GeoVirginia 2013
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Lessons Learned in Geotechnical Engineering

Ground Improvement for Liquefaction Risk Mitigation

Methods, Verification, and Recent Research

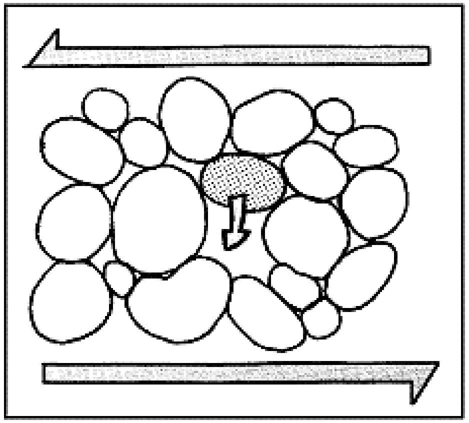
Allen L. Sehn, Ph.D., P.E
Vice President, Engineering
Hayward Baker Inc

ALSehn@HaywardBaker.com

Outline

- Liquefaction Evaluation & Liquefaction Mitigation Methods
- Verification of the Mitigation Effectiveness
  - Densification
  - Reinforcement
- Research on Shear Reinforcement Effects
  - Discrete Columns
  - Soilcrete Shearwall Grid

Liquefaction Prerequisites

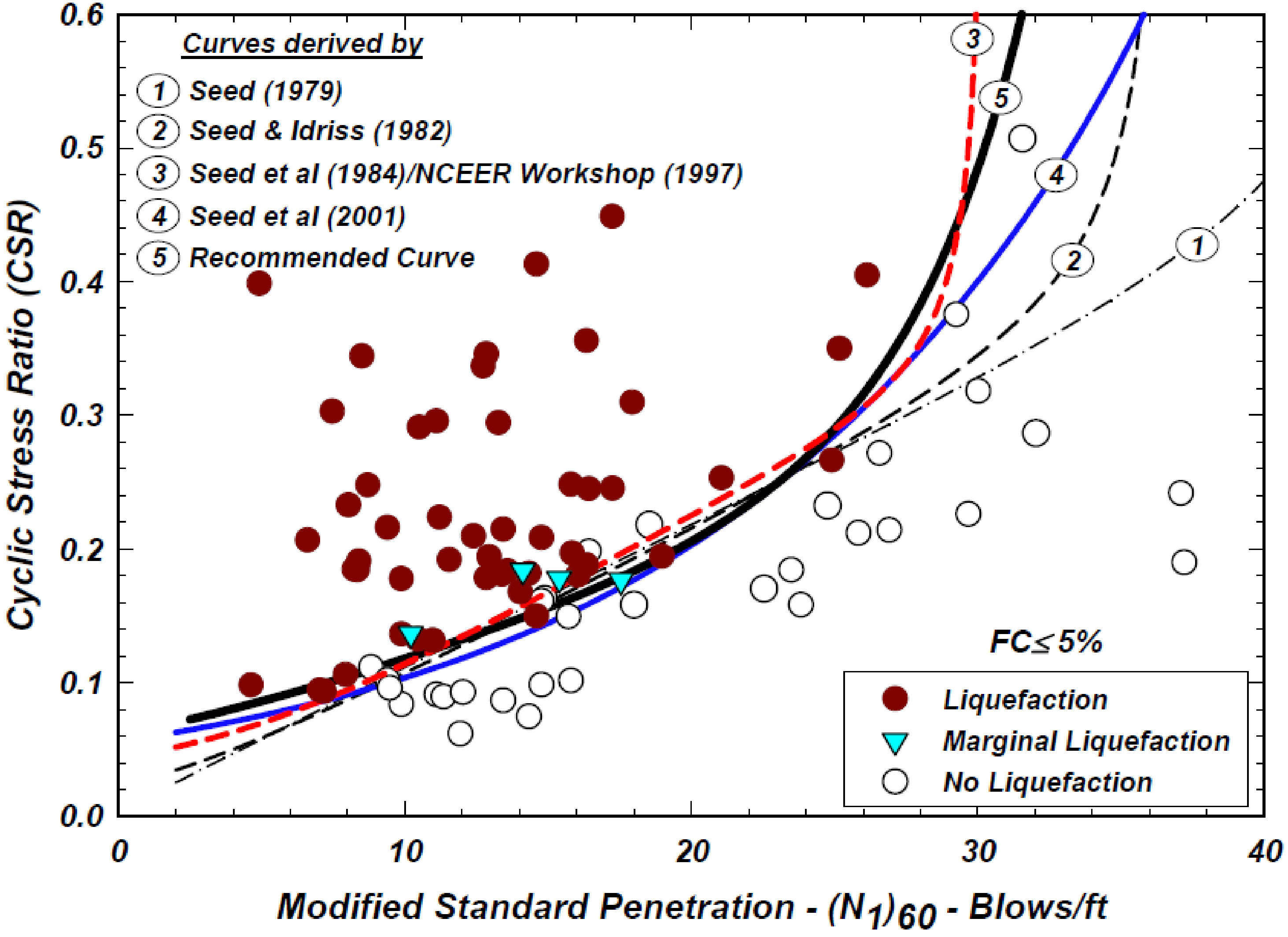


- Saturated soil
- Loose granular or other non-plastic soils.
- Strong ground motion.
  - Shear strains cause tendency for contraction.
  - Water cannot drain fast enough.
  - Pore water pressure increases and effective stress decreases (may approach zero).
  - After shaking stops pore water pressures dissipate and settlement occurs.

Liquefaction Evaluation

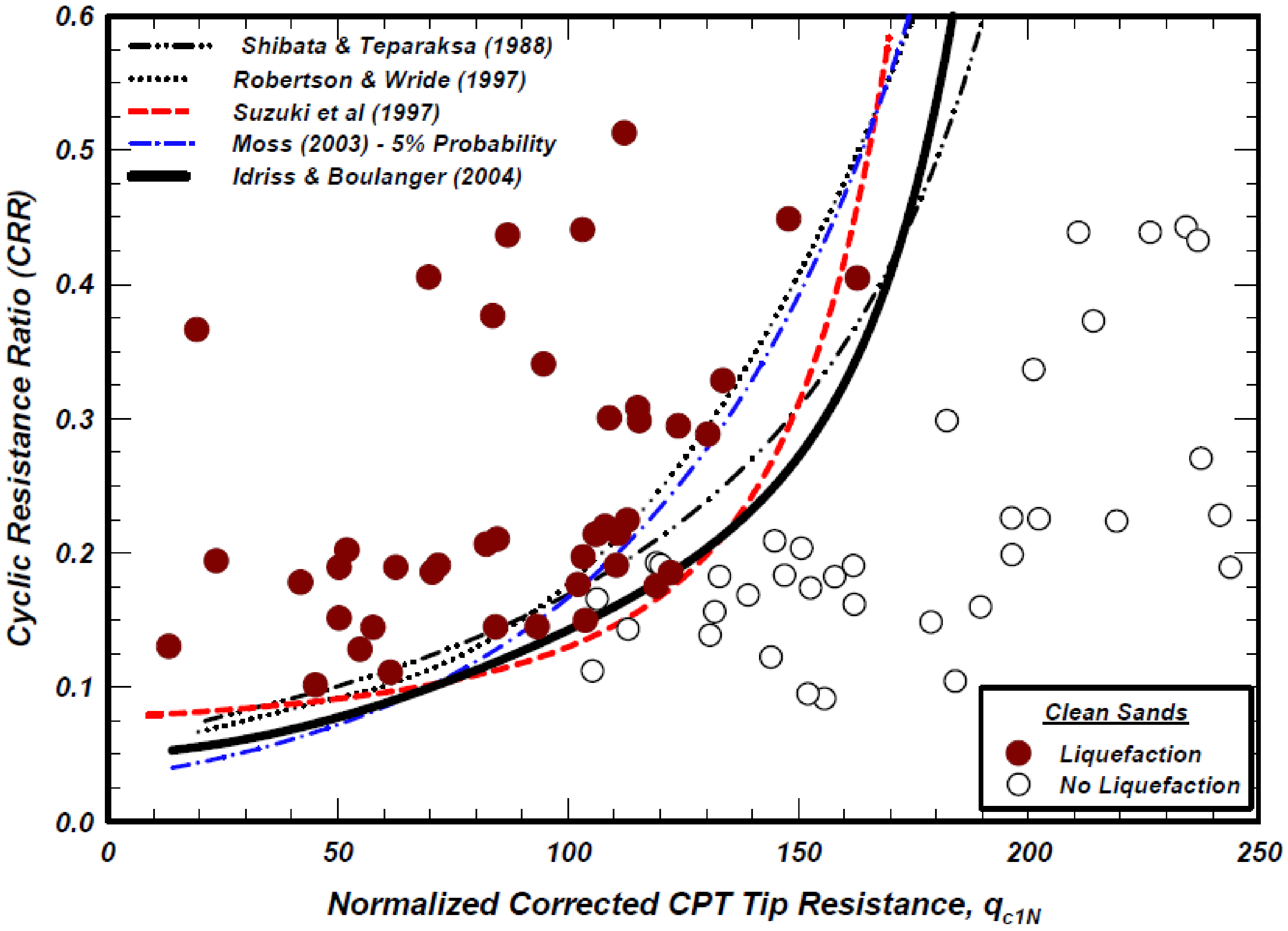
- Youd, et al. (2001)
  1998 NCEER/NSF Workshop
- California SP 117
- Robertson & Wang (2004)
- Idriss and Boulanger (2004 and 2008)
  EERI Monograph 12
- Baez and Martin (1993 and 1995)

SPT Based Approaches



From Idriss & Boulanger (2004)

CPT Based Approaches

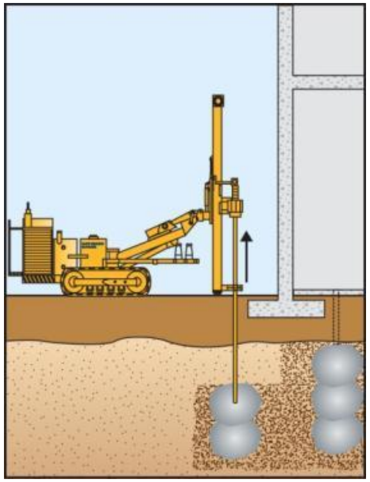


Liquefaction Mitigation Methods

1. Remove and replace with nonliquefiable soil
2. Densify loose granular soil
3. Modify cohesive properties of the soil
4. Provide shear reinforcement
5. Provide adequate drainage
6. Permanent lowering of the GWT
7. Deep Foundations piles or piers
8. Reinforced Shallow Foundations grade beams, combined footings, rigid raft foundations,
9. Design to accommodate settlement and loss of strength

Liquefaction Mitigation Methods

- Densification Methods
  - Deep Dynamic Compaction (DDC)
  - Vibro Compaction
  - Vibro Displacement (stone columns)
  - Compaction Grouting



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Liquefaction Mitigation Methods

- Improvement of Cohesive Properties
  - Deep Mixing
  - Jet Grouting
  - Permeation Grouting

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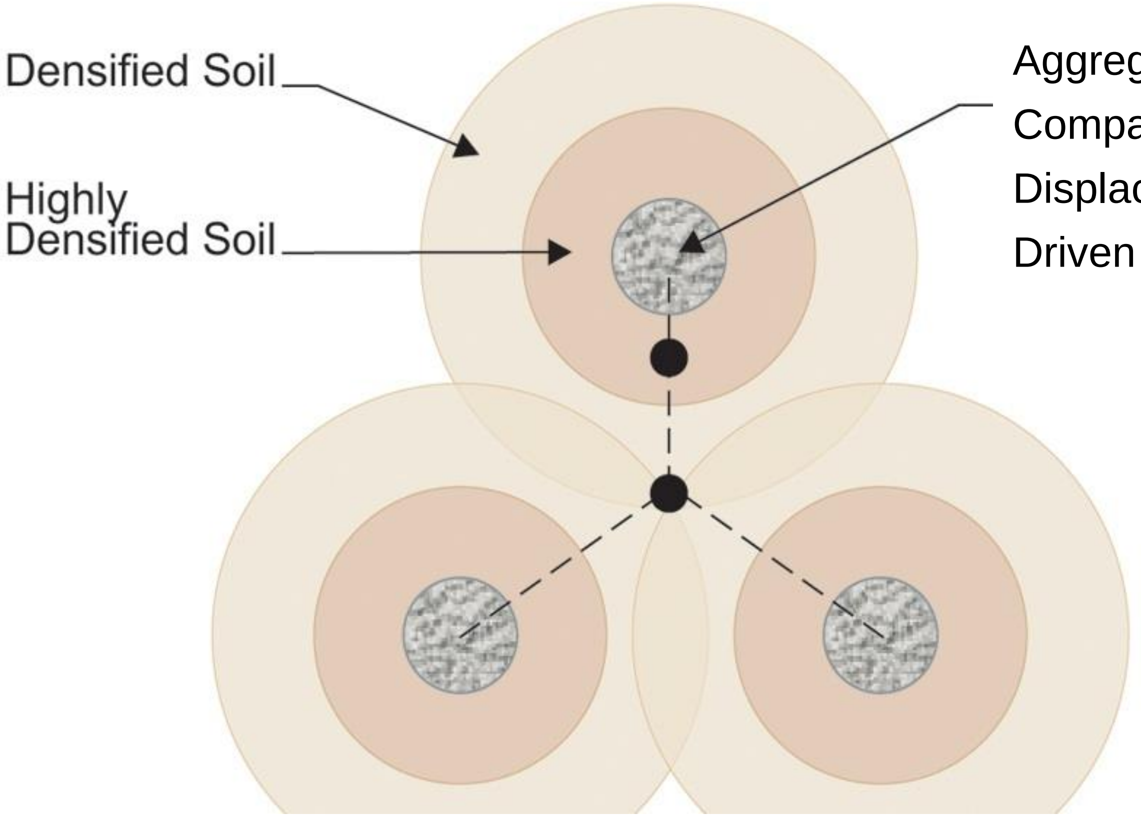
Verification of Liquefaction Mitigation

- Densification Verification
    - SPT
    - CPT
    - Shear Wave Velocity
    - Modulus/Plate Load Test?
    - Void Reduction vs. Volume Intake?
- Reinforcement Verification

Densification Verification

- SPT (ASTM D6066)
- CPT



Aggregate Column

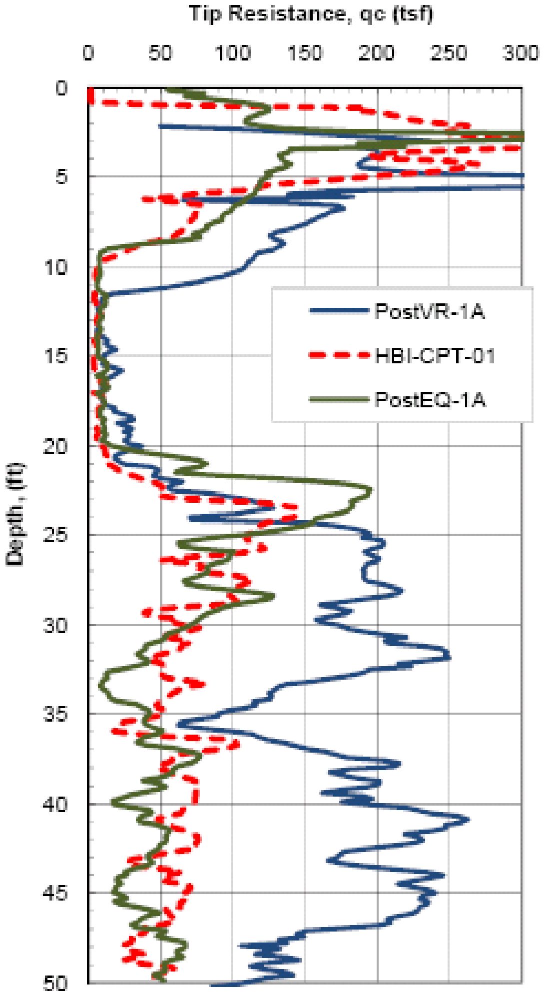
Compaction Grout

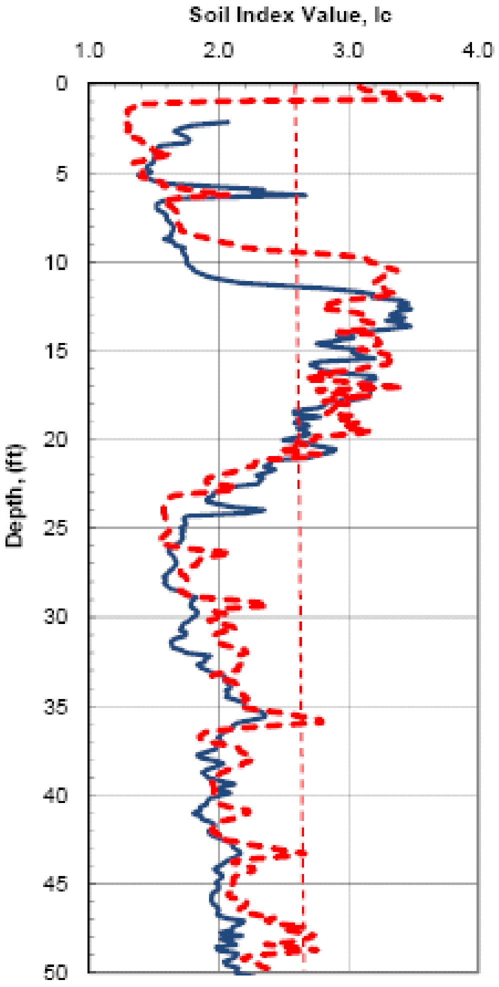
Displacement Pile

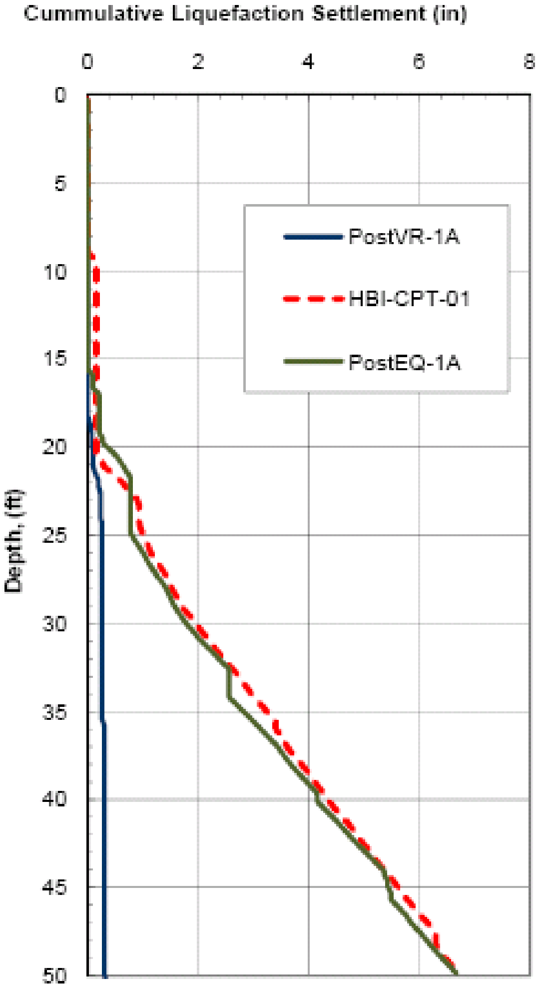
Driven Pile

CPT Comparison

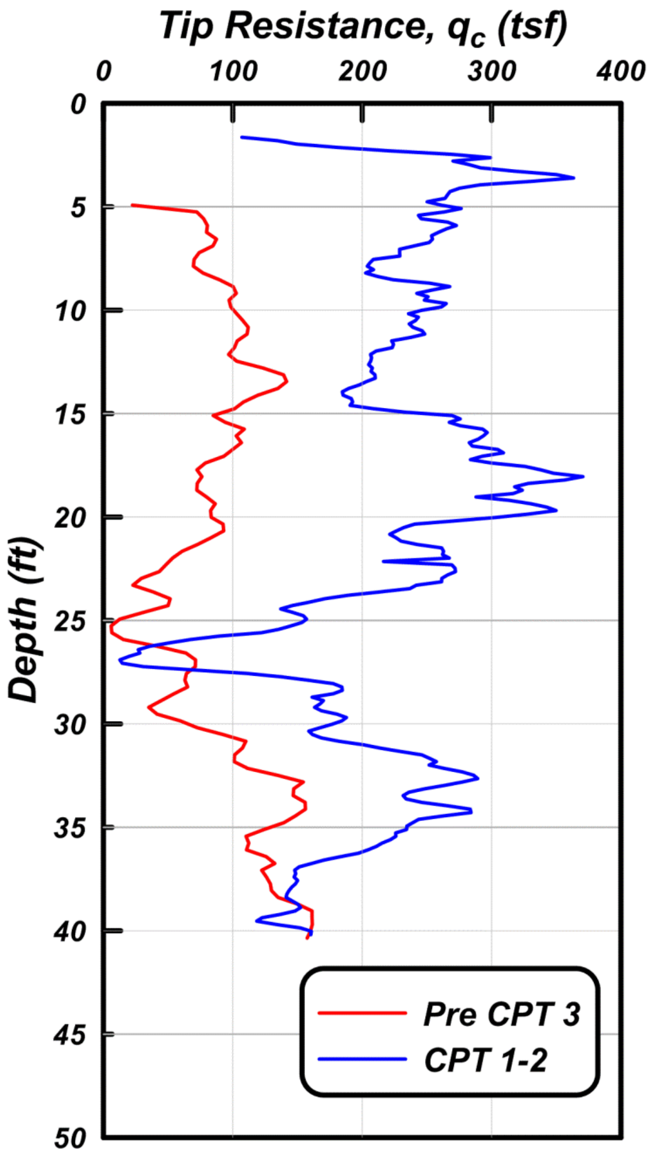
PostVR-1A M= 6.8 PGA= 0.37 g Fill= 0 ' GWT= 9 '
8 by 8 grid up to 50 ft
Ar= 15.0 % Without Thin Layer Correction Post-treat Dynamic Settlement = 0.48 "







Ic Shift


Tip Resistance, q_c (tsf)
0
100
200
300
400
Depth (ft)
0
5
10
15
20
25
30
35
40
45
50
Pre CPT 3
CPT 1-2

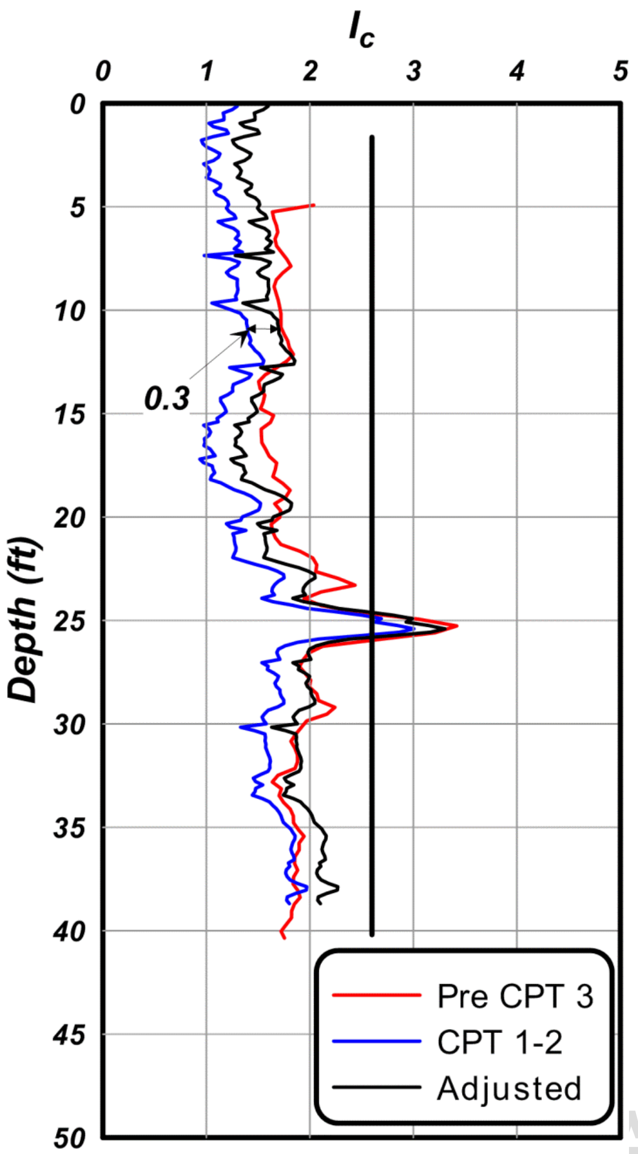
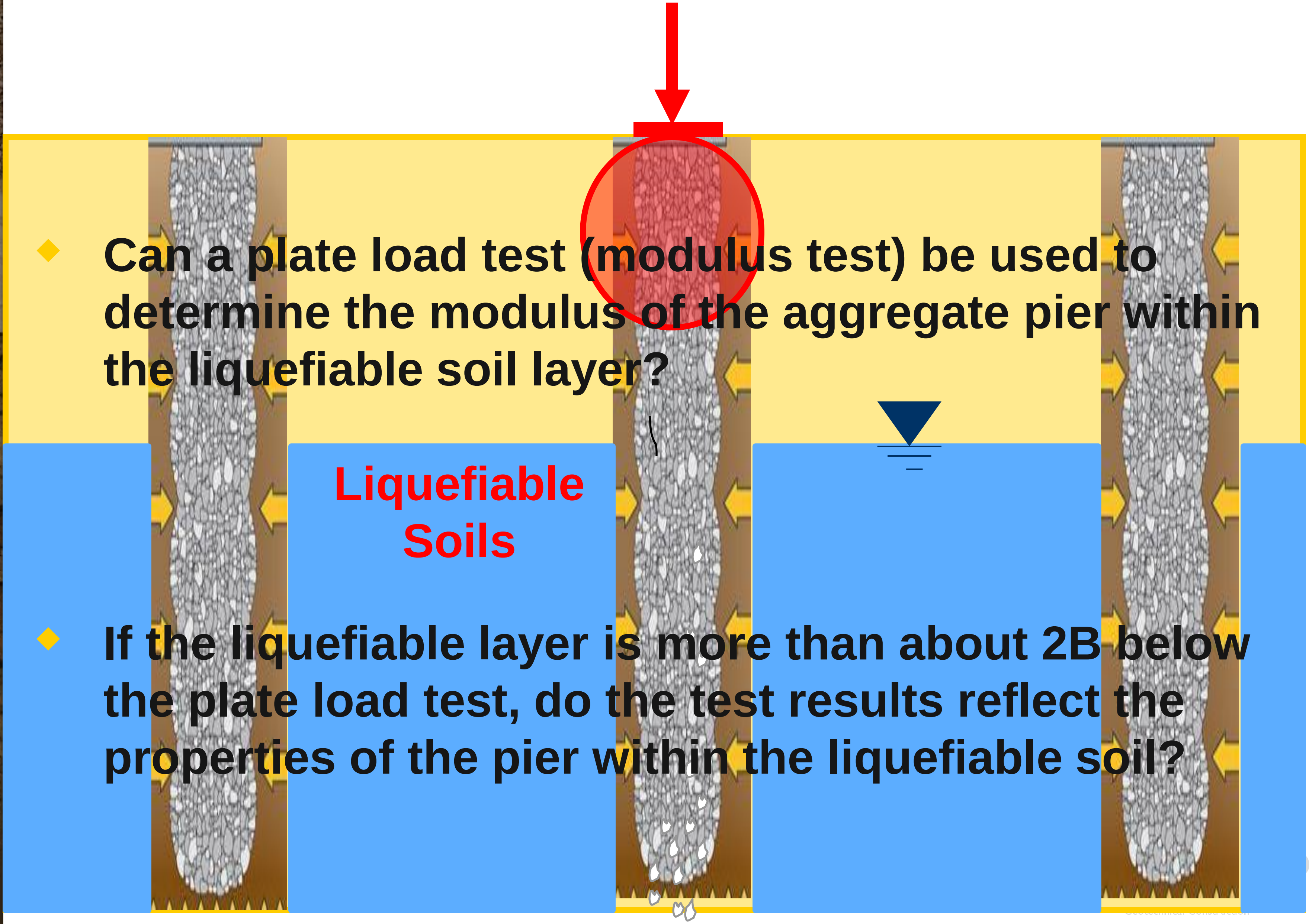

I_c
0
1
2
3
4
5
Depth (ft)
0
5
10
15
20
25
30
35
40
45
50
0.3
Pre CPT 3
CPT 1-2
Adjusted

Plate Load Test to Verify Stiffness?

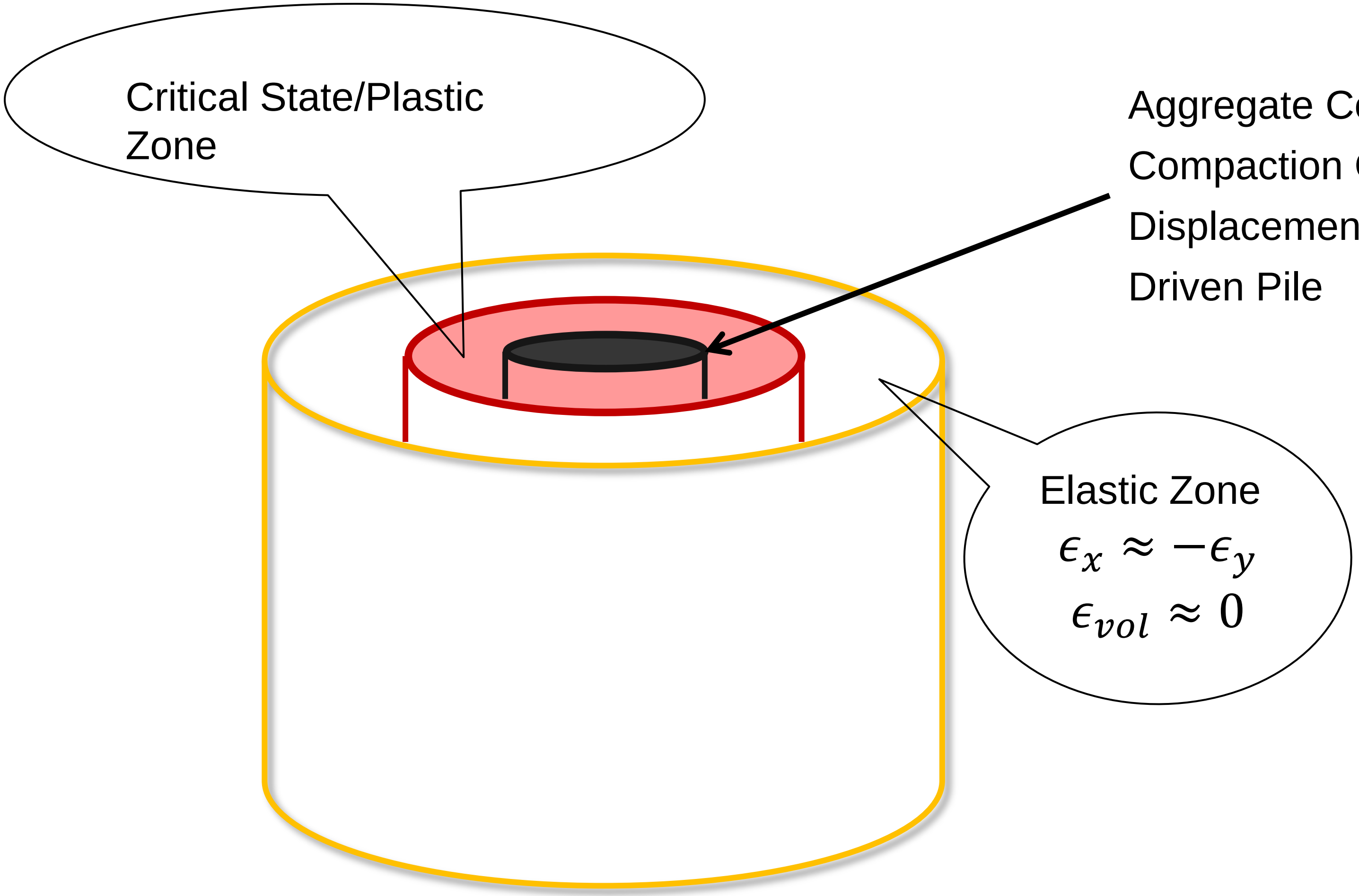


- Can a plate load test (modulus test) be used to determine the modulus of the aggregate pier within the liquefiable soil layer?

- If the liquefiable layer is more than about 2B below the plate load test, do the test results reflect the properties of the pier within the liquefiable soil?

Densification Verification

- Soil Void Reduction ≠ Volume Intake



Critical State/Plastic Zone

Aggregate Column

Compaction Grout

Displacement Pile

Driven Pile

Elastic Zone

$\epsilon_x \approx -\epsilon_y$

$\epsilon_{vol} \approx 0$

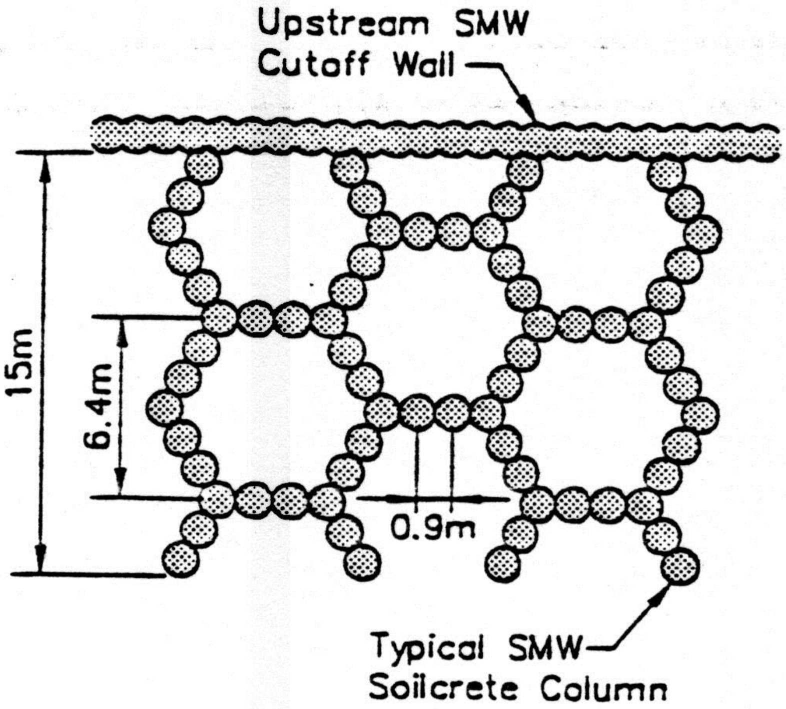
Verification of Liquefaction Mitigation

- Densification Verification
  - SPT
  - CPT
  - Shear Wave Velocity
  - Modulus/Plate Load Test?
  - Void Reduction vs. Volume Intake?
- **Reinforcement**

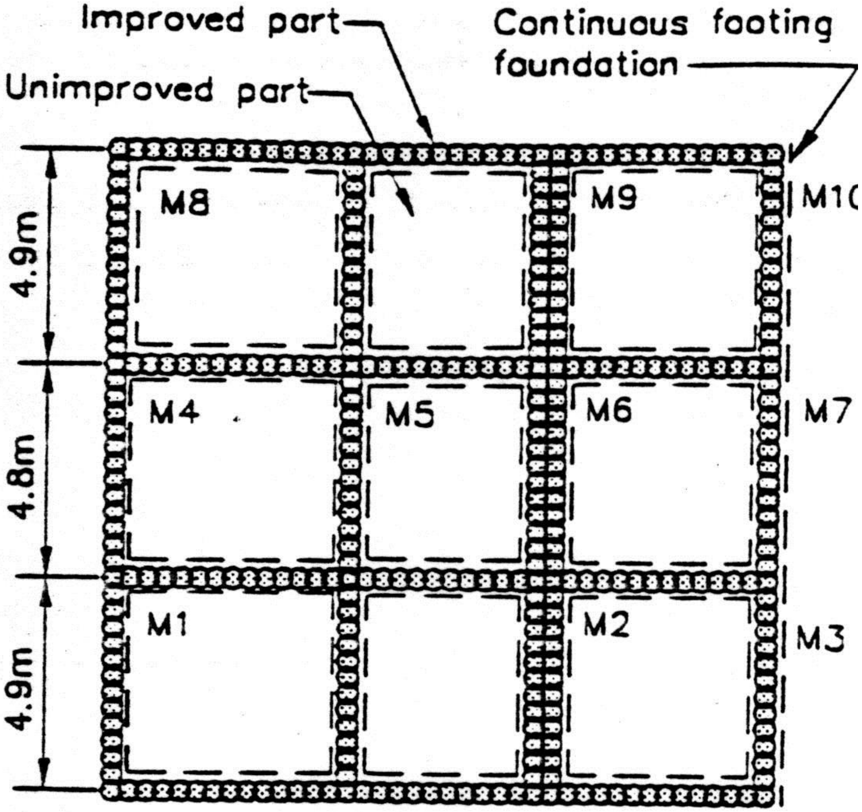
Verification of Reinforcement Effect

- Discrete Columns
    - Aggregate/Sand Columns
    - Soil Mixing/Jet Grouting Columns
    - Auger Displacement Piles
    - Compaction Grouting Columns
    - Rigid Inclusion Columns
- Cellular Structures (grids)
    - Soil Mixing/Jet Grouting Panels

Liquefaction Mitigation by Cells or Blocks



SMW Treatment Pattern,
Jackson Lake Dam Project, WY
(after Pujol–Rius, et. al., 1989)



Improved Soil Foundation for Building
Kagoshima City, Japan
(after Babasaki, 1991)

Failure Modes

- Aggregate does not have tensile strength
- Soilcrete is a brittle material
  - Failure strain <1%
  - Low residual strength
  - Low tensile strength
- Discrete columns may fail in bending
- Cellular configuration resists shear loading

Liquefaction Mitigation by Reinforcement

- Reduce cyclic shear stress applied to liquefiable soil by installing ‘stiffer’ elements within the soil matrix that will attract shear stress.
- Can be used in non-densifiable soils (silts, silty sands).
- Not easily verified by field testing
  - Post-installation CPT or SPT results will not differ from pre-installation.
  - Vertical load testing of elements is not applicable.

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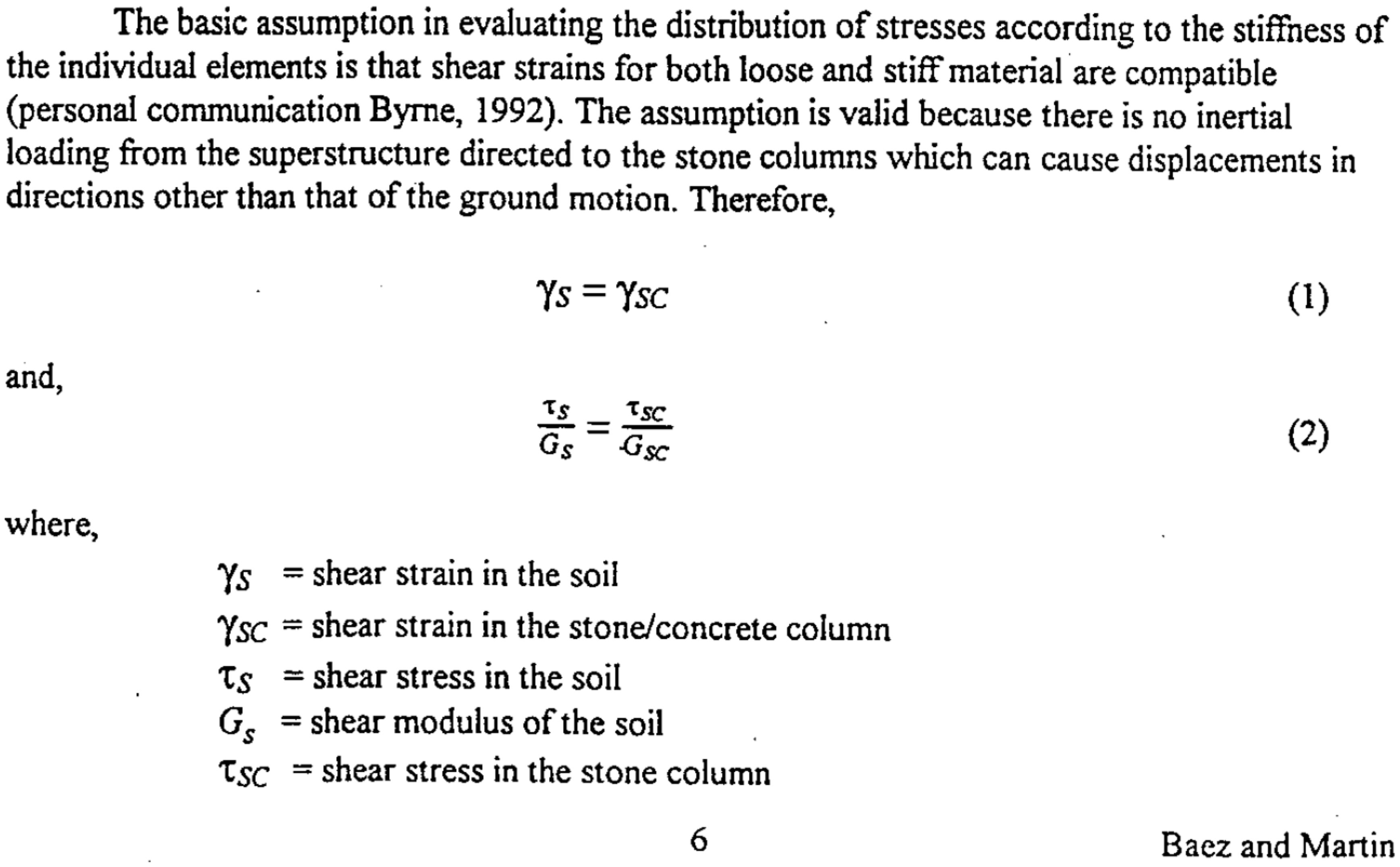
Reinforcement Analysis



The basic assumption in evaluating the distribution of stresses according to the stiffness of the individual elements is that shear strains for both loose and stiff material are compatible (personal communication Byrne, 1992). The assumption is valid because there is no inertial loading from the superstructure directed to the stone columns which can cause displacements in directions other than that of the ground motion. Therefore,

$$\gamma_S = \gamma_{SC} \qquad (1)$$

and,

$$\frac{\tau_S}{G_S} = \frac{\tau_{SC}}{G_{SC}} \qquad (2)$$

where,

γ_S = shear strain in the soil
γ_{SC} = shear strain in the stone/concrete column
τ_S = shear stress in the soil
G_s = shear modulus of the soil
τ_{SC} = shear stress in the stone column

Liquefaction Mitigation - Reinforcement

- Design Methodology
  - Shear stress reduction factor (K_G) (Baez and Martin, 1993):

$$K_G = \frac{1}{1 + ARR\left(\frac{G_{INC}}{G_{Soil}} - 1\right)}$$

- G_{INC}=Inclusion shear modulus
- G_{Soil}=Soil shear modulus
- $ARR = A_{inclusion} / A_{total}$

- Strain compatibility and force equilibrium
- $CSR_{applied\ to\ soil} = K_G * CSR_{earthquake}$

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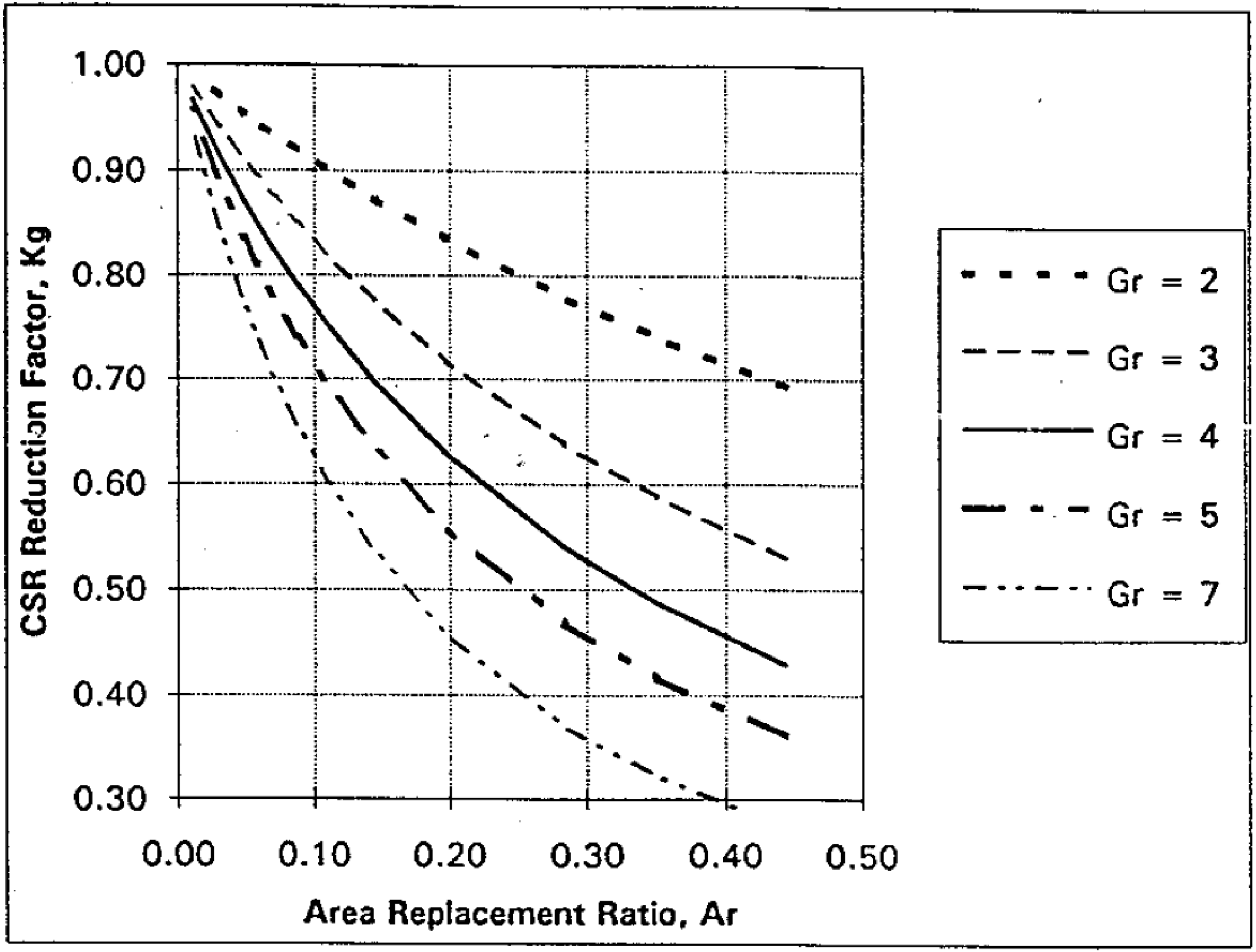
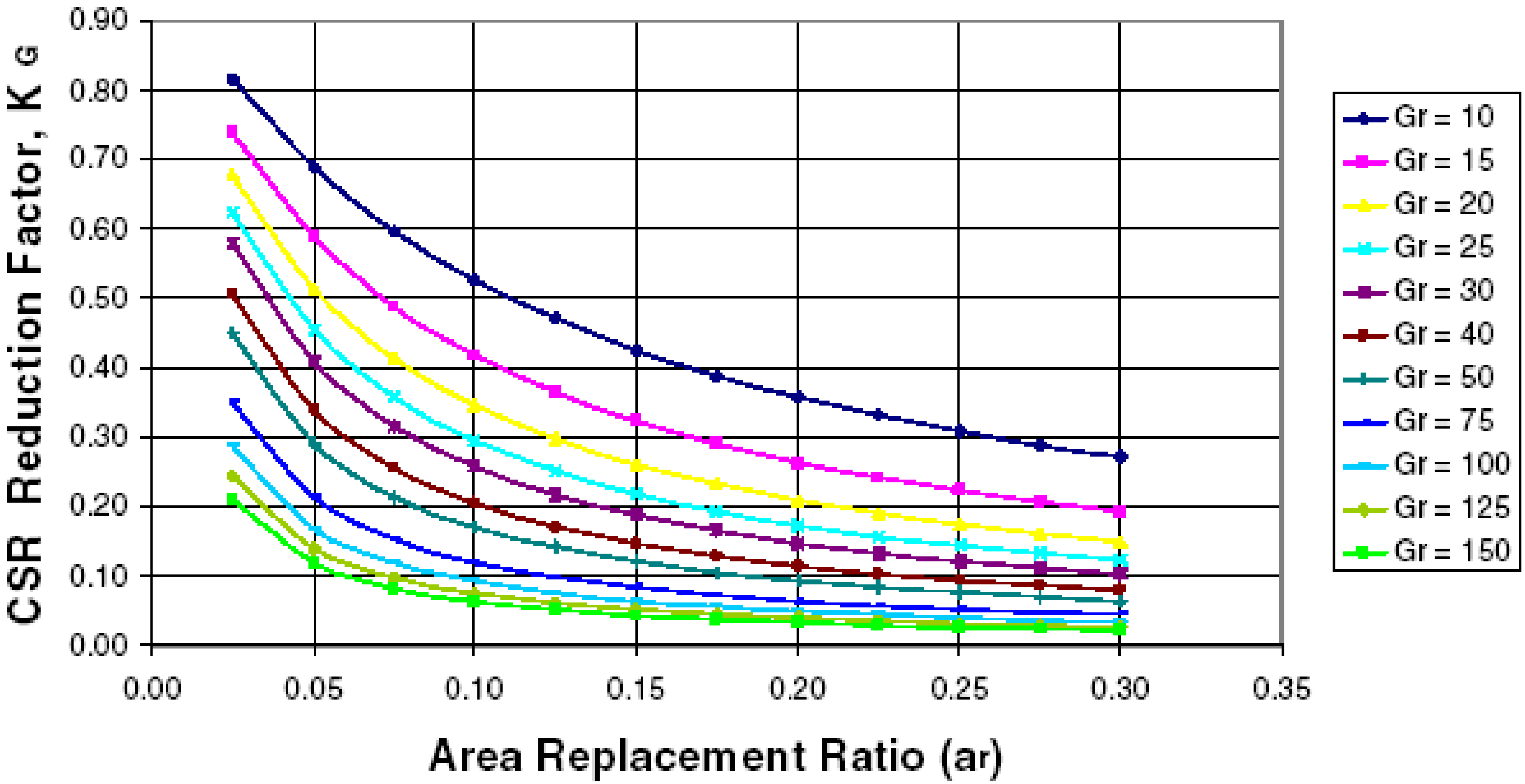


1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
CSR Reduction Factor, Kg
0.00
0.10
0.20
0.30
0.40
0.50
Area Replacement Ratio, Ar
Gr = 2
Gr = 3
Gr = 4
Gr = 5
Gr = 7



The variation of reduction factor $S_G = f(a_r, G_r)$ of Eq. 5. is given in Fig. 2. The G_r range of 10-150 values are utilized in the Fig. 2. It could be seen that area replacement ratio of a_r= 7-10% will be effective to obtain reduction factor of nearly S_G(%) 10-60. Since, the factor of safety is inversely proportional with S_G, a great increase in factor of safety could be obtained based on the specific values of modulus, and area replacement ratios.

Stiffness Values

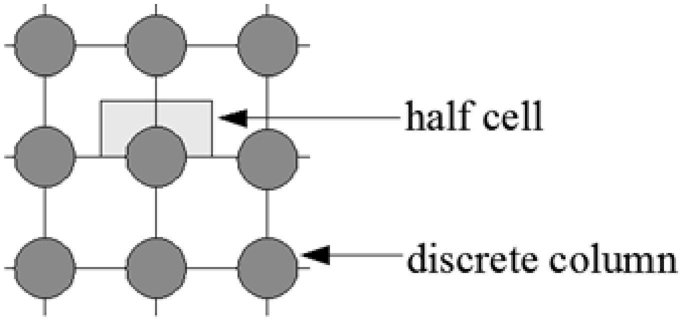
- Can a column be too stiff?
- Strain Compatibility?
- Failure mechanism of column
  - Bending
  - Shear

Shear Reinforcement for Liquefaction Mitigation Research Team

- PI: Dr. Ross Boulanger, UC Davis
  - Thang V. Nguyen (Hayward Baker Inc)
- Dr. Ahmed Elgamal, UCSD
  - Dr. Jinchi Lu
- Dr. Scott A. Ashford, OSU
  - Deepak Rayamajhi
- Dr. Lisheng Shao, Hayward Baker Inc

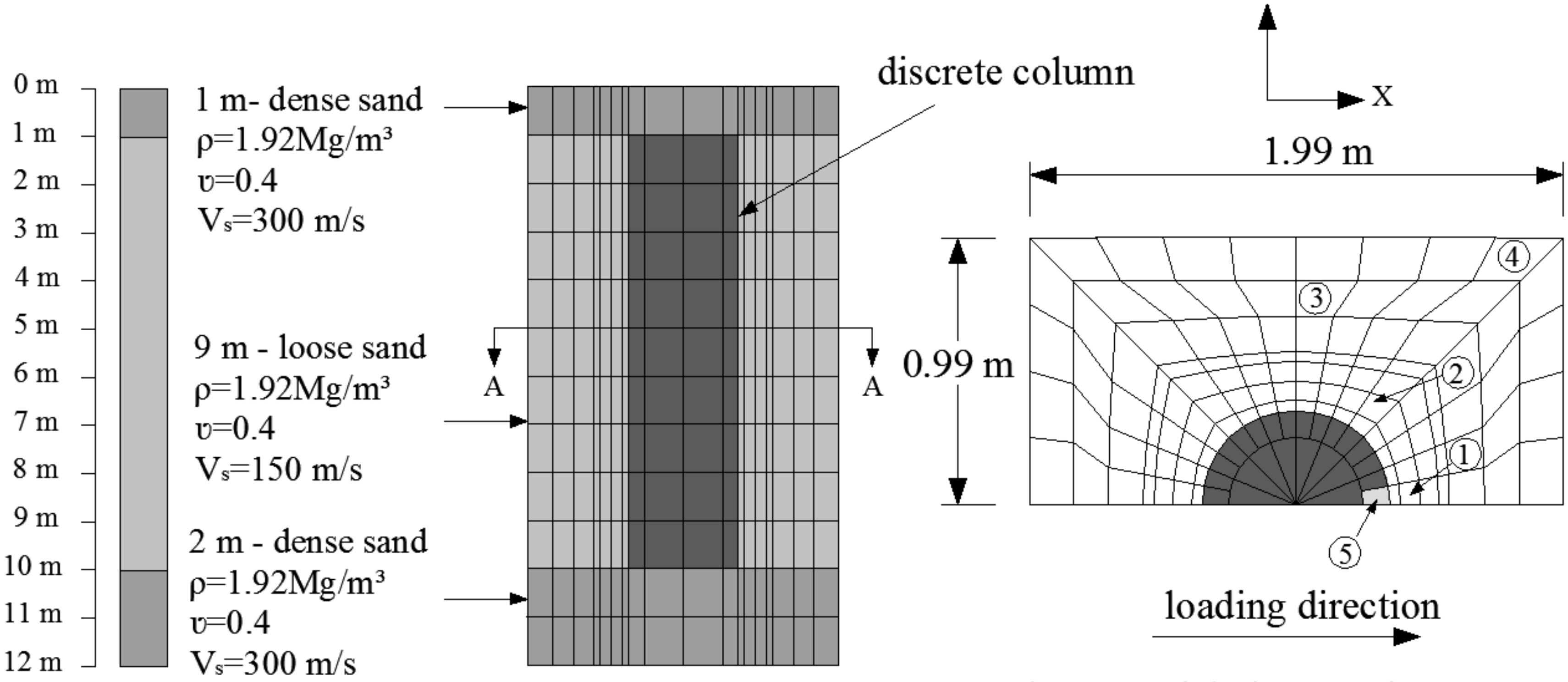
Discrete Columns

3D analyses by Nguyen et al. (2012)
explore a wide range of parameters and loadings
to develop a design relationship.



a) Plan view of discrete column layout

Discrete Columns



b) Soil profile

c) FE model elevation

d) FE model plan -section at A-A with selected points of analyses

Discrete Column

$$CSR_U = \frac{\tau_{s,U}}{\sigma'_v} = 0.65\left(\frac{a_{\max,U}}{g}\right)\left(\frac{\sigma_v}{\sigma'_v}\right)r_{d,U}$$

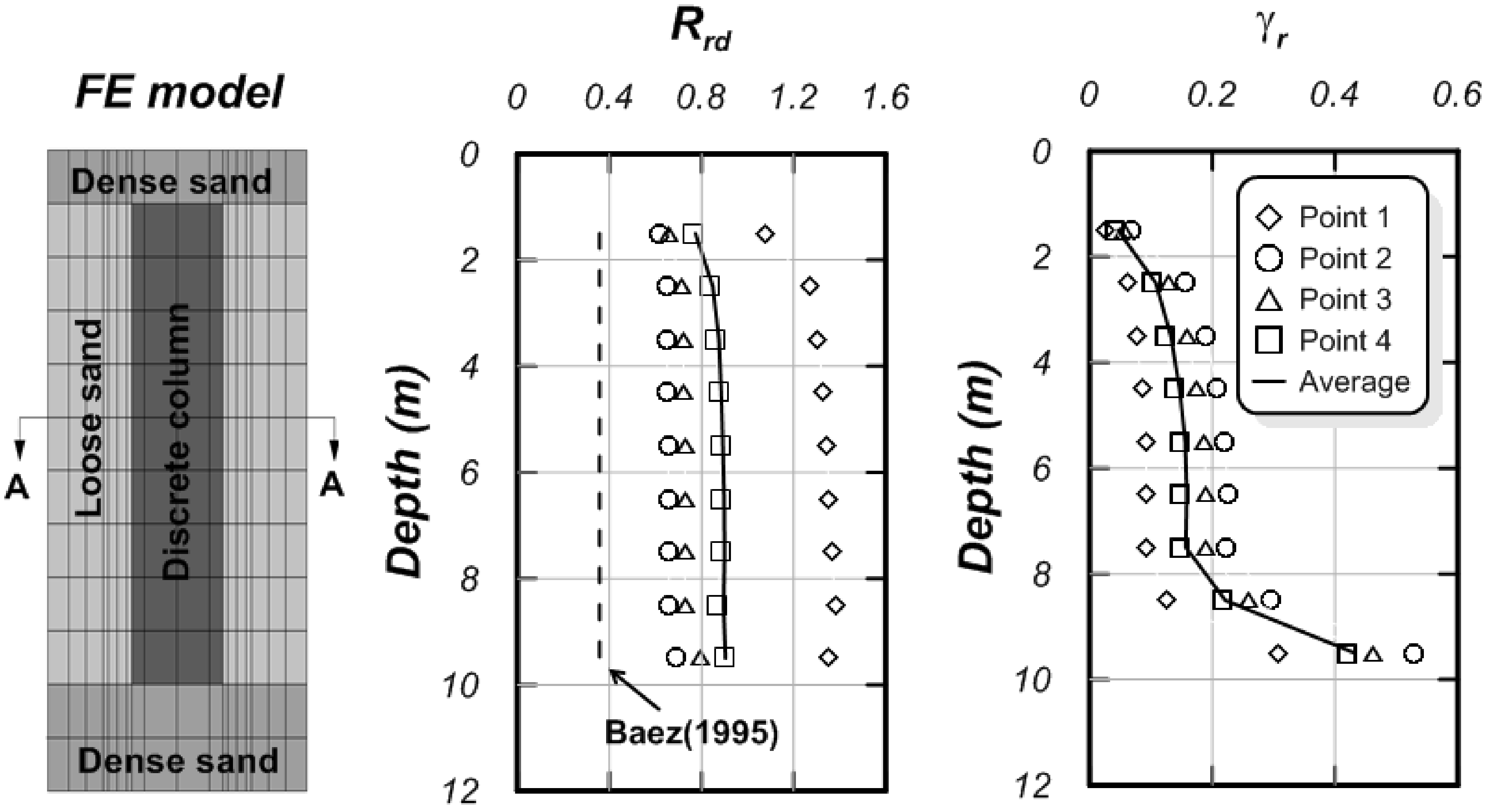
$$CSR_I = \frac{\tau_{s,I}}{\sigma'_v} = 0.65\left(\frac{a_{\max,I}}{g}\right)\left(\frac{\sigma_v}{\sigma'_v}\right)r_{d,I}$$

$$R_{CSR} = \frac{CSR_I}{CSR_U} = \left(\frac{a_{\max,I}}{a_{\max,U}}\right)\left(\frac{r_{d,I}}{r_{d,U}}\right) = R_{\mathrm{a\,max}}R_{rd}$$

R_{amax} - ratio of peak ground accelerations,
R_{rd} - ratio of shear stress reduction coefficient for improved & unimproved case
γ_r - ratio of shear strains in the column to shear strains in the surrounding soil

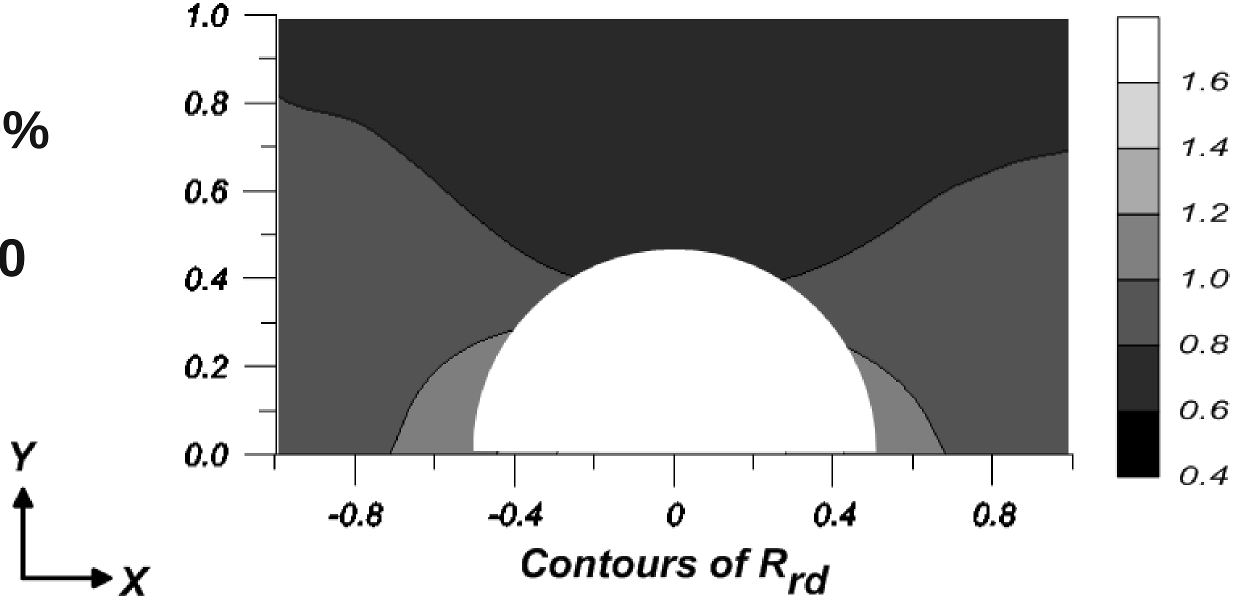
Pseudo-static loading

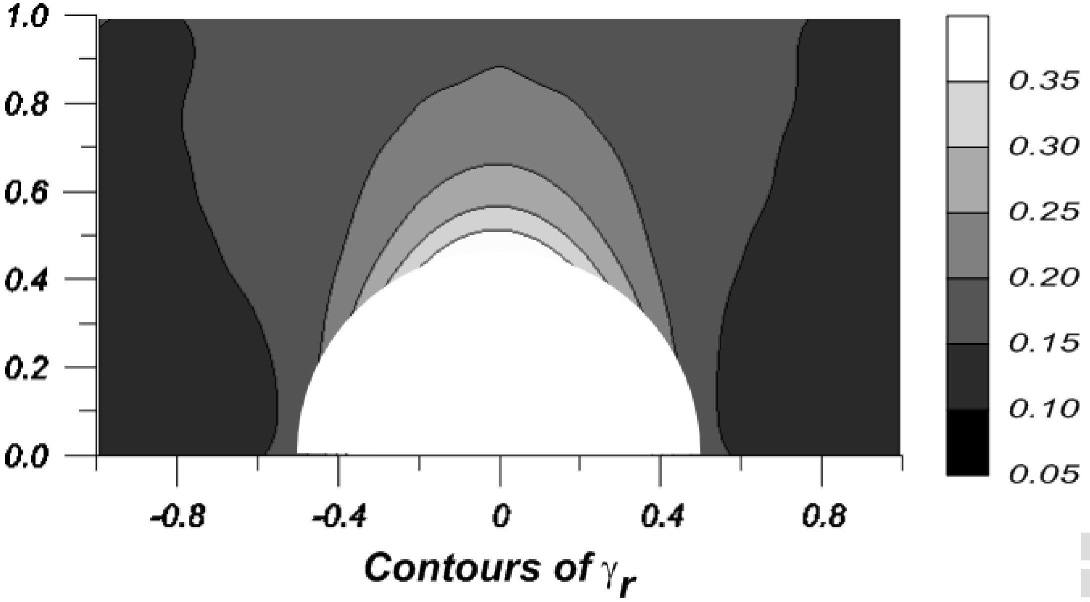
A_r=20% and G_r=10



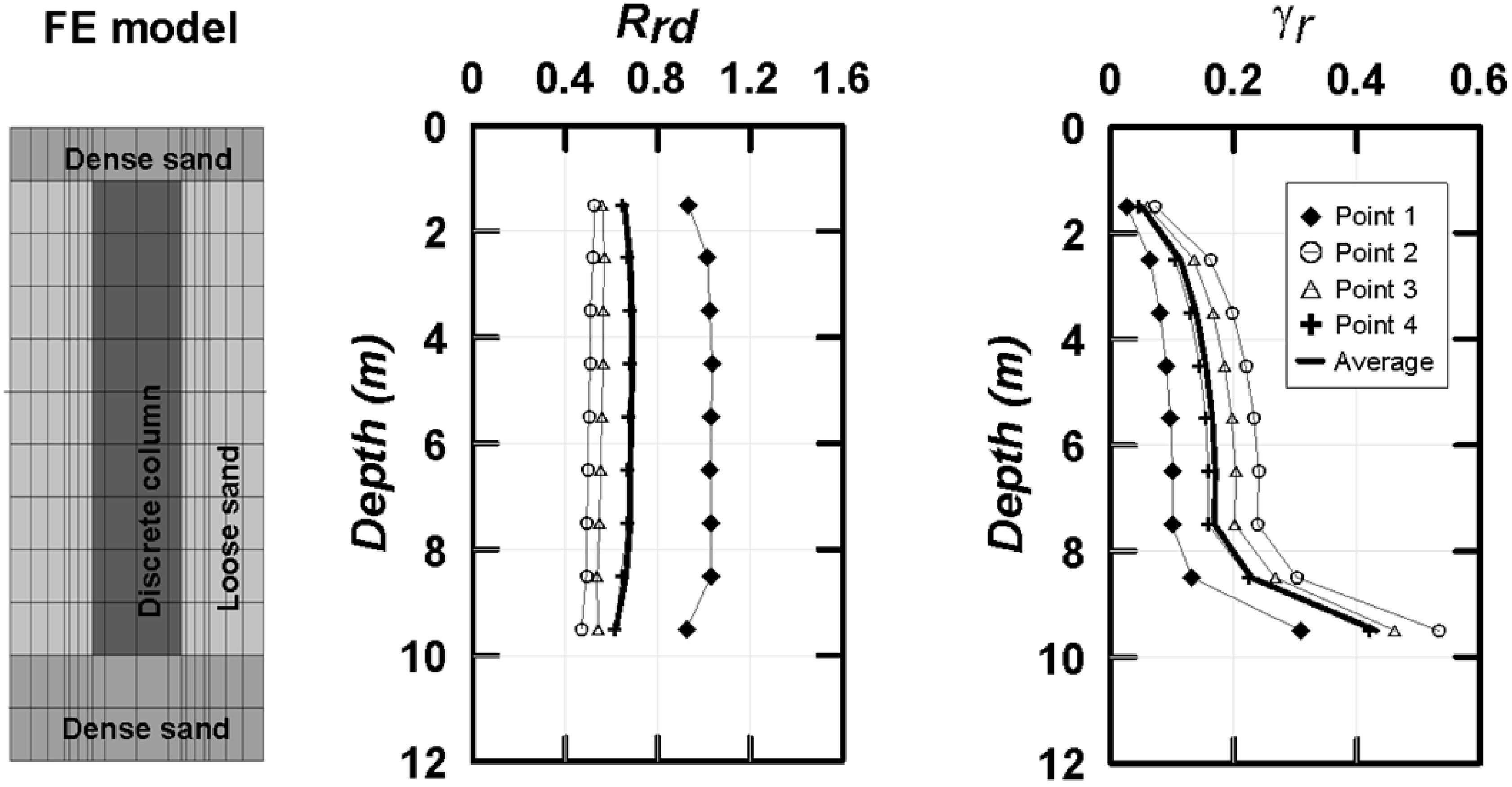
Pseudo-static loading

A_r = 20%
and
G_r = 10





Spatial distribution R_{rd} and γ_r from earthquake time history analysis with A_r=20% and G_r=10

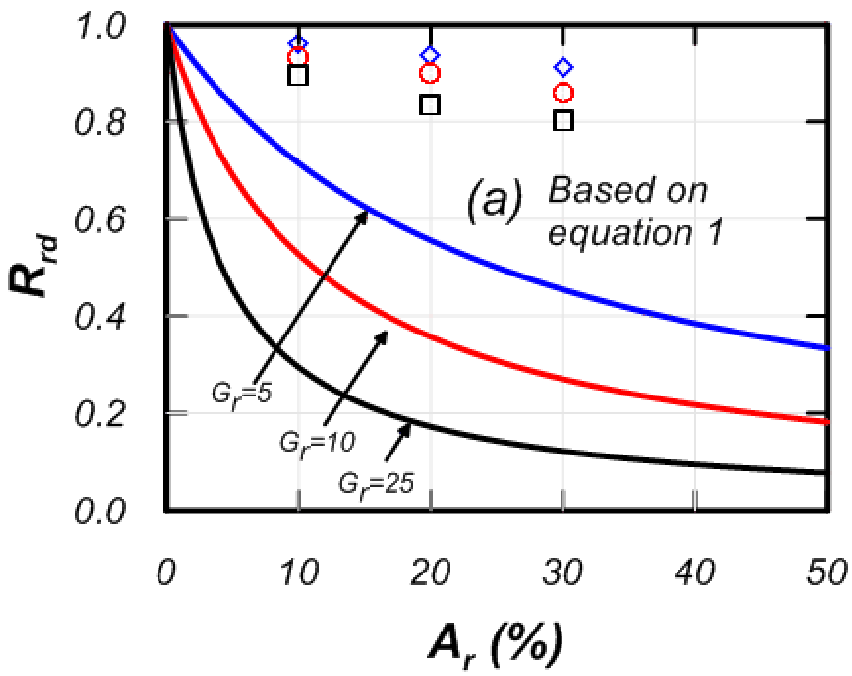


R_{rd} includes adjustment factors for the effects of discrete column flexure and shear strain incompatibility

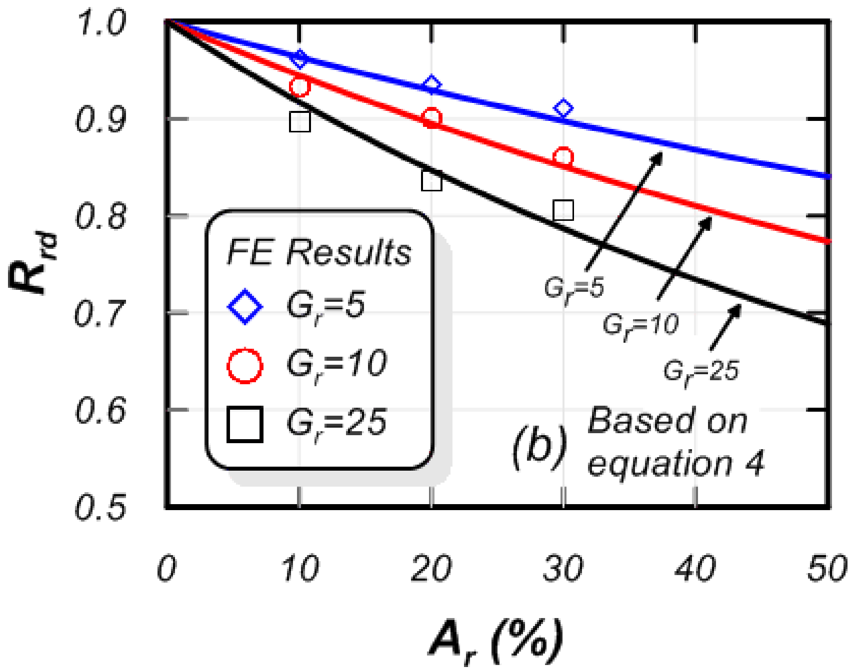
$$R_{rd} = \frac{1}{G_r\left[A_r\gamma_r C_G + \frac{1}{G_r}\left(1 - A_r\right)\right]}$$

- C_G - equivalent shear factor of the discrete column
  C_G = 1.0 for circular discrete columns
- γ_r - is dependent on G_r and independent of A_r.
- K_G - from Baez (1995), is equivalent to $R_{CSR} = (R_{rd})(R_{amax})$
  pseudo-static analyses, $R_{amax} = 1$ and $R_{CSR} = R_{rd}$

Comparison of R_{rd}



(a) based on strain compatibility



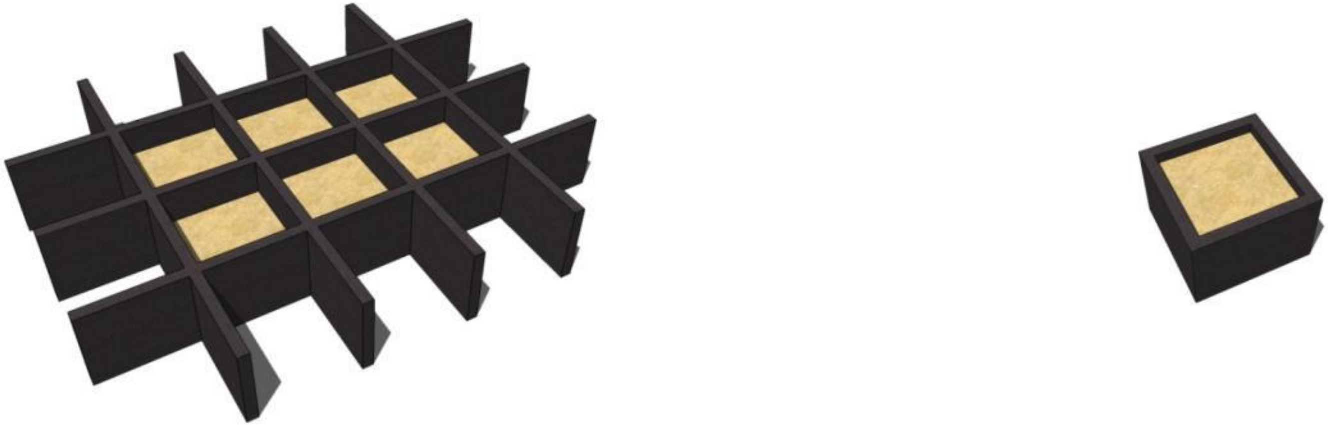
(b) based on proposed relationships

D. Rayamajhi, T.V. Nguyen, S. A. Ashford, R.W. Boulanger, J. Lu, A. Elgamal, and L. Shao. (2012). "Effect of discrete columns on shear stress distribution in liquefiable soil." *Geo-Congress 2012: State of the Art and Practice in Geotechnical Engineering*

Conclusions – Discrete Columns

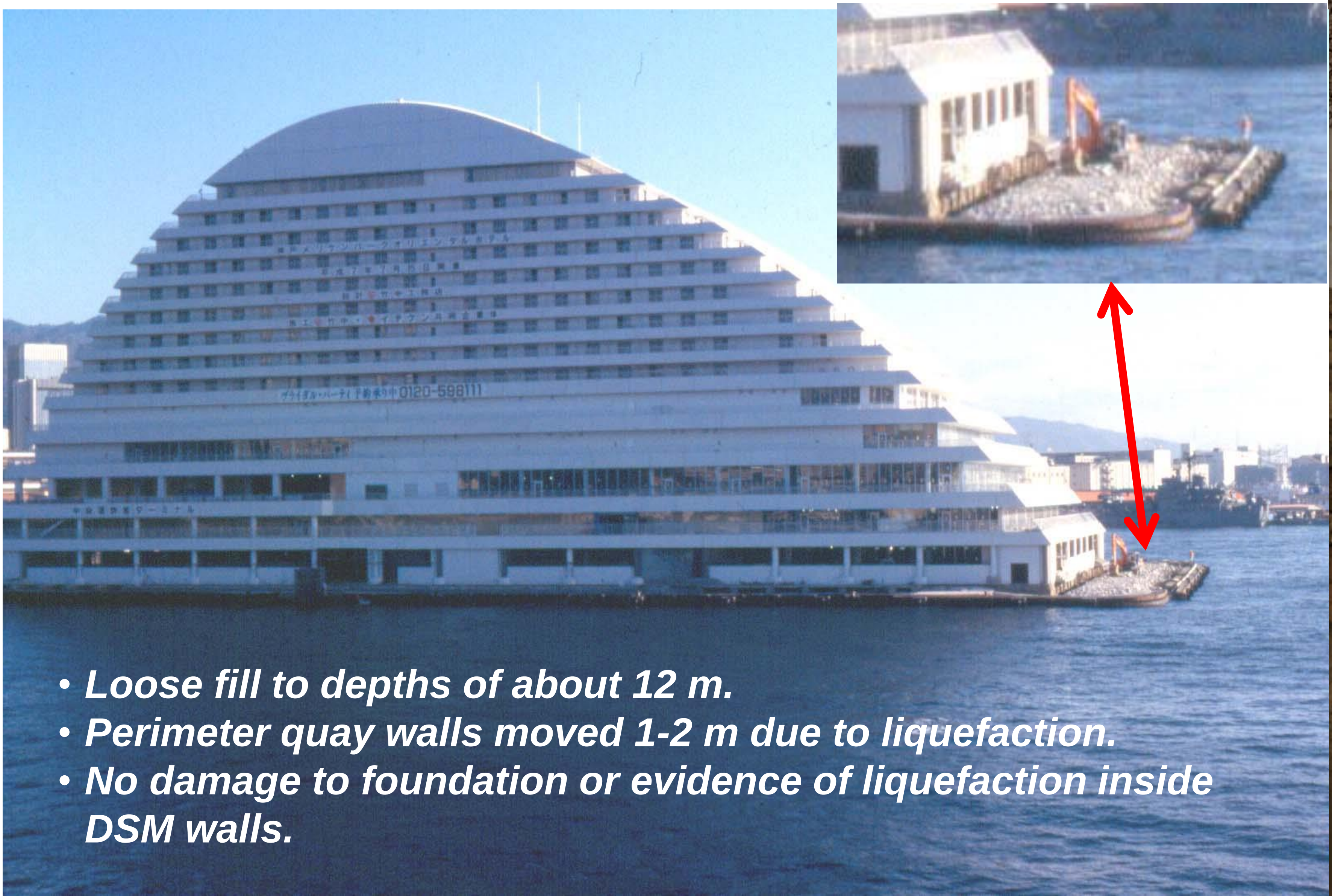
- Current (former?) design practice assumes that
  - discrete columns deforming in pure shear
  - shear strains are compatible between columns & soil
- 3D FEM analyses
  - discrete columns deformed in both flexure & shear
  - flexural & rotational deformations greatly diminished their ability to reduce dynamic shear stresses in the surrounding soils.
- Current design methods overestimate the reduction in dynamic shear stresses in the soil
- Revised design equation
  - accounts for column flexure & difference in shear strains between column & surrounding soil
  - more reasonable estimates of the shear stress reduction provided by discrete circular columns.

Linear Elastic Analyses of Cemented Soil Grids using OpenSees Platform

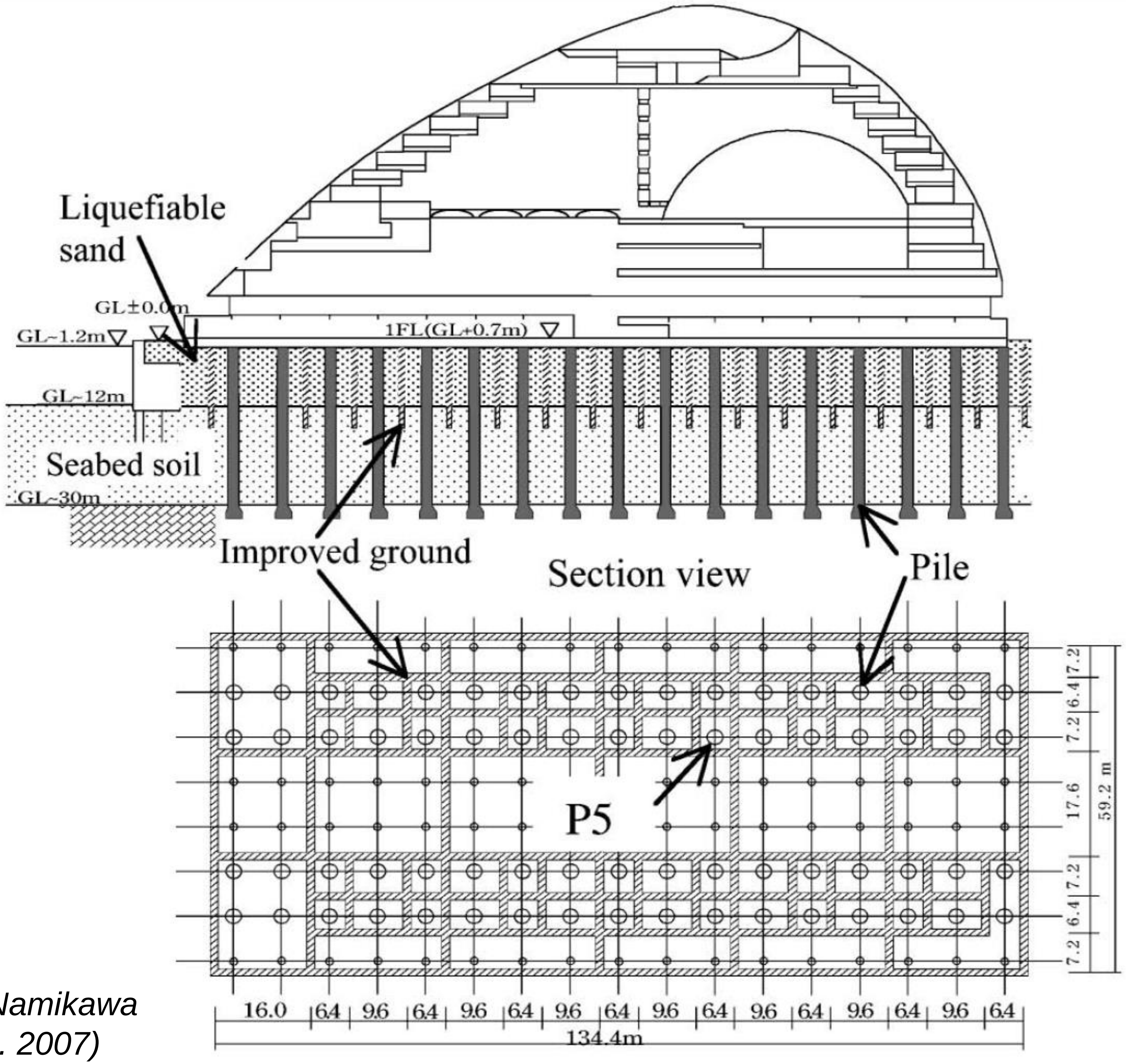


Boulanger

Oriental Hotel in Kobe, 1995

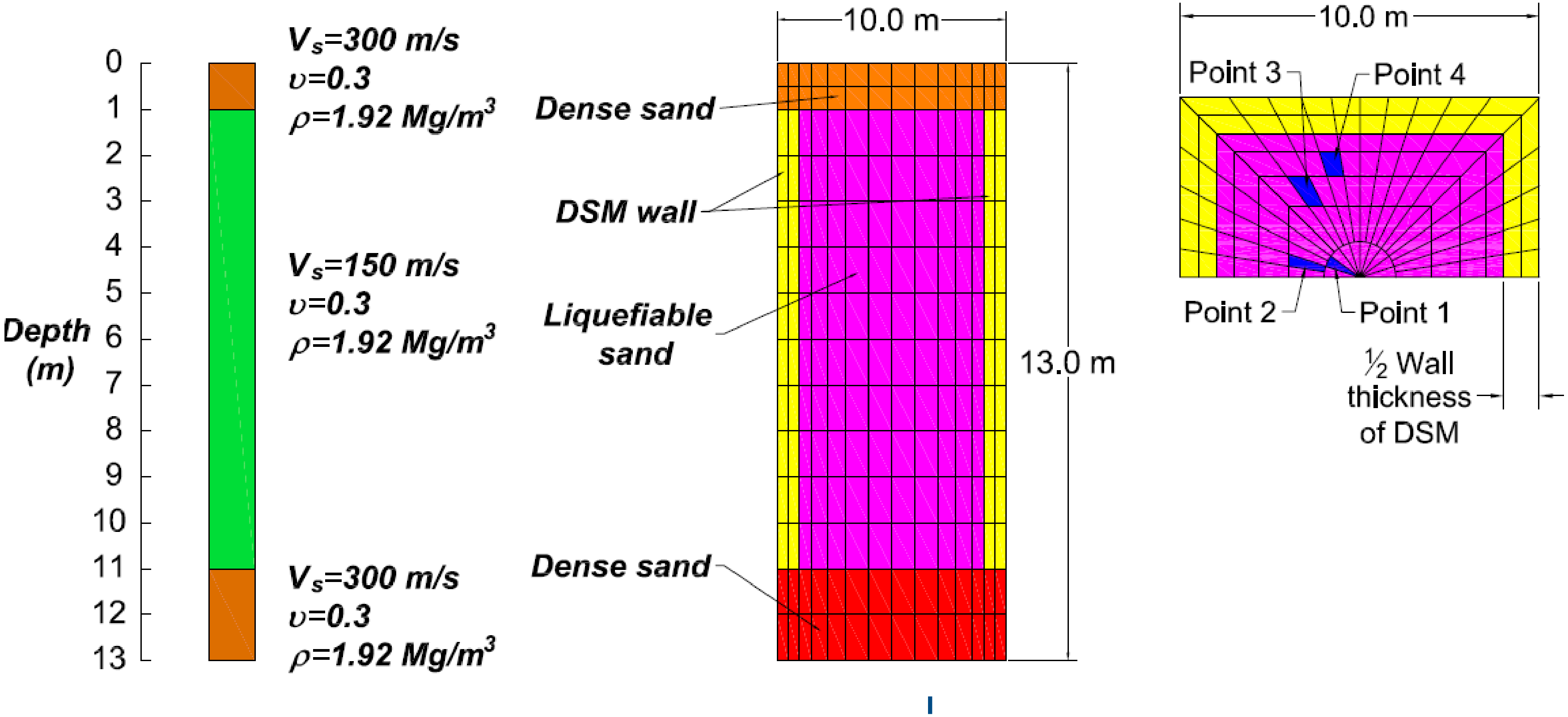


- *Loose fill to depths of about 12 m.*
- *Perimeter quay walls moved 1-2 m due to liquefaction.*
- *No damage to foundation or evidence of liquefaction inside DSM walls.*



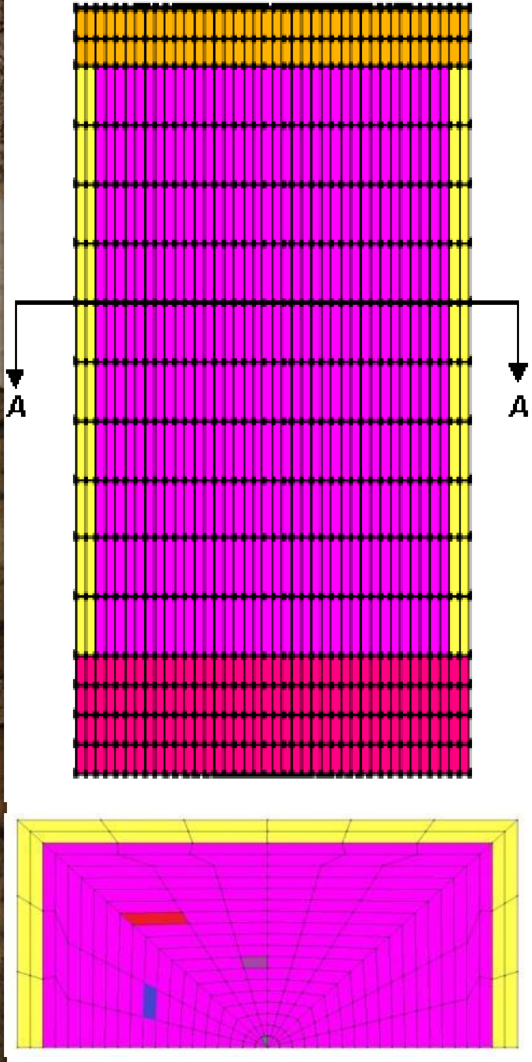
(from Namikawa et al. 2007)

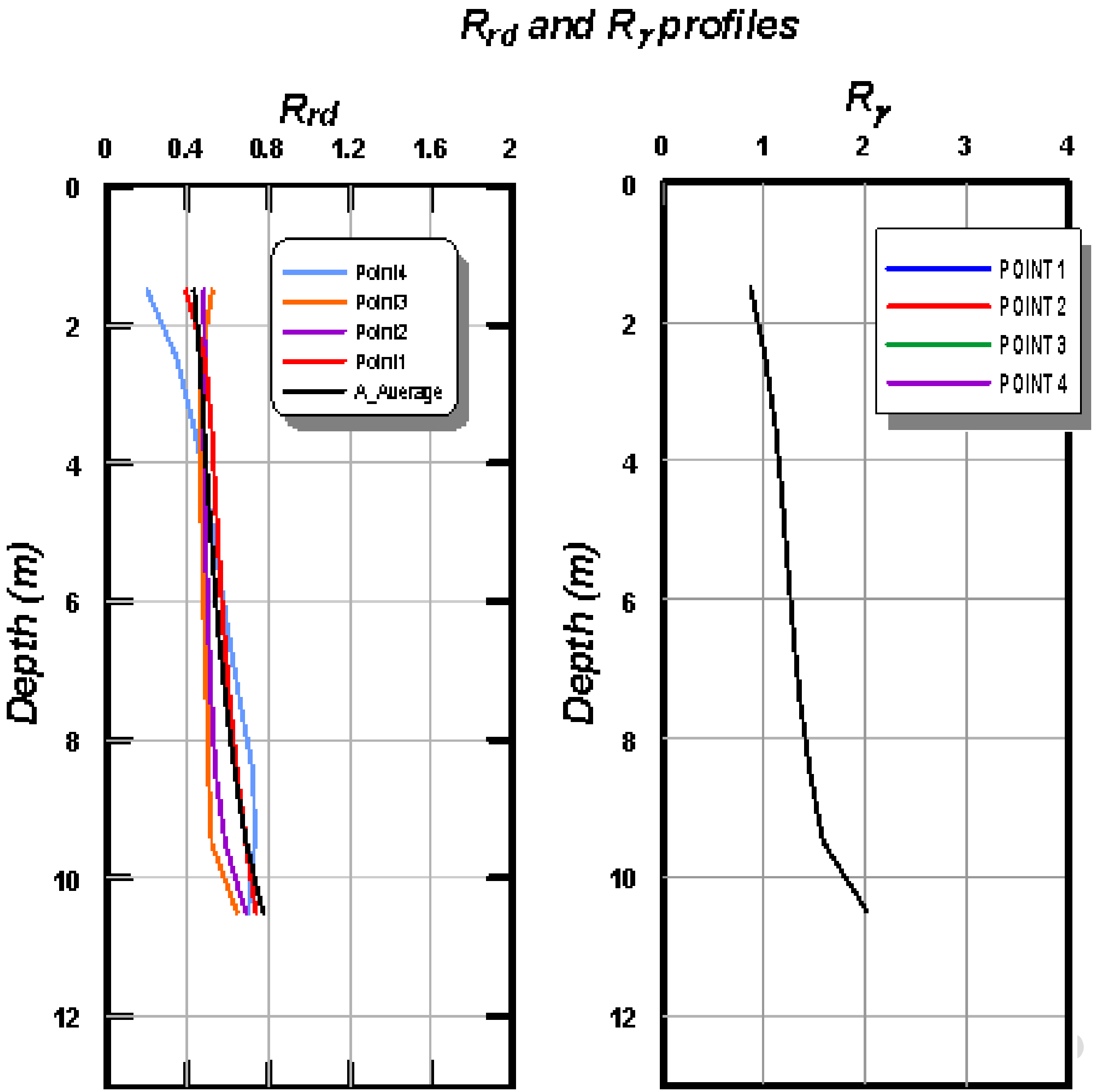
Linear Elastic FE Model - DSM



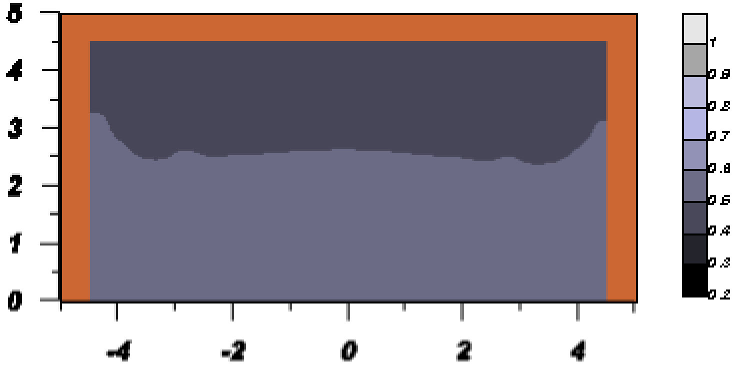
Half DSM Unit Cell Mesh in OpenSeesPL

Standard DSM Half Unit Cell Under Earthquake

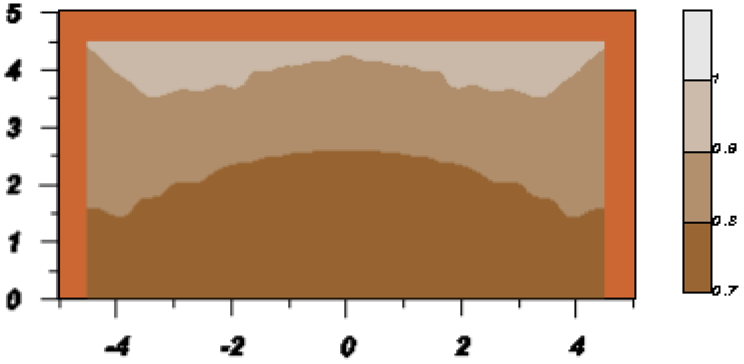




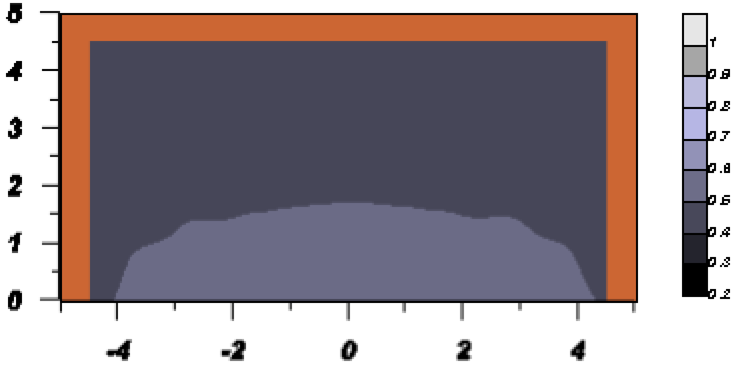
Spatial Variation



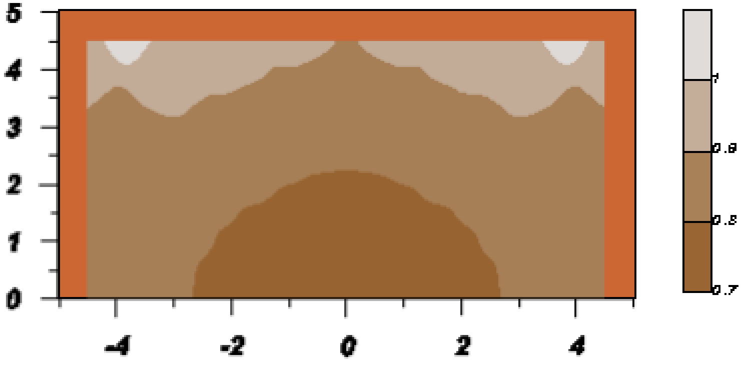
R_{rd} contour (cross section A-A)



γ_r contour (cross section A-A)

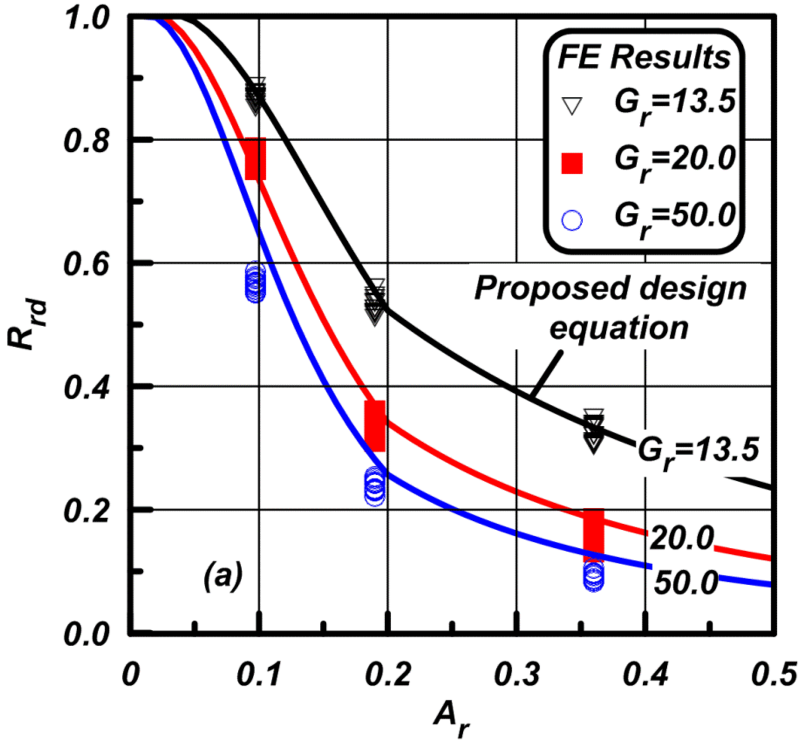


R_{rd} contour (cross section A-A)

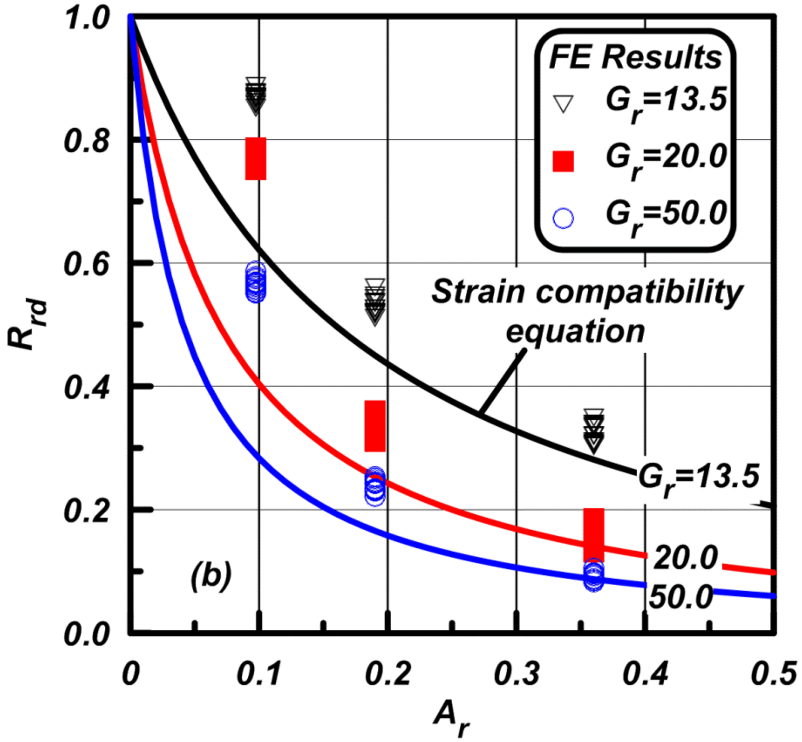


γ_r contour (cross section A-A)

Proposed Design Relationships



Proposed Equation



Strain Compatibility Equation

Scheduled for publication:

T.V. Nguyen, D. Rayamajhi, R.W. Boulanger, S.A. Ashford, J. Lu, A. Elgamal, and L. Shao, “Design of DSM Grids for Liquefaction Mitigation.” *Journal of Geotechnical and Geoenvironmental Engineering*, November, 2013

Conclusion – Soilcrete Grid

- DSM grids affect both:
    - seismic site response (e.g., a_{max})
    - seismic shear stress distributions (e.g. R_{rd})
- Effect of DSM grids on seismic site response can be significant and may require site-specific FEM analyses
- The reduction in seismic shear stresses by DSM grids can be over-estimated by current design methods that assume shear strain compatibility.
- A modified equation is available for estimating seismic shear stress reduction effects
- The top 2m-3m of DSM wall could potentially be the critical wall section in term of tension development.

Primary Lessons Learned from Recent Research on Reinforcement for Liquefaction Risk Mitigation

- Discrete columns are significantly less effective than predicted by methods based on the shear strain compatibility assumption.

- Soilcrete elements installed to create a grid or cellular pattern of shearwalls can result in a significant reduction in the cyclic shear stresses experienced by the soil during an earthquake.

References and Additional Resources

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Comments or Questions?

Al Sehn, Ph.D., P.E.
Hayward Baker Inc

ALSehn@HaywardBaker.com