THE UNIVERSITY OF BRITISH COLUMBIA

Multiaxial Constitutive and Numerical Modeling in Geo-mechanics within Critical State Theory

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SCEC Workshop on 3D Site Effects in Physics-Based Ground Motion Simulations
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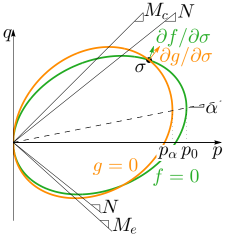
Outline

1. Constitutive modeling for clays
   - SANICLAY class
   - Model Performance
2. Constitutive modeling for sands
   - SANISAND class
   - Model Performance
3. Application in numerical modeling
   - Model implementations
   - Nonlinear effective stress seismic site response analysis
4. Discussion related to the SCEC workshop

SANICLAY: Simple ANIsotropic CLAY plasticity model

- SANICLAY

  (Dafalias et al., 2006)



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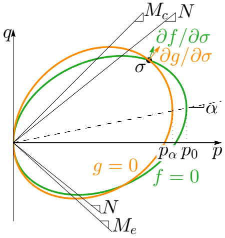

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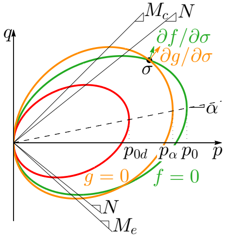
- SANICLAY-D

  (Taiebat et al., 2010a)



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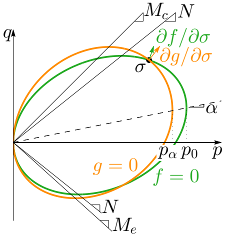

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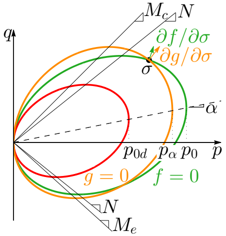

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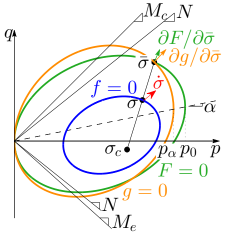
- SANICLAY-B

  (Seidalinov and Taiebat, 2014)



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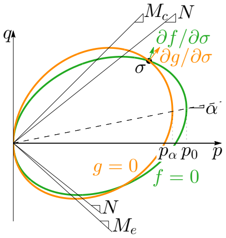

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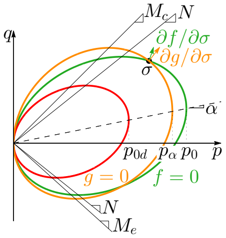

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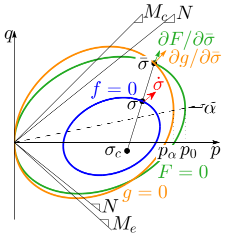

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- Systematic tensorial extension to multiaxial stress space

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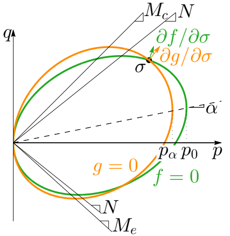

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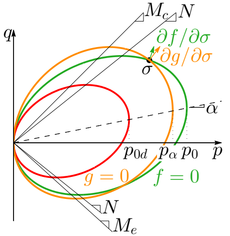

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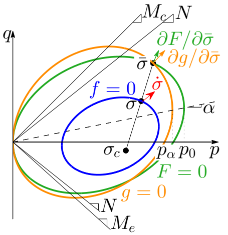


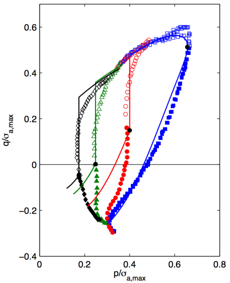
(e)

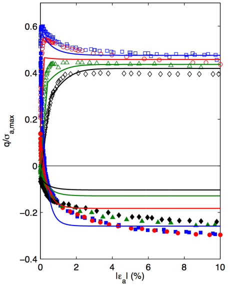
- Systematic tensorial extension to multiaxial stress space
- Relatively straightforward calibration process

	Model constant category	Designation	Georgia kaolin	Cloverdale	Ariake
MCC	Elasticity	κ	0.03	0.037	0.05
		ν	0.2	0.2	0.2
	Critical state	λ	0.21	0.121	0.41
		M_c, M_e	1.29, 1.27	0.87, 0.86	1.68, 1.65
SANICLAY	Yield surface	N	1	0.8	1.68
	Rotational hardening	C	3	3	15
		x	1.73	1.69	1.76
SANICLAY-D	Destructuration	k_i	2	0	0
SANICLAY-B	Bounding surface	h_0	550	50	1600
		a_d	68	7	80

Monotonic loading (iso. comp., oedometer, undrained triaxial comp./ext.)

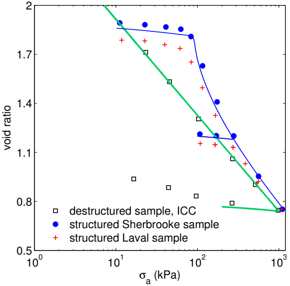
Lower Cromer Till

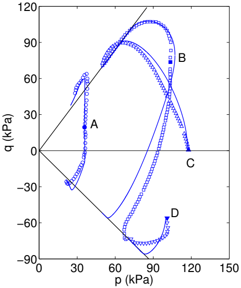




Data: after Gens (1982)

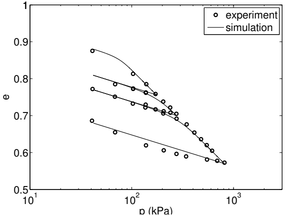
Bothkennar clay

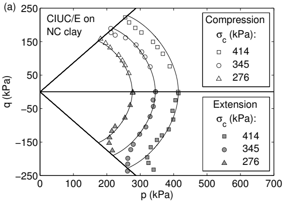




Data: after Smith et al. (1992)

Georgia kaolin clay

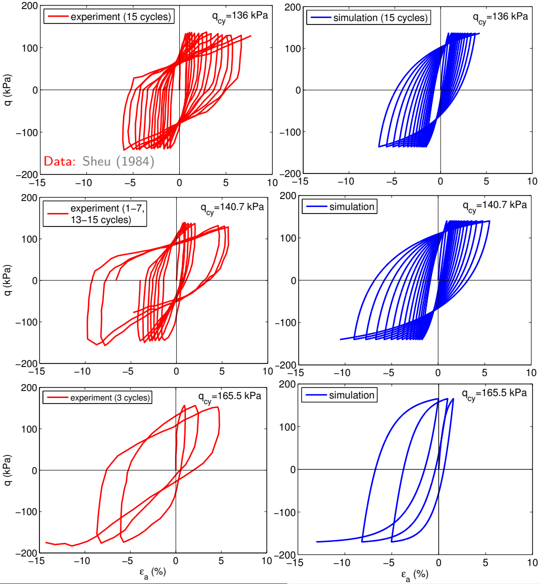




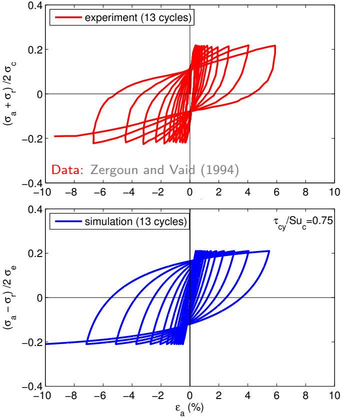
Data: after Sheu (1984)

Undrained cyclic triaxial tests

- Georgia kaolin clay (reconstituted)



- Cloverdale clay (structured)



Simulations: Seidalinov and Taiebat (2014)

Undrained cyclic triaxial tests

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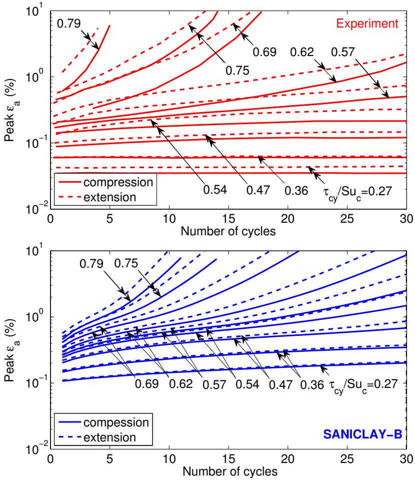
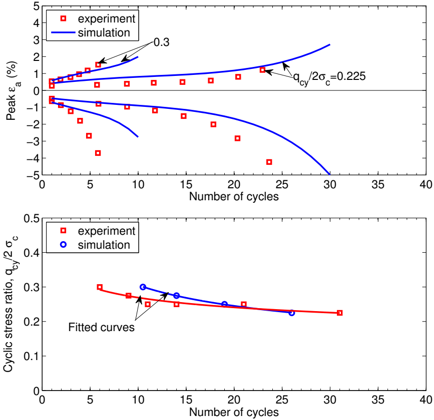


Data: Zergoun and Vaid (1994)

- Ariake clay (reconstituted)



Data: Yasuhara et al. (1992)

Simulations: Seidalinov and Taiebat (2014)

SANISAND: Simple ANIsotropic SAND plasticity model

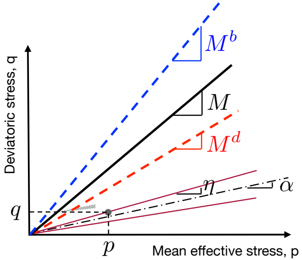
Dafalias, Manzari, Li, Papadimitriou, Taiebat (1997-2012)

- Formulation in triaxial stress space

$$f = |\eta - \alpha| - m = 0 \qquad \eta = \frac{q}{p}$$

$$\dot{\varepsilon}_q^p = \frac{\dot{\eta}}{hb} \qquad b = (M^b - \eta)$$

$$\dot{\varepsilon}_v^p = A_d d |\dot{\varepsilon}_q^p| \qquad d = (M^d - \eta)$$



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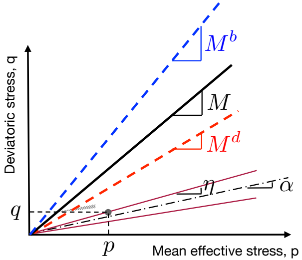
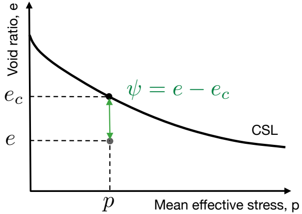


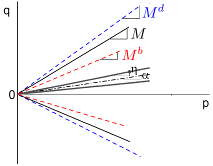
- Dependence on state parameter

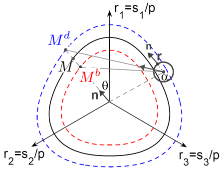
$$M^b = M \exp\left(-n^b \psi\right)$$
$$M^d = M \exp\left(n^d \psi\right)$$



Generalization and model constants

- Systematic tensorial extension to multiaxial stress space





- Relatively straightforward calibration process

Taiebat et al. (2010b)

Parameter	Symbol	Toyoura	Nevada	Sacramento
Elasticity	G_0	125	150	200
	ν	0.05	0.05	0.2
CSL	M	1.25	1.14	1.35
	c	0.712	0.78	0.65
	e_0	0.934	0.83	0.96
	λ	0.019	0.027	0.028
	ξ	0.7	0.45	0.7
Dilatancy	n^d	2.1	1.05	2.0
	A_0	0.704	0.81	0.8
Kinematic	n^b	1.25	2.56	1.2
Hardening	h_0	7.05	9.7	5.0
	c_h	0.968	1.02	1.03
Fabric dilatancy	z_{max}	2.0	5.0	–
	c_z	600	800	–

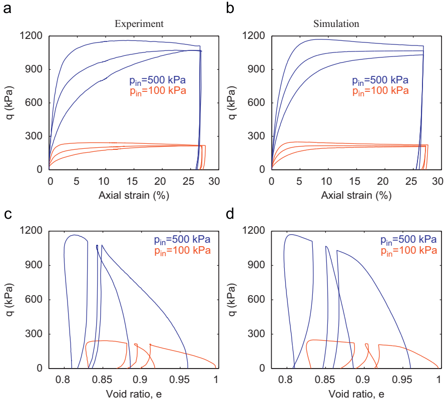
- Soil-specific set of constants for different densities & confining pressures.
- Constitutive ingredients to account for
  - ψ-dependent dilatancy stress-ratio (Manzari and Dafalias, 1997; Li and Dafalias, 2000)
  - evolving fabric anisotropy (Dafalias and Manzari, 2004)
  - inherent fabric anisotropy (Dafalias et al., 2004)
  - plastic strains under const. stress-ratio & particle crushing (Taiebat and Dafalias, 2008)
  - anisotropic critical state (Li and Dafalias, 2012)

Triaxial loading and unloading on Toyoura sand

- Drained triaxial tests

Experiment

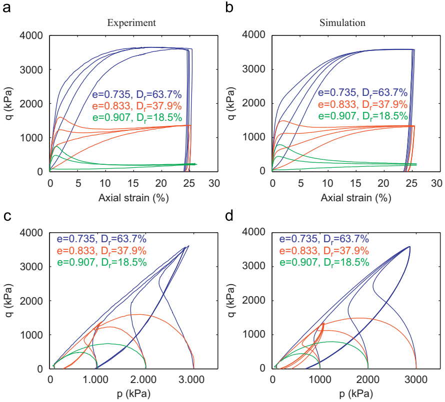
Simulation



- Undrained triaxial tests

Experiment

Simulation

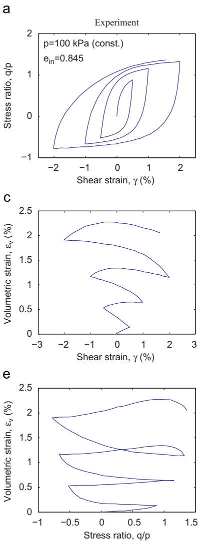


Data: Verdugo and Ishihara (1996); Simulations: Taiebat et al. (2010b)

Constant-p cyclic triaxial on Toyoura sand

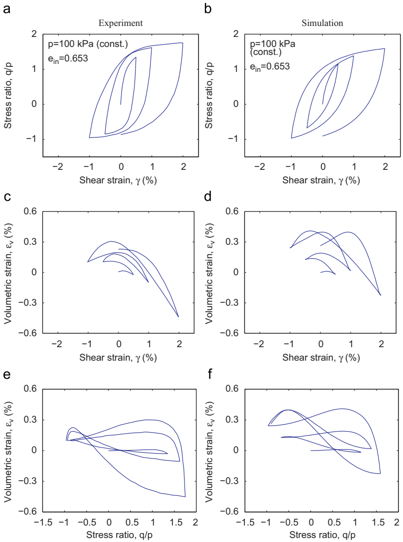
- Loose sample

Experiment | Simulation



- Dense sample

Experiment | Simulation



Data: Pradhan et al. (1989); Simulations: Taiebat et al. (2010b)

Finite Element platform and model implementation

- OpenSees: The Open System for Earthquake Engineering Simulation
  - Fully coupled nonlinear dynamic finite element program
  - Open-source: http://opensees.berkeley.edu
  - Variety of relevant element types for continuum modeling of soil medium
    - 2D (quad) and 3D (brick)
    - single phase (solid, u) and double phase (solid and pore fluid, u–p)
  - Variety of analysis types, integration schemes, and solvers

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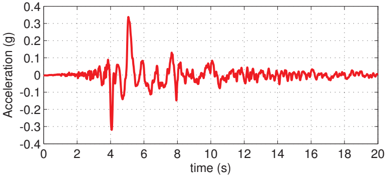
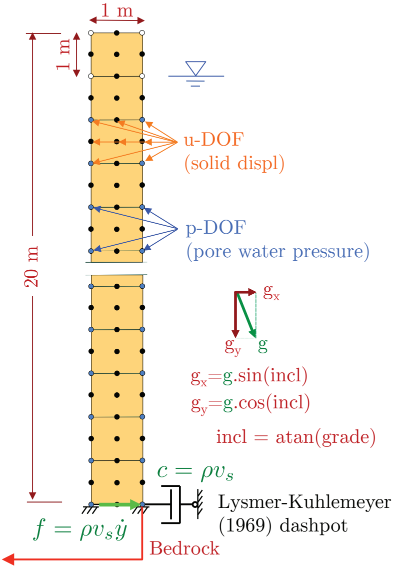
- SANICLAY and SANISAND implementation:
  - SANICLAY: Refined explicit integration scheme with automatic sub-stepping and error control (Seidalinov and Taiebat, 2014)
  - SANISAND: Various explicit and implicit integration schemes (Ghofrani and Arduino, 2014)
  - All implementations are in full tensorial forms of stresses and strains (3D)

Application of SANICLAY models

Modeling of infinite slope subjected to earthquake excitation:

- 20 m deep (2% grade) deposit of NC clay
  - SANICLAY & SANICLAY-B models
  - 1 m water table, permeability: 10^{-8} m/s
  - Periodic BCs to emulate 1D analysis
- Modeling
  - 9-node quad u–p element (Biot's theory)
  - Periodic BCs to emulate 1D analysis
  - Base dashpot to account for the finite rigidity of the underlying elastic medium
  - Velocity time history $\dot{u}(t)$ and high $V_{s,\mathrm{base}}$
- Imperial Valley record scaled to PGA=0.35g

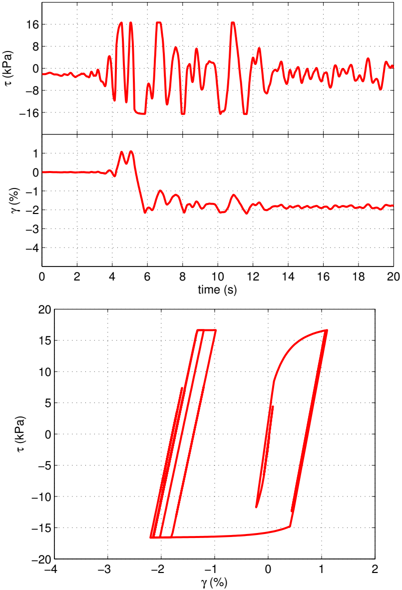




Adopted from McGann and Arduino (2013)

Results: shear stress (τ) & shear strain (γ) at depth of 5.5 m

- SANICLAY



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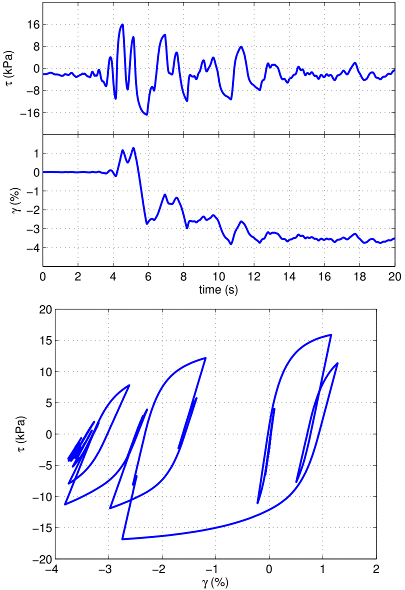
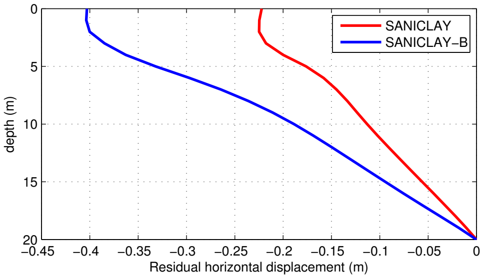
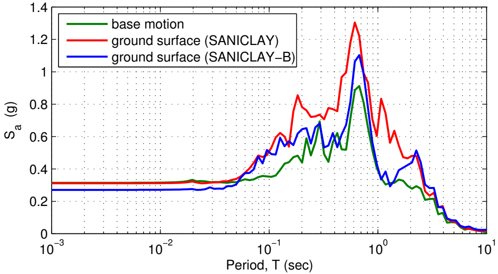


Results: Displacement profile and spectral accelerations

- Horizontal displacement profiles at the end of shaking



- Spectral acceleration at the base and top of soil columns



Application of SANISAND model in PRENOLIN

Modeling of free field soil column subjected to earthquake excitation in Sendai:

- 8 m deep deposit of sand
  - 0–7 m: SANISAND, and 7–8 m elastic
  - 1.5 m water table, permeability: 10^{-5} m/s
  - Periodic BCs to emulate 1D analysis
- Modeling
  - SSPquadUP element (Biot's theory)
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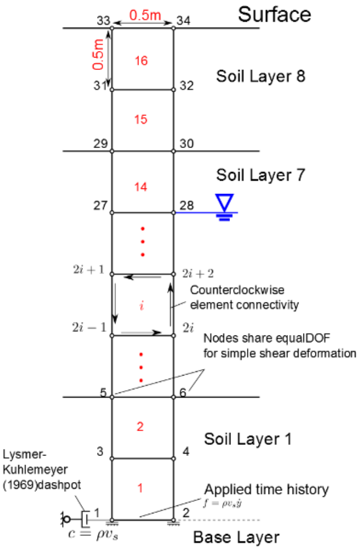
  - Base dashpot to account for the finite rigidity of the underlying elastic medium
  - Velocity time history $\dot{u}(t)$ and high $V_{s,\text{base}}$
- Several motions from downhole arrays at Sendai site

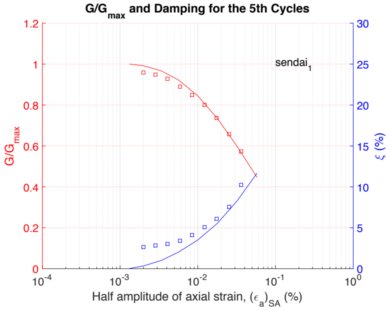
[Collaborative study with UW]

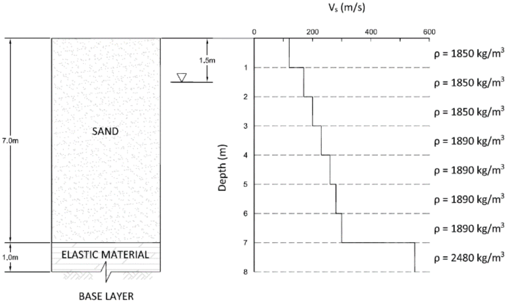


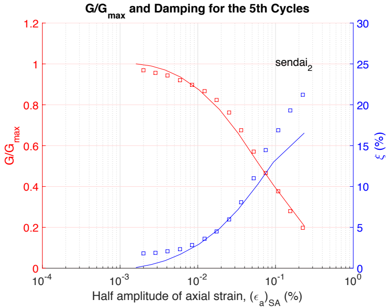
Adopted from McGann and Arduino (2013)

Soil properties

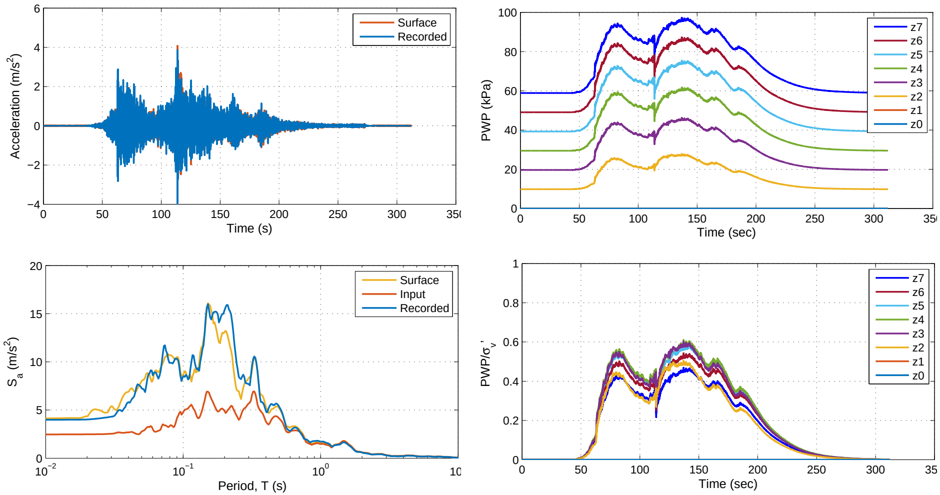
- Calibration based on data of
  - drained monotonic triaxial tests at three different confining pressures
  - undrained cyclic triaxial tests on two frozen samples at depths of 3.5 and 5.5 m, resulting in plots of $G/G_{\max}$ and ξ vs. $(\varepsilon_a)_{SA}$
- Stiffness adjusted based on profile of V_s







Analysis results for one of the ground motions



Challenges for 3D seismic site response?!

- Moving from 1D to 3D in regional-scale simulations:
  - Our models have always been 3D ✓
  - 3D is the same in any scale and our scale is that of continuum ✓

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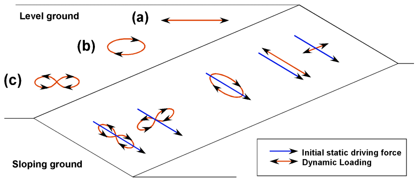
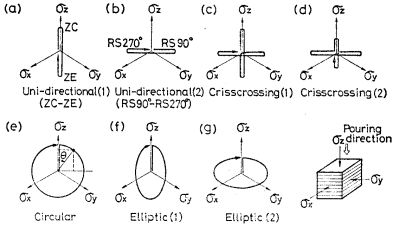
- Further works in constitutive modeling
  - Fabric-related strongly anisotropic response (next slide)
  - Constitutive modeling of intermediate soils ...
  - Validating the models for multiaxial loading ...



Kammerer (2002)



Yamada and Ishihara (1983)

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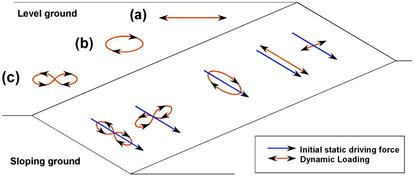

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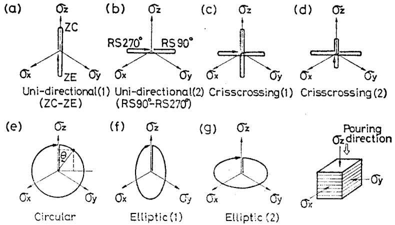
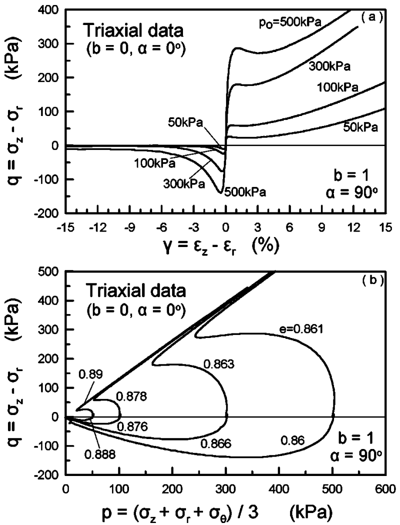
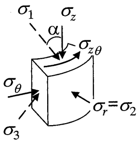


Yamada and Ishihara (1983)

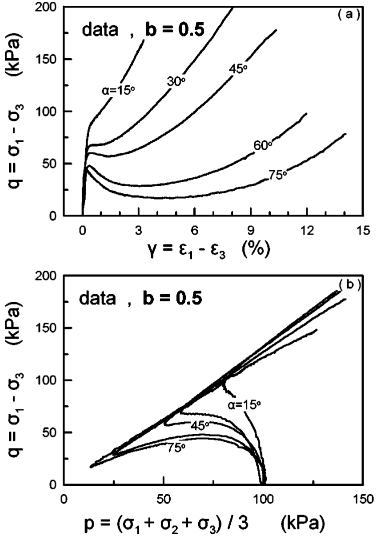
- Calibration and simulation
  - State parameters including internal variables from in-situ testing results?!
  - Statistical methods to deal with scarce and sparse input parameters?!
  - Professional programming and use of HPC techniques?!

Fabric-related strongly anisotropic response





$$b = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3}$$



Yoshimine et al. (1998)

THANK YOU!

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