ANALYSIS OF DEEP SOIL STABILIZATION GRIDS WITH OPENSEES PLATFORM
&
MITIGATION OF LATERAL SPREADING EFFECTS ON BRIDGES

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PEER Transportation System Research Program (TSRP)
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Figure : Photograph of a typical DSM grid

Figure : Close up view of DSM grid

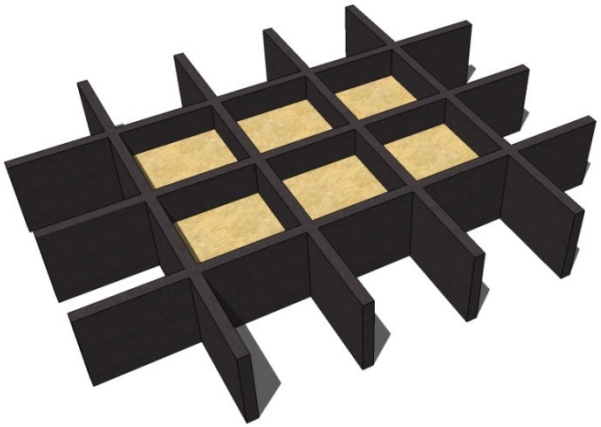
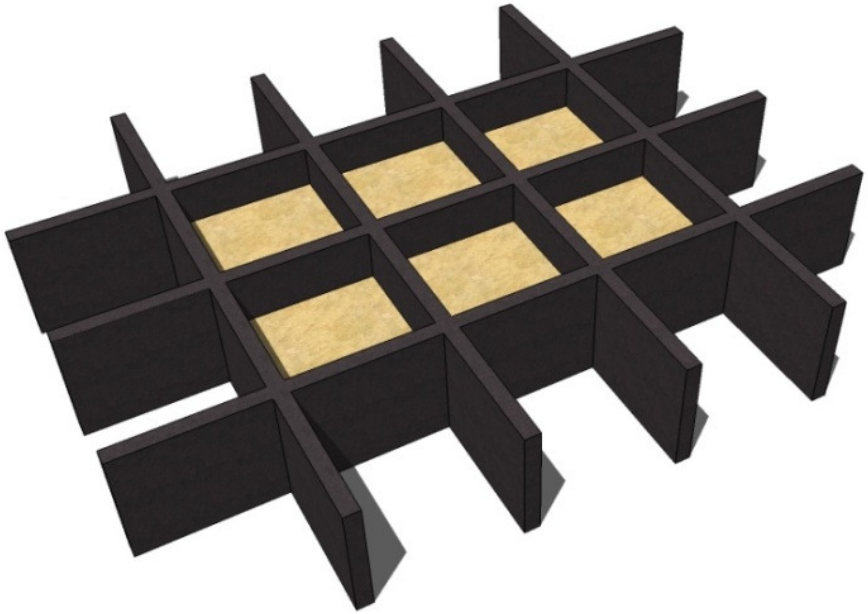


Figure 2: Idealized DSM grid

Figure : Artistic rendering of DSM grid

The issue

- How to estimate the degree to which a DSM grid reduces seismic shear stresses on the enclosed soil?
- A common assumption is shear strain compatibility between the DSM and enclosed soil (e.g., Baez 1990, Ozsoy and Durgunoglu 2003). The general applicability of this assumption has not been examined in detail and is debatable for certain conditions.



Outline

1. Deep Soil Mixing Technology
2. FE Model and Interpretation Framework
    1. Pseudo-static Response
    2. Harmonic Input Frequency Response
    3. Earthquake Response
    4. Proposed Design Relationships
3. Summary

Deep Soil Mixing Technology

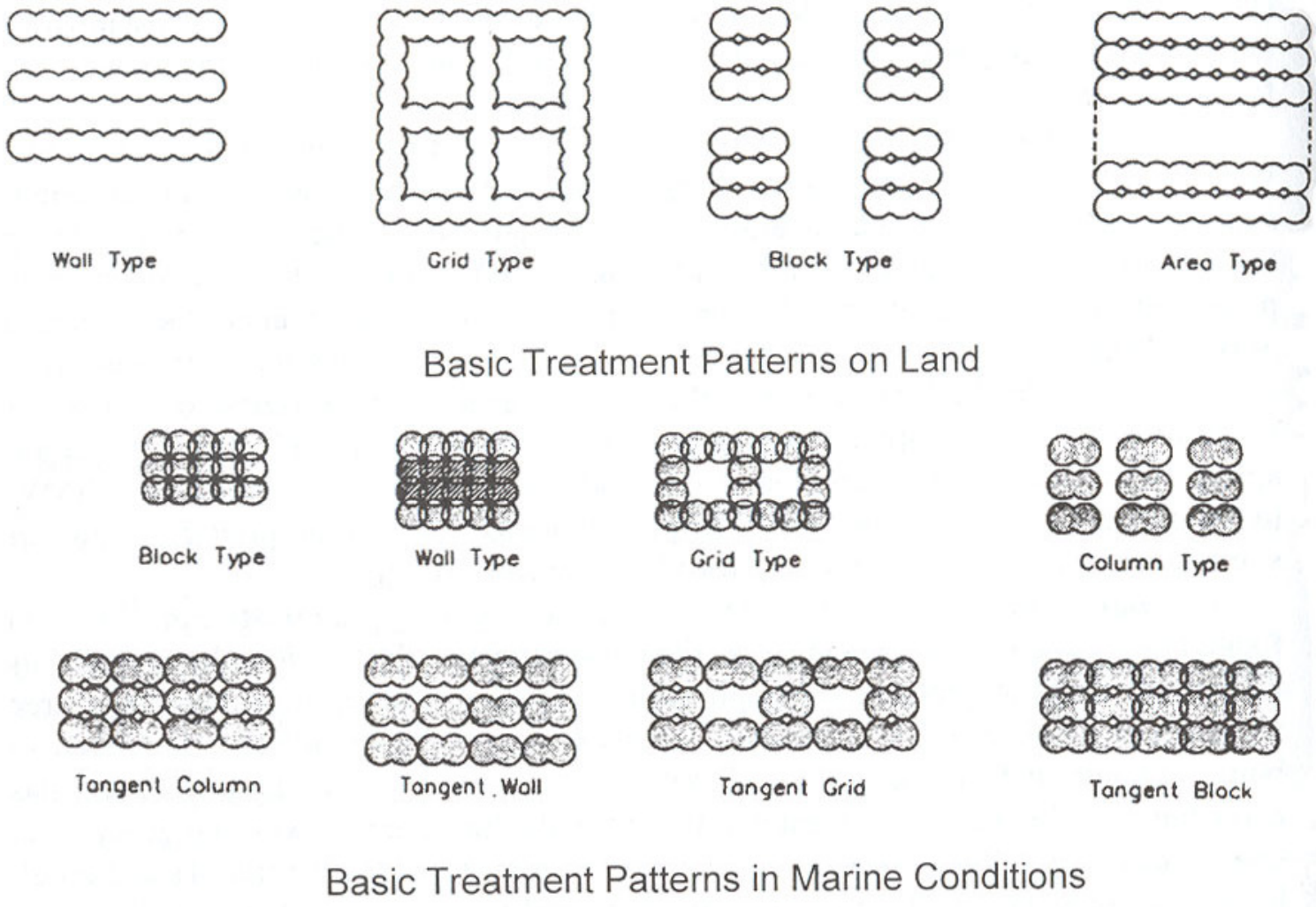


Figure : Basic Treatment Patterns (Bruce 2003)

DSM Step by Step

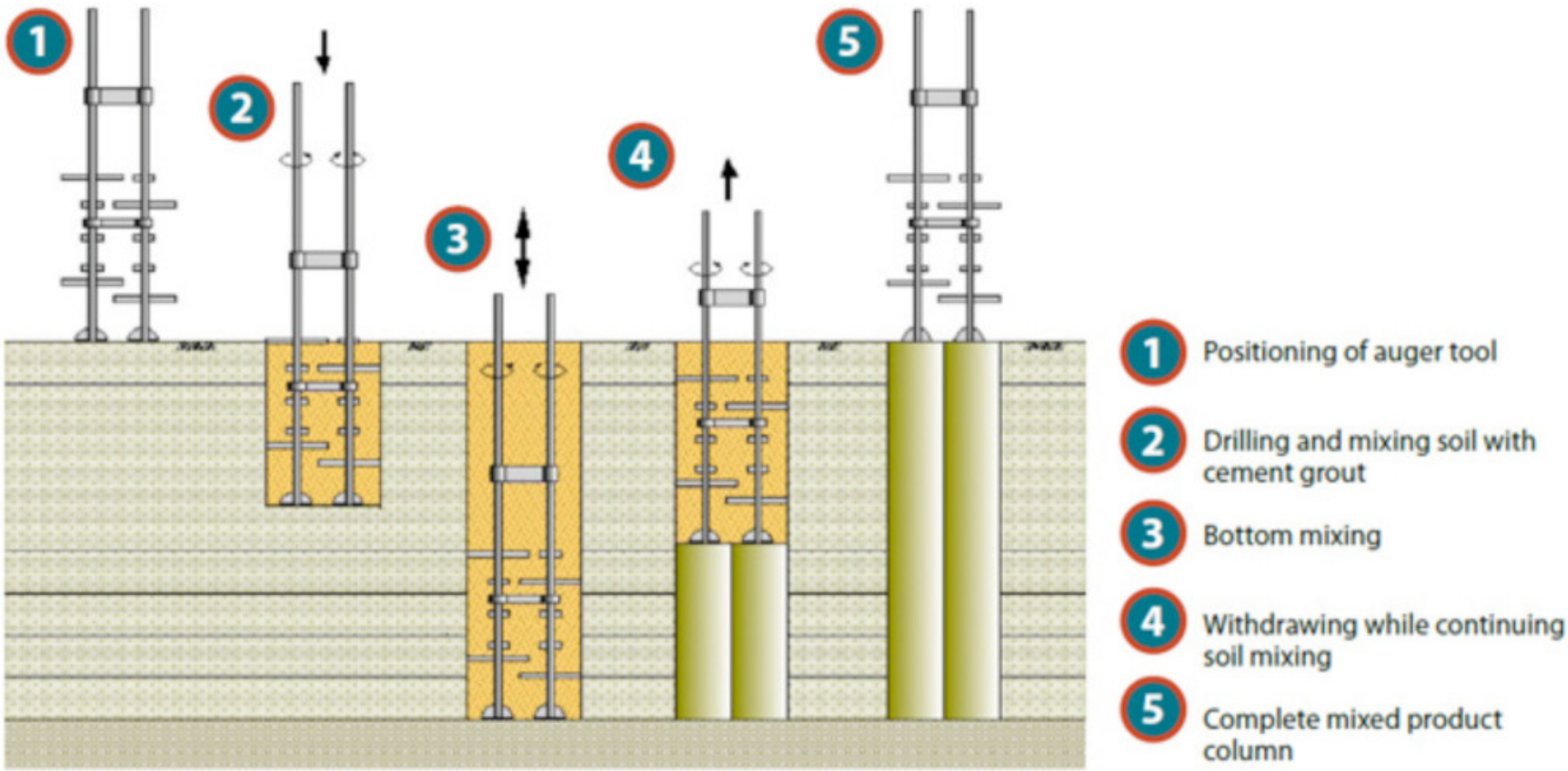
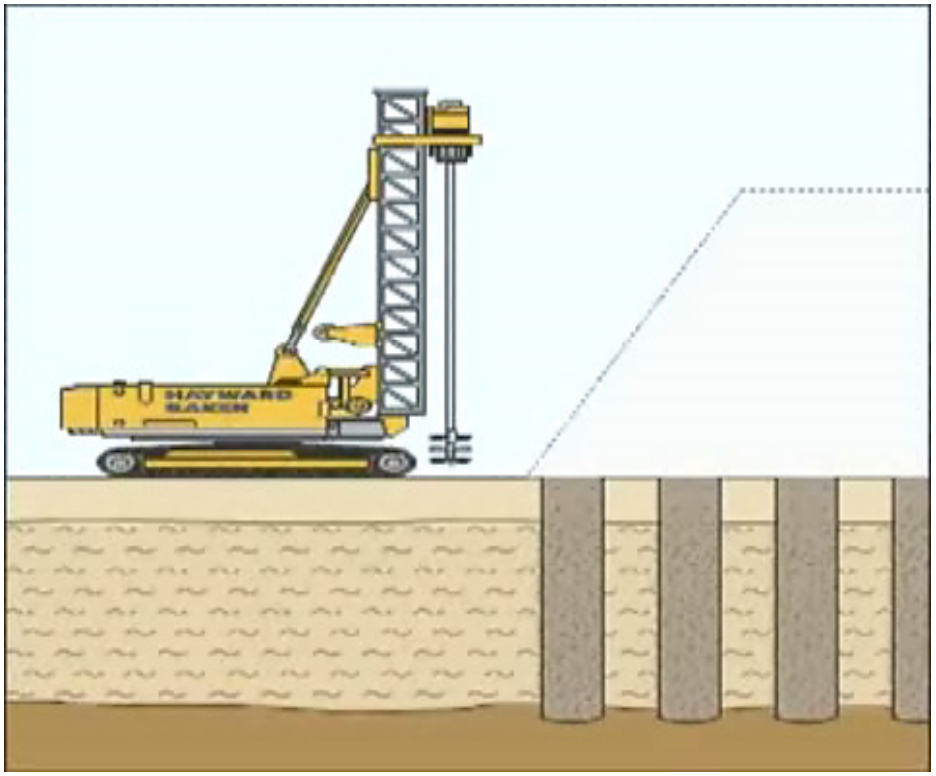


Figure 3: Step by Step DSM Installation Method (Courtesy of JAFEC USA)

DSM Construction Method



(Courtesy of Hayward and Baker)

FE Model and Interpretation Framework

Figure : Photograph of a typical DSM grid

Figure : Close up view of DSM grid

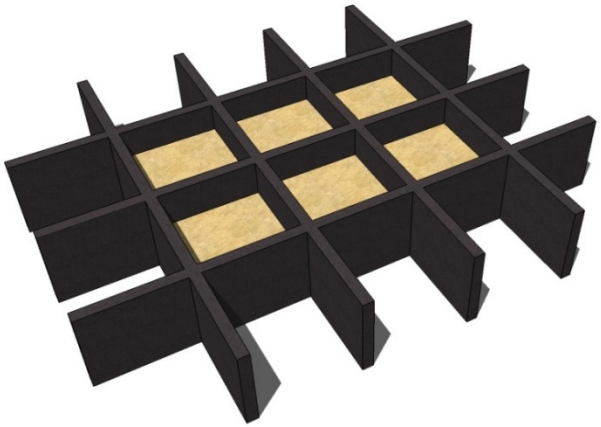
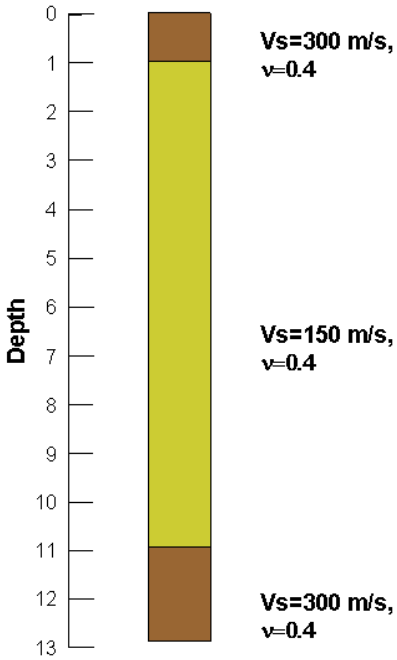


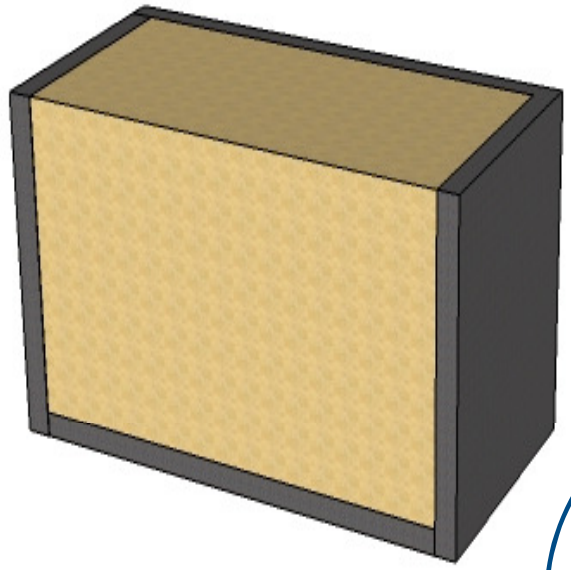
Figure 2: Idealized DSM grid

Figure 7: Artistic rendering of DSM grid

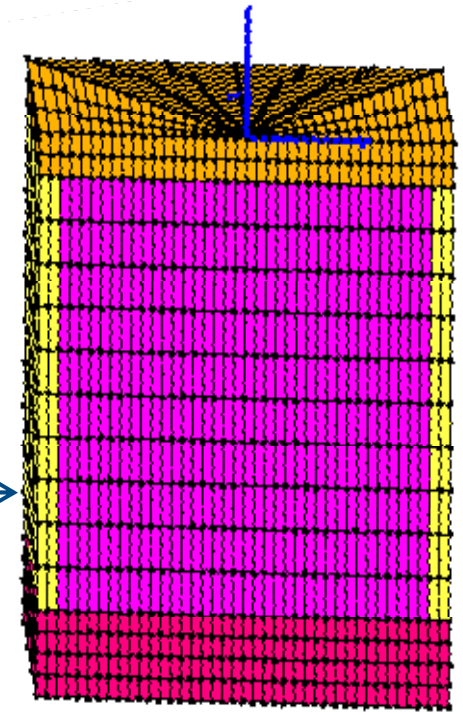
Linear Elastic FE DSM Model



Linear Elastic Soil Profile



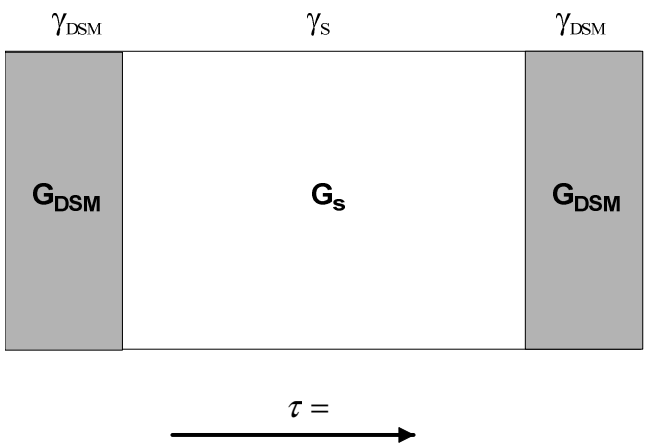
DSM Half Unit Cell



Half DSM Unit Cell Mesh in OpenSeesPL

- *DSM wall thickness=1m*
- *Vs=600 m/s, ν=0.4*

Interpretation Framework



Equilibrium:

$\tau_{ave}A_T = \tau_s A_s + \tau_{DSM} A_{DSM}$

Which can be rewritten in term of shear strain and shear modulus

$\gamma_{ave} G_{ave} A_T = \gamma s G_s A_s + \gamma_{DSM} G_{DSM} A_{DSM}$

Define the area replacement ratio, $A_r = A_{DSM}/A_T$

Define the shear modulus ratio, $G_r = G_{DSM}/G_S$

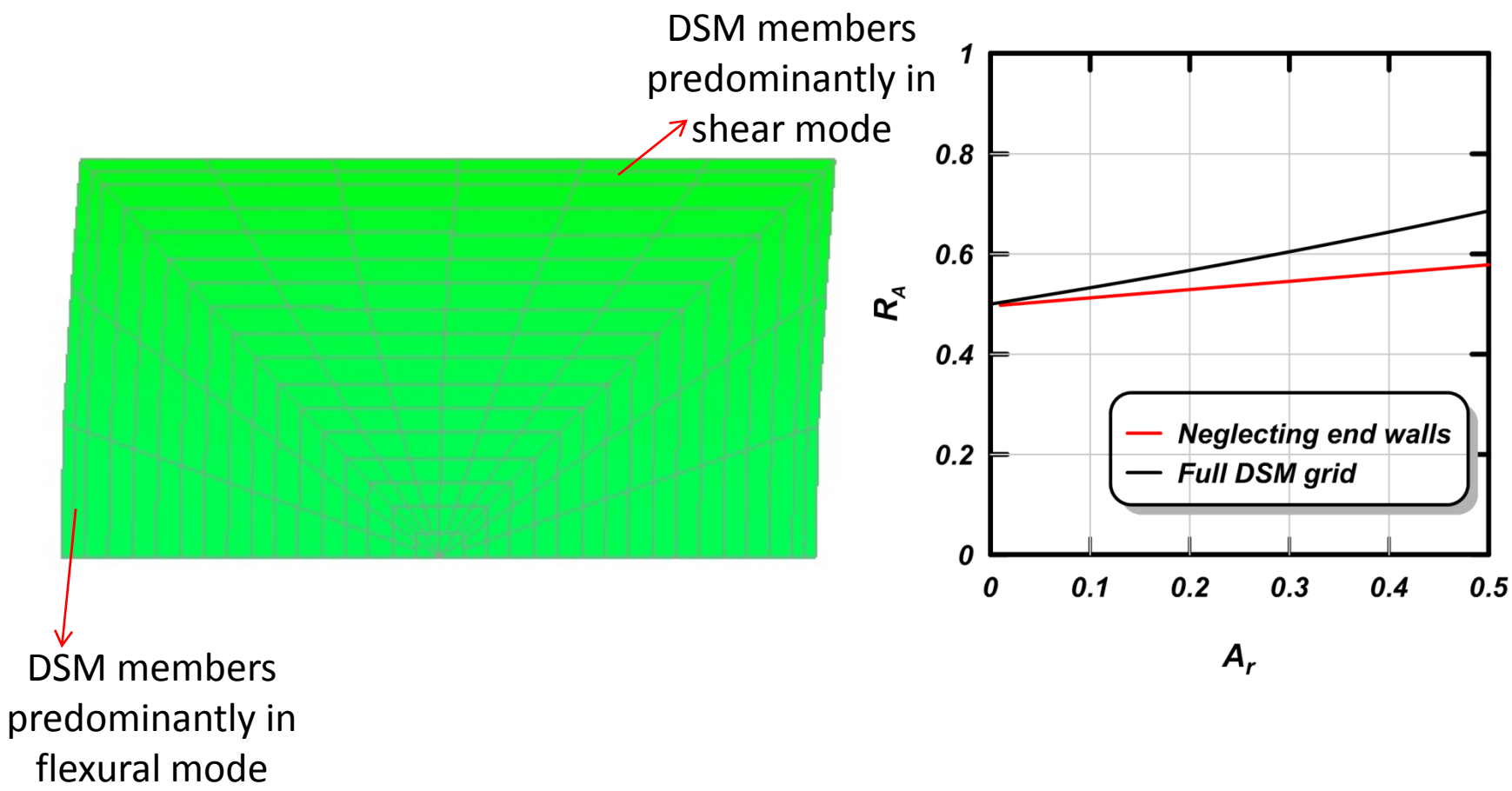
Define shear strain ratio, $R_\gamma = \gamma_s/\gamma_{DSM}$

Interpretation Framework (Cont'd)

The effective area replacement ratio is less than A_r because the DSM walls are not all acting in shear at the same time. We account for this as

$$\mathbf{A_{er}=R_A A_r}$$

where $\mathbf{R_A}$ *is the equivalent fraction of the DSM wall area that acts in shear.*



Interpretation Framework (Cont'd)

The shear stress reduction ratio for a treated soil mass is

$$S_G = \frac{\tau_s}{\tau_{ave}} = \frac{\gamma_s G_s}{\gamma_{ave} G_{ave}} = \frac{\gamma_s G_s}{\gamma_s G_s (1 - A_r) + \gamma_{DSM} G_{DSM} A_{er}}$$

$$S_G = \frac{1}{(1 - A_r) + \frac{R_A}{R_\gamma} G_r A_r}$$

For a special case of equation above when R_γ=1 and R_A=1, we have the familiar strain compatibility equation proposed by Baez et al (1990).

Interpretation Framework (Cont'd)

<u>Depth Reduction Ratio</u> (R_{rd})

For an untreated site, the cyclic stress ratio can be estimated using the "simplified method"

$$\mathrm{CSR}_{\mathrm{U}} = \left(\frac{\tau_S}{\sigma_v'}\right)_U = \left[0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_v}{\sigma_v'}\right)rd\right]_U \qquad \text{(Seed and Idriss 1972)}$$

Similarly, for a treated site, the cyclic stress ratio can also be estimated using the "simplified method"

$$\mathrm{CSR}_{\mathrm{I}} = \left(\frac{\tau_S}{\sigma_v'}\right)_I = \left[0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_v}{\sigma_v'}\right)rd\right]_I \qquad \text{(Seed and Idriss 1972)}$$

The ratio of CSR_I over CSR_U is the "CSR Reduction Factor", and it is related to the ratio of maximum accelerations and depth reduction factors as follow:

Interpretation Framework (Cont'd)

$$R_{CSR} = \left(\frac{CSR_I}{CSR_U} \right) = \frac{(a_{\max} r_d)_I}{(a_{\max} r_d)_U} = R_{a\_\max} R_{rd}$$

With $R_{amax}=(a_{max})_I/(a_{max})_U$ and $R_{rd}=(r_d)_I/(r_d)_U$

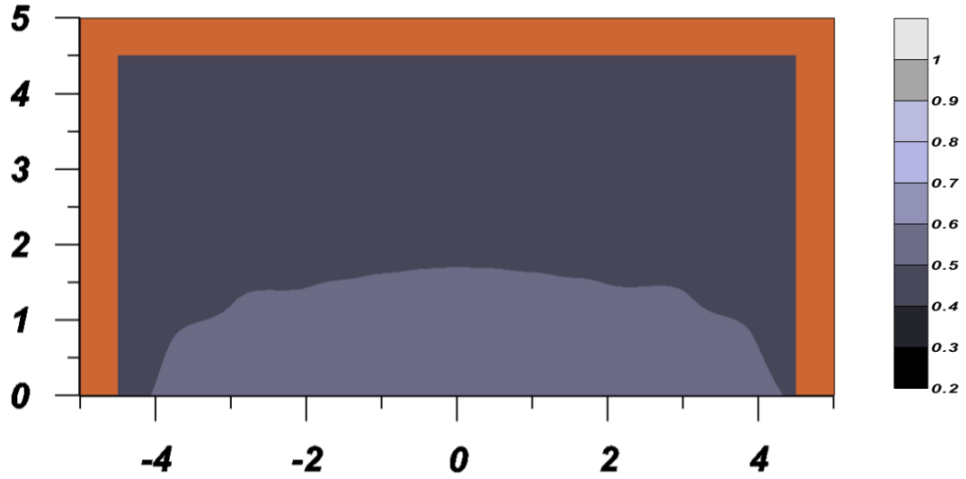
Note that the value of R_{rd} is equal to R_{CSR} and identical to S_G for pseudo-static loading (i.e $R_{amax}=1$).

However, $\mathbf{R_{rd}}$ or $\mathbf{S_G}$ would differ from $\mathbf{R_{CSR}}$ as dynamic response affects the distribution of shear with depth differently in the treated and untreated site.

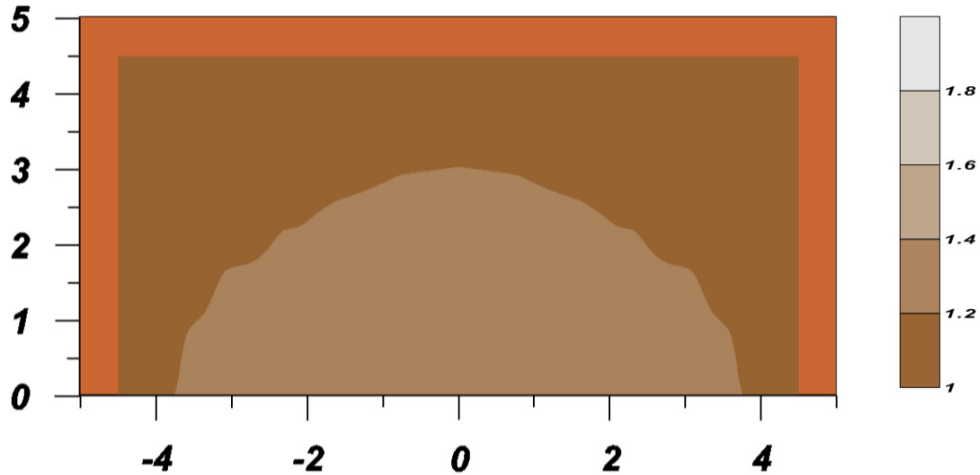
Nevertheless, commonly in practice $\mathbf{S_G}$ is often being used instead of $\mathbf{R_{CSR}}$ to estimated the benefits of DSM grids.

Result From Pseudo-Static Analysis

Spatial Variation

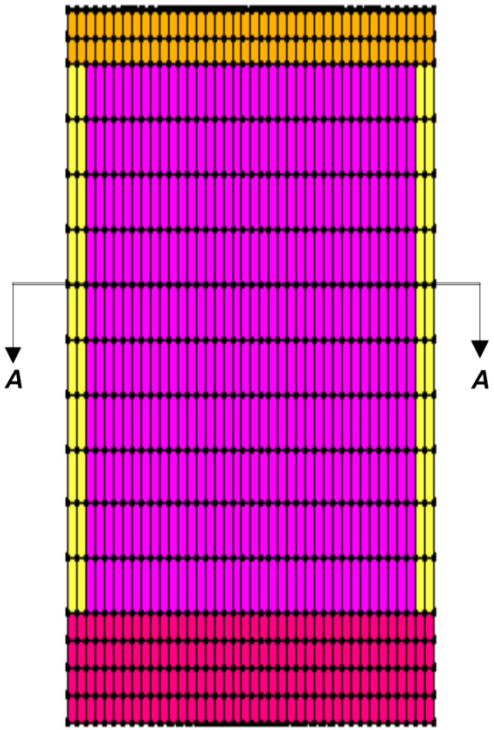


R_{rd} contour (cross section A-A)

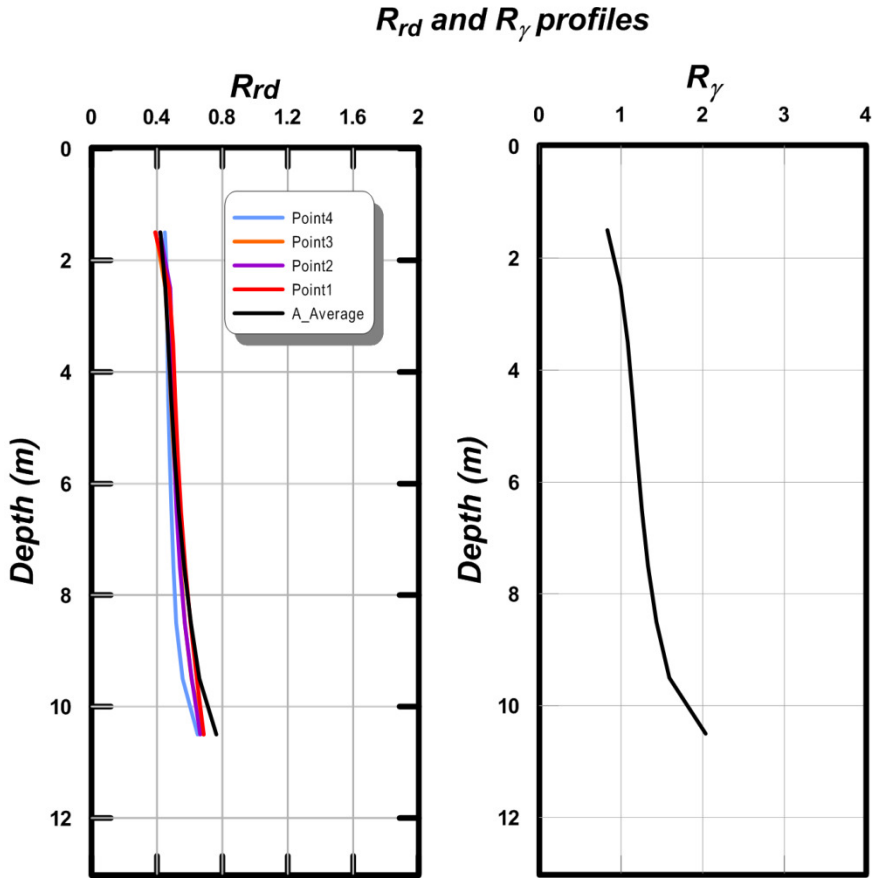


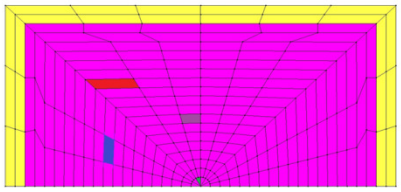
R_{γ} contour (cross section A-A)

Standard DSM Half Unit Cell Under Pseudo-Static Analysis

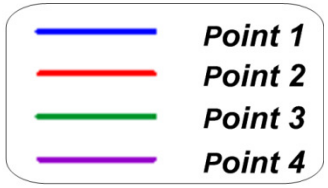


Front view of half unit cell

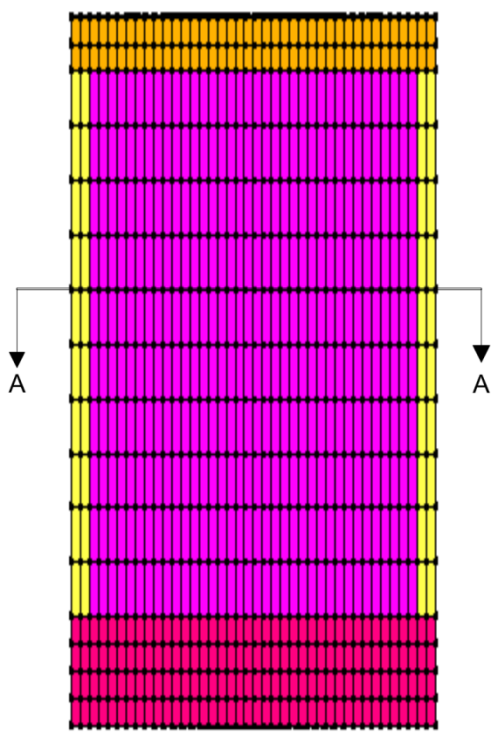




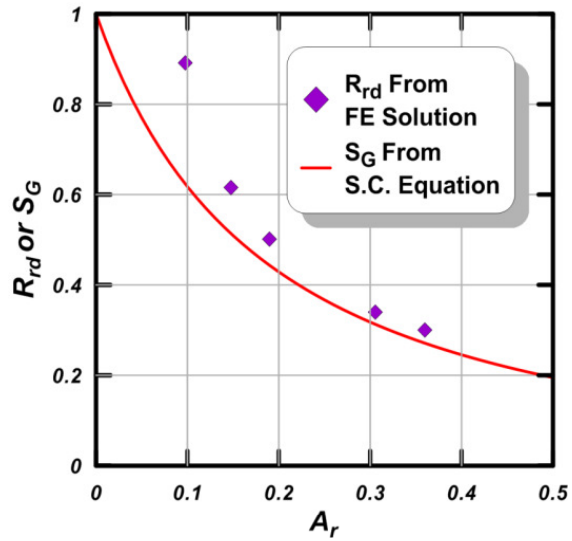
Plan view of half unit cell

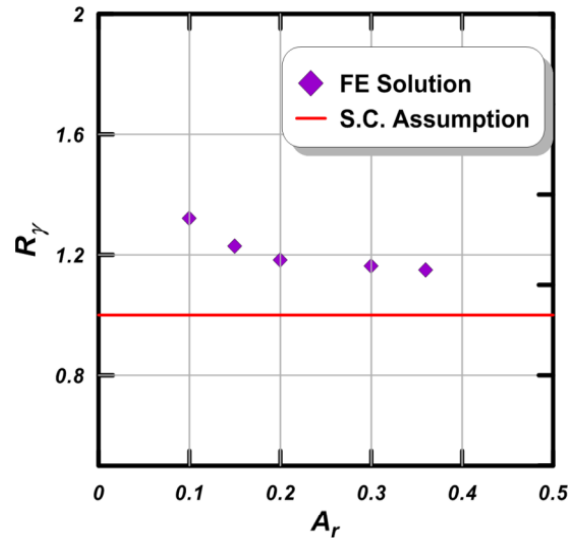


Shear Modulus Ratio G_r=13.5 and 20.0

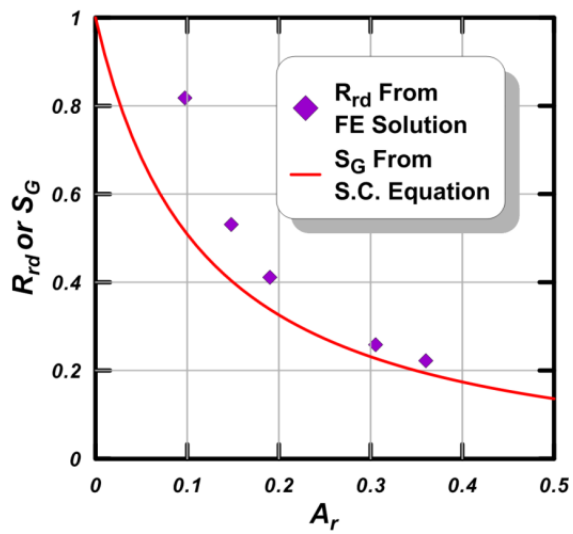


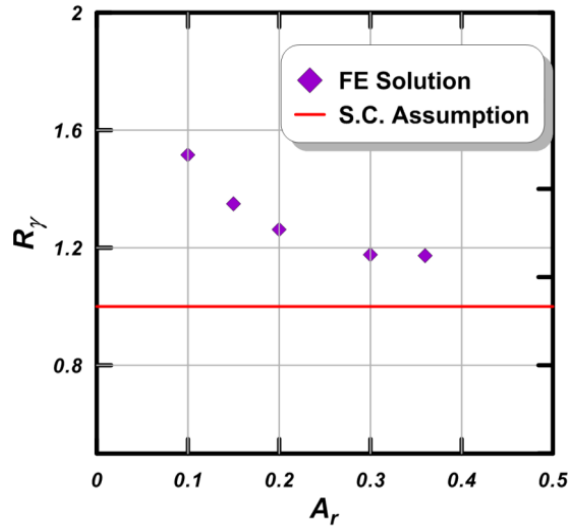
G_r=13.5





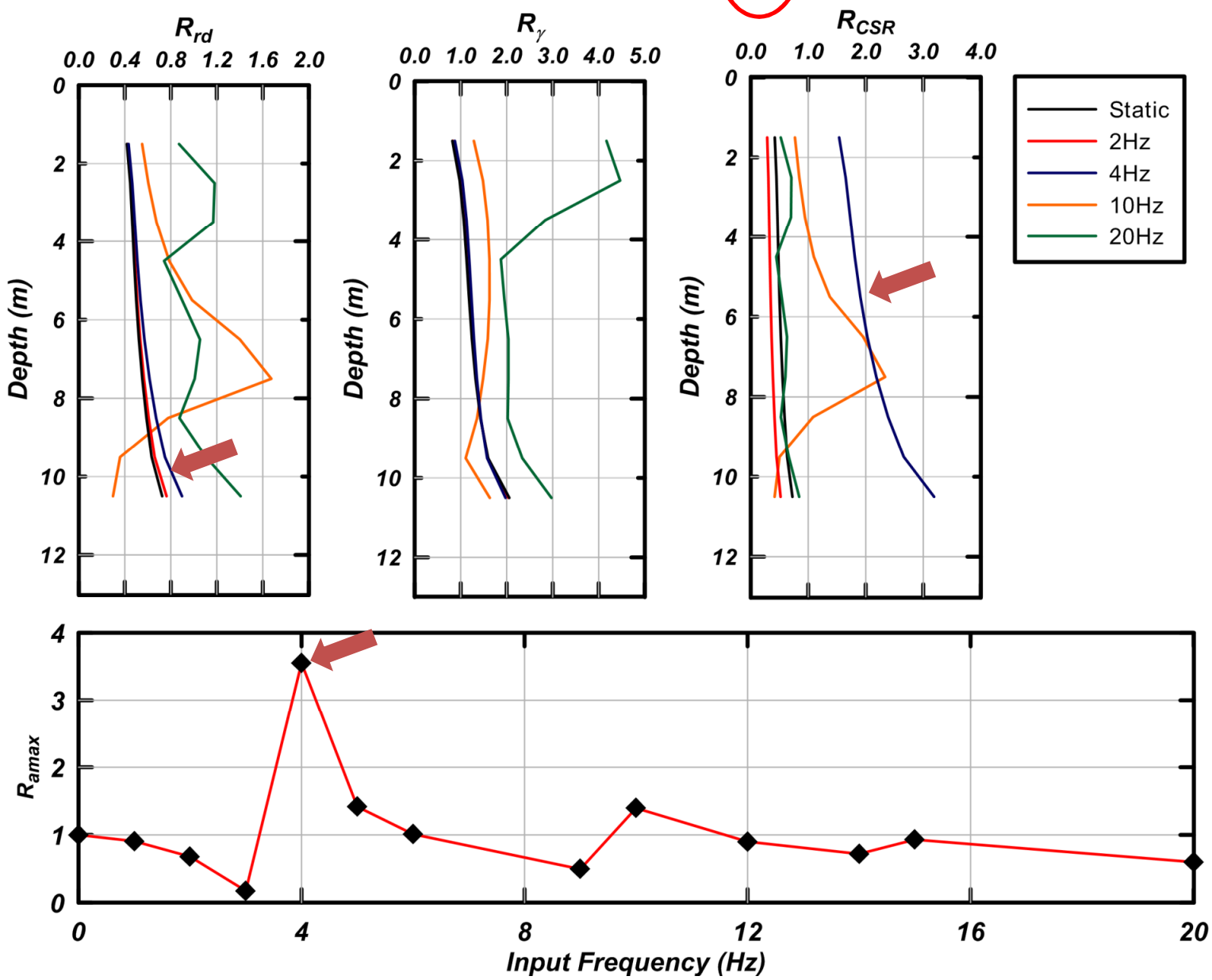
G_r=20.0



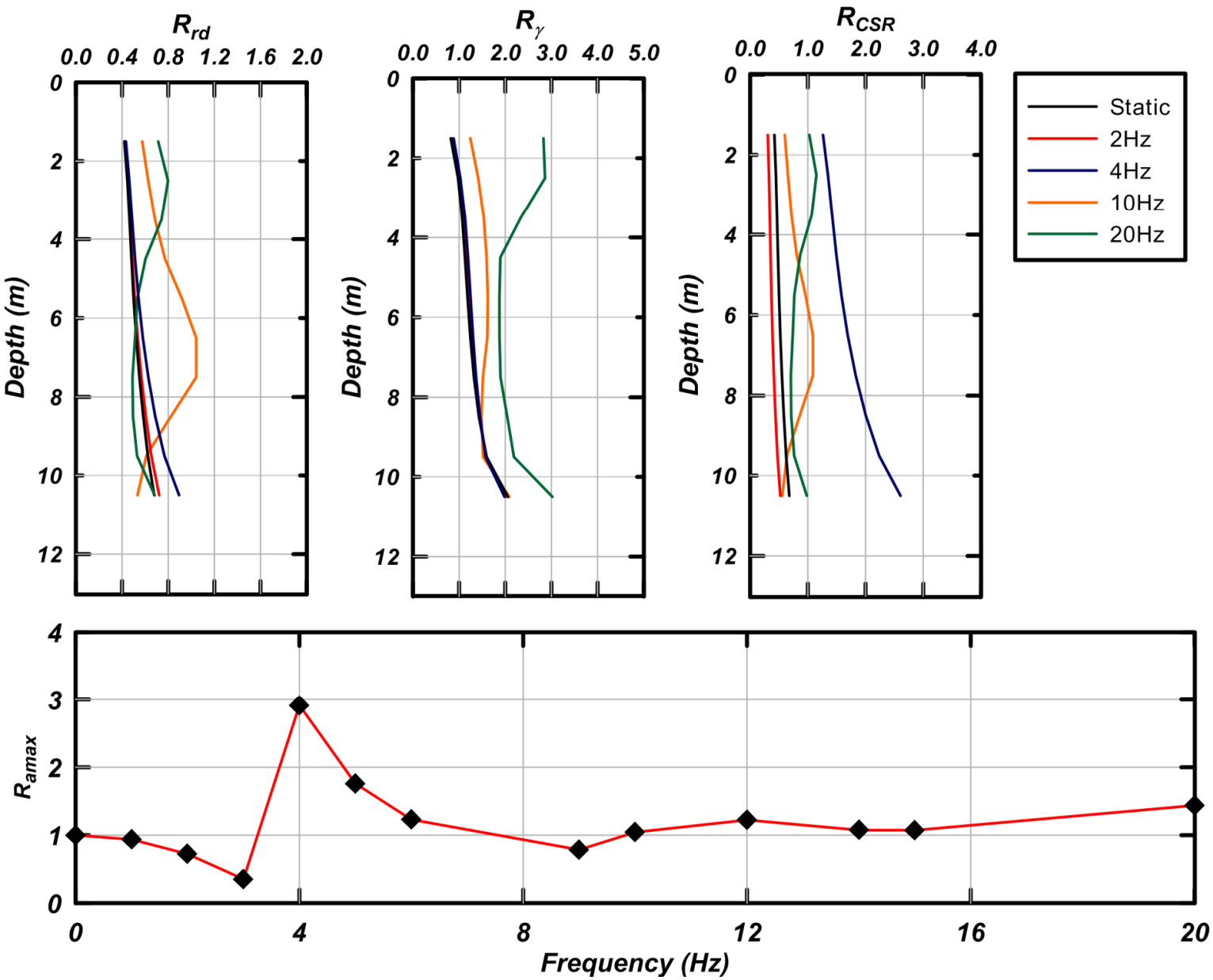


Result From Harmonic Base Shaking

A_r=20%, G_r=13.5 with 2% Damping

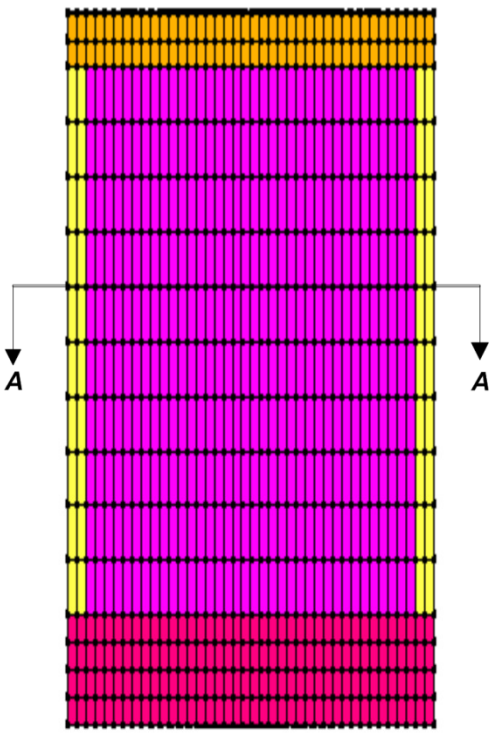


A_r=20%, G_r=13.5 with 10% Damping

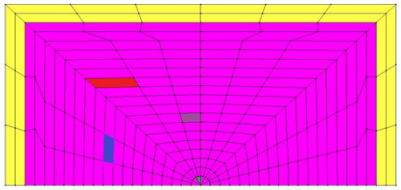


Earthquake Response

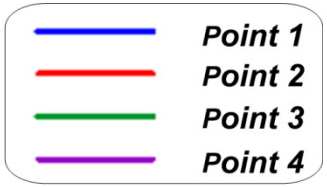
Response of Standard DSM Half Unit Cell Kocaeli Earthquake Motion

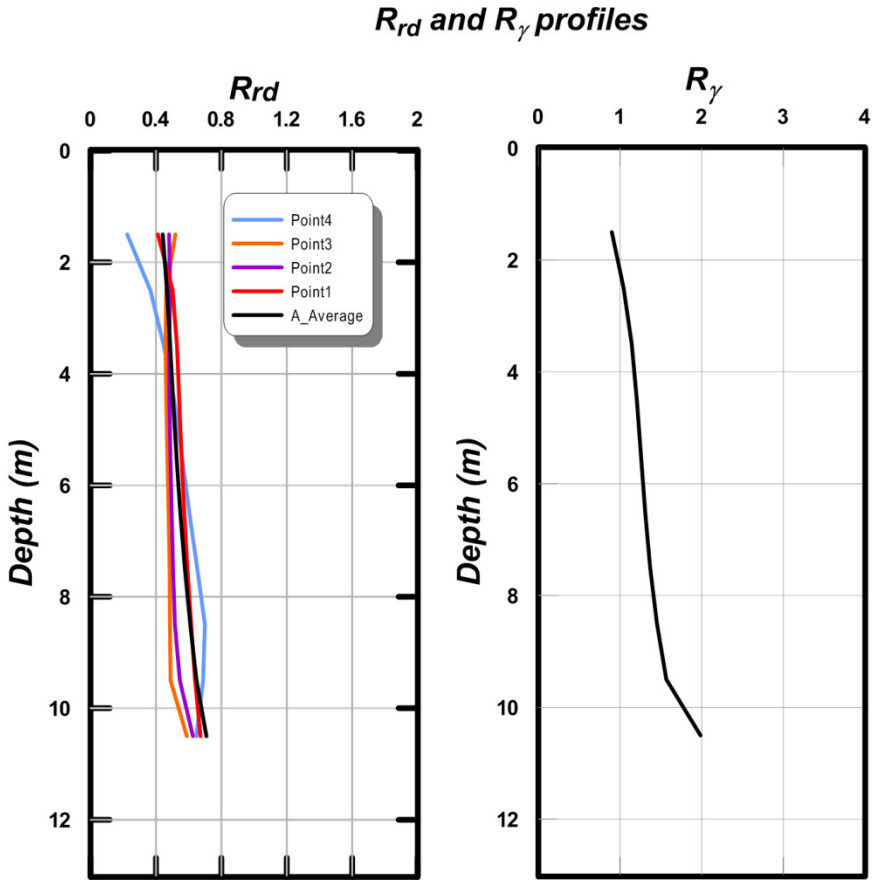


Front view of half unit cell

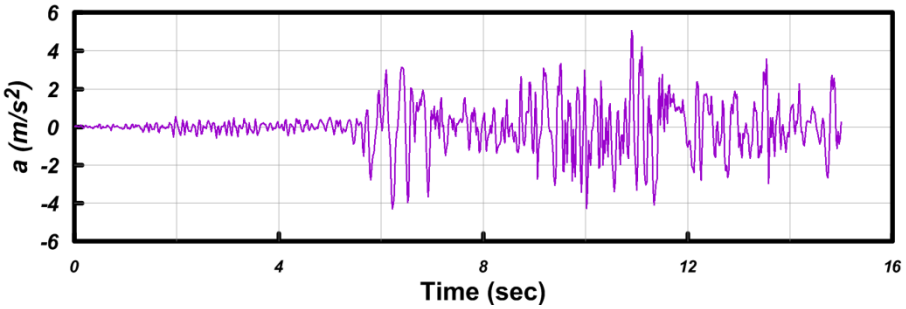


Plan view of half unit cell

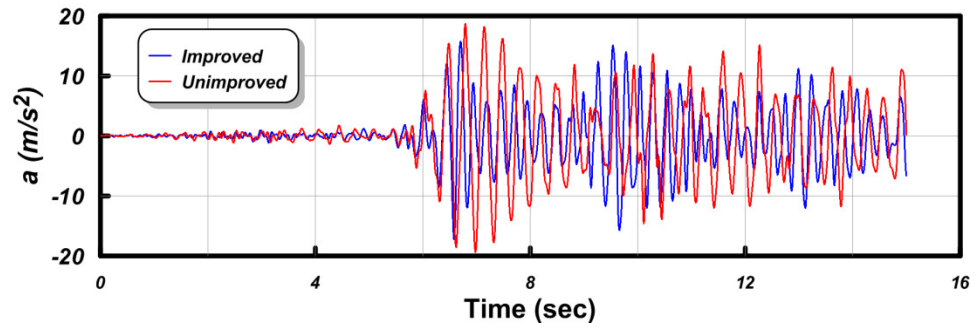


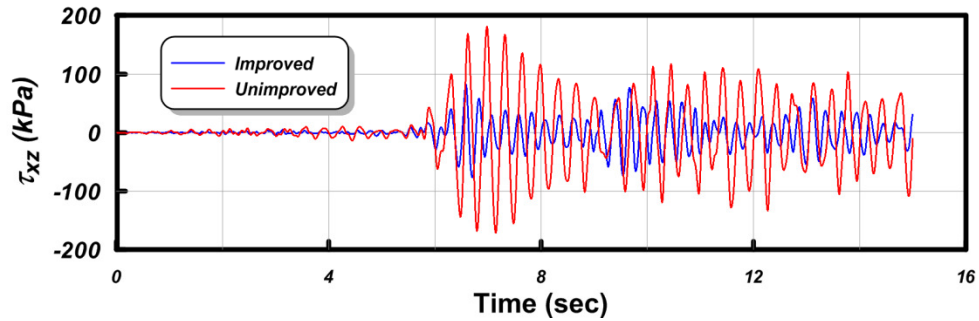


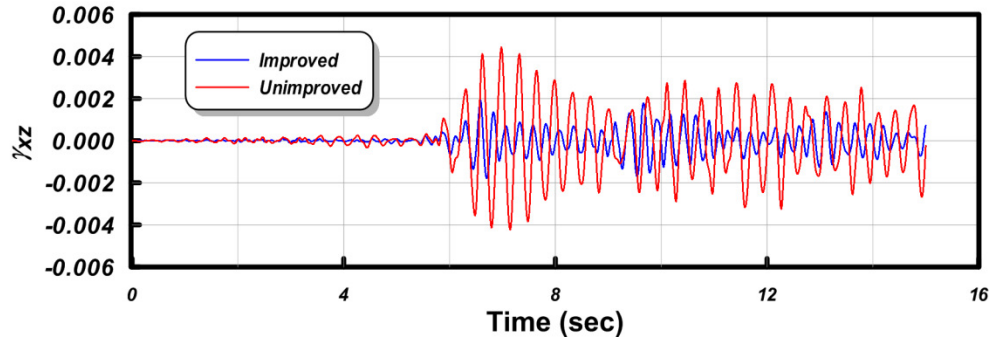
Time History Response of Cross Section **A-A**



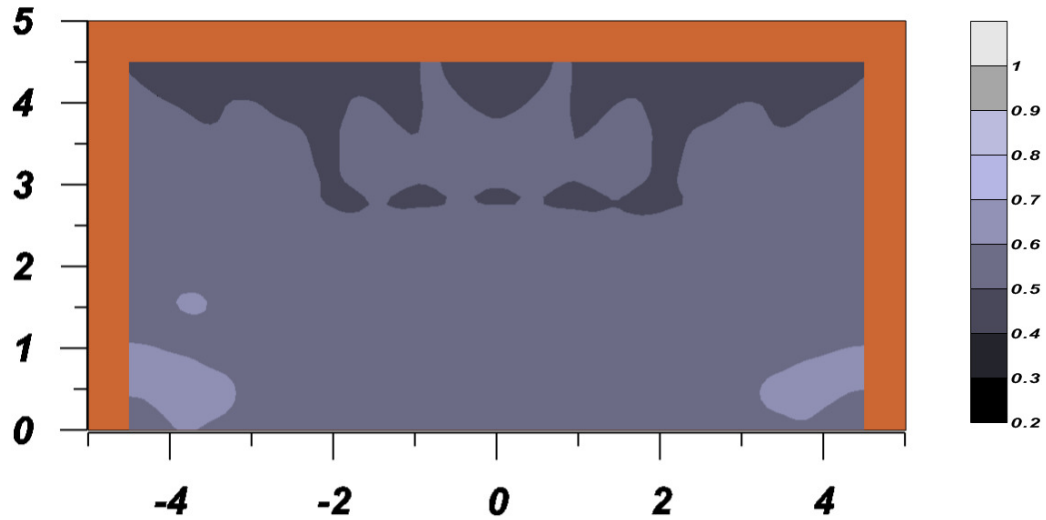
Input Motion Kocaeli Earthquake 1999



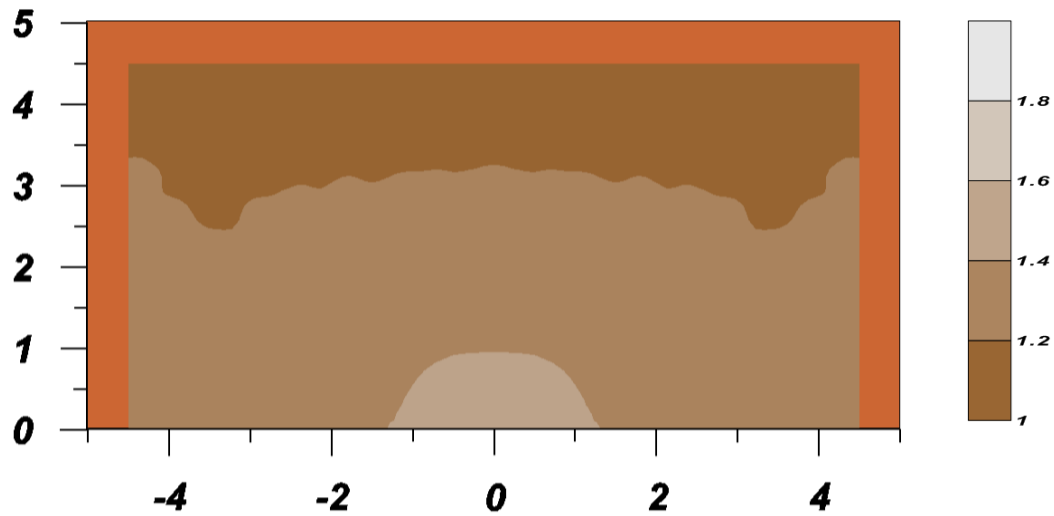




Spatial Variation of R_{rd} and $R\gamma$

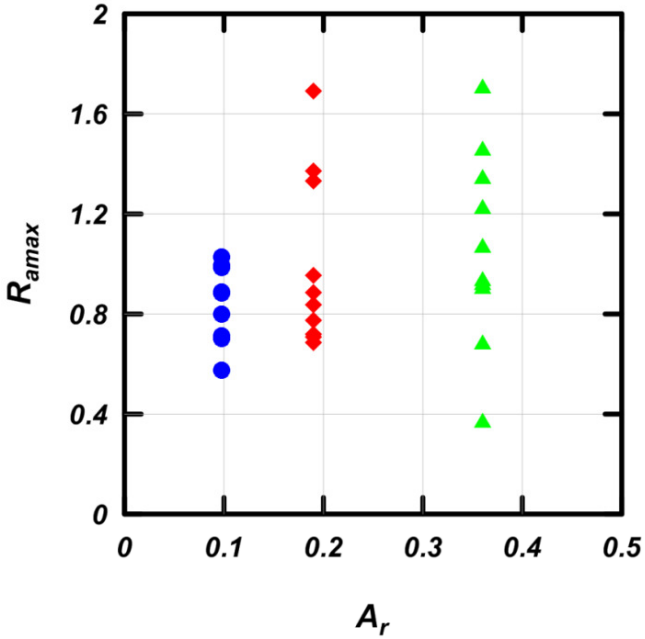


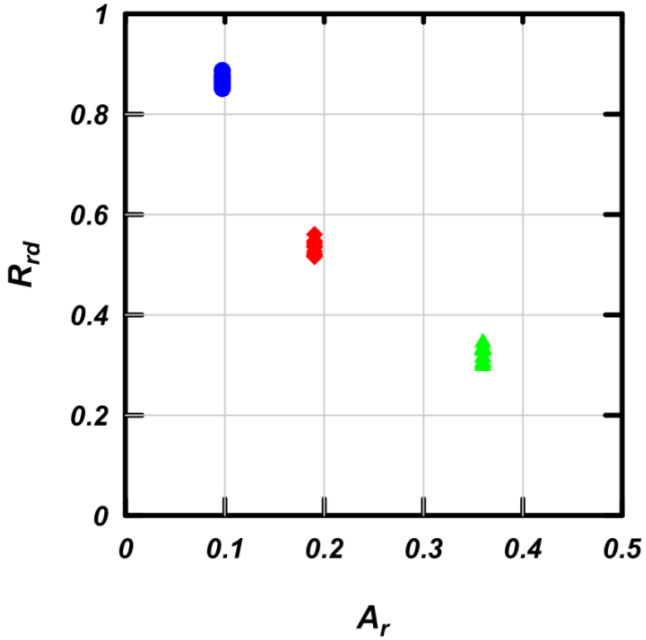
R_{rd} contour (cross section A-A)

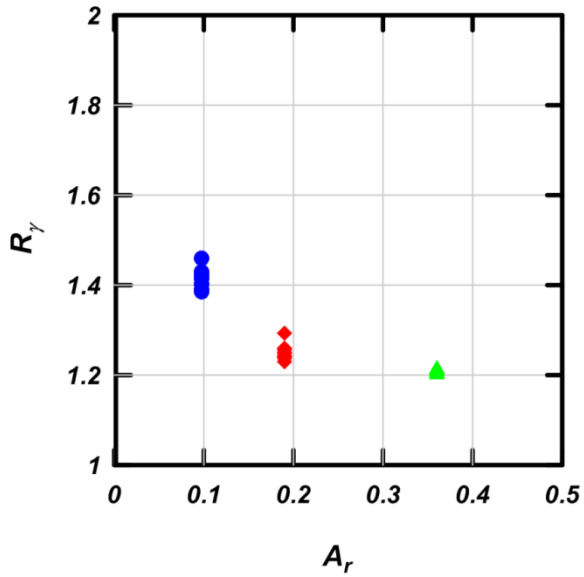


R_{γ} contour (cross section A-A)

Variation of Responses



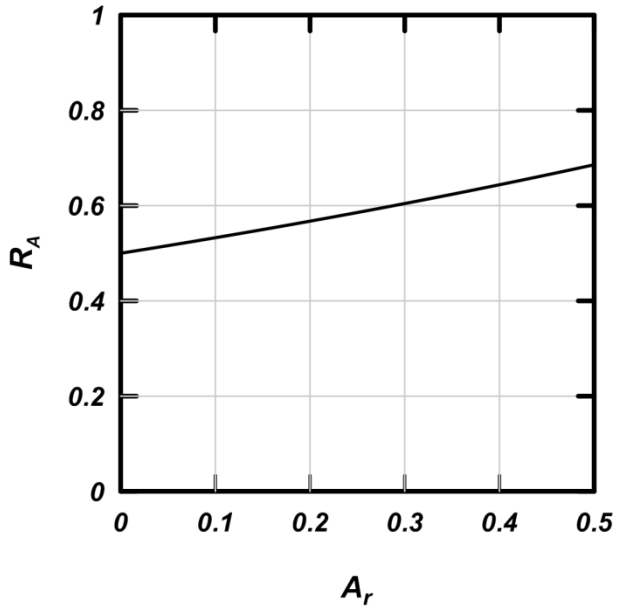


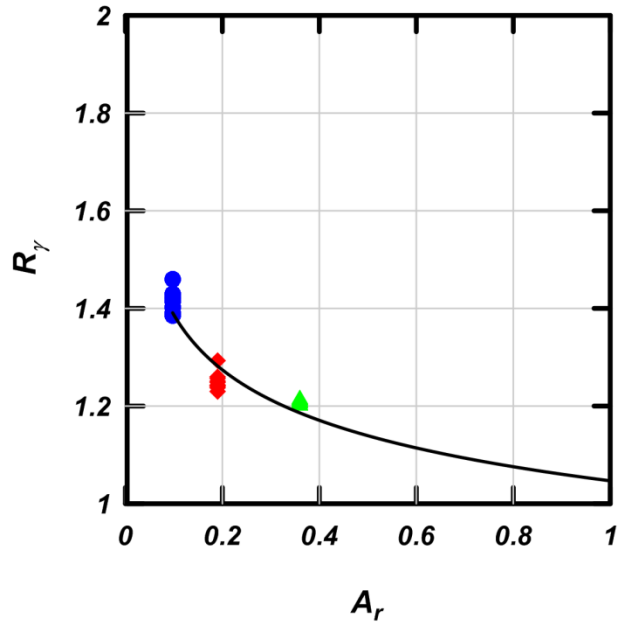


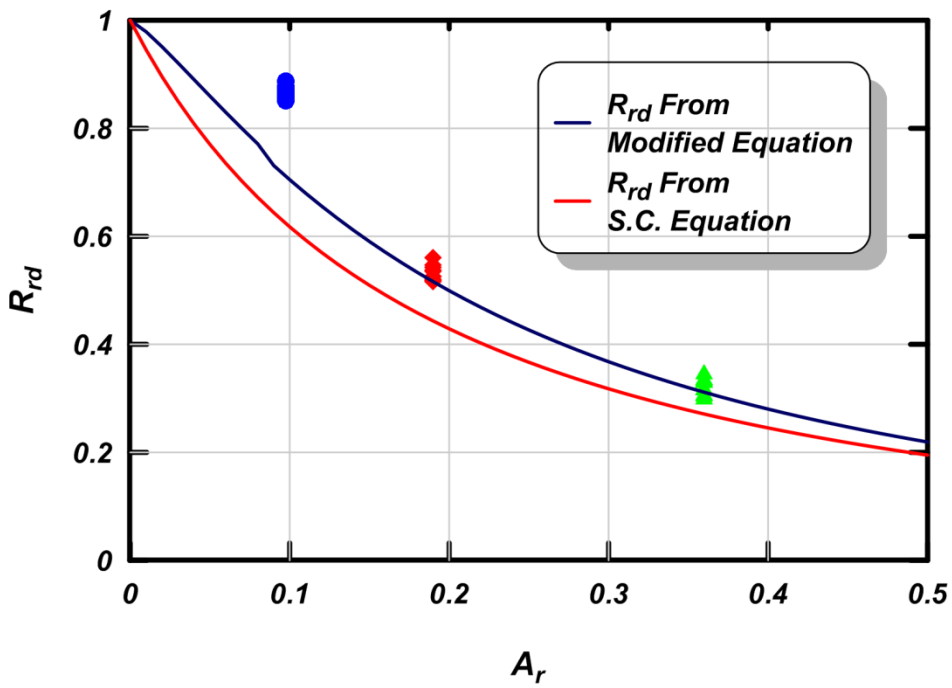
Proposed Design Relationship

Proposed Design Relationships (Preliminary)

G_r=13.5







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

$$R_A = 1 - 0.5\sqrt{1-A_r}$$

$$R_\gamma = 1.046 A_r^{-0.122}$$

SUMMARY

- DSM grids affect both:
  - seismic site response (e.g., a_{max})
  - seismic shear stress distributions (e.g. spatially averaged R_{rd})

  These two issues must be considered separately.

- The effect of DSM grids on seismic site response can be significant and may require site-specific analyses for design. OpenSeesPL platform may be used for this purpose.

- The reduction in seismic shear stresses provided by DSM grids can be significantly over-estimated by current design methods that assume shear strain compatibility.

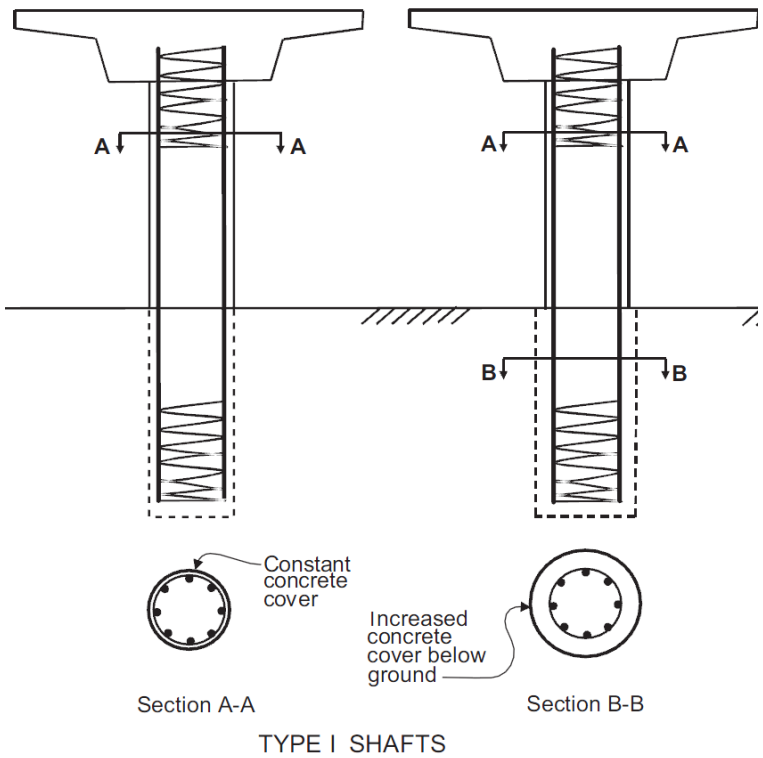
- A modified equation is proposed for estimating seismic shear stress reduction effects. The modified equations account for non-compatible shear strains and flexure in some wall panels. Currently, exploring $R\gamma$ as a function of both A_r and G_r.

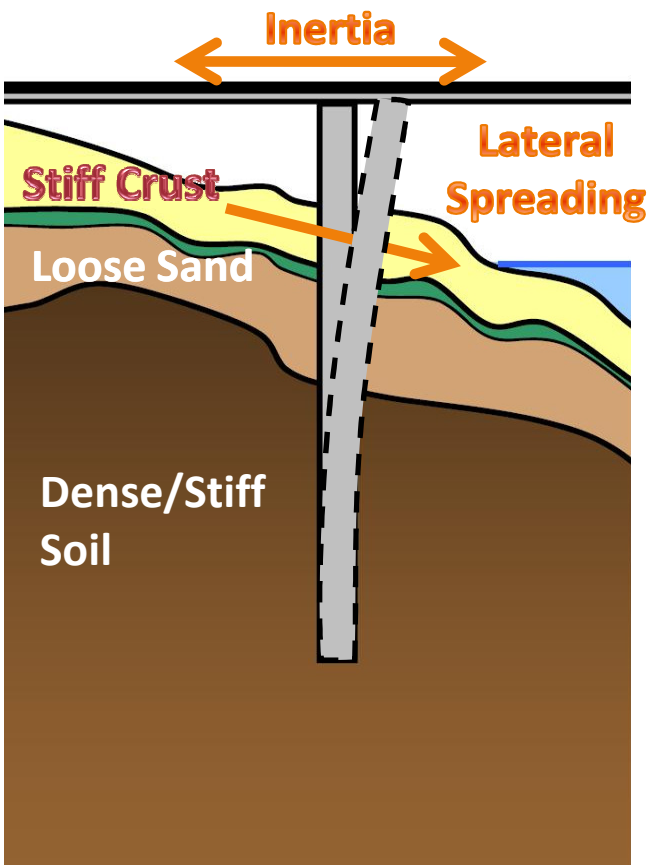
Thank You!
And
Questions

Design of Extended Pile Shafts for Liquefaction

(Arash Khosravifar, Graduate Student Researcher, UC Davis)

- **Large diameter extended pile shafts (2 to 3 m) can be an effective choice in areas of potential lateral spreading.**
- **How to design for effects of shaking and lateral spreading?**

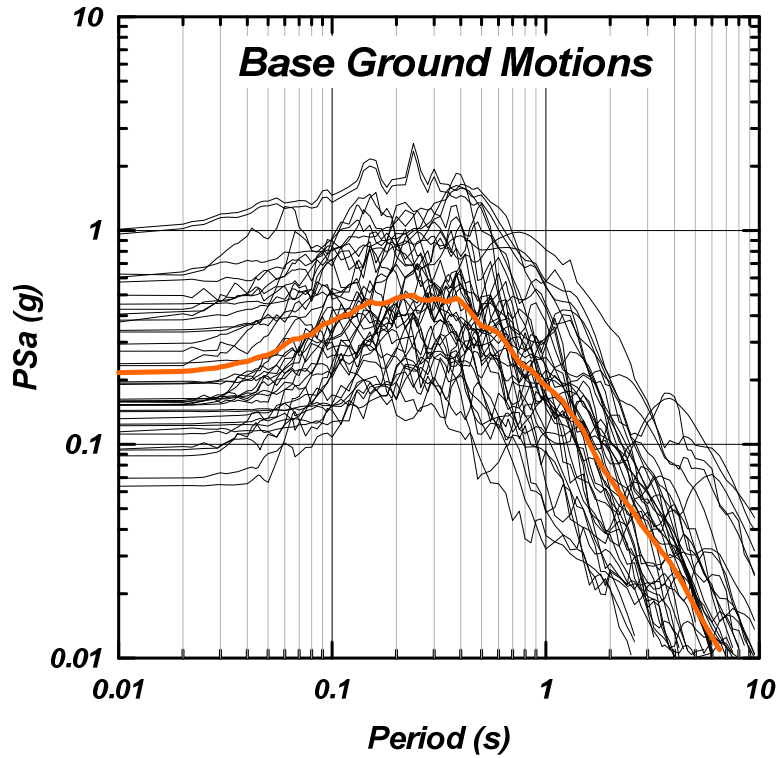




Nonlinear Dynamic Analysis (NDA)

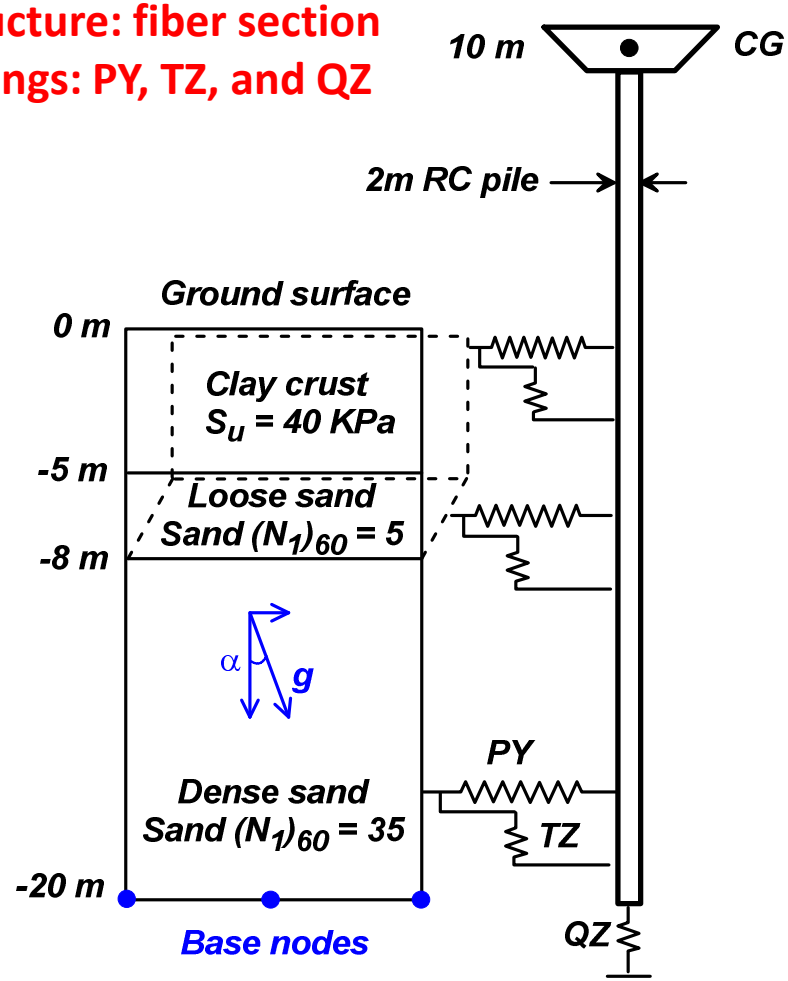
Input ground motions

- from Professor Jack Baker
- Broad-band rock site motions



FE model in Opensees

- Soil: PDMY02
- Structure: fiber section
- Springs: PY, TZ, and QZ



Calibration of the Soil Model (PDMY02 and PIMY)

Model parameters	Sand $(N_1)_{60}$=5	Sand $(N_1)_{60}$=35	Clay S_u = 40 KPa
$Material\ type$	PDMY02	PDMY02	PIMY
$Relative\ density, D_R*$	33%	87%	
$Density, \rho$	1.94 ton/m^3	2.06 ton/m^3	1.6 ton/m^3
$Reference\ pressure, p_r^{'}$	100 KPa	100 KPa	100 KPa
$Shear\ wave\ velocity, V_{s1}*$	141 m/s	210 m/s	
$Shear\ modulus, G_{max,1}*$	38.3 MPa	91.3 MPa	28 MPa
$Octahedral\ shear\ modulus, G_{max,1,oct}$	46.9 MPa	111.9 MPa	28 MPa
$Maximum\ shear\ strain, \gamma_{max,r}$	0.1	0.1	0.1
$Bulk\ modulus, B_r$	125.1 MPa	298.3 MPa	140 MPa
$Pressure\ dependent\ coeff., d$	0.5	0.5	0.0
$Frictoin\ angle, \varphi_{DSS}*$	30°	45°	0.0°
$Octahedral\ friction\ angle, \varphi_{oct}$	25.4°	42.2°	0.0°
$Phase\ transformation\ angle, \varphi_{PT}$	20°	32.2°	
$Contarction\ coeff., c_1$	0.06	0.001	
$Contarction\ coeff., c_2$	5.0	0.5	
$Contarction\ coeff., c_3$	0.2	0.0	
$Dilation\ coeff., d_1$	0.15	0.4	
$Dilation\ coeff., d_2$	3.0	3.0	
$Dilation\ coeff., d_3$	0.0	0.0	
liq_1	1.0	1.0	
liq_2	0.0	0.0	
$Number\ of\ Yield\ Surfaces, NYS$	20	20	20
$Cohesion, c$	0.1 KPa	0.1 KPa	34.6 KPa

Combination of Inertia and Lateral Spreading

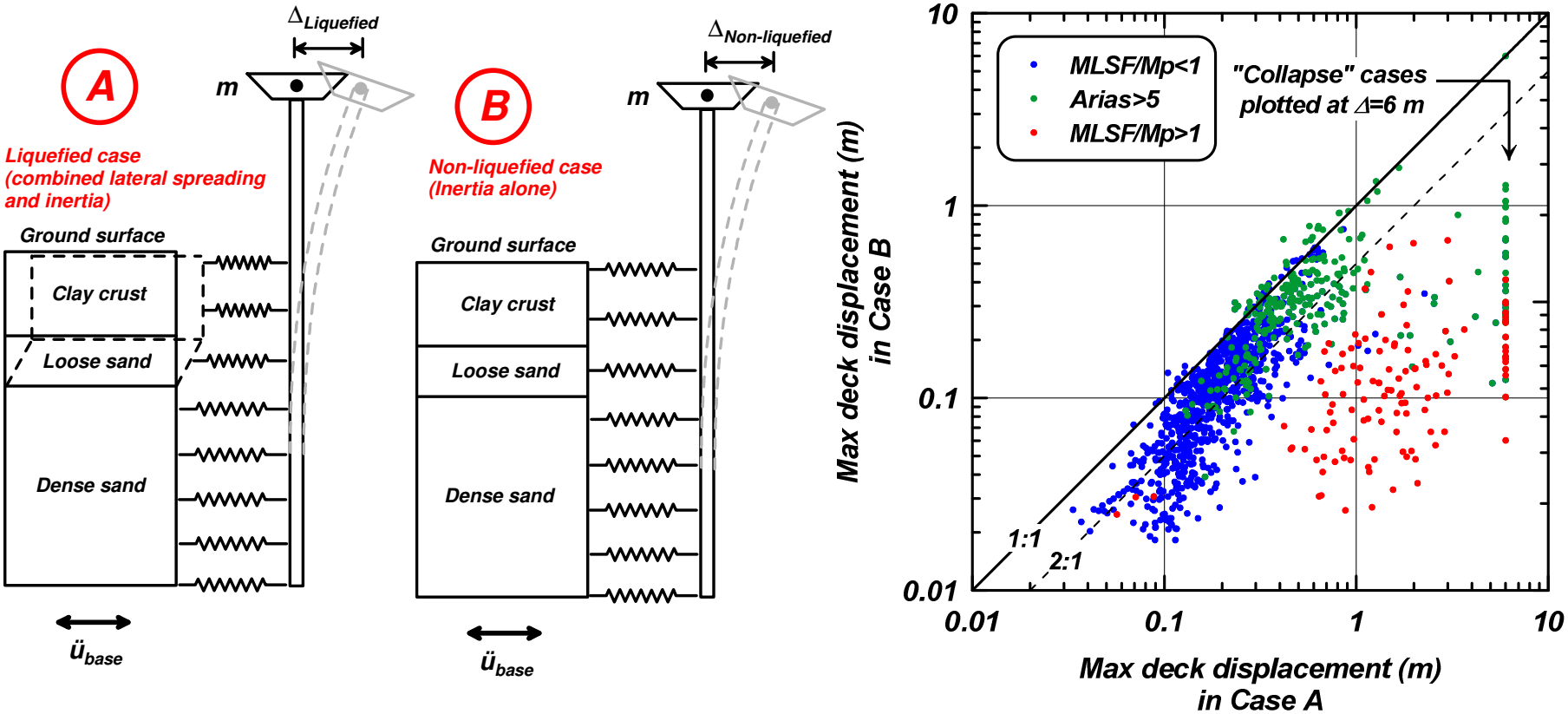
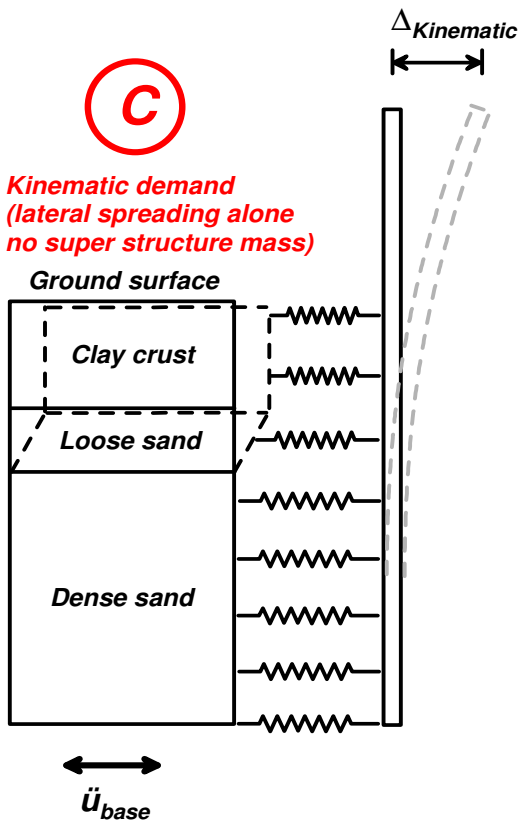


Figure. Liquefaction and the consequent lateral spreading produce higher demands compared to nonliquefied cases. The difference is significantly higher when $M_{LSF}/M_P>1$, or when the ground motion Arias Intensity is high.

Combination of Inertia and Lateral Spreading



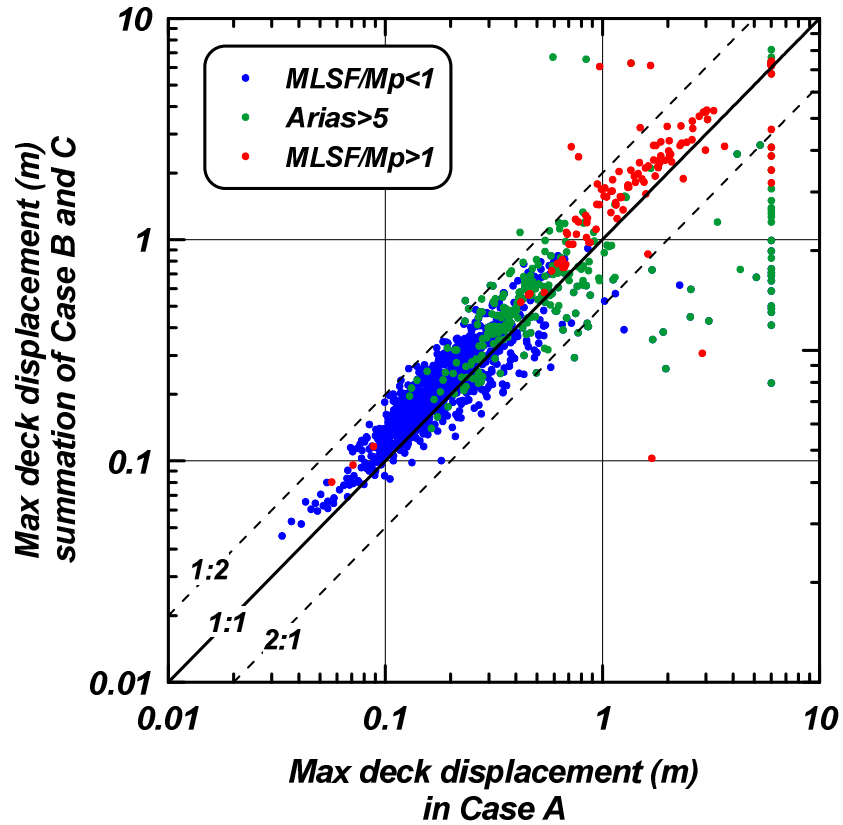
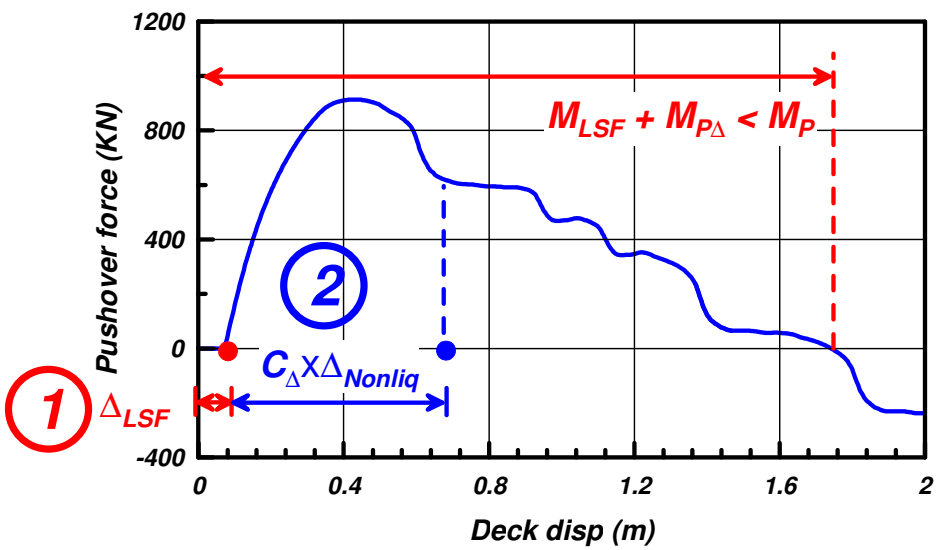
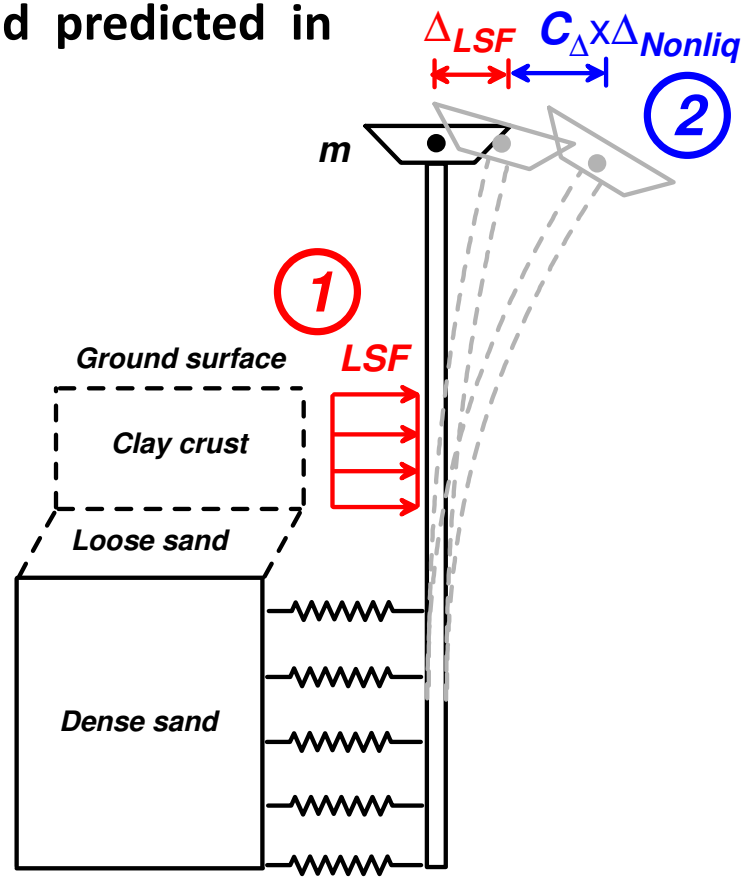


Figure. When $M_{LSF}/M_p>1$, the overall demands (Case A) can be captured by accounting for kinematic effects (Case C). However, for ground motions with high Arias intensity, overall demands (Case A) cannot be captured by adding demands from Case B and Case C.

Proposed Equivalent Static Analysis (ESA) for Liquefied Case

1. Apply full passive earth pressure from crust to get Δ_{LSF}
2. Impose an additional superstructure displacement $C_{\Delta L} x \Delta_{Nonliq}$, where Δ_{Nonliq} is the demand predicted in the absence of liquefaction.
3. Correct for PΔ effect.





Choice of C_Δ