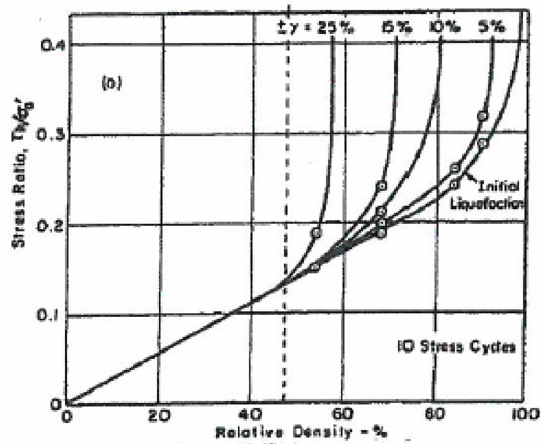


Representative/Cyclic Simple Shear Test Results (Peacock and Seed, 1968)

Stress Controlled Cyclic Simple Shear Tests

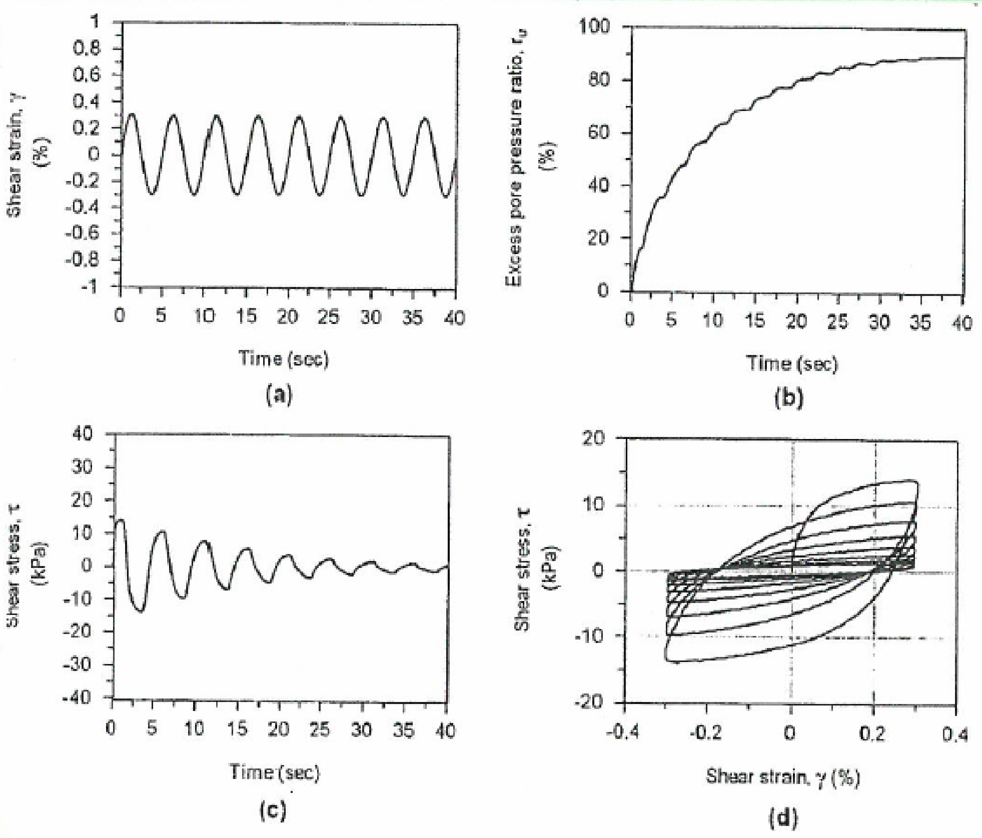


Stress Controlled Undrained Cyclic Simple Shear Test (D_r=60%)

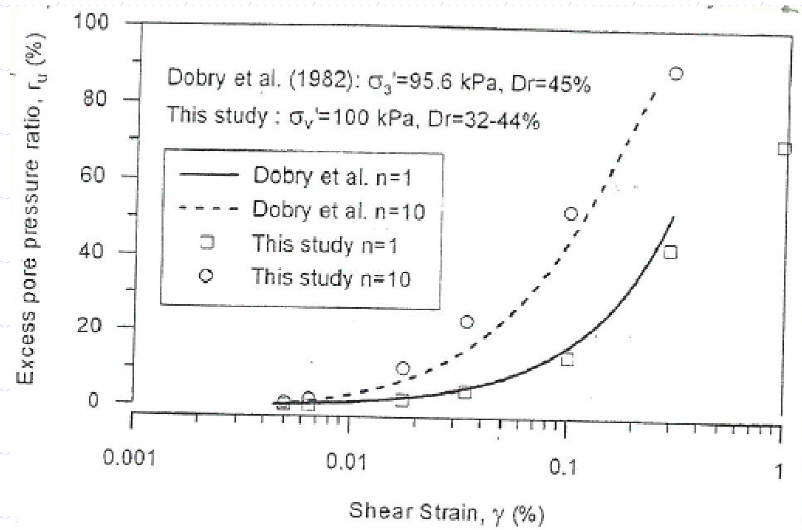


Limiting Shear Strains (after Seed, 1976)

Constant Volume Strain Controlled Cyclic Simple Shear Tests

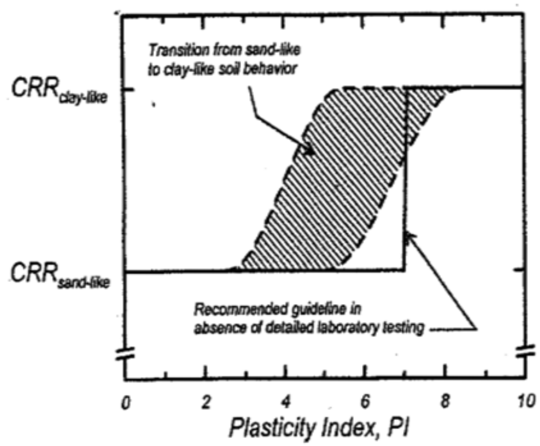


Typical Strain Controlled Constant Volume (undrained) Cyclic Simple Shear Test Results



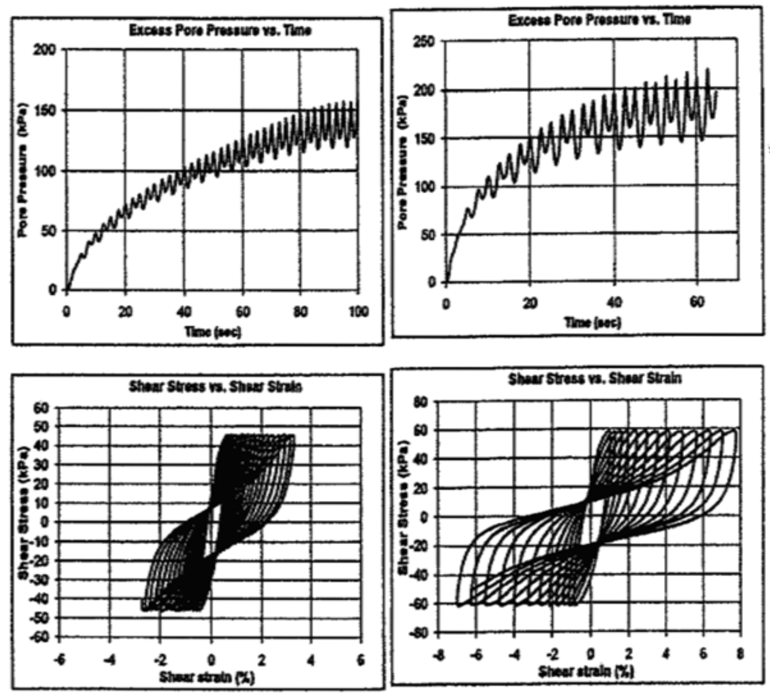
Pore Water Pressure Increases Versus Shear Strain Amplitude

Laboratory Tests: Silty Sand – Transitional Behavior



Schematics of the transition from sandlike
to clay-like behavior for fine-grained soils with increasing PI, and the recommended guidelines for practice.

Cyclic Simple Shear Test Results: U.C. Berkeley Laboratory

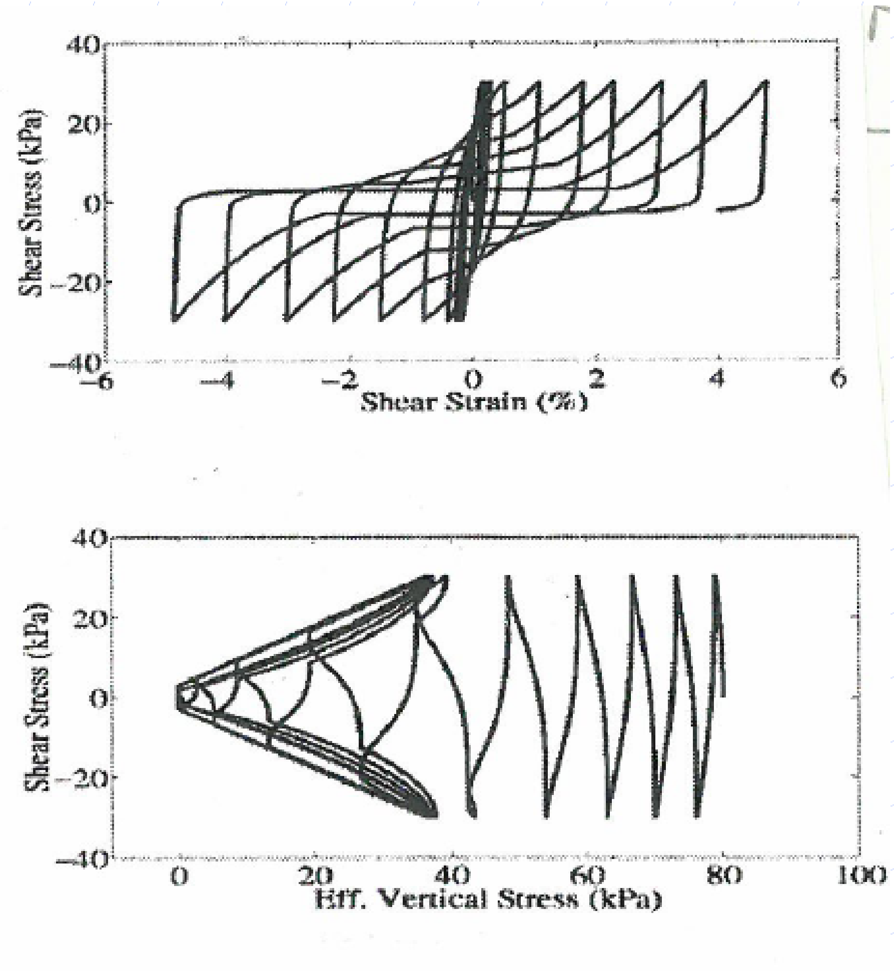


PI = 10 LL = 41 CSR = 0.20 PI = 8 LL = 42 CSR = 0.23

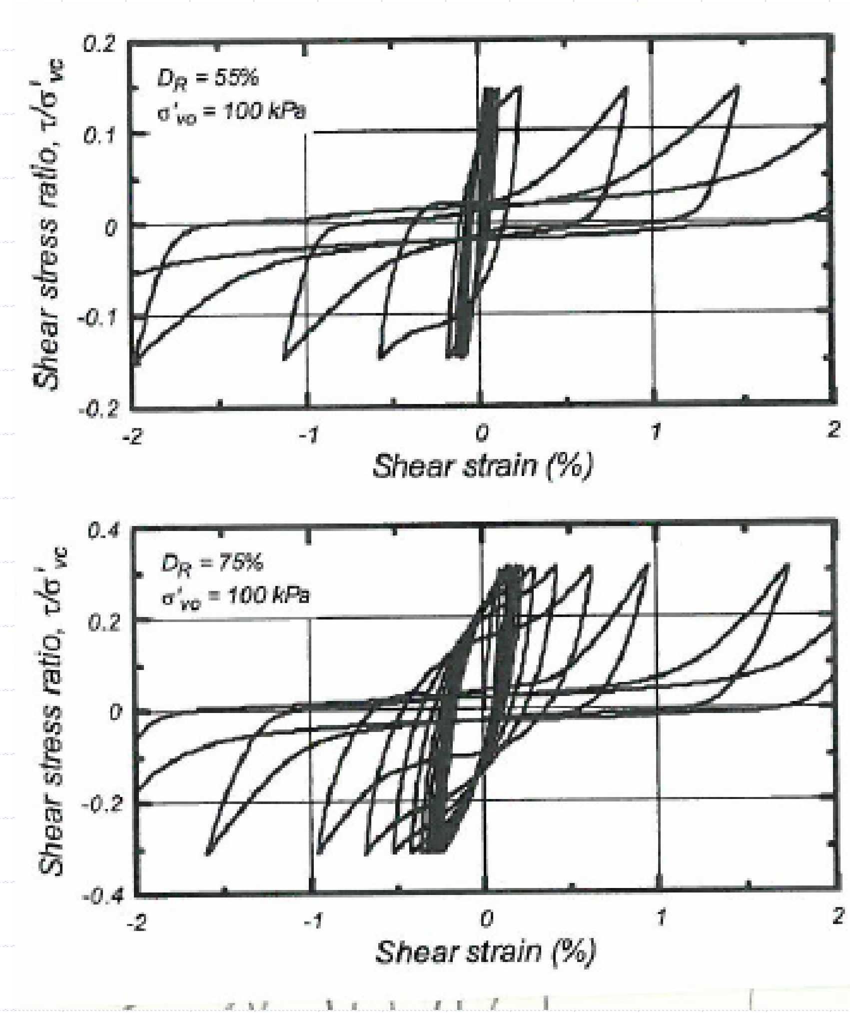
Effective Stress Site Response Analysis

- Finn et.al 1978 : DESRA
- Matasovic 1993 : D-MOD
- Martin/Qui 1998 : DESRA-MUSC
- Pyke 2000 : TESS
- Elgamal et.al 2002 : Cyclic/Opensees
- Hashash 2009 : DEEPSOIL
- Boulanger et.al 2010 : PM4 Sand Model/FLAC
- Byrne/Beaty 2011 : UBC Sand/FLAC and PLAXIS

Plasticity Based Constitutive Models



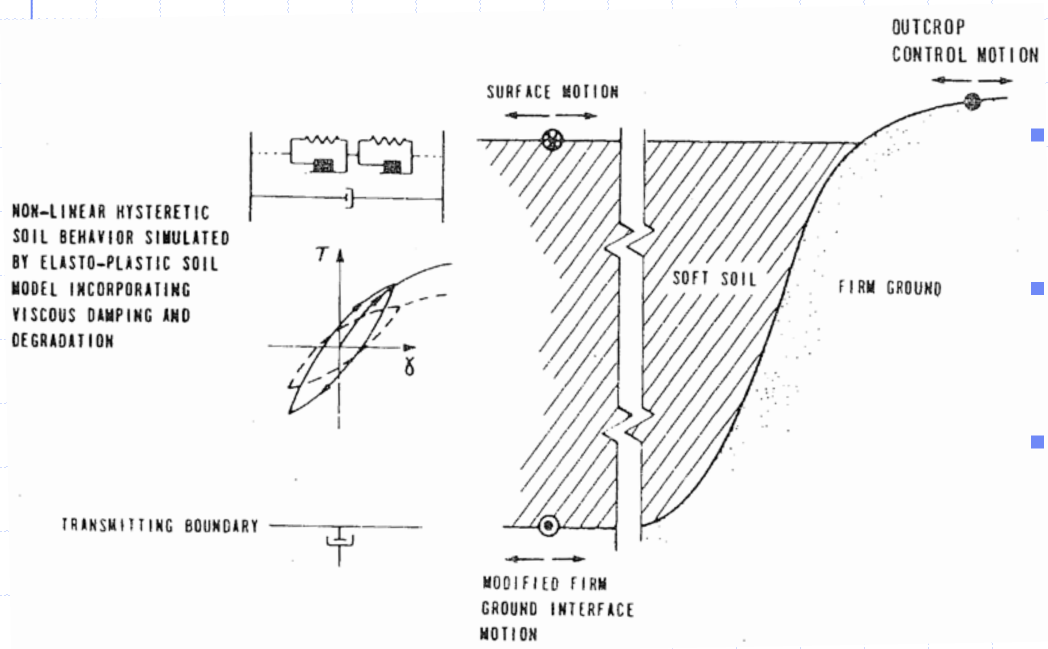
Cyclic 1D Model
Elgamal et. al.



PM4 Sand Model
Boulanger et. al.

Fundamentals Constitutive Model – 1D Effective Stress Site Response Analyses

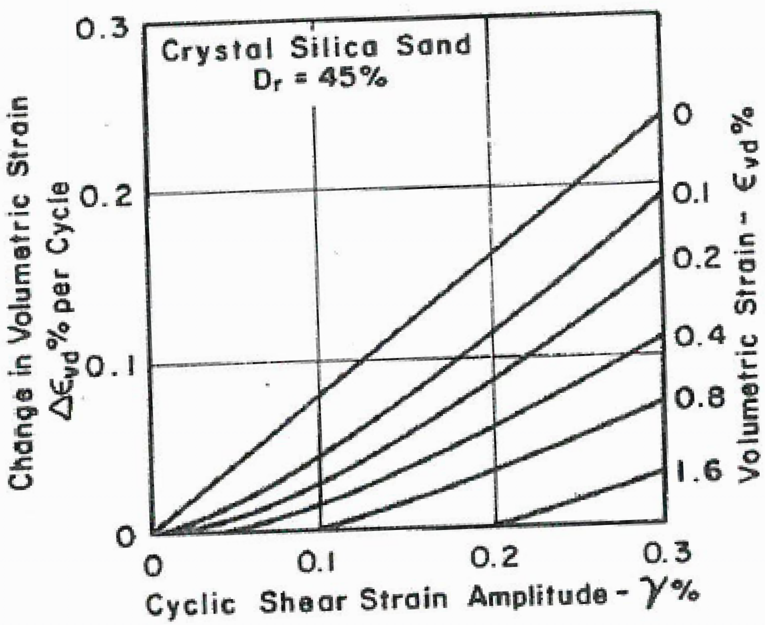
- Computer Programs: DESRA (Lee and Finn, 1978)
  DESRAMUSC (Qui, 1998)



Objectives:

- Time histories of pore water pressure increases in multi layer sites
- Determine critical layer for lateral spread analyses
- Determine effect of pore water pressure increases on ground surface response

DESRA Constitutive Model Fundamentals – Cyclic Strain Based Volume Change Parameters

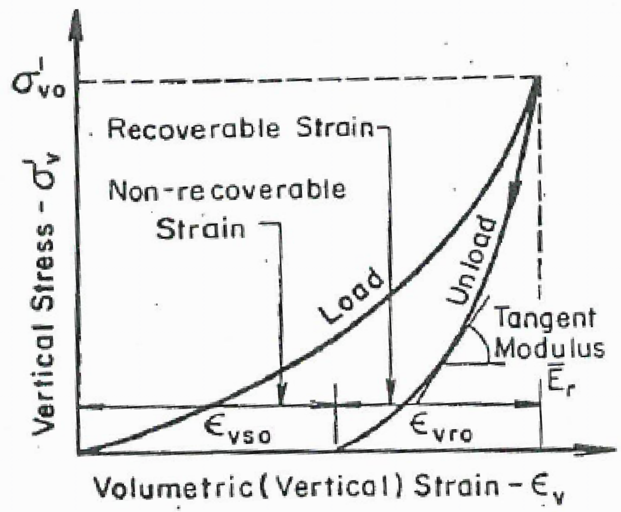


In an undrained test, for volumetric compatibility at the end of a load cycle we must have:

Change in Volume of Voids=Net change in Volume of Sand Structure

$$\frac{\Delta u . n_e}{k_w} = \Delta \varepsilon_{vd} - \frac{\Delta u}{\bar{E}_r} = 0 \text{ for } S_r = 1$$

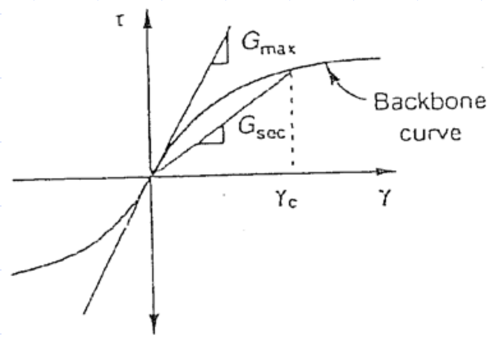
$$\therefore \Delta u = \bar{E}_r \, . \Delta \varepsilon_{vd}$$

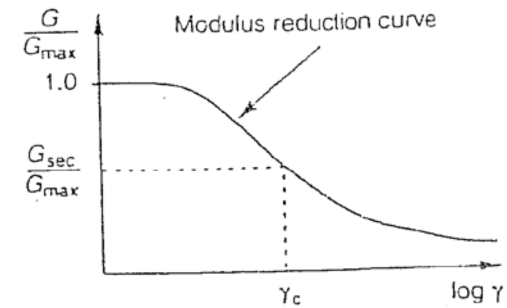


Fundamentals Constitutive Model – 1D Effective Stress Site Response Analyses

Input Data for Practical Applications

- Nonlinear initial τ/γ backbone curve matched to G/G_{max} curve
- Masing criteria used to simulate hysteretic behavior
- Strain hardening suppressed



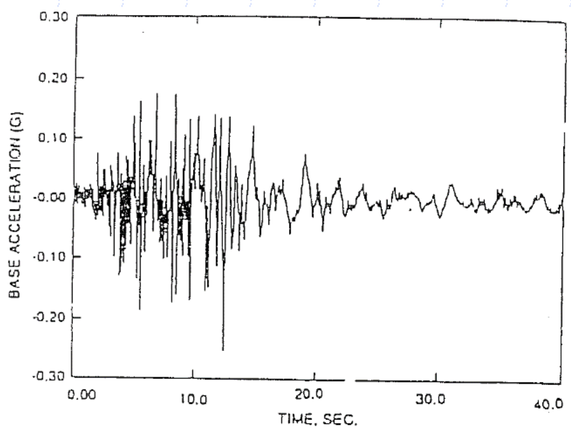


- Backbone curve degraded as a function of pore water pressure increase
- Representative elastic rebound curves chosen based on N_1 values
- Volume change parameters (simplified to 2) chosen based on N_1 values
- Volume change/rebound parameters adjusted to match field liquefaction strength curves
- Pore water pressure dissipation/re-distribution during analyses a program option

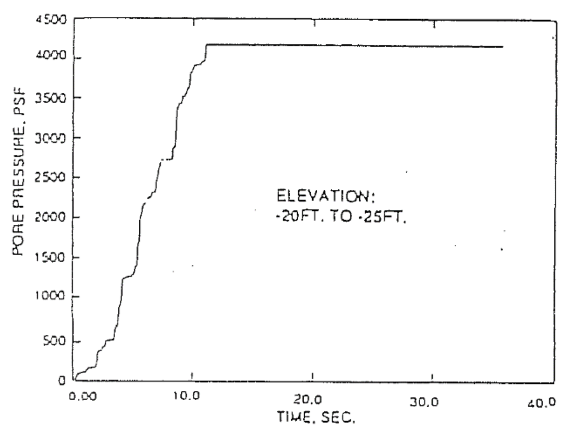
(Note $m_v = \frac{1}{\bar{E}_r}$)

Fundamentals Constitutive Model – 1D Effective Stress Site Response Analyses

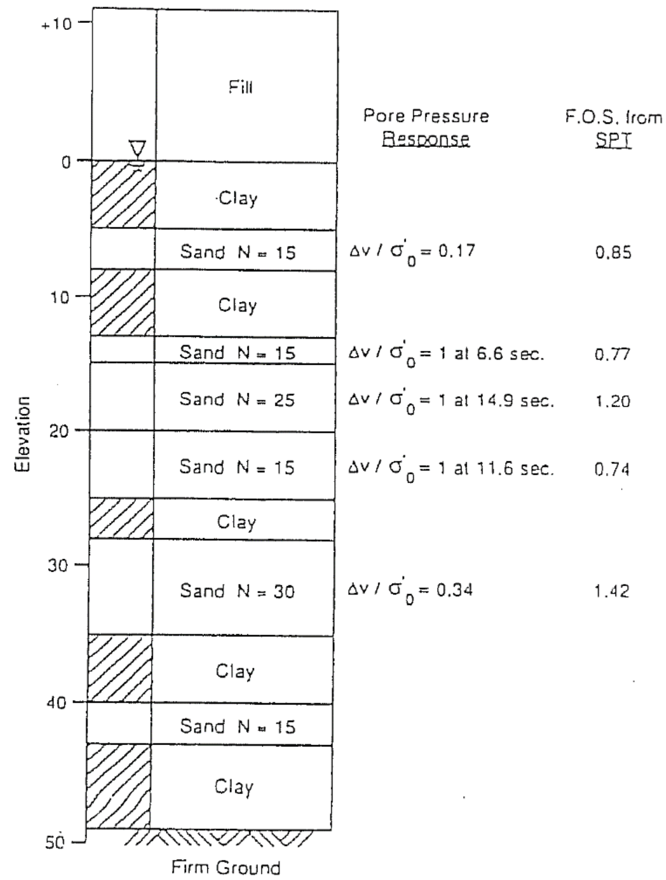
- Example illustrating effects of pore water pressure redistribution and sequential liquefaction



Acceleration Time History



Representative Pore Pressure Time History



DESRA Pore Pressure Response vs. SPT F.O.S.

Stratified Soil Condition at a Bridge Site

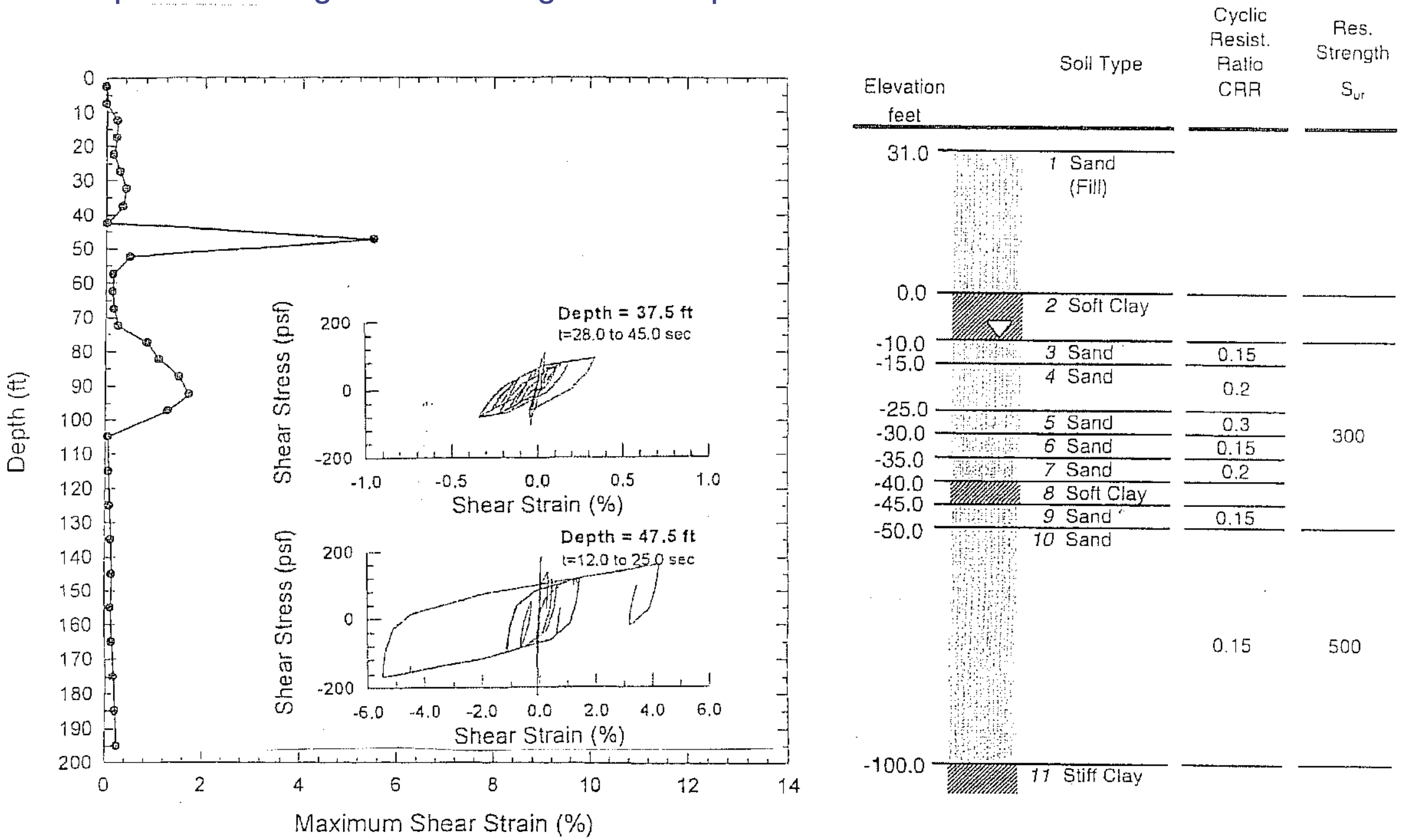
Table 1. Soil Conditions for Boring R-05-001 (Abutment 1)

Layer	Depth (ft)	Elevation (ft)	Soil Type	Density/Consistency	N60
1	0 to 7	30 to 23	clayey sand	medium dense	14
2L	7 to 12	23 to 18	gravel	very loose	4
3L	12 to 16	18 to 14	silty gravel	medium dense	12
4L	16 to 29	14 to 1	gravel	medium dense	15 to 19
5L	29 to 32	1 to -2	sand	medium dense	14
6	32 to 45	-2 to -15	clay	stiff	8
7	45 to 50	-15 to -20	sandy clay	stiff	8

Notes: 1. N60 (blow count) values are field N values corrected for hammer efficiency (ERi = 55%).
2. "L" indicates a liquefiable layer.

Fundamentals Constitutive Model – 1D Effective Stress Site Response Analyses

- Example illustrating effects of large strain liquefaction



LIQUEFACTION POTENTIAL OF SATURATED SAND DEPOSITS UNDERLYING FOUNDATION OF STRUCTURE

Liu Huishan (I)
Qiao Taiping (II)
Presenting Author: Liu Huishan

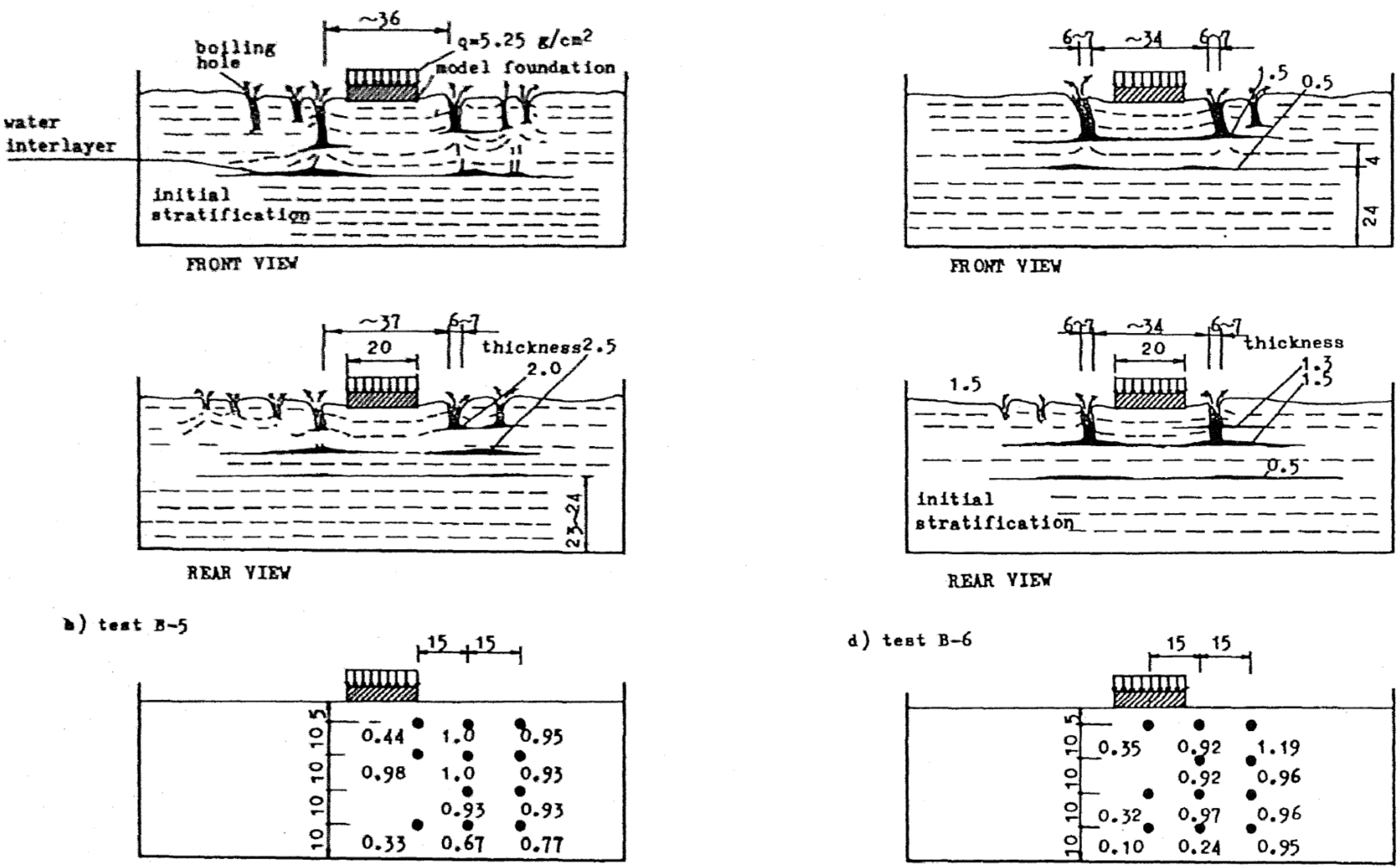
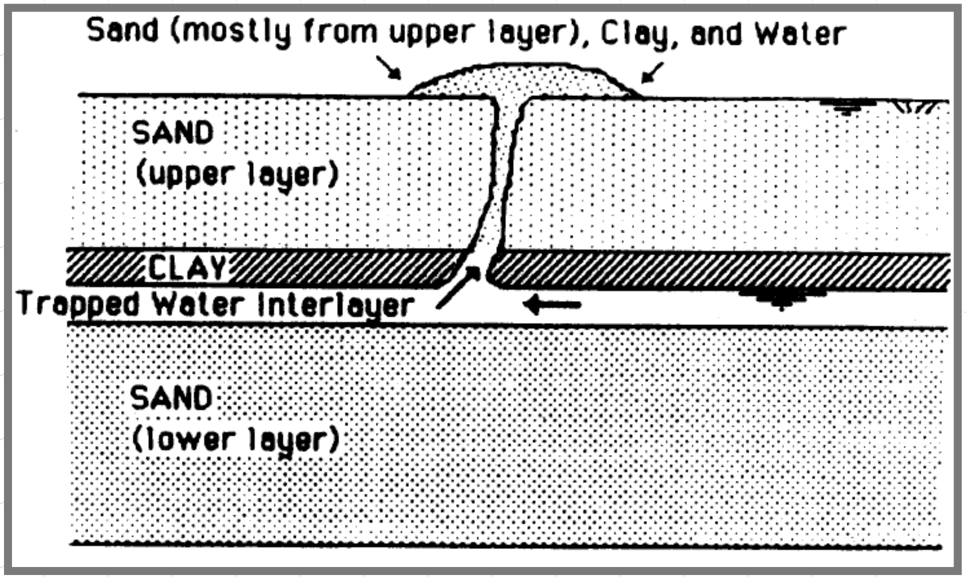
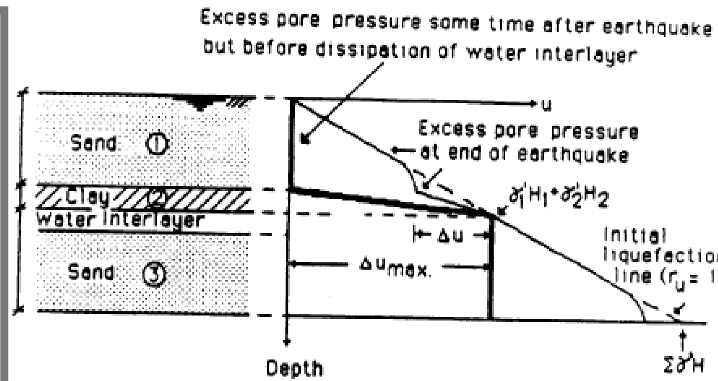


Fig. 5. Liquefaction tests of stratified deposits
(a),(c) — water interlayers and boiling holes
(b),(d) — measured maximum pore pressure ratio

8th WCEE, 1984

Site Liquefaction (Soil Liquefaction)





Average hydraulic gradient in clay layer = $\Delta u / (\gamma_w H_2)$

Average maximum hydraulic gradient in clay layer = $\Delta u_{max} / (\gamma_w H_2)$

$$\Delta u_{max} = \gamma_1' H_1 + \gamma_2' H_2$$

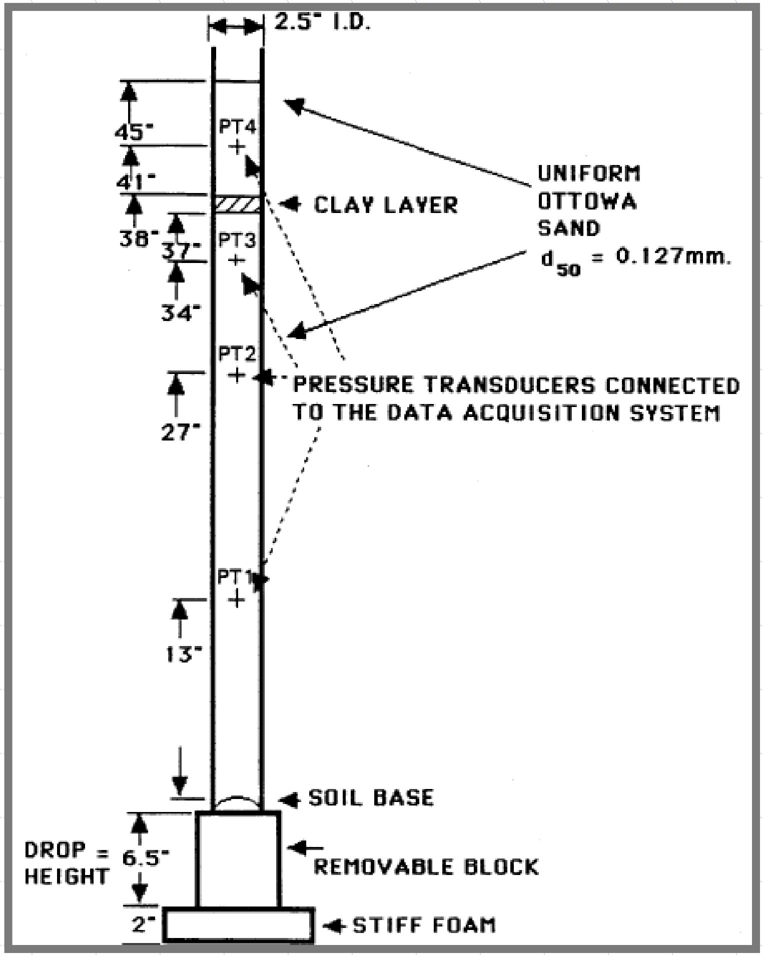
Example: ($\gamma_1' = \gamma_2' = \gamma_w$)

H_1 (ft.)	H_2 (ft.)	Average Max. Hydraulic Gradient In Clay Layer
5	5	2
5	1	6
10	5	3
10	1	11

Elgamal et al. 1989

Fig. 4.19 Development of high gradients in clay layer. Notice that the average hydraulic gradients in the clay layer reaches a maximum of $\Delta u_{max}/\gamma_w H_2$ some time after the earthquake. Local gradients at the lower boundary of the clay layer will be even larger due to low clay permeability (Elgamal et al. 1989).

Site Liquefaction (Soil Liquefaction)



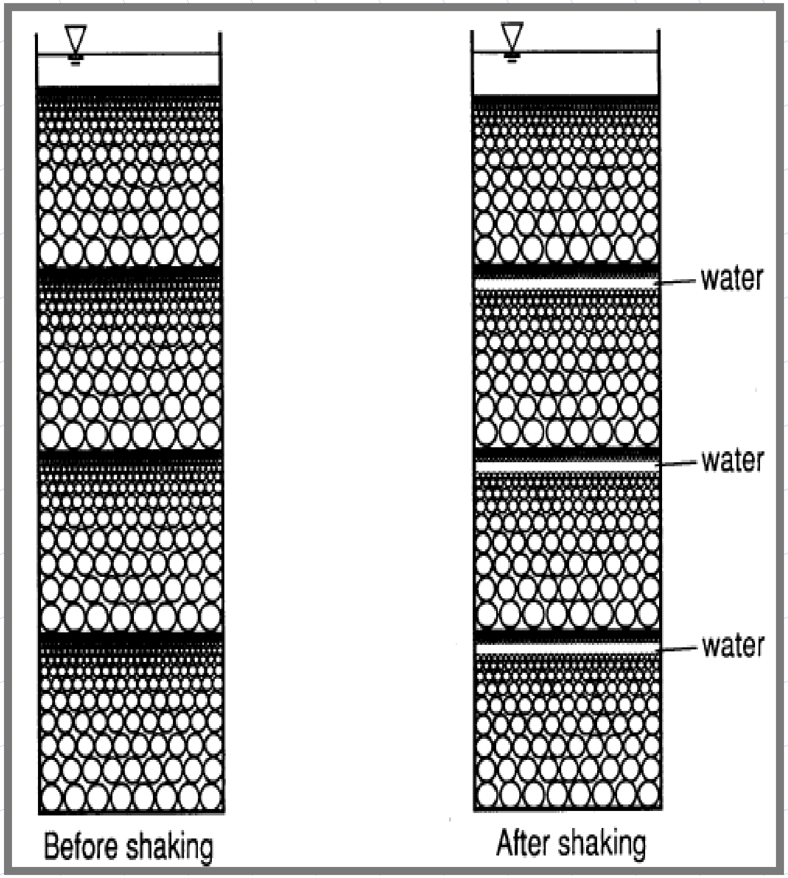


Fig. 4.29 Hydraulic fill liquefaction.

Adalier and Elgamal 1992

Site Liquefaction (Soil Liquefaction)

Fig. 1. Photograph of slope for soil investigation in dewatered trench

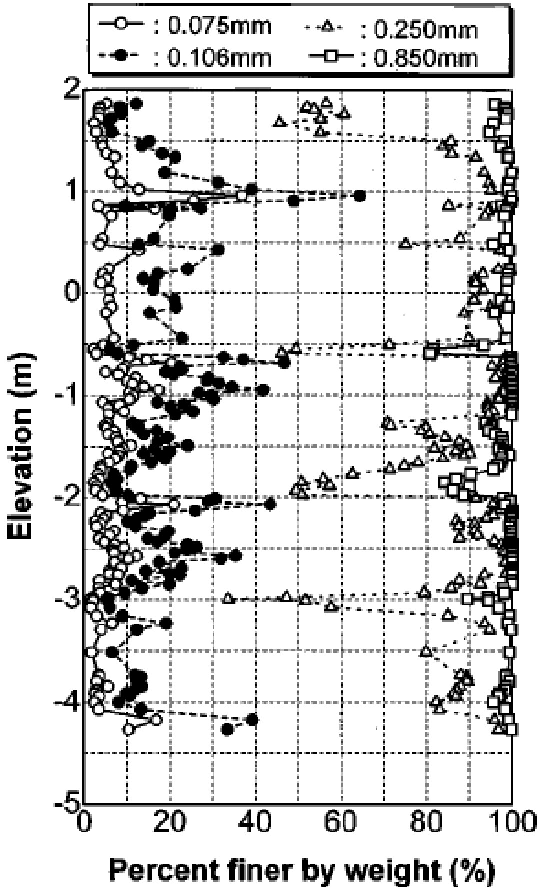


Fig. 3. Vertical change in grain size distribution along depth for reclaimed land

Kokusho et al. (2000)

Site Liquefaction (Soil Liquefaction)

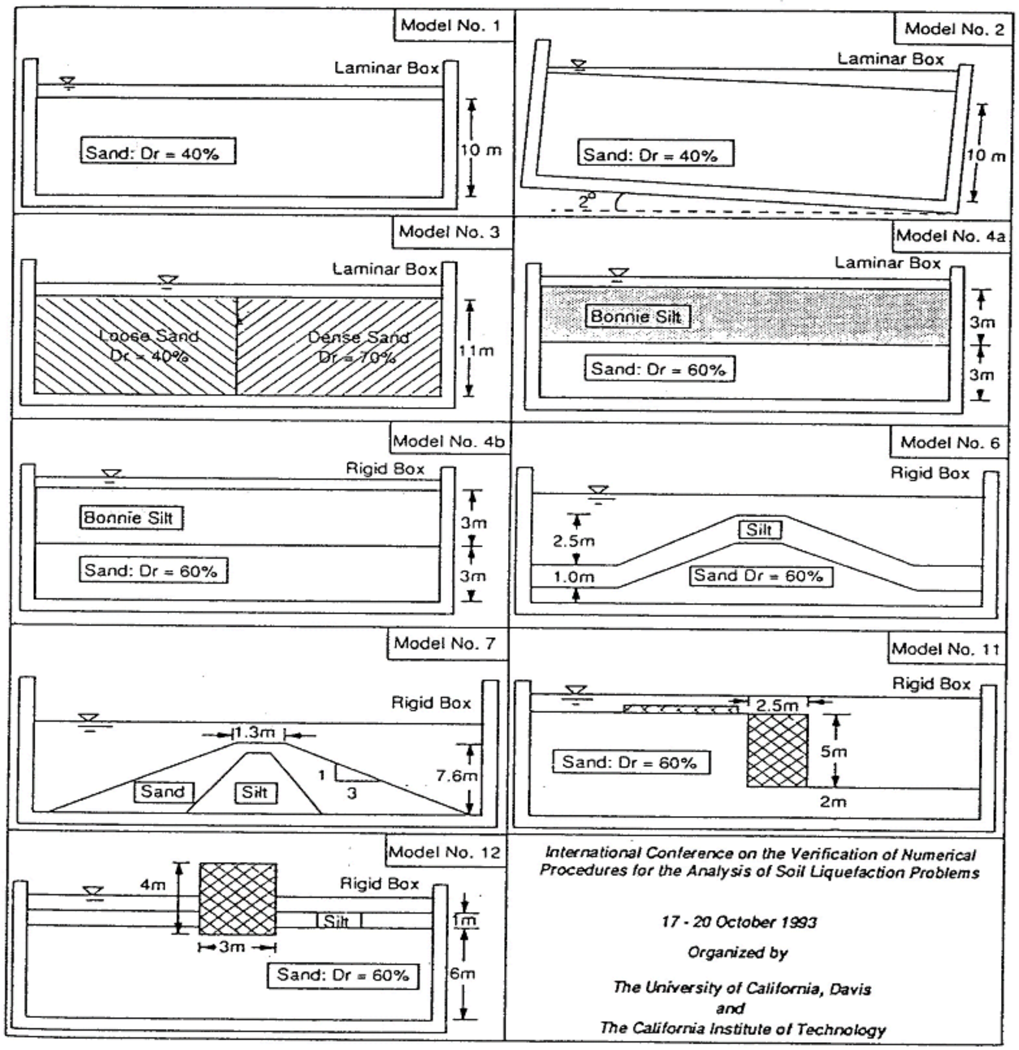
Project VELACS (1993)

(Verification of Liquefaction Analyses by Centrifuge Studies)

Simple Configurations

Few sensors

Bonnie Silt!



Fiegel and Kutter 1994

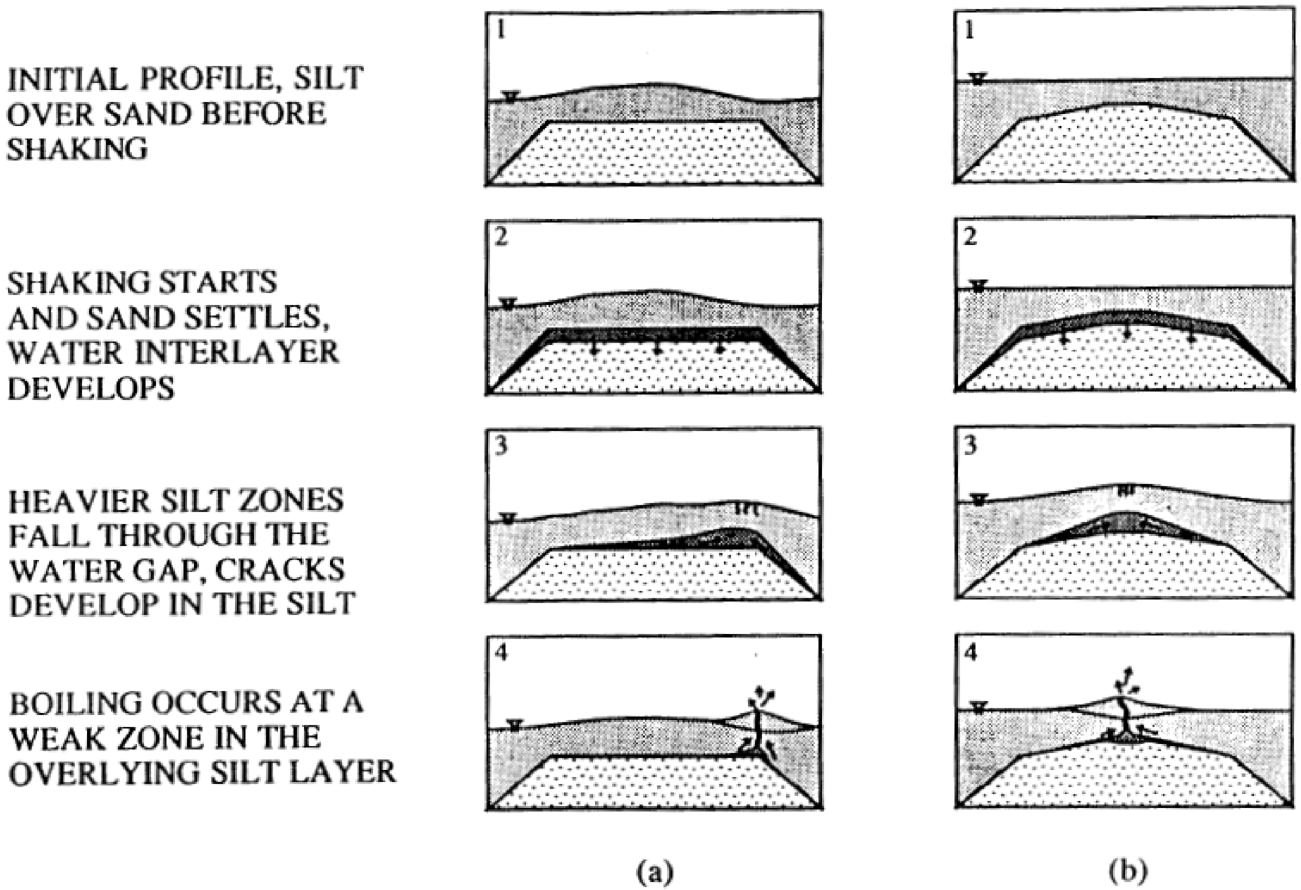
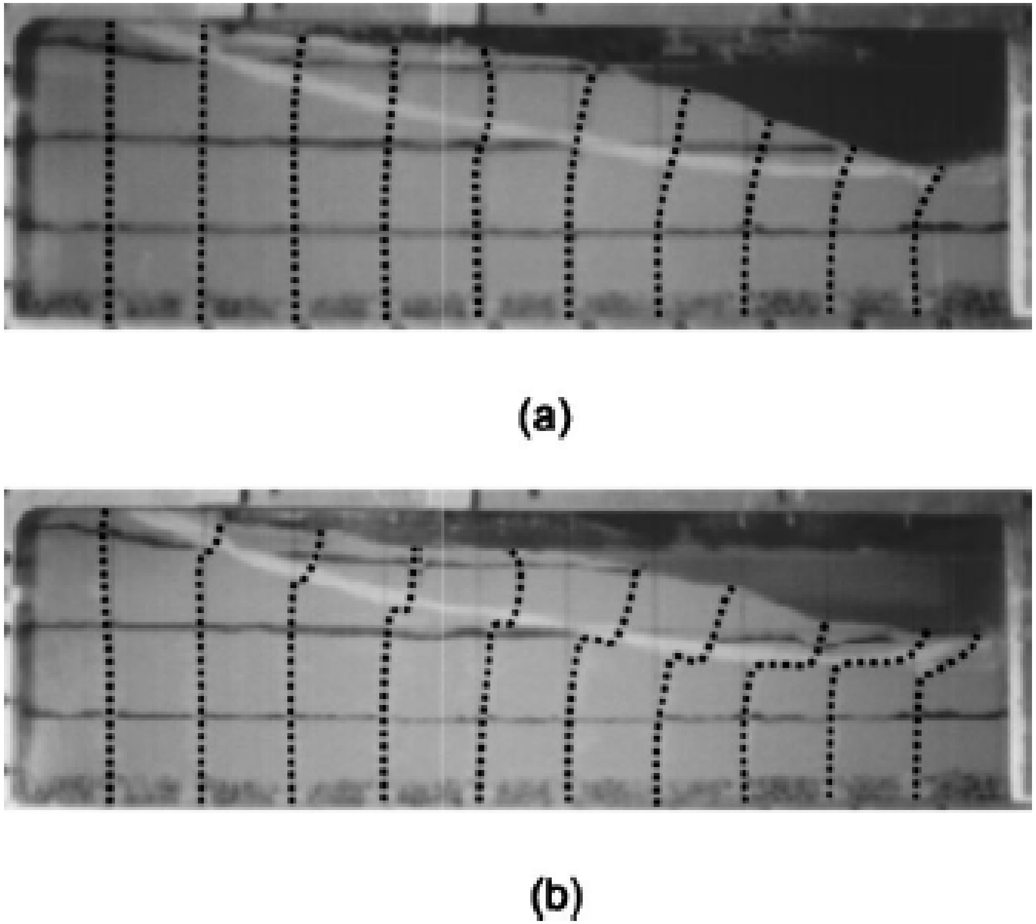


Figure 1: The mechanism of liquefaction in layered soils as observed in centrifuge model tests: (a) a sloping surface and a level interface leads to a thin zone at the right side of the model, test GF4, and (b) a level surface with a sloping interface leads to a thin zone at the center of the model, tests GF5 and GF6.

Boulanger et al. and Kutter et al. 2001-2004



Strength Loss and Localization at Silt Interlayers in Slopes of Liquefied Sand

R. Kulasingam, M.ASCE[1]; Erik J. Malvick, M.ASCE[2]; Ross W. Boulanger, M.ASCE[3]; and Bruce L. Kutter, M.ASCE[4]

Fig. 8. Photos of Test 3 (initial D_R=35%) after; (a) event 1: Motion A, base $a_{max} \approx 0.32\ g$ and (b) event 2: Motion B, base $a_{max} \approx 0.32\ g$

Site Stratification (Wildlife Array, Imperial County, CA)

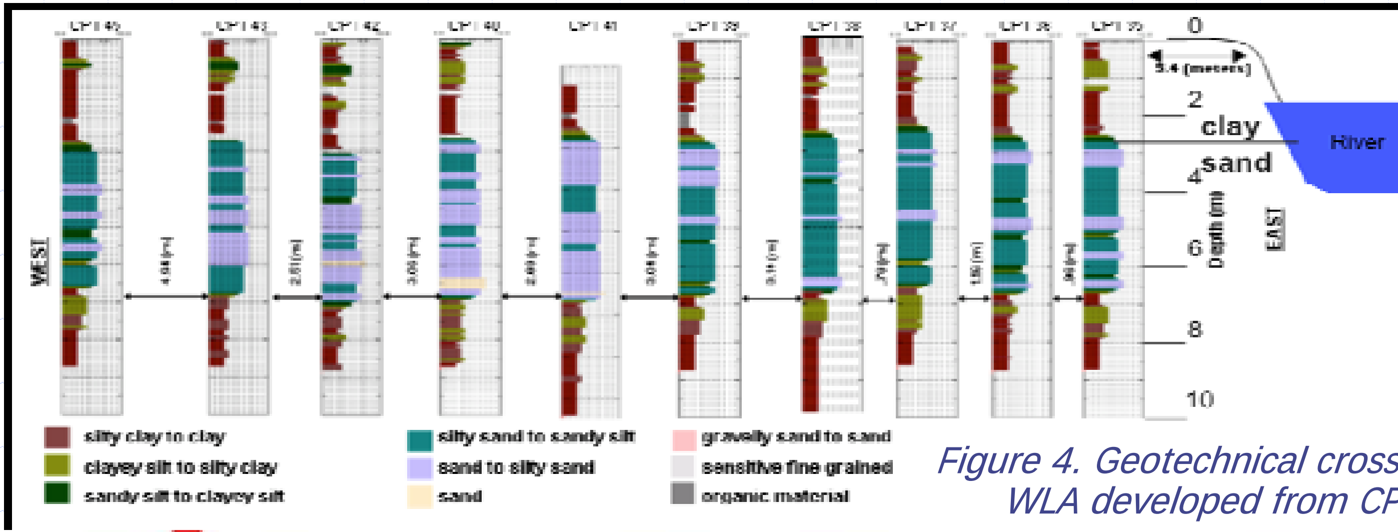
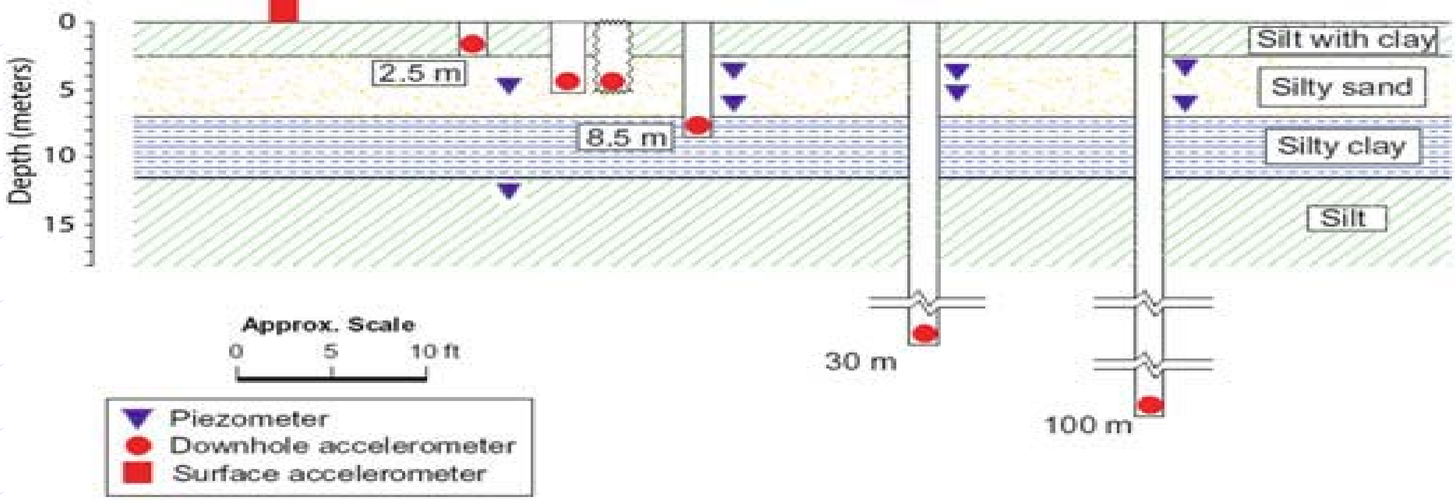


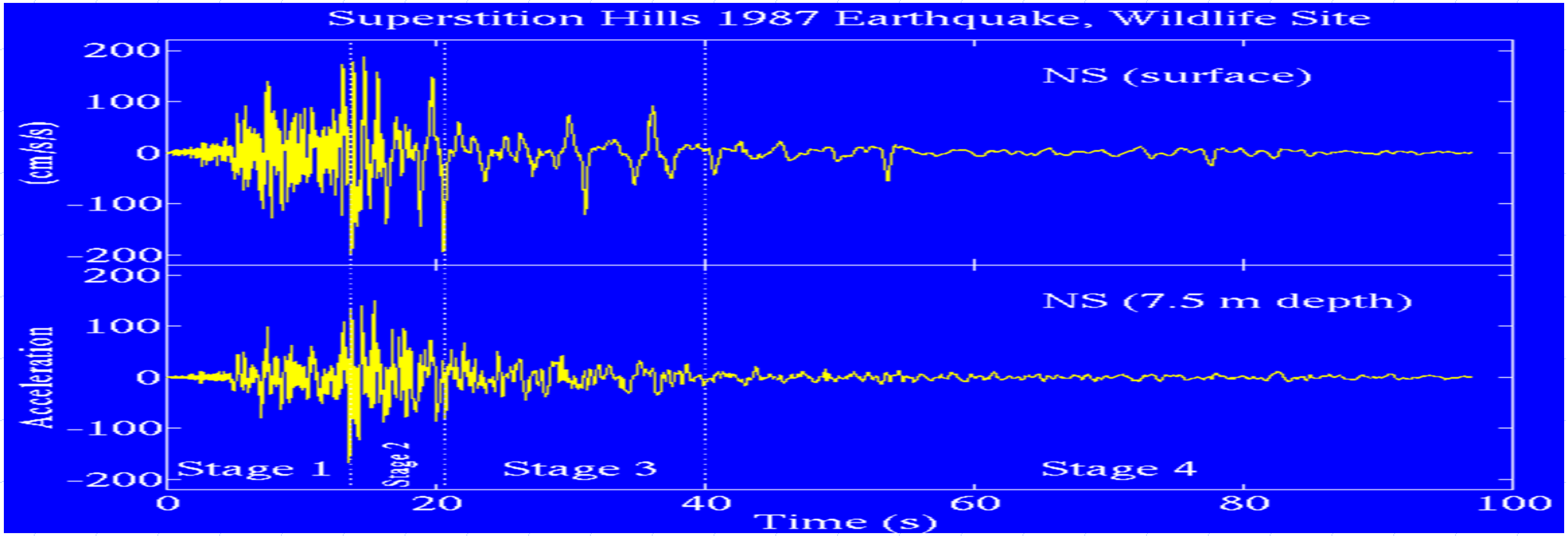
Figure 4. Geotechnical cross-section for WLA developed from CPT data.

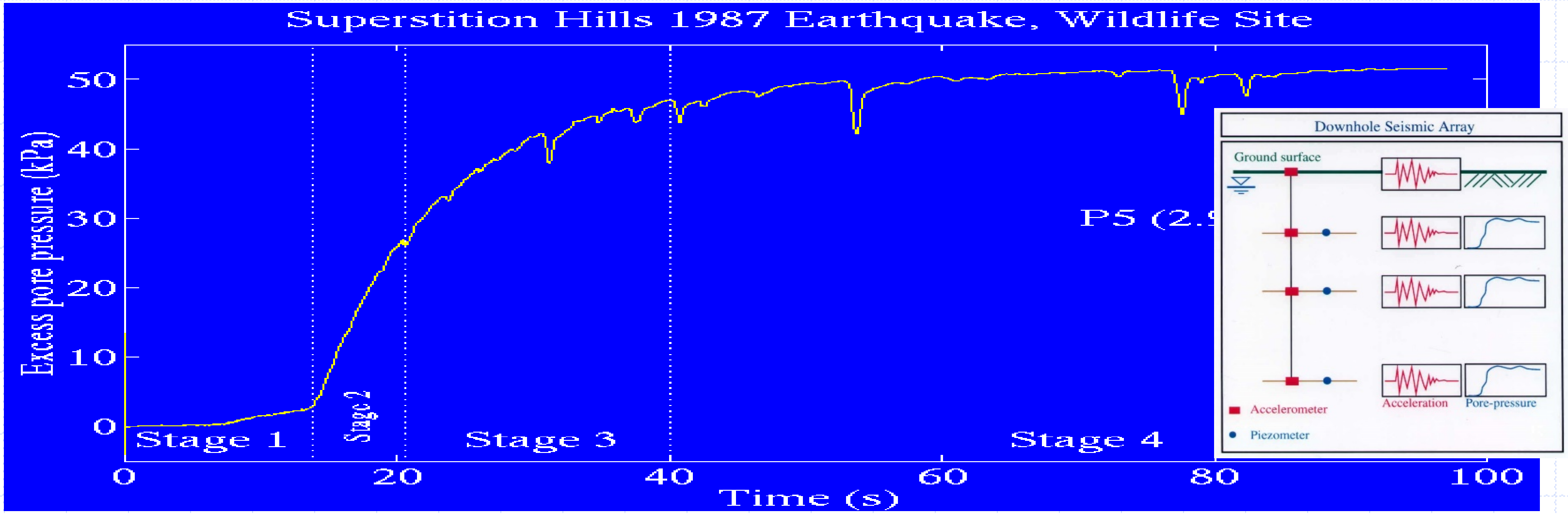


Youd and Holzer 1994 **Steidl and Seale 2010**

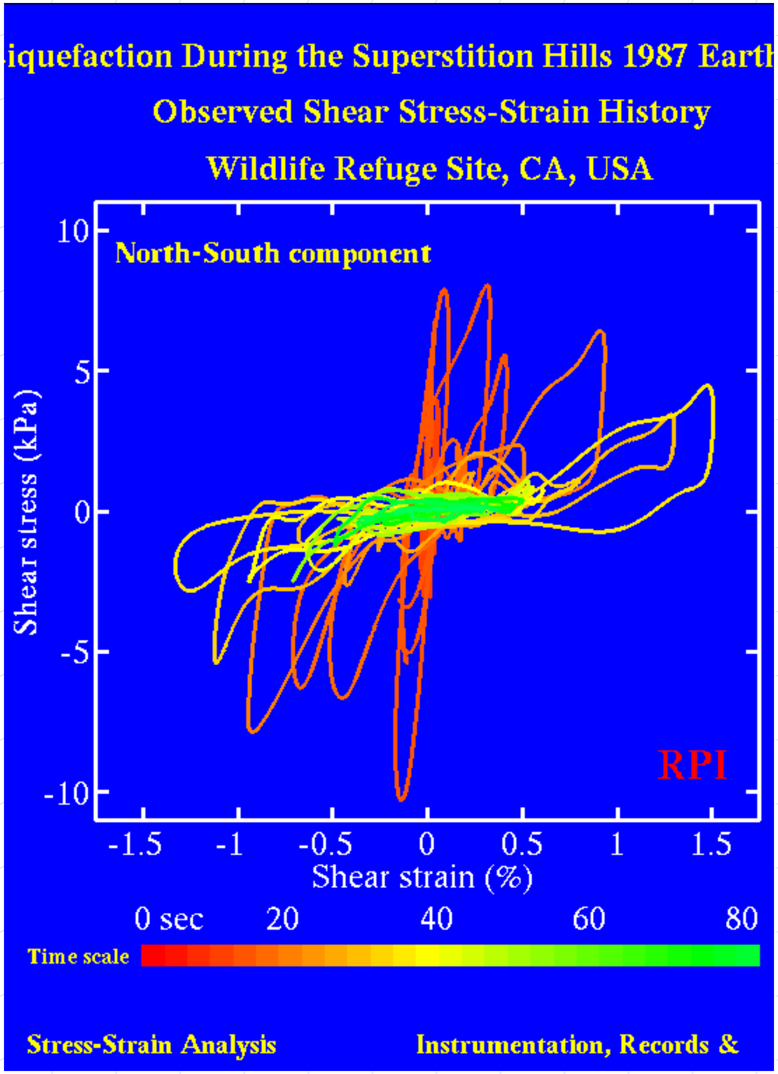
EERI_San Diego_Sept_2014_Martin_Elgamal

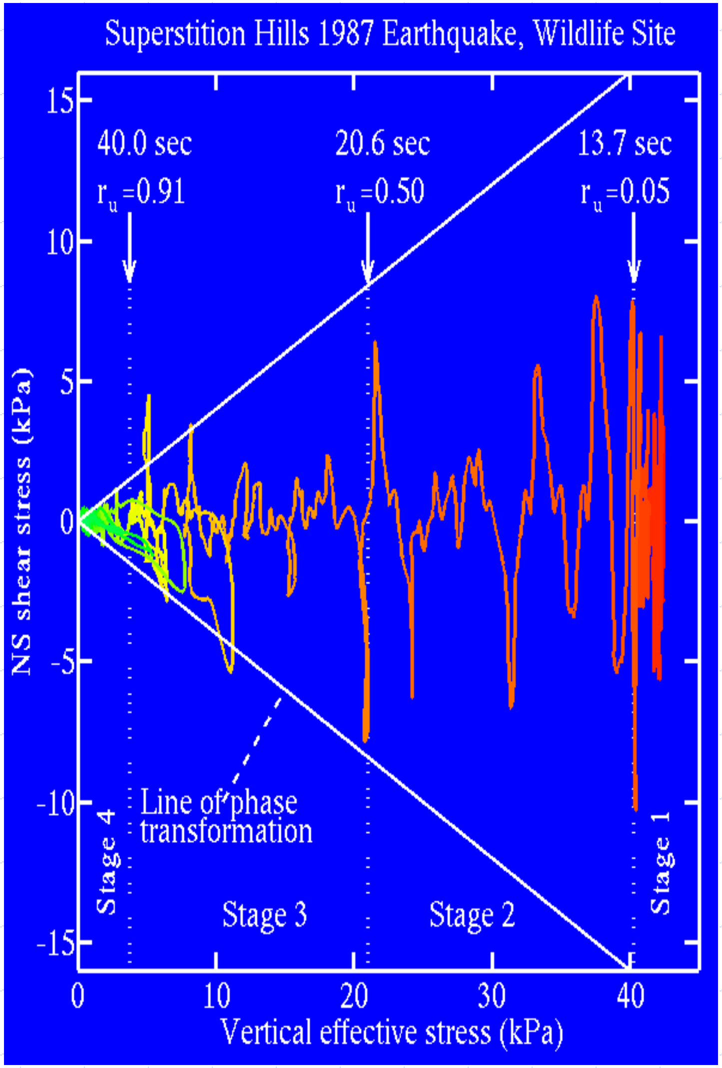
Cyclic mobility at large shear strain (Zeghal and Elgamal 1994)





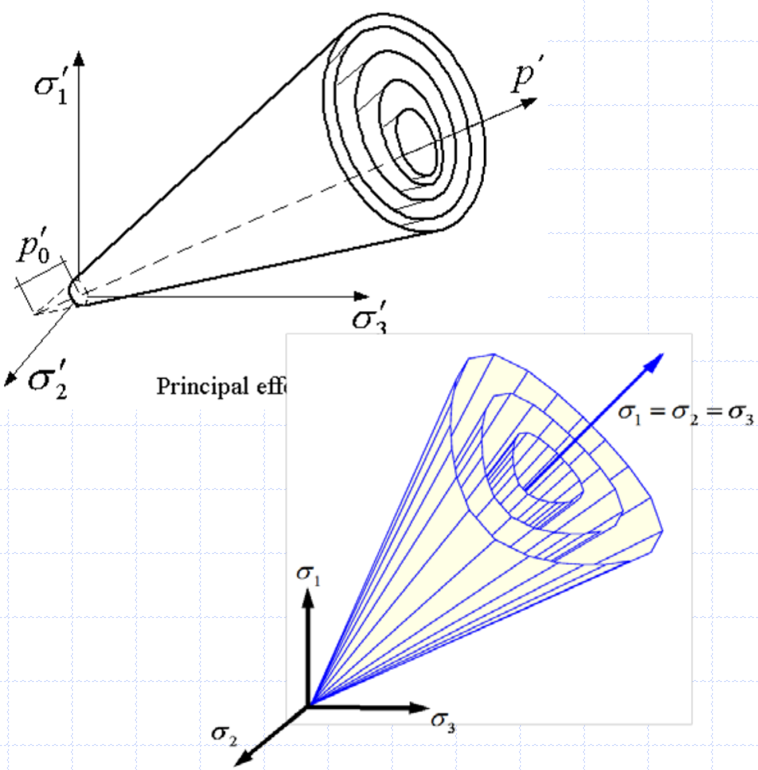
Cyclic mobility at large shear strain (Zeghal and Elgamal 1994)



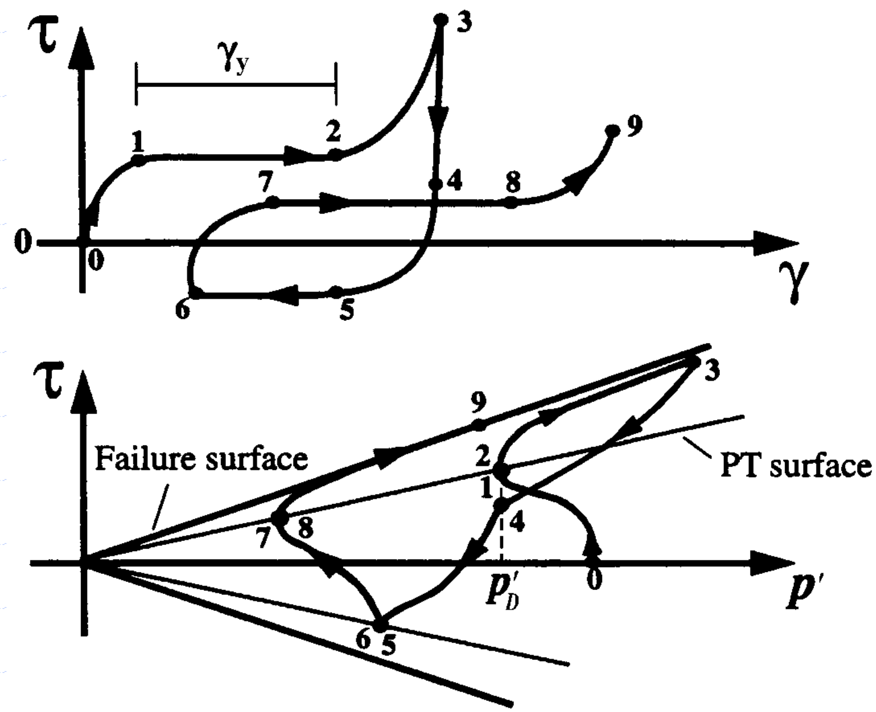


Soil Constitutive Model

- Multi-yield surface plasticity model (based on Prevost 1985)
  - Incorporating dilatancy and cyclic mobility effects

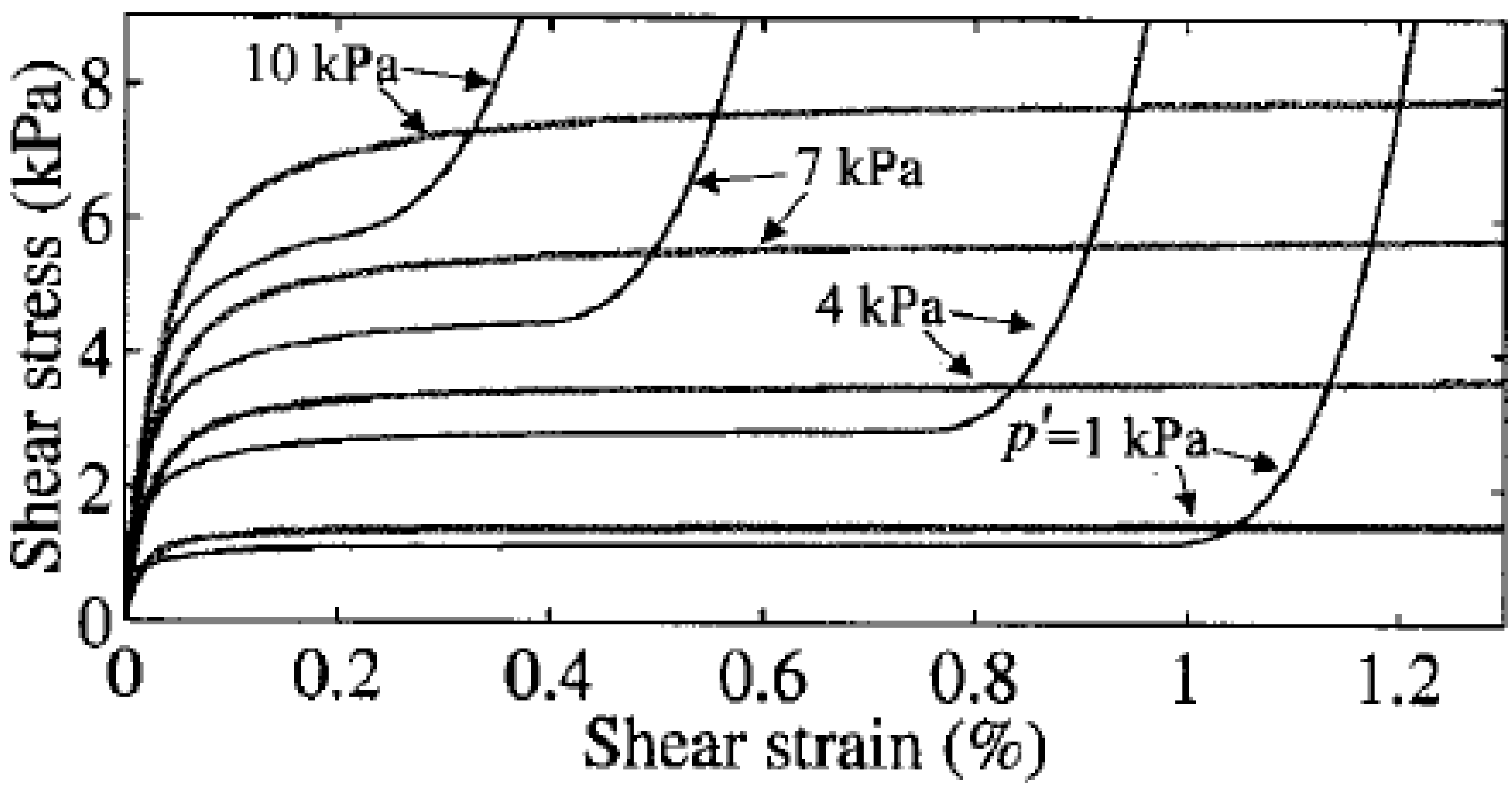


Conical yield surfaces for granular soils (Prevost 1985; Elgamal et al. 2003; Yang and Elgamal 2008)



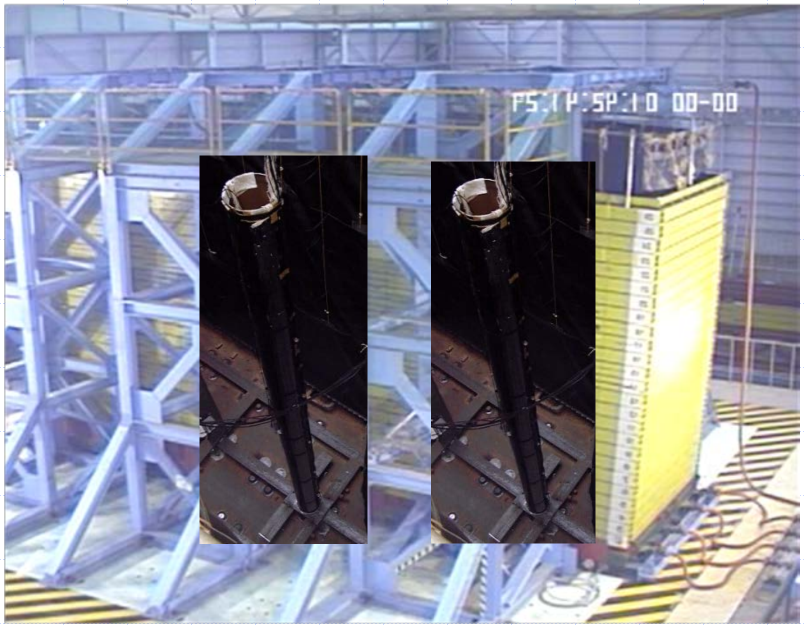
Shear stress-strain and effective stress path under undrained shear loading condition (Parra 1996, Yang 2000, Yang and Elgamal 2002)

Permeability is a critical parameter for the estimation of liquefaction-induced lateral deformations



Yang, Z. and Elgamal, A. "Influence of Permeability on Liquefaction-Induced Shear Deformation," Journal of Engineering Mechanics, ASCE, 128, 7, July 2002.

Shaking Table Tests: US-Japan Research (UCSD, NSF, NIED, PEER, CALTRANS)
5m height: Liquefaction-Induced lateral Spreading Effects on Piles (NIED, Tsukuba)
Professor Kohji Tokimatsu, Dr. Masayoshi Sato, and Dr. Akio Abe

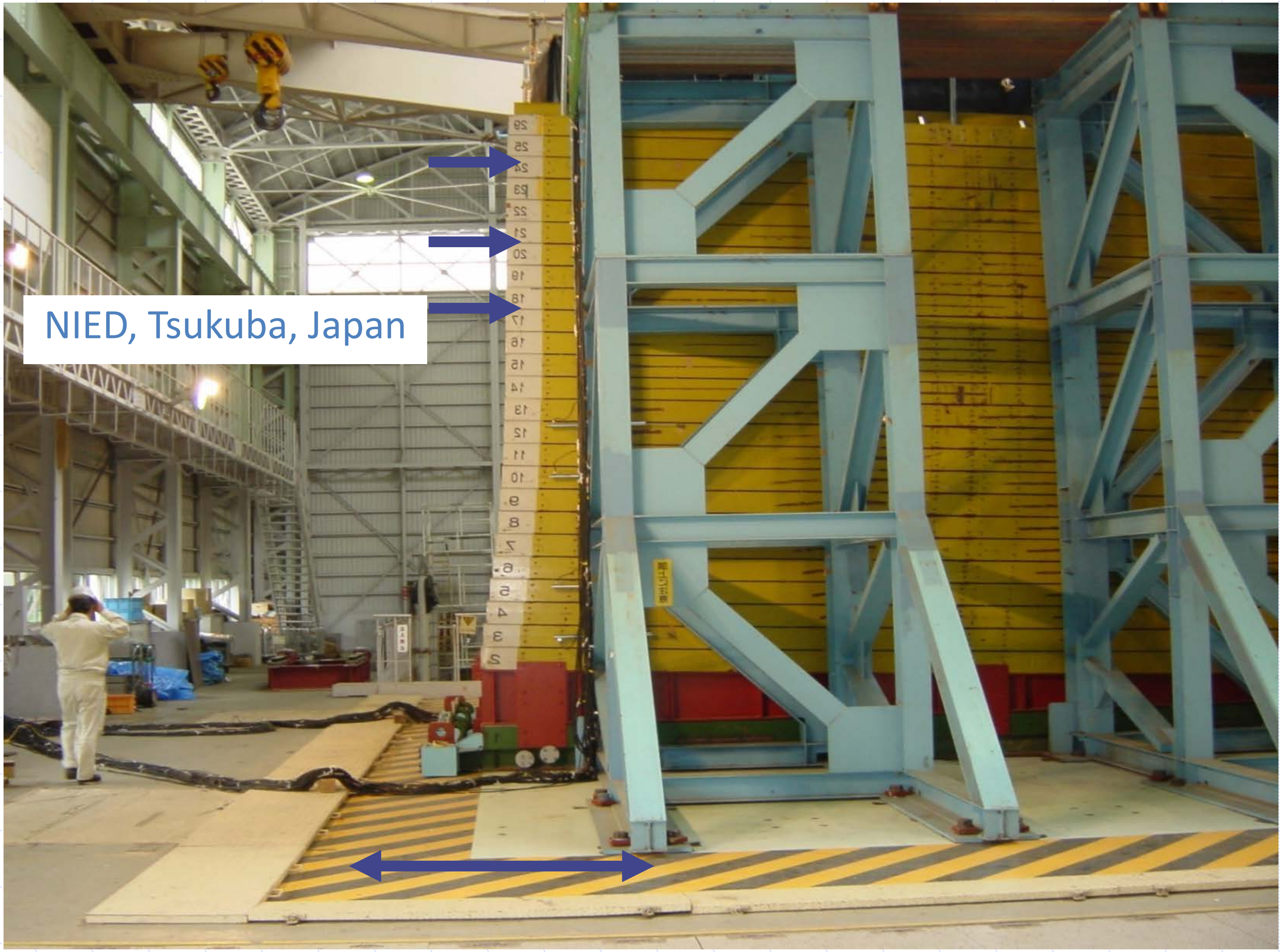


Before After

1m of Lateral Spreading (> 3 pile diameters)

NIED, Tsukuba, Japan

Shaking Table Tests: US-Japan Research (UCSD, NSF, NIED, PEER, CALTRANS)
5m height: Liquefaction-Induced lateral Spreading Effects on Piles (NIED, Tsukuba)
Professor Kohji Tokimatsu, Dr. Masayoshi Sato, and Dr. Akio Abe



Shaking Table Tests: US-Japan Research (UCSD, NSF, NIED, PEER, CALTRANS)
5m height: Liquefaction-Induced lateral Spreading Effects on Piles (NIED, Tsukuba)
Professor Kohji Tokimatsu, Dr. Masayoshi Sato, and Dr. Akio Abe

Shaking Table Tests: US-Japan Research (UCSD, NSF, NIED, PEER, CALTRANS)
5m height: Liquefaction-Induced lateral Spreading Effects on Piles (NIED, Tsukuba)
Professor Kohji Tokimatsu, Dr. Masayoshi Sato, and Dr. Akio Abe

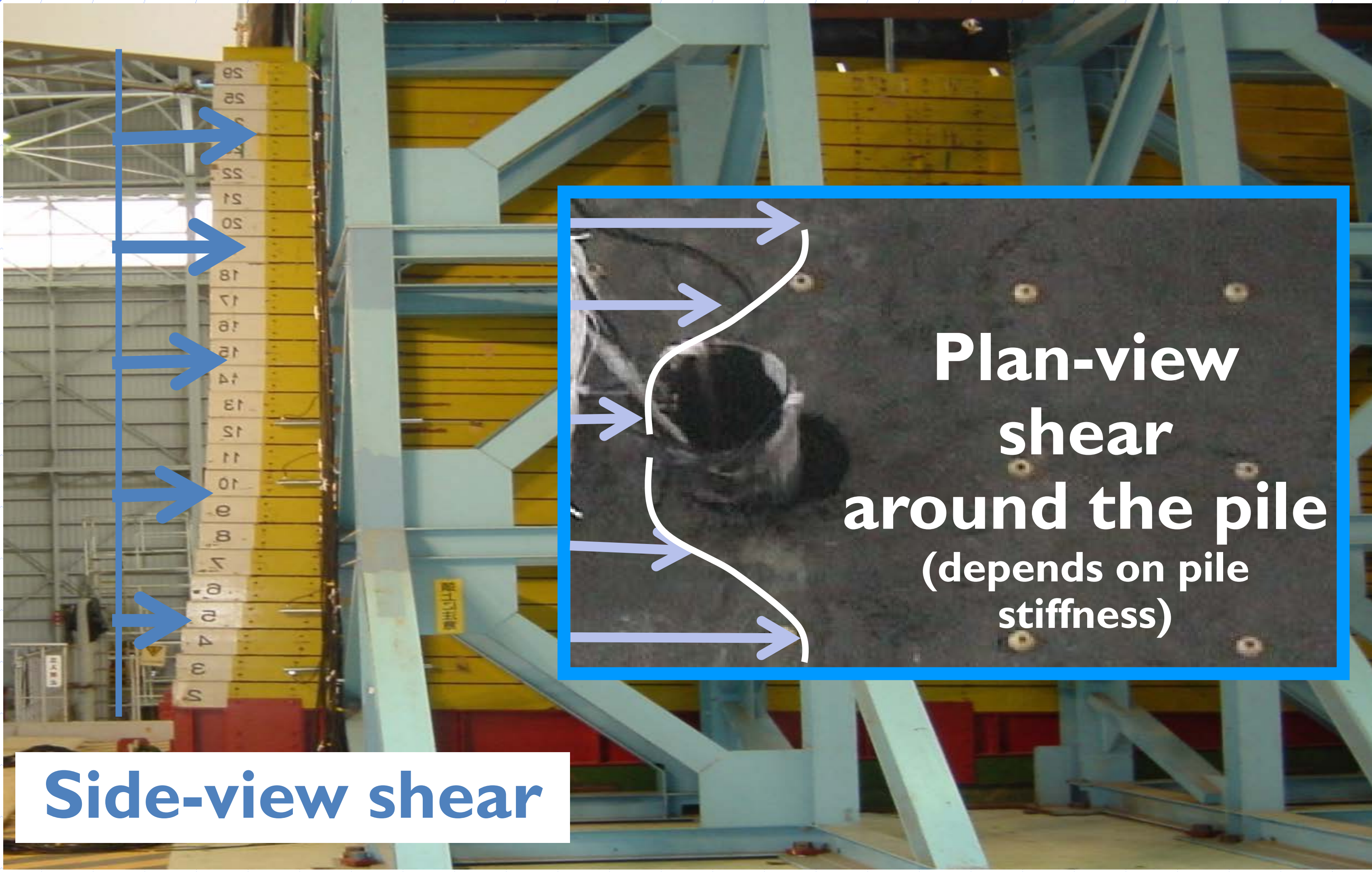
Shaking Table Tests: US-Japan Research (UCSD, NSF, NIED, PEER, CALTRANS)
5m height: Liquefaction-Induced lateral Spreading Effects on Piles (NIED, Tsukuba)
Professor Kohji Tokimatsu, Dr. Masayoshi Sato, and Dr. Akio Abe

Shaking Table Tests: US-Japan Research (UCSD, NSF, NIED, PEER, CALTRANS)
5m height: Liquefaction-Induced lateral Spreading Effects on Piles (NIED, Tsukuba)
Professor Kohji Tokimatsu, Dr. Masayoshi Sato, and Dr. Akio Abe

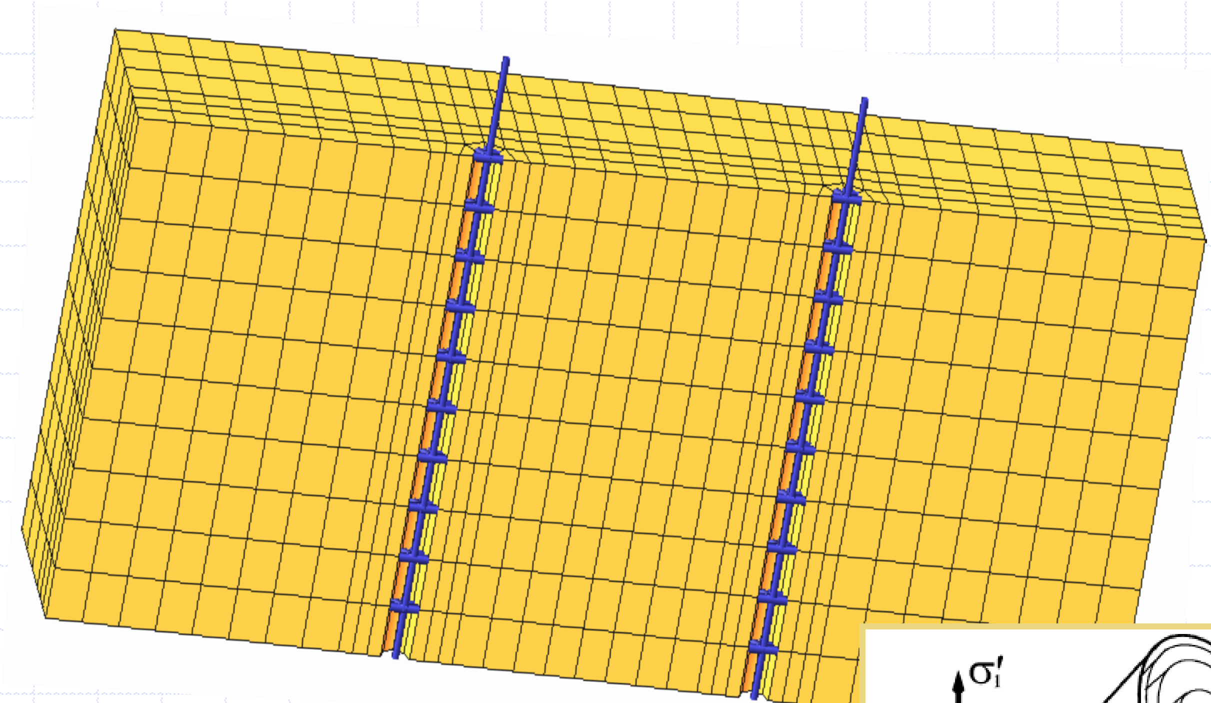
Shaking Table Tests: US-Japan Research (UCSD, NSF, NIED, PEER, CALTRANS)
5m height: Liquefaction-Induced lateral Spreading Effects on Piles (NIED, Tsukuba)
Professor Kohji Tokimatsu, Dr. Masayoshi Sato, and Dr. Akio Abe

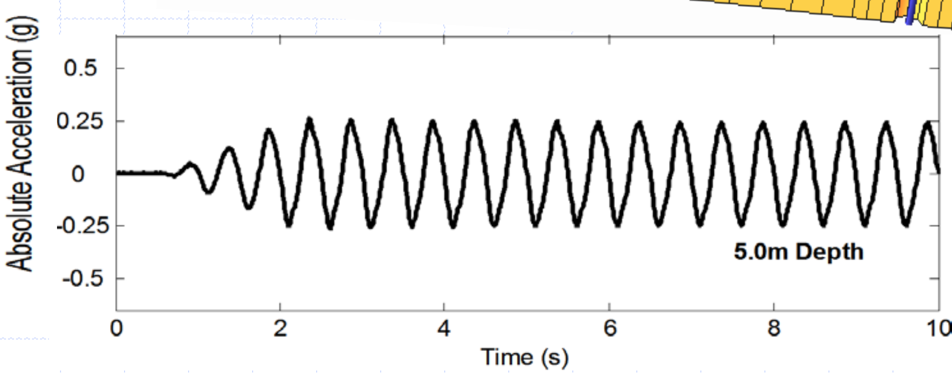
Shaking Table Tests: US-Japan Research (UCSD, NSF, NIED, PEER, CALTRANS)
5m height: Liquefaction-Induced lateral Spreading Effects on Piles (NIED, Tsukuba)
Professor Kohji Tokimatsu, Dr. Masayoshi Sato, and Dr. Akio Abe

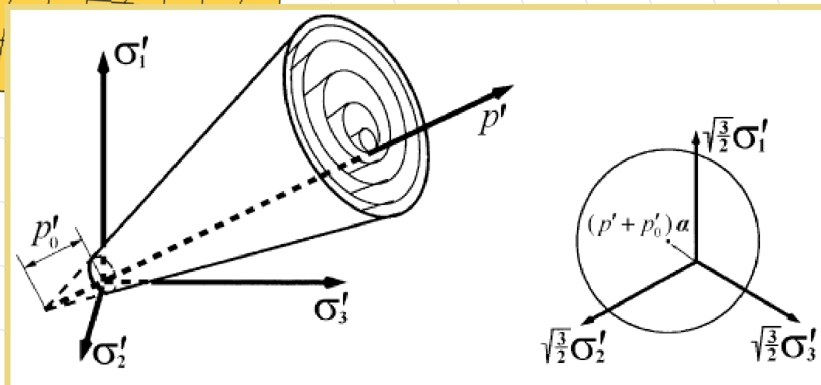
Shaking Table Tests: US-Japan Research (UCSD, NSF, NIED, PEER, CALTRANS)
5m height: Liquefaction-Induced lateral Spreading Effects on Piles (NIED, Tsukuba)
Professor Kohji Tokimatsu, Dr. Masayoshi Sato, and Dr. Akio Abe



OpenSees FE Model

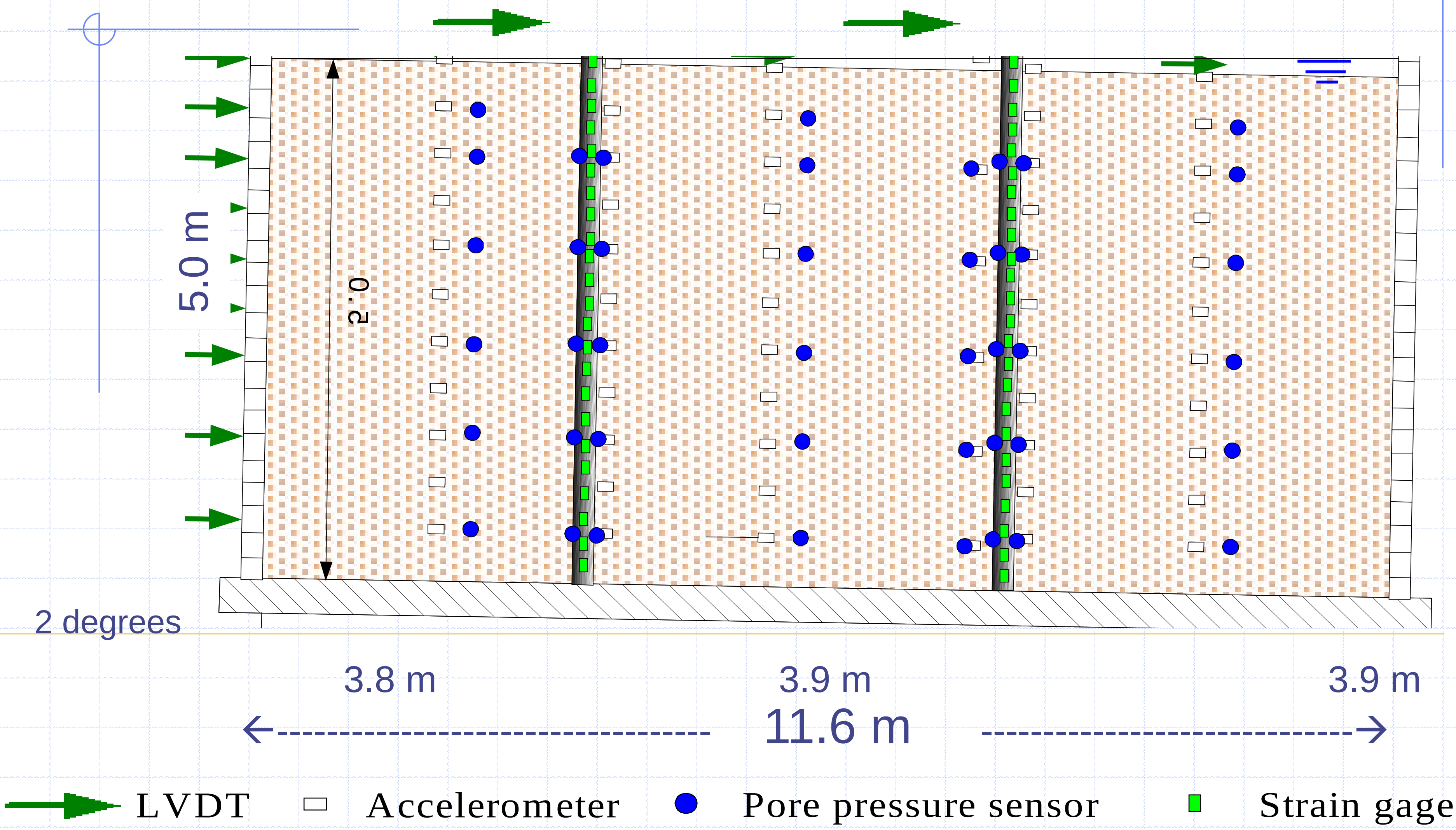






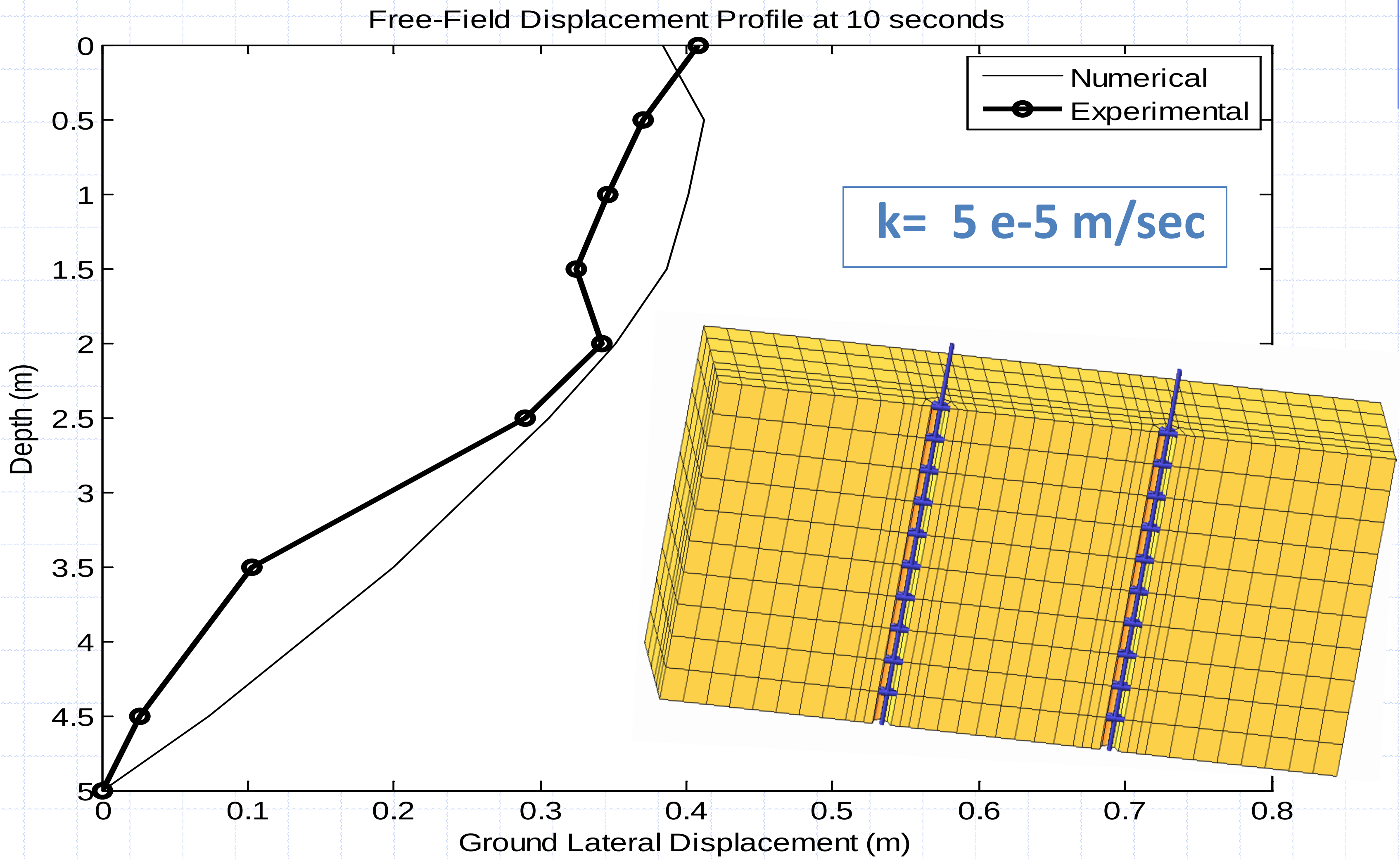
Principal effective stress space **Deviatoric plane**

Instrumentation Layout/Experimental Data



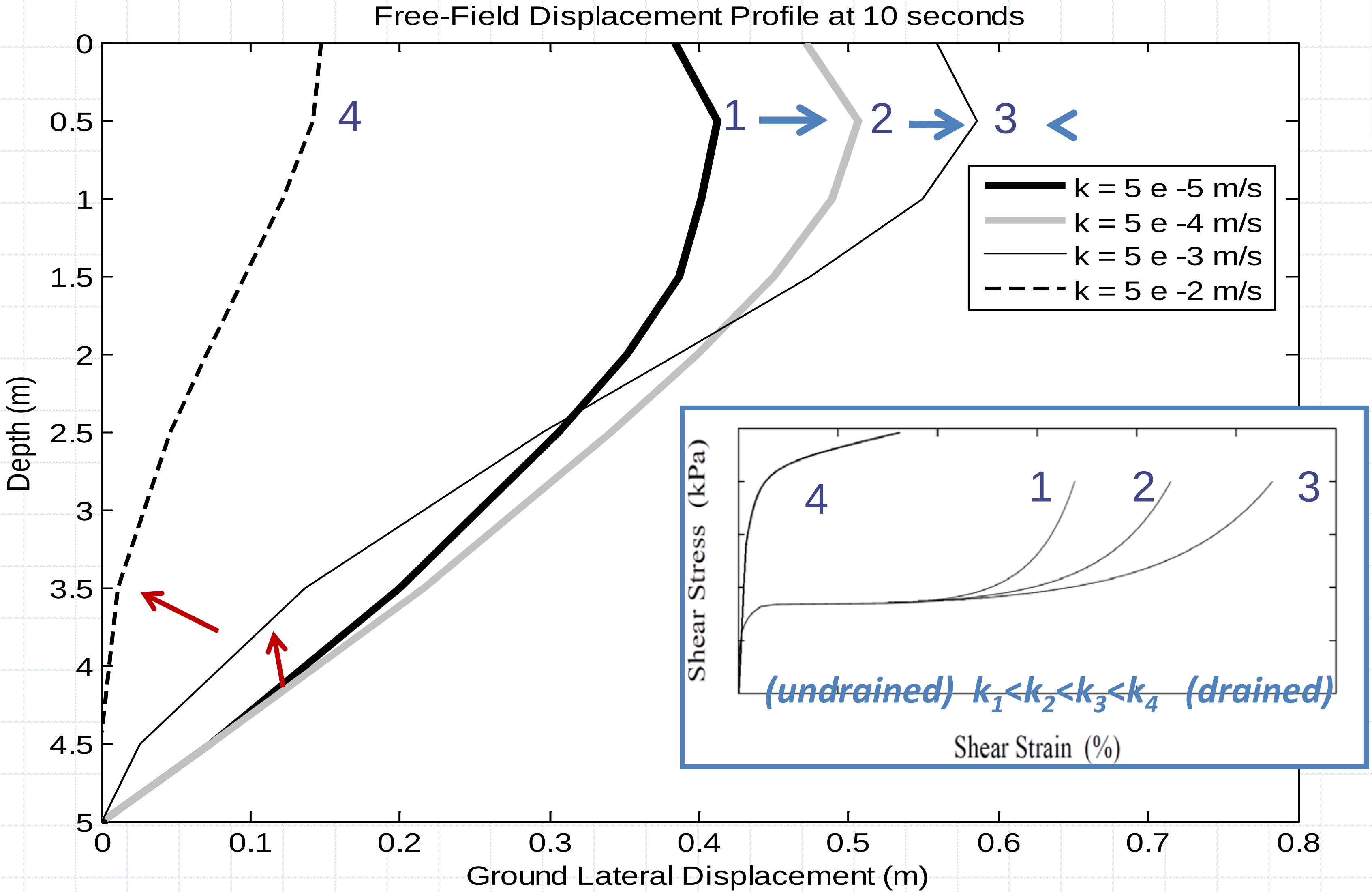
EERI_San Diego_Sept_2014_Martin_Elgamal

Recorded and computed free-field displacement profile at 10 seconds



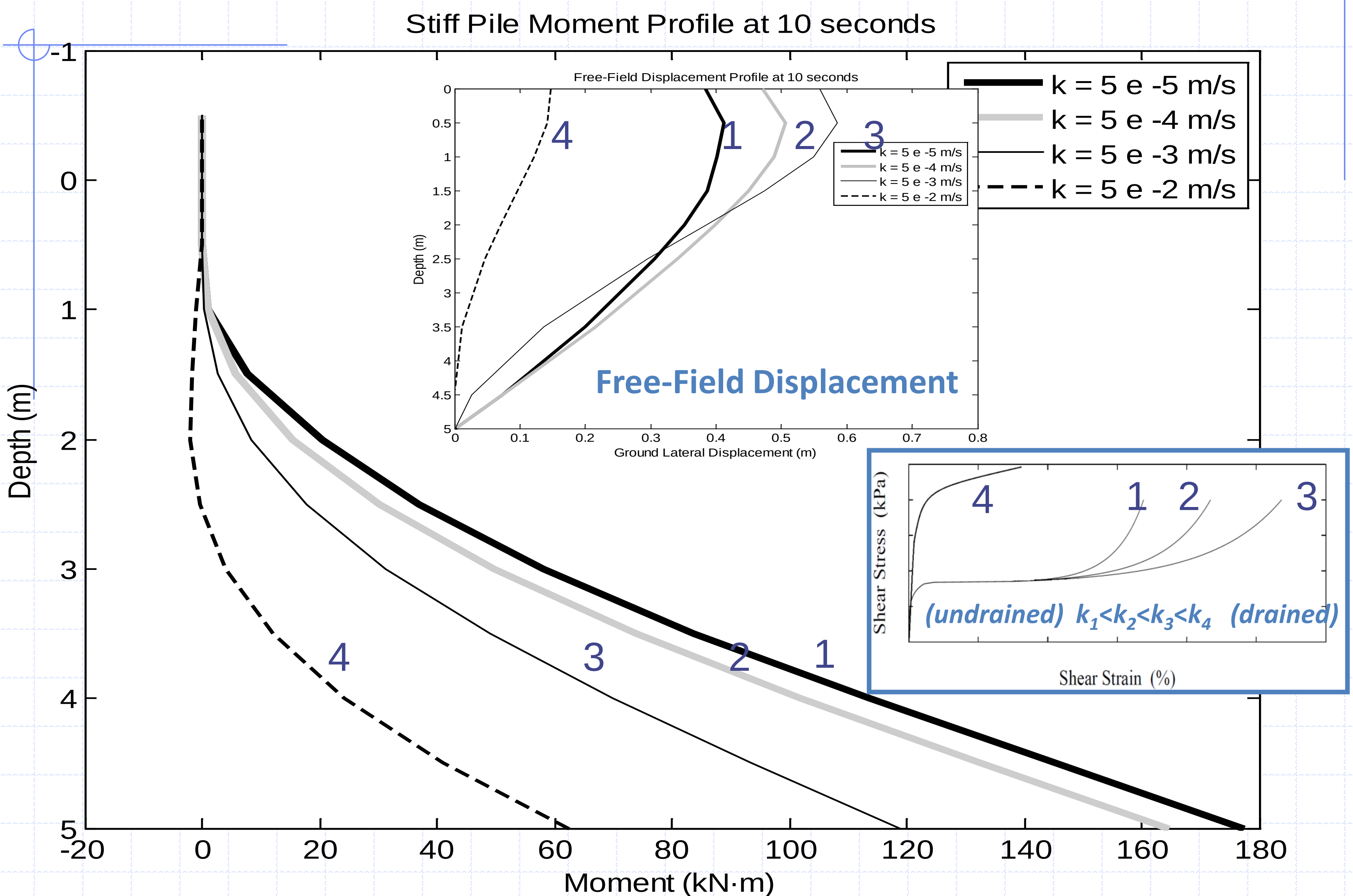
EERI_San Diego_Sept_2014_Martin_Elgamal

Influence of permeability on free-field displacement profile at 10 seconds



EERI_San Diego_Sept_2014_Martin_Elgamal

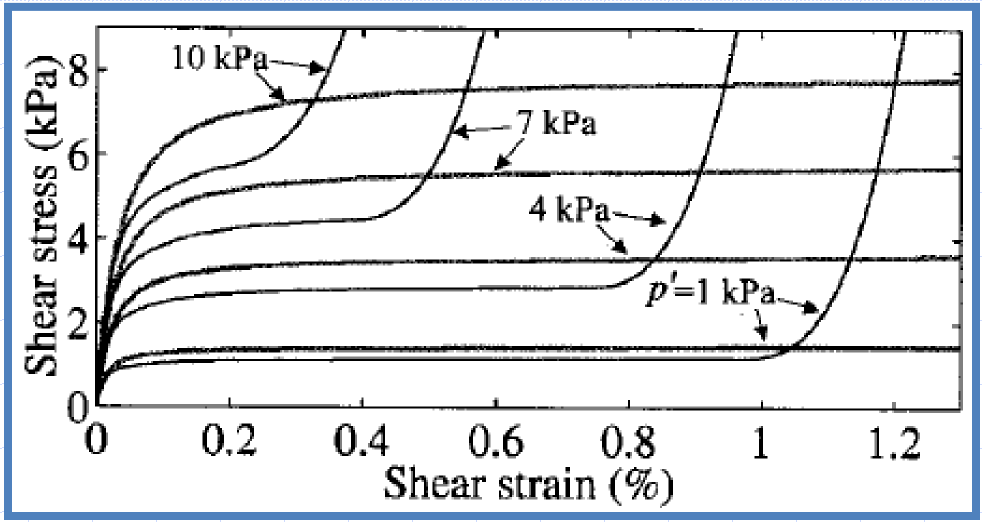
Influence of permeability on stiff pile moment profile at 10 seconds



EERI_San Diego_Sept_2014_Martin_Elgamal

Conclusion

-Permeability is a critical parameter for the estimation of liquefaction-induced lateral deformations
- Permeability is a critical parameter for the estimation of pile moments due to liquefaction-induced lateral ground deformation
- **Larger ground displacement is not always proportional to higher moment in piles**



Yang, Z. and Elgamal, A. "Influence of Permeability on Liquefaction-Induced Shear Deformation," Journal of Engineering Mechanics, ASCE, 128, 7, July 2002

For Saturated Cohesionless soils…

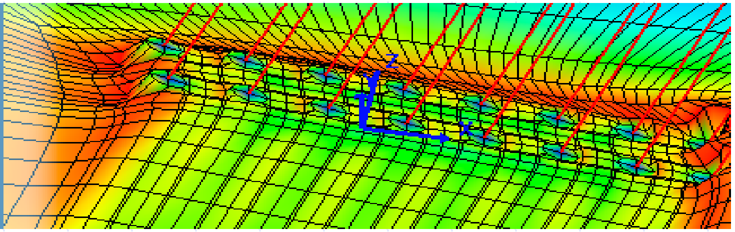
Shear resistance depends on:

1) $N_{1(60)}$, CPT q_{c1} , V_s

2) Soil/System Permeability k

OpenSeesPL

3D Lateral Pile-Ground Interaction



http://soilquake.net/openseespl/

Home Copyright Examples FAQ References

OpenSeesPL is a PC-based graphical pre- and post-processor (user-interface) for three dimensional (3D) ground and ground-structure response. The 3D Finite Element (FE) computations are conducted using OpenSees developed by the Pacific Earthquake Engineering Research Center (PEER). The analysis options available in **OpenSeesPL*** include: 1) Pushover Analysis, 2) Mode Shape Analysis and 3) Base Input Acceleration Analysis.

OpenSeesPL is recently re-written in Microsoft .NET Framework (WPF or Windows Presentation Foundation). OpenTK (OpenGL) library is used for visualization of FE mesh and .NET Chart Component is employed for x-y plotting.

*Lu, J., Elgamal, A., and Yang, Z. (2011). OpenSeesPL: 3D Lateral Pile-Ground Interaction, User Manual, Beta 1.0.

Also, check the publications below for examples of different pile, footing, embedded structure, pile group, and ground modification scenarios:

- Elgamal, A., Lu, J., Yang, Z., and Shantz, T. (2009). Scenario-focused three-dimensional computational modeling in geomechanics, Alexandria, Egypt, 4 iYGEC'09 – Proc. 4th International Young Geotechnical Engineers' Conference (2 – 6 October), ISSMGE [View PDF File]

Related Software
- Cyclic1D
- OpenSees Soil Models

Register/login to download OpenSeesPL
- Register
- Log in

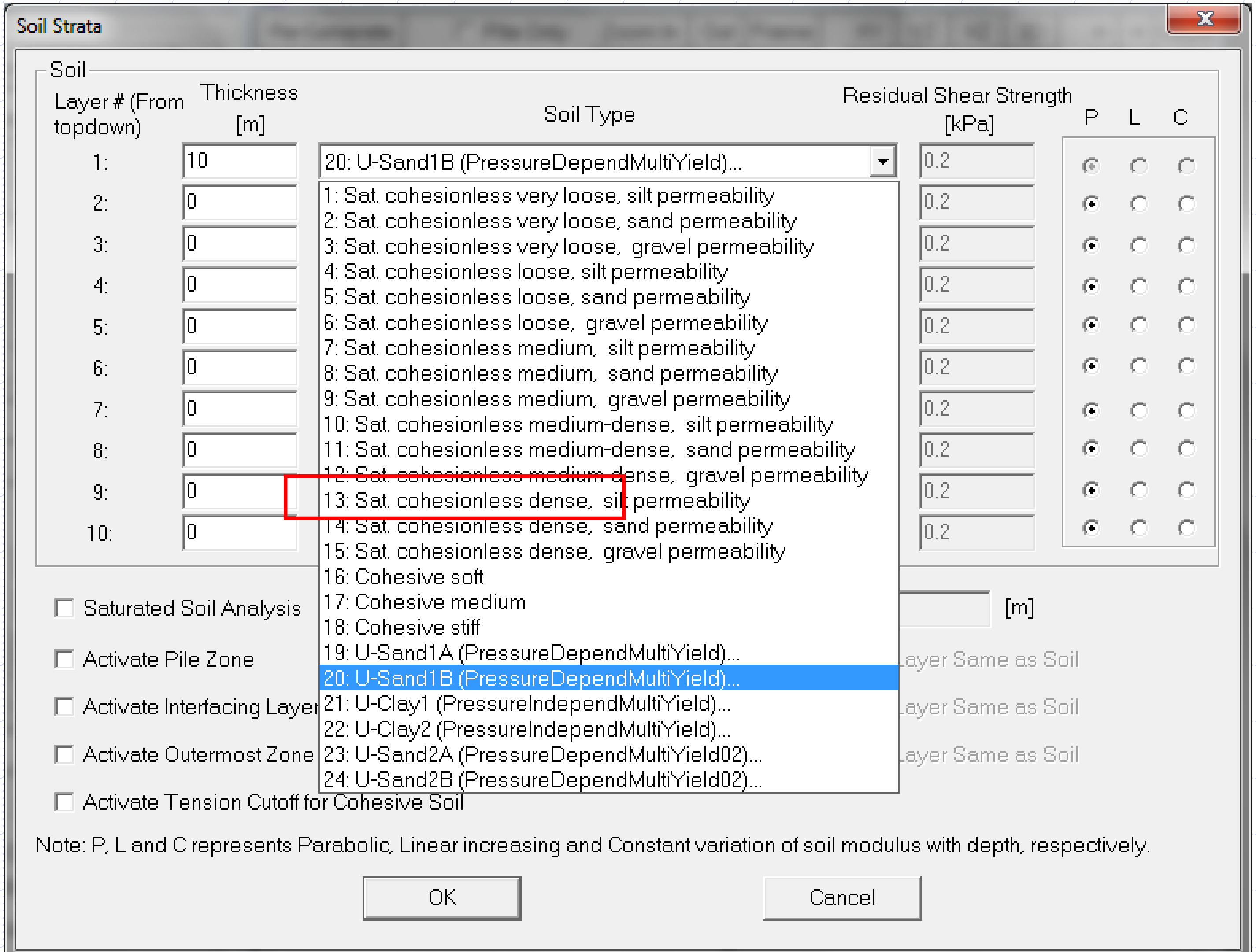
Earthquakes
- M6.5 Barbados 2 hours ago
- M4.1 South Carolina 3 days ago
- M6.9 China 6 days ago
- M6.5 Vanuatu 2 weeks ago
- M6.5 New Zealand 2 weeks ago

Last update : Tue 11:14:58 (UTC)

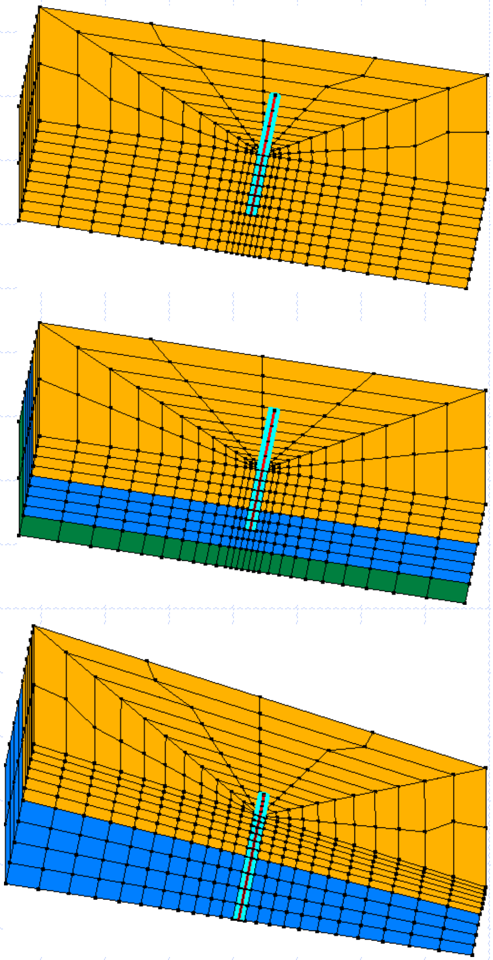
February 2014

M	T	W	T	F	S	S
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28		

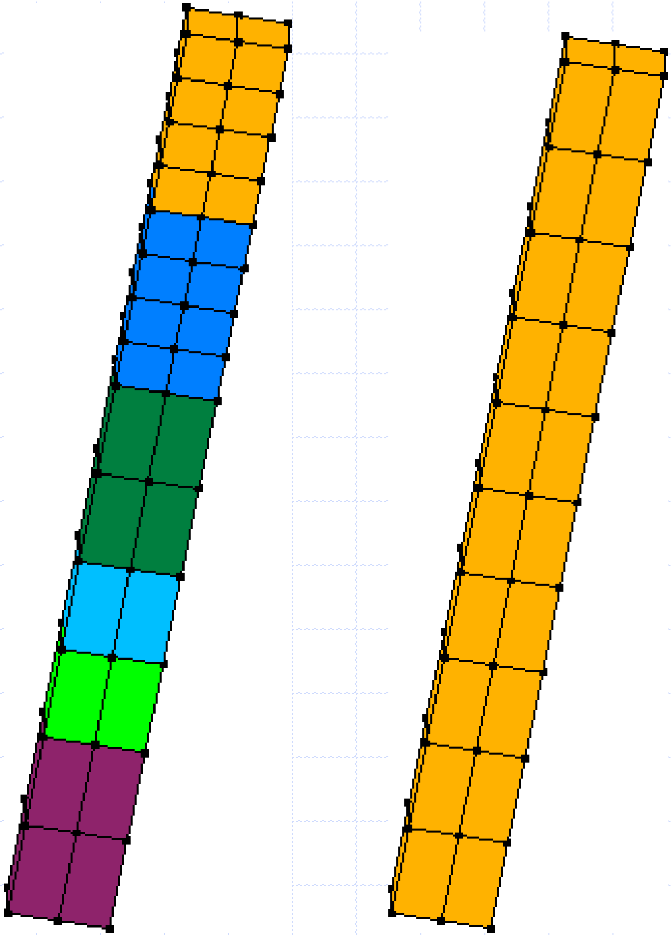
OpenSeesPL: http://soilquake.net/openseespl/



OPENSEESPL Example Input Files (http://soilquake.net/openseespl/example_input_files/)

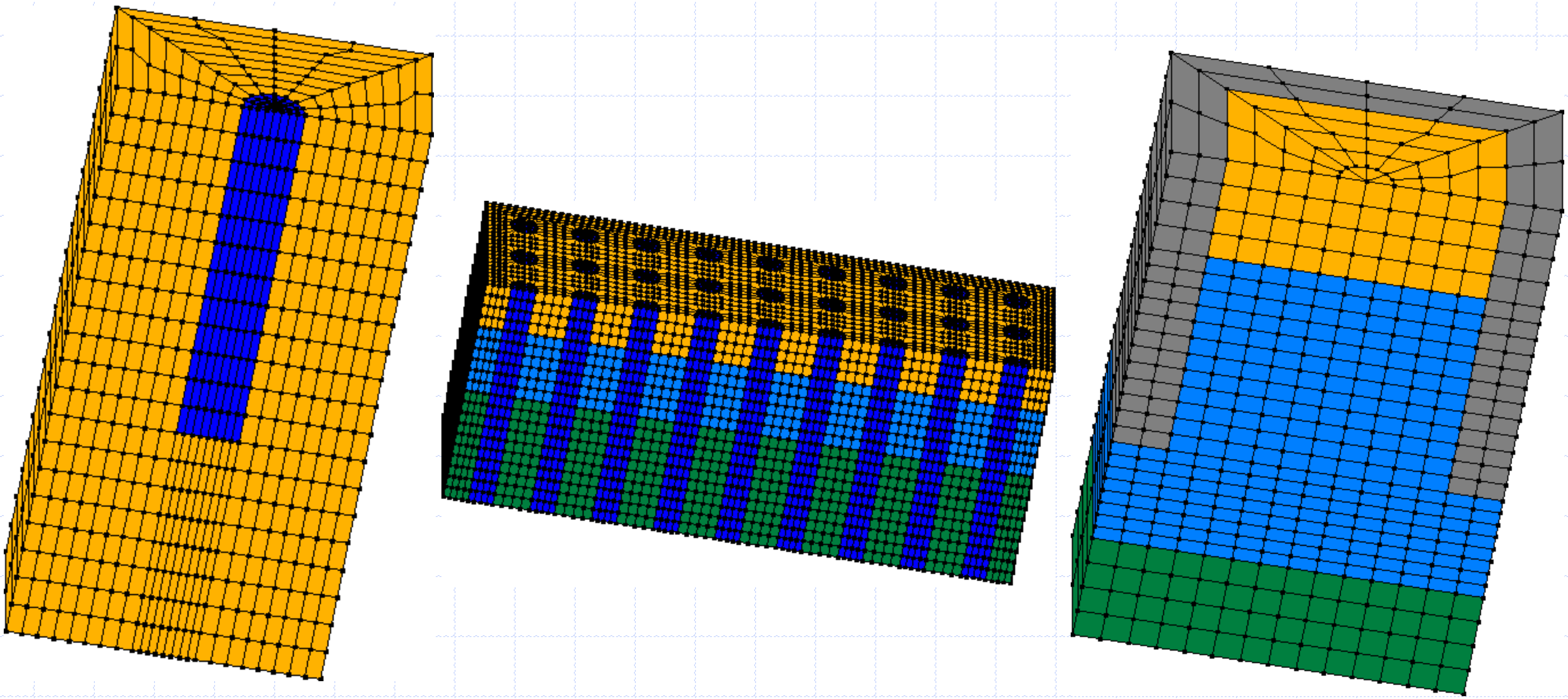


Pile in Ground Strata



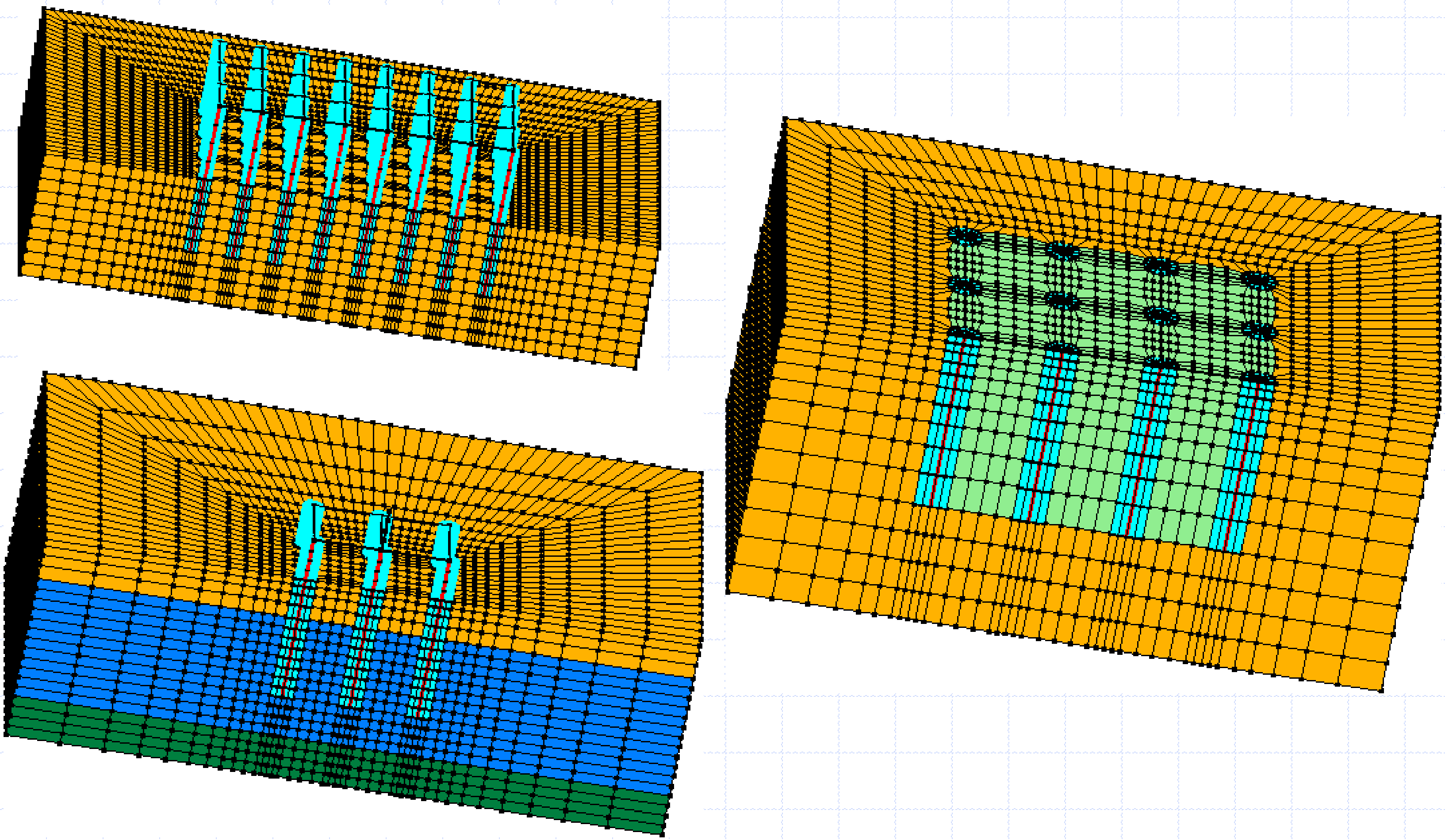
3-D Shear Beam Site Amplification

OPENSEESPL Example Input Files (http://soilquake.net/openseespl/example_input_files/



Ground Modification by Stone Columns. Pile-pinning, Earthquake Drain, or Deep Soil Mixing Grids

OPENSEESPL Example Input Files (http://soilquake.net/openseespl/example_input_files/)



Pile Groups and Piled Rafts