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

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Figure: Photograph of a typical DSM grid

Figure: Close up view of DSM grid

Figure: 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 1: Photograph of a typical DSM grid

Figure 2: Idealized DSM grid

Figure 7: Artistic rendering of DSM grid

Figure: Close up view of DSM grid
Linear Elastic FE DSM Model

- DSM wall thickness = 1 m
- $V_s = 600 \text{ m/s, } \nu = 0.4$

Linear Elastic Soil Profile

DSM Half Unit Cell

Half DSM Unit Cell Mesh in OpenSeesPL
Equilibrium:
\[ \tau_{\text{ave}} A_T = \tau_s A_s + \tau_{\text{DSM}} A_{\text{DSM}} \]

Which can be rewritten in terms of shear strain and shear modulus
\[ \gamma_{\text{ave}} G_{\text{ave}} A_T = \gamma_s G_s A_s + \gamma_{\text{DSM}} G_{\text{DSM}} A_{\text{DSM}} \]

Define the area replacement ratio,
\[ A_r = A_{\text{DSM}} / A_T \]

Define the shear modulus ratio,
\[ G_r = G_{\text{DSM}} / G_s \]

Define shear strain ratio,
\[ R_\gamma = \gamma_s / \gamma_{\text{DSM}} \]
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

$$A_{er} = R_A A_r$$

where $R_A$ is the equivalent fraction of the DSM wall area that acts in shear.
The shear stress reduction ratio for a treated soil mass is

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

\[ S_G = \frac{1}{(1 - A_r) + \frac{R^A}{R^\gamma} G_r A_r} \]

For a special case of equation above when \( R_\gamma = 1 \) and \( R_A = 1 \), we have the familiar strain compatibility equation proposed by Baez et al (1990).
**Depth Reduction Ratio** ($R_{rd}$)

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

$$CSR_U = \left( \frac{\tau_s}{\sigma_v} \right)_U = \left[ 0.65 \left( \frac{a_{\text{max}}}{g} \right) \left( \frac{\sigma_v}{\sigma_v} \right) rd \right]_U$$  (Seed and Idriss 1972)

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

$$CSR_I = \left( \frac{\tau_s}{\sigma_v} \right)_I = \left[ 0.65 \left( \frac{a_{\text{max}}}{g} \right) \left( \frac{\sigma_v}{\sigma_v} \right) rd \right]_I$$  (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 \( R_{a_{\max}} = (a_{\max})_I/(a_{\max})_U \) 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 \( R_{a_{\max}} = 1 \)).

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

Nevertheless, commonly in practice \( S_G \) is often being used instead of \( R_{CSR} \) to estimated the benefits of DSM grids.
Result From Pseudo-Static Analysis
Spatial Variation

\[ R_{rd} \text{ contour (cross section A-A)} \]

\[ R_{\gamma} \text{ contour (cross section A-A)} \]
Standard DSM Half Unit Cell Under Pseudo-Static Analysis

Front view of half unit cell

Plan view of half unit cell

$R_{rd}$ and $R_\gamma$ profiles

Depth (m)

$R_{rd}$

Depth (m)

$R_\gamma$

Point 1
Point 2
Point 3
Point 4
A-Average
Shear Modulus Ratio $G_r=13.5$ and $20.0$
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
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)

$R_\gamma$ contour (cross section A-A)
Variation of Responses

![Graphs showing variation of responses](image)
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., $a_{\text{max}}$)
- 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)

<table>
<thead>
<tr>
<th>Model parameters</th>
<th>Sand (N(<em>1)(</em>{60})=5)</th>
<th>Sand (N(<em>1)(</em>{60})=35)</th>
<th>Clay (S_u = 40) KPa</th>
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<tr>
<td><strong>Material type</strong></td>
<td>PDMY02</td>
<td>PDMY02</td>
<td>PIMY</td>
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<td><strong>Relative density, (D_R^*)</strong></td>
<td>33%</td>
<td>87%</td>
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<td><strong>Density, (\rho)</strong></td>
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<td><strong>Reference pressure, (p'_r)</strong></td>
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<td>100 KPa</td>
<td>100 KPa</td>
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<td><strong>Shear wave velocity, (V_{s1}^*)</strong></td>
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<td>210 m/s</td>
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<td><strong>Shear modulus, (G_{\text{max,1}}^*)</strong></td>
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<td>91.3 MPa</td>
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<td><strong>Octahedral shear modulus, (G_{\text{max,1,oct}})</strong></td>
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<td>111.9 MPa</td>
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<td><strong>Phase transformation angle, (\varphi_{\text{PT}})</strong></td>
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<td>(\text{liq}_2)</td>
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<td>0.1 KPa</td>
<td>34.6 KPa</td>
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</tbody>
</table>
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 $\frac{M_{LSF}}{M_p}>1$, 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 $\Delta_{LSF}$
2. Impose an additional superstructure displacement $C_{\Delta_L} \times \Delta_{\text{Nonliq}}$, where $\Delta_{\text{Nonliq}}$ is the demand predicted in the absence of liquefaction.
3. Correct for $P\Delta$ effect.
Choice of $C_\Delta$

Model #1

Back calculated $C_\Delta$

Curvature ductility ($\mu$) in the combined load case (A)

$C_\Delta = 1.54$

Model #2

Back calculated $C_\Delta$

Curvature ductility ($\mu$) in the combined load case (A)

$C_\Delta = 0.9\mu^{0.9}$