Physics-based modeling of liquefaction phenomena

Ronaldo I. Borja
Stanford University
What is physics-based modeling?

- Satisfies conservation laws – mass, momentum, energy
- Multi-physics – involves two or more conservation laws
- Multi-field – solid deformation, fluid pressure, temperature
- Constitutive laws close the boundary-value problem
- **Computational models are needed for solution**
- Multi-physics problems generate large systems
- Numerical algorithms must be robust
Issues

• Role of finite deformation in triggering failure
• Role of heterogeneity in triggering failure
• Mechanism: is it liquefaction or strain localization?
• Post-liquefaction: do we have tools to model cyclic mobility and flow liquefaction?

Tools

• Stabilized mixed finite elements
• Enhanced finite elements for cyclic mobility
• Meshless methods (SPH, etc.) for flow liquefaction
Geometry of the specimen is altered during testing

Reference: Borja et al., JMPS, 2013
Measurement of heterogeneity

Density

Degree of saturation

Courtesy of A. Rechenmacher

Toyoura sand

Courtesy of R. Orense
Experimental visualization/measurement of sand deformation:

- Embedded markers: Stroud (1971)
- Grid points on membrane: Desrues (1984), Alshibli et al. (2000)
- Tracking sand grains: Harris et al. (199), Mooney et al. (1998)
- Gamma ray: Desrues et al. (1985)
- Digital image correlation: Rechenmacher (2006)

Nondestructive measurement of degree of saturation:

- X-ray and light transmission: Tidwell & Glass (1994)
- Synchrotron X-ray and image analysis: DiCarlo et al. (1997)
- Multispectral image analysis (NAPL): Kechavarzi et al. (2000)
- Color and digital image processing: Yoshimoto et al. (2011)
Liquefaction or strain localization?

Degree of saturation

Reference:
Borja et al., CMAME, 2013
Liquefaction or strain localization?

Stress ratio

Reference:
Borja et al., CMAME, 2013
Liquefaction or strain localization?

In the presence of heterogeneity:

• **Compactive shear band localization** is possible on the compression cap
• **How do we distinguish between liquefaction and strain localization?**

Reference:
Borja et al., CMAME, 2013
Soil with random heterogeneity

Nearly homogeneous specimen

Specific volume

Degree of saturation

Volumetric strain

Localization function

Song and Borja, VZJ, 2014
Soil with random heterogeneity

Song and Borja, VZJ, 2014
In the presence of a deformation band:

- Response at post-peak is **not** a constitutive response
- How do we reconcile with true material softening?
- Ideally, we should analyze the specimen response as a BVP

Song and Borja, VZJ, 2014
Dynamics of deformable, porous media

- Conservation of mass and momentum (isothermal)
- Solid and fluid velocities, fluid pressure
- Available formulations: $U-u$, $U-u-p$, $U-w-p$, etc.
- For earthquakes, $U-p$ is sufficient (Zienkiewicz et al. 1999)

Challenges

- Need anisotropic constitutive model with hysteresis
- System of equations can be very large
- Low-order finite elements satisfying inf-sup condition
Finite element modeling

Low-order stabilized finite elements

• 43K nodes
• 36K 3D elements
• 173K DOF’s

References:
White & Borja, CMAME, 2008
Borja et al., AG, 2012
Cyclic mobility
Cyclic mobility

- deformations are "not too large"
- displacements are discontinuous
Cyclic mobility

Discontinuous displacement

- Align element sides with the crack
- No good if crack is propagating
Cyclic mobility

Discontinuous displacement
Discontinuous displacement

- Allow crack to pass through element interior
Finite elements with enhancements

- Displacement discontinuities should be able to cut through the element interior
- Enhancements can be local or global

Available enhancements

- Strong discontinuity – also called assumed enhanced strain (AES) – local
- Extended finite element method (XFEM) – global

Ref: Borja, CMAME, 2008
Cyclic mobility

AES Method

- Enrichment is local – no extra unknowns
- Easy to implement, but crack interpolation is discontinuous across element boundaries
Cyclic mobility

**XFEM**

- Enrichment is global – introduces additional unknowns
- Crack interpolation is continuous across element boundaries
Comparison of AES and XFEM

Ref: Borja, Book Chapter 7, 2013
Cyclic mobility

Fault rupture dynamics with XFEM

Ref: Liu & Borja, IJNAMG, 2013
Fault rupture dynamics with XFEM

Ref: Liu & Borja, IJNAMG, 2013
Flow liquefaction

- deformations are very large
- kinematics is similar to debris flow
- difficult to model with FEM
Flow liquefaction

Continuum solutions

- Computational fluid dynamics
- Meshless methods, e.g. SPH
- Bingham fluid rheology

Kinematical descriptions

- Eulerian description (spatial)
- Lagrangian description (material)
Flow liquefaction

Sand flow on a steep slope

Ref.: Moriguchi et al., AG, 2009
Flow liquefaction

CFD with Bingham fluid – Eulerian

0.4sec

0.8sec

1.2sec

1.6sec

Ref.: Moriguchi et al., AG, 2009
Smoothed Particle Hydrodynamics (SPH)

- one of several meshless methods currently available

Ref.: Pastor et al., IJNAMG, 2009
Flow liquefaction

SPH with Bingham fluid – Lagrangian

Ref.: Pastor et al., IJNAMG, 2009
Lausanne experiment – SPH with Bingham fluid

Ref.: Pastor et al., IJNAMG, 2009
Summary

- Advocate finite deformation kinematics
- Heterogeneity is critical for specimen scale modeling
- Deformation band and liquefaction are in the same “mix”
- Computational tools available for post-liquefaction modeling
- Physics-based modeling = experiment + computation