The Effect of Soil Gradation on the Dynamic Performance of an Earthen Embankment

[Example of PEER funding leveraging an NSF award]

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PEER

NHERI
Natural Hazards Engineering Research Infrastructure

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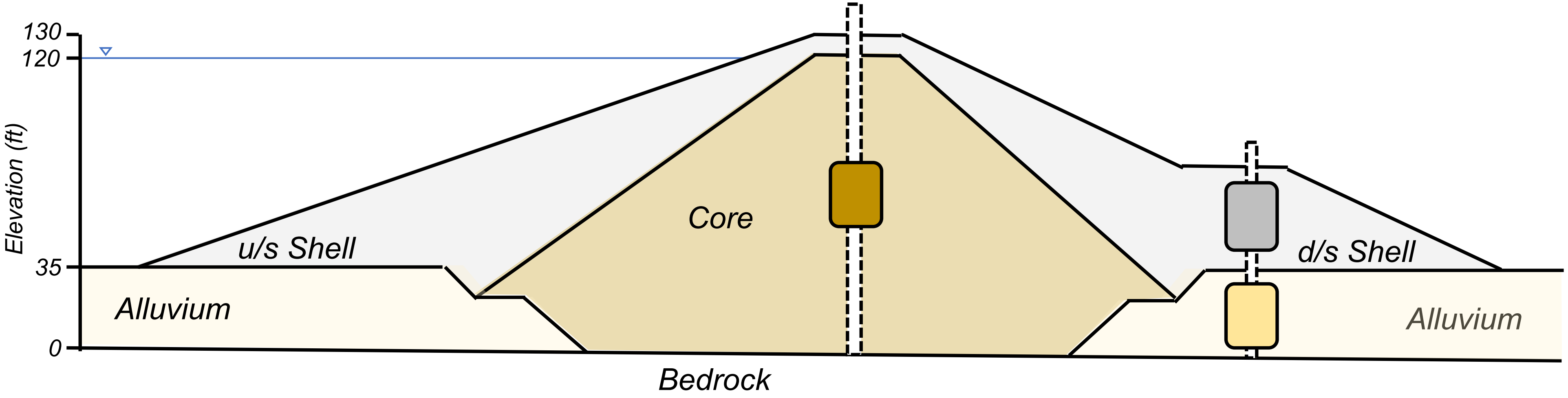
The problem in practice

- *Performance based-evaluation of infrastructure (e.g. dams) comprised of or founded on gravelly soils contains high uncertainty*
- *Case histories document that gravelly soils can liquefy (trigger), but the post-triggering response (system performance) is highly uncertain or unknown*
- *Current engineering practice follows methods for sands, and does not explicitly consider gradation or particle size effects*

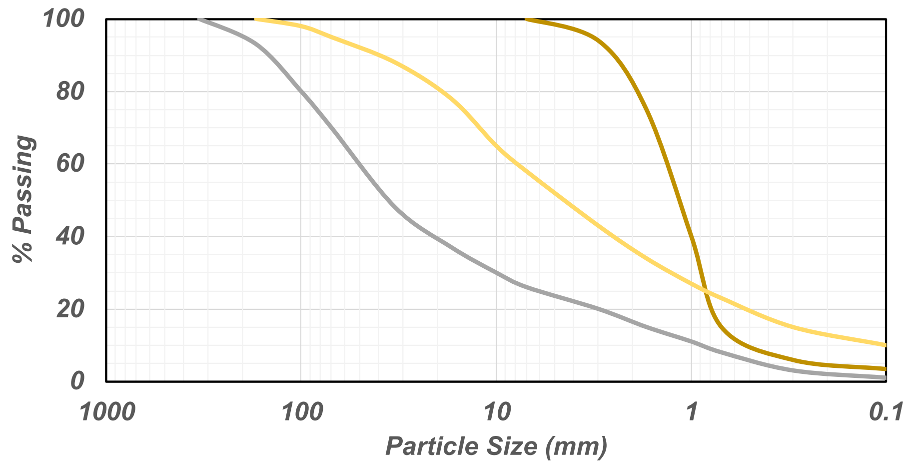


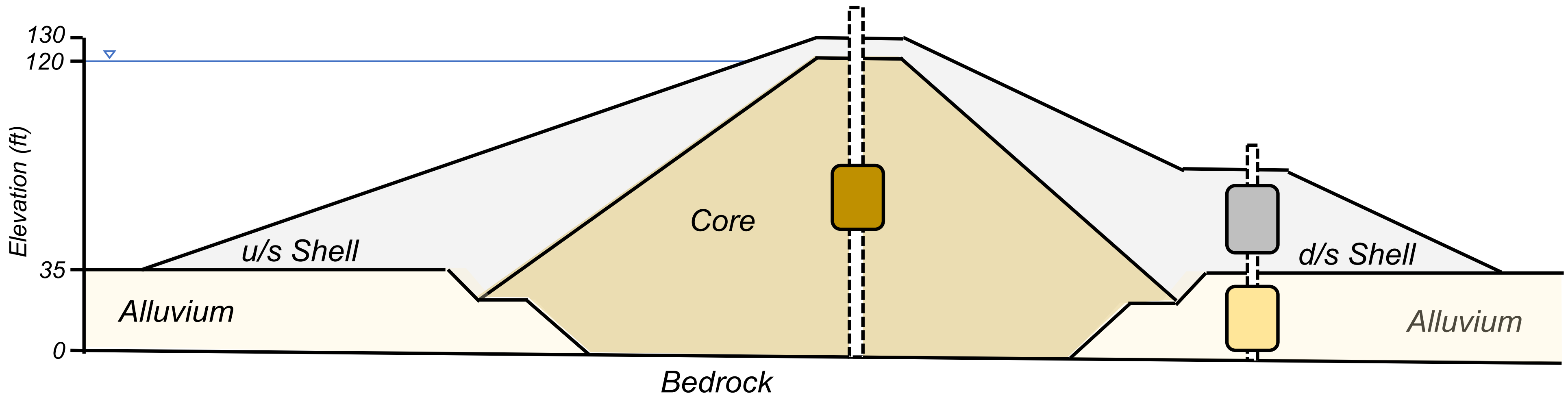
The problem in practice

- However, as the soil becomes more well-graded there are fundamental changes to index & engineering properties of gravelly soils:
  - particle packing & void ratios
  - hydraulic conductivity
  - stiffness, stress-dilatancy, & critical state

… which directly influence…

  - penetration resistance (CPT, DPT, iBPT, etc.)
  - liquefaction triggering (pore pressure generation)
  - strains (shear strain accumulation, reconsolidation)



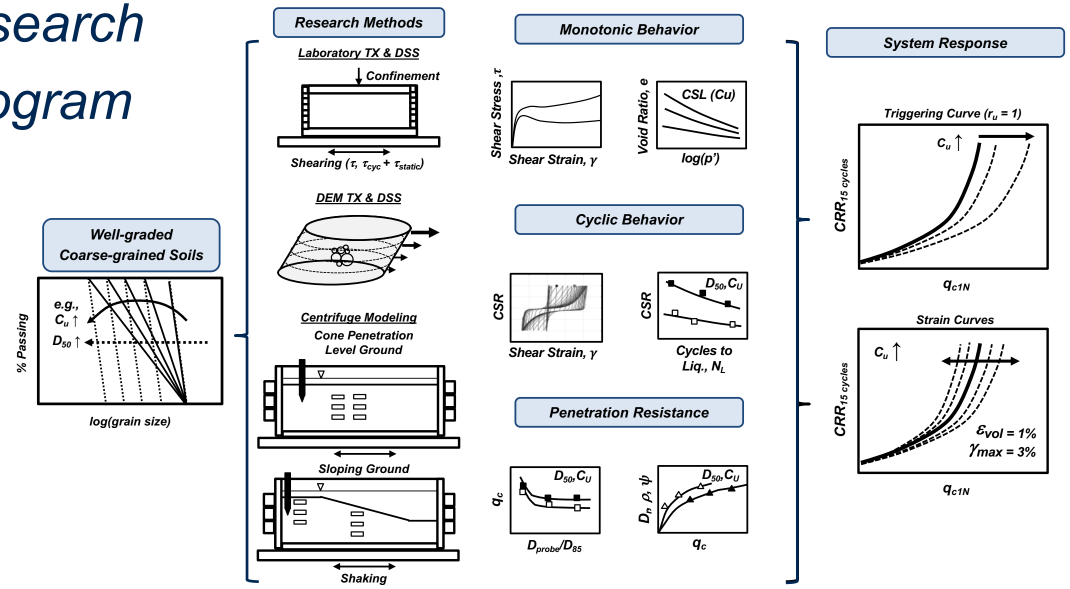


Engineering workflow

- *The engineering workflow required for performance-based assessment requires multiple dependent steps for soil characterization, evaluation of susceptibility to liquefaction triggering, and estimation of strains and deformations*
- *All steps must be revisited and revised/expanded for gravelly soils*

Penetration Measurement → *Corrected Penetration Measurement* → *Relative Density / State Parameter* → *Liquefaction Triggering (r_u = 1)* → *Strains and Deformations*

Research Program



- *Accomplished through:*
  - *case history review*
  - *lab testing*
  - *numerical modeling*
  - *in situ testing*
  - *centrifuge modeling*

Case history synthesis

- Compilation of 159 datasets from test soils, geologic deposits, and anthropogenic (project) soils
- Transition zone in void ratio indices primarily occurs from C_u = 2 to 12
- Effect saturates above $C_u \approx 12$ (likely also saturates penetration resistance and soil properties)

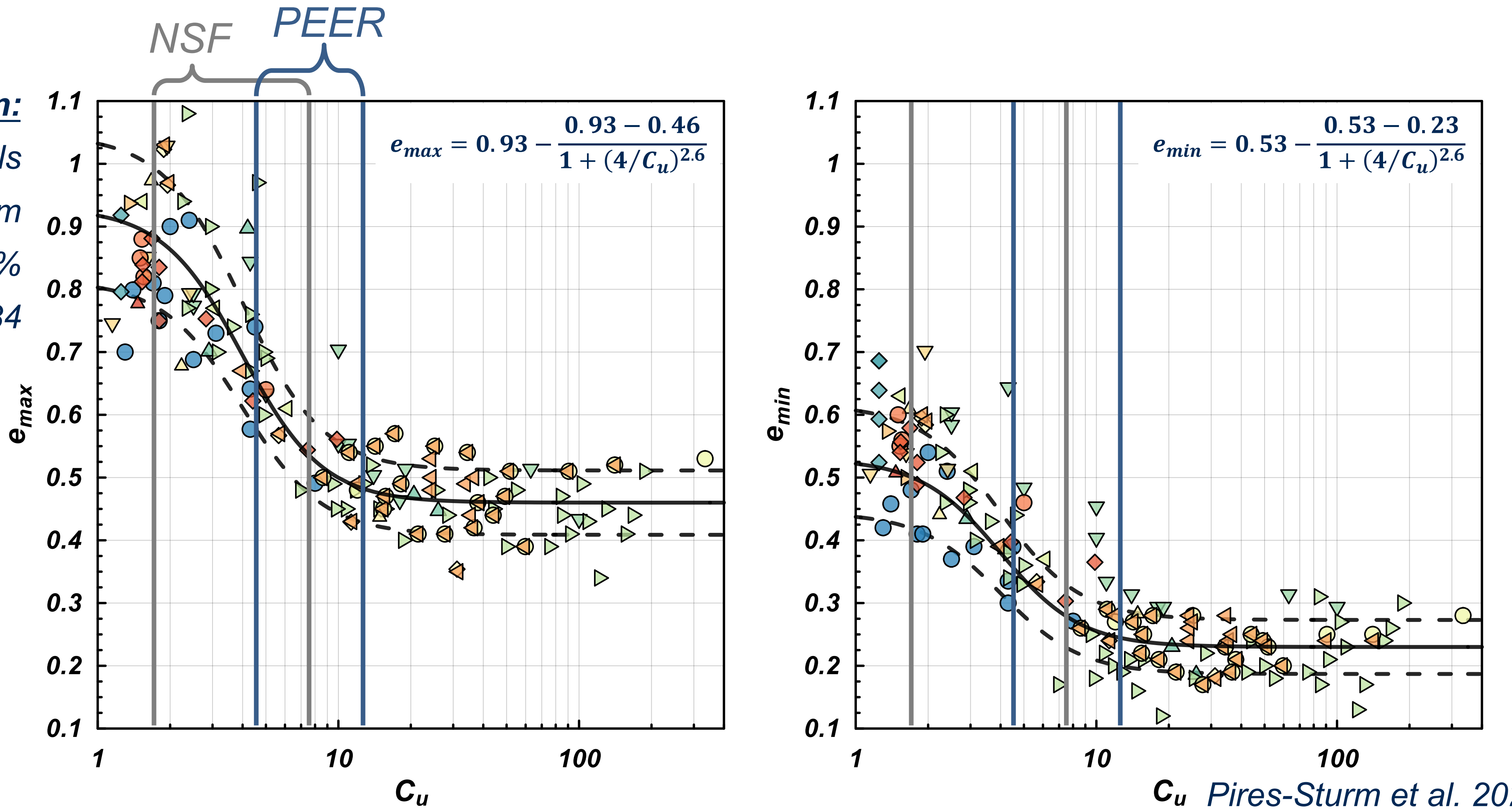
<u>Database Composition:</u>

Quartz and silica soils

D_{50} = 0.1 – 115 mm

Fines = 0 – 10%

C_u = 1.2 - 334

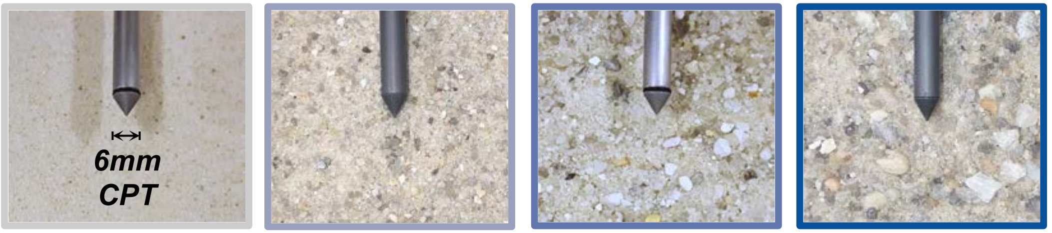


Pires-Sturm et al. 2022

Research program – test soil properties

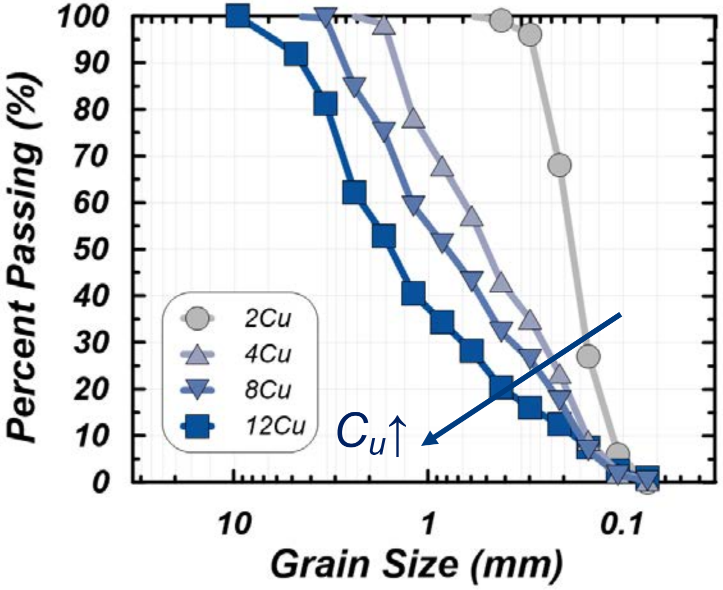
- Suite of 10 test soils of varying C_u and D_{50}

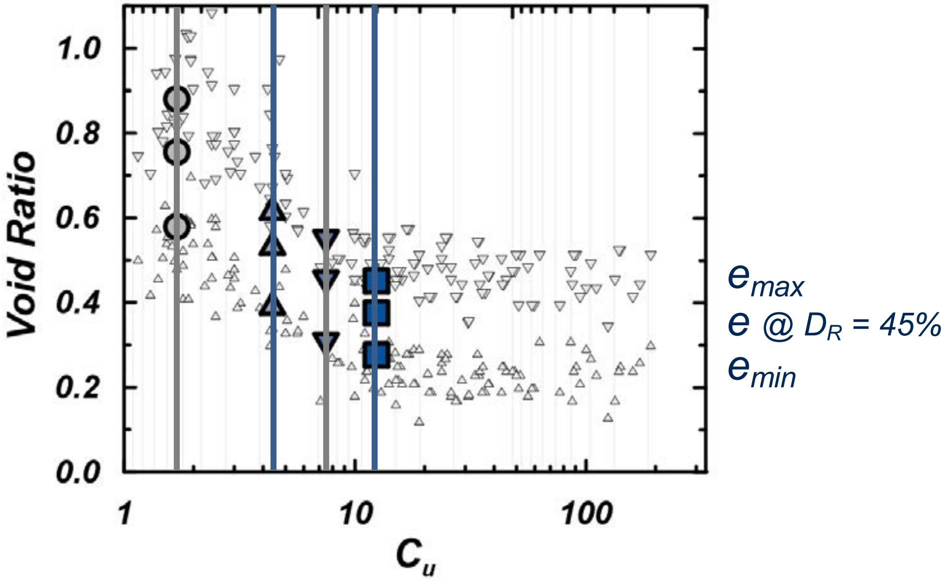
2Cu | 4Cu | 8Cu | 12Cu



	Sand	C_u	e (D_R = 45%)	k [cm/s]	V_s @ 90 kPa [m/s]
NSF	2Cu	1.7	0.76	0.025	164
PEER	4Cu	4.4	0.54	0.029	188
NSF	8Cu	7.5	0.45	0.022	199
PEER	12Cu	12.4	0.38	0.025	217

- secondary parameters held constant
- fines content < 5% for all soils

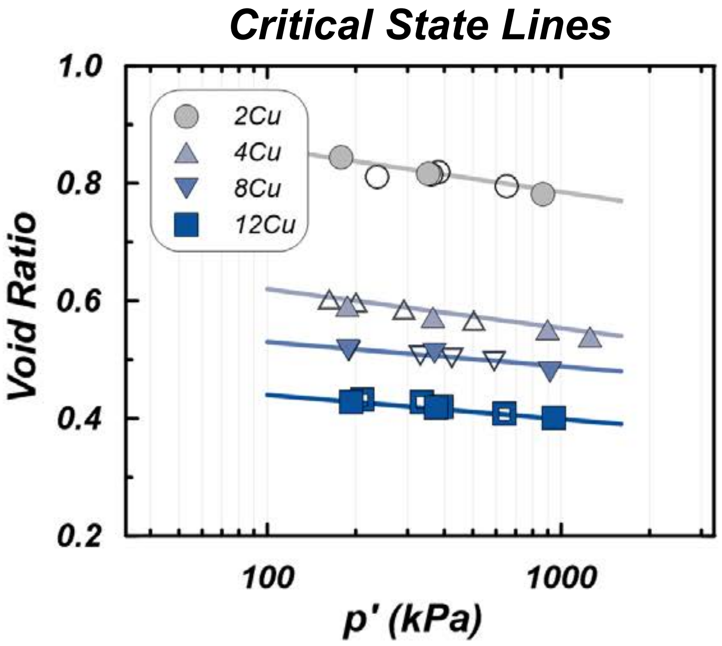


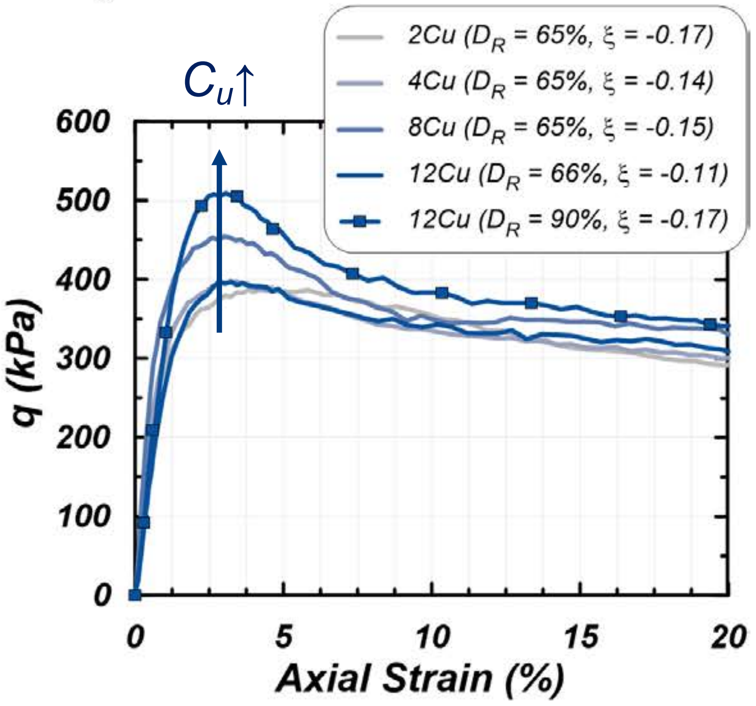


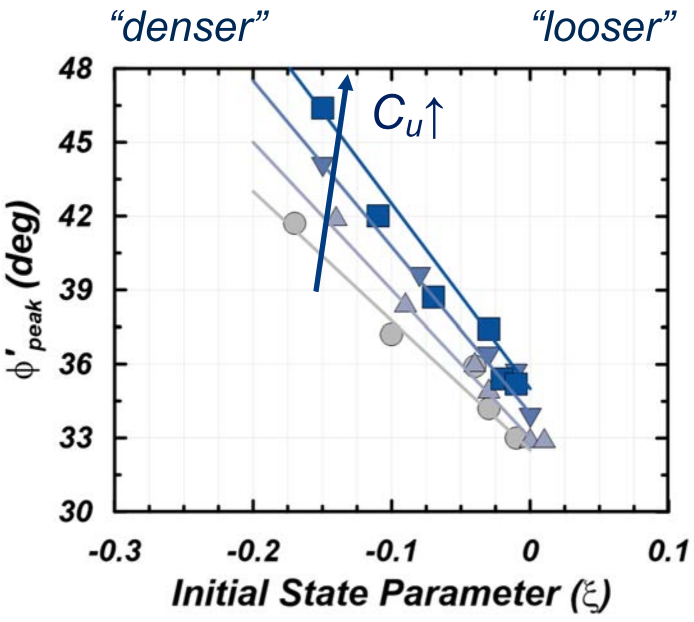
Pires-Sturm et al. 2022, Love 2022

Experimental/Numerical – ICU/ICD triaxial behavior

- Monotonic behavior (at constant D_R, ξ)
  - drained behavior
    - $C_u \uparrow$, $\phi'_{peak} \uparrow$, $\phi'_{cs} \rightarrow$
  - critical state line
    - $C_u \uparrow$, $\Gamma \downarrow$ (lower), $\lambda \downarrow$ (flatter)
- Experimental trends confirmed and explained at particle-scale by DEM





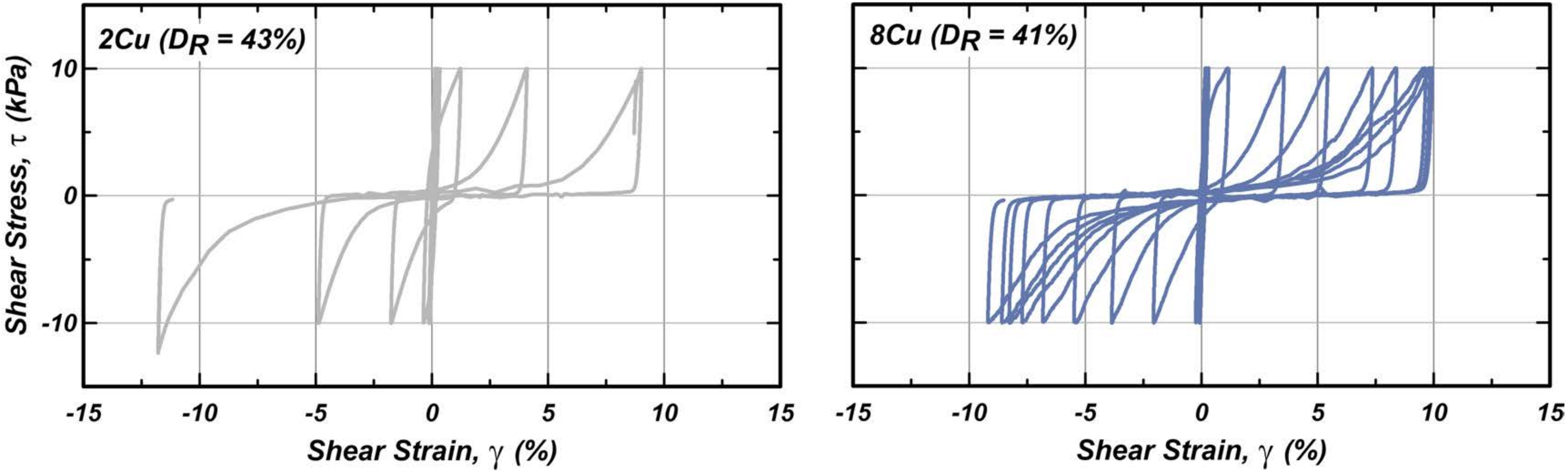


Ahmed et al. 2023, Basson et al. 2023a

Experimental/Numerical – cyclic DSS

- Cyclic behavior (at constant D_R, ξ)
  - Undrained DSS @ CSR = 0.10, $\alpha = 0$
  - $N_{SASS=3\%}$ for triggering decreases or unchanged
  - Strain accumulation ($\Delta\gamma$ / cycle) post-triggering decreases

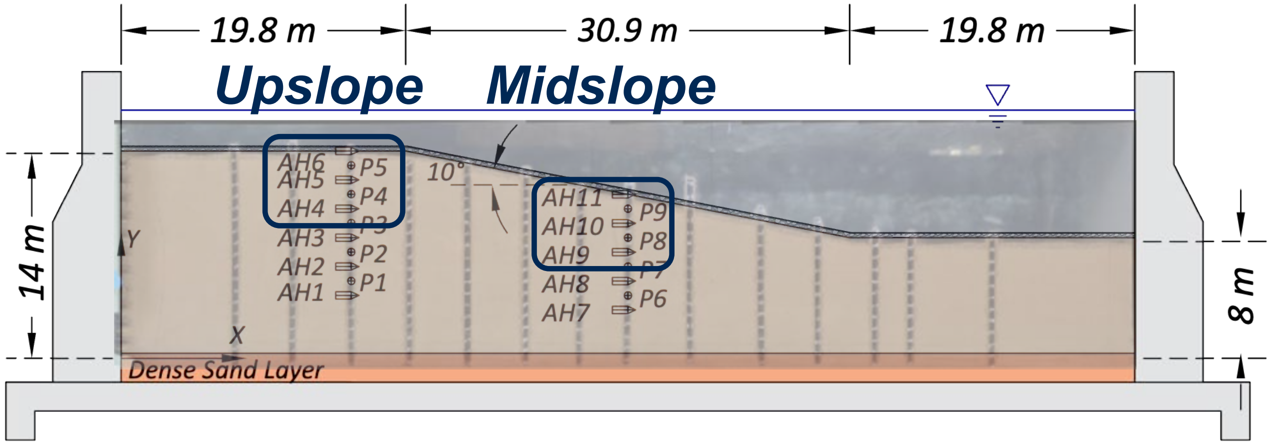
- Experimental trends confirmed and explained at particle-scale by DEM



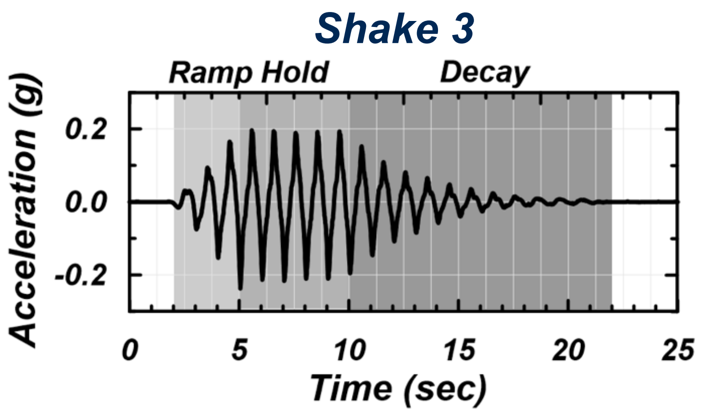
Humire et al. 2023, Reardon et al. 2023, Basson et al. 2023b

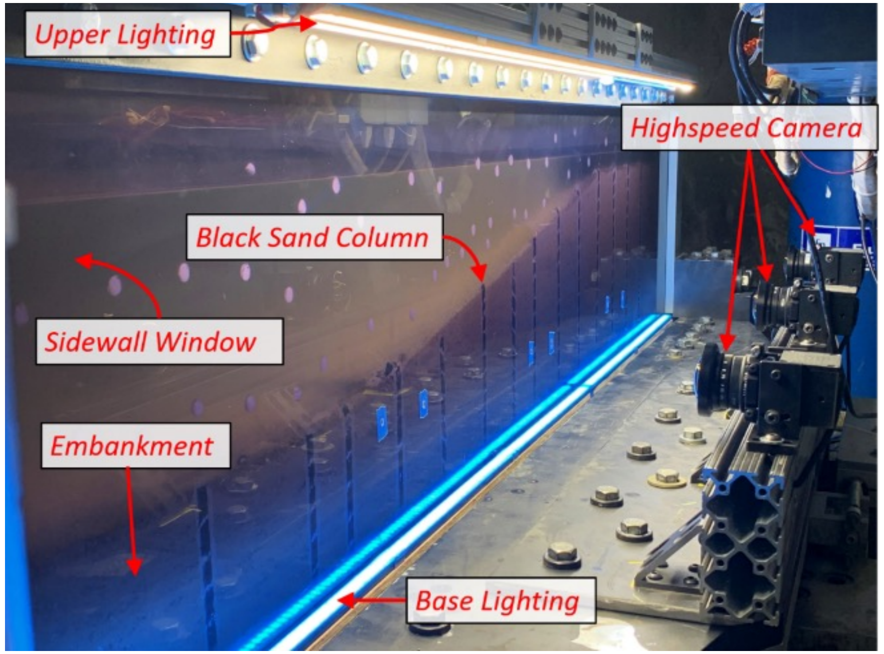
Centrifuge modeling – sloping ground

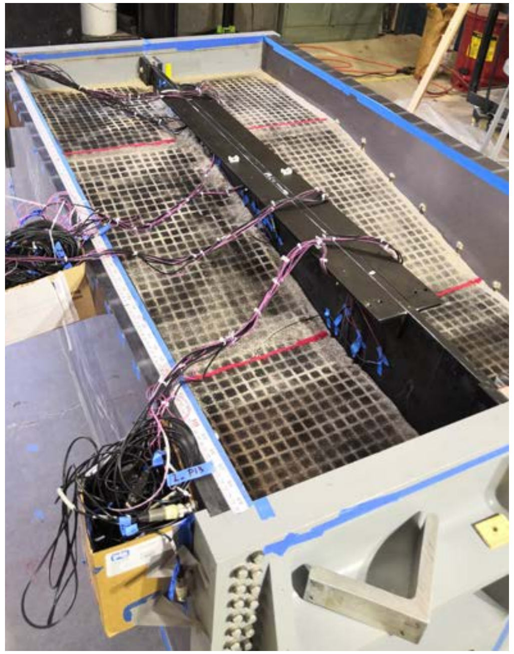
- 9m radius UC Davis NHERI centrifuge
  - 40x gravitational field and fluid viscosity
- 6 slopes (4 @ $D_{R\_initial} \approx 45\%$, 2 @ 65%)
- Repeated shaking to track triggering, strains, and deformations
  - 1Hz motion @ PBAs of 0.13g – 0.49g
- 10 mm CPT profiling



- High speed recording of deformations
  - GEOPIV analysis

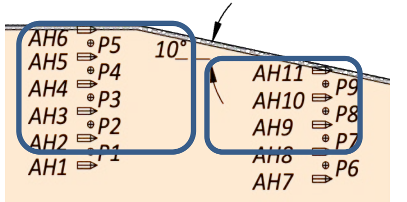






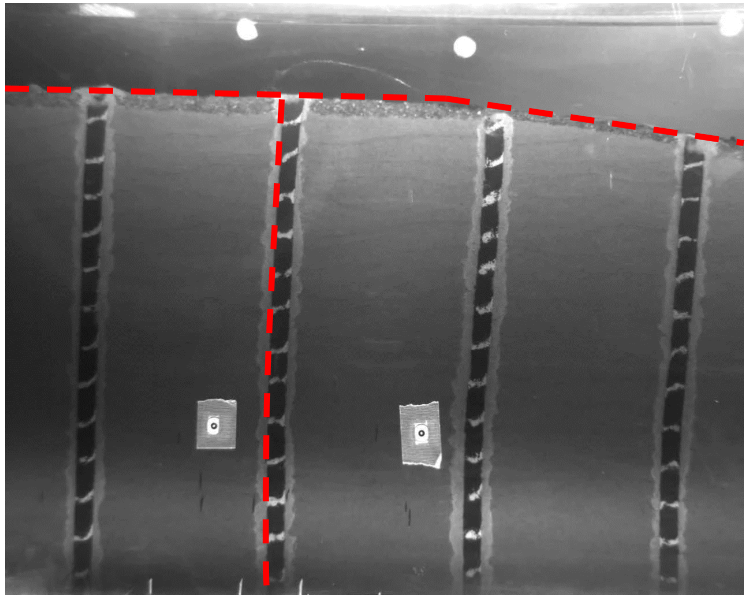
Carey et al. 2022, 2023, Love et al. 2023

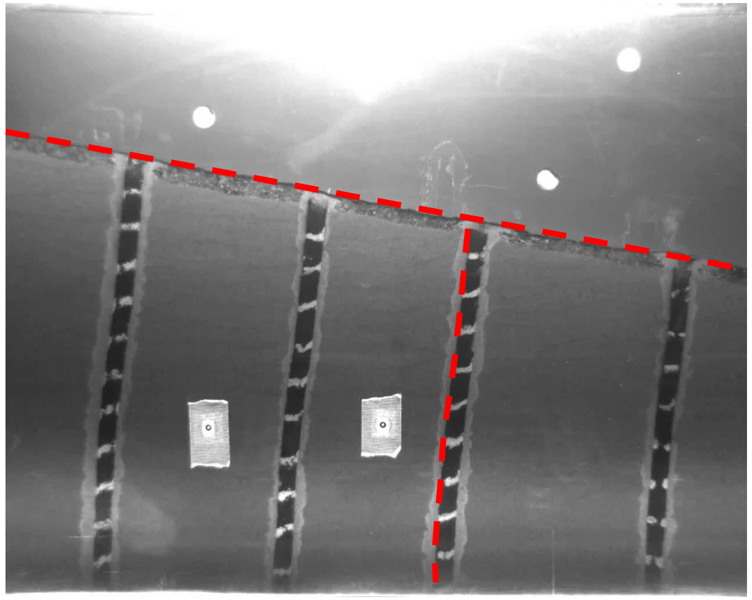
High-speed video ($D_{R\_initial}$ ≈ 45%, Shake 3)



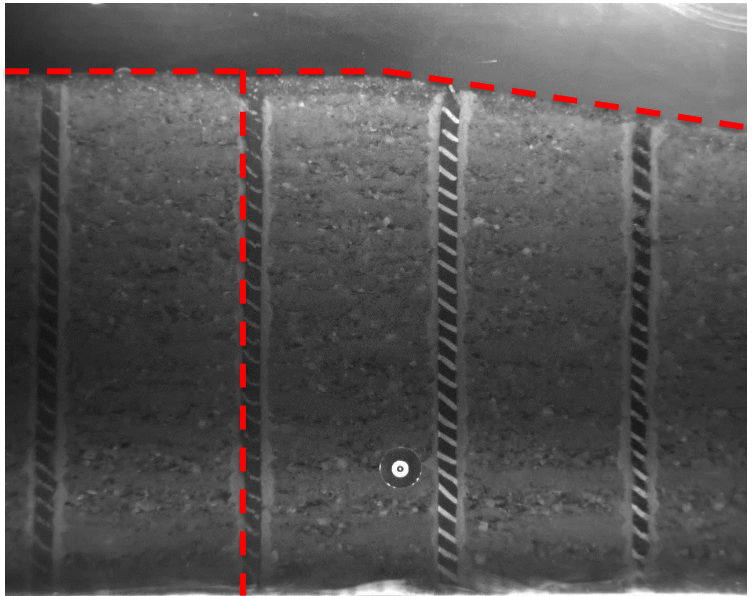
Upslope Camera | **Midslope Camera**

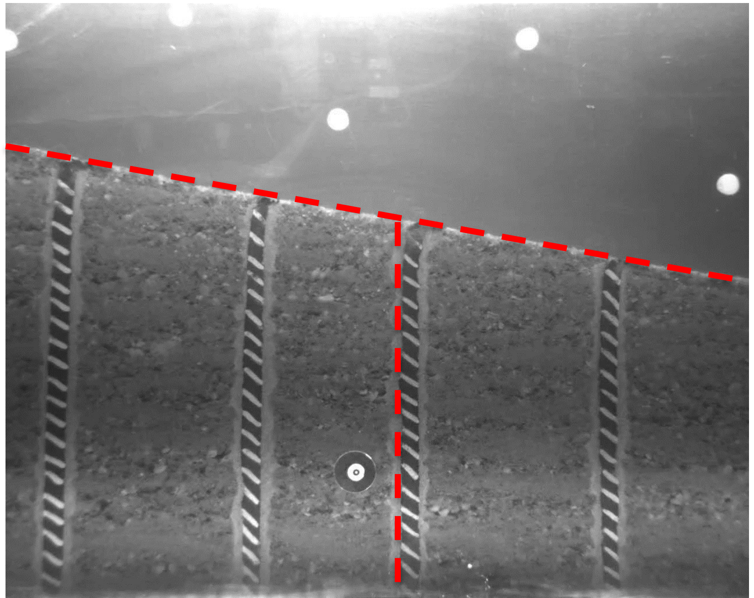
2Cu



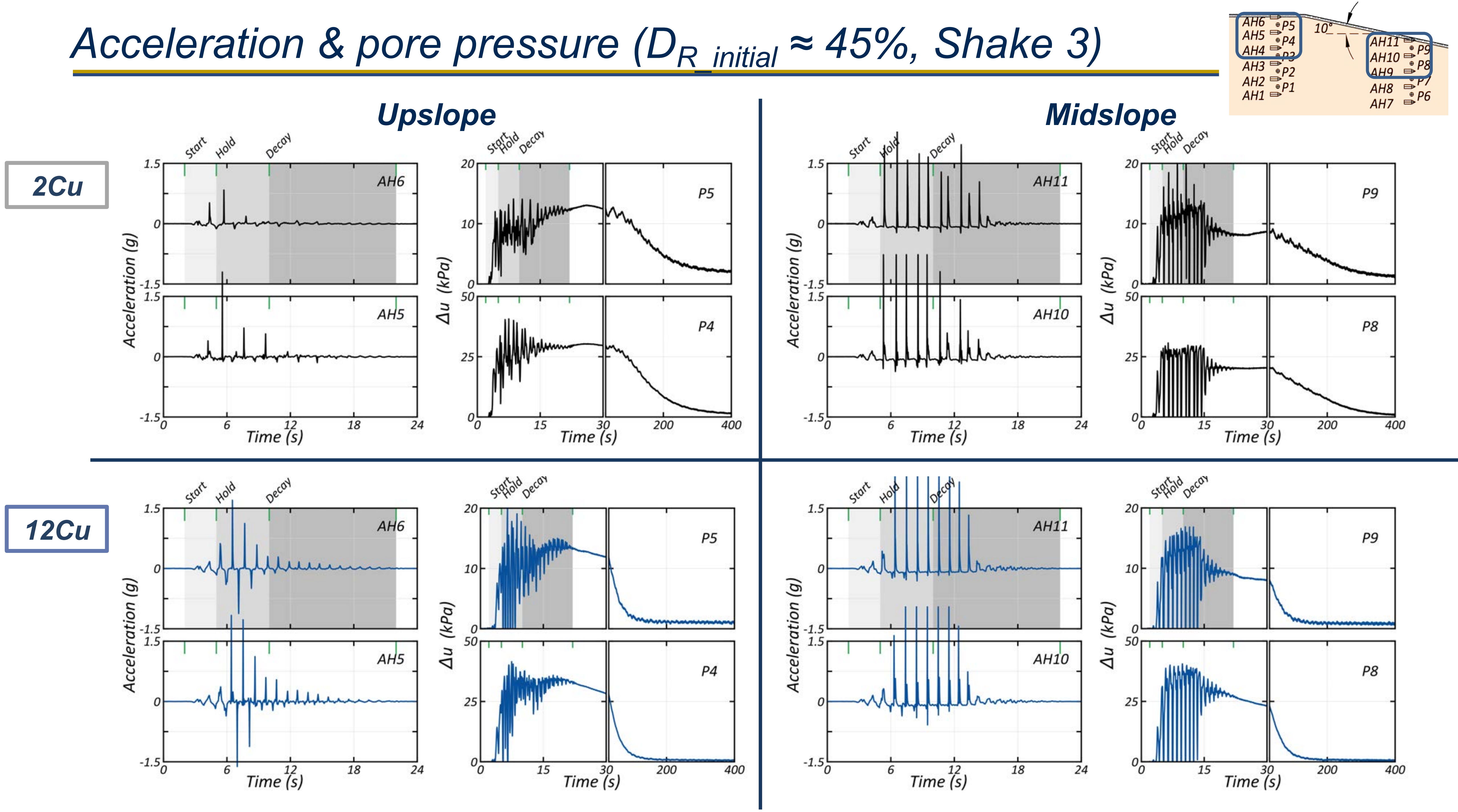


12Cu

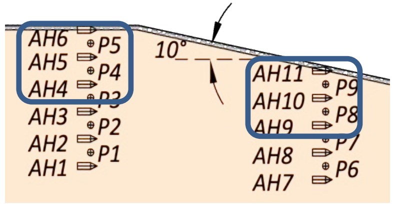




Acceleration & pore pressure ($D_{R\_initial}$ ≈ 45%, Shake 3)



Dynamic stress-strain response ($D_{R\_initial}$ ≈ 45%, Shake 3)

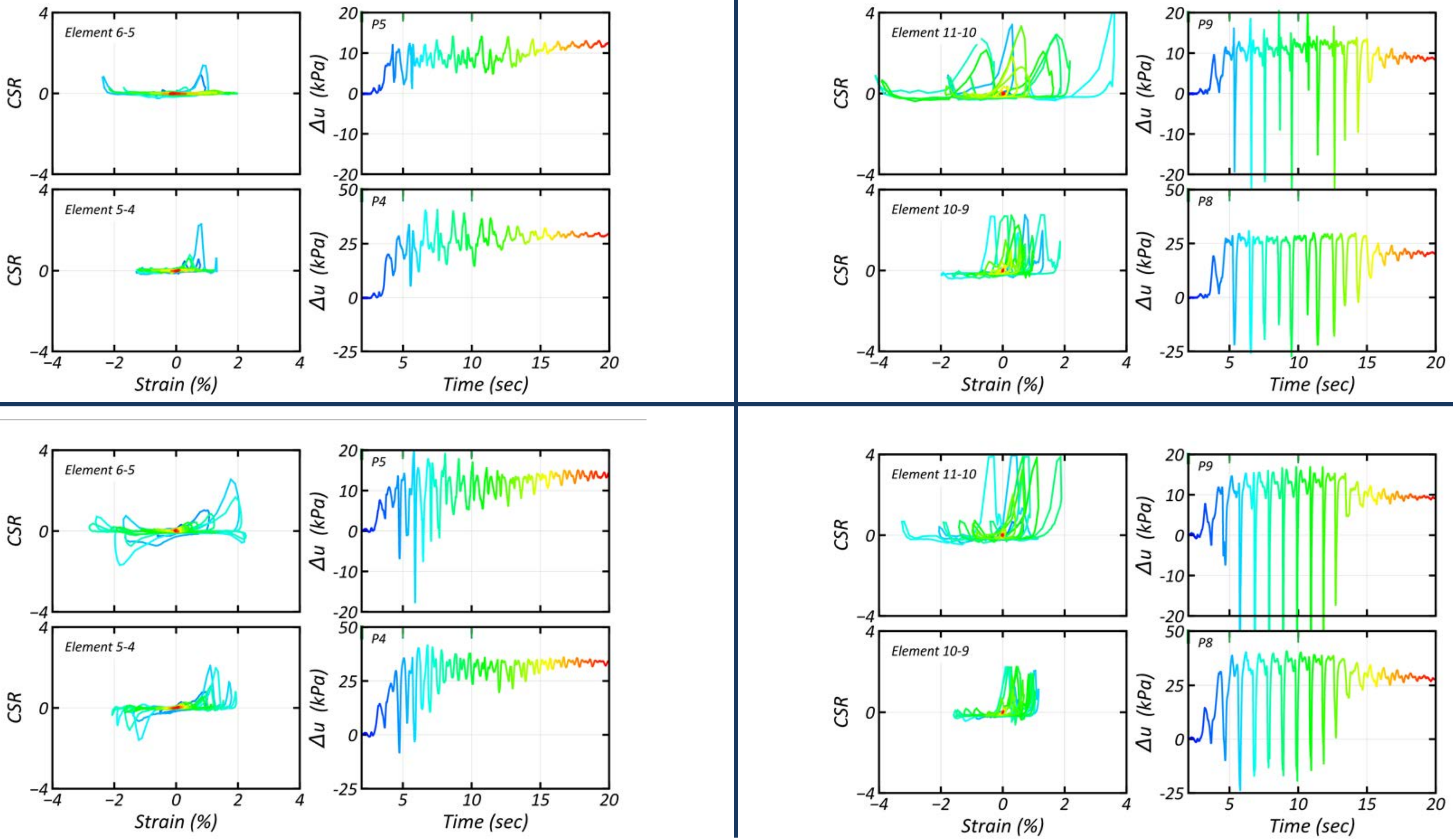


Upslope

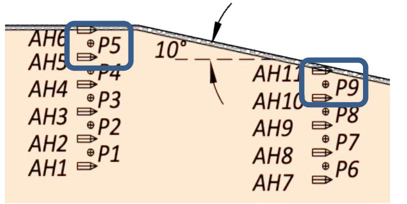
Midslope

2Cu

12Cu

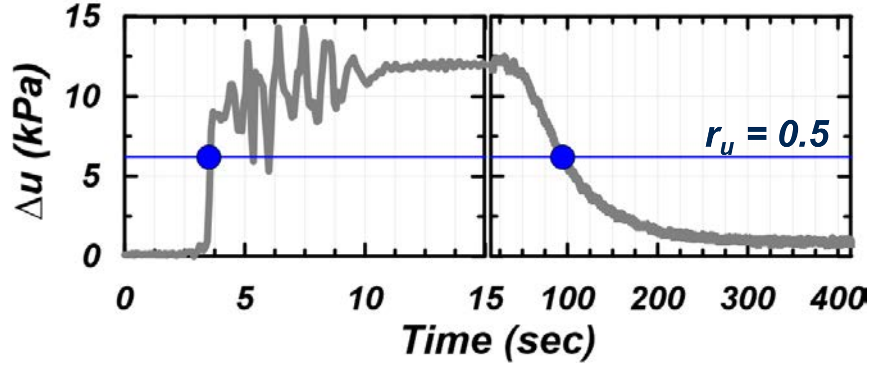


Pore pressure generation & dissipation ($D_{R\_initial}$ ≈ 45%)

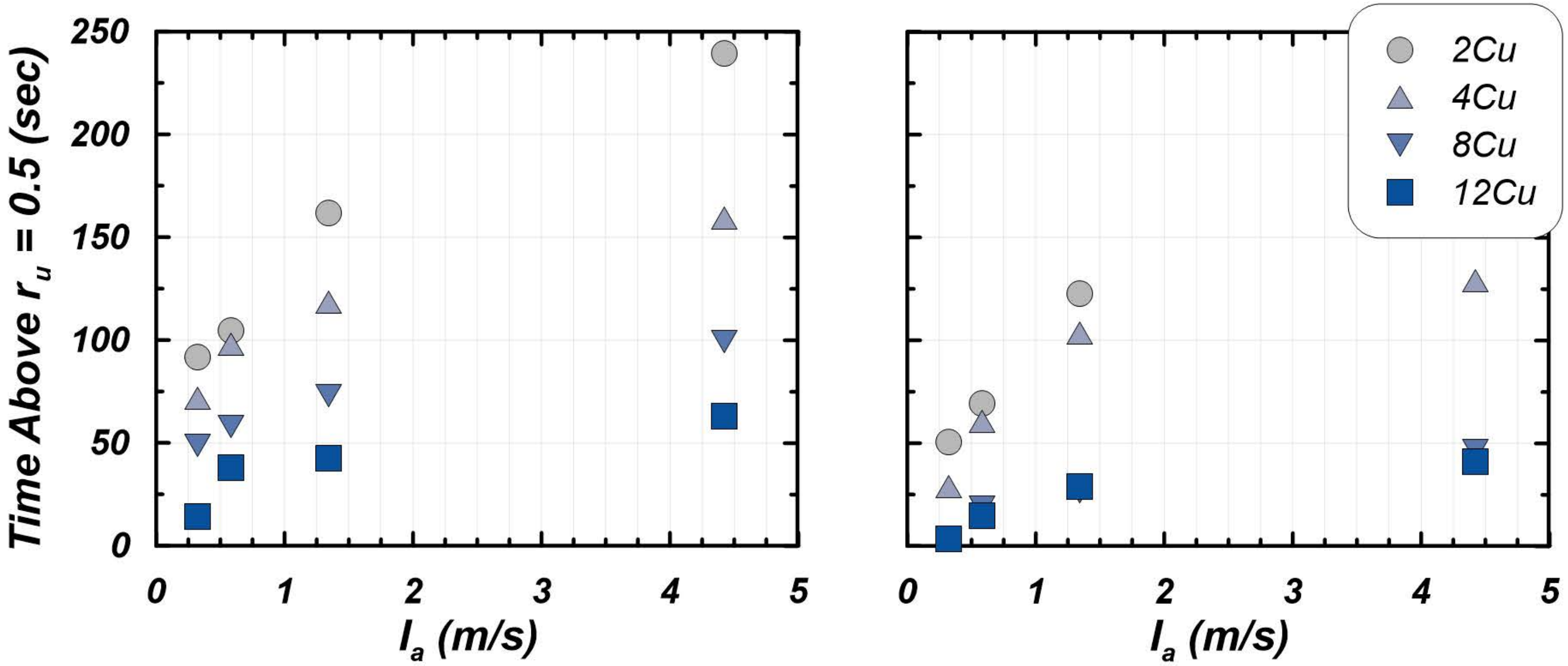


- *Time duration above r_u = 0.5 decreases by up to 80% as C_u increases from 2 to 12*
- *Recall hydraulic conductivities are comparable*
- *Faster dissipation of excess porewater pressure due to:*
  - *lower initial void ratio*
  - *higher bulk modulus (K)*

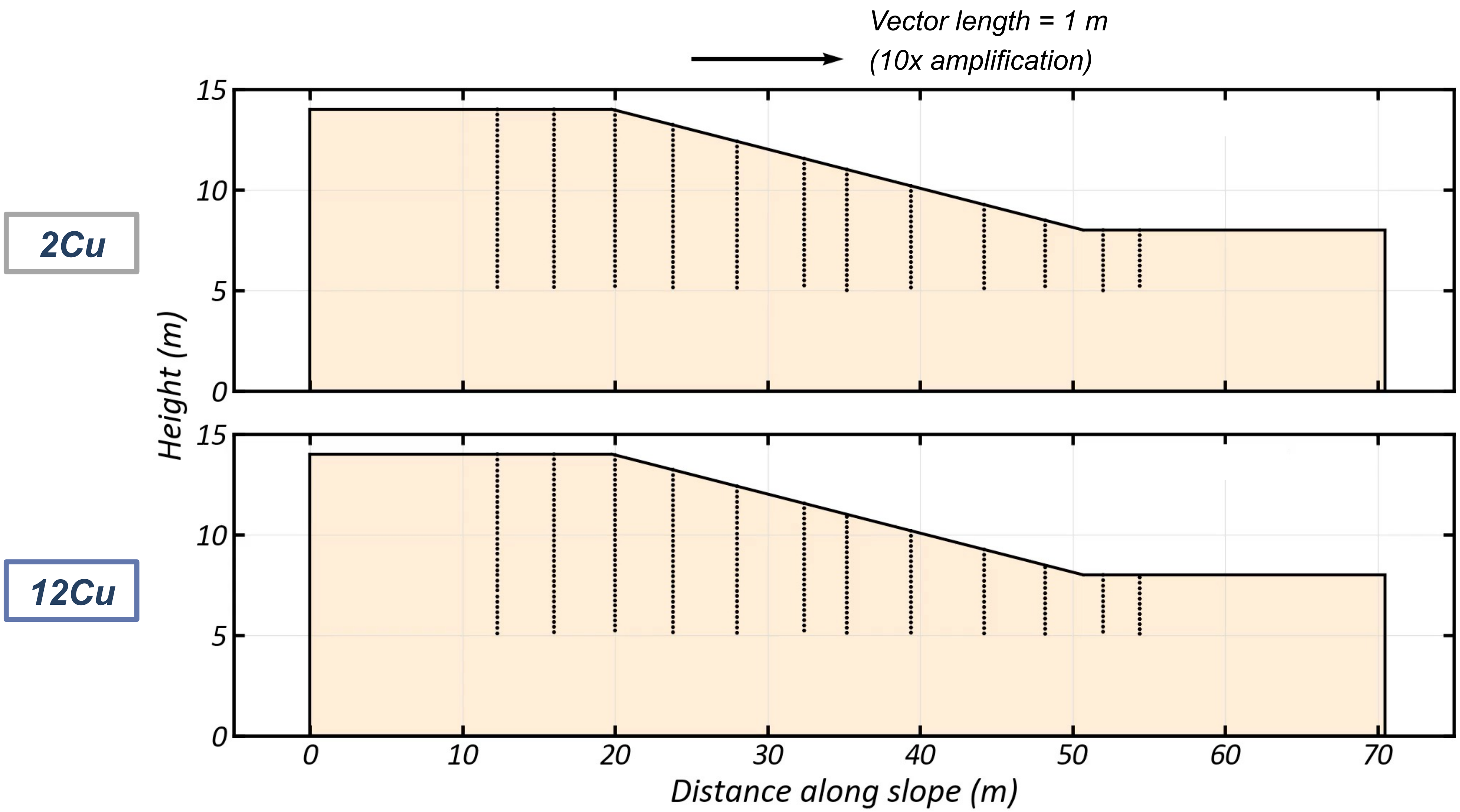
2Cu Model, Shake 1



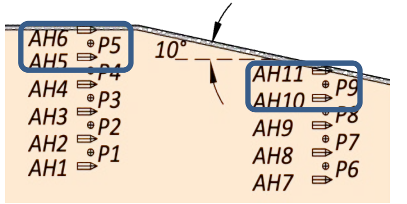
Upslope **Midslope**



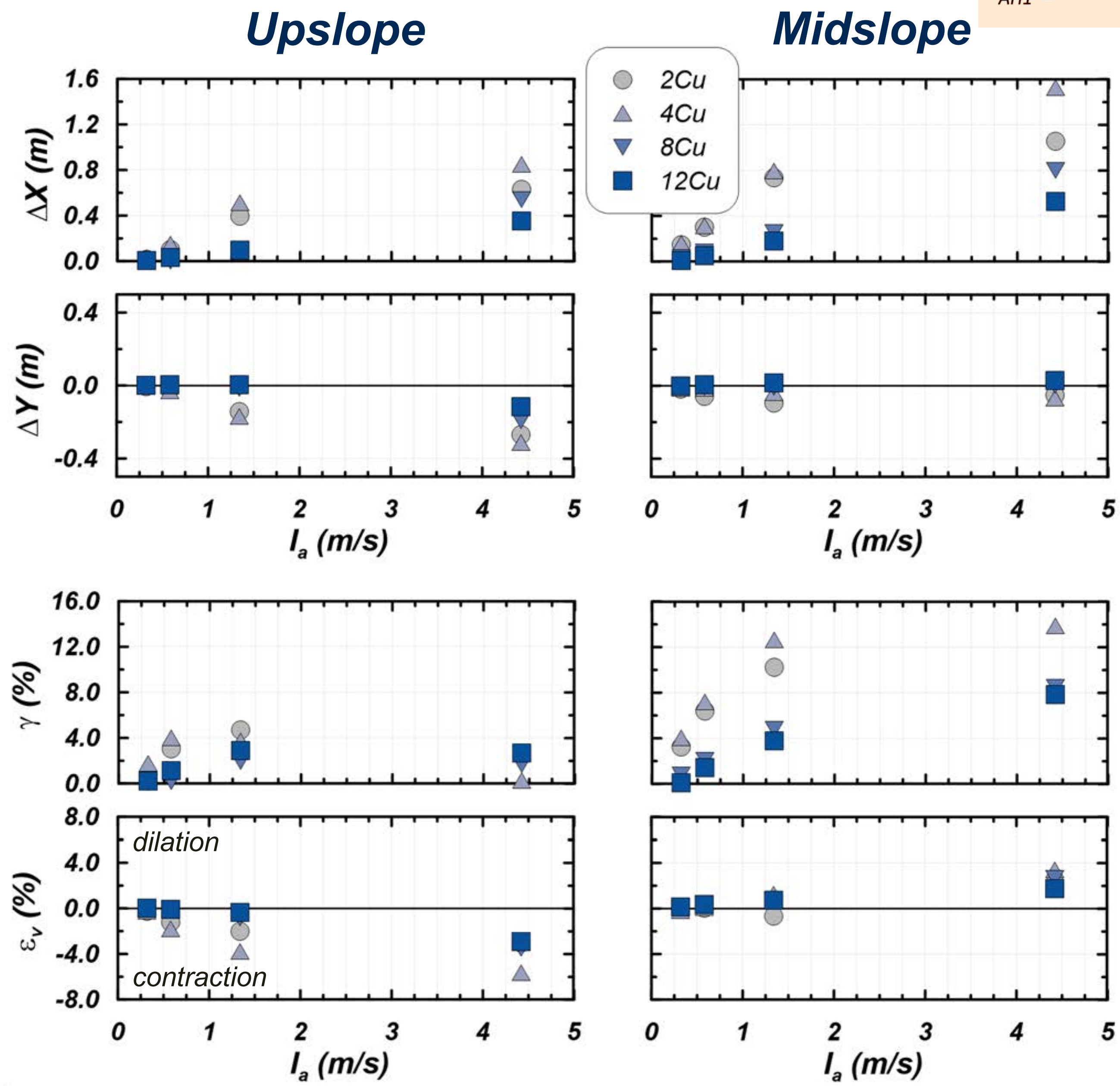
Permanent displacement (PIV) ($D_{R\_initial}$ ≈ 45%, Shake 3)



Permanent displacements & strains ($D_{R\_initial} \approx 45\%$)



- *Displacements reduced throughout model as C_u increases*
- *Driving static shear stress on midslope mobilizes greater dilatancy as C_u increases*
- *Displacements from 2Cu to 12Cu:*
  - *ΔX reduced by 50 to 80%*
  - *ΔY reduced by >60% and in some cases heaves*
- *Strains from 2Cu to 12Cu:*
  - *γ reduced by 40 to 90%*
  - *ε_v reduced >60%, and the midslope dilates*



Thank You

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