Liquefaction of gravelly soils and the impact on critical infrastructure

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PEER

Liquefaction of Gravels and their Impact on Infrastructure

1948 Fukui EQ – gravelly sand
1964 Alaska EQ – sandy gravel
1975 Haicheng EQ – gravelly sand
1976 Tangshan EQ – gravel and sand
1976 Friuli, Italy EQ – gravel and sand
1983 Borah Peak EQ – silt and gravel
1993 Hokkaido-Nansei-Oki EQ – gravelly sand
1995 Kobe EQ – sandy gravel
1999 Chi-Chi EQ – gravel, sand, silt

2008 Wenchuan EQ – gravel and sand
2014 Cephalonia EQ – gravel
2016 Kaikoura EQ – gravelly sand

2014 Cephalonia EQ

Nikolaou et al. GEER (2014)

2016 Kaikoura EQ

Cubrinovski et al. (2018)

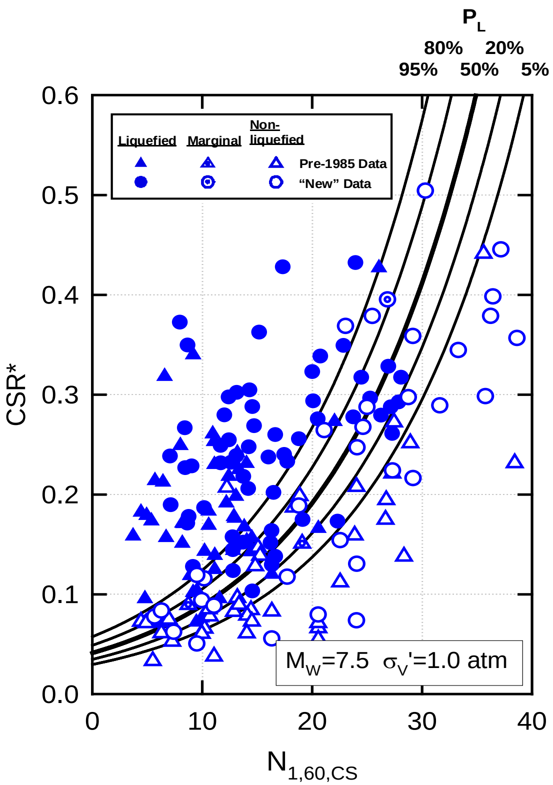
January 26 and February 3 2014 Cephalonia, Greece EQ, M_w = 6.1

4 Major Ports:

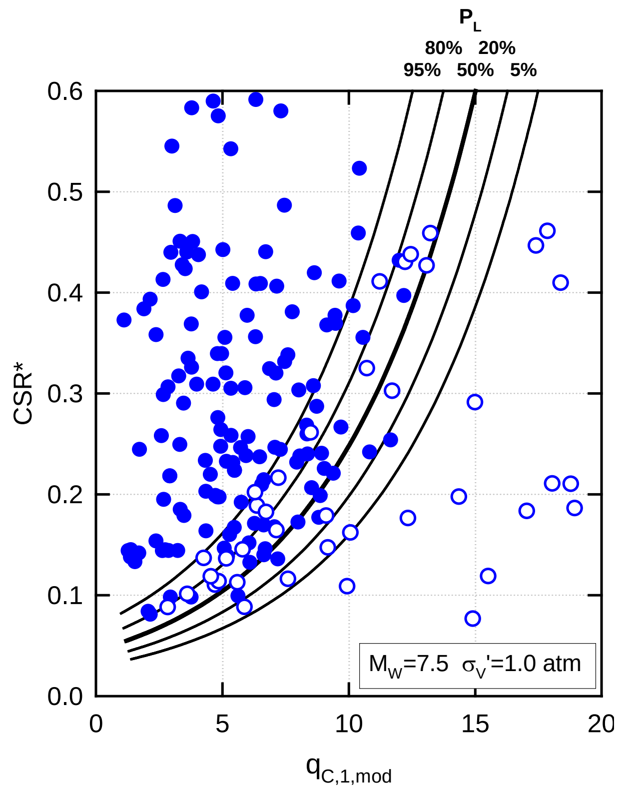
- **Devastating** Lixouri
- **Moderate** Argostoli
- **Minor/Insignificant** Sami
- **No Damage** Poros

Reliable assessment charts have been developed for sands, but not for gravels

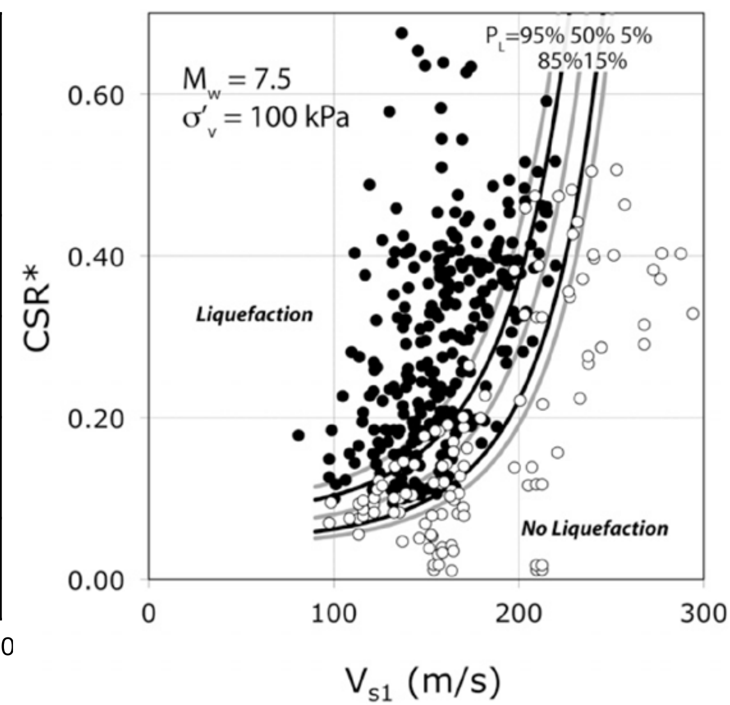
SPT



CPT

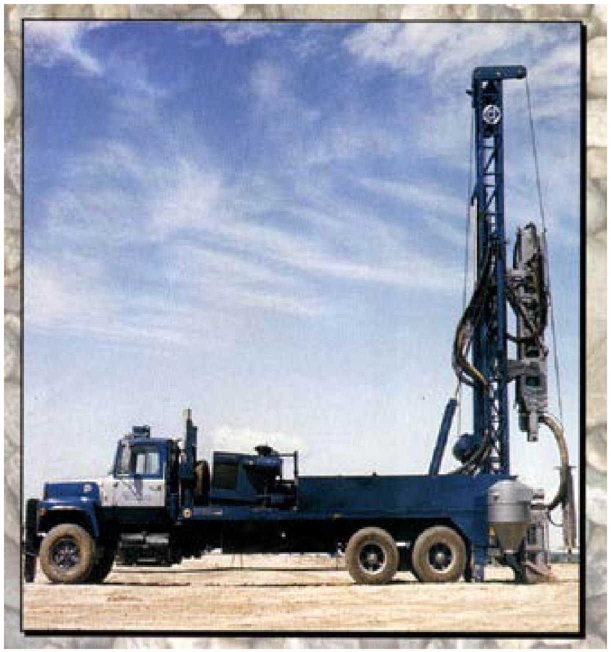


Vs



(Cetin et al, 2004; Moss et al, 2006; Kayen et al, 2013)

Gravels are challenging to characterize in the field due to their particle size



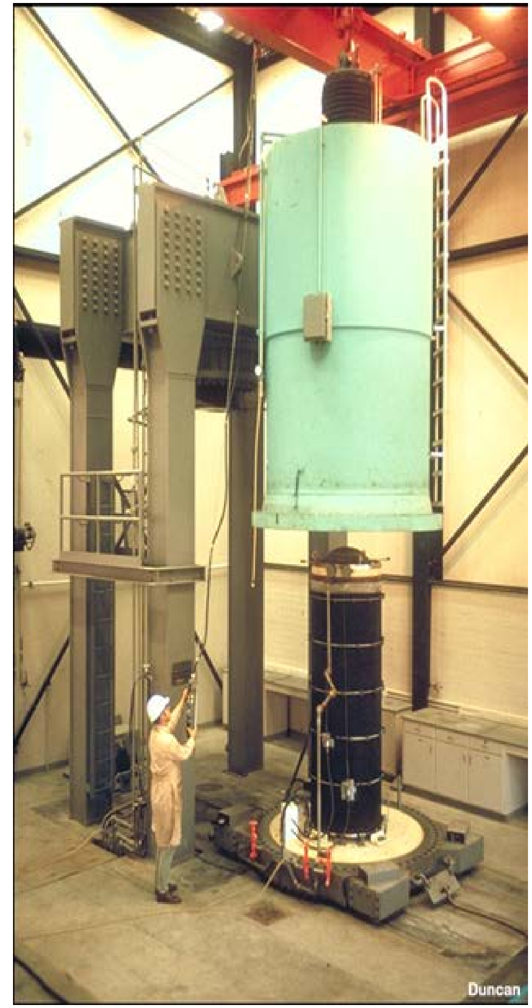
Becker Penetration Test (BPT)

Dynamic Penetration Test (DPT)

Shear Wave Velocity Measurements (Vs)

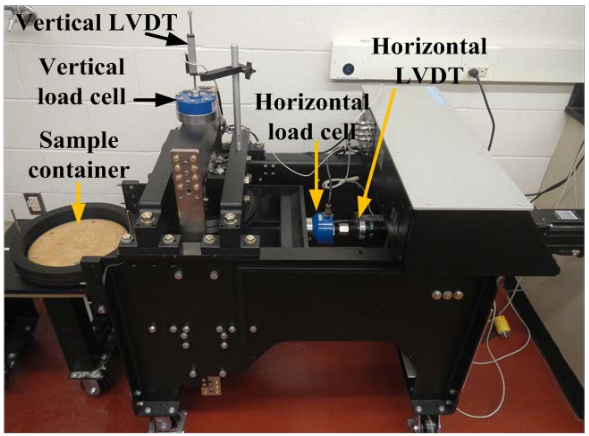
Gravelly soils can also be difficult to test in the laboratory

- Need large devices to accurately capture response
- Significant time to prepare specimens
- Most tests are Triaxial - Possible membrane compliance issues (Evans and Seed, 1987; Nicholson, Seed and Anwar, 1989)



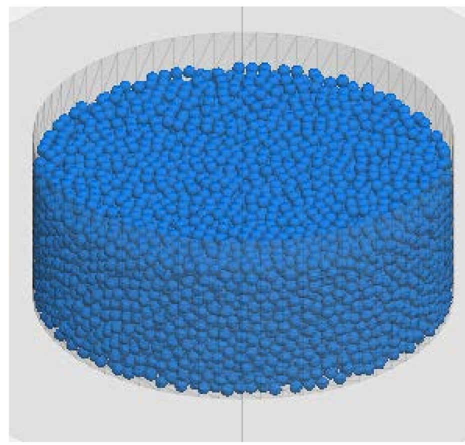
Integrated approach: Micro to Macro Response

Laboratory Testing



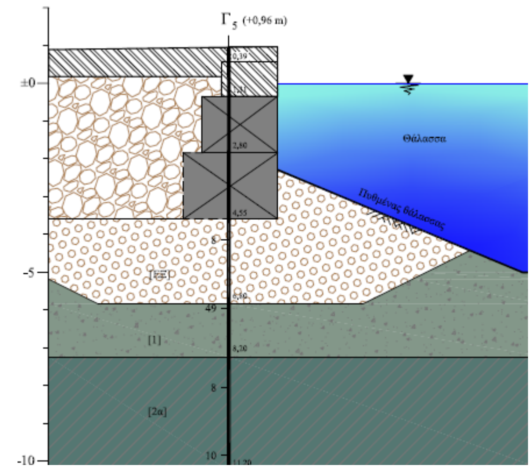
Large-scale CSS used for constant-volume monotonic, cyclic, and post-cyclic shear tests with Vs measurements

Numerical Modeling



3D DEM analyses

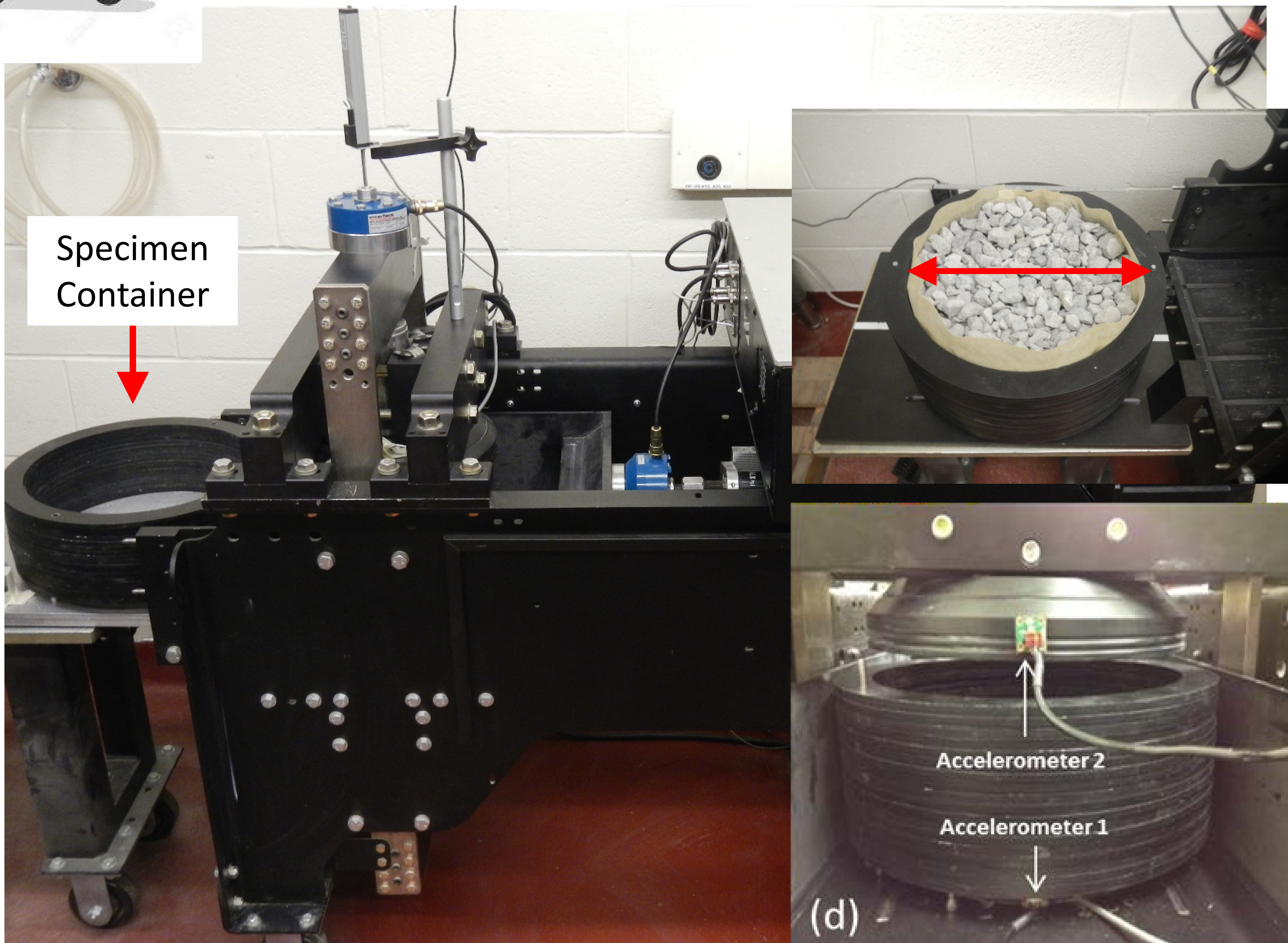
Field Response



Vs and DPT measurements in the field.

Back-analysis of case histories.

Large-size Cyclic Simple Shear (CSS)



Monotonic, cyclic and post-cyclic tests were performed on three uniform gravels,

Pea Gravel

Rounded to Subrounded

8 mm Crushed Limestone

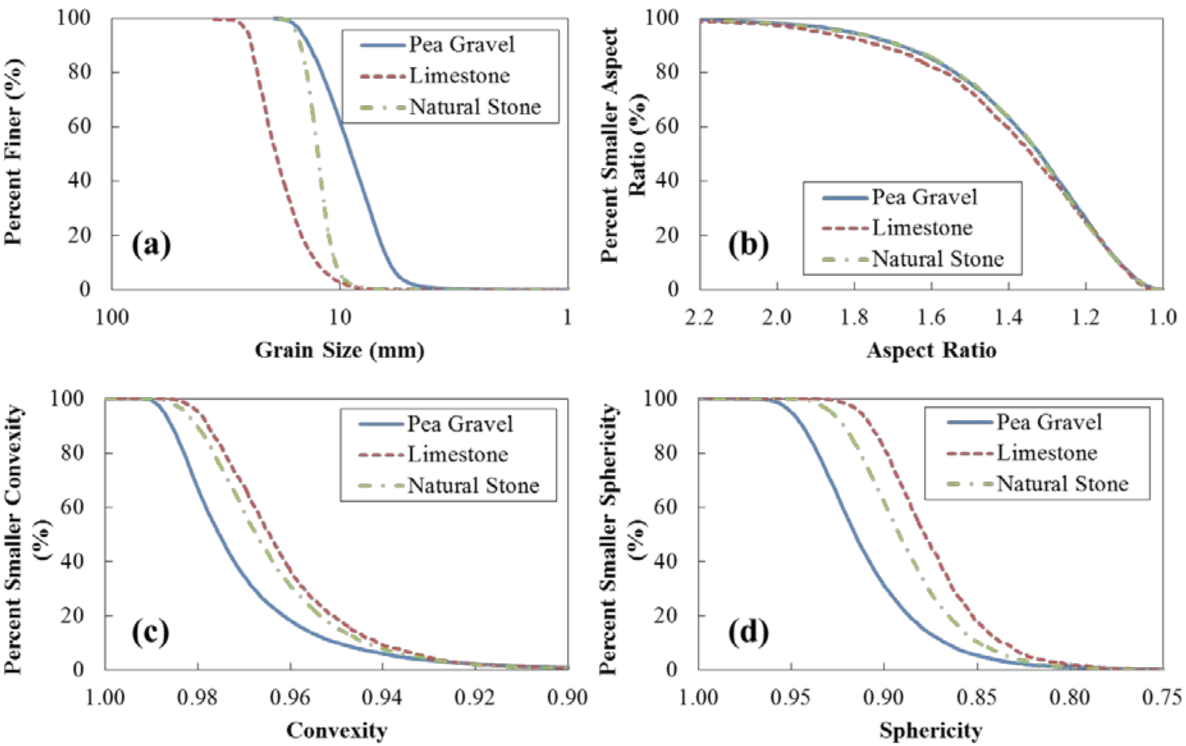
Angular

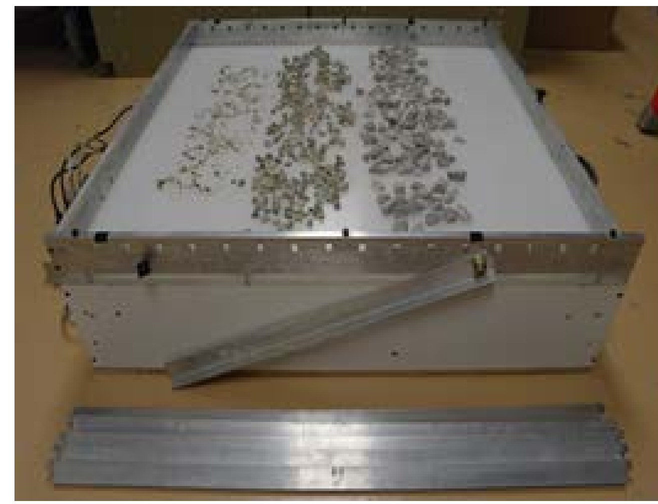
5 mm Crushed Limestone

Angular

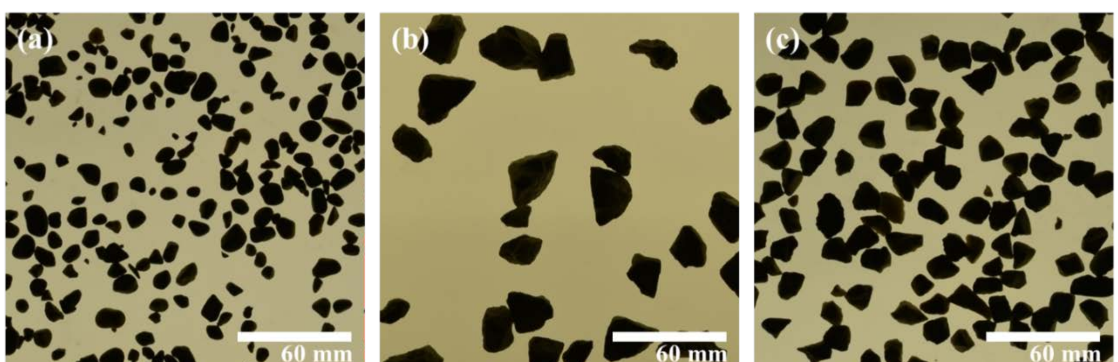
V_s was measured in every specimen

Translucent Segregation Test for Particle Morphology

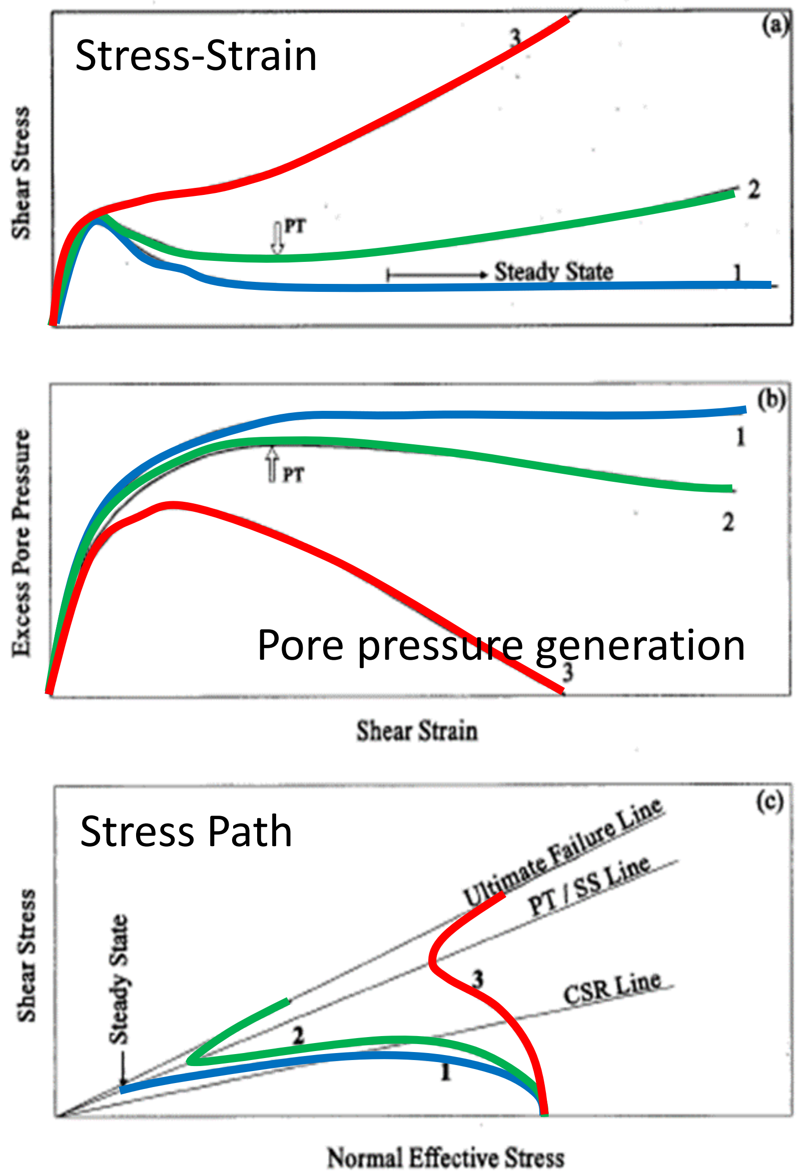




Test per Ohm and Hryciw, 2013



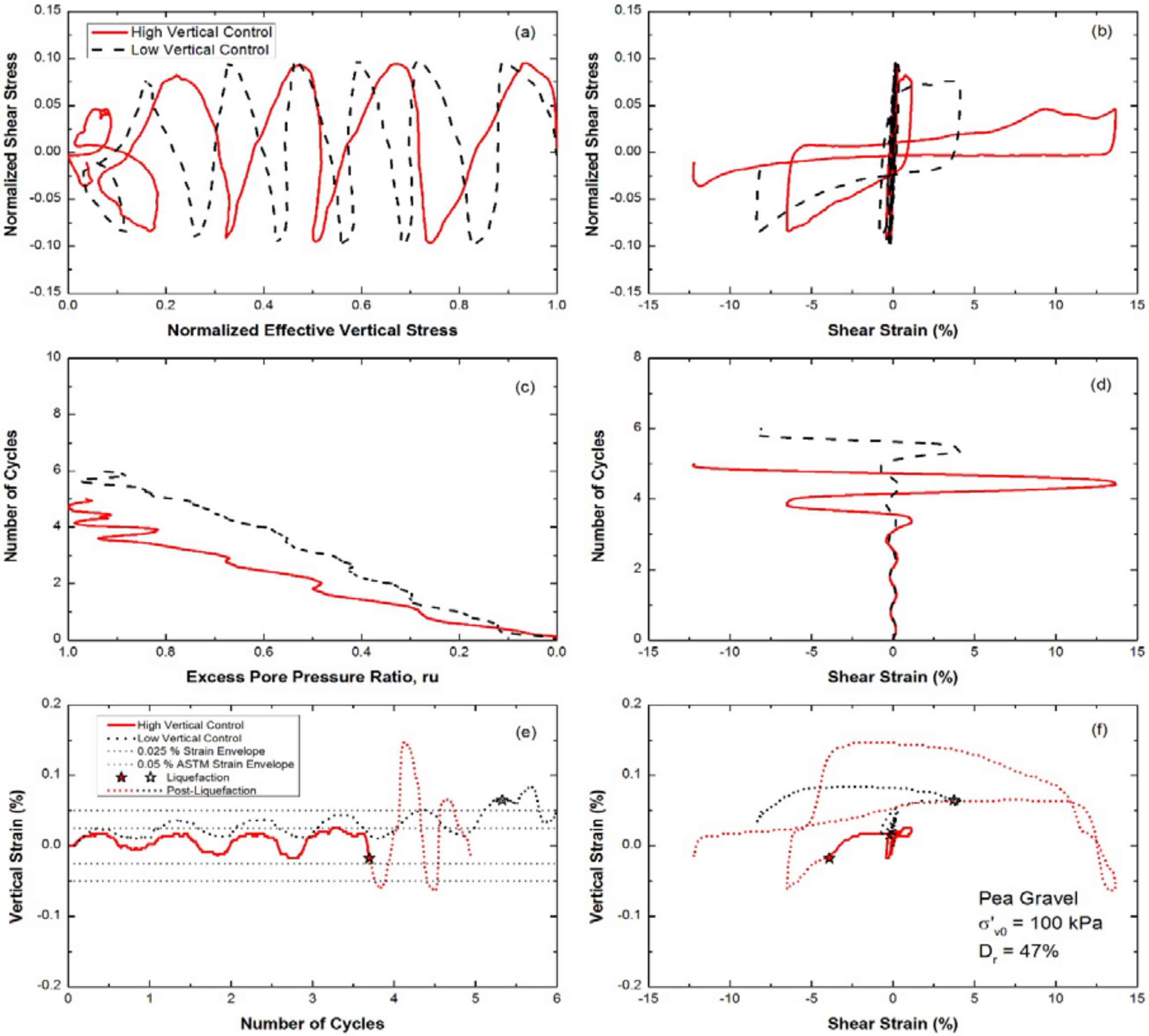
Critical state-based framework for granular soils

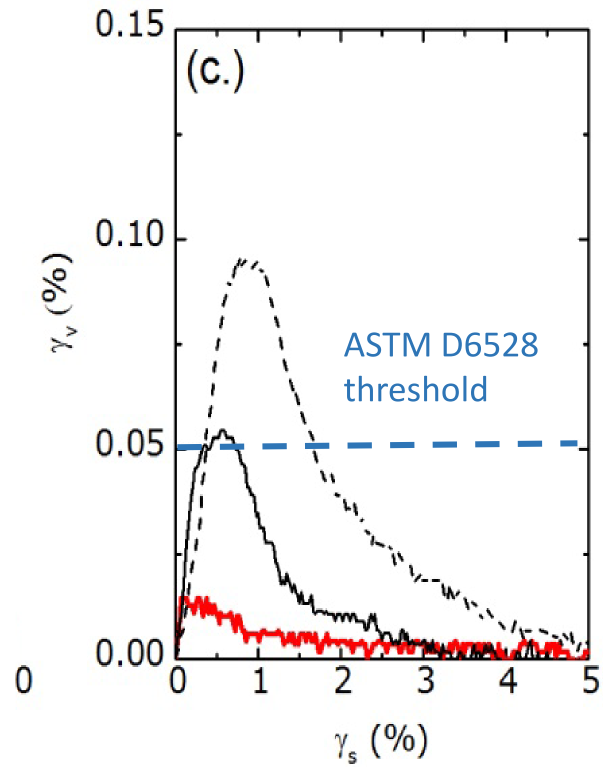


We expect gravels to follow a similar framework

(Sivathayalan, 1996, after Chern, 1985)

True constant volume conditions?

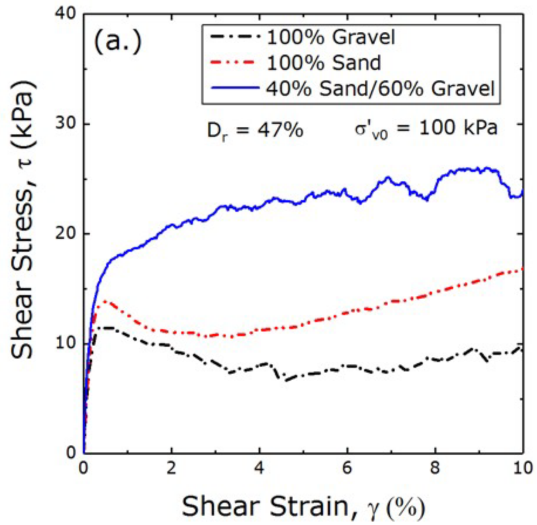


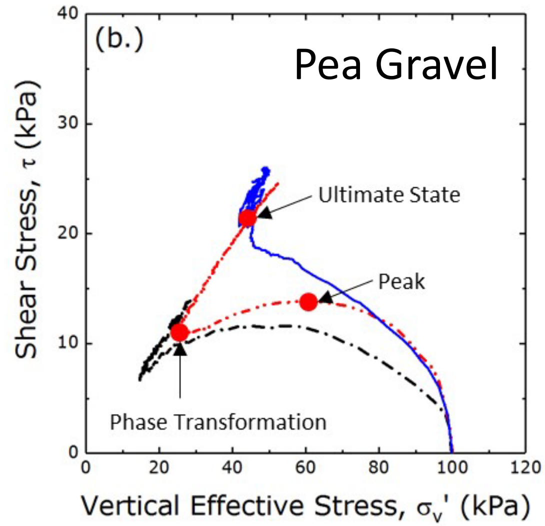


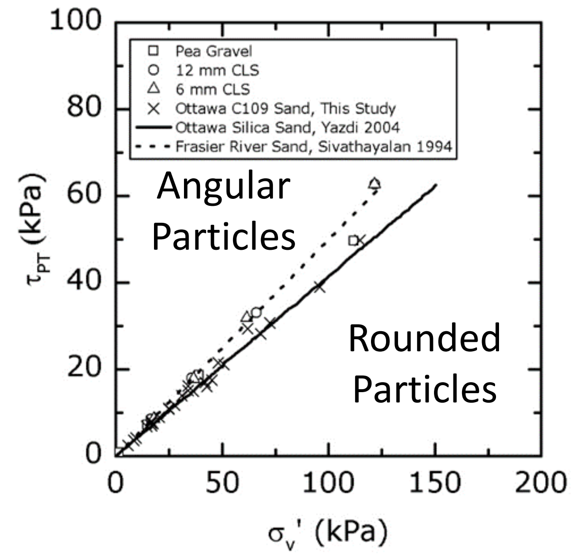
ASTM D6528 threshold needs to be reduced by 50%, and evolution of vertical strain should be always reported.

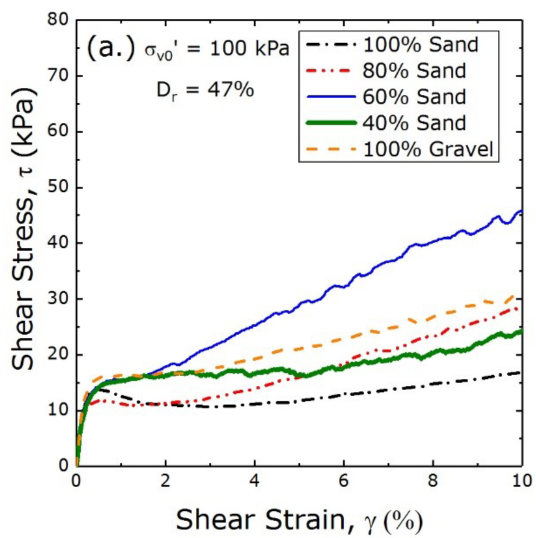
Zekkos, D., Athanasopoulos-Zekkos, A., Hubler, J., Fei, X., Zehtab, K.H., and Marr, A. (2017) “Development Of A Large-Size Cyclic Direct Simple Shear Device For Characterization Of Ground Materials With Oversized Particles”, Geotechnical Testing Journal, doi.org/10.1520/GTJ20160271.

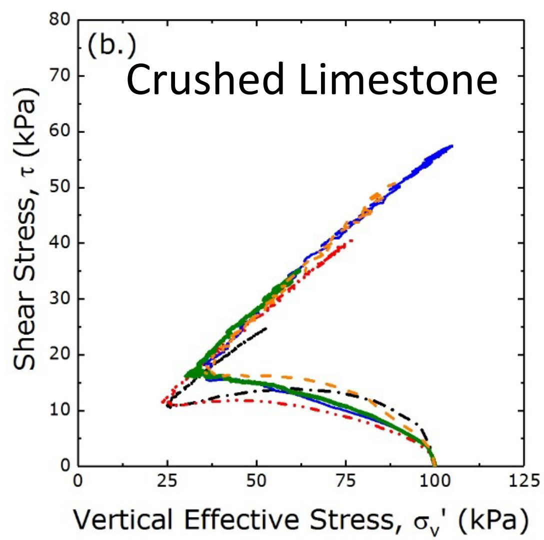
Effect of particle angularity is important



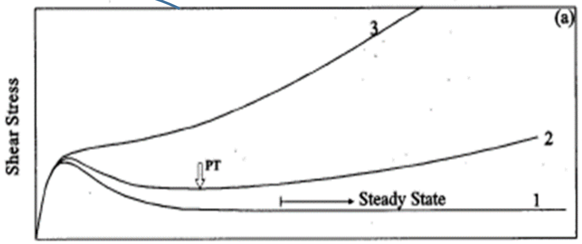


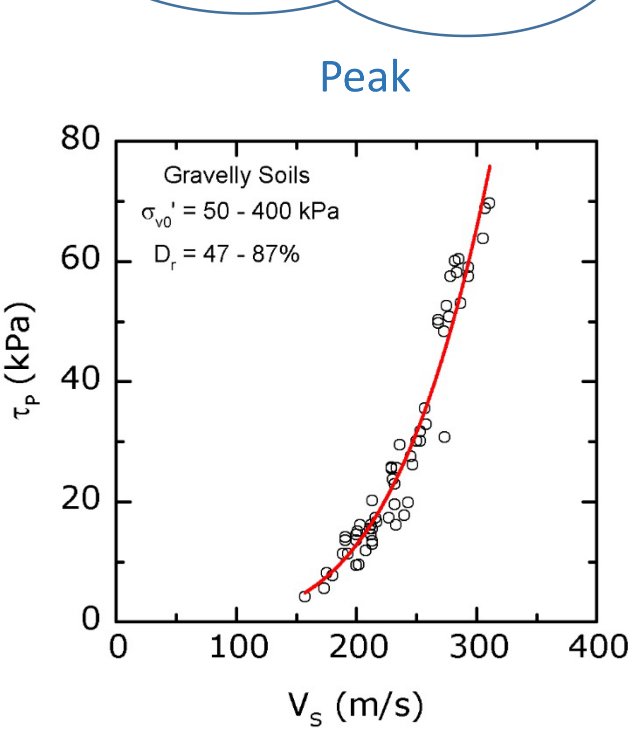




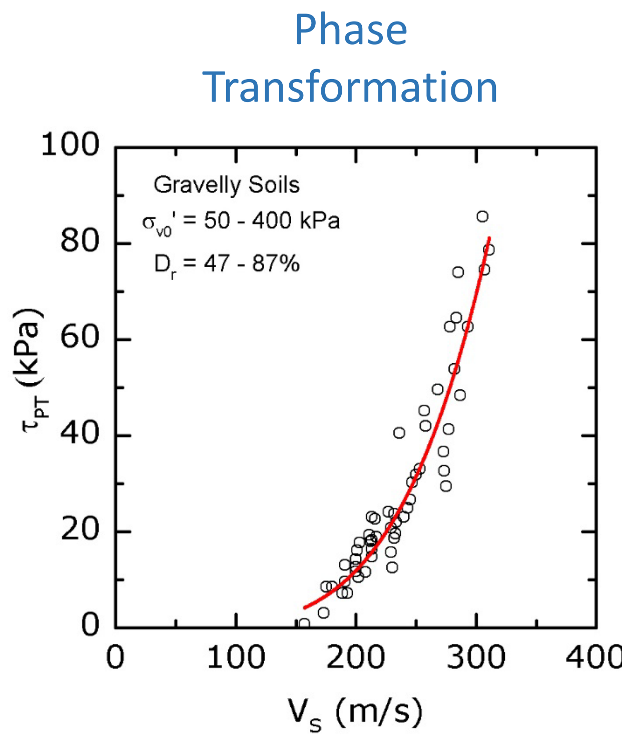


Correlation of Shear Wave Velocity with peak, phase transformation and ultimate state

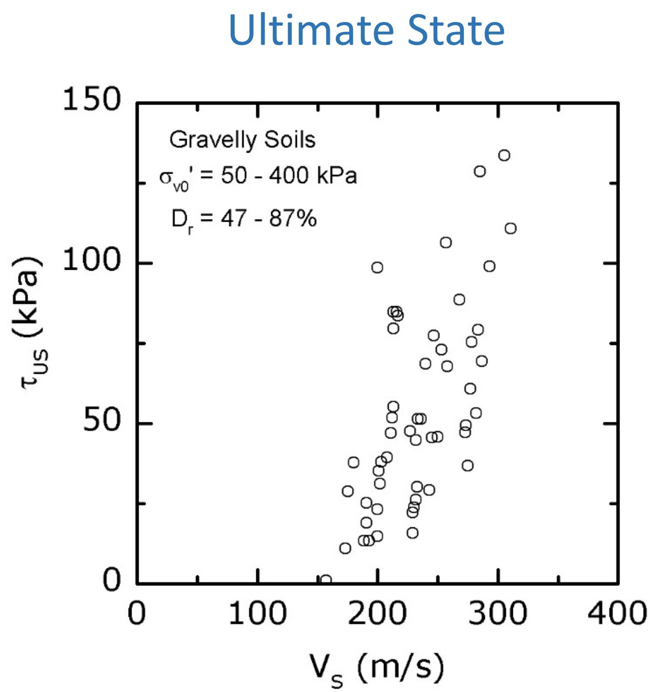




Shear Strain = 0-1%

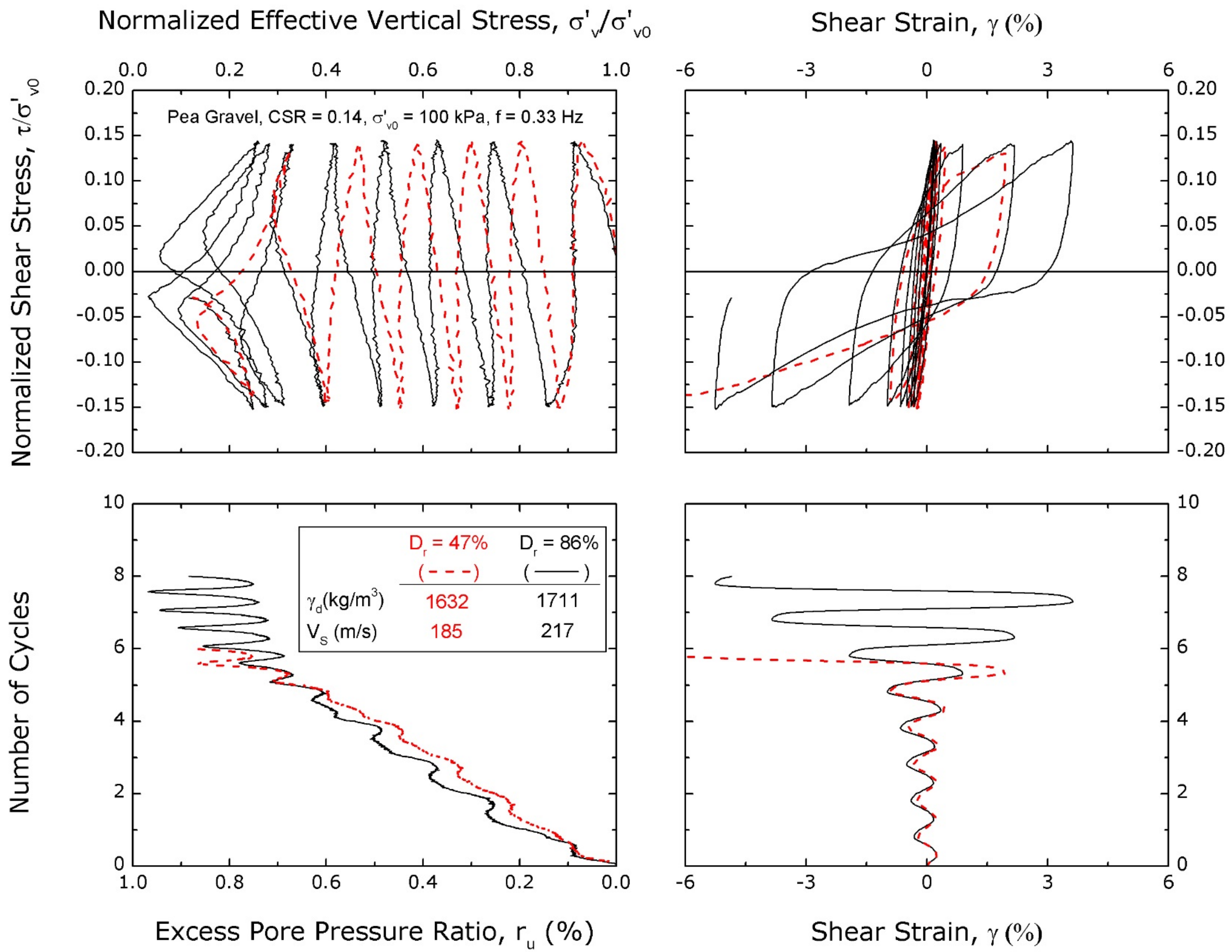


Shear Strain = 1-5%



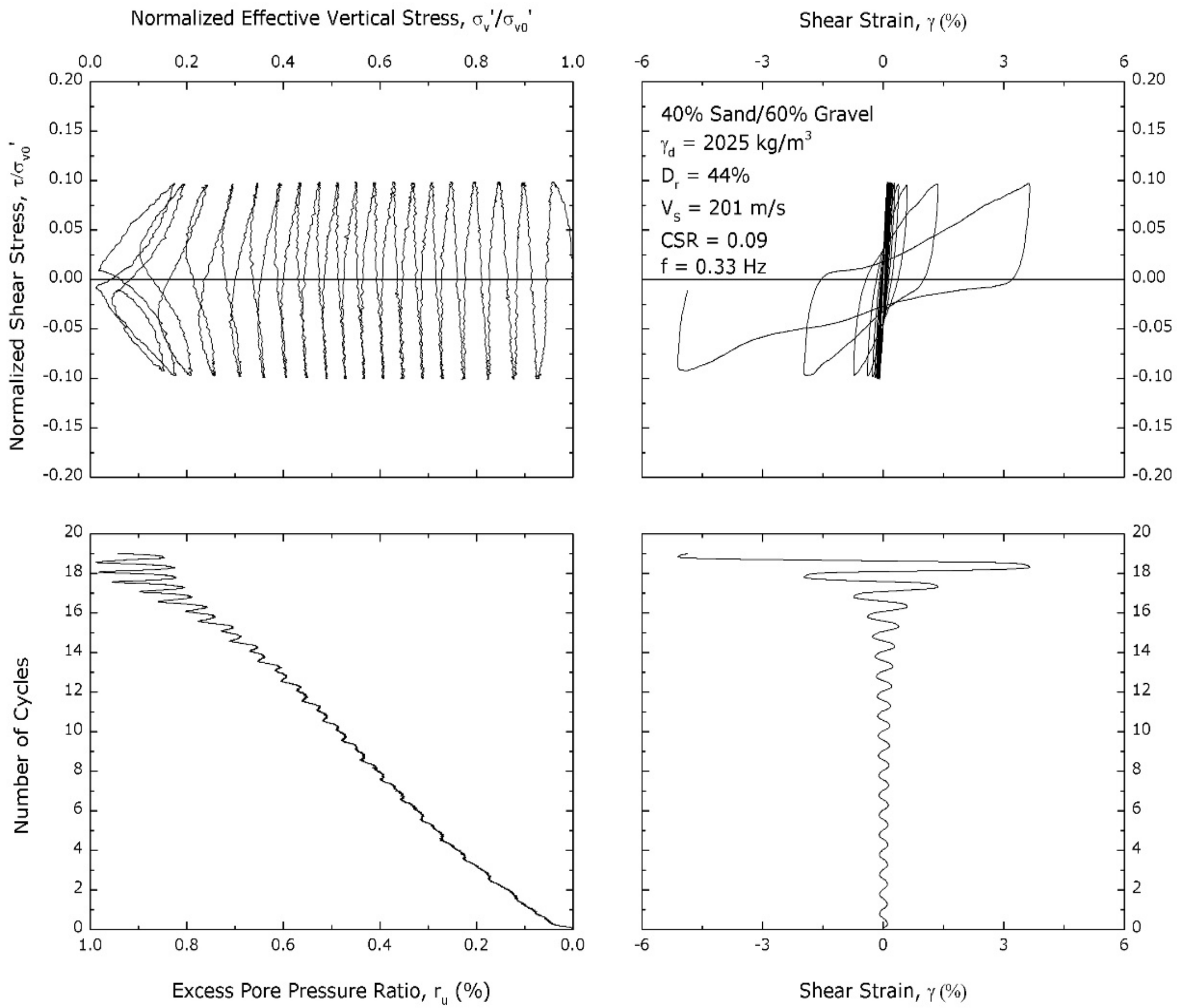
Shear Strain = 15-20%

Cyclic Simple Shear Test Results for Pea Gravel



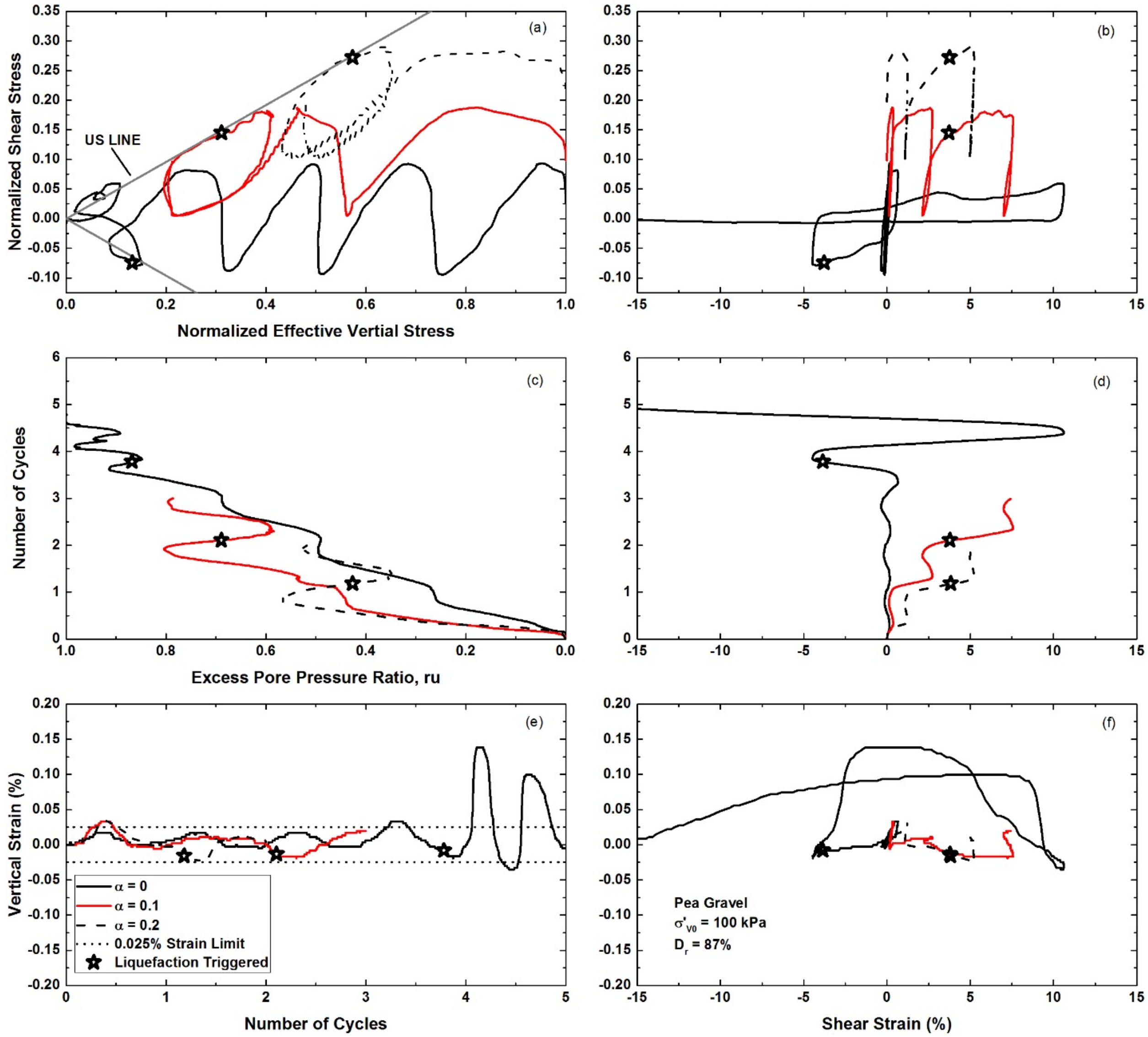
Hubler, J., Athanasopoulos-Zekkos, A., and Zekkos, D. (2017). “Monotonic, Cyclic and Post-Cyclic Simple Shear Response of Three Uniform Gravels in Constant Volume Conditions”, ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 143, Issue 9

Cyclic Simple Shear Test Results for Sand/Gravel Mix



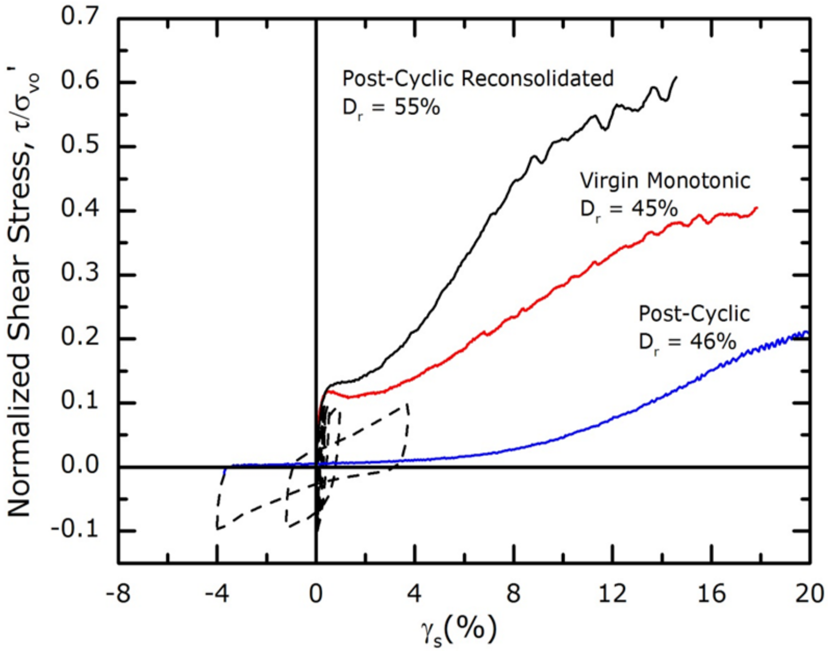
Hubler, J., Athanasopoulos-Zekkos, A., and Zekkos, D. (2018) "Monotonic and Cyclic Simple Shear Response of Gravel-Sand Mixtures", *Soil Dynamics and Earthquake Engineering, Vol 115, pp. 291-304, Dec 2018,* doi.org/10.1016/j.soildyn.2018.07.016

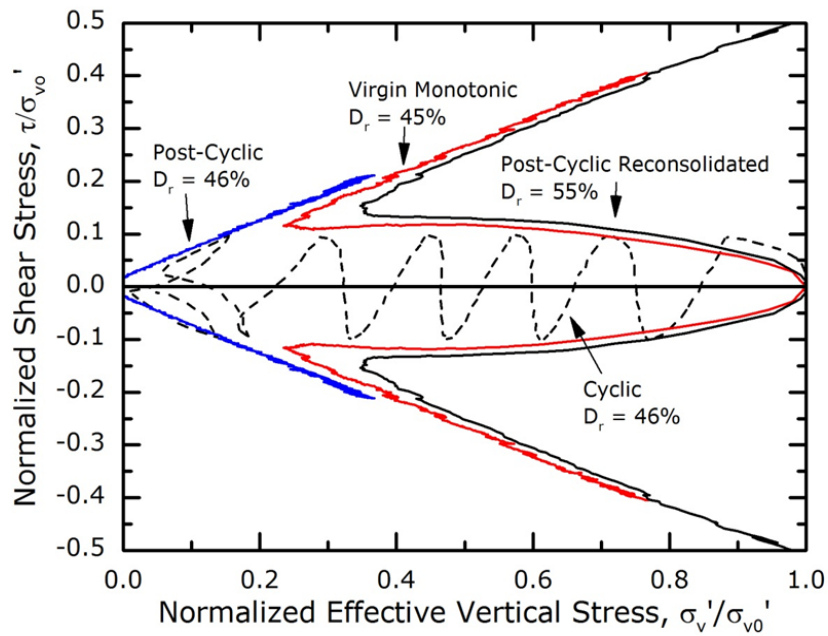
Cyclic Simple Shear Test Results for Gravel-Kα



Basham, M., and Athanasopoulos-Zekkos, A. (2020) "Effect of Static Shear Stress on Cyclic Resistance of a Uniform Gravel", *ASCE GeoCongress, Minneapolis, MN Feb 2020*

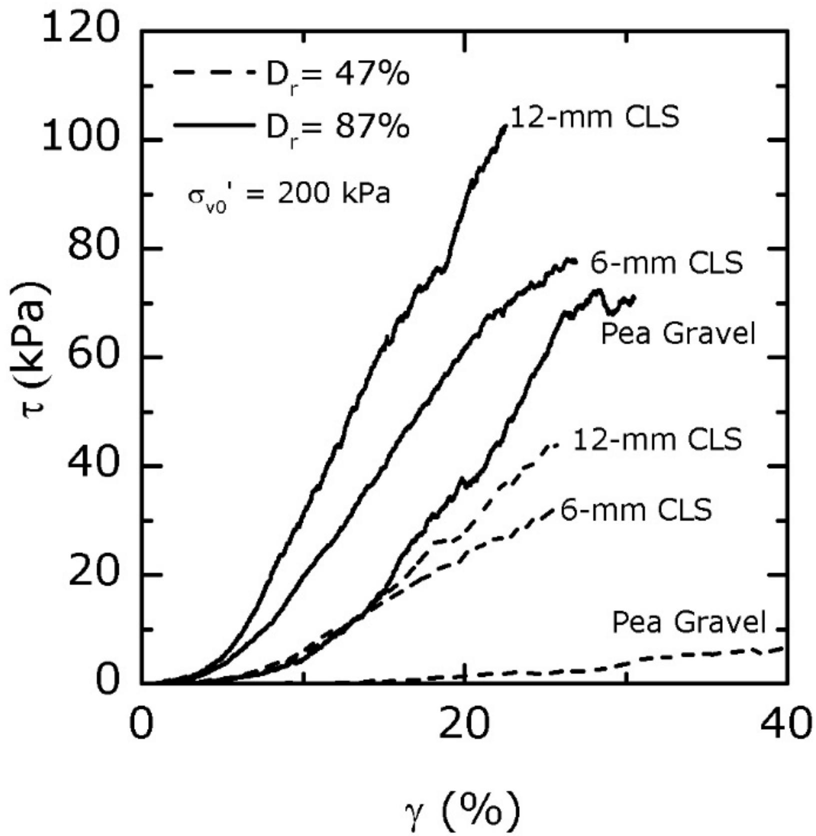
Monotonic shear results give insight into cyclic and post-cyclic shear response

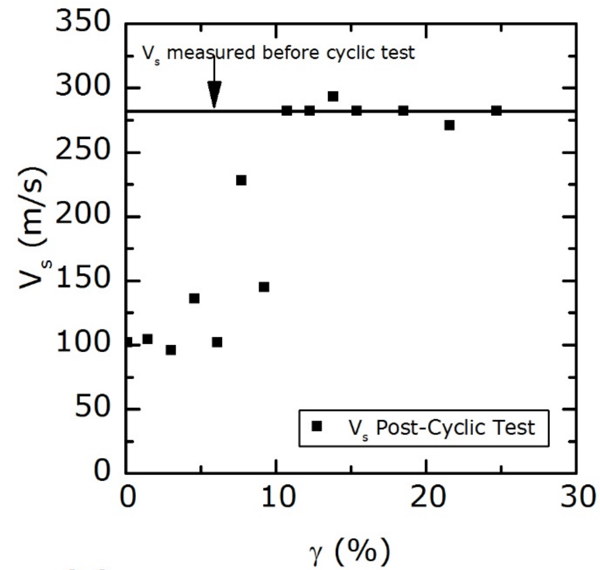


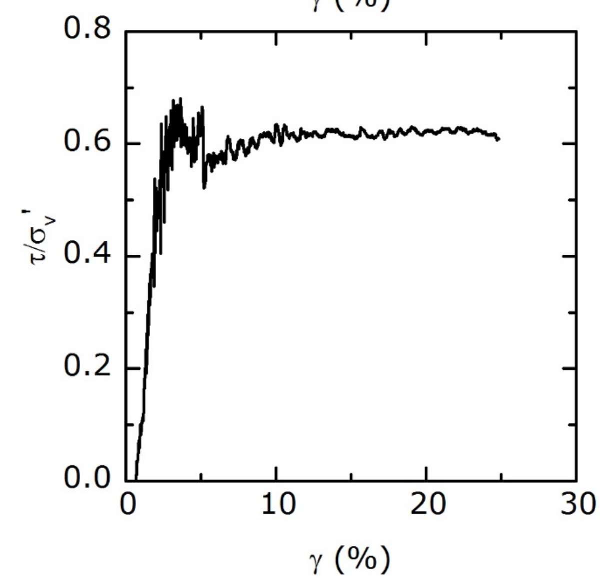


Hubler, J., Athanasopoulos-Zekkos, A., and Zekkos, D. (2017). "Monotonic, Cyclic and Post-Cyclic Simple Shear Response of Three Uniform Gravels in Constant Volume Conditions", ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 143, Issue 9

Post-cyclic shear response of Gravels

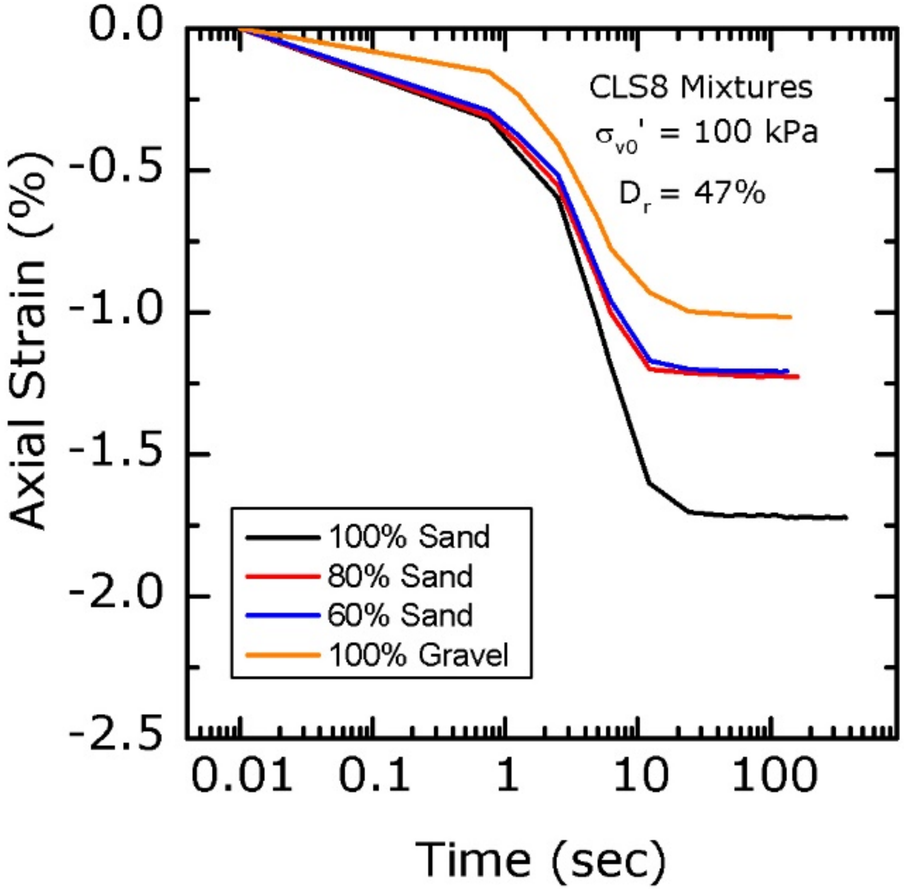






- Post-liquefaction shear resistance is affected by particle angularity

Post-cyclic shear response for gravelly soils



<u>Typical Volumetric strains:</u>

All Denser specimens: ~ 1%
Looser Pea Gravel 1.5%
Looser Crushed Limestone 1.0%

Looser Ottawa Sand ~2%

Hubler, J.F., Athanasopoulos-Zekkos, A. and Zekkos, D. (2018). "Post-Liquefaction Volumetric Strain of Gravel-Sand Mixtures in Constant Volume Simple Shear." Geotechnical Earthquake Engineering and Soil Dynamics V 2018, June 10-13

Field testing was performed in Utah, Alaska and Greece to compare with laboratory results

Ferron, UT

Cephalonia, Greece

Valdez, Alaska

DPT and Vs measurements were performed at both Cephalonia ports

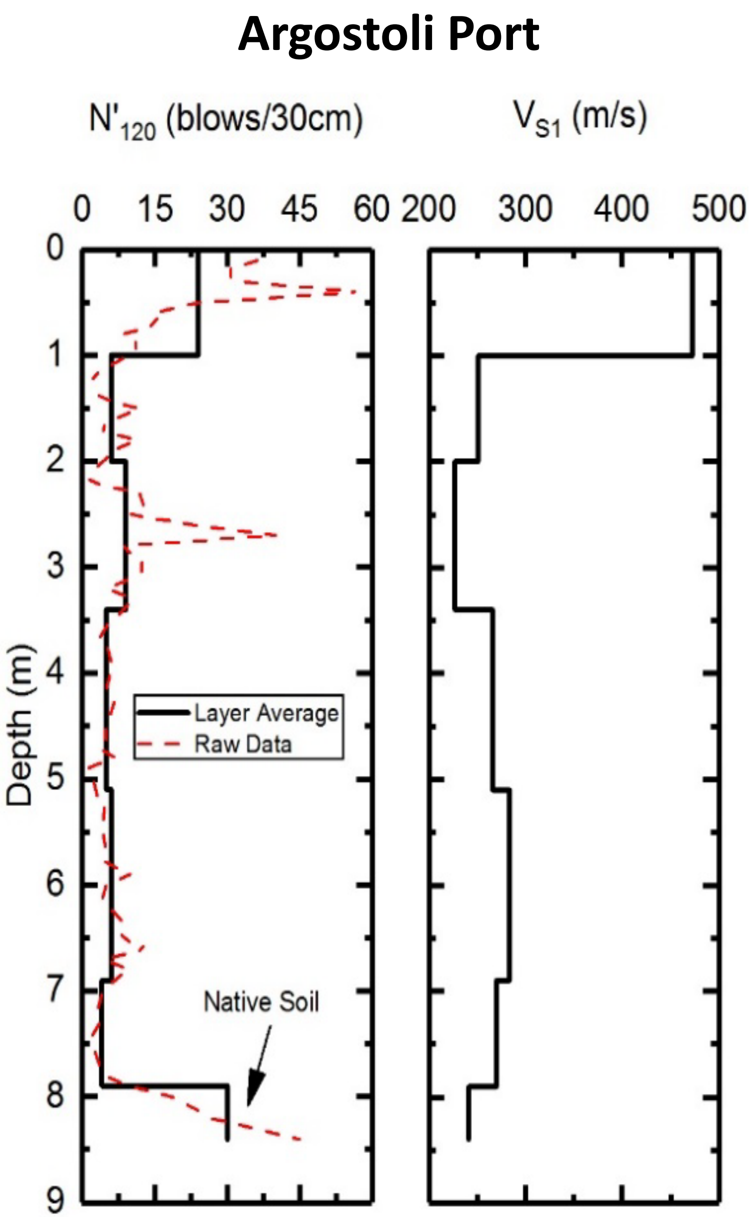
DPT Testing Rig

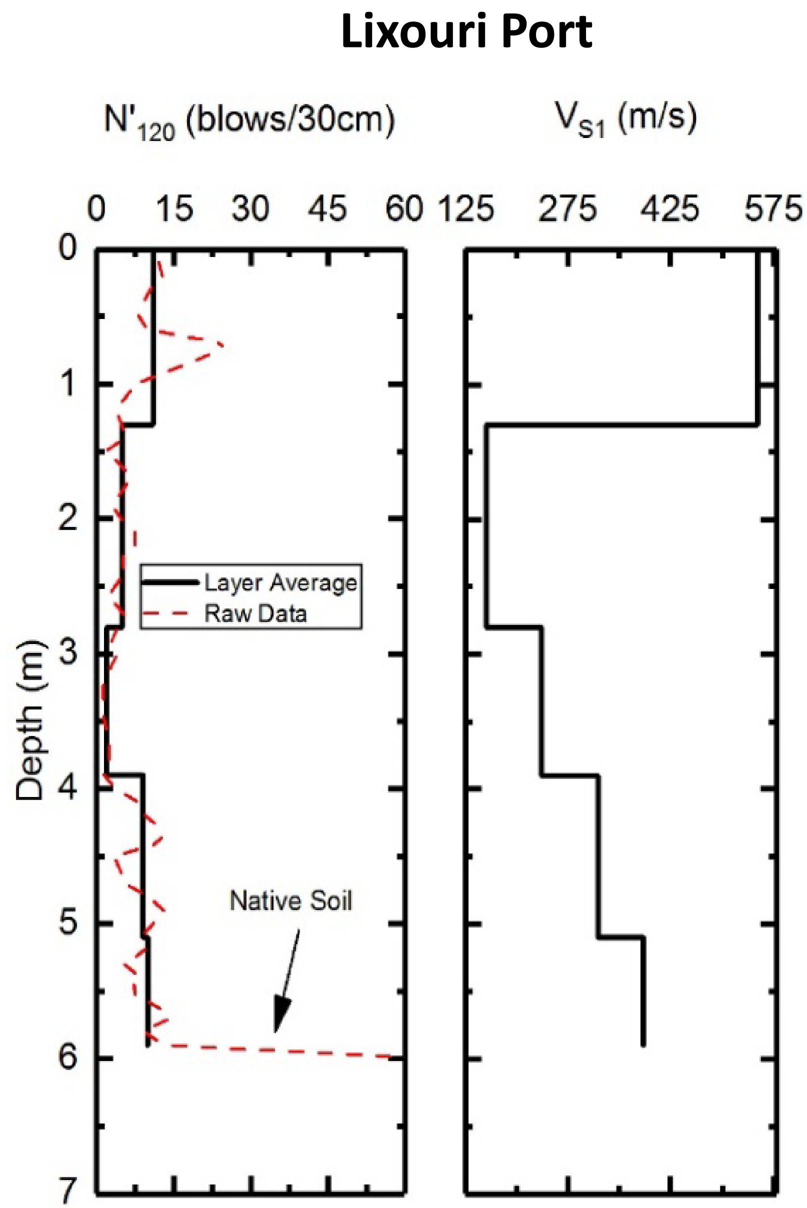
Athanasopoulos-Zekkos, A., Zekkos, D., Rollins, K., Hubler, J., Higbee, J. and Platis, A. (2019). “Earthquake Performance and Characterization of Gravel-Size Earthfills in the Ports of Cephalonia, Greece, following the 2014 Earthquakes”, 7th International Conference on Earthquake Geotechnical Engineering, Rome 17-20 June, 2019

DPT Cone and Instrumented Rod for Energy Measurements

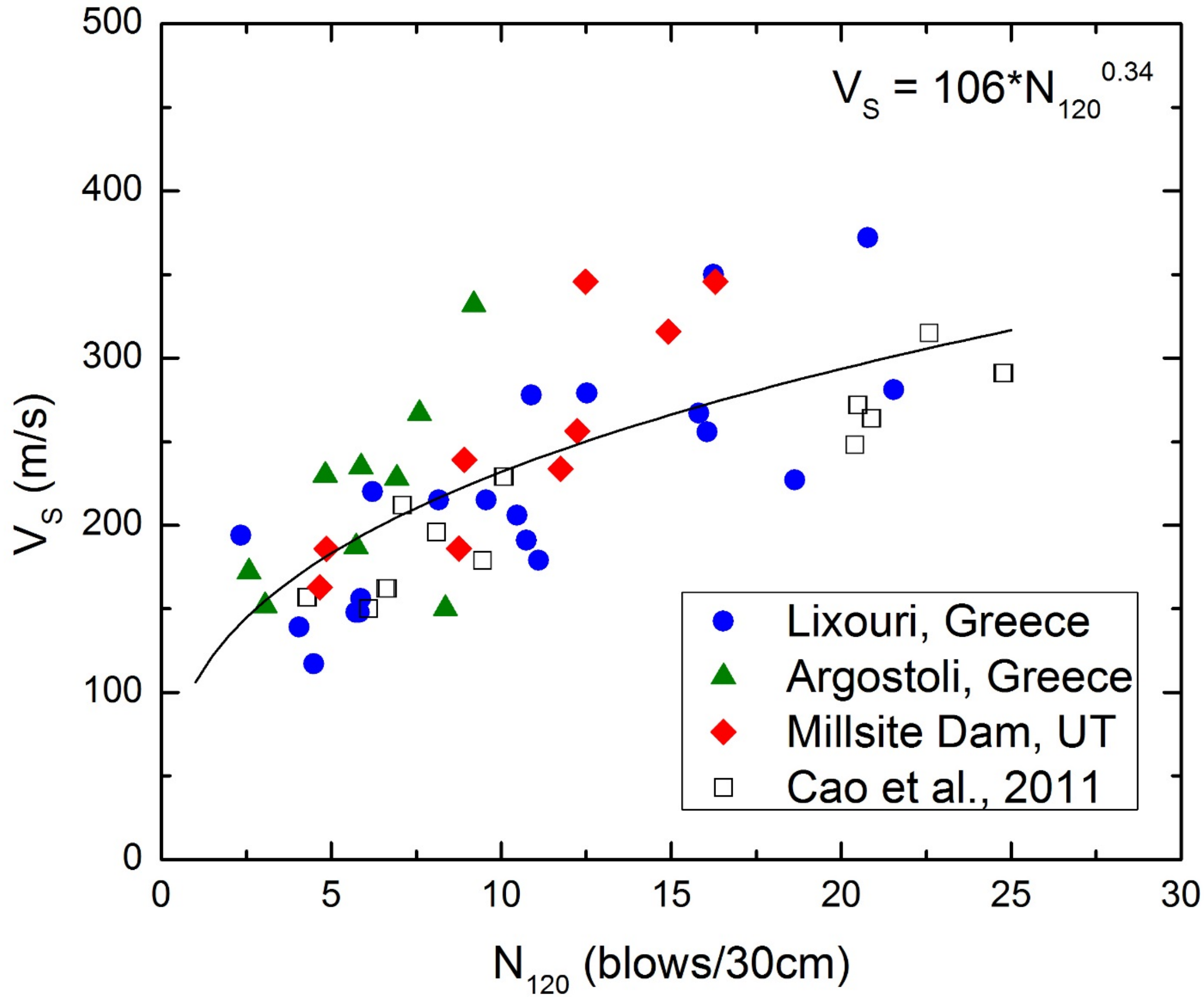
V_s Measurement setup – MASW

DPT and V_s correlate well at test locations



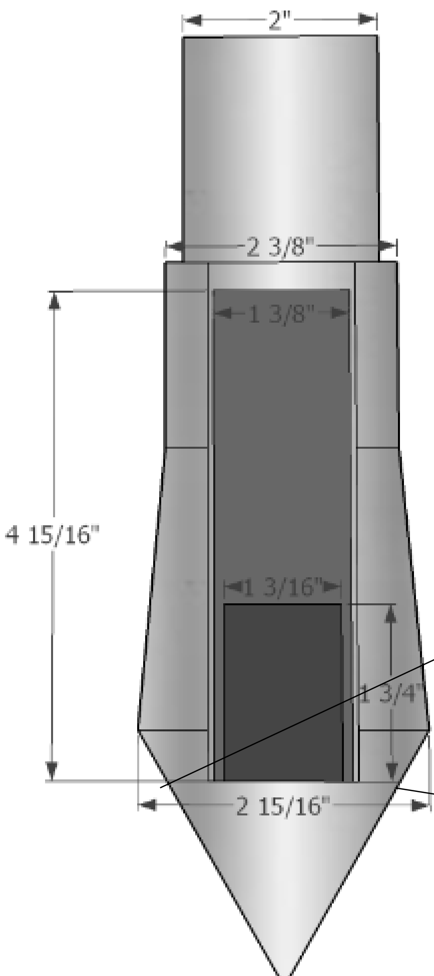


Correlation between DPT and V_s



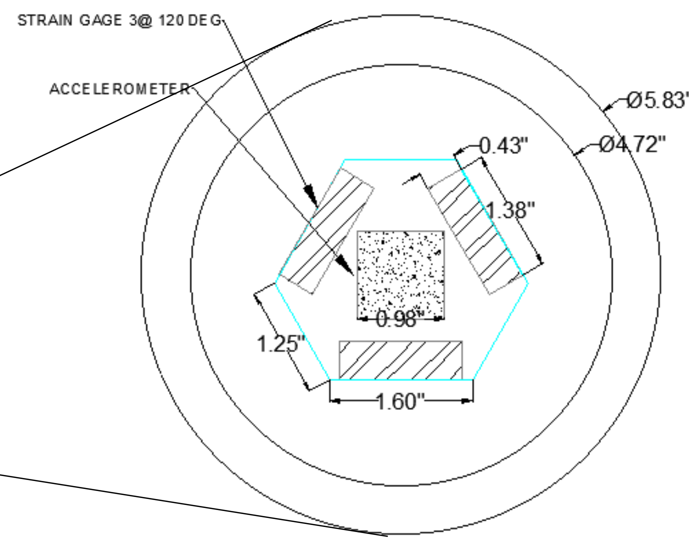
eDPT: Adding new sensing capabilities

TYPICAL DPT CONE

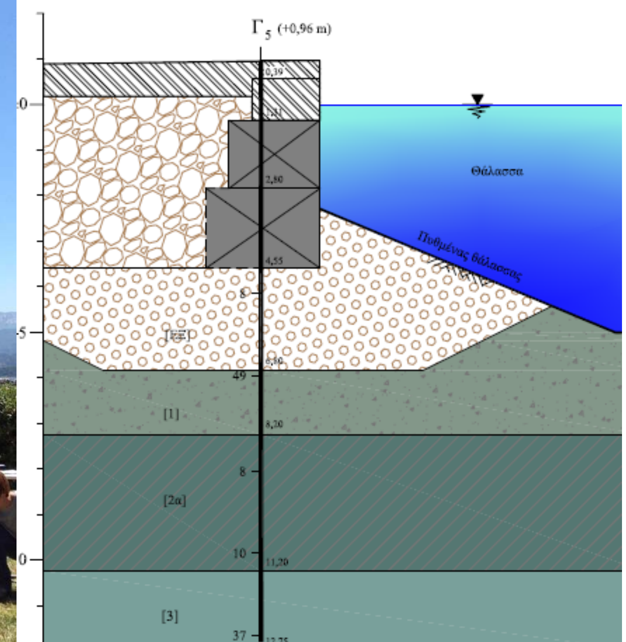


PDA equipment:

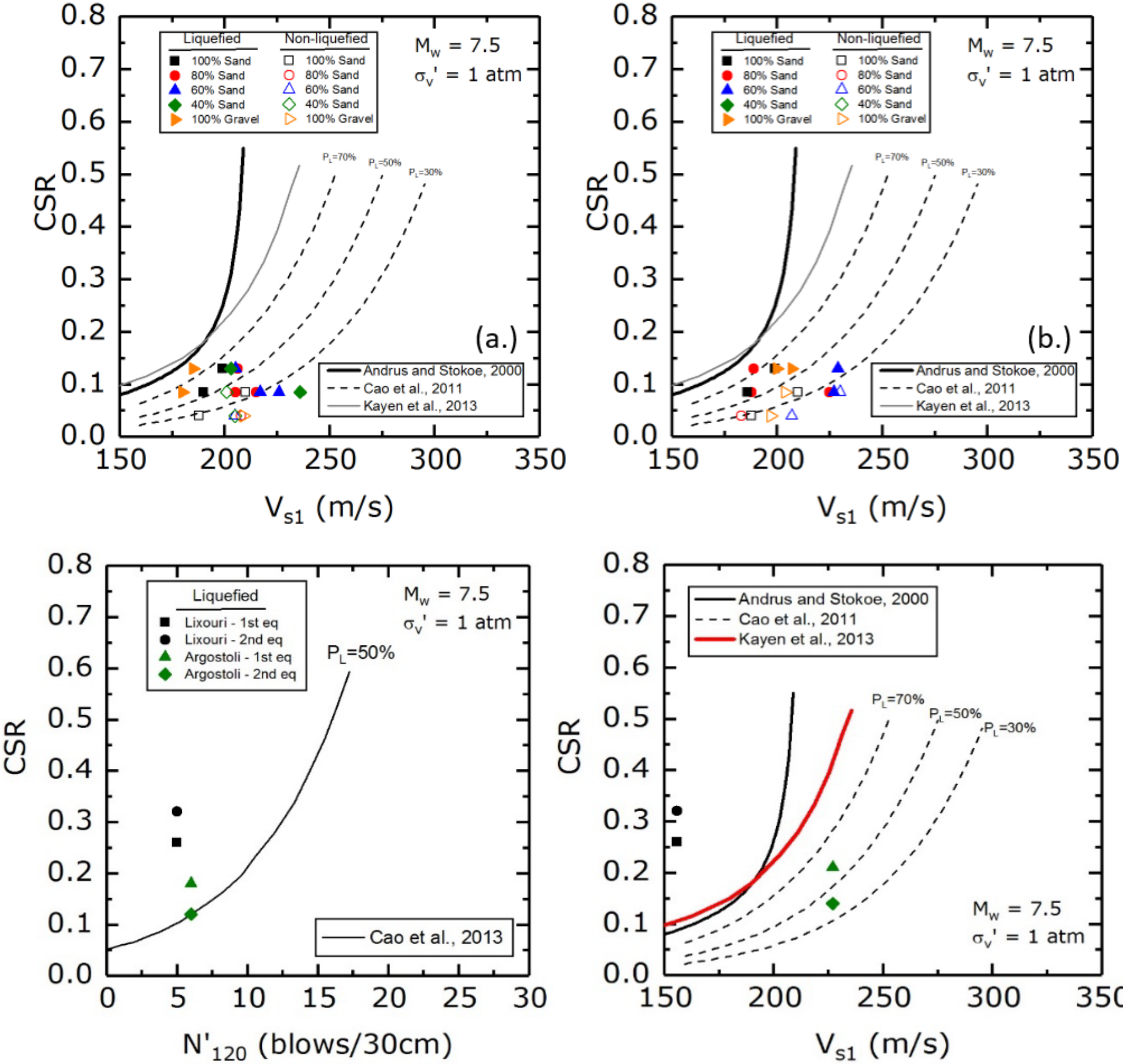
- Accelerometer:
  - 20,000 g range, 4.5 kHz Freq range
  - Size: 45 x 25 x 30 mm
- Strain gage:
  - 3000 micro-strain range
  - Size: 126 x 35 x 11 mm



Field Testing and Numerical Modelling of Field Behavior



Comparison of laboratory tests and case history analysis results to existing relationships



- Gravels and Gravel Sand mixes are readily liquefiable in the **laboratory** even for Vs>200m/s
- Gravelly soils liquefied **in the field** at higher Vs values than previously expected (Vs>200m/s)
- Evidence of liquefaction in the field may not always be as pronounced due to layering, smaller volumetric strains
- Need to connect micro (e.g. DEM) to macro scale response (e.g. infrastructure)

Acknowledgements

<u>Collaborators:</u>
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Xunchang Fei, PhD
Rachel Thompson
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Andrea Ventola

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