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Shear reinforcement effects for liquefaction mitigation

UCDAVIS
UNIVERSITY OF CALIFORNIA

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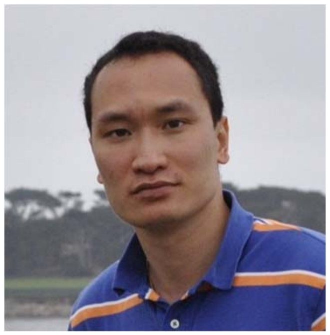
UCD – OSU – UCSD – HB collaboration



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Hayward Baker

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The motivation

- ***Several ground improvement methods for liquefaction mitigation reinforce the ground, thereby reducing the cyclic stress ratios (CSRs) induced in the soil.***

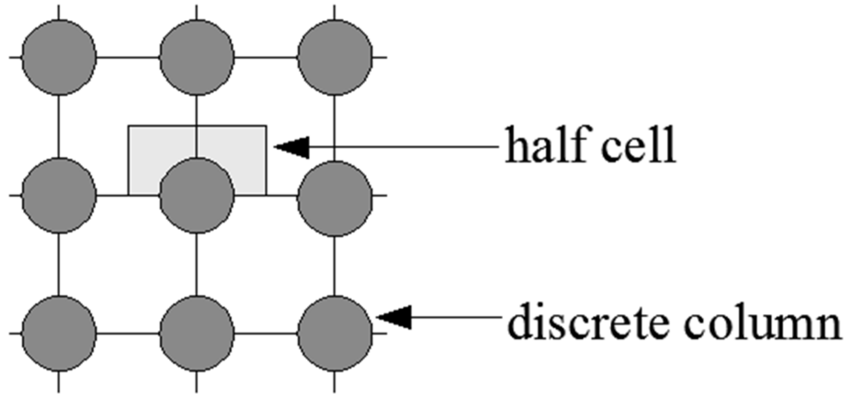
- ***The assumption of shear strain compatibility for stone columns (Baez and Martin 1993) has been widely used for various discrete column systems, although results of numerical studies have raised questions about the validity of this assumption.***

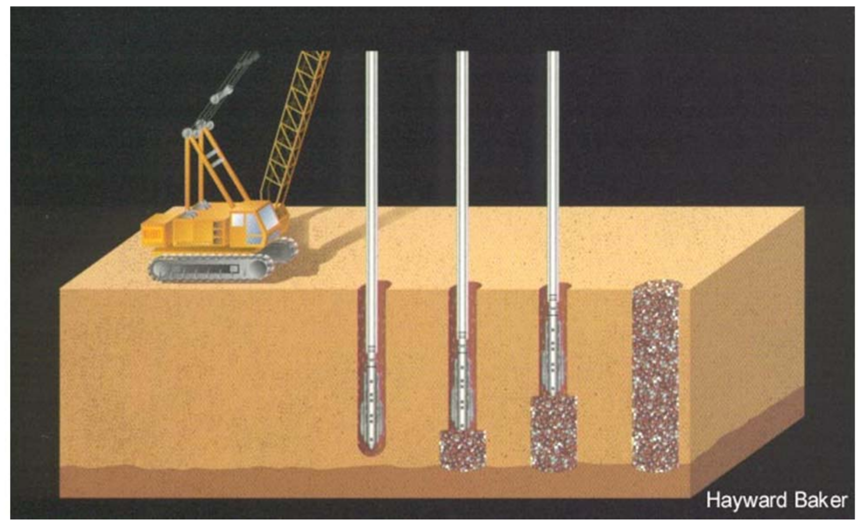
- ***Our goals were to:***
    - ***Advance OpenSeesPL capabilities for site specific analyses of: (i) discrete columns, and (ii) shear grid systems.***
    - ***Use OpenSeesPL to evaluate the shear strain compatibility assumption for a broad range of conditions: (i) first for elastic systems, and (ii) second for nonlinear systems.***
    - ***Proposed revised design relationships for idealized simple cases, as may be appropriate.***

Discrete columns: Stone & soil-cement

Discrete columns

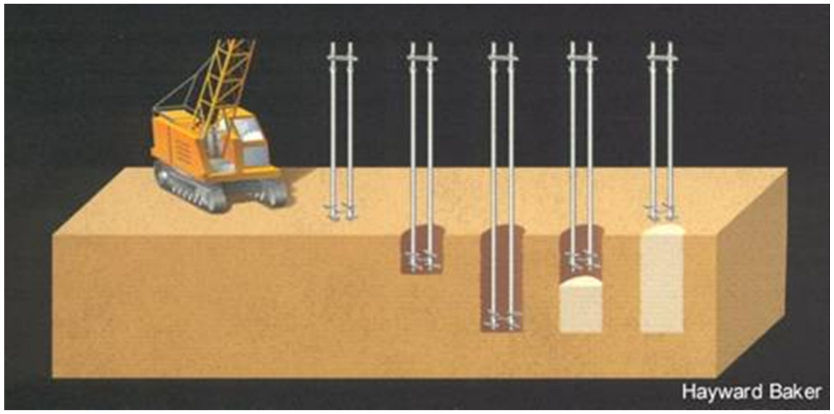
Jet grout columns
(John Dillon 2009)



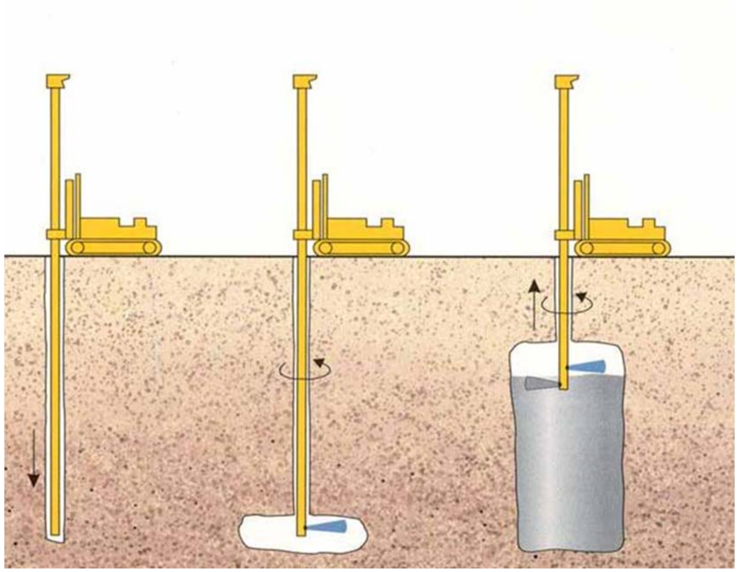


Stone columns

Construction methods

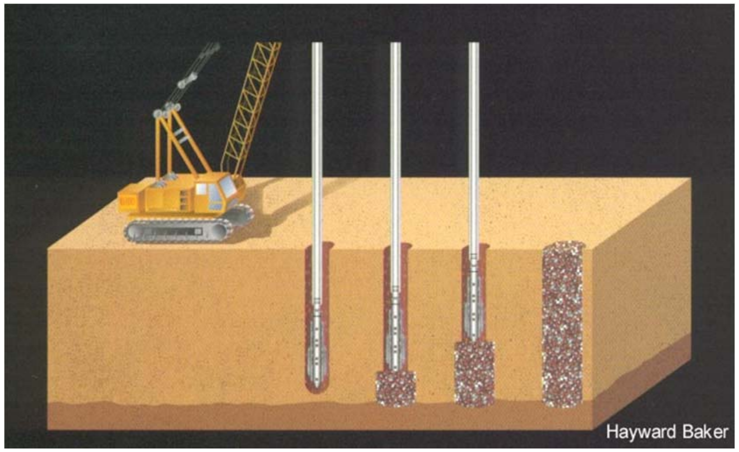


Deep soil mixing



Jet grouting

Rammed aggregate piers



Stone columns

Mechanisms of improvement

- ***Stone columns improve liquefiable deposits by:***
  - ***densification***
  - ***increase in lateral stress (K_o)***
  - ***reinforcement***
  - ***drainage (during & after shaking)***

- ***Soil cement columns primarily provide reinforcement.***

- ***Reinforcement:***
  - ***Reduces earthquake-induced shear strains in the treatment zone, thereby limiting pore pressure generation.***
  - ***Increases the composite strength of the improved ground even if the enclosed soils liquefy, and thus can reduce settlement of overlying structures and reduce lateral ground deformations.***

- ***Soils with high FC may be difficult to densify or drain, such that reinforcement effects become more important.***

Case histories & physical models

- ***Stone or sand compaction columns have repeatedly been found to be effective in remediating against liquefaction during earthquakes: Mitchell & Wentz (1991), Mitchell et al. (1995), Boulanger et al. (1997), Hausler & Sitar (2000)***

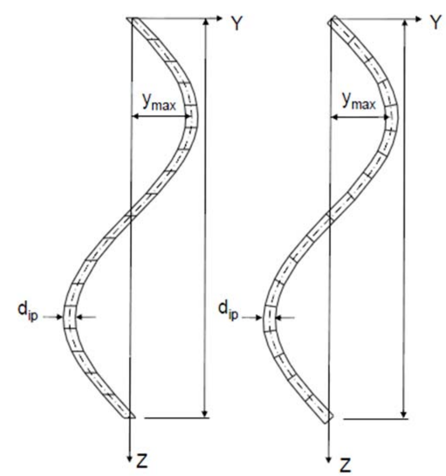
- ***Case histories of soil cement columns are rare. The Carrefour Shopping Center (Martin et al. 2003) with jet grout columns in soft silty clays was undamaged while untreated areas in the same complex had settlements of up to 10 cm.***

- ***Centrifuge tests by Adalier et al. (2003) showed "stone" columns reduced settlements of shallow foundations over nonplastic silts by ≈ 50%.***

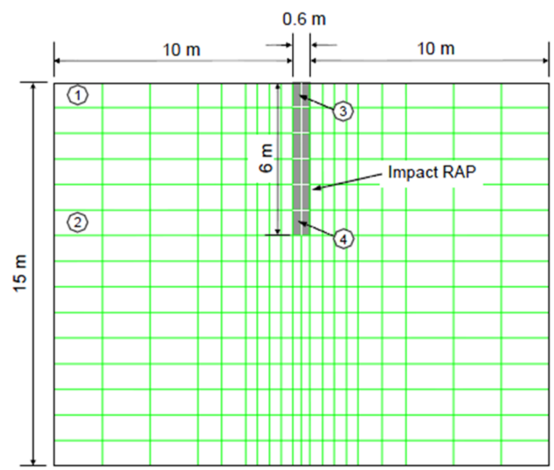
- ***For case histories of stone or soil-cement columns, it is generally not possible to directly discern the contribution or roles of the different improvement mechanisms.***

Numerical analyses

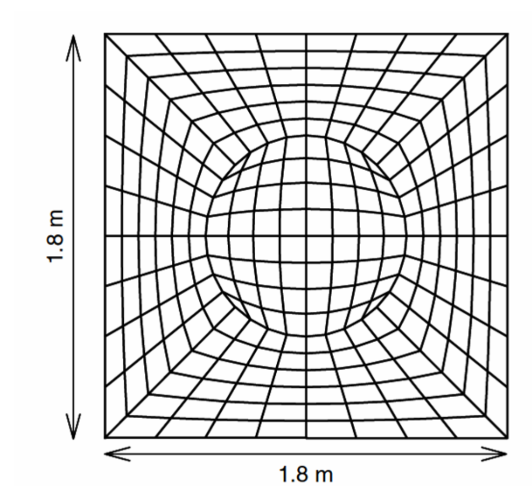
- **_Column flexure has been shown to significantly reduce their effectiveness for reducing shear stresses on the enclosed soils:_**
  - **_Equivalent beam analyses by Goughnour & Pestana (1998),_**
  - **_2D plane-strain FE analyses by Green et al. (2008), and_**
  - **_3D FE analyses by Olgun & Martin (2008)._**



Goughnour & Pestana (1998)



Green et al. (2008)

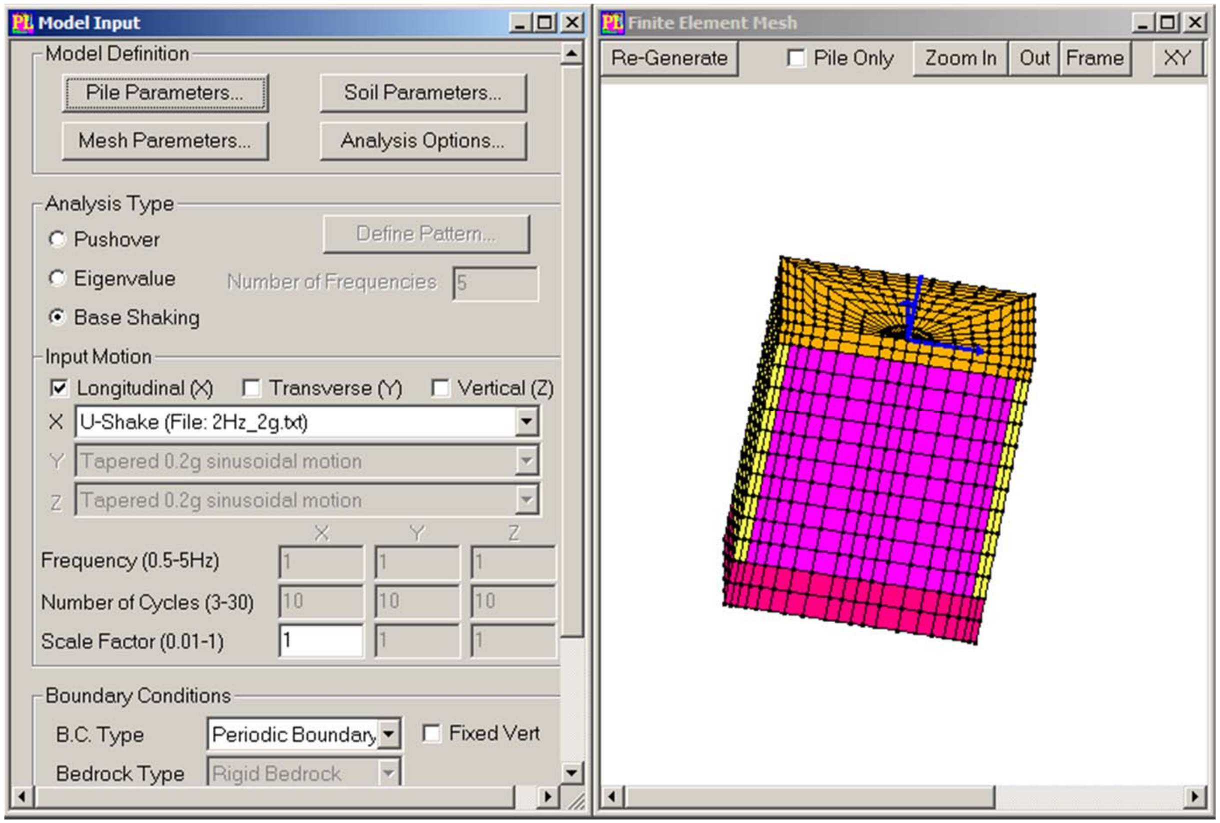


Olgun & Martin (2008)

Discrete columns:
Estimating the shear stress reduction

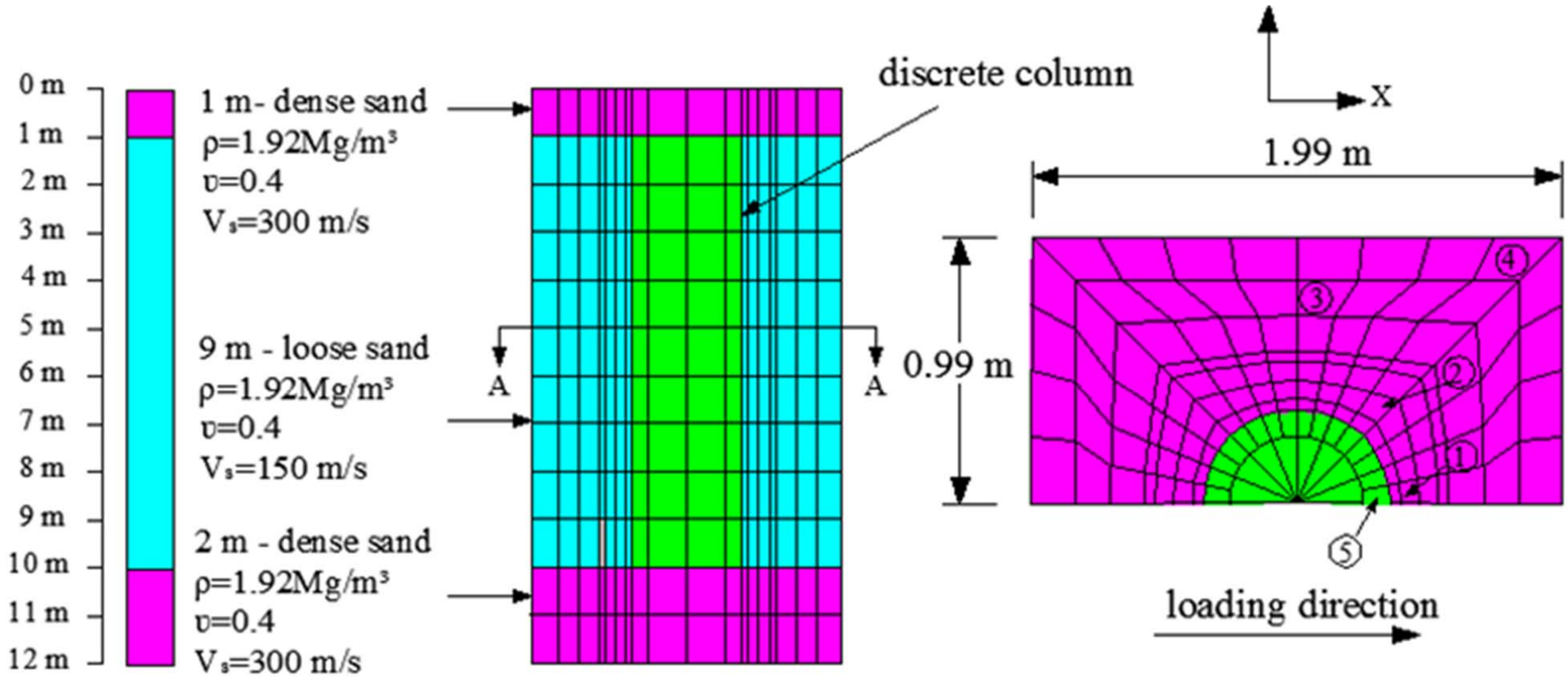
FE model

- ***OpenSeesPL platform:***
  - ***User interface that builds on PEER's OpenSees platform; e.g., Elgamal, Lu, and Forcellini, D. (2009)***
  - ***http://cyclic.ucsd.edu/openseespl***



FE models – present study

- ***3D analyses of unit cell (Rayamajhi et al. 2012) to explore a wider range of parameters to develop a design relationship.***



b) Soil profile

c) FE model elevation

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

Framework for presenting results

- ***Follows Simplified Procedure (Seed & Idriss 1971) for computing the <u>soil's</u> CSR for the unimproved (U) and improved (I) cases:***

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

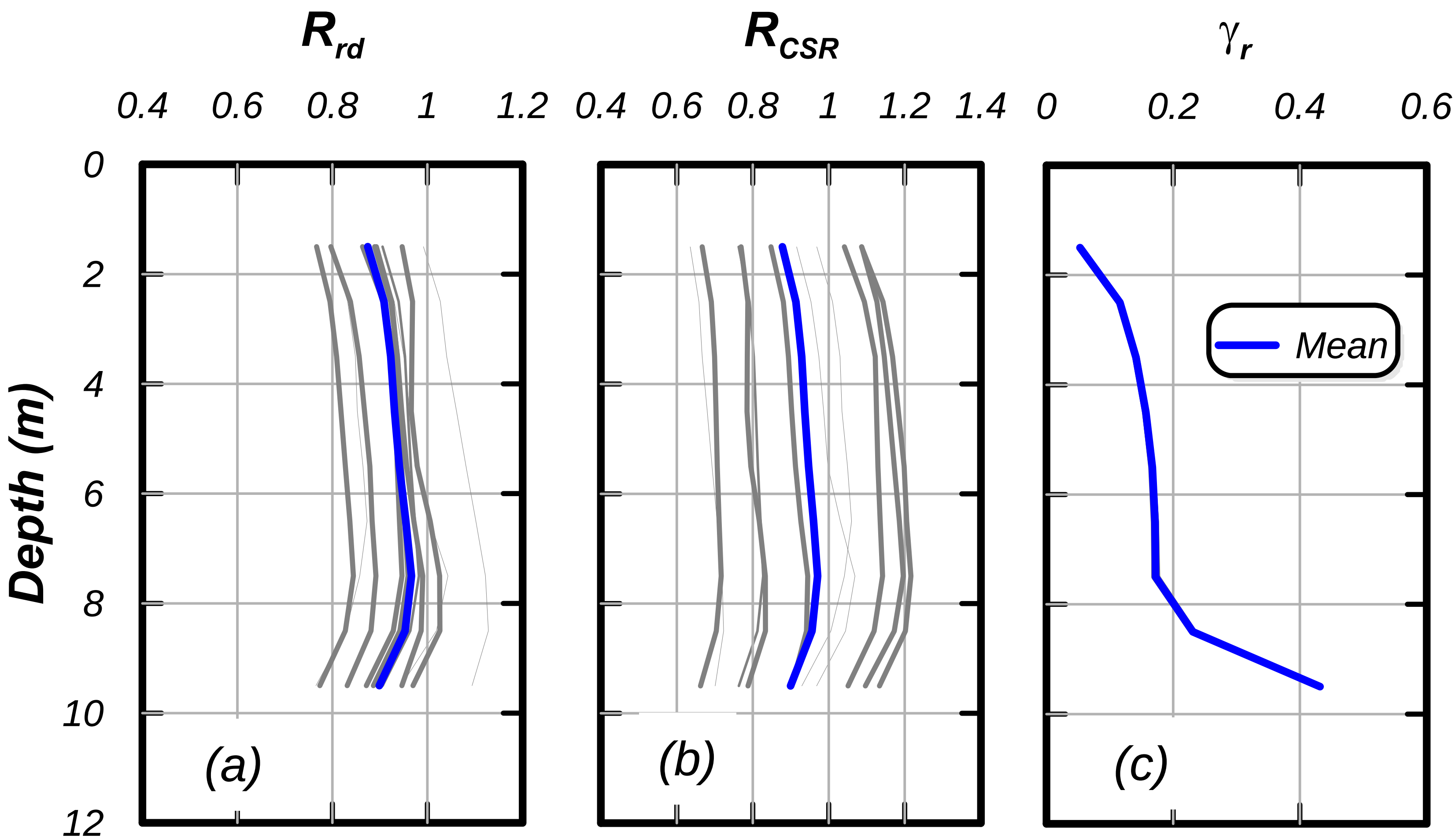
$$CSR_I = \frac{\tau_{s,I}}{\sigma_v'} = 0.65\left(\frac{a_{\max,I}}{g}\right)\left(\frac{\sigma_v}{\sigma_v'}\right)r_{d,I}$$

- ***Ratio of CSR in the <u>soil</u> is:***

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

Earthquake loading

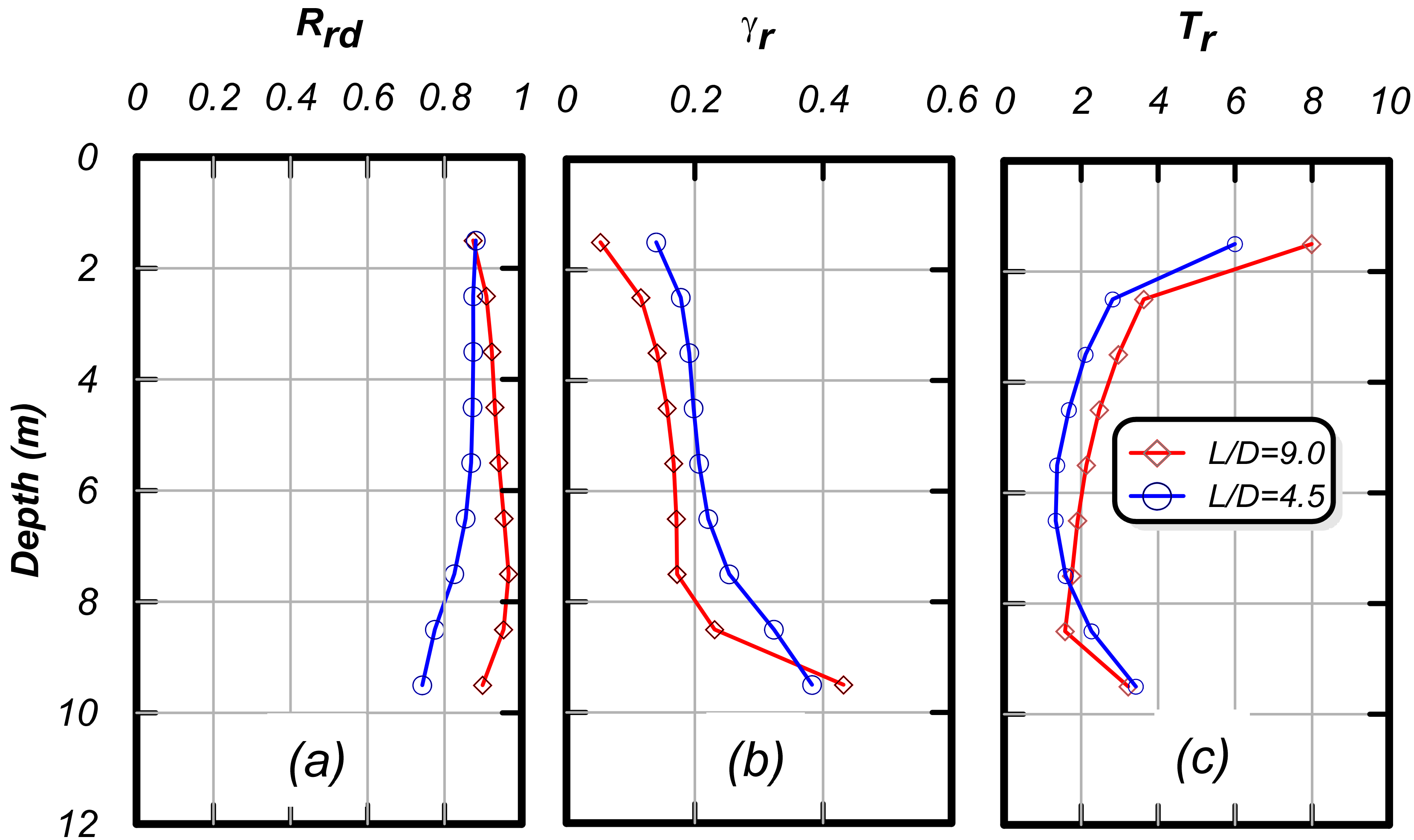
- **A_r=20% and G_r=10**



Area-averaged values for R_{rd}, γ_r, and R_{CSR}

Earthquake loading

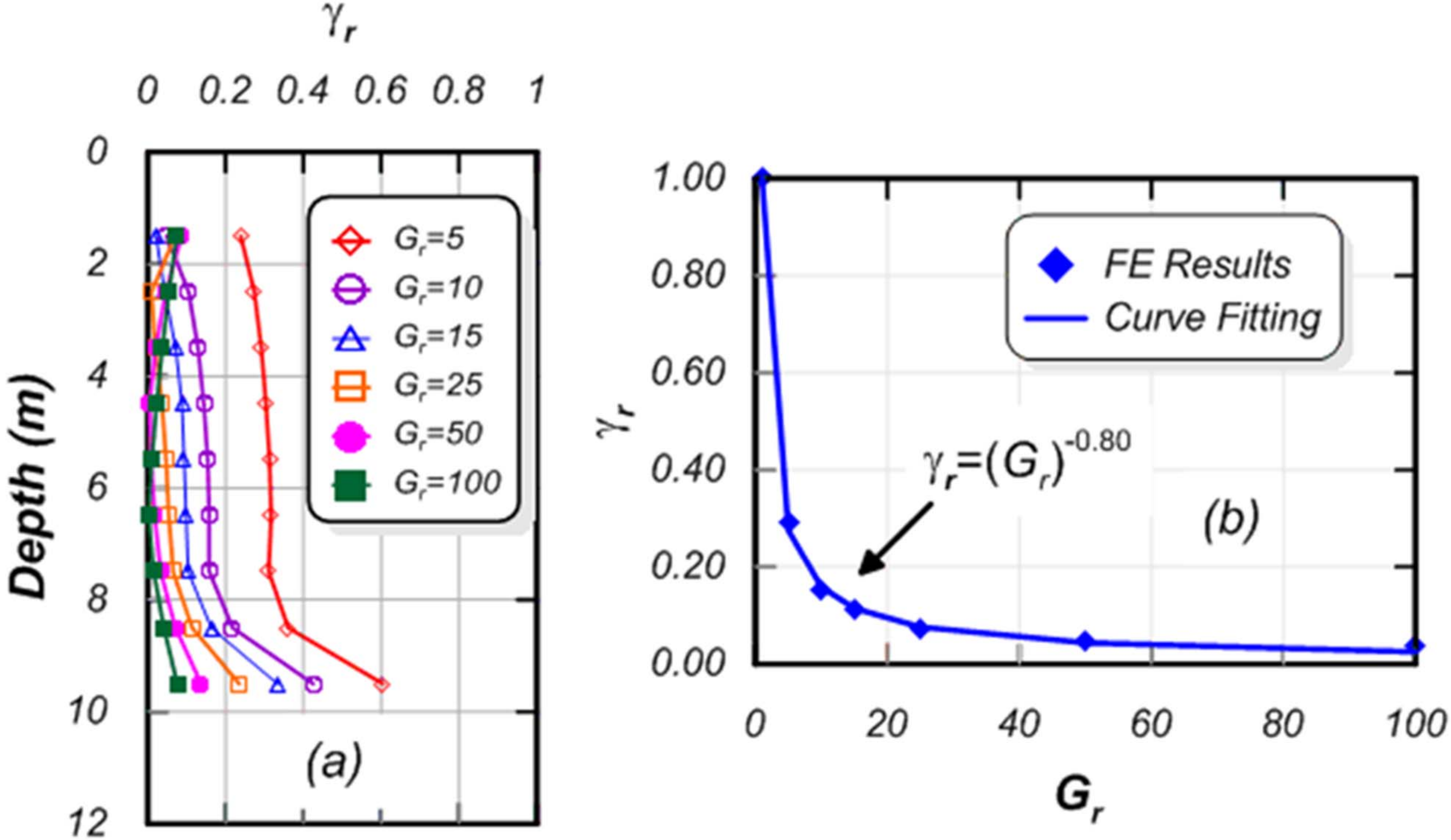
- **Comparisons for L/D = 9 and 4.5 for A_r=20% and G_r=10**
- **Define a dynamic tensile stress increment ratio, $T_r = \Delta\sigma_{dyn}/(a_{max}\sigma_v)$**



Area-averaged values for R_{rd} and γ_r

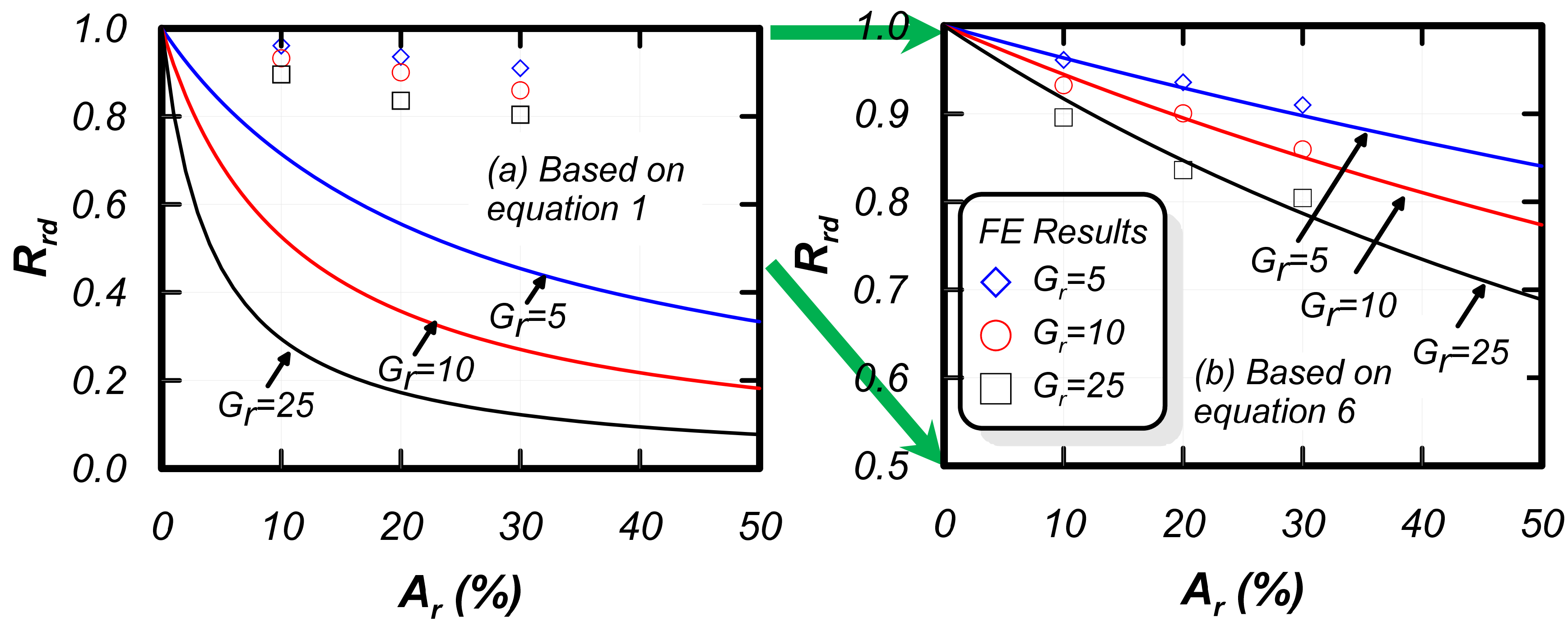
Earthquake loading

- **A_r=20% and L/D = 9**



Design equations

- ***(a) based on strain compatibility, and (b) based on proposed relationships***



$$R_{rd} = \frac{1}{G_r A_r + (1 - A_r)}$$

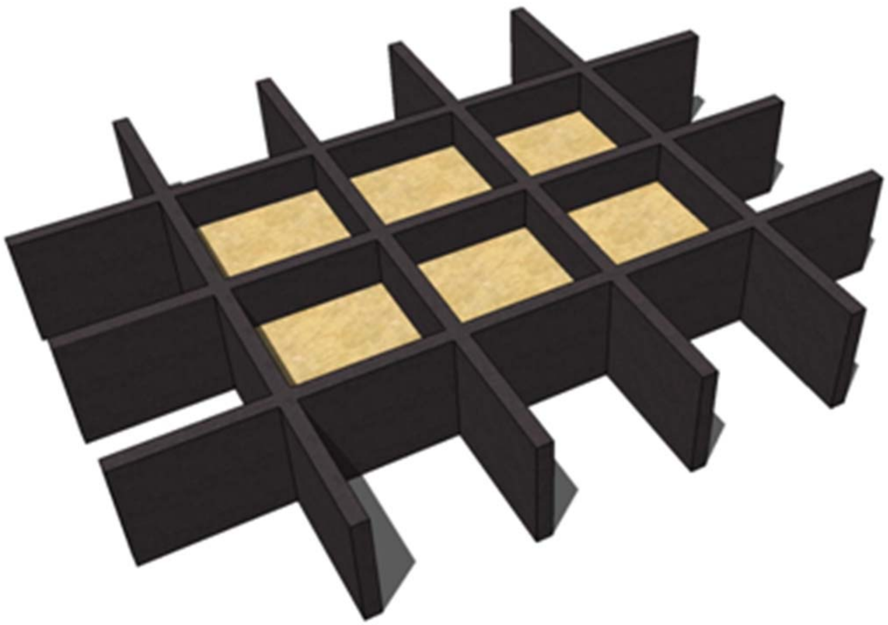
$$R_{rd} = \frac{1}{\gamma_r G_r A_r + (1 - A_r)}$$

Concluding remarks on discrete columns

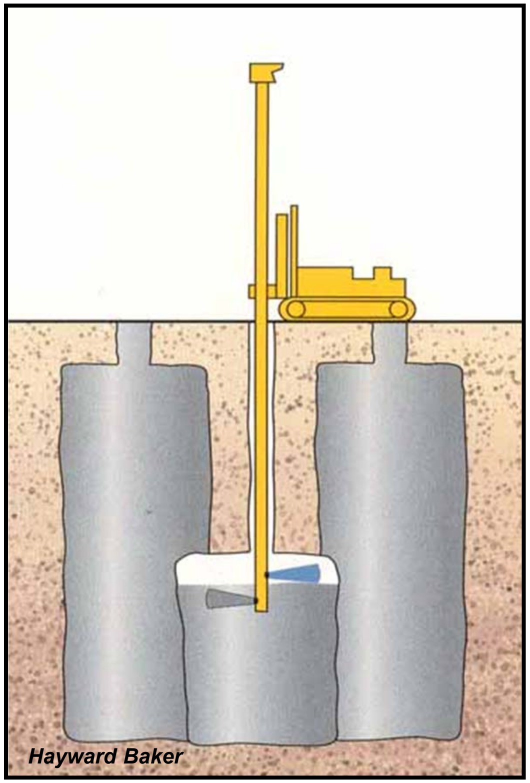
- ***FE results confirmed previous numerical studies in showing flexure greatly reduces the shear reinforcement effect of discrete columns for the range of conditions examined (A_r = 0-50%, G_r = 5-100, D = 1 & 2 m, L/D = 4.5 & 9).***
- ***Prudence suggests discontinuing use of the shear strain compatibility assumption for discrete columns in the absence of any numerical analysis results to support it.***
- ***These results do not diminish the evidence that stone or soil-cement columns can be effective for remediating against liquefaction triggering and its consequences.***
- ***There is no experimental or field data that can isolate the shear stress reduction mechanism from the other beneficial mechanisms (densification, drainage, shear reinforcement).***
- ***Further advances in the design of stone and soil-cement columns will require analyses using nonlinear soil and column material models, more detailed field and physical modeling studies, and more detailed examination of case histories.***

In-ground shear wall grids

Shear wall grids



Shear wall grids



Jet grouting

Deep soil mixing

Trenching methods

Mechanisms of improvement

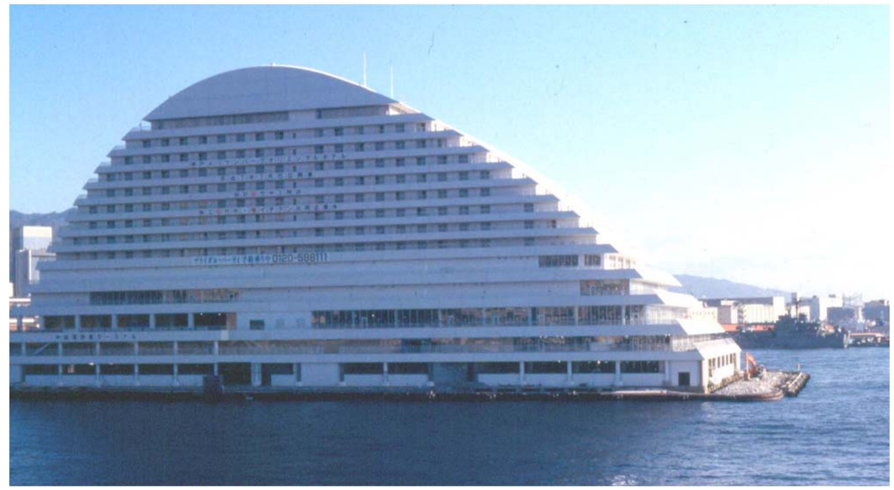
- ***A grid of in-ground walls improves a liquefiable site by:***
  - ***Reducing earthquake-induced shear strains in the treatment zone, thereby limiting pore pressure generation.***
  - ***Containing the enclosed soil should it liquefy, and thus contributing to the composite strength.***
  - ***Acting as a barrier to the migration of excess pore pressures from the adjacent untreated zones into the treatment area.***

- ***Can be used in a wide variety of soils, including sensitive clays, silts, and sandy silts.***

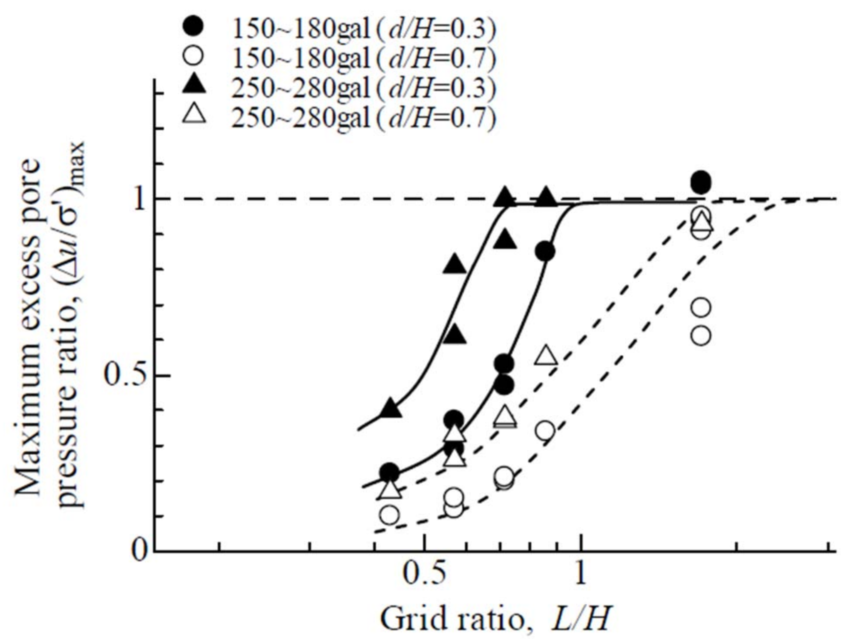
- ***Cracking of soil-cement is a concern.***

Case histories & physical models

- Oriental Hotel performed well in the 1995 Kobe earthquake. DSM grids extended through loose fills to 12 m depth; liquefaction with 1-2 m movements observed outside DSM grids.

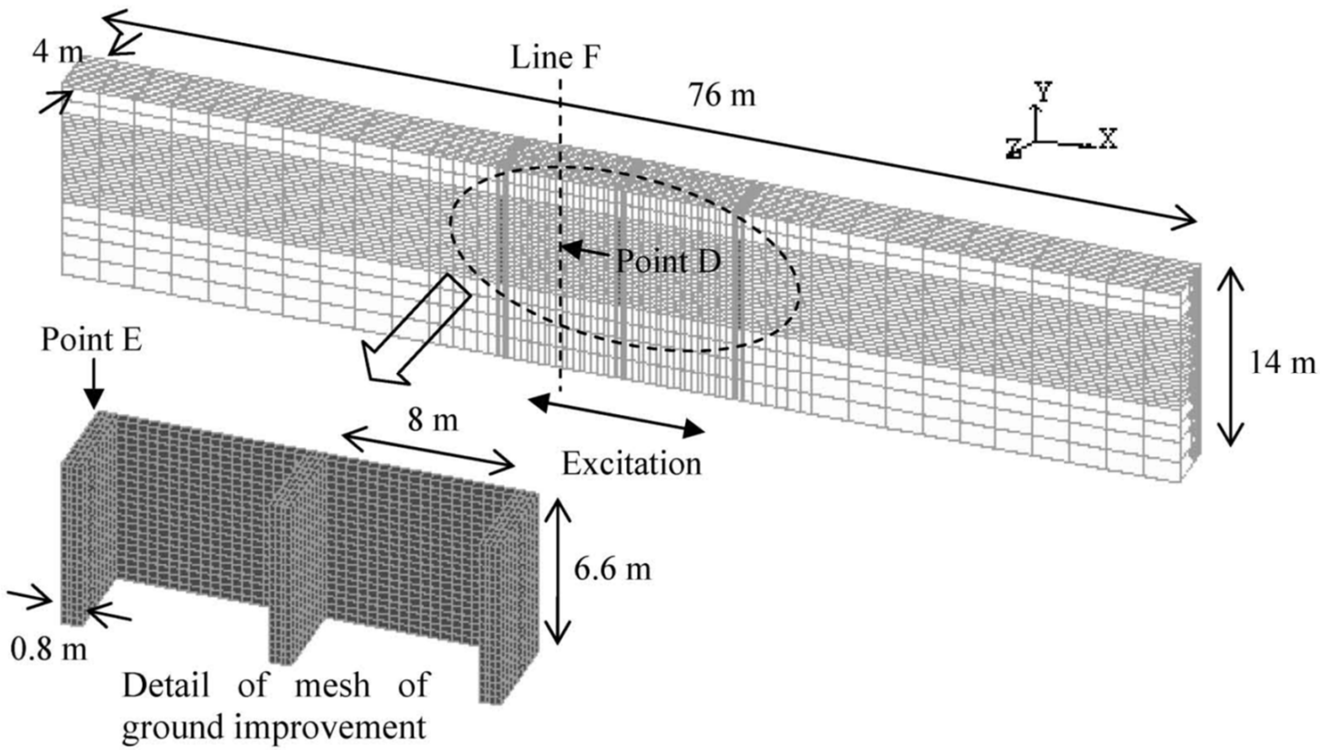


- Centrifuge tests by Kitazume and Takahashi (2010), Suzuki et al. (1991) and Funahara et al (2012) have shown grids reduce pore pressure generation inside the grids.



Numerical analyses

- ***3D analyses by Namikawa et al. (2007) used elastic and elasto-plastic material models. Showed effectiveness depends on area ratio and soil-cement shear modulus, and that walls could develop some damage and still perform well.***

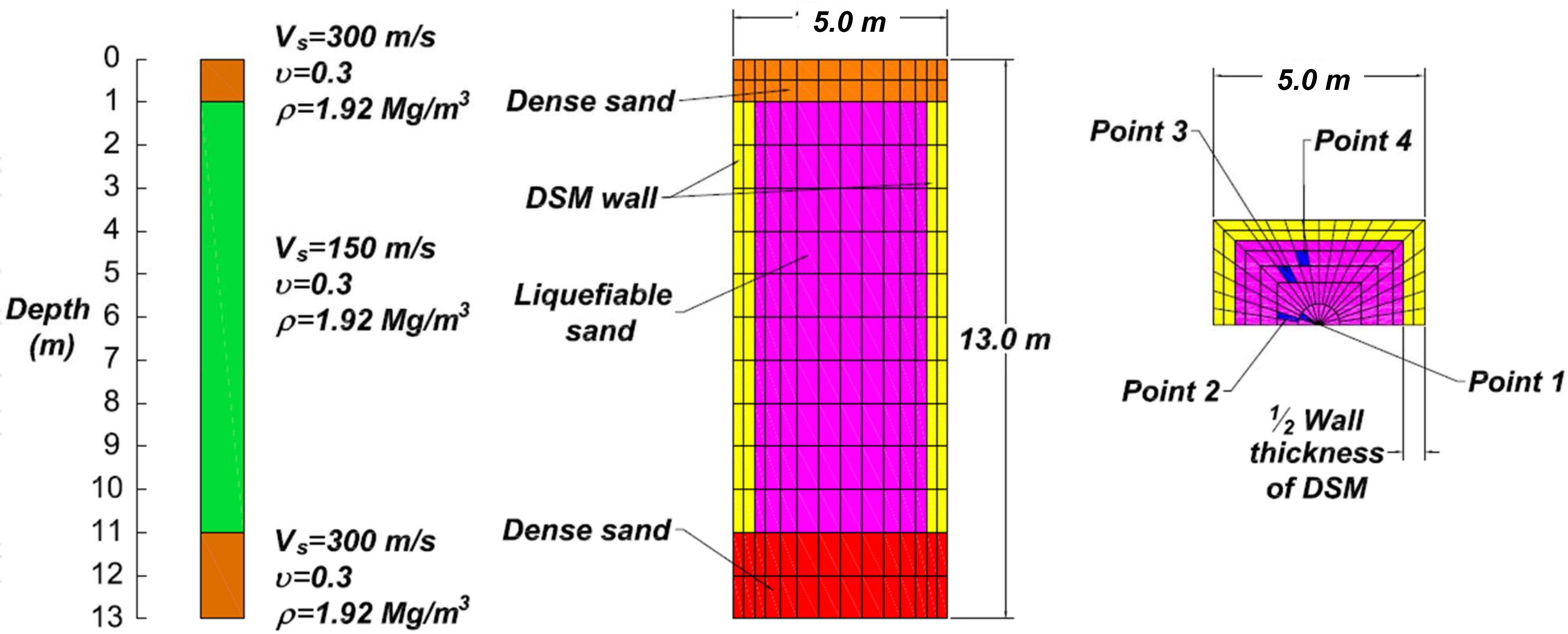


- ***Equivalent 2D FE analyses by O'Rourke and Goh (1997) led to similar conclusions regarding their effectiveness.***

In-ground shear wall grids:
Estimating the shear stress reduction

FE model – This study

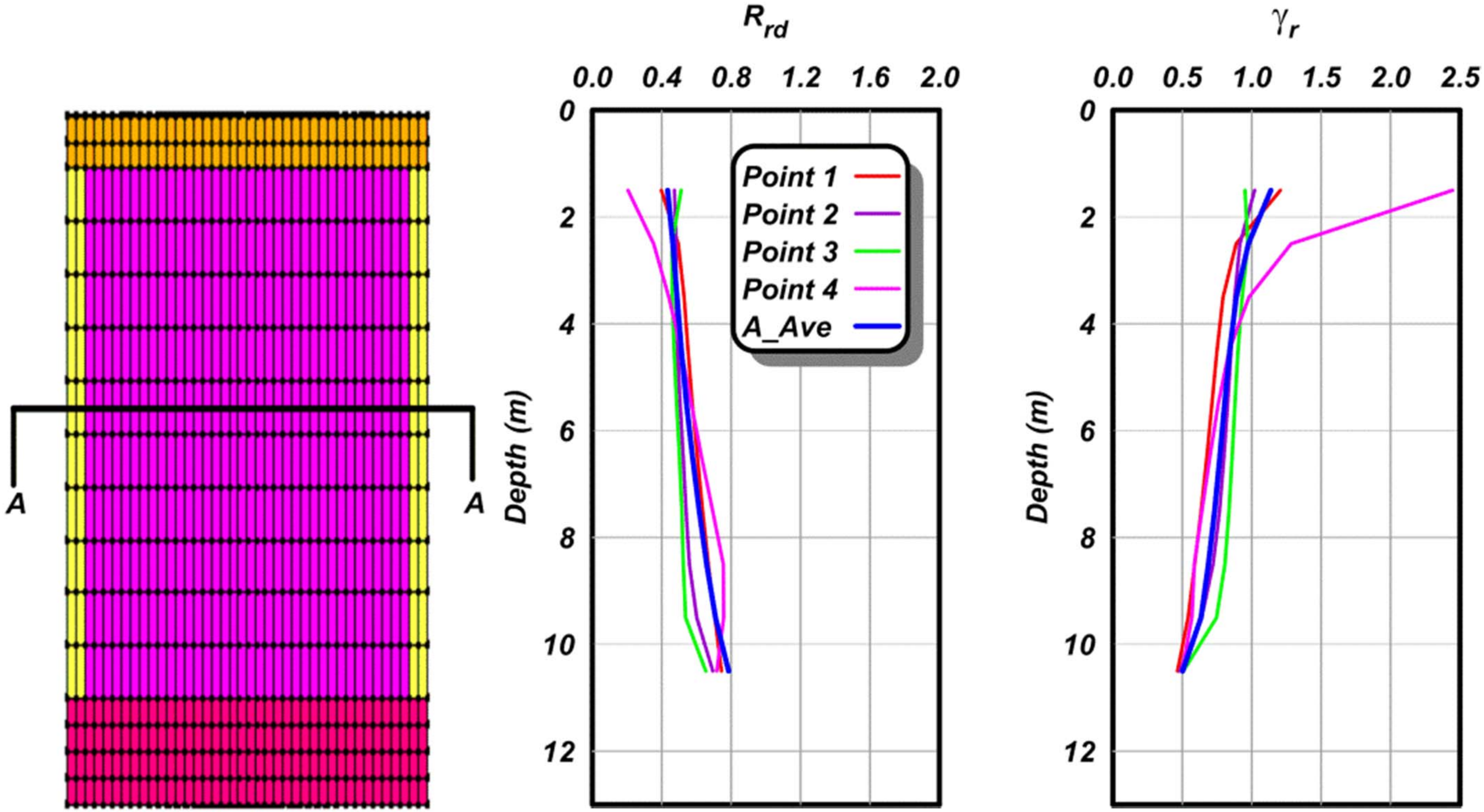
- ***3D analyses of unit cell (Nguyen et al. 2012) to explore a wider range of parameters to develop a design relationship.***



(a): soil profile (b) front view (c) horizontal cross-section

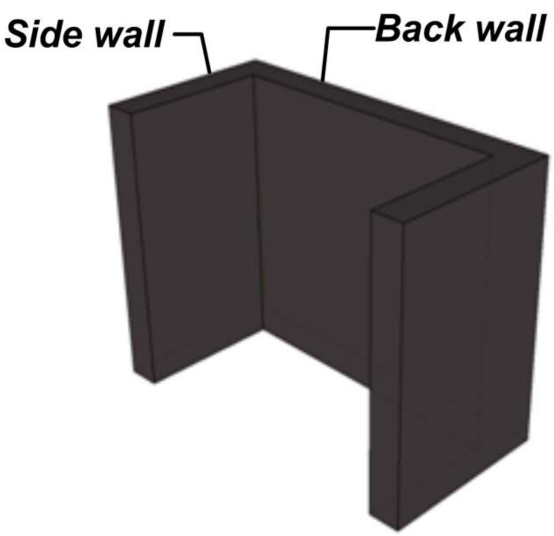
Earthquake loading

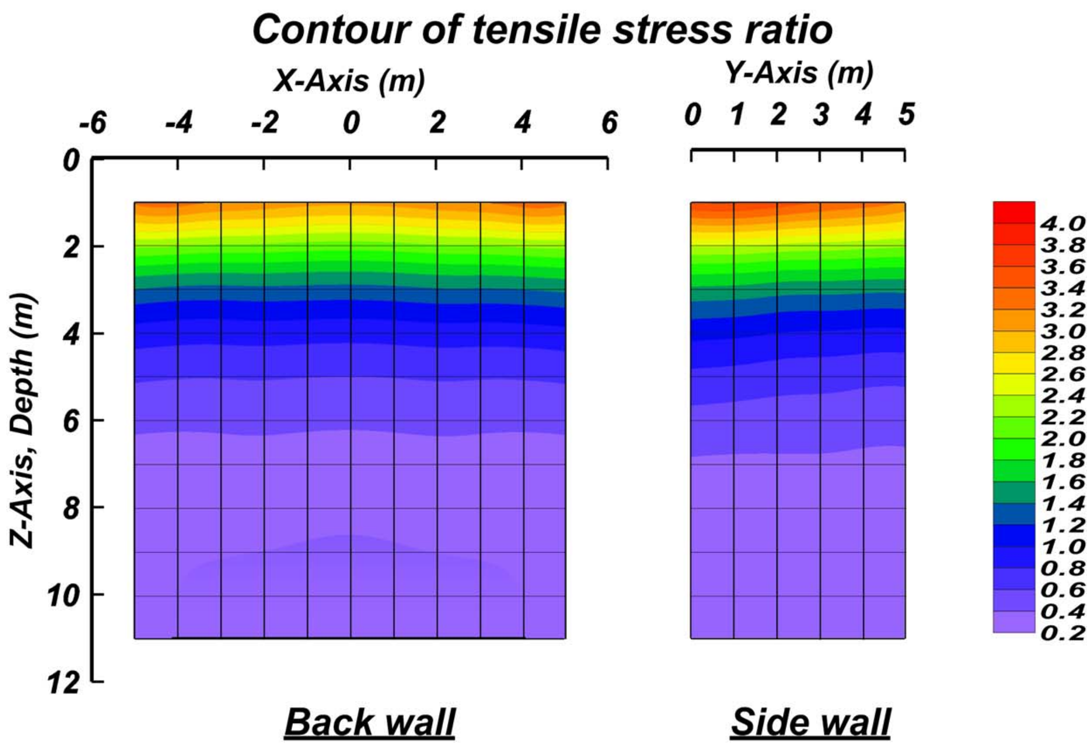
- **A_r=19% and G_r=13.5 for one motion**



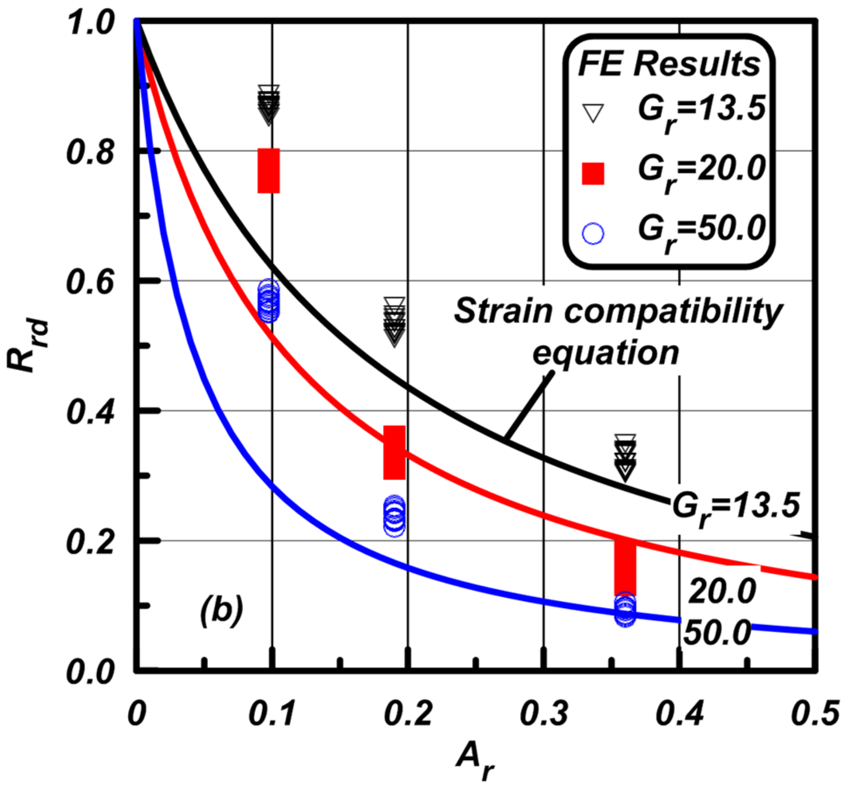
Earthquake loading

- ***A_r=19% and G_r=13.5 for one motion***
- ***Define a dynamic tensile stress increment ratio, $T_r=\Delta\sigma_{dyn}/(a_{max}\sigma_v)$***

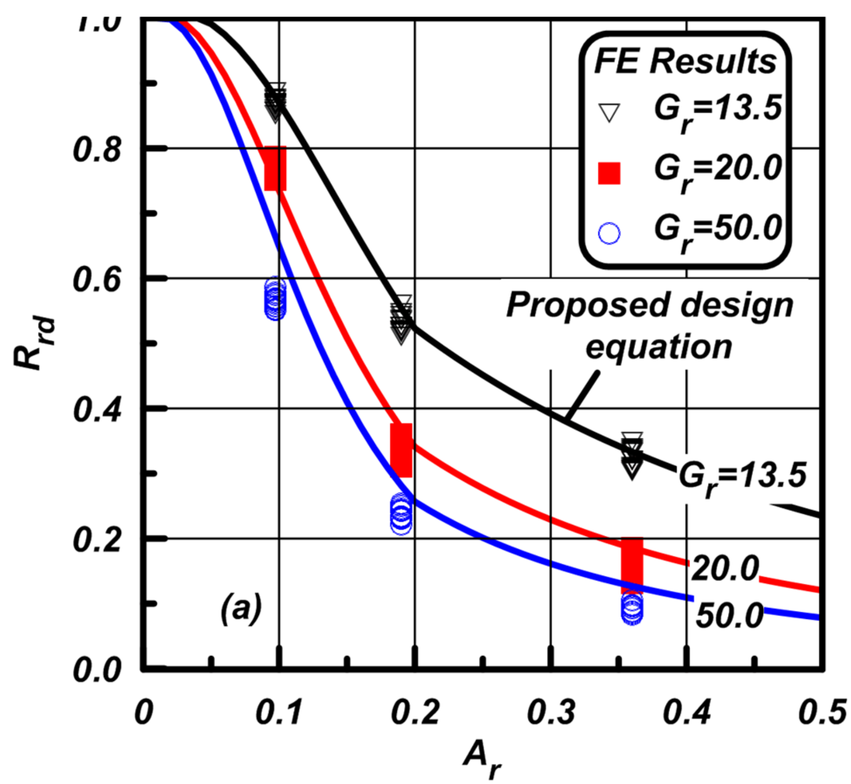




Design equations



(a) Assuming γ_r = 1 & C_G = 0.5



(b) Proposed γ_r & C_G

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

Concluding remarks

- ***For discrete columns:***
  - ***FE results confirmed previous numerical studies in showing flexure greatly reduces the shear reinforcement effect of discrete columns.***
  - ***Prudence suggests discontinuing use of the shear strain compatibility assumption in the absence of any numerical analysis results to support it.***
  - ***A revised design relationship was developed.***

- ***For shear wall grids:***
  - ***FE results indicate that the assumption of shear strain compatibility is only slightly unconservative.***
  - ***A revised design relationship was developed.***

- ***OpenSeesPL:***
  - ***Valuable design tool for elastic and inelastic analyses of both discrete column & shear wall grid systems.***

Acknowledgments

- ***Pacific Earthquake Engineering Research (PEER) Center***
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- ***Hayward Baker, Inc.***
- ***Comments and suggestions from Dr. Juan Baez and Professor Russell Green improved the results of this study.***

Questions?

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