Liquefaction effects – Designing tests to identify mechanisms
Designing tests

- Articulate the fundamental mechanism(s) that you are studying or most concerned about.
- Articulate how you will be using the experimental data:
  - Validation of numerical simulations?
  - Validation of design methodologies?
  - Identification of mechanisms and behaviors using back-analyses or system identification methodologies?
- Design your model configuration so that it has the desired sensitivity to the fundamental mechanism of interest or will provide an appropriate test of your analysis method.
- For every sensor, ask yourself what you expect to see, how you will use the data, and why you need it. Focus your sensors where they will be useful for you.
Examples:

Mechanisms of soil-pile-structure interaction
Early example: p-y behavior of liquefying sand

- acceleration
- pore pressure
- displacement
- moment bridge

3.8 m

9.1 m loose or medium dense sand

11.4 m dense sand

1990's – sensor #s limited
Early example: $p$-$y$ behavior of liquefying sand

Depth of 1 diameter ($D=0.73$ m)

Depth of 2 diameters

Depth of 3 diameters

$D_R \approx 35\%$ upper sand

$D_R \approx 55\%$ upper sand
Later example: Lateral spreading effects

- Clay $s_u$ of 22, 33 & 44 kPa.
- Pile diameters of 0.73 & 1.17 m.
- Structure $T_{\text{fixed base}} = 0.3$ & 0.8 s.
- Santa Cruz & Kobe motions from 0.15 to 0.65 g.
Model scale dimensions:

- 3.81 cm dia.
- 0.95 cm dia.
- 1.91 cm dia.

Prototype dimensions at 40-g:

- 1.52 m
- 0.38 m
- 0.73 m

2000's – expanding sensor capacities
SJB03 (D=1.17 m)
Santa Cruz motion
\(a_{\text{base, max}} = 0.35g\)
Anticipate deformation patterns – design your markers!
Eight tests as part of a 3-year project.

Three levels of analyses:
  • Back-calculation of load transfer mechanisms
  • Nonlinear static pushover analyses
  • Dynamic FE analyses

Four graduate students involved.
  • Each student took lead responsibility on 2 or 3 tests, and assisted on 2 or 3 others (some for training, some as trainer).
  • Lead student took 3 to 4 months to complete each test (design through documentation) with classes at the same time, while the helper required about 1 month for each test.
  • So each student spends 1 full year testing, about another 4 months helping on tests, and the rest doing their analyses.
Examples:

Void redistribution in liquefying soils
Void redistribution

- Void ratio can locally increase and strength decrease.
- This means that pre-earthquake $D_R$ or $(N_1)_{60}$ are insufficient predictors of the in-situ $S_r$.

After Whitman (1985)
Traditional monotonic "drained" (shown for constant $p'$) and "undrained" tests are often incorrectly assumed to bound possible field strengths.
Examining mechanisms: 9-m-radius centrifuge

- Nevada sand, $D_R \approx 35\%;$ 9-m radius centrifuge

(Malvick et al. 2008)
Midslope PPT array

Excess Pore Pressure (kPa)

Displacement of Slide Mass (m)

Time after end of shaking (s)

Time after end of shaking (s)
Midslope PPT array

![Diagram of Midslope PPT array]

- **Excess Pore Pressure (kPa)**
- **Time after end of shaking (s)**
- **Displacement of Slide Mass (m)**

- **Position along array**

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\[ \Delta u \text{ in an infinite slope, } \theta = 18.3^\circ \text{ and } \phi'_{mob} = 33^\circ \]
Midslope PPT array

- The diagram shows excess pore pressure measurements along an array of points labeled A to E.
- Each point (A to E) is marked on a graph with time after end of shaking (s) on the x-axis and excess pore pressure (kPa) on the y-axis.
- The graph indicates a comparison between different arrays (a) and (b).
- Point A is highlighted, indicating a specific measurement.
- The image references Malvick et al. (2008) for further information.

\[ \Delta u \text{ in an infinite slope, } \theta = 18.3^\circ \text{ and } \phi'_{\text{mob}} = 33^\circ \]
Midslope PPT array

(a) Array 1

\[ \Delta u \text{ in an infinite slope, } \theta = 18.3^\circ \text{ and } \phi'_{\text{mob}} = 33^\circ \]

(Malvick et al. 2008)

(point A)

(point C)
**Midslope PPT array**

\[ \Delta u \text{ in an infinite slope, } \theta = 18.3^\circ \text{ and } \phi'_\text{mob} = 33^\circ \]

(Malvick et al. 2008)
Midslope PPT array

Excess Pore Pressure (kPa)

(a) Array 1

\[ \Delta u \] in an infinite slope, \( \theta = 18.3^\circ \) and \( \phi'_\text{mob} = 33^\circ \)

Silt

(Malvick et al. 2008)
Flow analysis of PPT arrays

Algorithm (assuming 1D flow along the array):

\[ i = \frac{\partial(\Delta u)}{\partial z} \frac{1}{\gamma_w} \]

\[ \frac{\partial \varepsilon_v}{\partial t} = \frac{k_s}{\gamma_w} \frac{\partial^2 (\Delta u)}{\partial z^2} \]

Numerical Differentiation:
- Weighted Residuals
- Exponential fitting function

\( \varepsilon_v = \text{flow out} - \text{flow in} \)

(Malvick et al. 2006; Kamai & Boulanger 2010)
Flow analysis of PPT arrays

(Malvick et al. 2006)
Effectiveness of prefabricated drains for liquefaction mitigation (Rathje, Howell, Kamai, Boulanger, and others)

1m clay overlying 5m sand, $D_r = 40\%$, 3° slope.

Spinning – 15g

Shaking – sinusoidal, 2Hz, 20 cycles

- Amplitudes: 0.01, 0.03, 0.07, 0.11, 0.3 g.
**Displacement and strain profiles**

![Graph showing displacement and strain profiles](image_url)

- **Depth (m)**
- **Displacement (m)**
- **Strain (%)**

Kamai et al.
Stress-strain response: Shake 4, 0.11g

Kamai et al.
Excess pore pressure profiles

Kamai et al.
Volumetric strain profiles

Kamai et al.
Simulating void redistribution

(Kamai & Boulanger 2011)
Simulating void redistribution

(Kamai & Boulanger 2011)
Concluding remarks

- Fundamental interaction mechanisms can be identified using dense instrumentation arrays and data processing techniques.
  - Also provides an improved basis for validating numerical simulation and analysis methods.
  - Lots of generic instrumentation does not necessarily help unless it is placed where you need it.
- Future needs?
  - More precise ways for locating sensors and tracking positions over time.
  - Instrumentation arrays and data processing techniques that can incorporate 2- and 3-dimensional effects and boundary conditions.
  - Integration with video imagery (PIV).
  - Improved sensors for local measurements of volumetric strain, shear strain, or displacement.
Concluding remarks (Cont'd)

- Focus on the mechanism you want to understand, and design the test accordingly.
- Yes, it is possible to ..., but it costs $ and takes time to do anything the first time. And there will be surprises!
- When proposing, remember the difference between conceptual designs and final designs. Include some contingency funds and time.
- We've had good experiences with self-starting, get-it-done types of visiting researchers. Know your student's limitations, & only send them when they are fully prepared.
Questions?