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Challenges in Nonlinear Deformation Analyses of Dams and Levees

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Introduction

Analysis requirements for dams shifting from deterministic approach to risk-based approach

Deterministic

Objective is to confidently determine when a dam is "safe"

→*safe is not defined*

Risk-based

Objective is best estimate of actual response

A risk-based evaluation significantly raises demand on analyst

Non-Linear Deformation Analysis

Observations from practice

1. NDA framework
2. Seismic loading
3. Soil behavior and constitutive models
4. Analysis uncertainty
5. Dam/levee performance

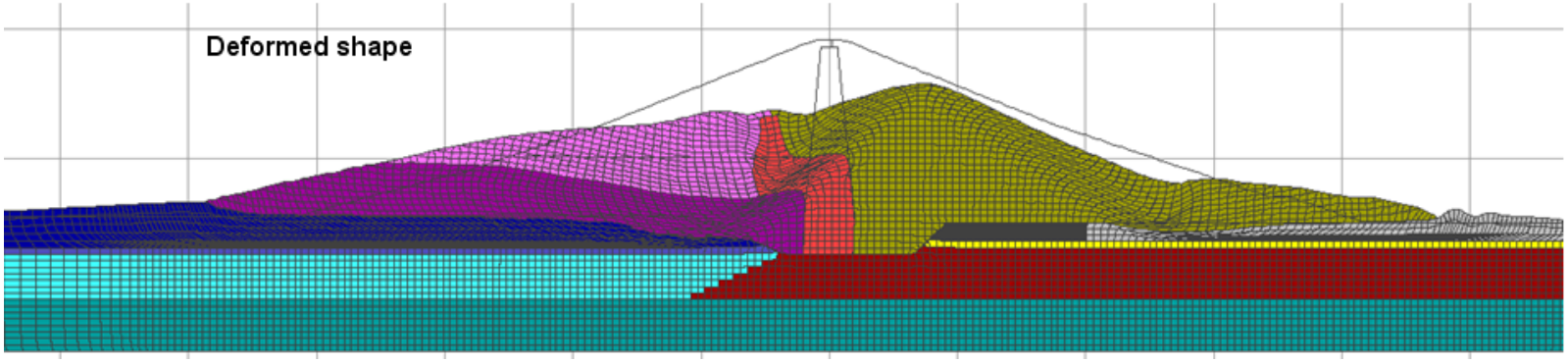
1. NDA Framework

NDA commonly used for critical infrastructure

→ More frequently used for routine structures

Many solvers: FLAC, PLAXIS, OpenSees, …

→ Explicit (nodal equilibrium) versus Implicit (matrix equilibrium)



Perlea and Beaty (2010)

Choice: Modeling approach

Simple – Uncomplicated stress-strain models. Few material parameters. Cyclic strength loss imposed. Typically undrained (total stress) analysis. Often considered "conservative."

Moderate – Constitutive models are more complex. Triggering analysis performed for liquefaction. Additional soil properties needed to describe evolving behavior. May be undrained or effective stress. Often considered "conservative."

Complex – Effective stress analyses. Constitutive models predict volumetric strains due to contraction and dilation. Pore pressure migration considered. Sophisticated material parameters may be required. Conservatism is less clear due to complexity.

2D versus 3D

2D most common

Routine 3D is emerging

Sometimes 3D would be nice

Narrow canyons

Longitudinal stress history (cracking)

Ground remediation

Levee penetrations (pump structures, etc.)

3D challenge

Confirming constitutive model behavior under very complex stress paths

Coupled Flow for Complex Analyses

Neglect is often perceived as producing larger deformations

→ *e.g., excess pore pressures dissipate prior to liquefaction*

→ *e.g., little pore pressure migration will occur*

Importance depends on structural geometry and soil strata

Analysis reliability not well established

Can influence best estimates

2. Seismic Loading

NDA results sensitive to character of EQ record

Typical givens:

Source event(s): magnitude, distance

Target spectrum: deterministic, UHS, CMS

Typical wants:

Estimate of most likely structural response for design earthquake

- *Site specific estimates of potential range computationally demanding*

Problem: Typical "givens" not sufficient to easily produce "wants"

- *NDA deformations can vary by factors of 2 or more*
- *Response spectrum useful to constrain frequency content, but …*
- *And then there can be directivity pulse and fling ….*

Seismic Loading

Some additional guidance available

Typically based on Newmark analysis (or variations)

Uncertain correlation to general 2D and 3D NDA

Not yet incorporated into PSHA

Still need more

Incorporate into PSHA

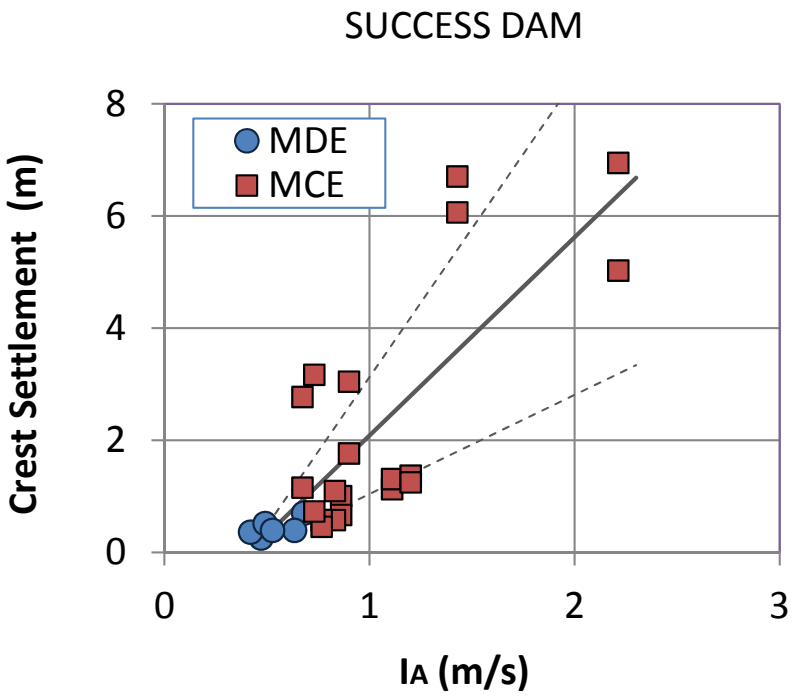
Vector IM?

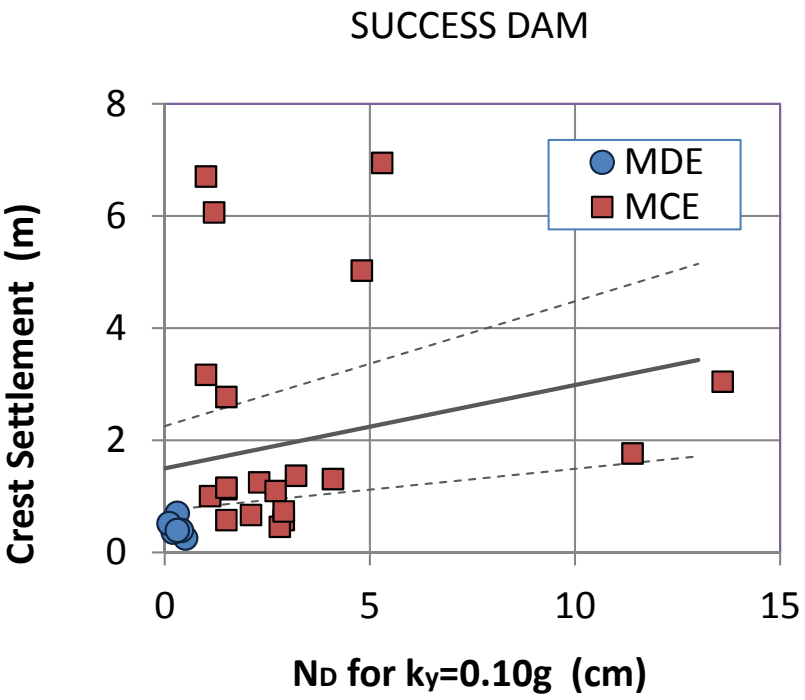
Seismic Loading

Limited study of simple IMs

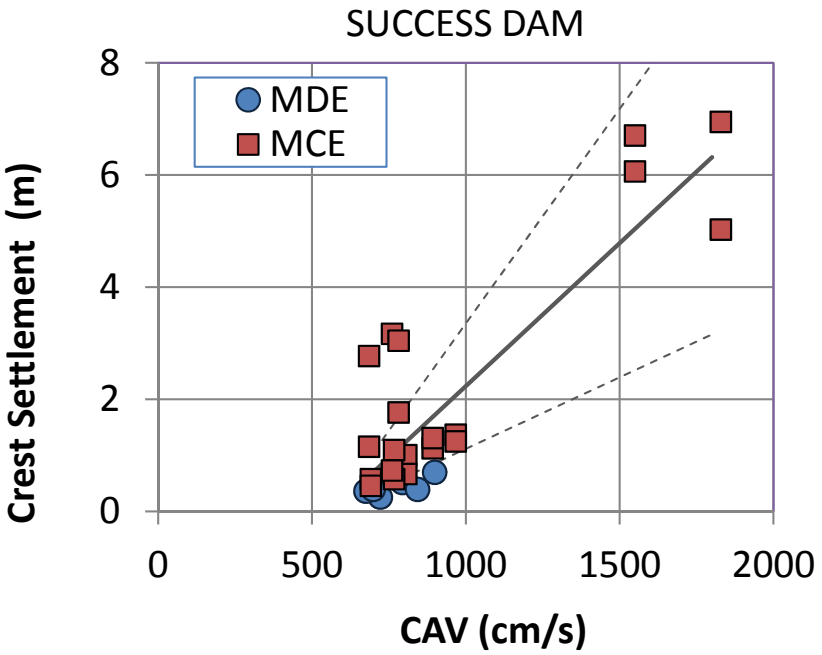
→ *Effect of record characteristics on estimated crest deformation of Success and Isabella Dam*

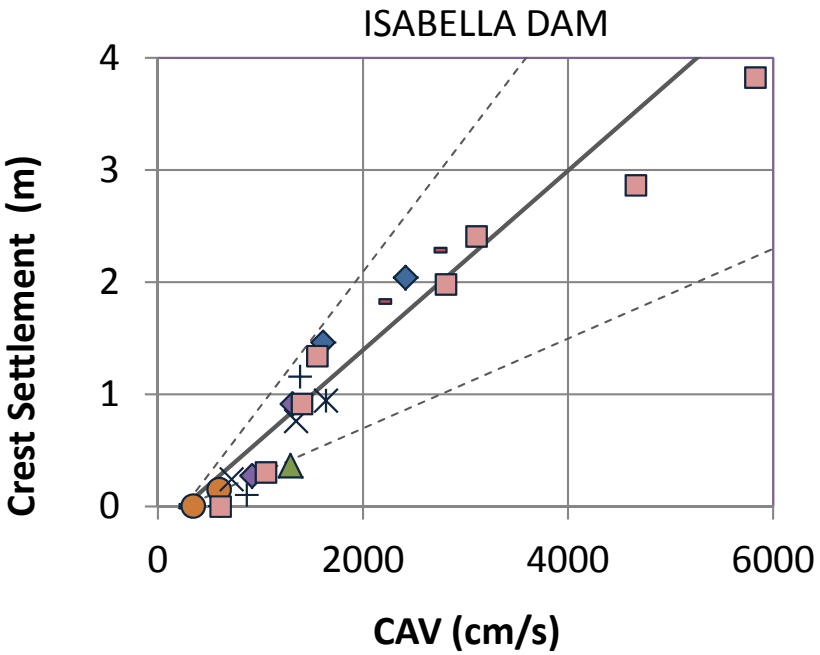
→ *IMs evaluated after spectral scaling*





Seismic Loading





Potentially useful: Arias Intensity, CAV, Specific Energy Density

Less promising: PGA, PGV, ND, significant duration, bracketed duration

3. Soil Behavior and Properties

Foundation Inspection Trench
(B.F. Sisk Dam)

Site characterization

→ *a particular challenge with levees*

Liquefaction (sand-like soils)

→ *triggering or initiation*

→ *residual strength*

→ *settlement*

Cyclic failure (clay-like soils)

→ *stiffness and strength loss with cycles*

Intermediate soils (e.g., low plasticity silts)

Organic soils

Stratigraphy

At range of scales (vertical and horizontal)

Impact on response and uncertainty?

Strain localization?

Void ratio redistribution?

How to best incorporate into analysis?

How address variability within strata?

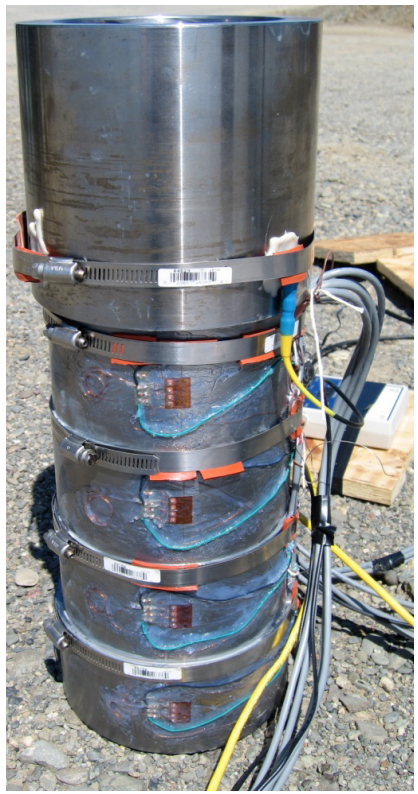
How best to define?

Pronounced layering of dam shell
(photo from Upper San Fernando Dam)

Response of Lower San Fernando Dam
(EQIIS, Steinbrugge collection)

Large Particles

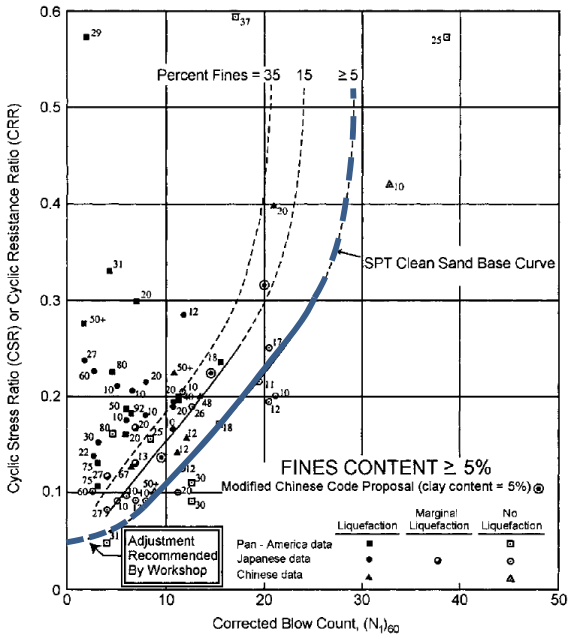
(Boulanger, 2012)



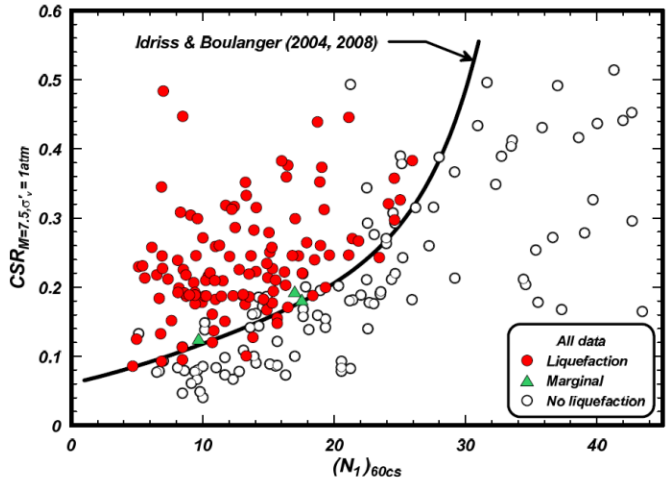
Instrumented Becker Penetration Test Device
Joint UC Davis – CA DSOD
(DeJong, 2012)

Liquefaction triggering

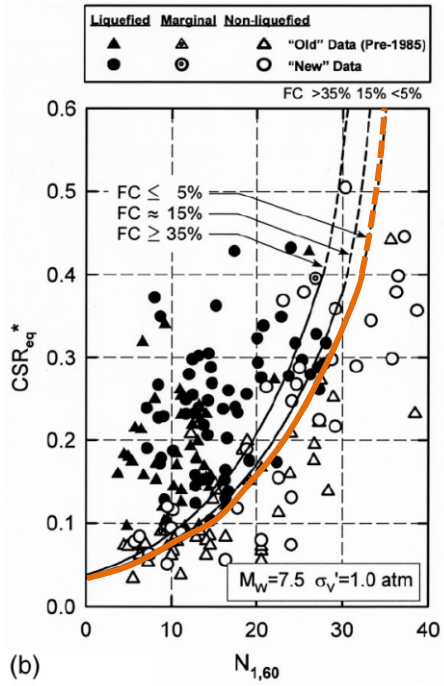
Typically semi-empirical correlations



NCEER Workshop (1997)



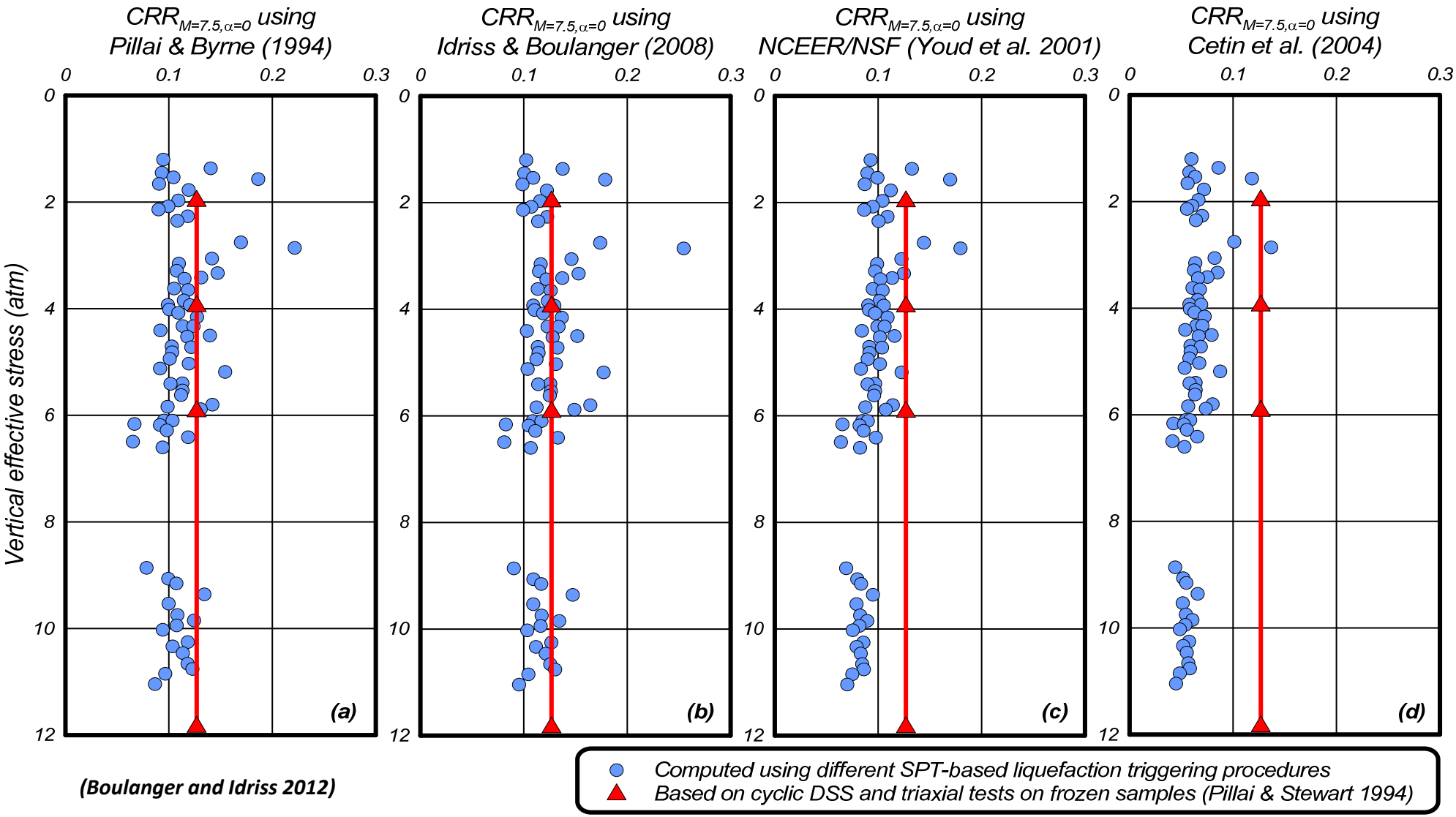
Idriss and Boulanger (2010)



Cetin et al. (2004)

plus Vs, CPT, BPT, DMT, …

CRR estimates for Duncan Dam



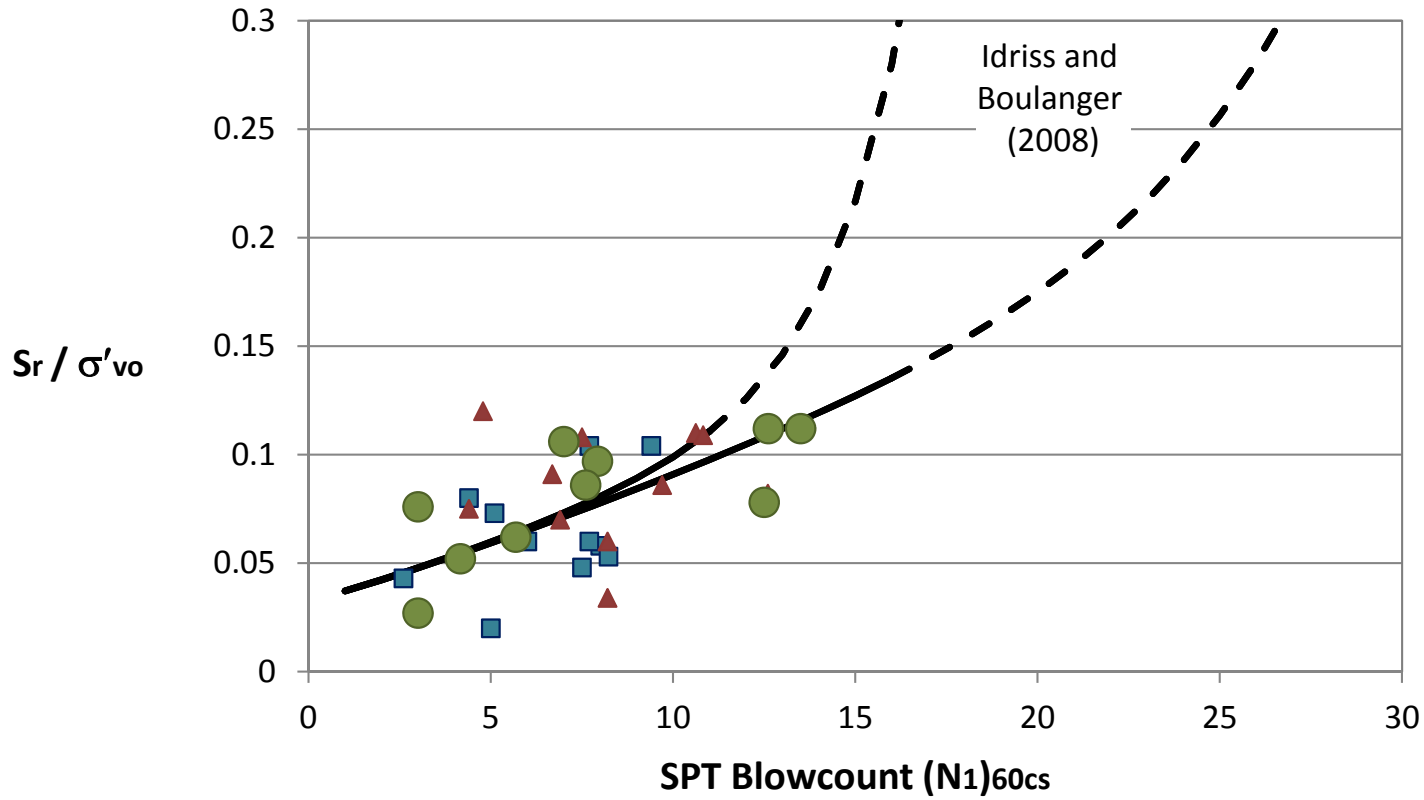
(Boulanger and Idriss 2012)

Residual Strength

Semi-empirical data as compiled by Olson and Stark (2002)

→ *32 case histories*

→ *SPT values corrected for fines content*



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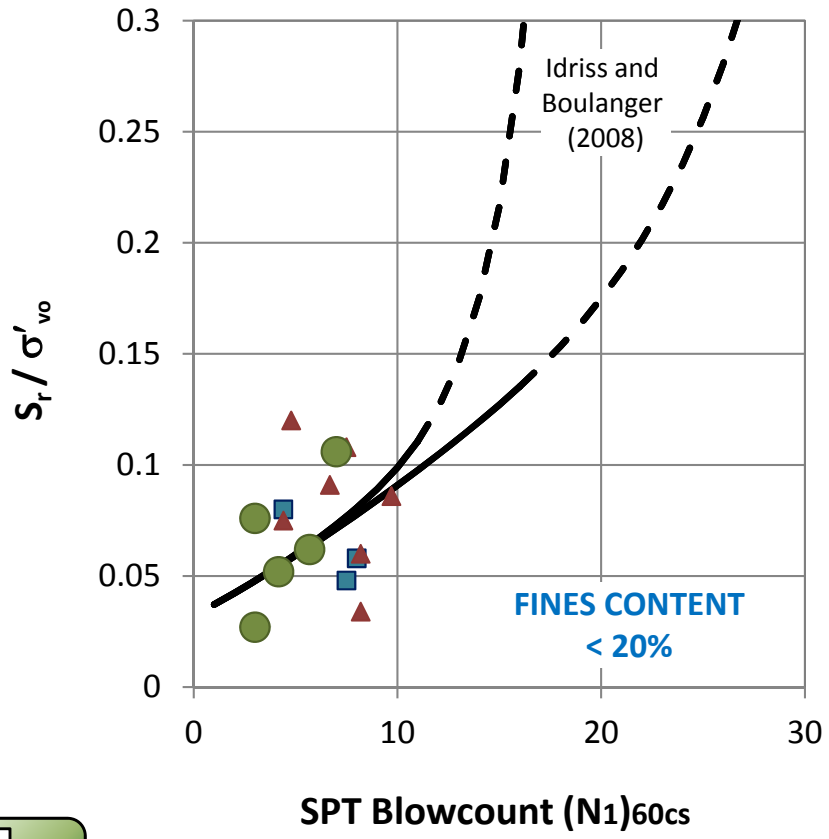
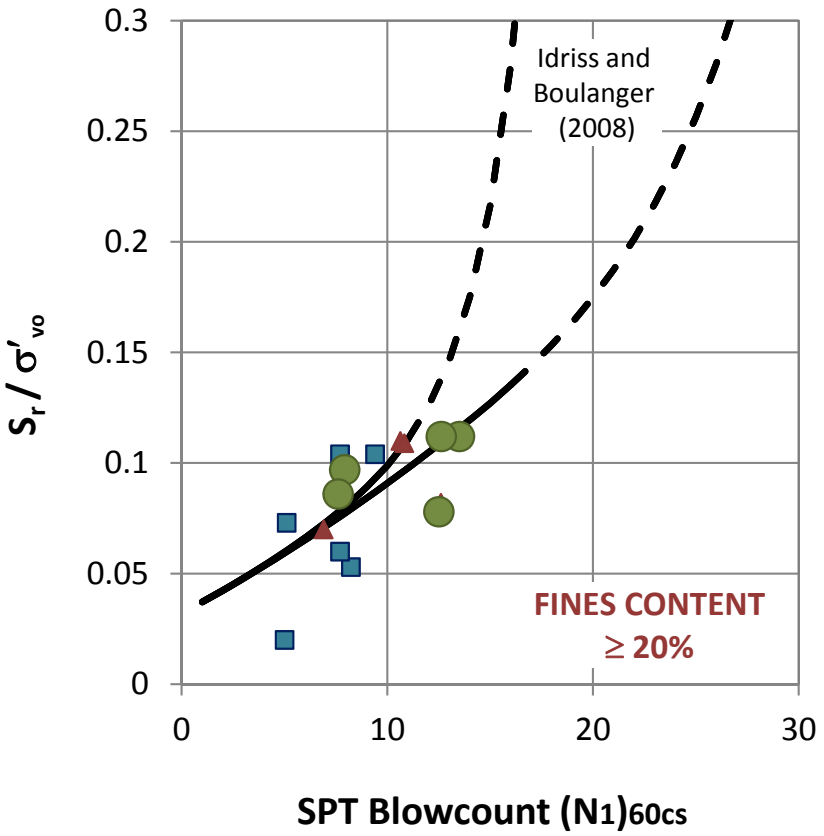




Residual Strength

Rate of strength loss

Some processes may require time

→ *void ratio redistribution*

Some failures after shaking

→ *Lower San Fernando dam (1971) [inferred from limited information]*

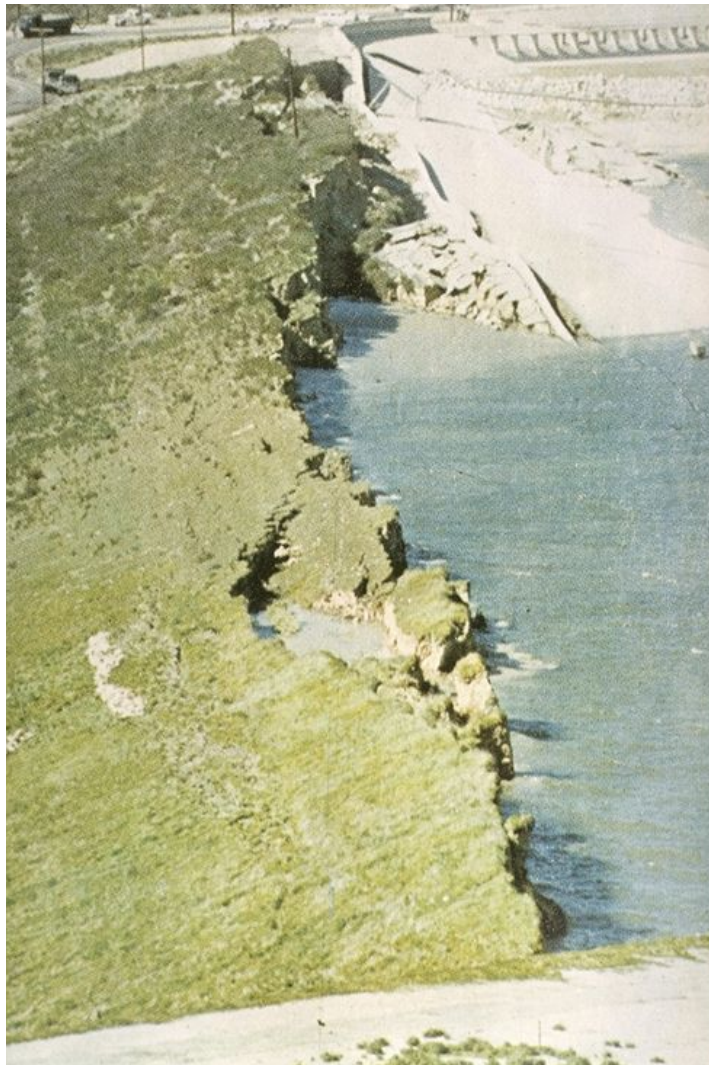
→ *Mochikoshi Tailings Dam No. 2 (1978) [24 hour delay]*

Influenced by relative density?

Importance to NDA?

→ *stiffness change*

→ *energy of dam when softens*



Lower San Fernando dam
(NISEE, 2012)

Cyclic Failure (clay-like)

Accumulation of strain with load cycles

→ *softening of shear modulus*

→ *importance of static shear stress bias*

Soil properties for NDA

→ *How does stiffness and strength of clay degrade with increasing number of cycles?*

→ *Cyclic testing often desirable for NC clays, particularly with relatively low PI*

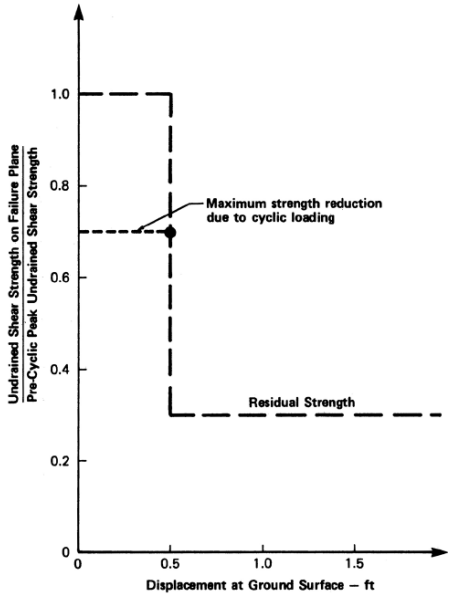
Progress

→ *Cyclic testing of clay-like soils is increasing in use*

Cyclic Failure (clay-like)

Sensitivity?

When will strains accumulate sufficiently to induce strength loss in moderately sensitive soils?



Assumed strength reduction
(Idriss, 1985)

4th avenue slide, Anchorage (1964)
(Hansen, 1971)

Strain Localization

Strains can localize in field during yielding

→ *strain softening soils*

→ *dilative soils*

Strains localize in NDA

→ *Dependent on mesh size*

→ *If constitutive model uses strain as model parameter, mesh density becomes very important*

- *goal is to adequately capture anticipated field behavior*

Strength versus strain relationship can be difficult to define

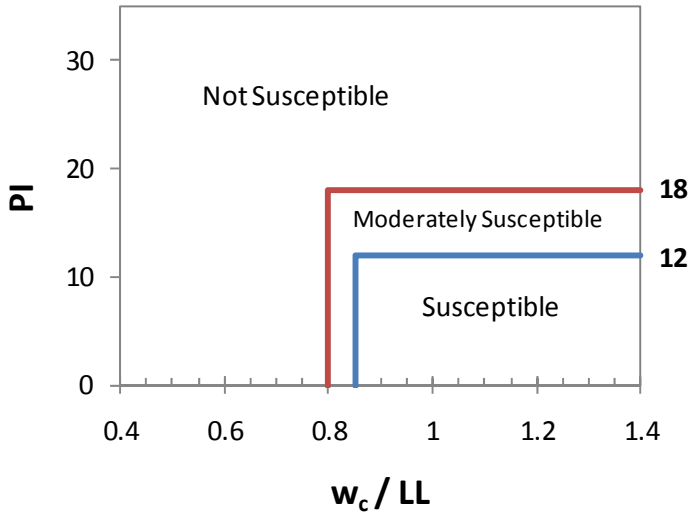
→ *Strains to 20% in laboratory*

→ *Large strain from in situ (e.g., vane shear, CPT friction sleeve)*

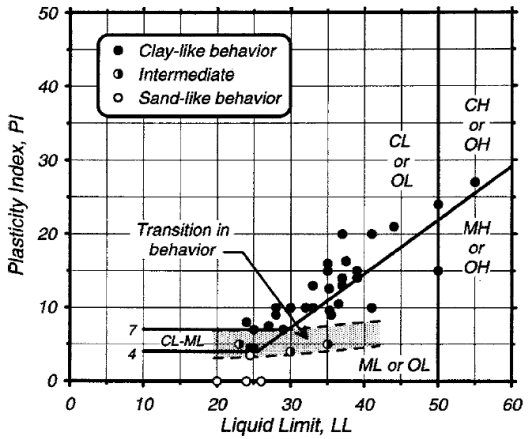
Intermediate Soils

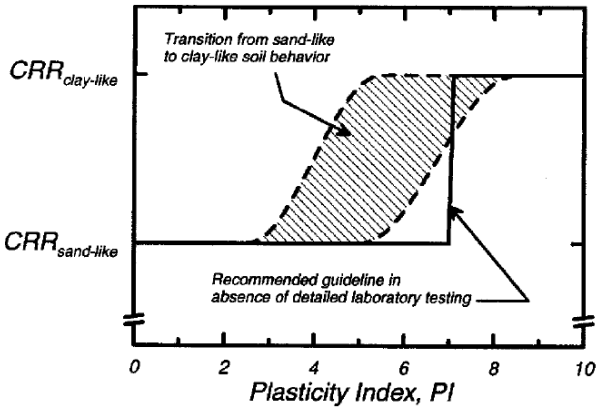
Silts and clays with PIs of ~ 5 to 18

Bray and Sancio
(ASCE , 2006)



Boulanger and Idriss
(ASCE 2006)





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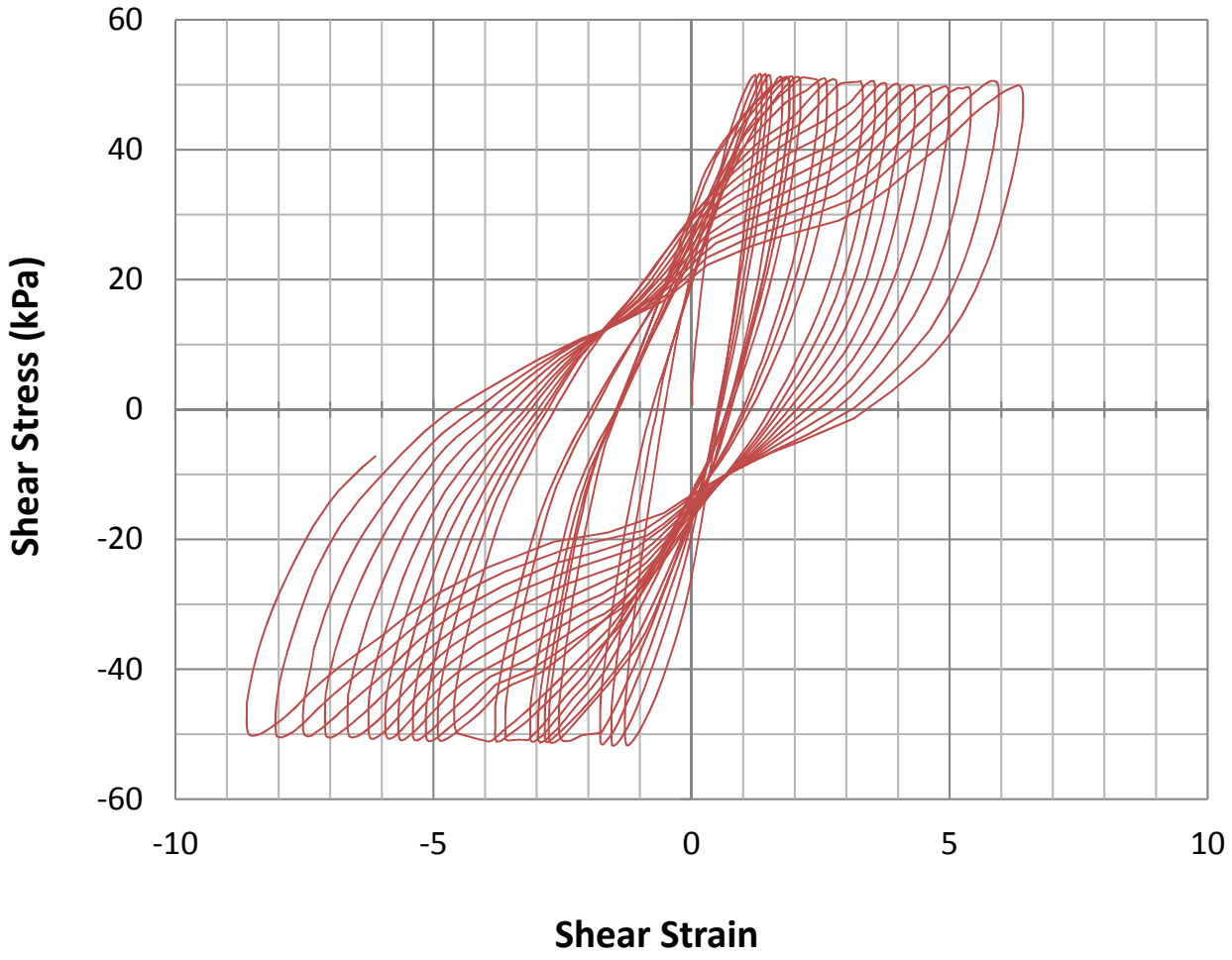
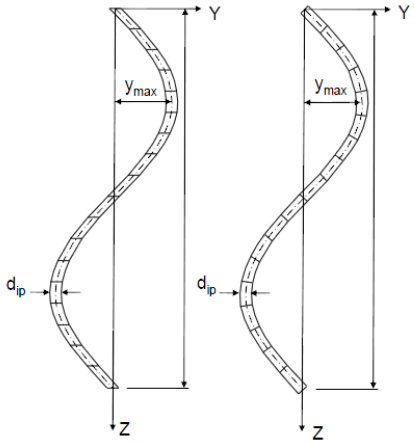


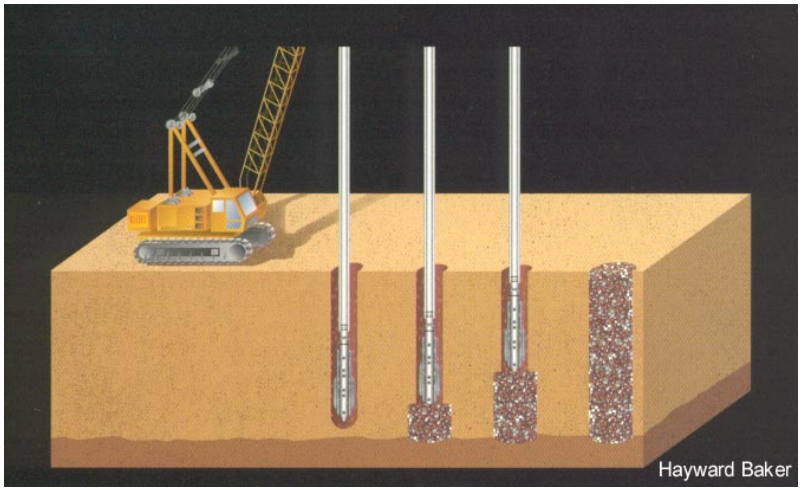
Ground Improvement

Jet grout columns
(John Dillon 2009)

Piles
(Sardis Dam)

Analytical research
(e.g., Goughnour & Pestana 1998)





Stone columns
(Hayward Baker, 2012)

Other Challenges

Aging

Cementation

Impact of large imposed load?

Organic soils

Effect on compressibility and strength

Site response

Post-cyclic strength

Cyclic failure?

Fibrous peats versus dispersed organics

4. Uncertainty

Deterministic approach has a natural conservative bias

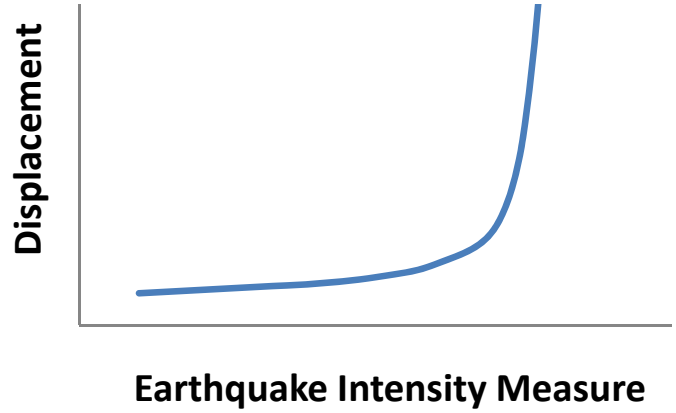
→ *Both in model formulation and property selection*

→ *Most available methods have developed out of deterministic approach*

→ *Conservative bias may cloud usefulness of analysis result*

How to address fragility?

Possible fragility curve for liquefiable site



Uncertainty in Analysis Process

Many available techniques, constitutive models, and processes

Transparent documentation key for peer reviewers, regulators

NDA needs case history validation and element calibration

NDA needs support from simplified evaluation

Parametric study is a necessity on any project

NDA as a commodity

5. Analysis → Performance

Initial objective of NDA for dams (& levees):

ESTIMATE LOSS IN FREEBOARD (OVERTOPPING)

Additional concerns:

→ *Transverse cracking*

→ *Disruption of filters*

→ *Disturbance of (or along) embedded structures*

Cracking of Dams and Levees

Transverse cracking (dams)

Analysis guidelines are very limited and supported by limited empirical data

Effect of duration uncertain

Assumption on depth can be significant to risk analysis due to erosion potential

(EERI, 2011)

(EERI, 2011)

Validation

Current state of case history catalog (dams)

Earthquake response teams provide valuable information

→ *(e.g., GEER, ASCE)*

But few case histories are sufficiently documented to allow NDA validation

→ *Focus is on most poorly-behaved structures*

→ *Range of potential response is not well represented*

- *e.g., need liquefaction at depth, foundations with $(N_1)_{60} > 15$, organic soils, moderately sensitive clays and silts, clayey sands, etc.*

Need

Industry, university, and government support to promote detailed investigation, documentation and use

Concluding Remarks

NDA

- → *is a valuable tool*
- → *has a long (40 year?) history of advancement and refinement*
- → *requires transparency and thoughtful application*
- → *has additional challenges when used for risk analysis*

Many areas for improvement

- → *problem soil behavior*
  - *residual strength, moderate sensitivity, intermediate soils*
  - *stratigraphy*
- → *criteria for seismic loads*
- → *validation*
  - *well documented case histories*
  - *centrifuge tests*