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Numerical modeling of liquefaction effects:

Development & initial applications of a sand plasticity model

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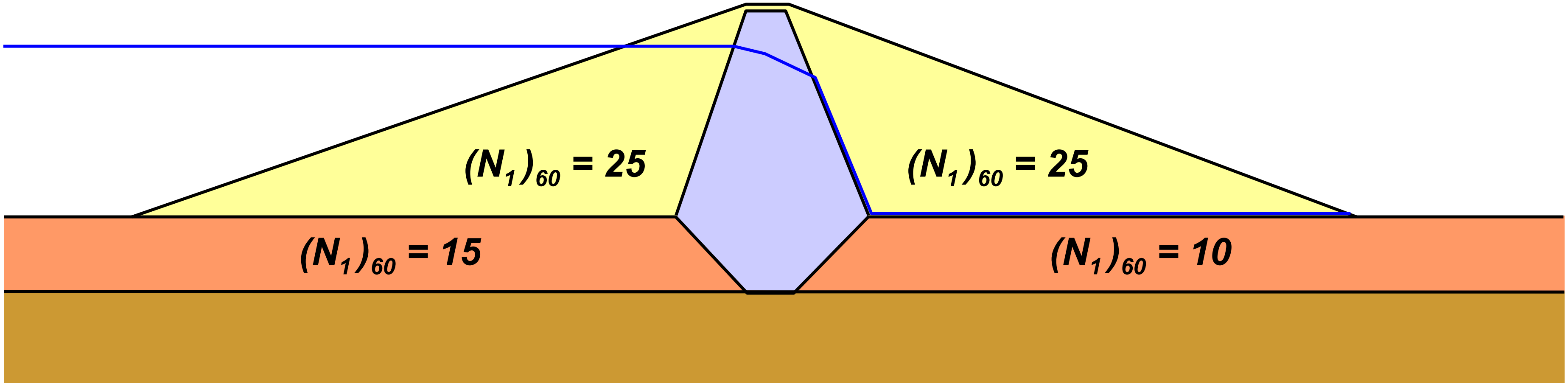
PM4-Sand:
A sand plasticity model for nonlinear seismic deformation analyses

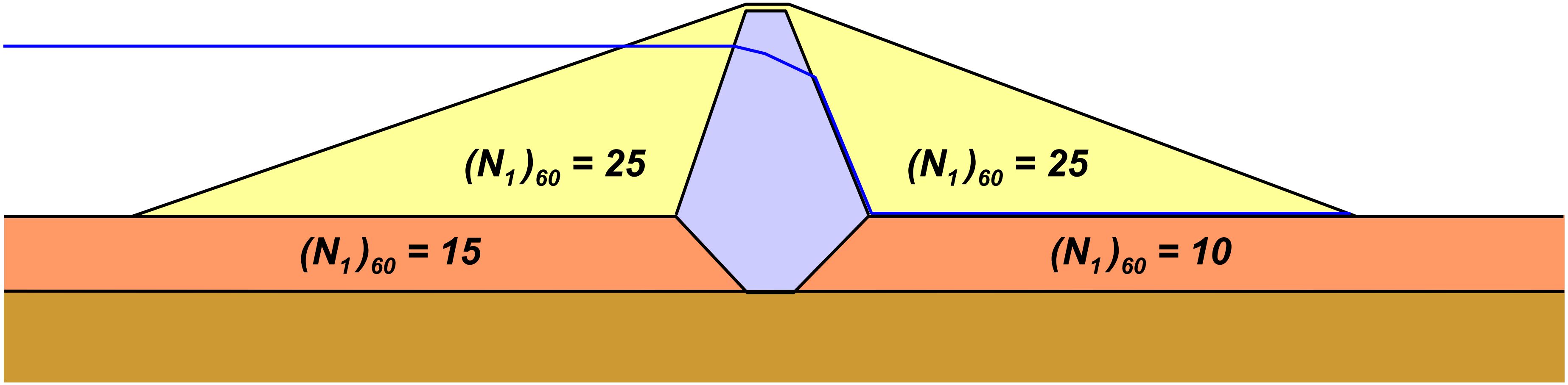
The challenge for a constitutive model

- ***Varied conditions:***
  - ***Loose to dense zones***
  - ***Drained to undrained loading***
  - ***Low to high confining stresses***
  - ***Low to high initial static shear stress ratios***
- ***Common data: V_s, N_{60}, q_c, gradations***

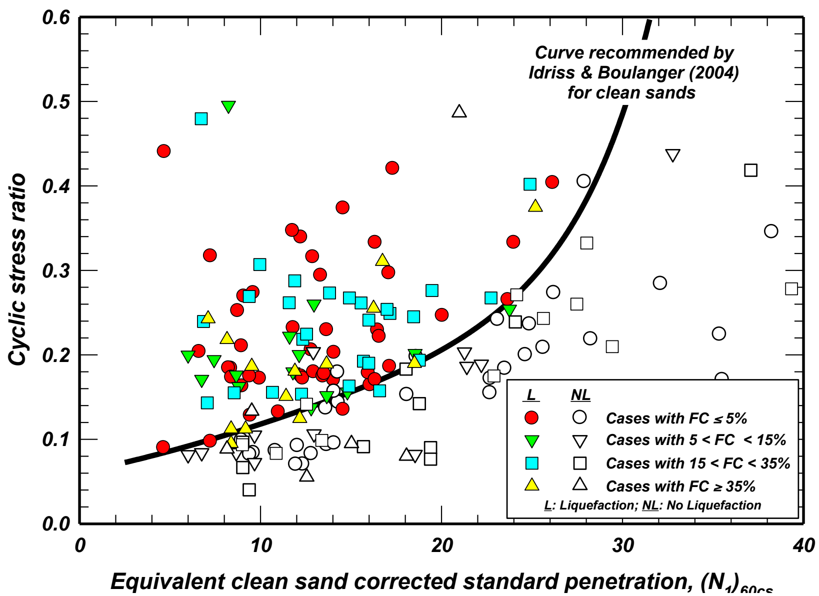


The challenge for a constitutive model

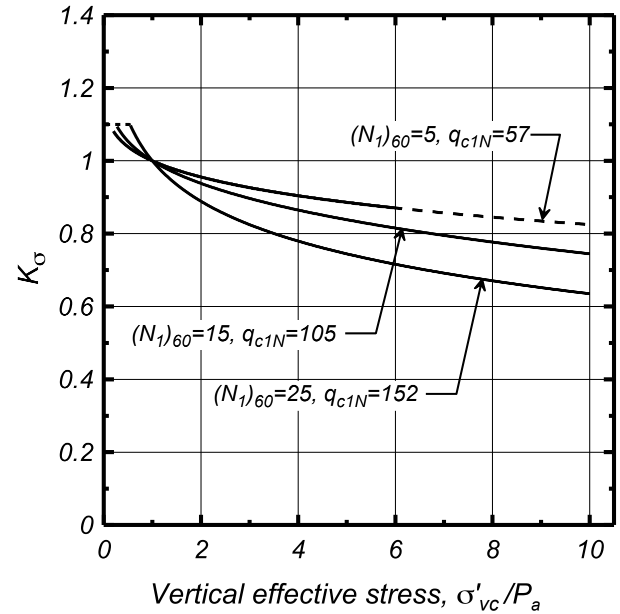
- ***Calibration to design correlations:***
  - ***Triggering & cyclic mobility/ratcheting***
  - ***G/G_{max} and damping***
  - ***Strengths***
  - ***Others depending on the structure (e.g., volumetric strains)***



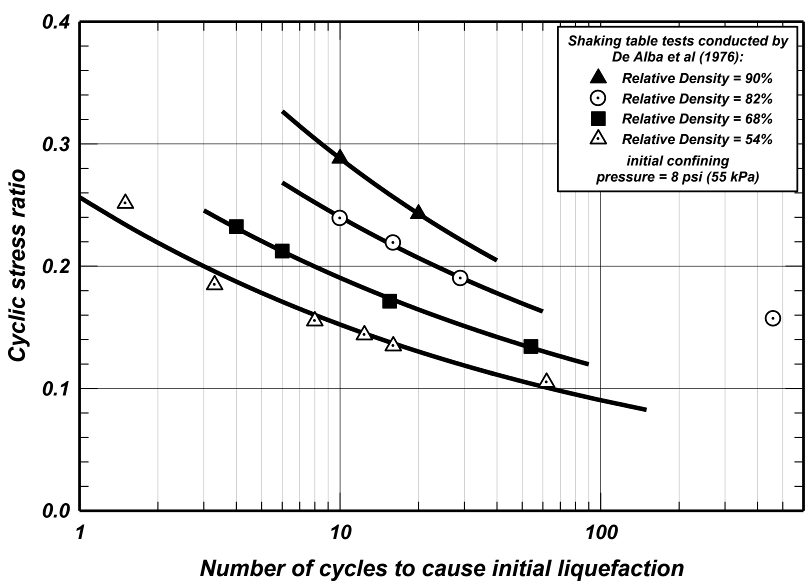
Triggering



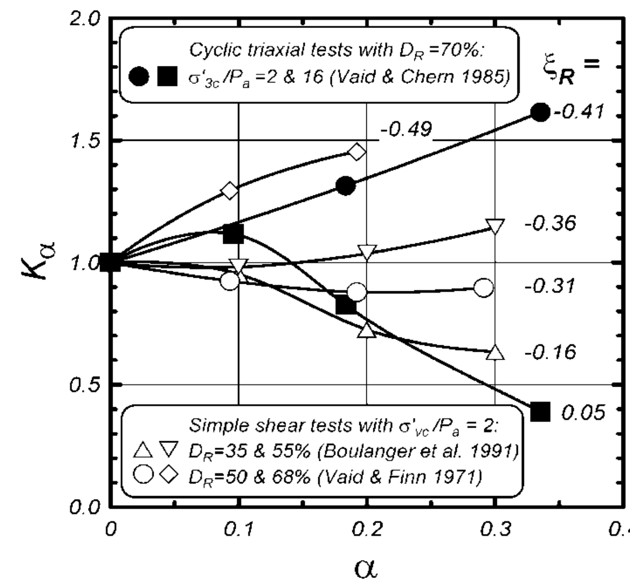
Curve recommended by Idriss & Boulanger (2004) for clean sands
Cyclic stress ratio
Equivalent clean sand corrected standard penetration, $(N_1)_{60cs}$
L
NL
Cases with FC ≤ 5%
Cases with 5 < FC < 15%
Cases with 15 < FC < 35%
Cases with FC ≥ 35%
L: Liquefaction; NL: No Liquefaction



K_σ
$(N_1)_{60}$=5, q_{c1N}=57
$(N_1)_{60}$=15, q_{c1N}=105
$(N_1)_{60}$=25, q_{c1N}=152
Vertical effective stress, σ'_{vc}/P_a



Shaking table tests conducted by De Alba et al (1976):
Relative Density = 90%
Relative Density = 82%
Relative Density = 68%
Relative Density = 54%
initial confining pressure = 8 psi (55 kPa)
Cyclic stress ratio
Number of cycles to cause initial liquefaction



Cyclic triaxial tests with D_R =70%:
σ'_{3c}/P_a =2 & 16 (Vaid & Chern 1985)
ξ_R =
-0.41
-0.49
-0.36
-0.31
-0.16
0.05
K_α
Simple shear tests with σ'_{vc}/P_a = 2:
D_R=35 & 55% (Boulanger et al. 1991)
D_R=50 & 68% (Vaid & Finn 1971)
α

Plasticity model for sand – Starting point

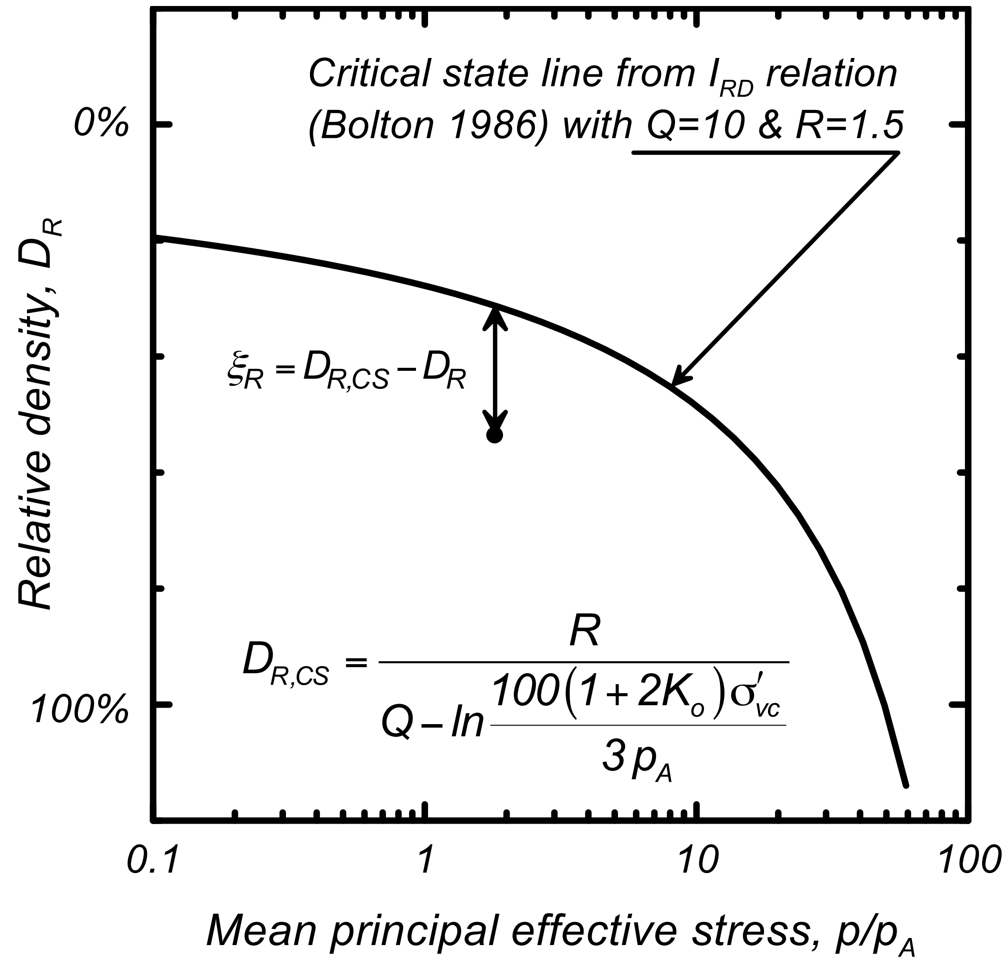
- ***Starts with framework of Dafalias-Manzari (2004) model***
  - ***Critical state, stress-ratio based***
  - ***Bounding and dilation surfaces rotate with changes in state***
  - ***Fabric tensor used to enhance contraction rates***

Plasticity model for sand – Modifications

- ***Modified & calibrated at equation level to approximate design correlations for practice***
  - ***Modified fabric tensor to depend on plastic shear strains***
  - ***Added fabric history, including cumulative fabric term***
  - ***Plastic modulus (K_p), elastic moduli (G), and dilatancy (D) depend on fabric and fabric history***
  - ***D constrained by Bolton's (1986) dilatancy relationship***
  - ***Recast in terms of relative state parameter index (ξ_R)***
  - ***Inclusion of sedimentation effects***
  - ***Modified logic for updating initial back-stress ratio***
  - ***Neglects Lode Angle dependence***
- ***Implemented as a user-defined material model in FLAC (Itasca 2010)***

Relative state parameter index

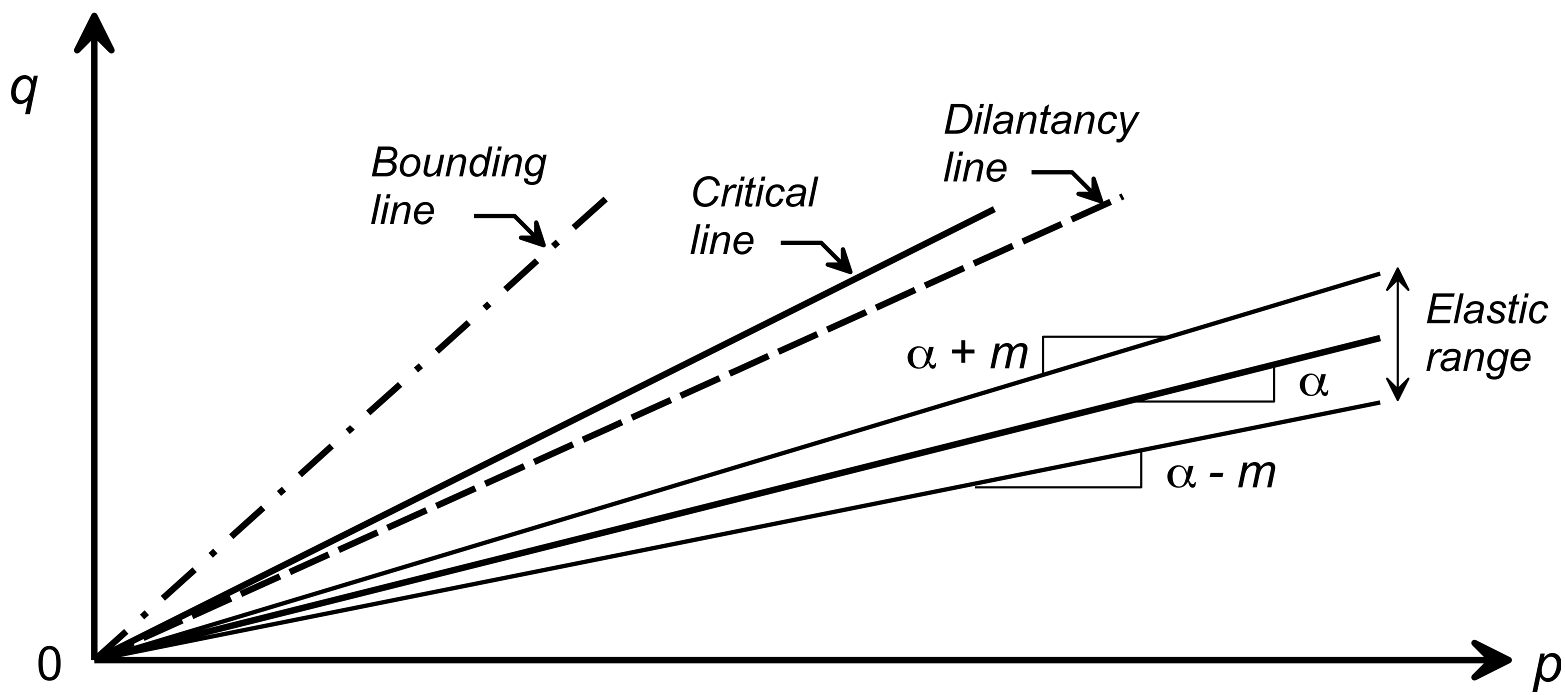
- ***Practical means for including critical state framework***



Stress ratio based

- **Dilatancy & bounding surfaces collapse to M at critical state ($\xi_R = 0$)**

$$M^b = M \cdot exp\left(-n^b \xi_R\right) \qquad M^d = M \cdot exp\left(n^d \xi_R\right)$$



Fabric effects

- **Fabric**

$$d\mathbf{z} = -\frac{c_z}{1+\left\langle \frac{z_{cum}}{2z_{max}} - 1 \right\rangle} \frac{\left\langle -d\varepsilon_v^p \right\rangle}{D} \left(z_{max}\mathbf{n} + \mathbf{z} \right)$$

- **Elastic modulus**

$$G = G_o p_A \left(\frac{p}{p_A} \right)^{1/2} C_{SR} \left(\frac{1+\frac{z_{cum}}{4z_{max}}}{1+\frac{z_{cum}}{4z_{max}} C_{DG}} \right)$$

- **Plastic modulus**

$$K_p = G \cdot h_o \cdot \frac{\left[\left(\boldsymbol{\alpha}^b - \boldsymbol{\alpha} \right) : \mathbf{n} \right]^{0.5}}{\left[exp\left(\boldsymbol{\alpha} - \boldsymbol{\alpha}_{in} \right) : \mathbf{n} - 1 \right] + C_{\gamma 1}} \cdot \frac{C_{K\alpha}}{1 + C_{Kp} \left(\frac{z_{peak}}{z_{max}} \right) \left\langle \left(\boldsymbol{\alpha}^b - \boldsymbol{\alpha} \right) : \mathbf{n} \right\rangle}$$

- **Dilatancy**

$$D = A_d \cdot \left[\left(\boldsymbol{\alpha}^d - \boldsymbol{\alpha} \right) : \mathbf{n} \right]$$

$$A_d = \frac{A_{do}\left(C_{zin2} \right)}{\left(\frac{z_{cum}^2}{z_{max}} \right) \left(1 - \frac{\left\langle -\mathbf{z} : \mathbf{n} \right\rangle}{\sqrt{2} \cdot z_{peak}} \right)^3 \left(C_\varepsilon \right) \left(C_{pzp} \right) \left(C_{p\,min} \right) \left(C_{zin1} \right) + 1}$$

$$D = A_{dc} \cdot \left[\left(\boldsymbol{\alpha} - \boldsymbol{\alpha}^{in} \right) : \mathbf{n} + C_{in} \right]^2 \frac{\left(\boldsymbol{\alpha}^d - \boldsymbol{\alpha} \right) : \mathbf{n}}{\left(\boldsymbol{\alpha}^d - \boldsymbol{\alpha} \right) : \mathbf{n} + C_D}$$

$$A_{dc} = \frac{A_{do}}{h_p} \qquad A_{dc} = f\left(\mathbf{z}, \xi_R, \ldots \right)$$

Functionality versus simplicity

- Simple parts, easy to understand

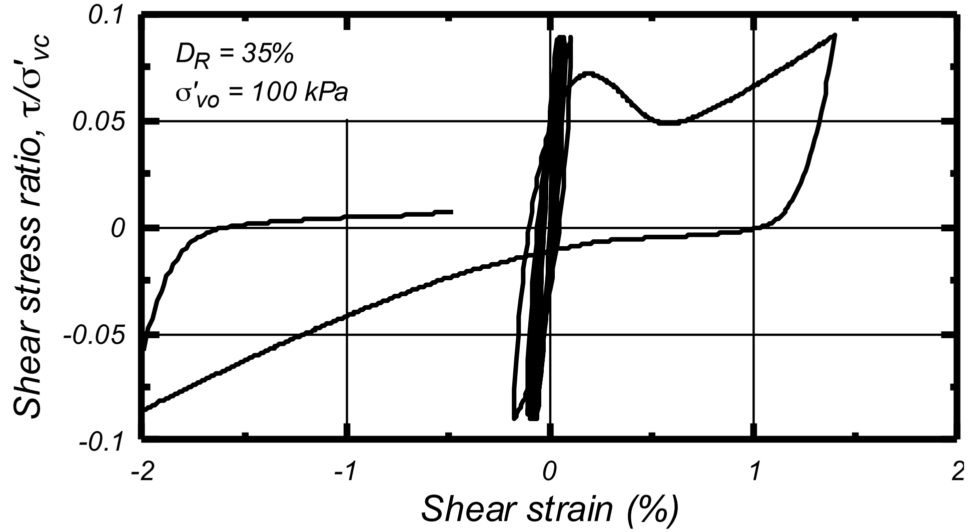
- Rides well

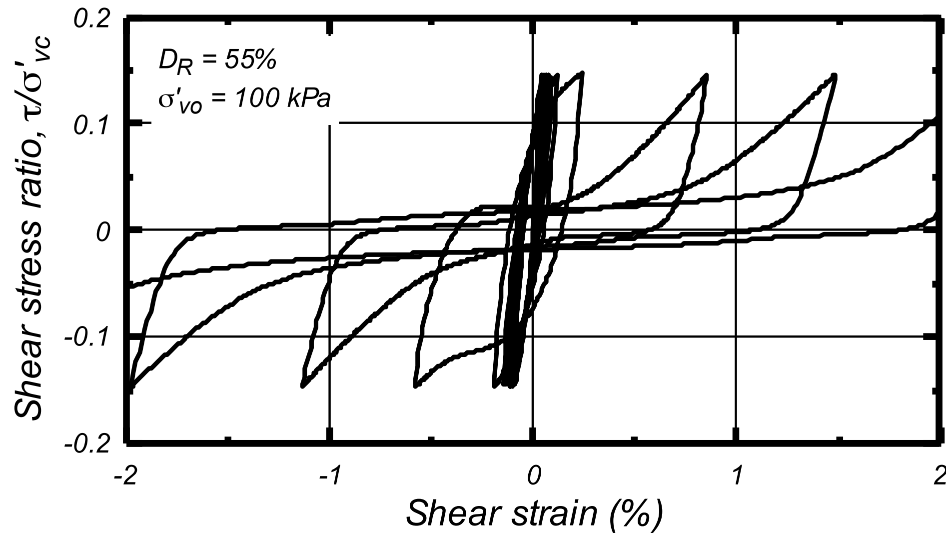
Parameters

- ***Relative density (D_R)***
  - ***Estimate from SPT or CPT; adjusts stress-strain responses***
- ***Shear modulus coefficient (G_o)***
  - ***Calibrate to in-situ V_s data or correlations***
- ***Contraction rate parameter (h_{po})***
  - ***Calibrate to CRR estimated from SPT- or CPT-based liquefaction correlations***

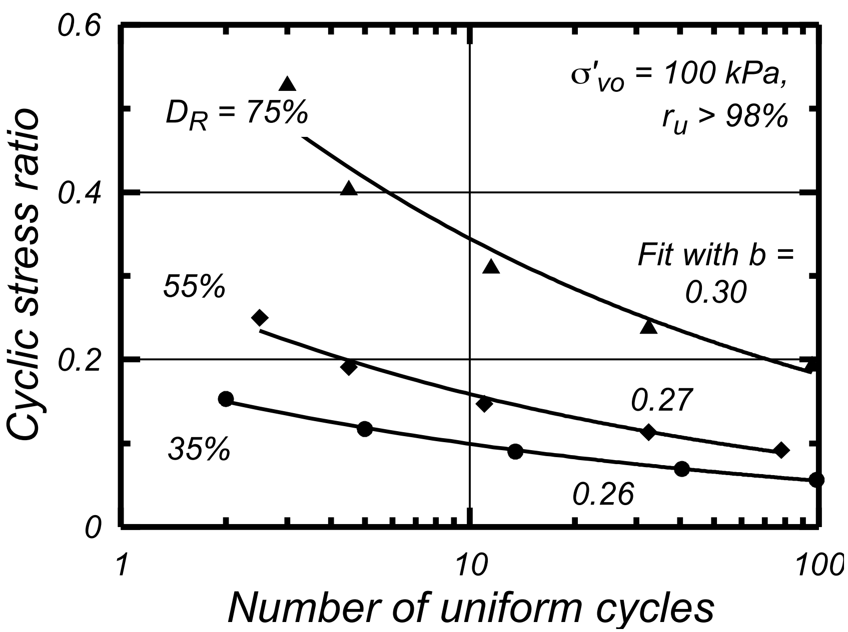
- ***Secondary parameters***
  - ***18 secondary parameters with default values chosen to approximate design correlations***

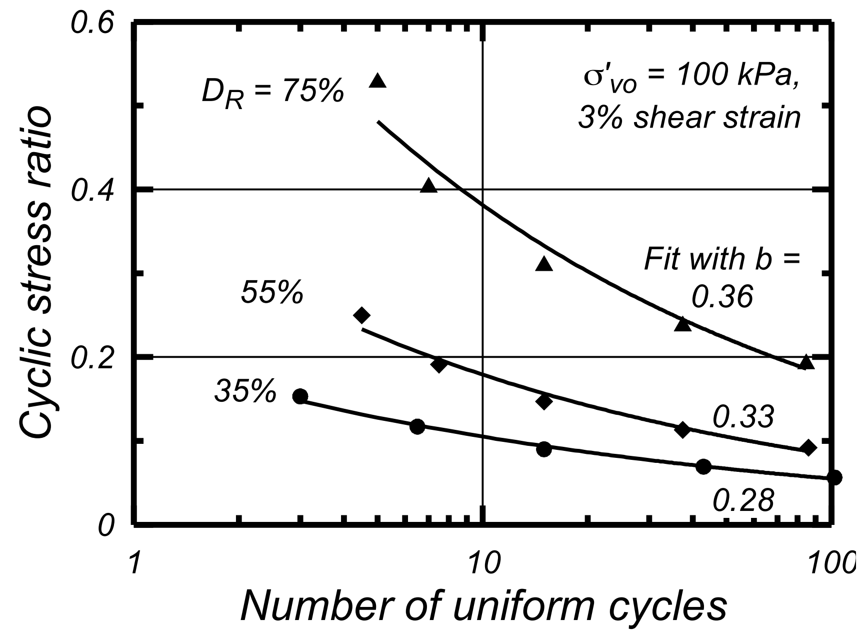
Example responses



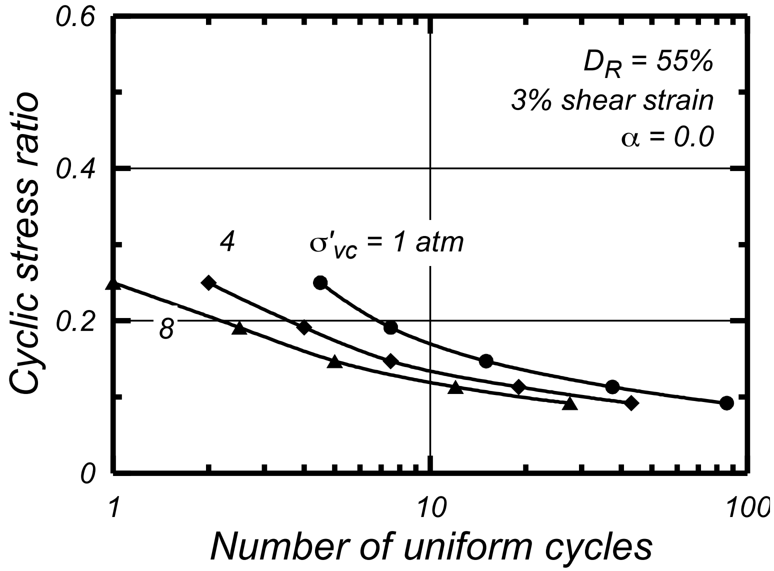


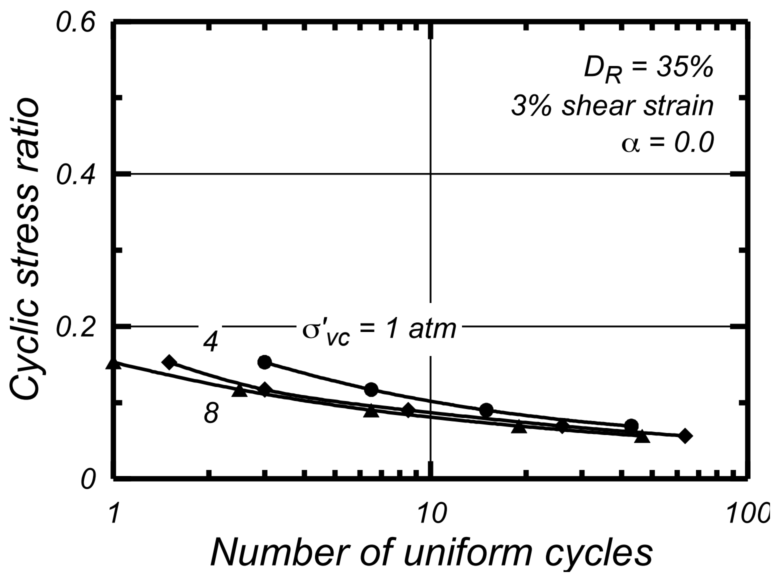
Example responses

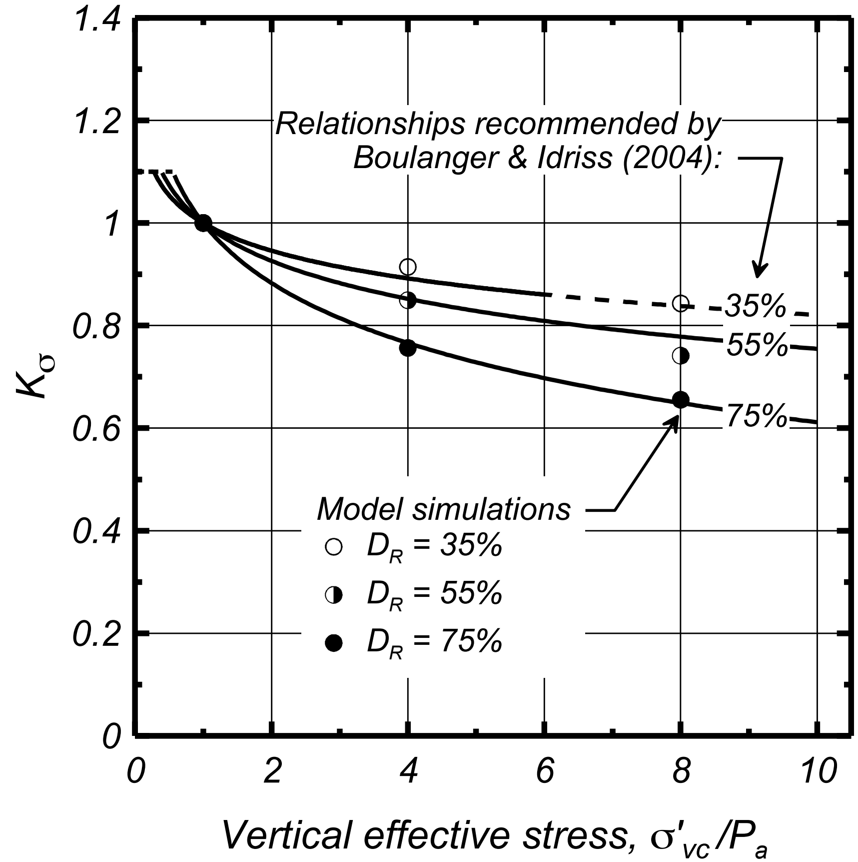




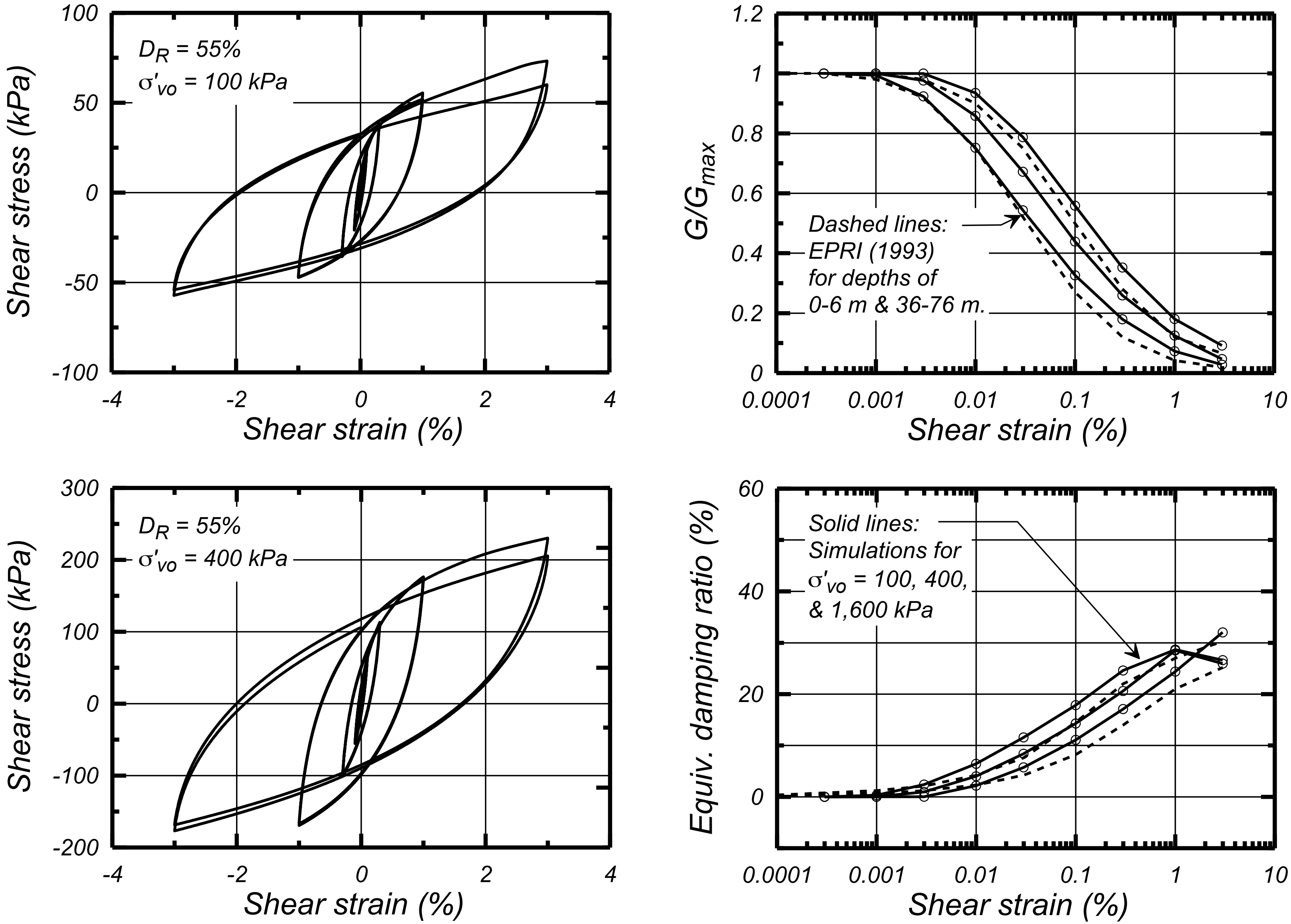
Example responses





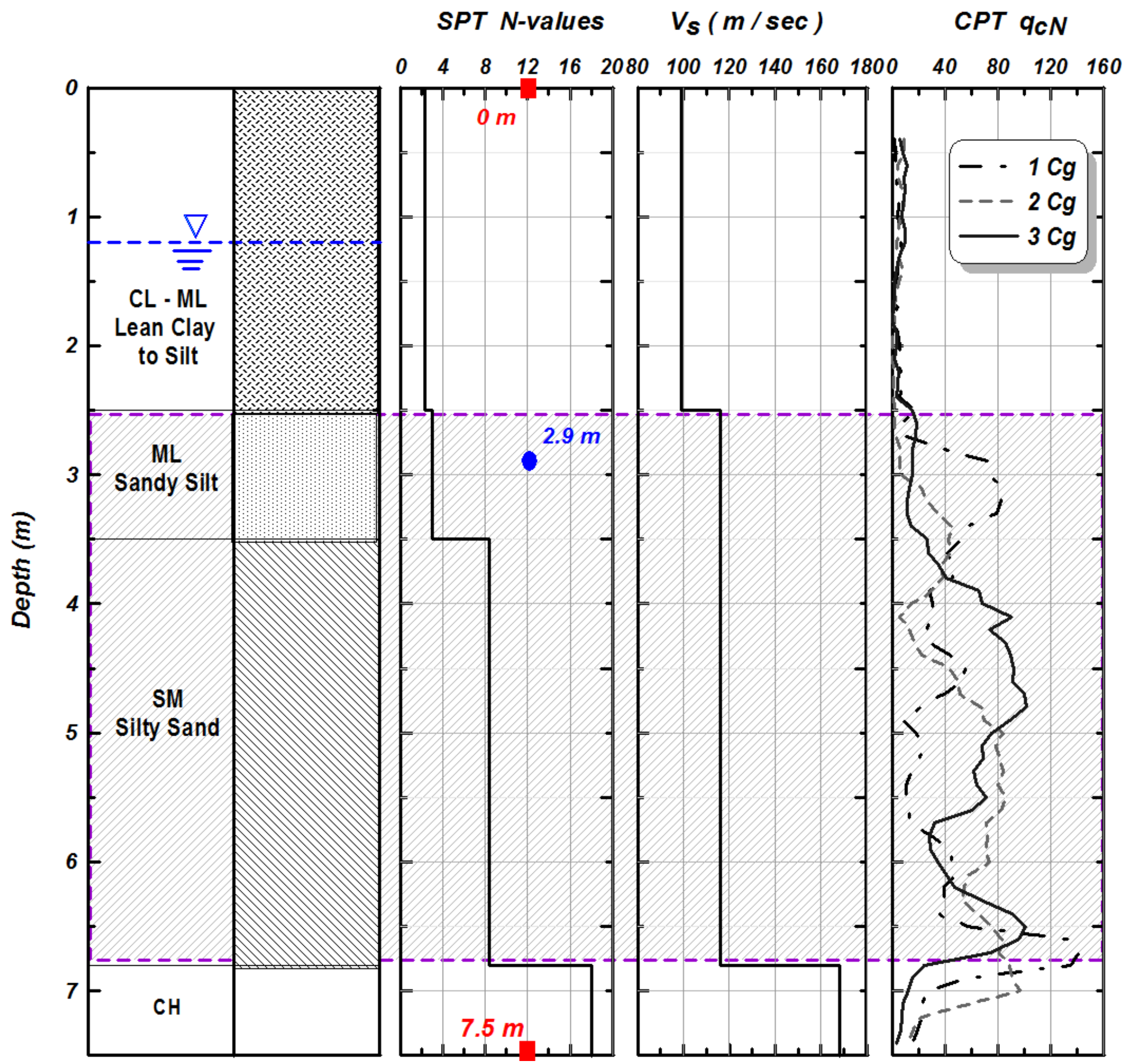


Example responses



Site response of Port Island and Wildlife Liquefaction Arrays

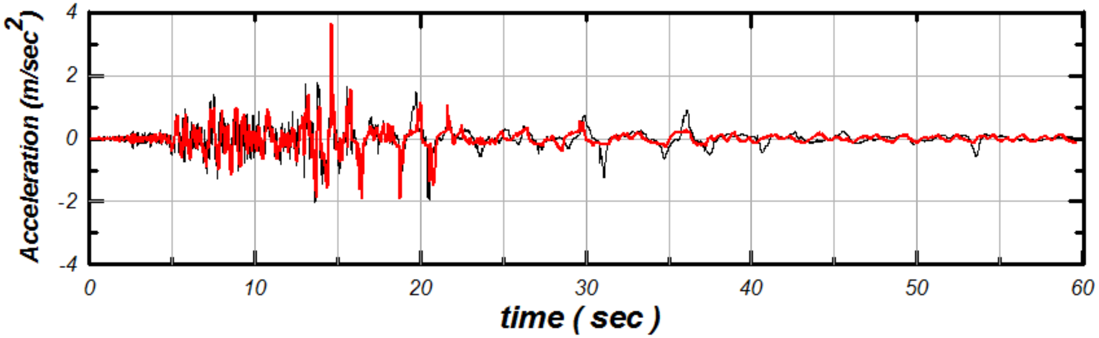
Wildlife liquefaction array

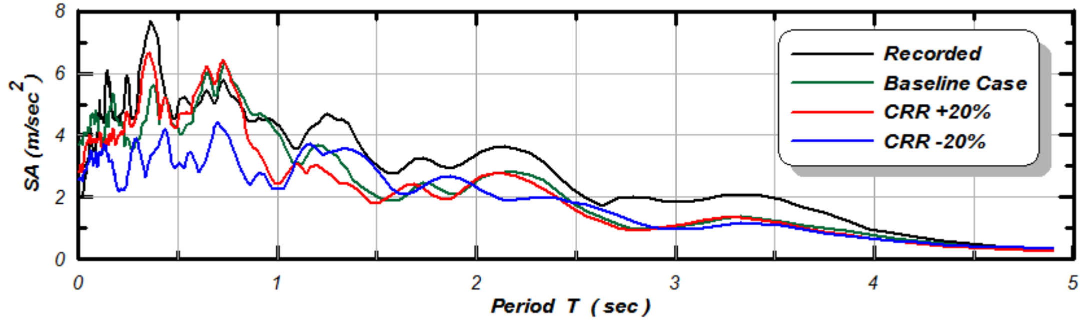


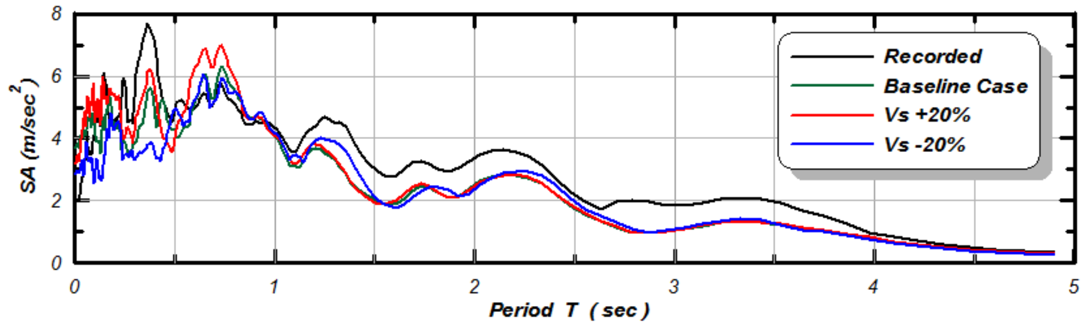
[Data from Bennett et al. 1984, Holzer & Bennett 2010 personal comm.]

WLA response in 1987 Superstition Hills Eq.

- *Surface motion*

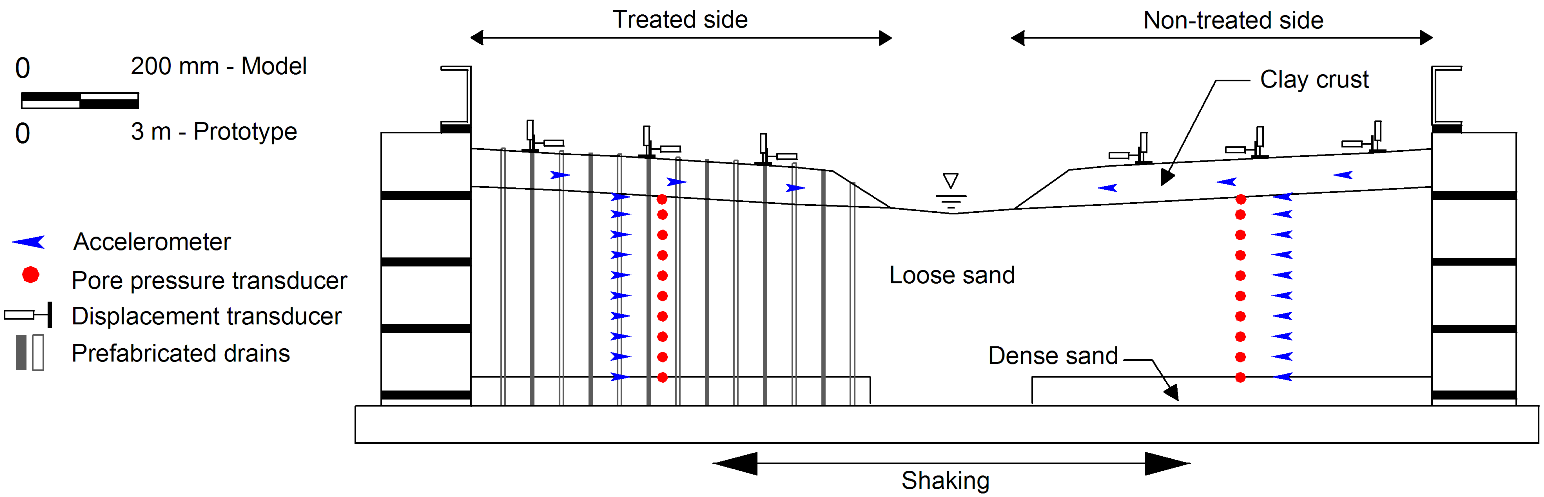


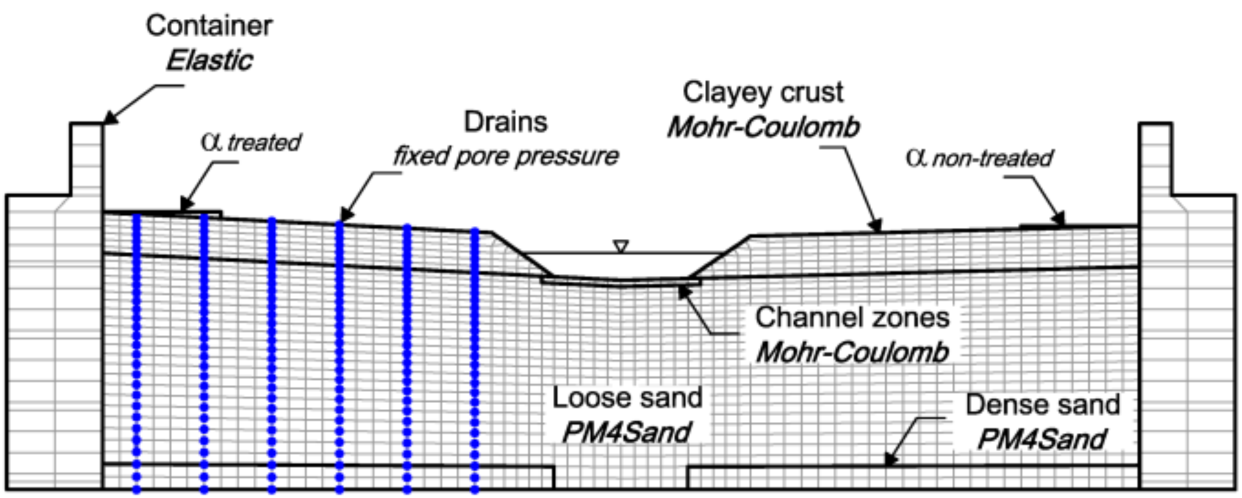




Centrifuge test with lateral spreading

Centrifuge model SSK01

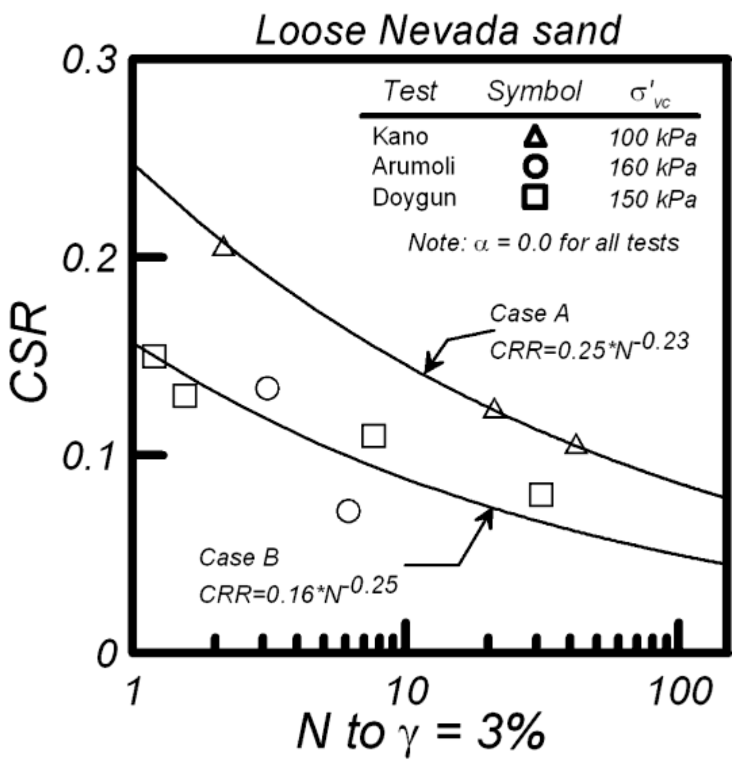


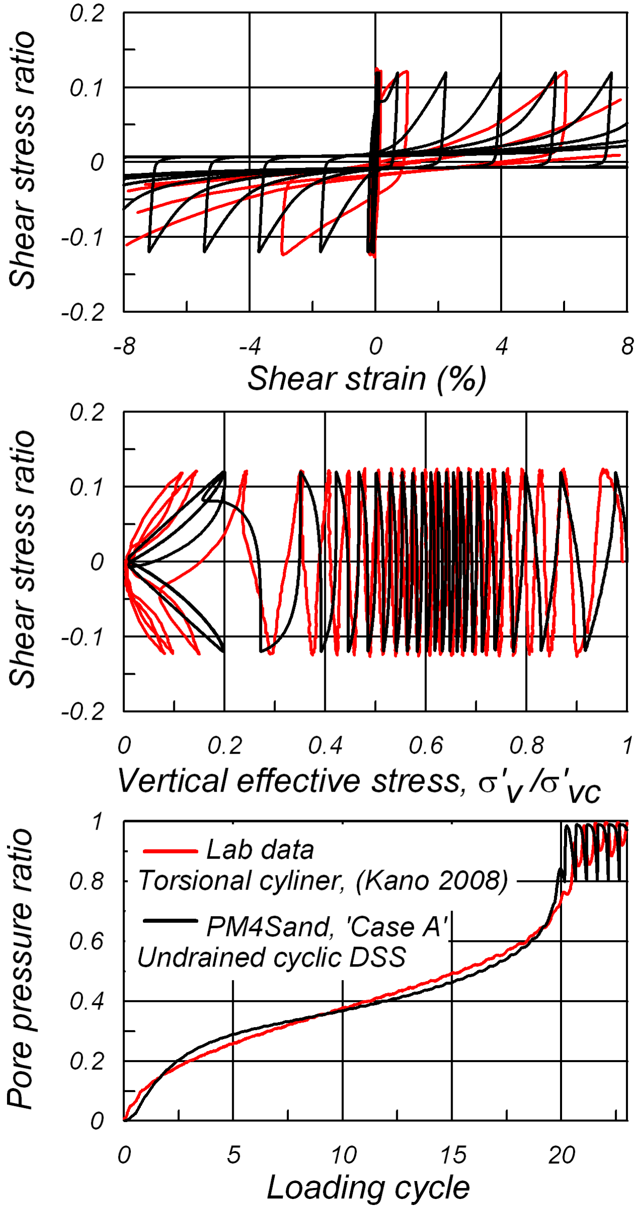


[NEES test by Kamai, Kano, Conlee, Marinucci, Boulanger, Rathje, Rix, and Howell 2008]

Calibration

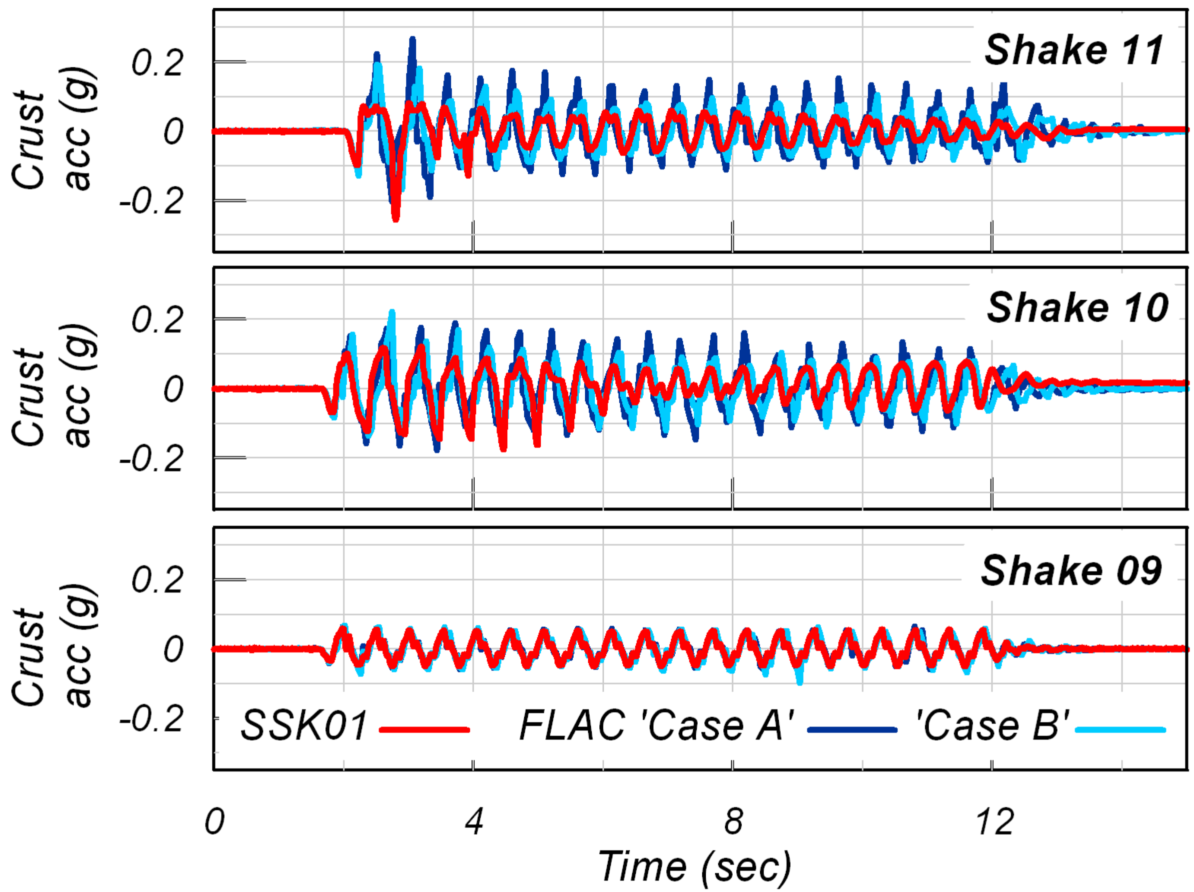
- V_s measured in the model
- CRR from lab tests



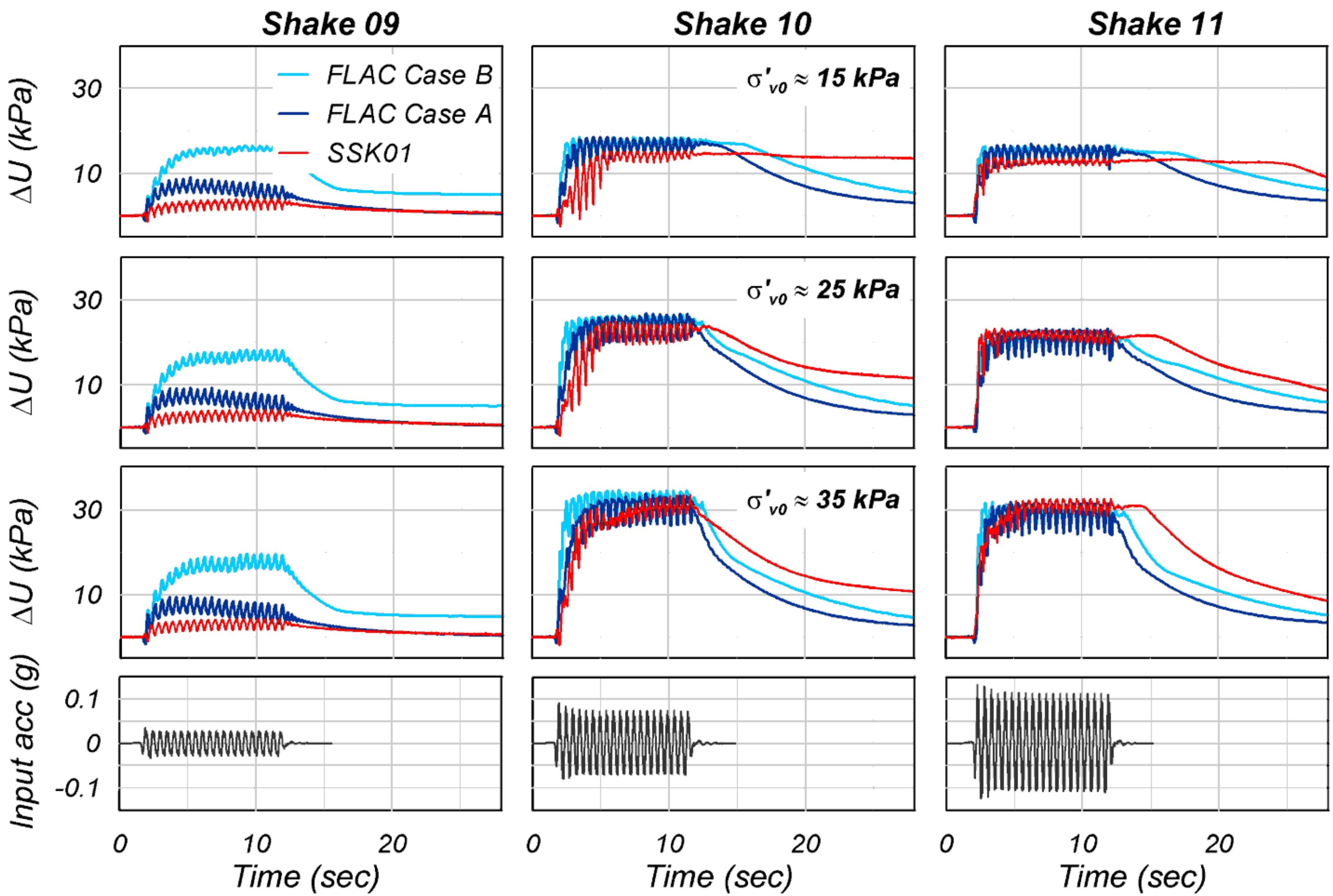


Accelerations

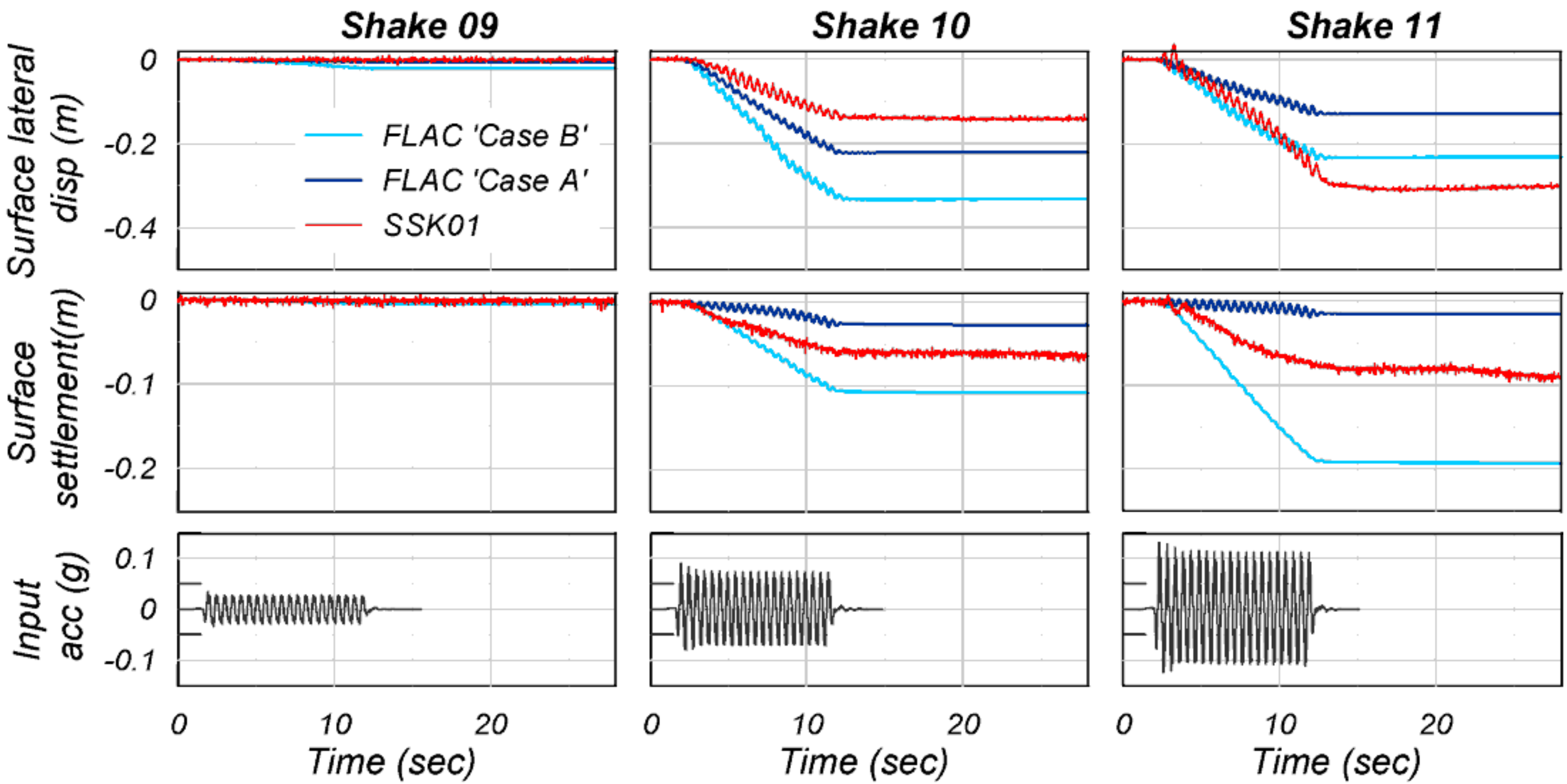
- ***Input motion: Sequence of progressively stronger shaking events, each being 20 cycles at 2Hz***



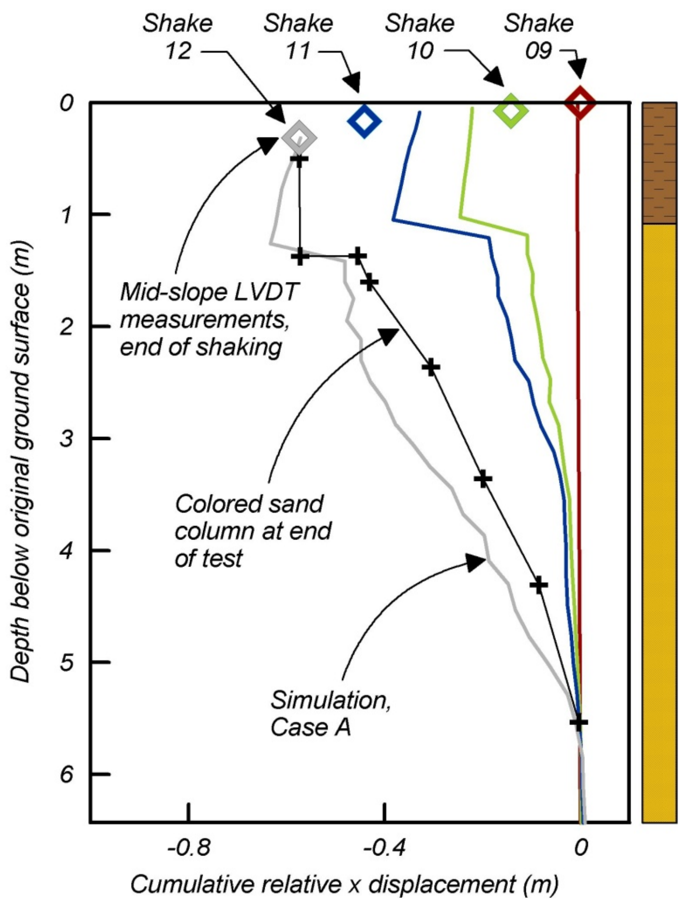
Excess pore pressures



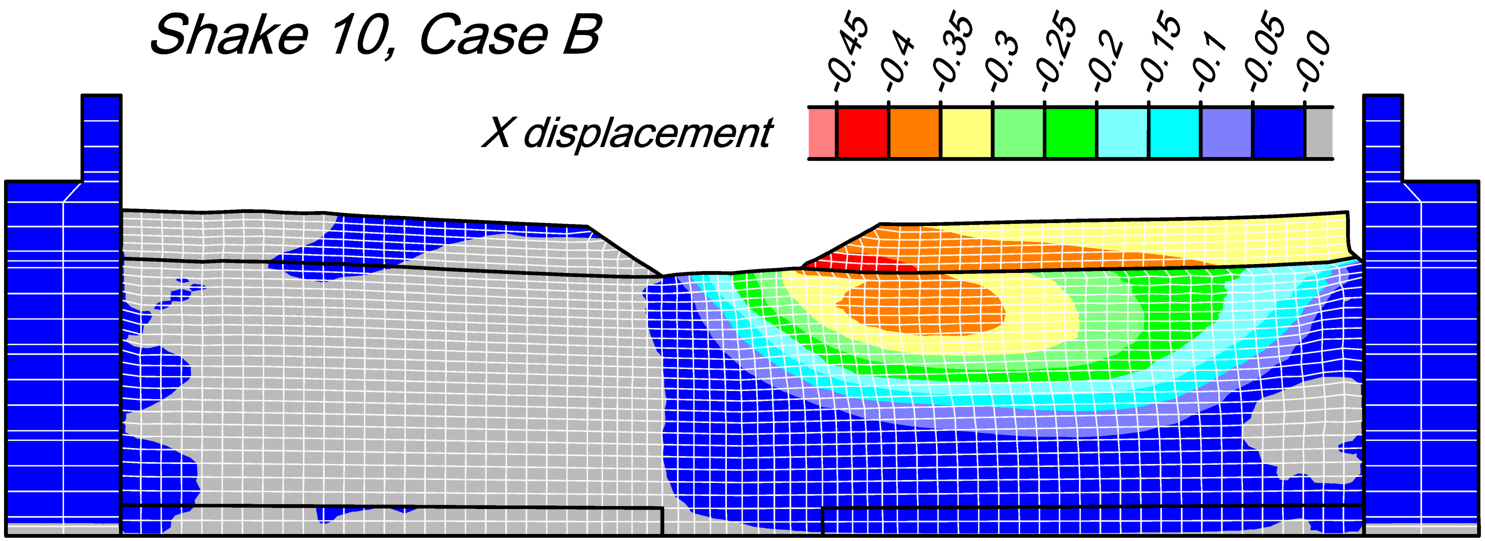
Displacements

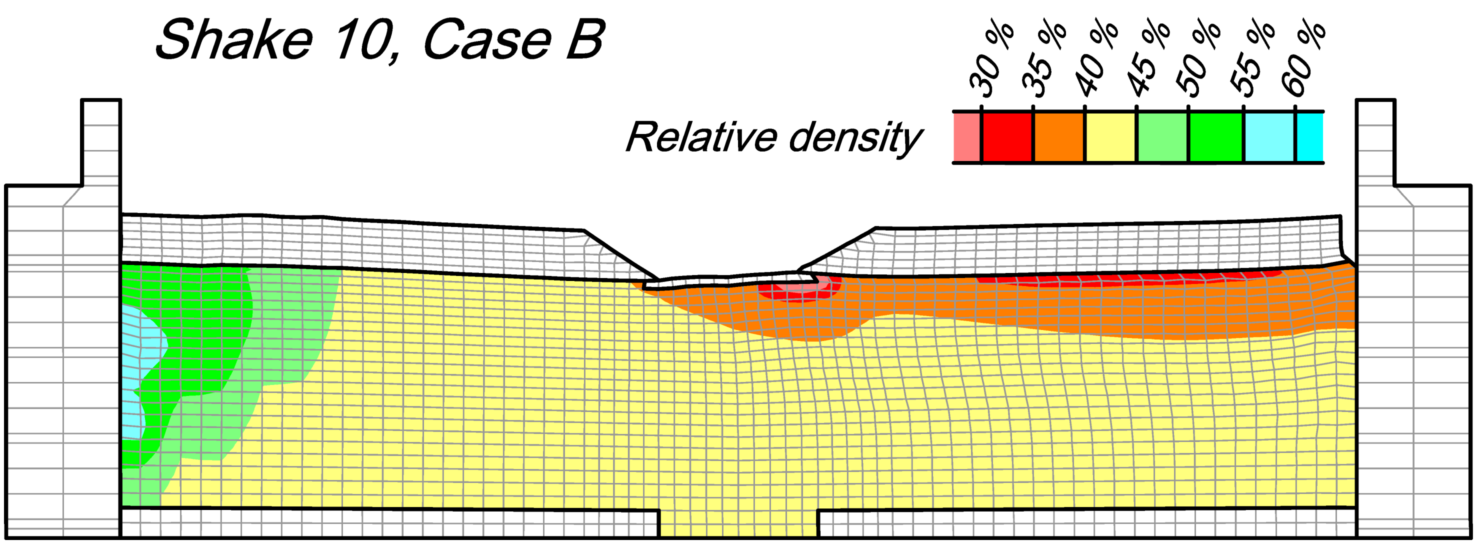


Strain concentration beneath clay crust



Strain concentration beneath clay crust

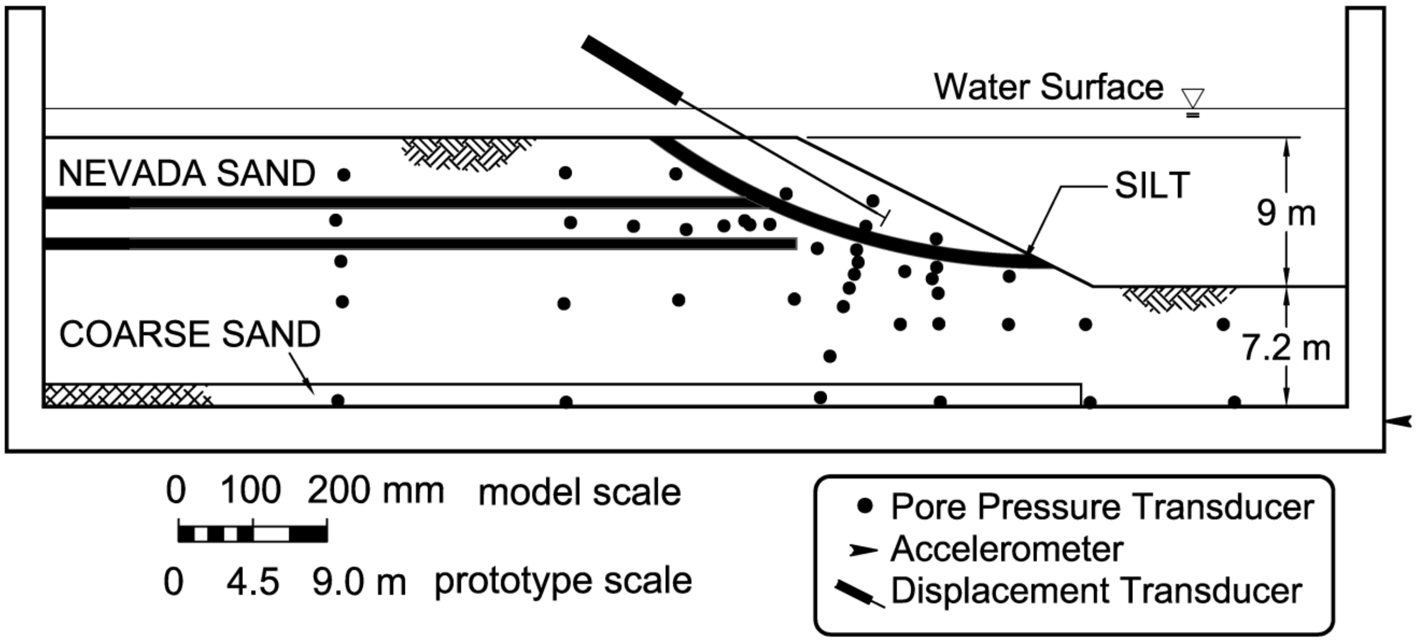


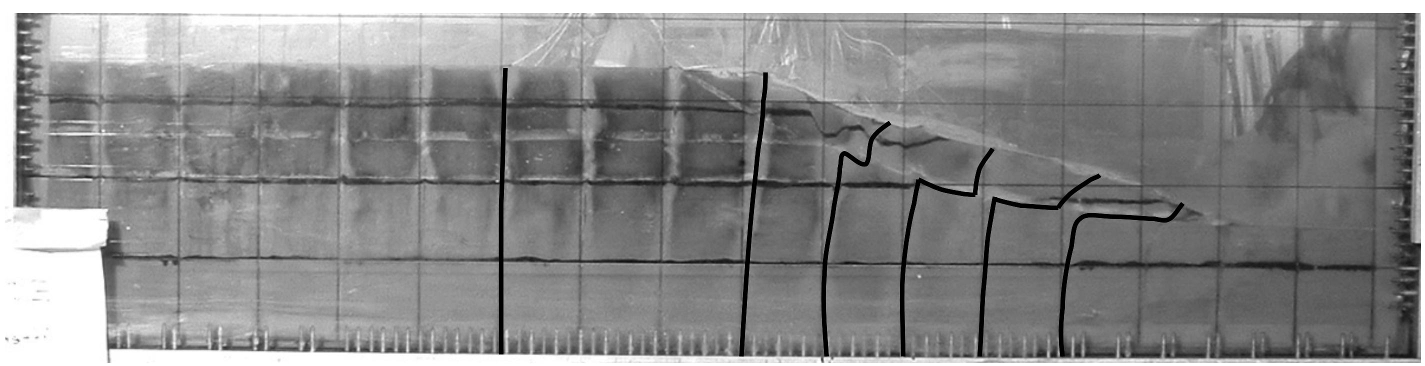


Centrifuge test of slope with silt interlayers

Centrifuge test of slope with silt interlayers

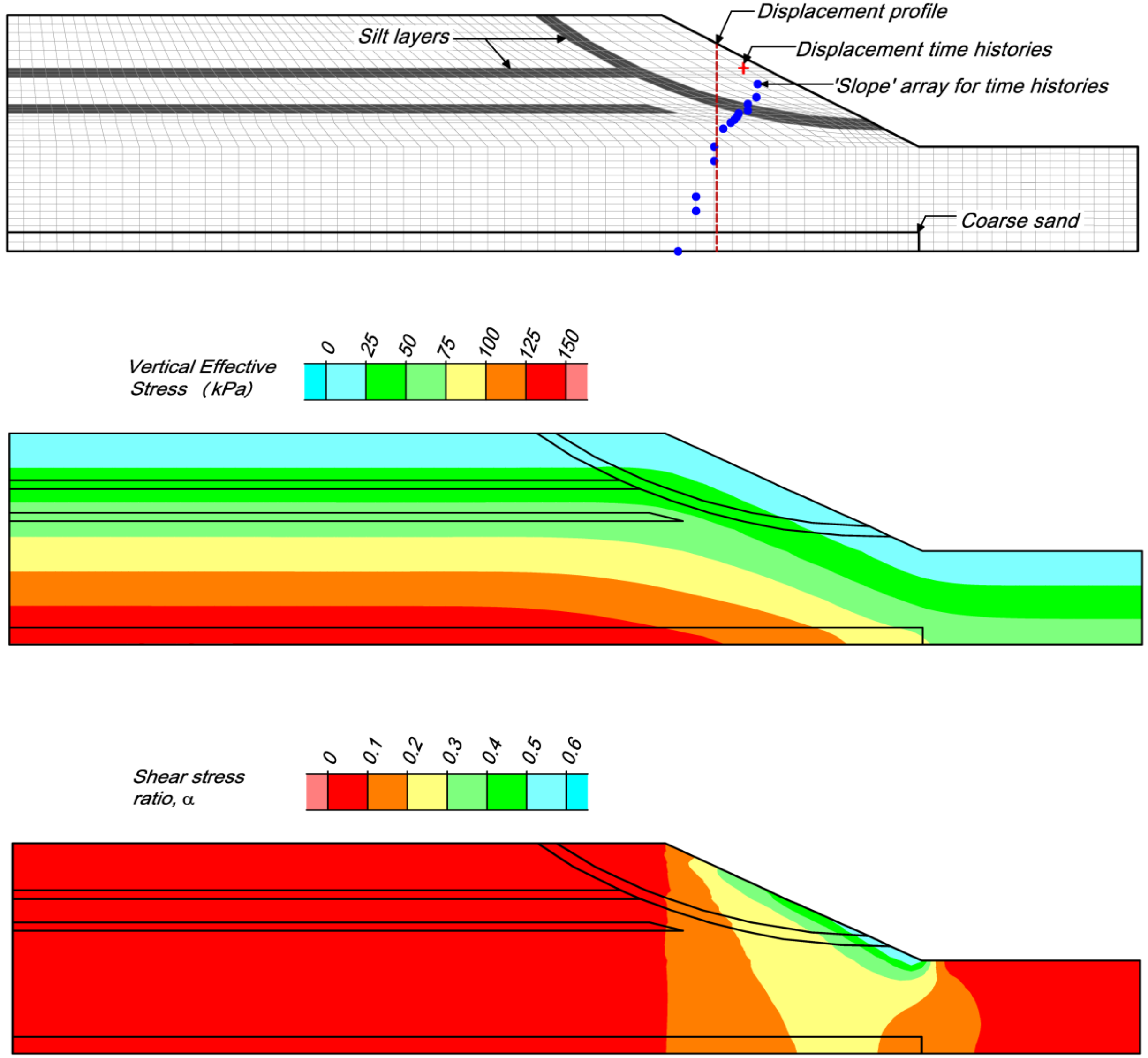
- *Nevada sand, $D_R \approx 35\%$*



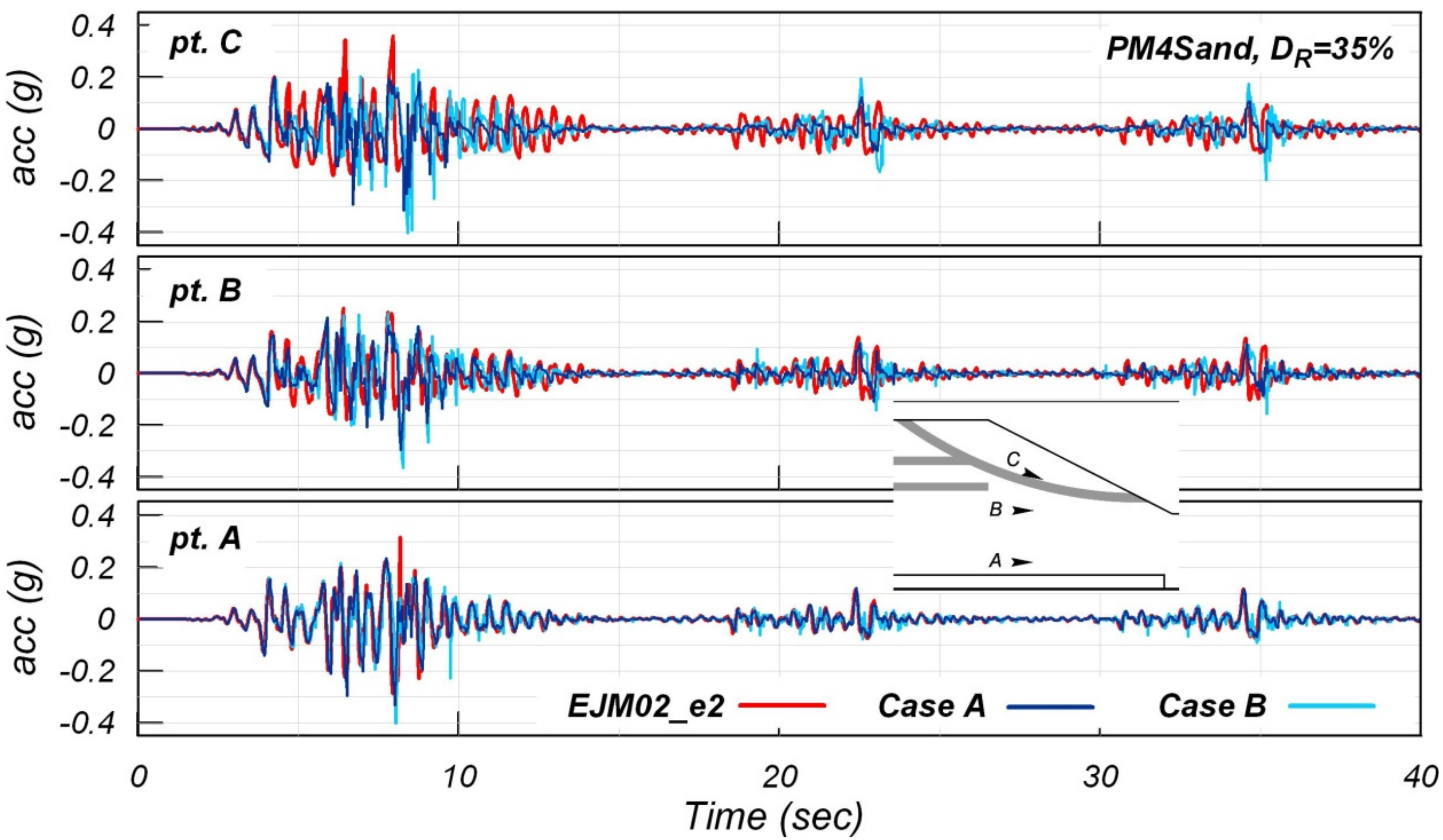


(Malvick, Kutter, & Boulanger 2008)

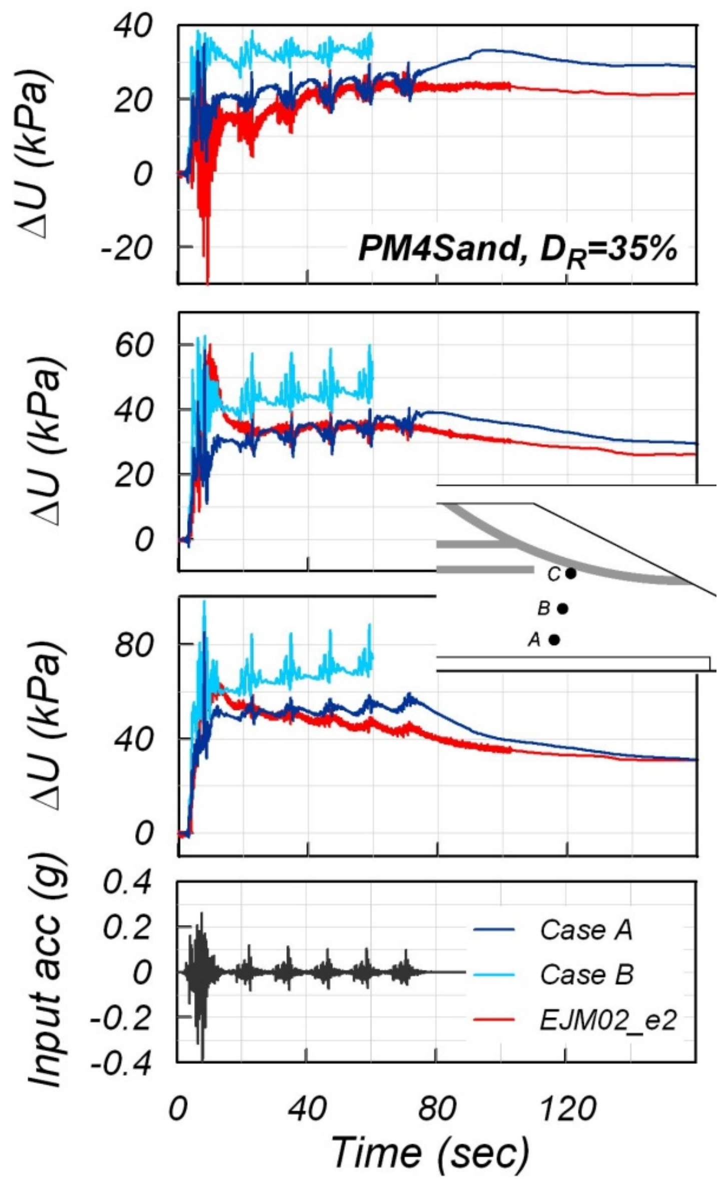
Initial stresses



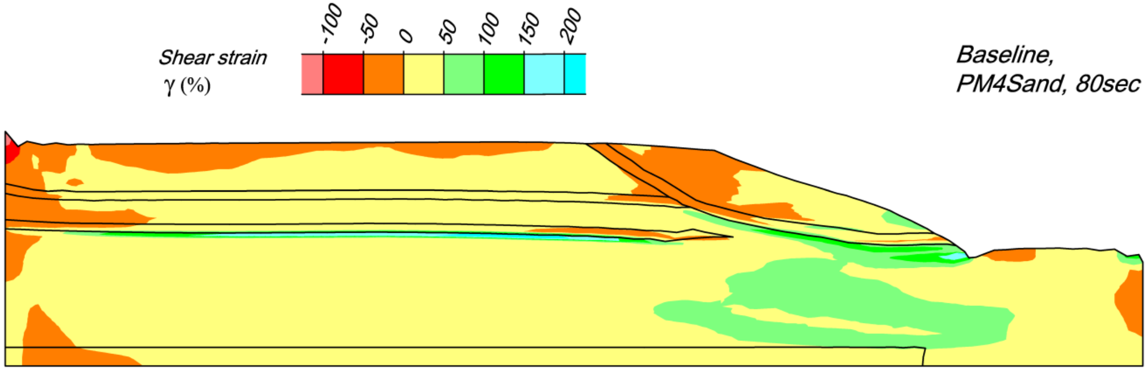
Accelerations

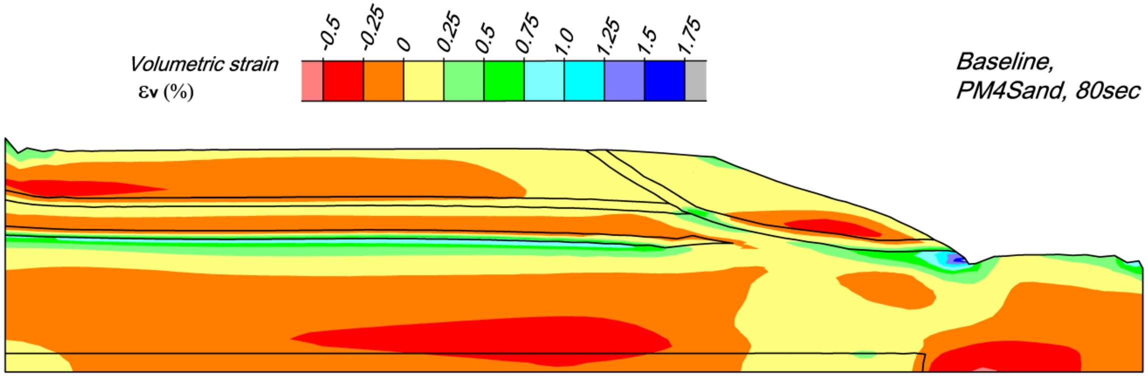


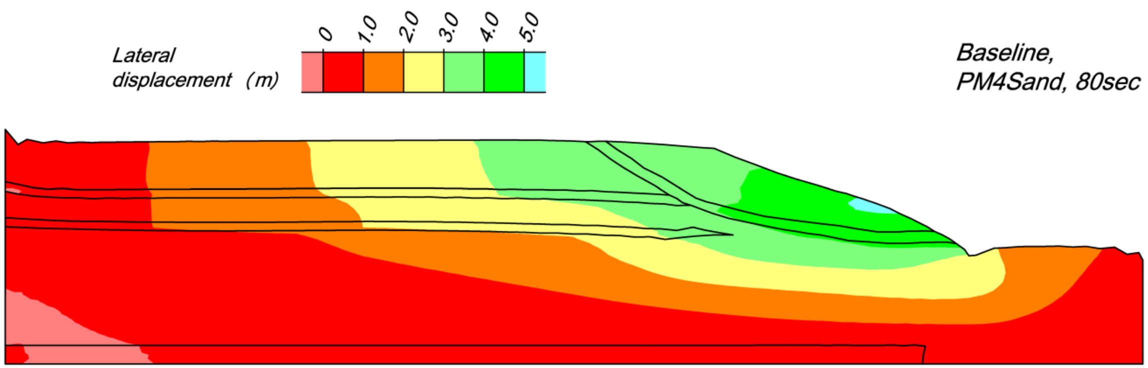
Excess pore pressures



Strains & displacements

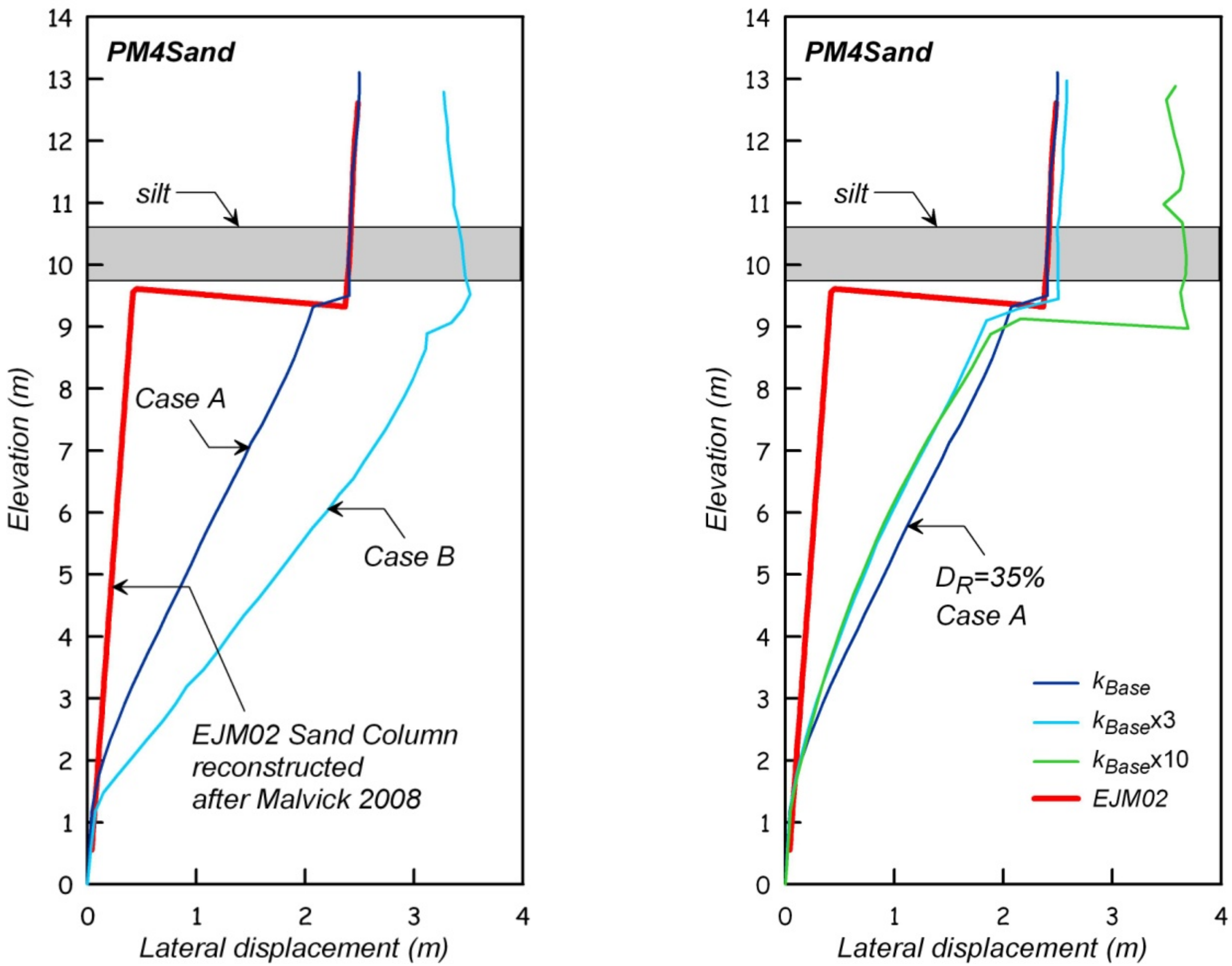






Strain concentration at silt seam

- *Influence of localization scale, permeabilities, re-sedimentation strains and other factors.*



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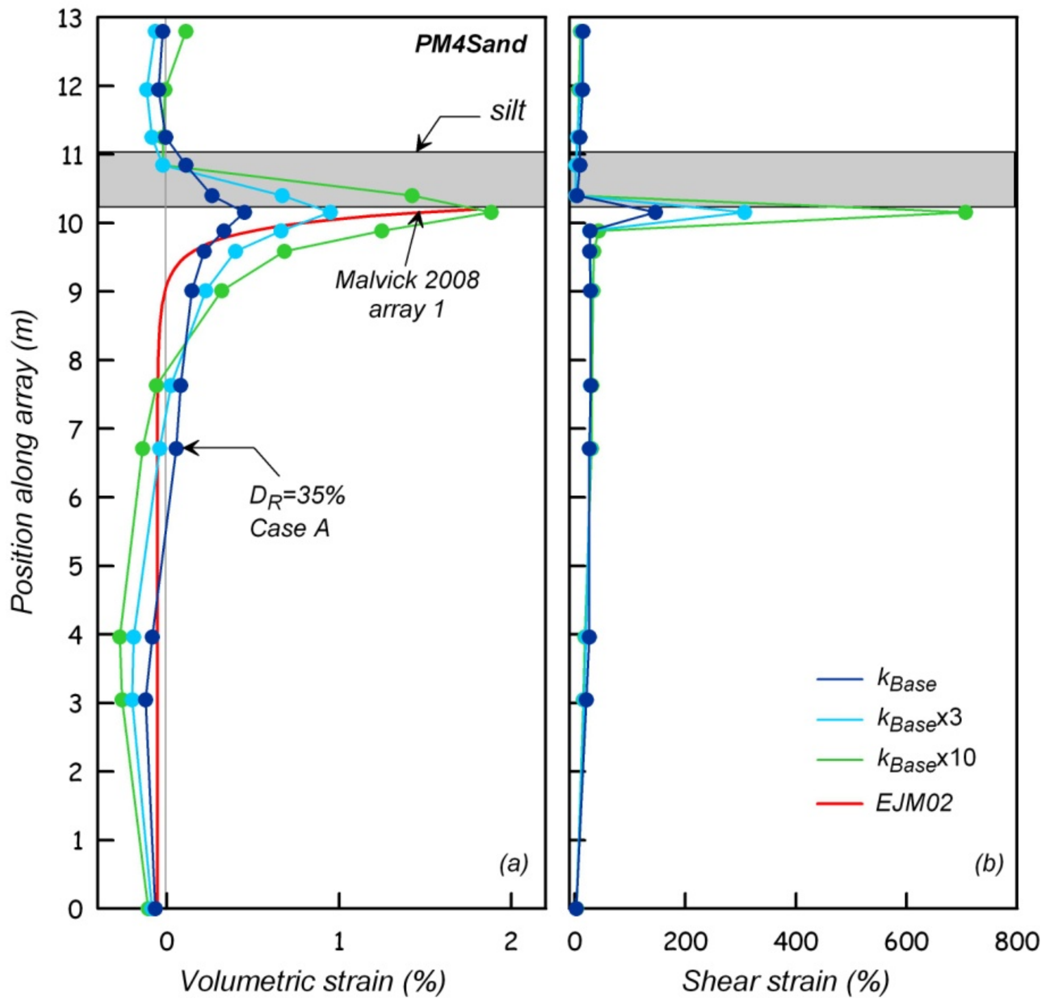

Concluding remarks

- *PM4-Sand is a stress-ratio controlled, critical state compatible, bounding surface plasticity model with fabric which was developed and calibrated to approximate trends in design correlations commonly used in the USA.*
- *Initial applications of PM4-Sand have been promising, suggesting that it reasonably approximates the principle behaviors of liquefying sands.*
- *Numerical analyses of liquefaction effects*
    - *can provide valuable insights regarding complex mechanisms of behavior, but*
    - *can have significant bias and dispersion in computed responses depending on the specific problem (and on the numerical procedures & calibration protocols).*
- *Dynamic centrifuge model studies provide a valuable basis for systematically evaluating numerical analysis methods.*

Support

- ***U. S. Geological Survey (Award G09AP00121)***
- ***International Fulbright Science and Technology Award from the Institute of International Education and U.S. Department of State***
- ***National Science Foundation (NSF) for support for the centrifuge tests***

Thank you.

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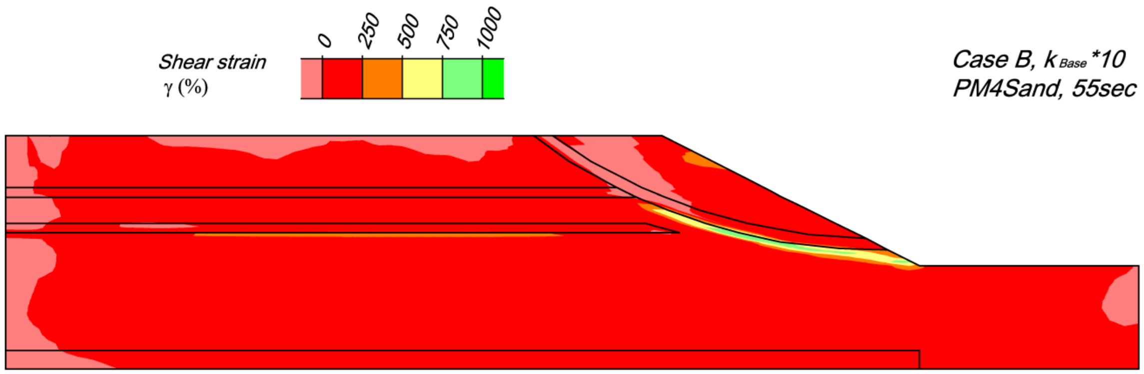
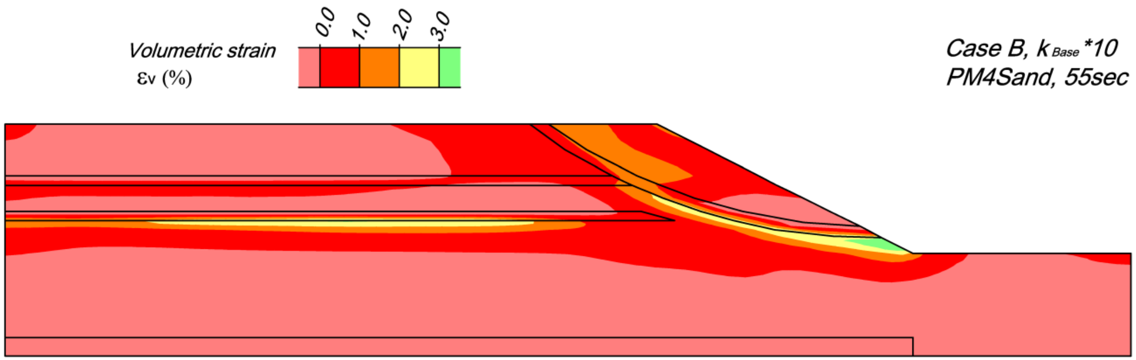
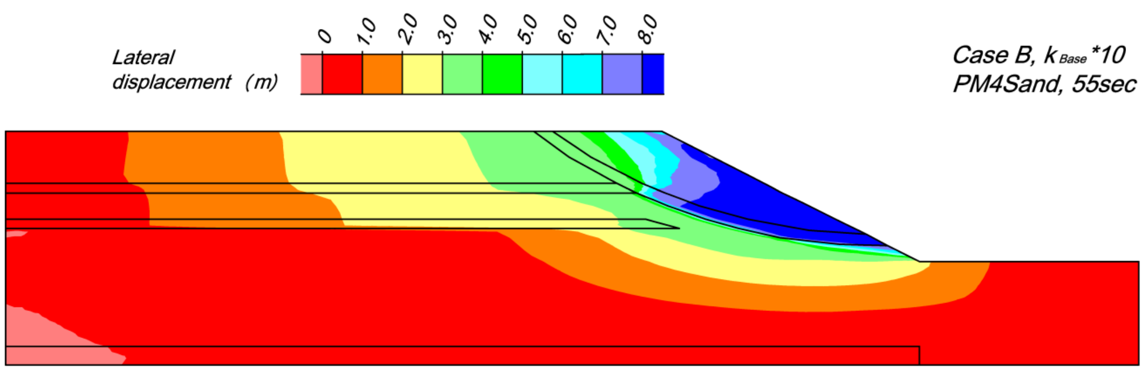
Strains & displacements



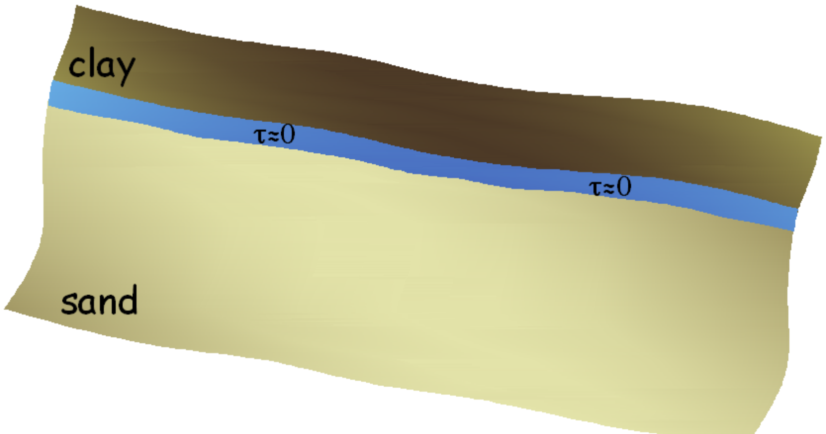




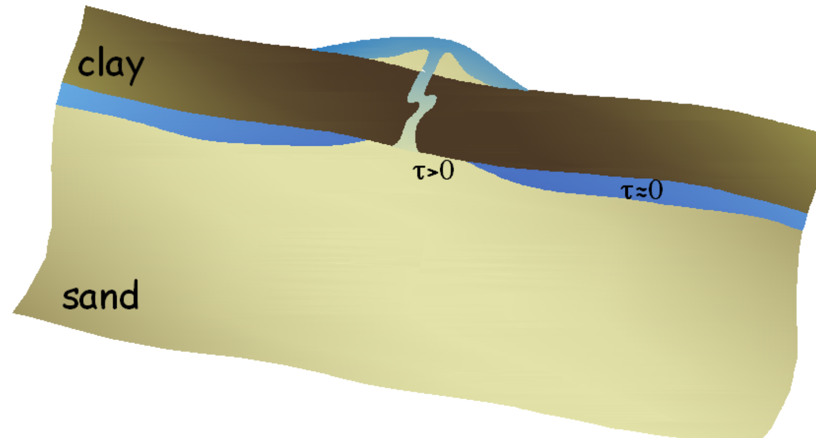
Localization scales in the field?

Localization scales in the field?

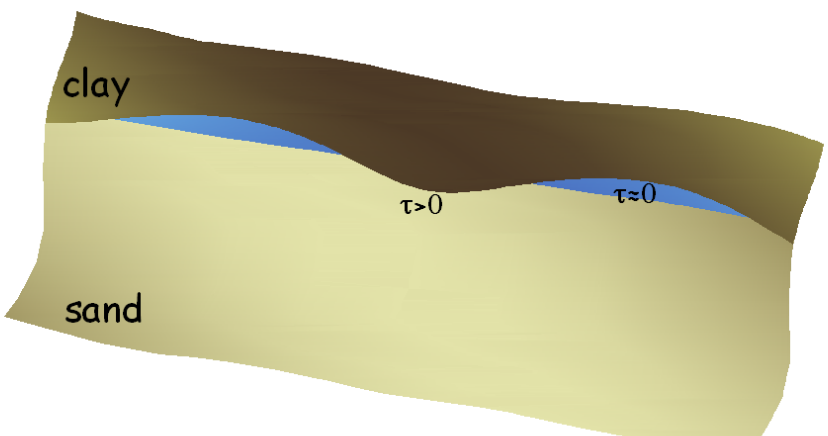
(modified after Naesgaard et al. 2006)



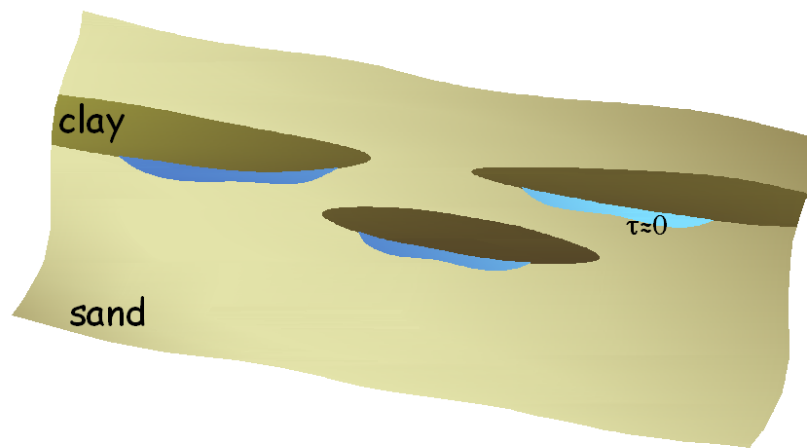
a) Continuous water film



b) Venting + collapse of water film

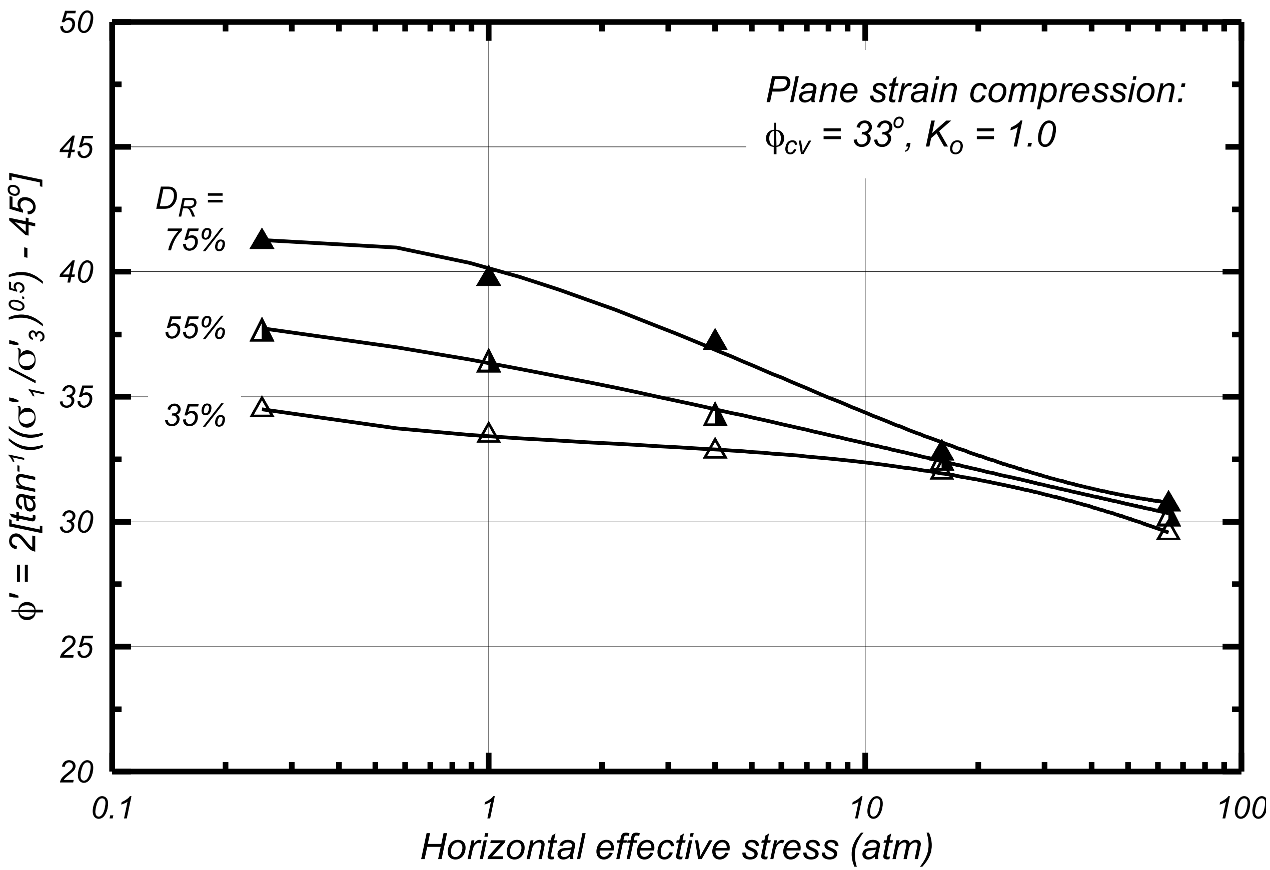


c) Undulating surface

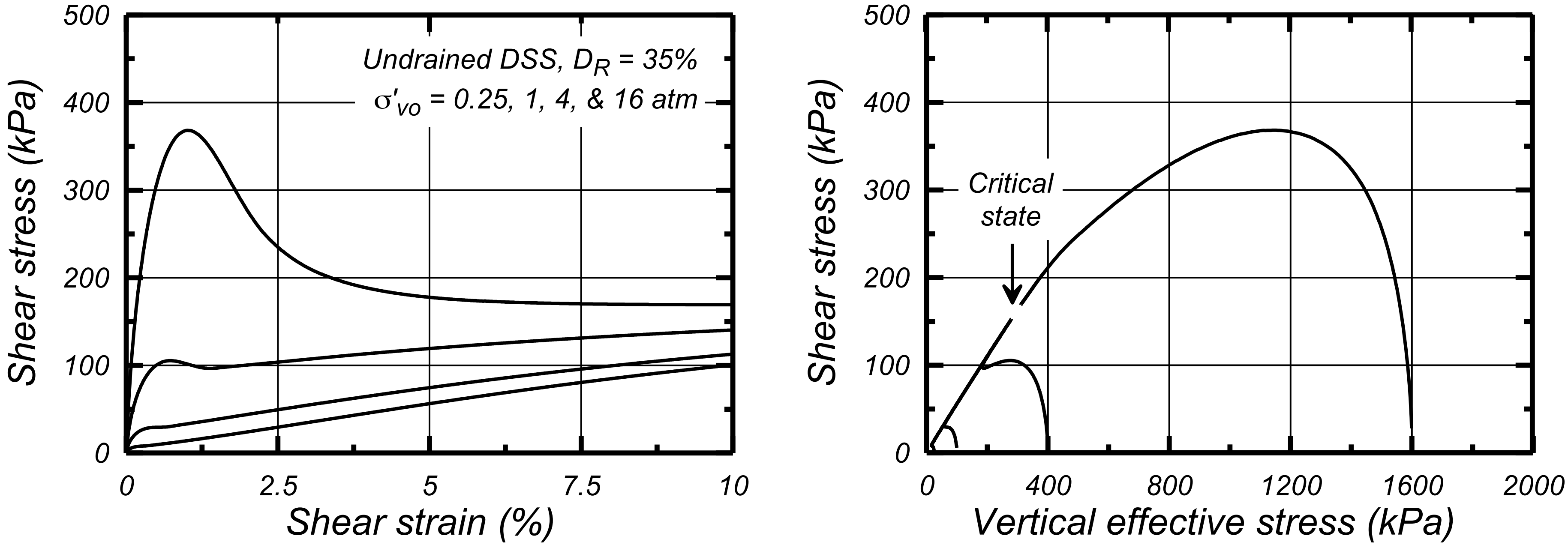


d) Spatial discontinuity of barriers

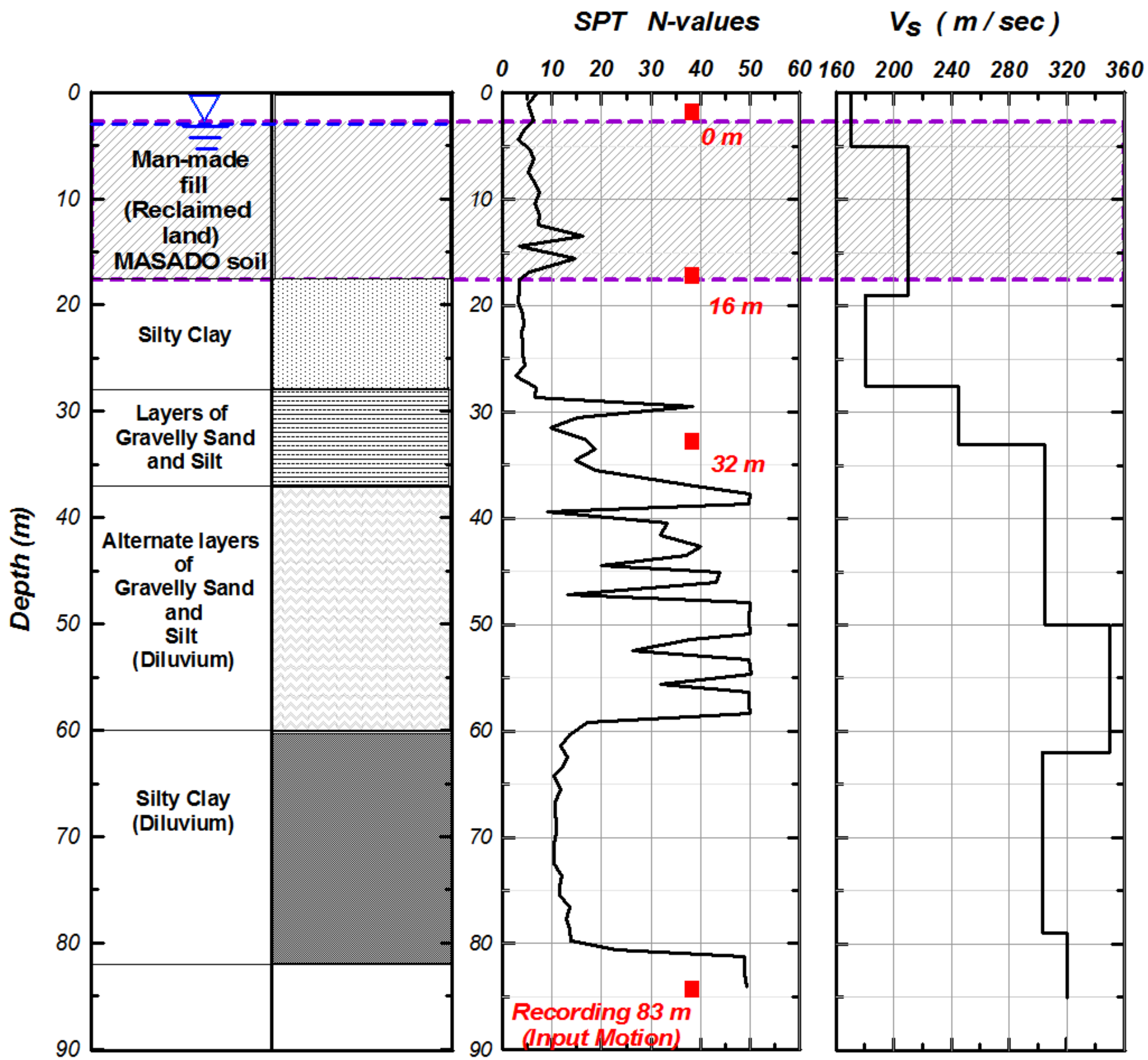
Example responses



Example responses



Port Island Array, Kobe



[Data from]

PIA response in 1995 Kobe Earthquake

- *Surface motion*