Liquefaction of gravelly soils and the impact on critical infrastructure

Adda Athanasopoulos-Zekkos, PhD
Assistant Professor

University of California, Berkeley
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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

Nikolaou et al. GEER (2014)
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

Segment #1

Segment #2

$M_w 6.1$

02/03/2014
Reliable assessment charts have been developed for sands, but not for gravels

(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.

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

Cyclic Simple Shear Test Results for Sand/Gravel Mix

Cyclic Simple Shear Test Results for Gravel-Kα

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

Post-cyclic shear response of Gravels

- Post-liquefaction shear resistance is affected by particle angularity

➢ Post-liquefaction shear resistance is affected by particle angularity
Post-cyclic shear response for gravelly soils

Typical Volumetric strains:

All Denser specimens: ~ 1%
Looser Pea Gravel  1.5%
Looser Crushed Limestone  1.0%
Looser Ottawa Sand  ~2%

Field testing was performed in Utah, Alaska and Greece to compare with laboratory results.
DPT and Vs measurements were performed at both Cephalonia ports
DPT Testing Rig

DPT Cone and Instrumented Rod for Energy Measurements
$V_s$ Measurement setup – MASW
DPT and $V_s$ correlate well at test locations

**Argostoli Port**

- $N_{120}'$ (blows/30cm)
- $V_{S1}$ (m/s)

**Lixouri Port**

- $N_{120}'$ (blows/30cm)
- $V_{S1}$ (m/s)
Correlation between DPT and $V_s$

$V_s = 106 \times N_{120}^{0.34}$

- Lixouri, Greece
- Argostoli, Greece
- Millsite Dam, UT
- Cao et al., 2011
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
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 $V_s > 200\text{m/s}$
- Gravelly soils liquefied in the field at higher $V_s$ values than previously expected ($V_s > 200\text{m/s}$)
- 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)
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adda.zekkos@berkeley.edu