EERI BC Chapter & VGS Joint Meeting
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Liquefaction:
Lessons, challenges, and opportunities

UCDAVIS
UNIVERSITY OF CALIFORNIA

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Liquefaction awareness and the 1964 Alaska & Niigata earthquakes

Niigata (NISEE)

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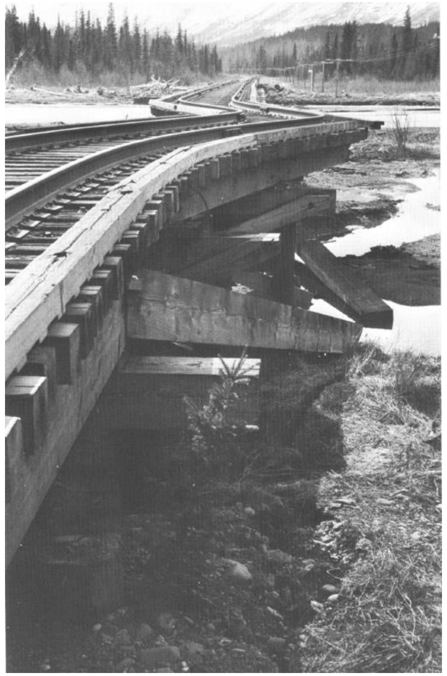
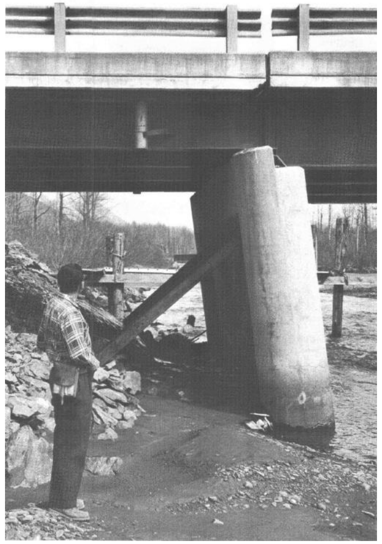


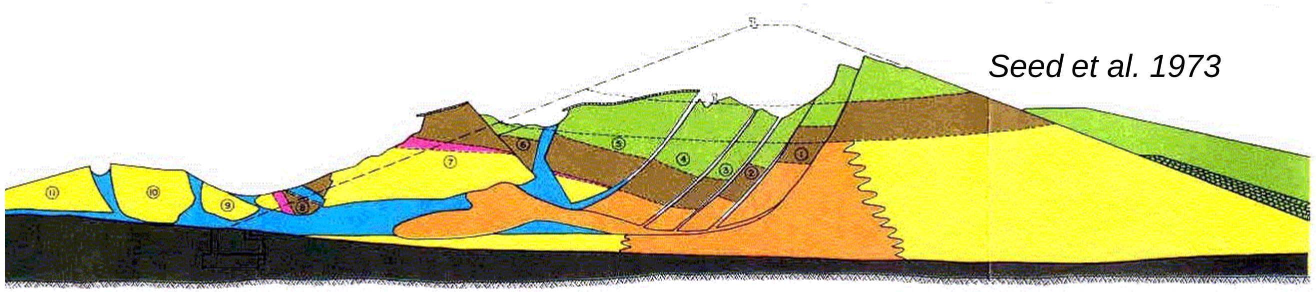
Alaska (USGS)



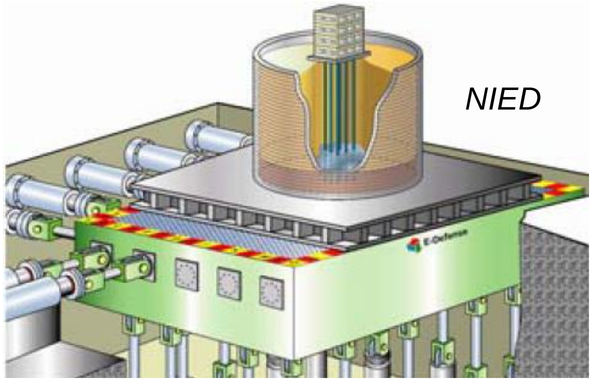
Anchorage Daily News

Alaska (USGS)

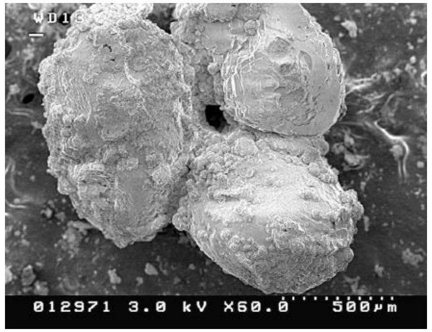
Half century of liquefaction studies



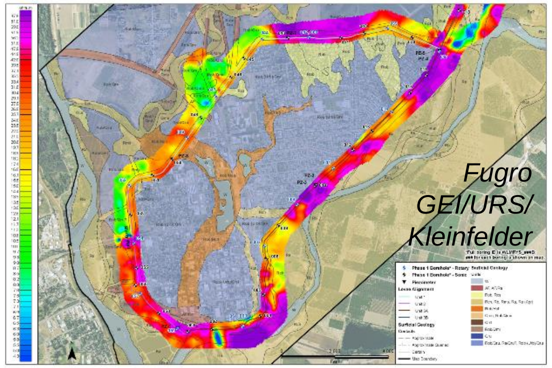
Seed et al. 1973



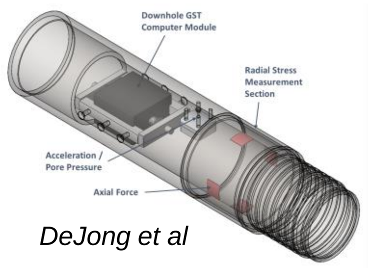
NIED



DeJong et al



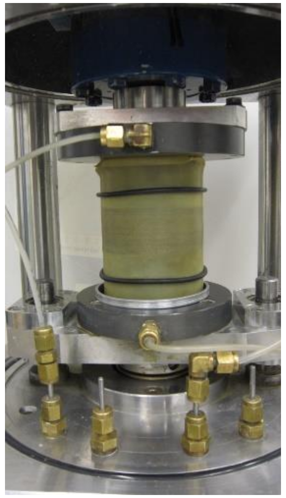
Fugro GEI/URS/ Kleinfelder

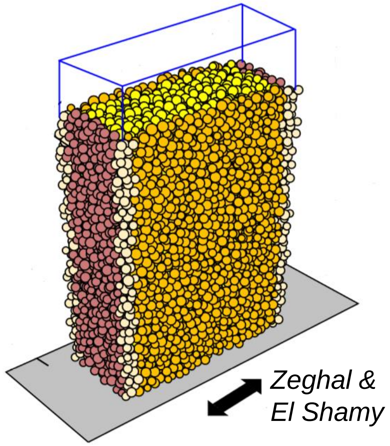


DeJong et al

Obermeier

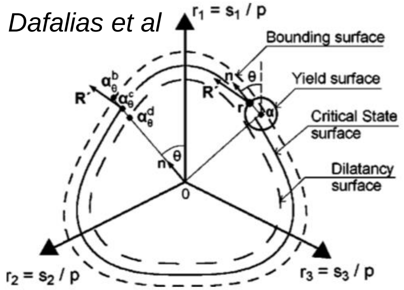
DGI-Menard

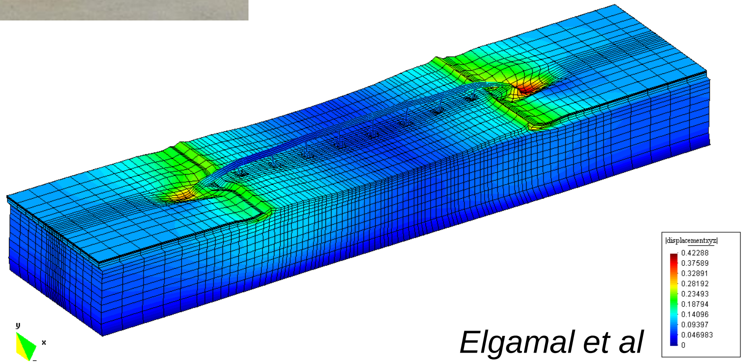




Zeghal & El Shamy

Dafalias et al





Elgamal et al

$$\lambda(\boldsymbol{DV}) = \iiint G(\boldsymbol{DV} \mid \boldsymbol{DM}) \left| dG(\boldsymbol{DM} \mid \boldsymbol{EDP}) \right| \left| dG(\boldsymbol{EDP} \mid \boldsymbol{IM}) \right| \left| d\lambda(\boldsymbol{IM}) \right|$$

Half century of liquefaction studies

- *Past studies of liquefaction have produced major advances in our*
  - *scientific understanding*
  - *engineering procedures*
  - *policies and regulatory practices*
- *Current state of engineering practices*
  - *Liquefaction hazards are widely recognized and addressed*
  - *Range of technical approaches (simple to complex) to chose from*
  - *Situations persist where knowledge gaps and limitations hinder the efficient evaluation and mitigation of earthquake-induced liquefaction hazards*

This presentation

- *Objective*
  - *Suggest needs & future directions for more effectively addressing liquefaction hazards*
  - *Lessons, challenges, or opportunities*
- *Outline*
  - *Site characterization*
  - *Challenging soil types*
  - *Residual strength*
  - *Nonlinear dynamic analyses*
  - *Remediation methods*
  - *Risk management approaches*

Site characterization
(for liquefaction hazards)

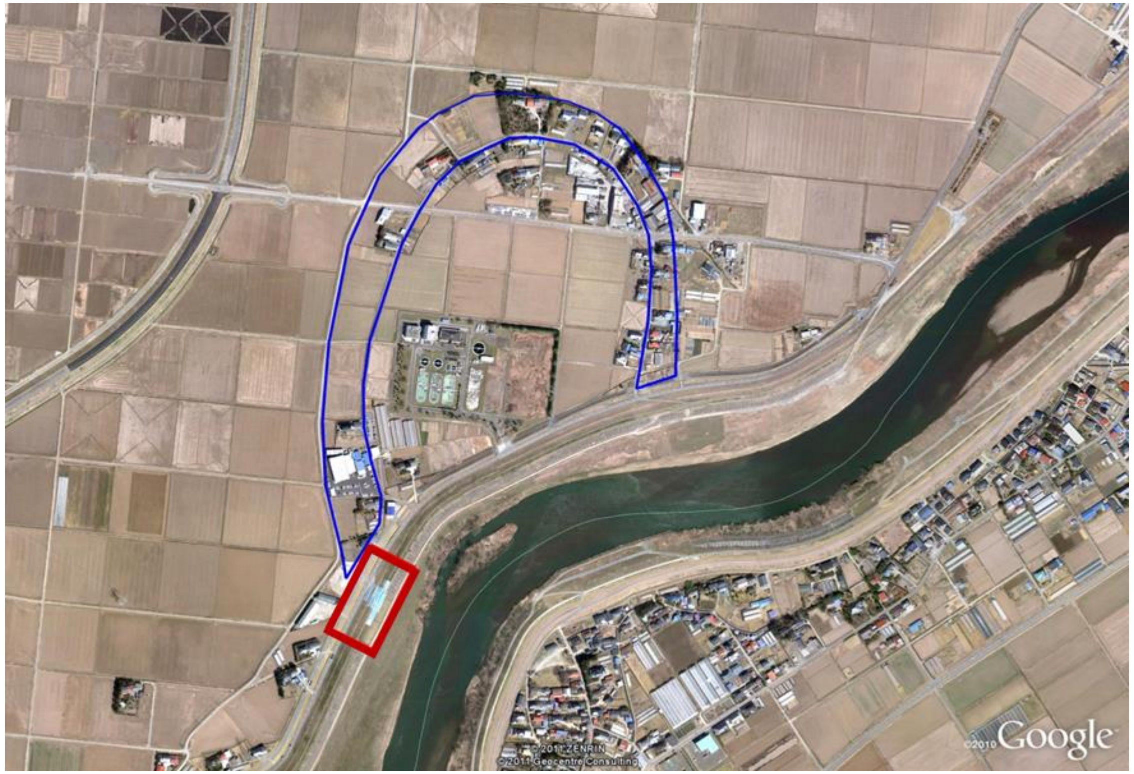
Lessons from claims data

- *Institute of Civil Engineers (2013) examined 28 UK projects*
  - *76% of issues attributable to inadequate site characterization*
- *Yabusaki (2015 with Lucia & DeJong) examined 1500 claims from 1988-2013*
  - *44% of claims associated with site investigation services*
  - *48% of allegations associated with inadequate investigations (19%) and design error/negligence (29%) largely attributed to failure to identify problematic soils*
  - *Claim rates were greatly reduced by the promotion of risk management practices*
- *Lesson: Don't compromise on your site investigations. Resist any pressure to unduly reduce upfront site characterization costs.*

Easypolicy

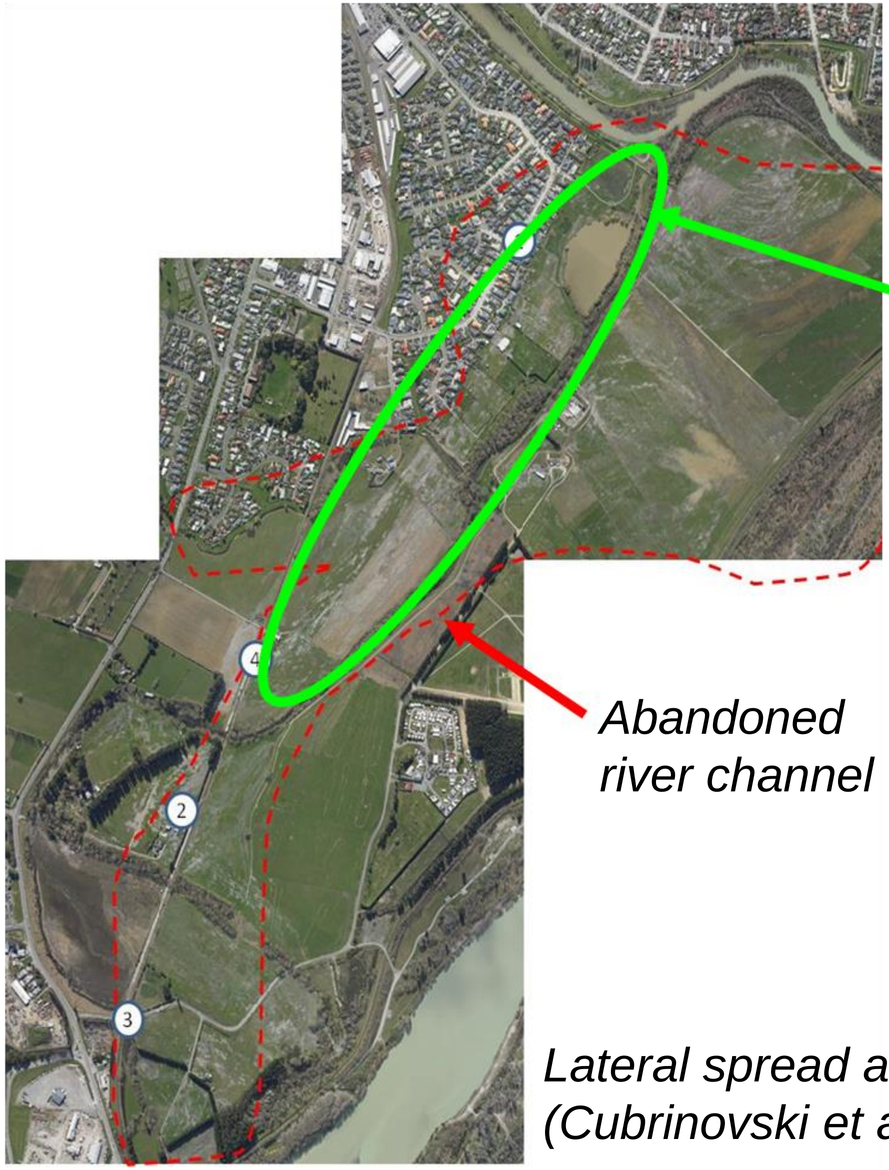
Geologic features can control performance

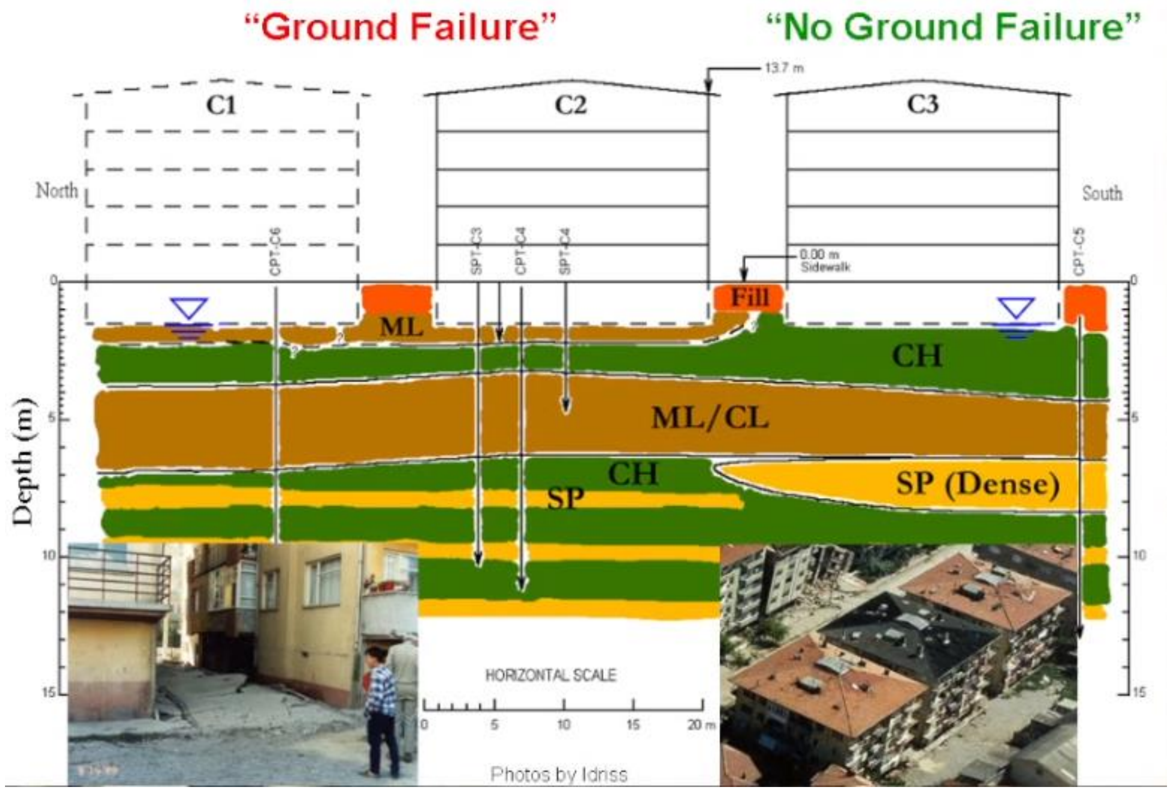
Utility & roadway damage along filled historic channel (GEER 2011)



Levee damages coinciding with a mapped paleochannel (MLIT 2011, GEER 2011)

Geologic features can control performance



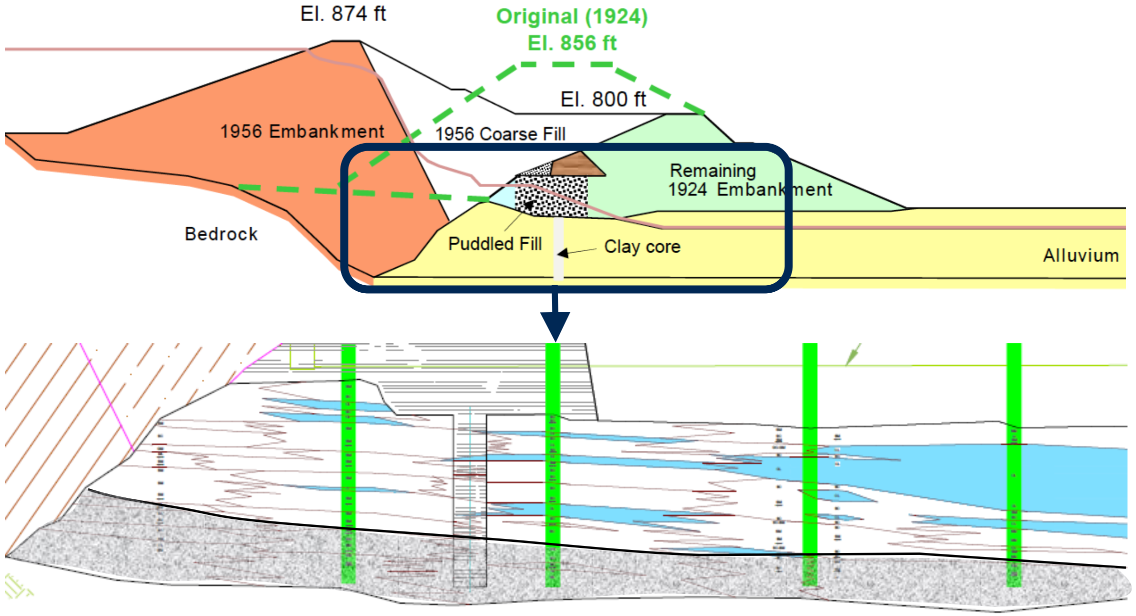


"Tale of three buildings in Adapazari"
(Jon Bray 2013 – Peck Lecture)

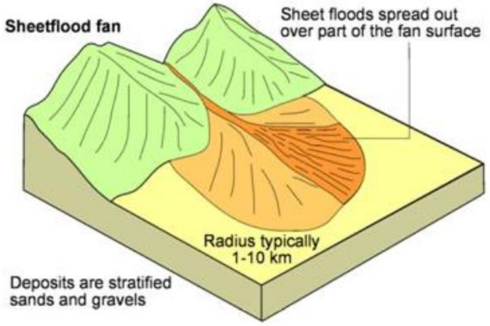
Lateral spread along South Kaiapoi
(Cubrinovski et al. NZJGG 2012; courtesy of Liam Wotherspoon)

Depositional processes inform interpretation of exploration data

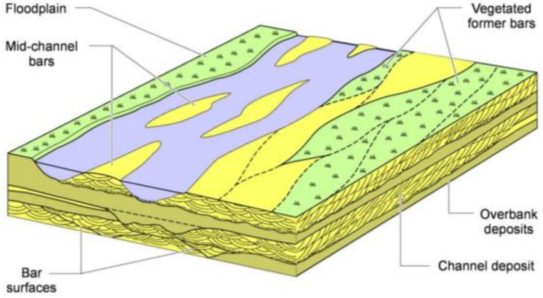
- *Multiple processes in a narrow canyon*



Nichols (2009)



Fan deposits off canyon sides (colluvium source)



Reworking by stream (sorting & lateral variability)

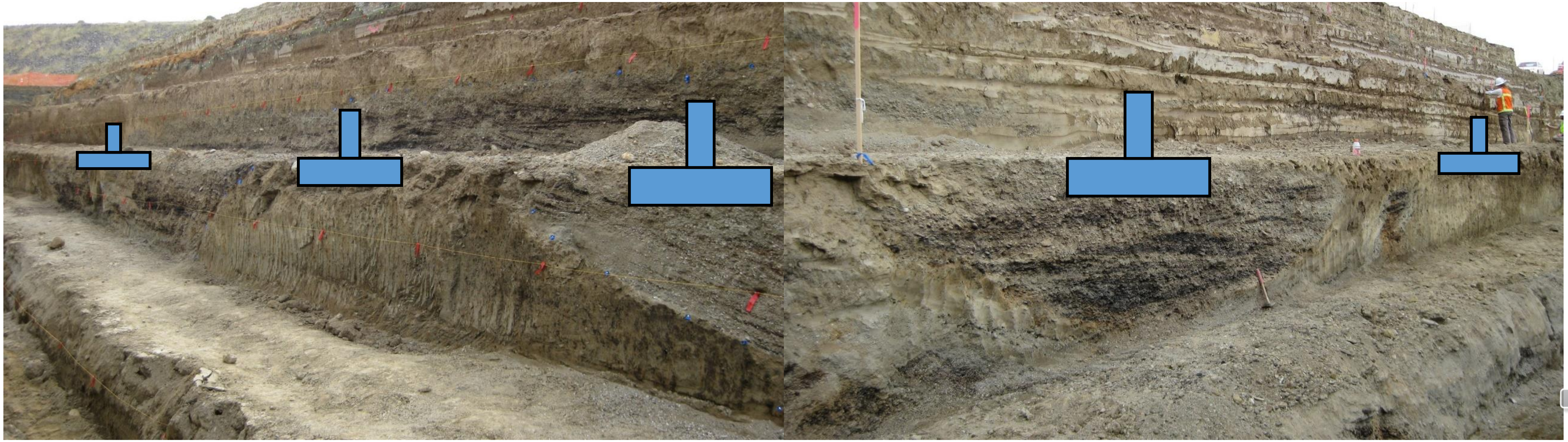
Ponding (finer-grained sediment accumulates)

Arroyo flash floods (poorly sorted)

Sections courtesy LADWP, AECOM (Goetz), DeJong

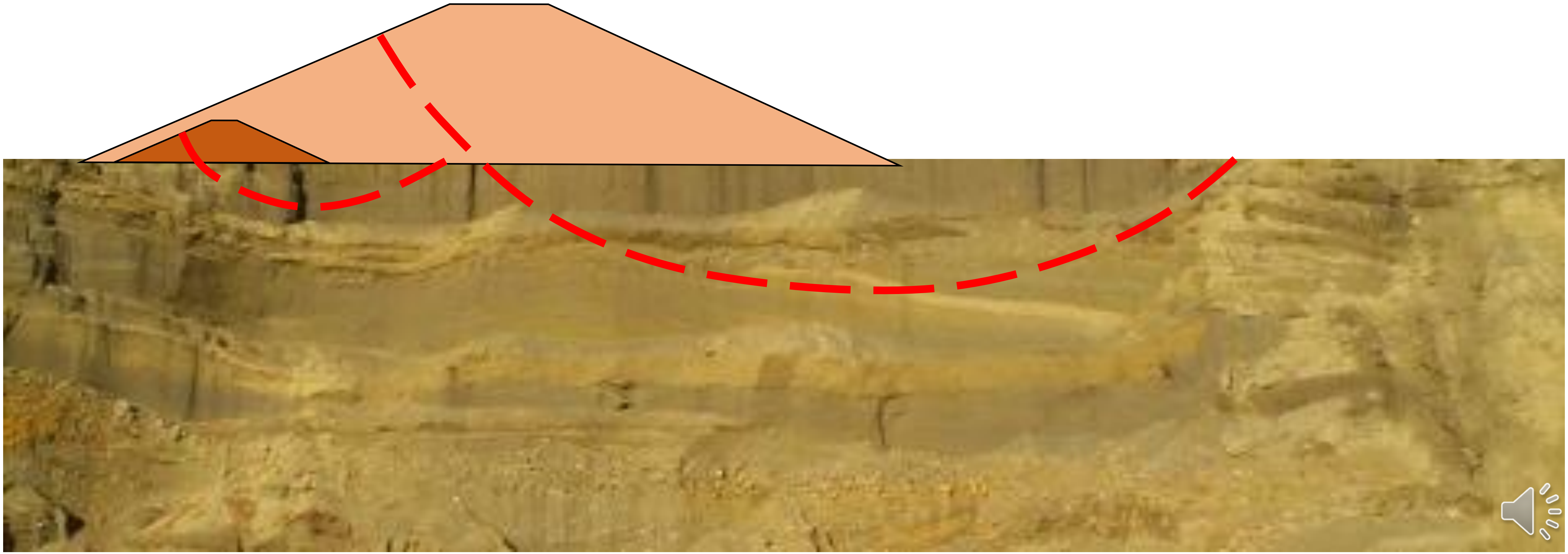
Spatial variability & deformation variability

- *Deformation variability depends on the:*
  - *Spatial variability (e.g., stratigraphy, scales of fluctuation)*
  - *Scale of the deformation mechanism*
- *Explorations provide only limited sampling of the subsurface*
  - *Are there geologic features, consistent with the depositional environment, that could have been missed by the exploration program?*



Spatial variability & deformation variability

- *Larger structures engage greater volumes of soil, which provides greater averaging across weaker/stronger zones*
- *Smaller structures engage smaller volumes of soil, and thus are more adversely affected by the looser zones and can show greater variability in deformations*



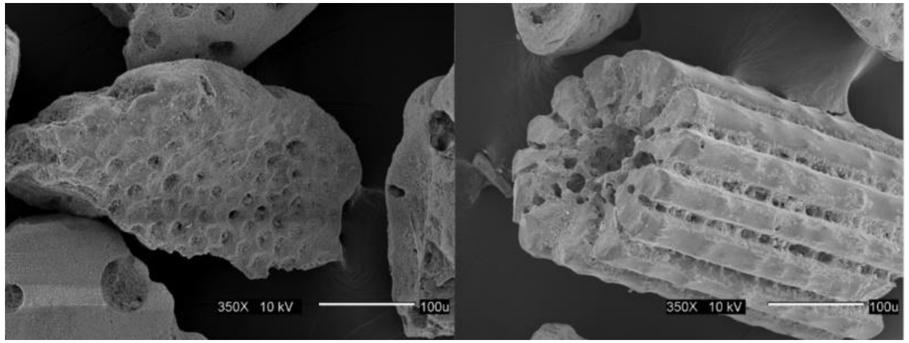
Site characterization – Future efforts

- *Site characterization*
  - *Inadequate site characterization is a major cause of geotechnical claims*
  - *Don’t compromise (skimp) on your site investigations*
- *Geologic features and models*
  - *Often constrain the boundaries of lateral spreading*
  - *Often essential for selecting properties & analysis sections*
  - *Inform expectations for deformation variability*
  - *Basis for evaluating risk of unidentified features*
- *Opportunities*
  - *Community-based efforts to increase expectations for the standards of practice*
  - *Integrated site characterization practices: tailor efforts to project-specific concerns and geology, and leverage opportunities for iteration from desk studies through construction*
  - *Further improvements in tools and procedures (particularly for challenging soils)*

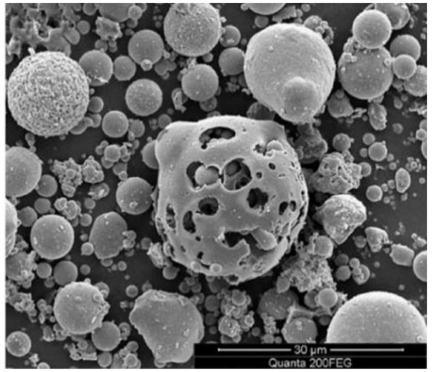
Challenging soil types
(for liquefaction evaluations)

Challenging soils

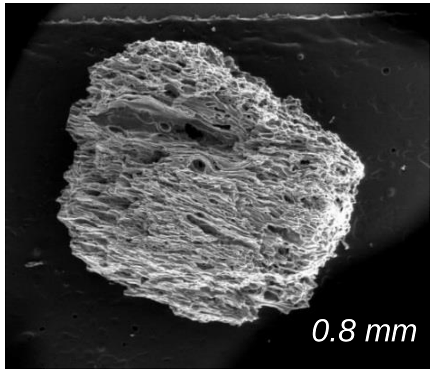
- *Fundamentally different from silica sands (e.g., more crushable, compressible)*
- *In-situ tests are biased or difficult to interpret (e.g., thinly interbedded, large particles)*
- *Insufficient case histories and supporting knowledge (e.g., intermediate soils, aged soils)*



Calcareous sand (Sandoval & Pando 2012)

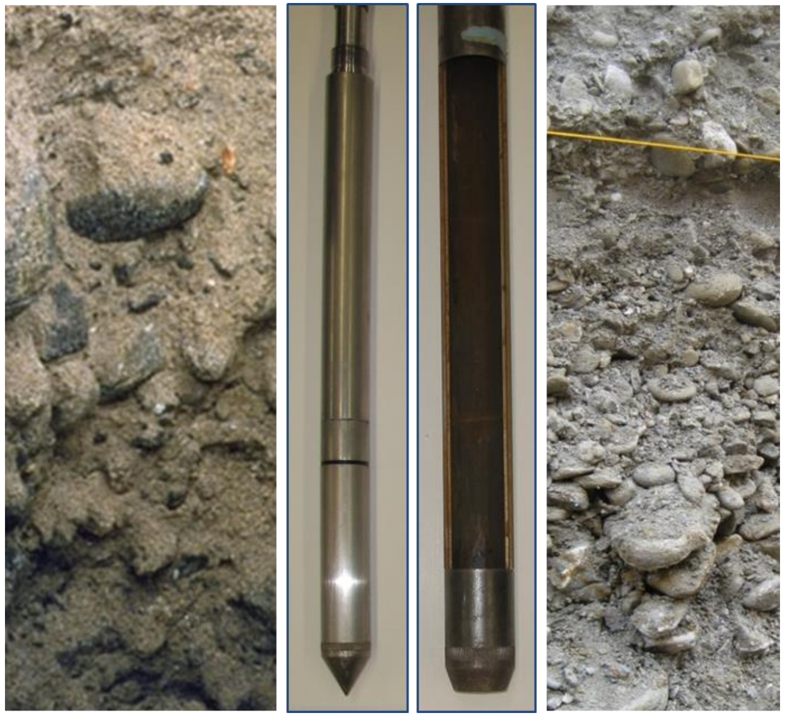


Fly Ash (Bachus et al 2019)



Pumice sand (Orense et al. 2017)

Interbedded sand, silt, clay (woostergeologists.scotblogs .wooster.edu/2012/03/)



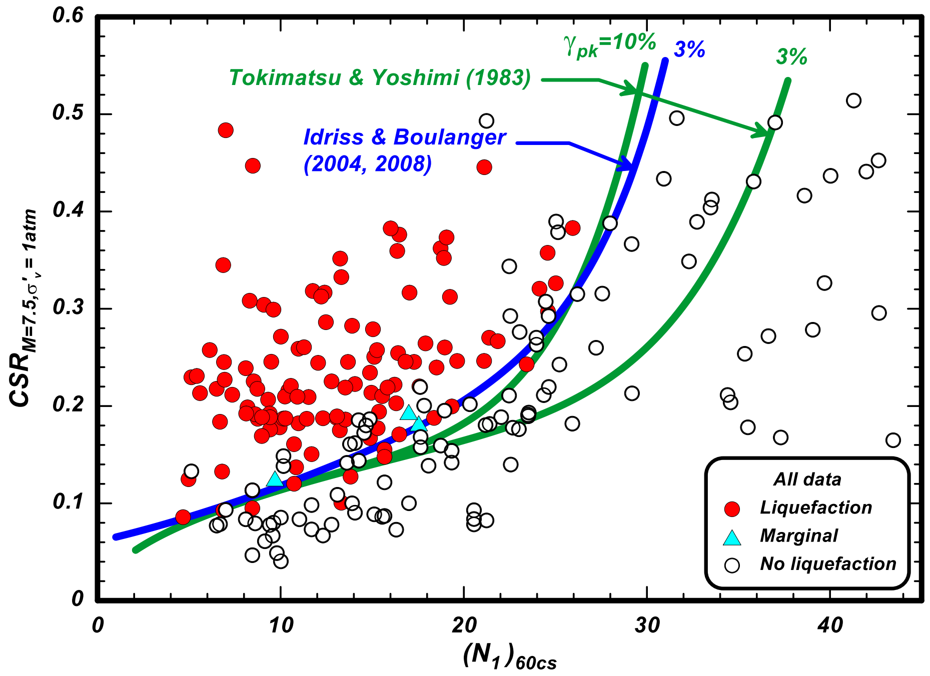
Coarse-grained gravelly soils with cobbles or boulders

A 50-year learning curve for silica sands

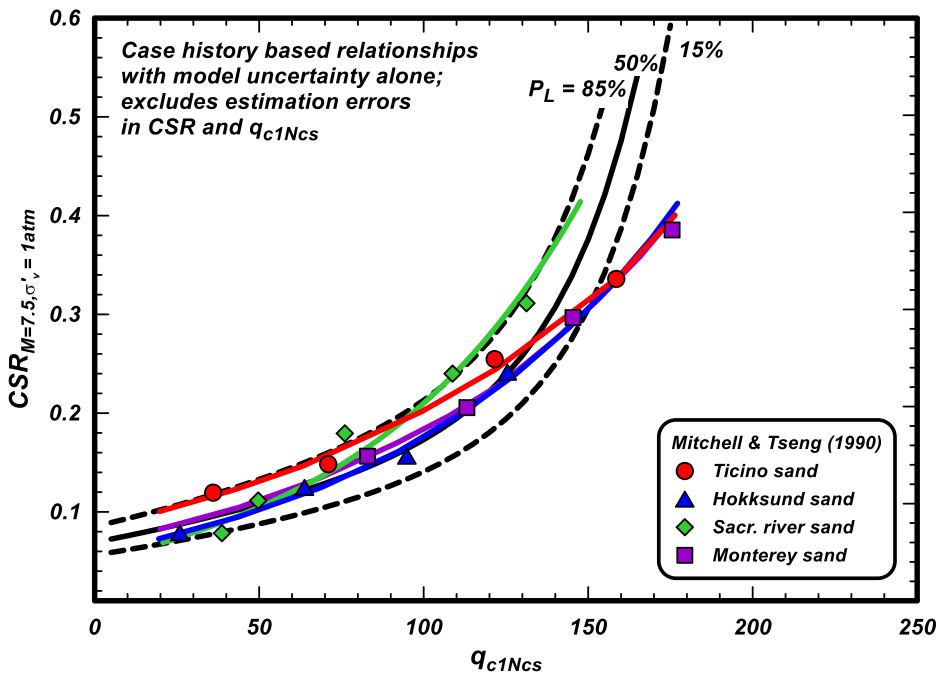
- *Laboratory testing*
  - *Reconstituted specimens – Identified influencing factors*
  - *Field samples – Disturbance was an overwhelming issue (except with frozen sampling)*
- *Penetration & other in-situ testing methods*
  - *Reconstituted specimens – Calibration chamber and centrifuge model tests*
  - *Field testing – Case history and applied experiences*
- *Theoretical understanding*
  - *Simulations of in-situ tests (e.g., CPT) connect the test data to the fundamental soil properties (via the constitutive models)*
- *Case histories*
  - *Provided calibration of semi-empirical procedures*

A 50-year learning curve for silica sands

- *Several studies have mechanistically derived correlations between cyclic strength and in-situ test results that are reasonably consistent with case history based correlations*
  - *Field sampling by freezing techniques coupled with in-situ testing in the same strata*
  - *Cyclic and in-situ testing of reconstituted soils prepared by the same methods (e.g., composing data from element tests, calibration chamber tests, centrifuge models)*



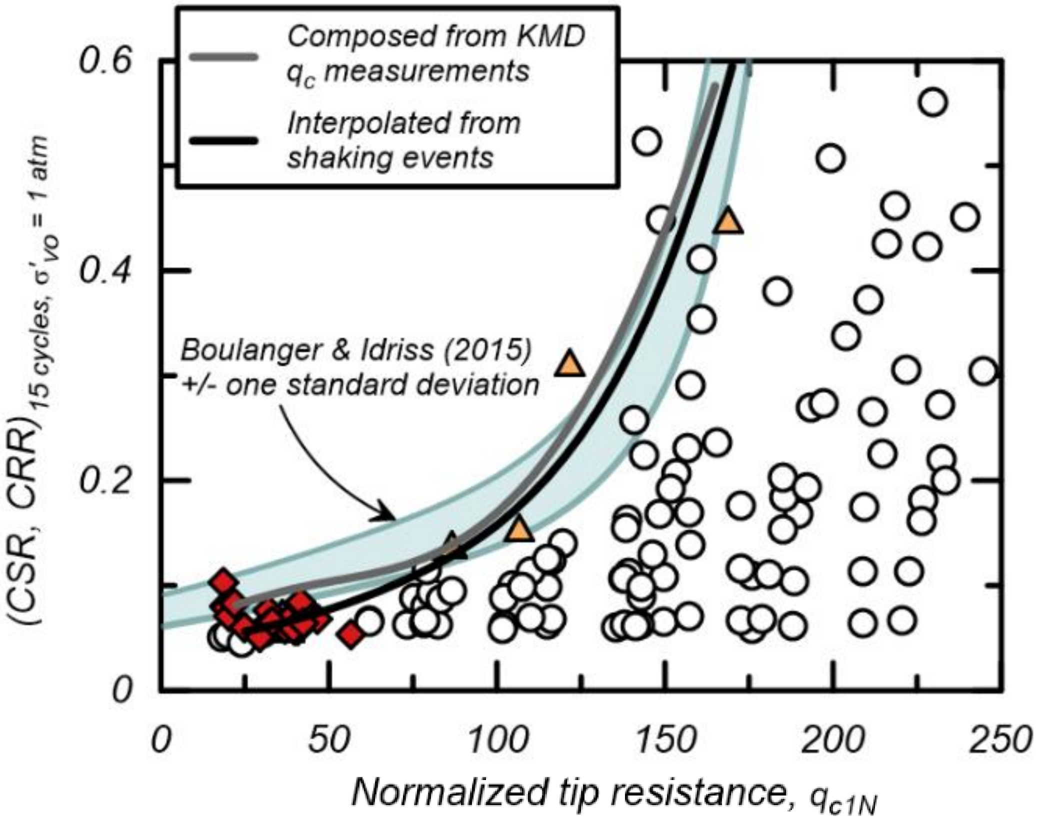
Tokimatsu & Yoshimi (1983)



Mitchell & Tseng (1990)

A 50-year learning curve for silica sands

- *Moug et al (2019) examined several mechanistic approaches*
  - *Different ways of composing centrifuge (CPT, CRR), lab (CRR) and simulation (CPT) data*
  - *All were generally consistent, but the best results used measured CPT resistances*

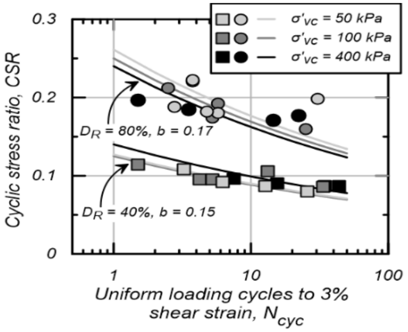


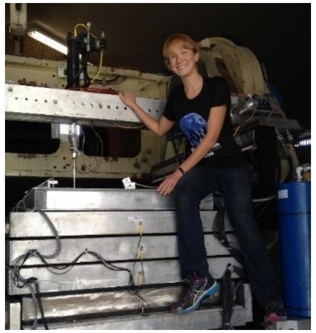
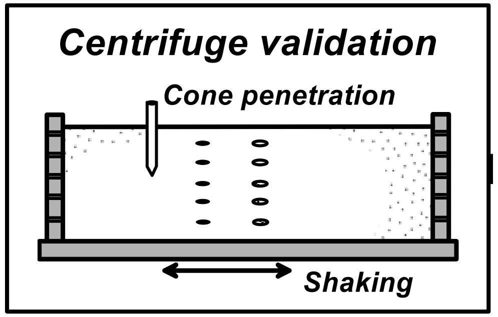
Team: Moug, Price, Parra Bastidas, Darby, Boulanger, DeJong

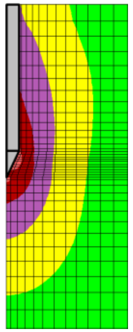
Challenging soils – Paths forward

- *Recognize large uncertainties in extending relationships derived for predominantly silica sands*
  - *Carbonate soils, pumice sands, flyash, tailings for different ores, ….*
  - *Thinly interbedded soils*
  - *Soil with large particles (gravels, cobbles, boulders)*
  - *Intermediate soils (e.g., sandy silts, clayey sands, …)*
  - *Aged soils*
- *Opportunities for advancement*
  - *Case histories invaluable – but too limited in number for most challenging soil types*
  - *Mechanistic approaches – require cyclic strengths and penetration/V_s tests in the same soils placed to a range of densities with a range of loading/environmental histories*
  - *Well-suited to coordinated team efforts (and a pooling of funds)*







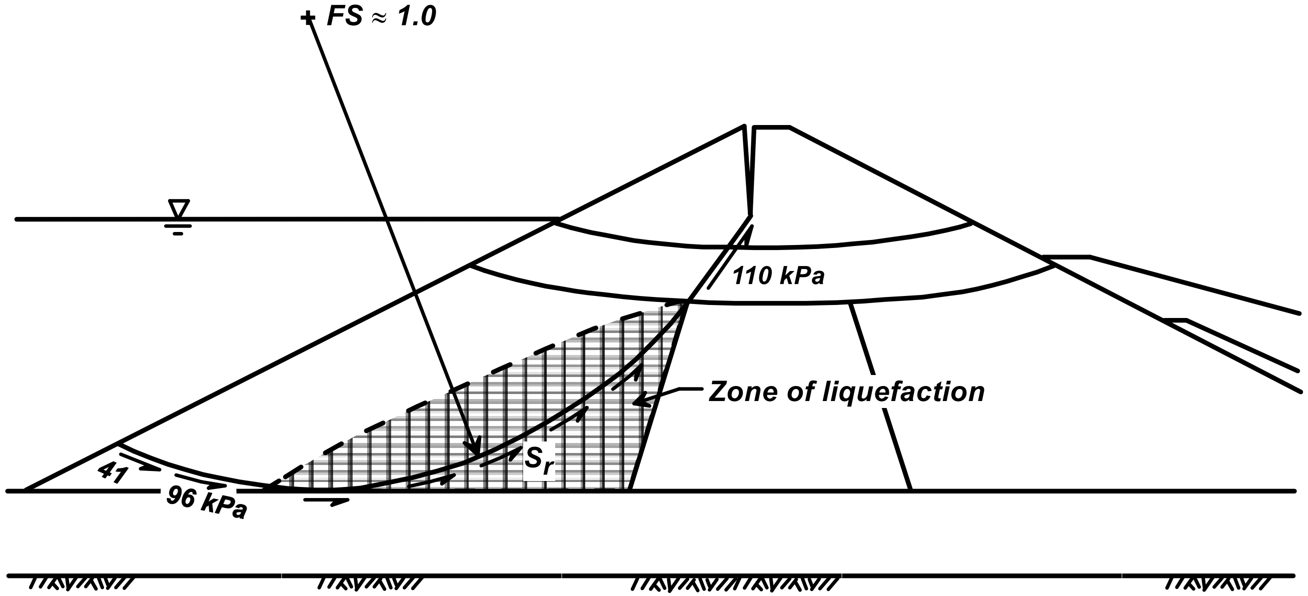
Residual shear strength of liquefied soil

Topic 3 of 6

Residual shear strength – Science and empiricism

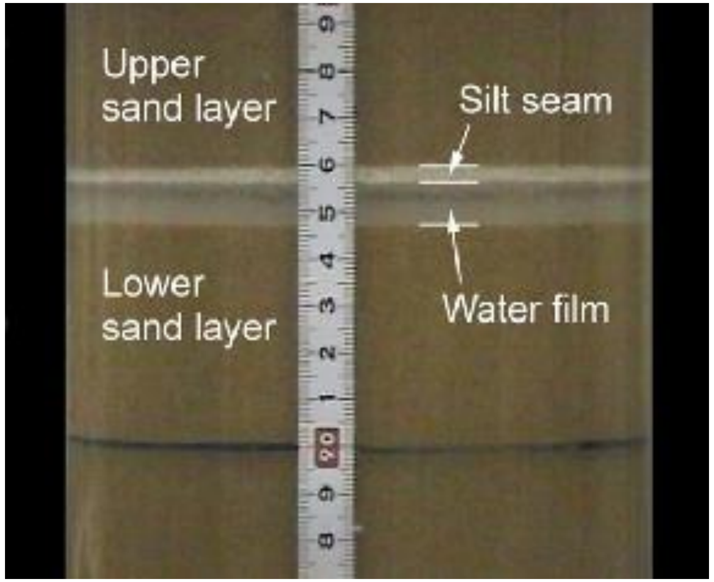
- *Empirical correlations for residual shear strength (S_r) of liquefied soils*
  - *Back analyses of case histories using limit equilibrium stability analyses*
  - *Values for S_r reflect the simplifications inherent to the assumed analysis model*

Lower San Fernando Dam in 1971 (DSOD files)

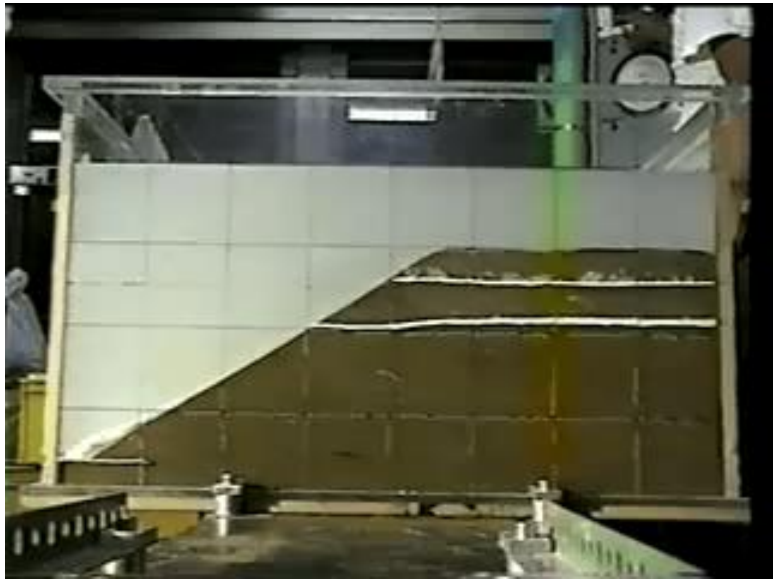


Residual shear strength – Physical models

- Demonstrated role of pore pressure diffusion (void redistribution) on strength loss and deformations during and after strong shaking (e.g., cases of delayed deformations)

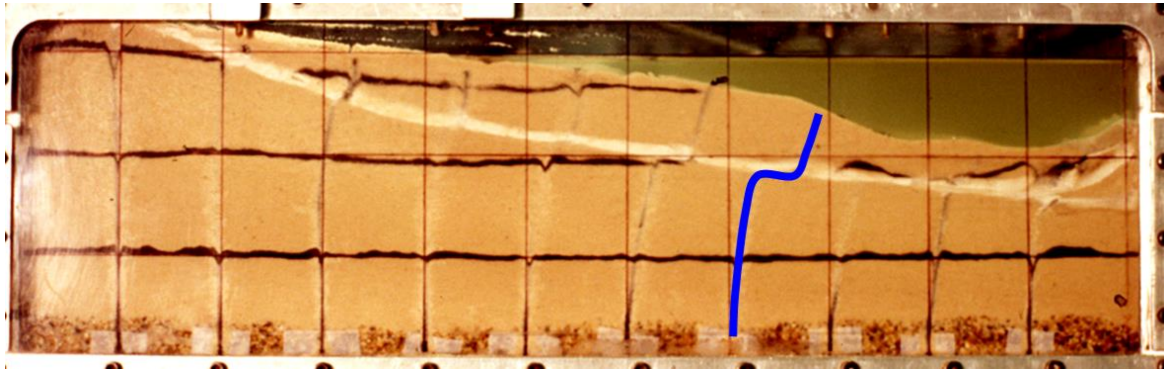


Kokusho

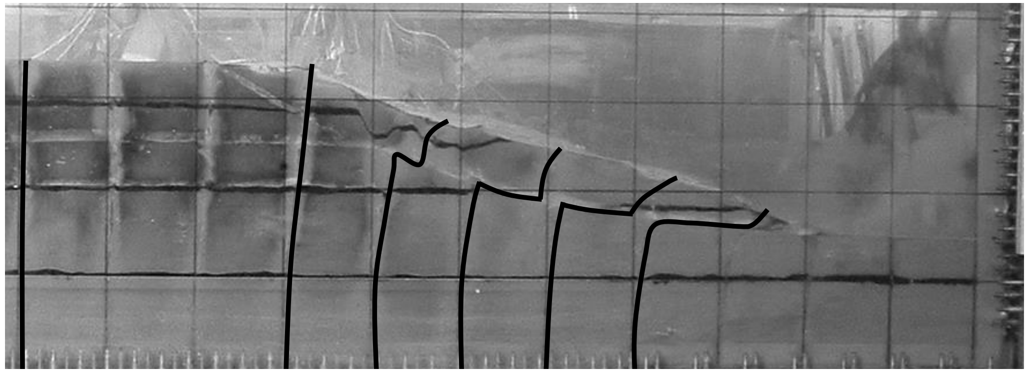


Kokusho

Kamai et al



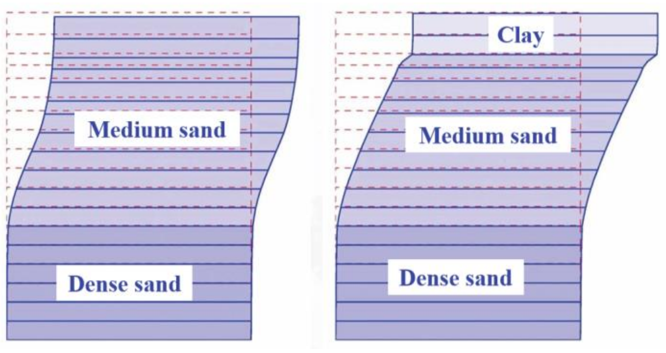
Kulasingam et al



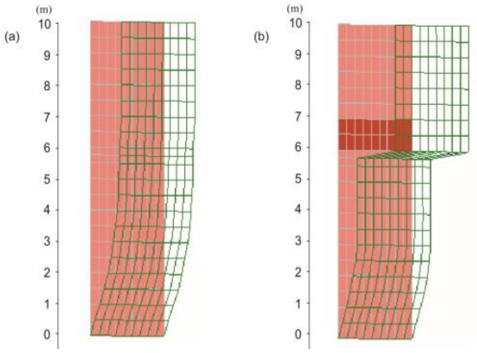
Malvick et al

Residual shear strength – Numerical & analytical models

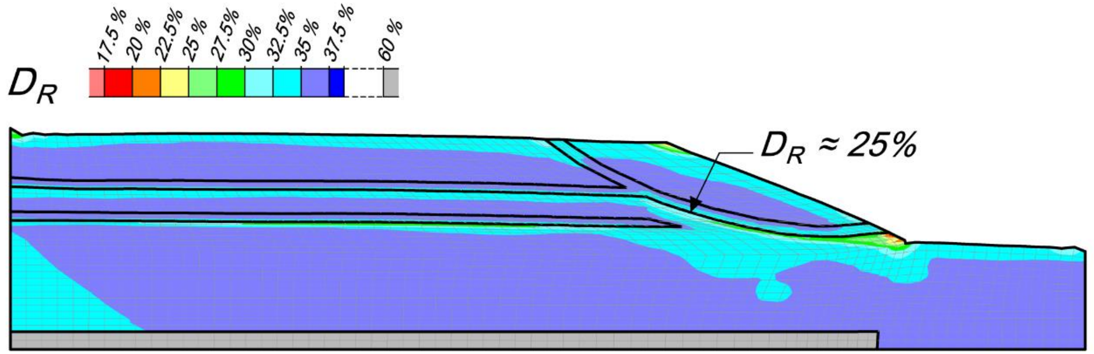
- Demonstrated role of pore pressure diffusion (void redistribution) on strength loss and deformations during and after strong shaking (for models of sufficient completeness)



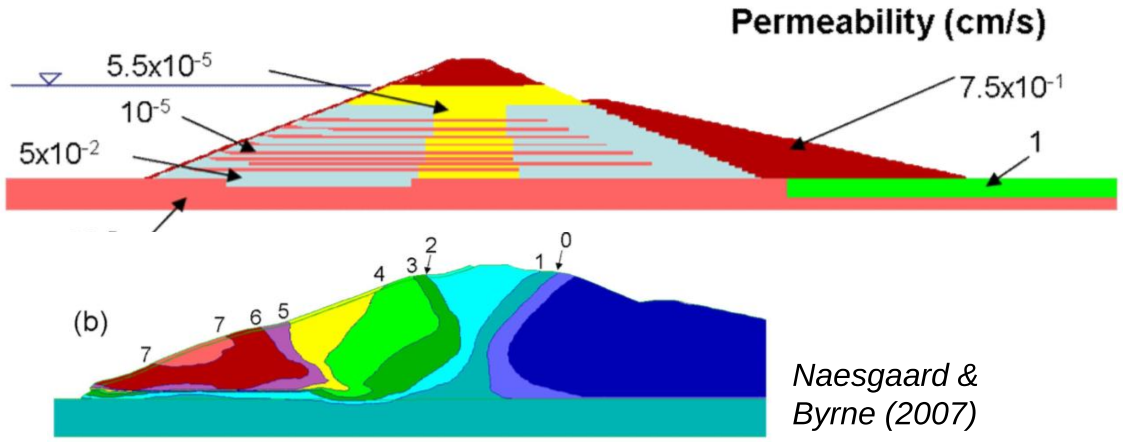
Yang & Elgamal (2002)



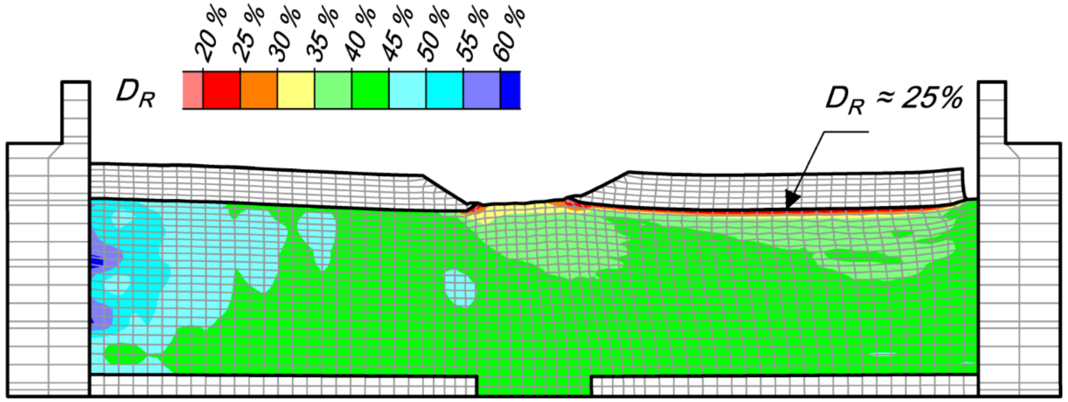
Byrne & Seid-Karbasi (2006)



Boulanger et al



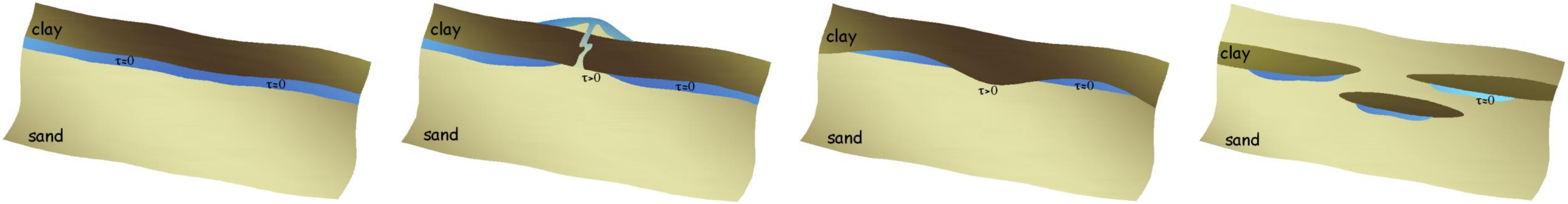
Naesgaard & Byrne (2007)



Kamai & Boulanger

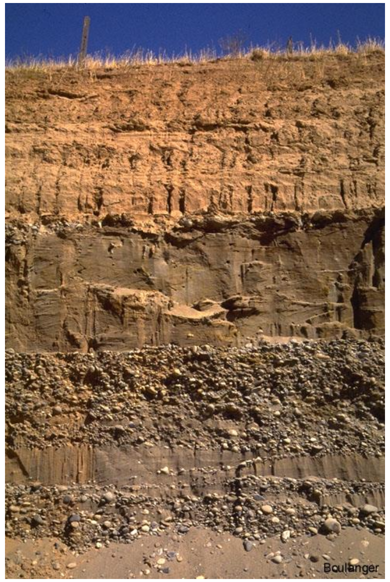
Residual shear strength – Role of stratigraphy

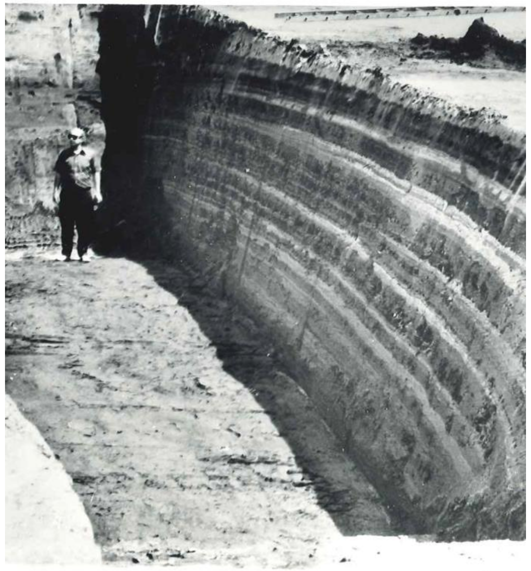
➢ *Conceptual influences of stratigraphy & cracking*



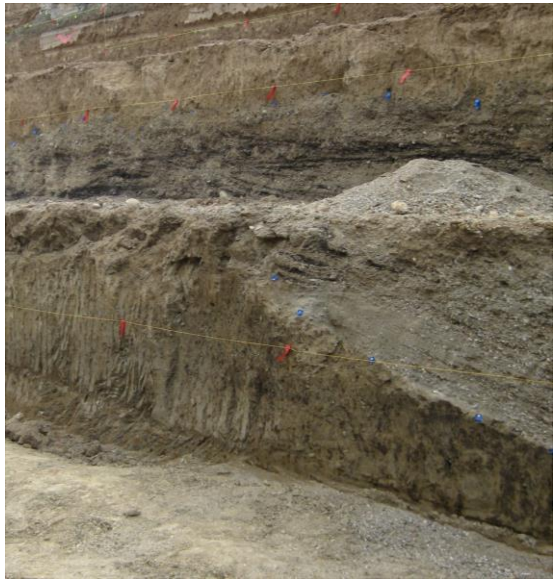
(modified after Naesgaard et al. 2006)

➢ *Natural deposits and fills*





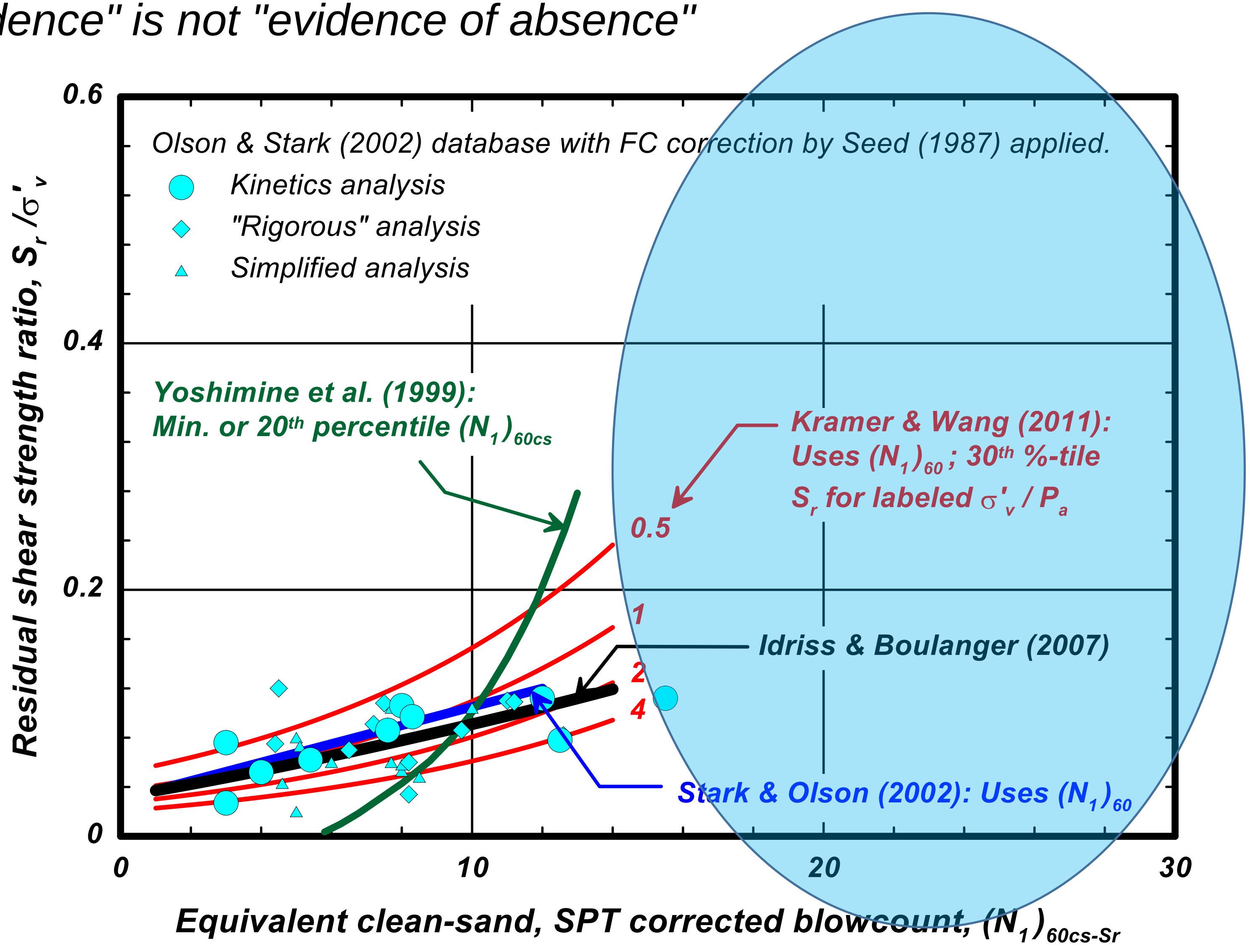
C. Davis



D. Serafini

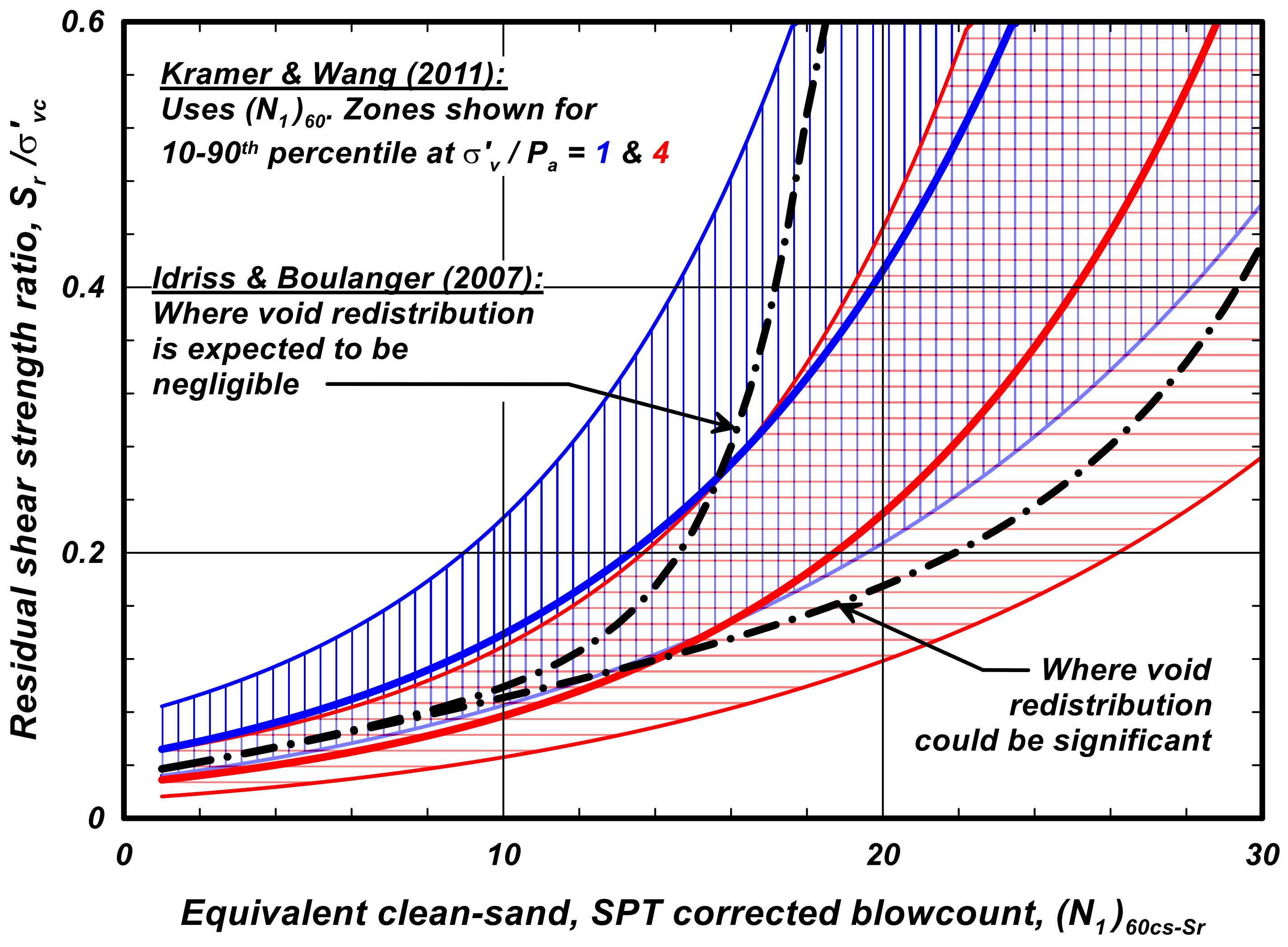
Residual shear strength – Empirical data from case histories

- "Absence of evidence" is not "evidence of absence"



Residual shear strength – Extrapolating is unavoidable

- Uncertainties are huge when extrapolating because we are unsure of the mechanisms



Residual shear strength – Addressing this persistent challenge

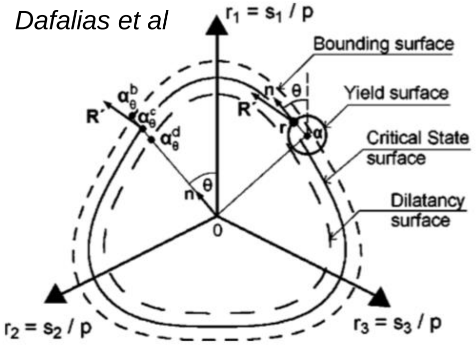
- *Physical data*
  - *Field instrumentation to identify roles of void redistribution & diffusion in future events*
  - *Large-scale physical model tests with more complex stratigraphy and dense arrays to define mechanisms at a finer scale*
- *Numerical models and analysis methods*
  - *Handle localizations more robustly*
  - *Differentiate between cases that did and did not have significant void redistribution*
- *Guidance for practice*
  - *Conditions that do and do not lead to significant void redistribution and strength loss*
  - *Representing the uncertainty in S_r for different conditions*
- *Opportunity*
  - *A coordinated team effort (possible pooling of funds) that brings together the necessary range of expertise and capabilities*

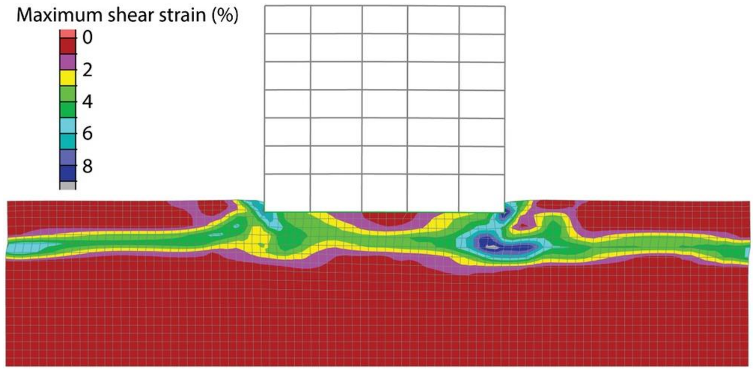
Nonlinear dynamic analyses (involving liquefaction)

Nonlinear dynamic analyses (NDAs) with liquefaction

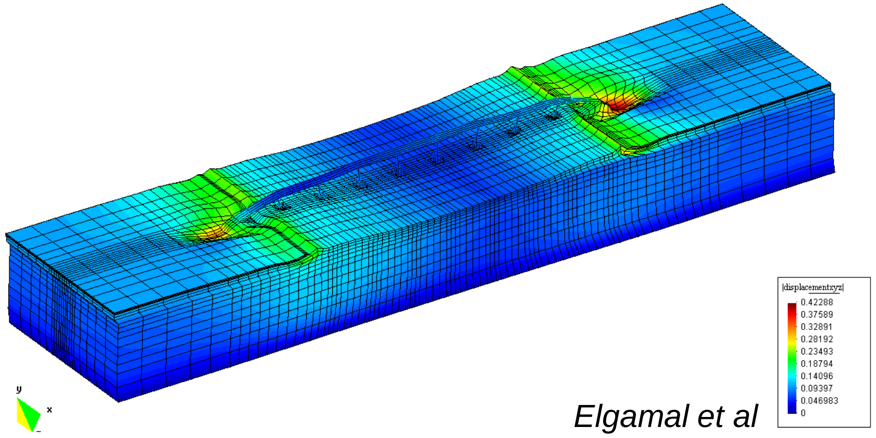
- *Where are we at?*
  - *Now widely used by geotechnical engineering firms for a range of infrastructure*
  - *Simple to complex constitutive models and numerical methods*
  - *One concern is variability across users and models*

Dafalias et al

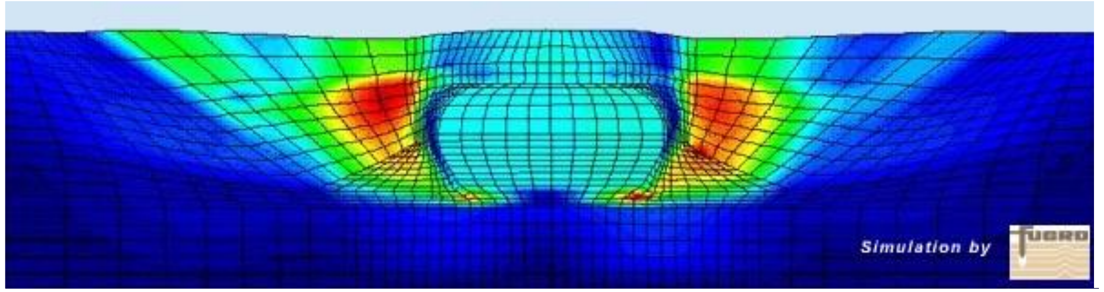




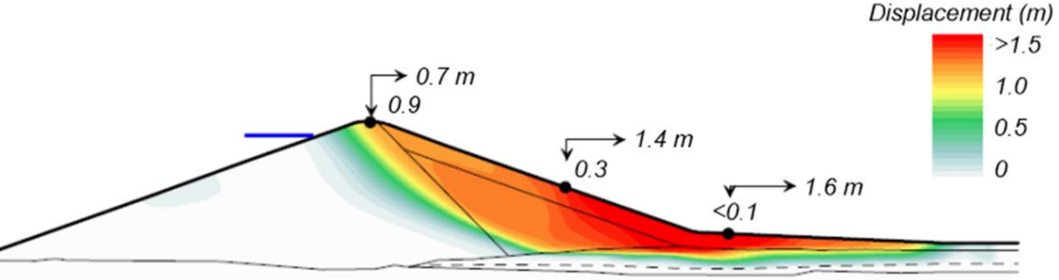
Luque & Bray



Elgamal et al

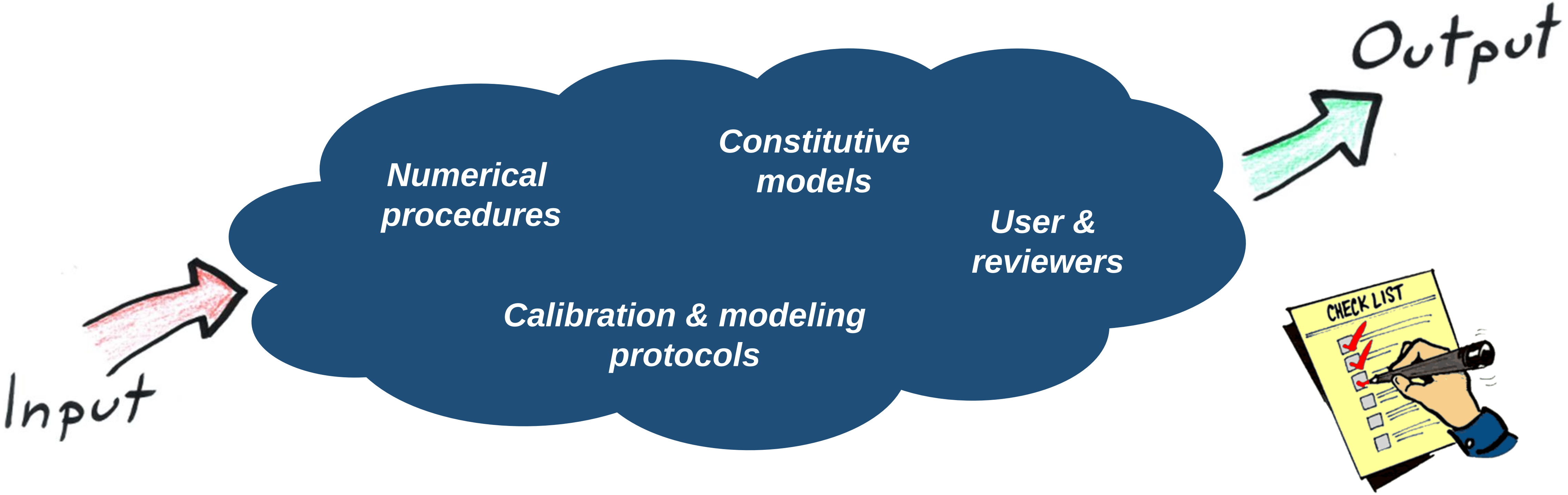


Hadidi et al



Validation of an NDA procedure

- *Validation applies not just to the tools, but also the protocols and users*
  - *Ongoing process of identifying and resolving sources of variability*
- *Need improved documentation requirements in practice*
  - *Foster improvements in the standard of practice and tools*



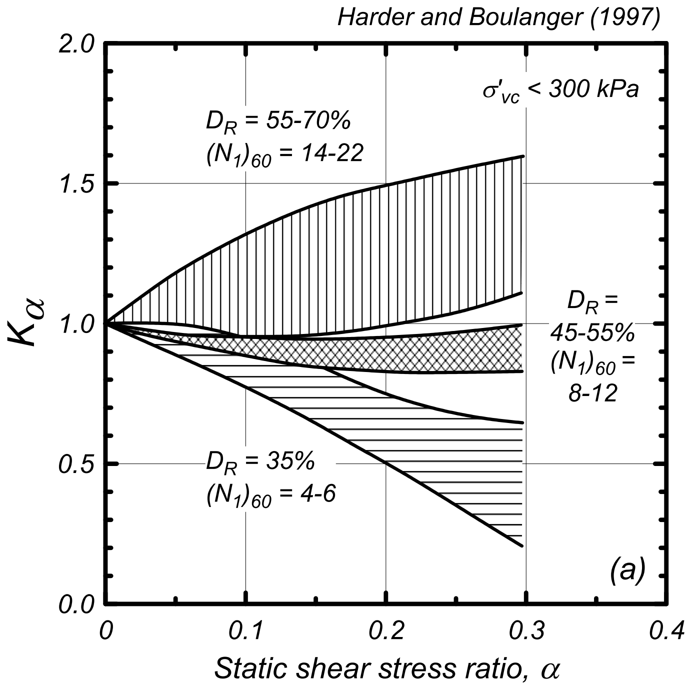
A reviewer's checklist
(Boulanger & Beaty 2016)

Example – Validation of constitutive models against empirical trends

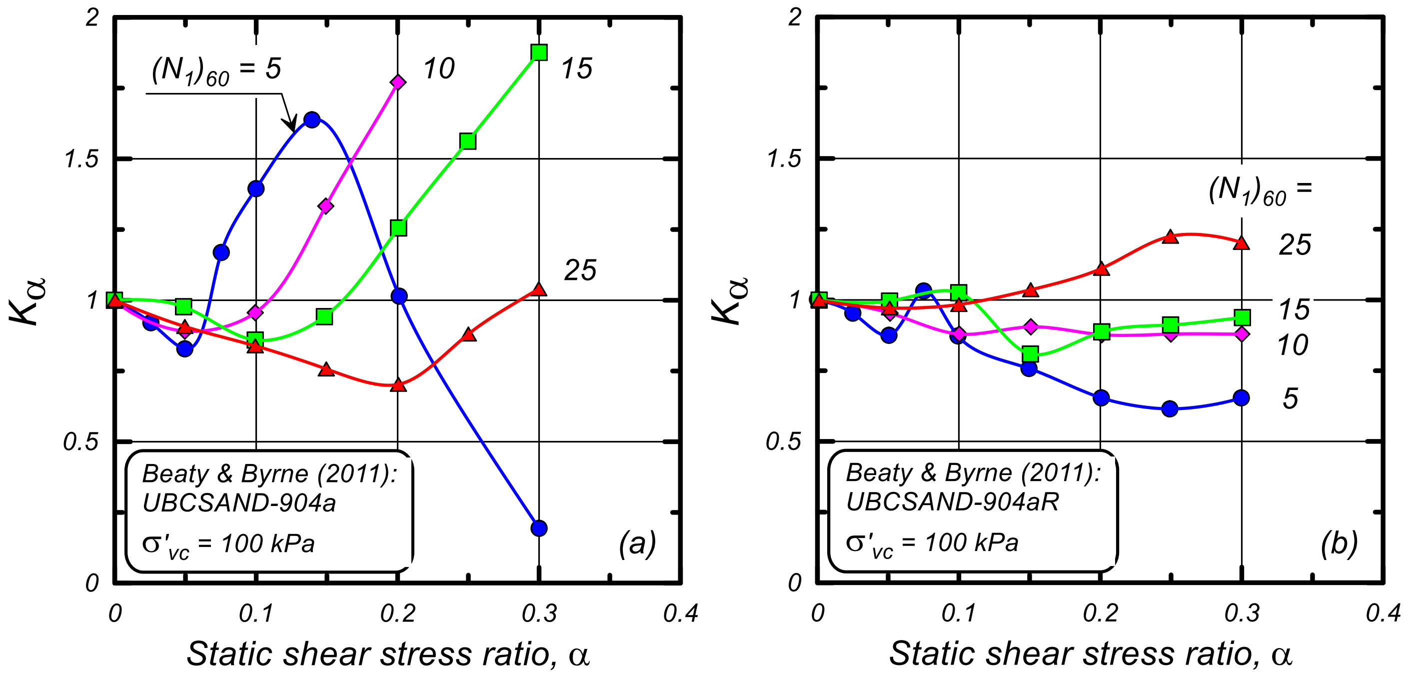
- Testing constitutive models against empirical trends has repeatedly identified significant limitations in models, leading to improvements over time
- Need to know what a model does, and does not, do well

$$K_\alpha = \frac{CRR_\alpha}{CRR_{\alpha=0}}$$

Laboratory trends



Improving a model



Nonlinear dynamic analyses – Advancing the standards of practice

- *Promote and advance best practices*
  - *Systematic validation of NDA procedures for liquefaction problems*
  - *Higher expectations for comprehensive documentation and review*
  - *Comparisons of single element simulations with empirical data for key loadings conditions*
  - *Comparisons using two or more constitutive models for evaluating modeling uncertainty and promoting improvements*
  - *Identify, resolve or understand situations leading to variability across models and users*
- *Opportunities for group efforts*
  - *LEAP research project is identifying limitations and promoting improvements in physical and numerical modeling procedures across an international community*
  - *Opportunity for a practice-oriented group effort for advancing best practices in industry*

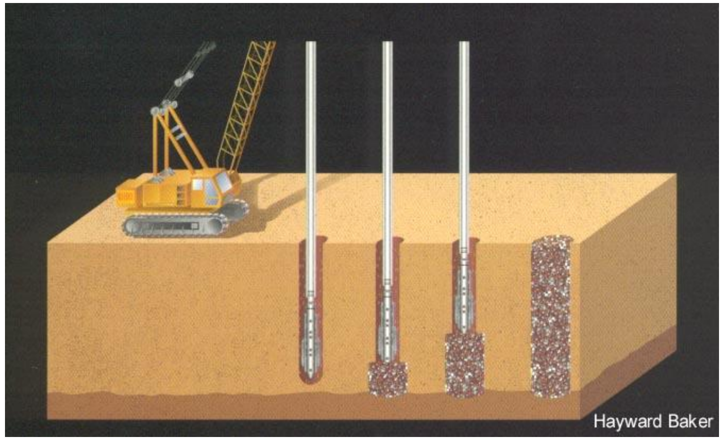
Remediation

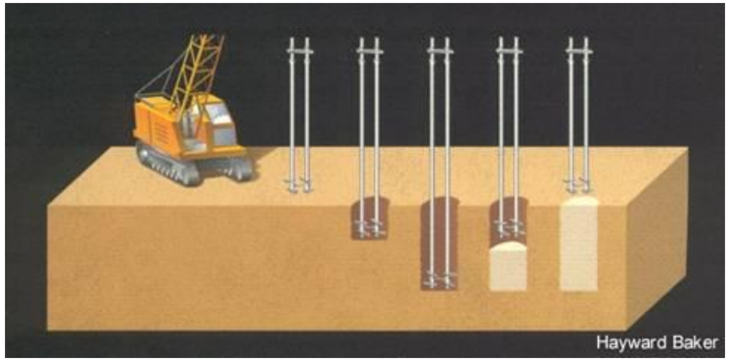
Remediation – Ever evolving tools and techniques

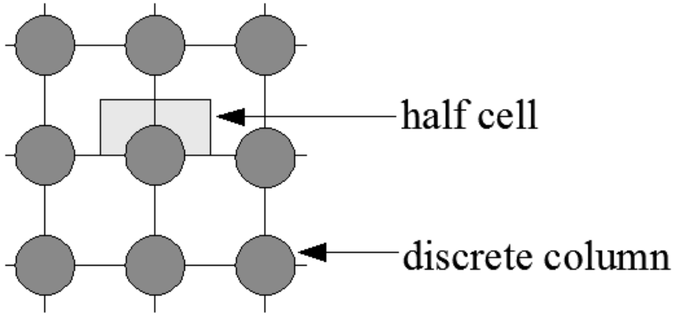
- Contractors are always innovating with new tools and techniques
- Complex mechanisms & limited seismic experiences can pose challenges for designers

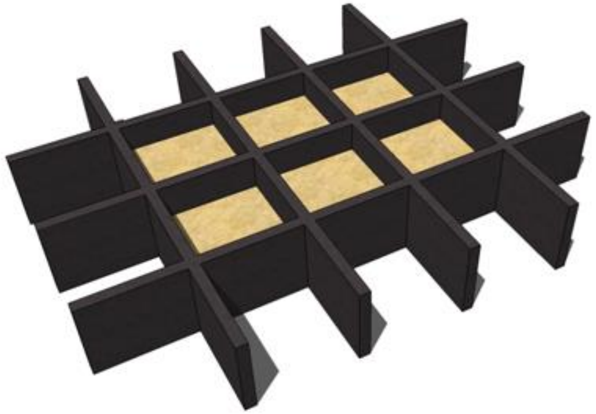
Example 1: Soil cement columns versus grids

- *Design procedures based on assumption of shear strain compatibility established in 1990s*
  - *Applied to both column and grid reinforcements*
  - *Large reductions in the cyclic shear stresses imposed on the soils*
  - *Questions raised about general applicability of this established design assumption*





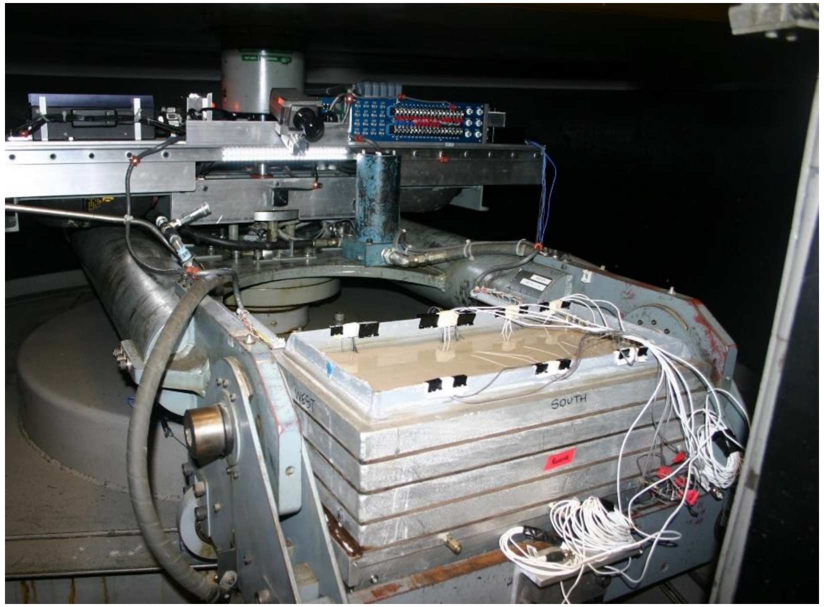


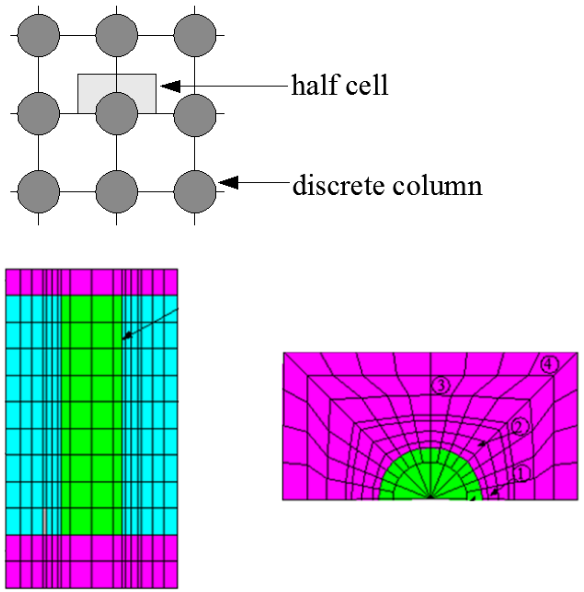


Jet grout columns (John Dillon 2009)

Soil cement columns – Role of physical modeling

- *Several numerical studies (1998-2014) had shown that column bending and rotation greatly reduces the shear stress reduction compared to that predicted by shear strain compatibility*
- *Centrifuge test results (Rayamajhi et al 2015) confirmed these numerical findings*
  - *Columns were ineffective at slowing the triggering of liquefaction, but could still help support overlying structures after liquefaction triggering*
  - *Physical data helped advance acceptance of revised design practices by different groups*

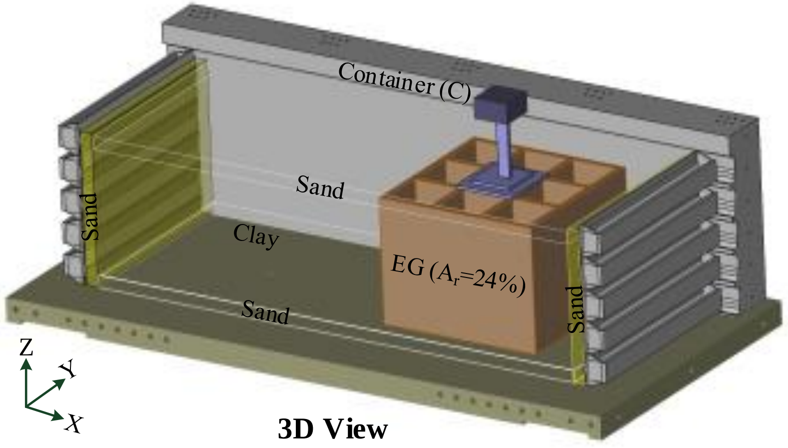


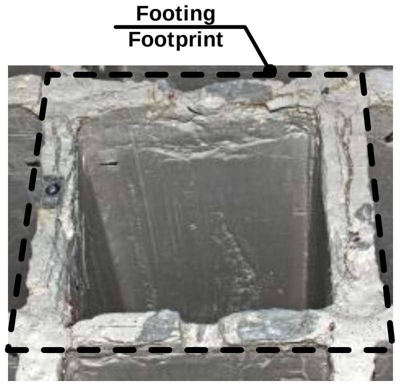


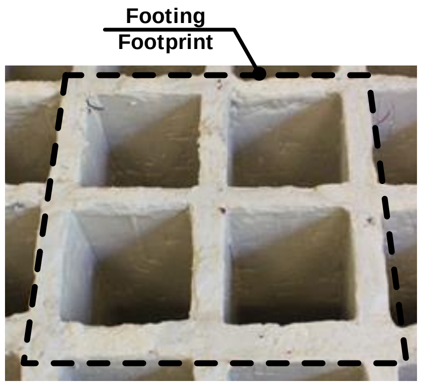
Rayamajhi et al (2014,2015) – Part of collaboration across UCD, OSU, TIT, UCSD, VPI, HBaker

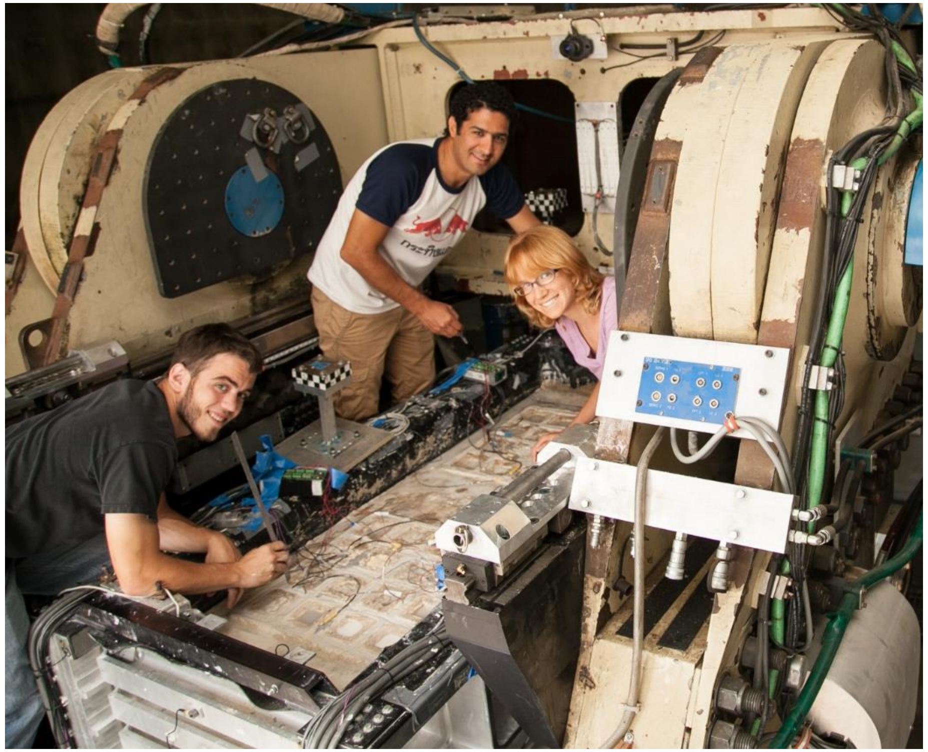
Soil cement grids – Role of physical modeling

- *Several numerical and centrifuge model studies have shown that grids (as opposed to columns) are effective at reducing ground strains and cyclic stresses on enclosed soils*
- *Large centrifuge models (Khosravi et al 2017-19) supported those conclusions, with higher resolution on details (e.g., cracking) than are possible with smaller models*

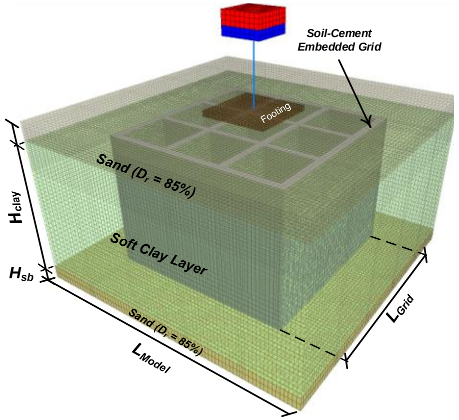


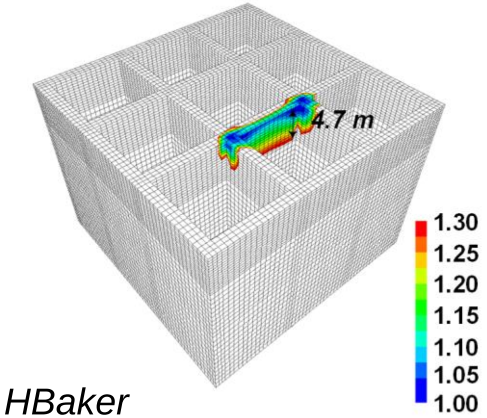






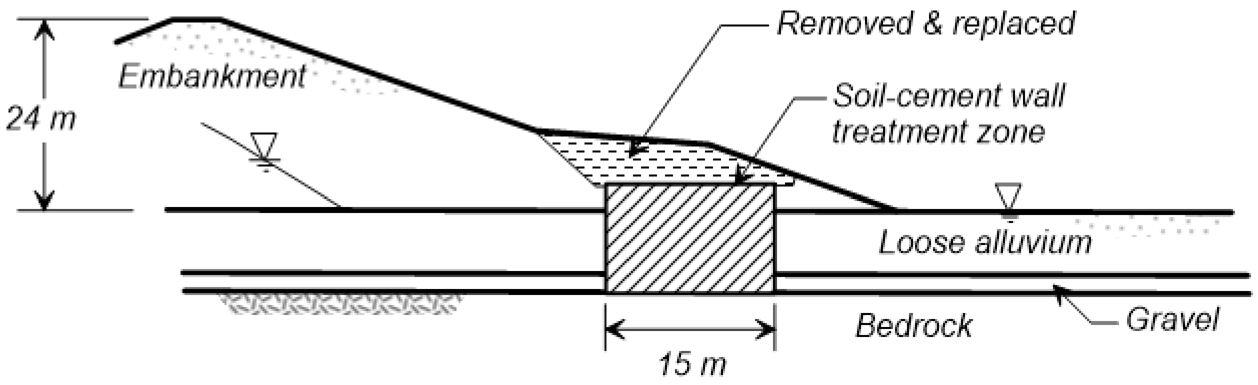
Part of collaboration across UCD, VPI, TIT, OSU, UCSD, HBaker



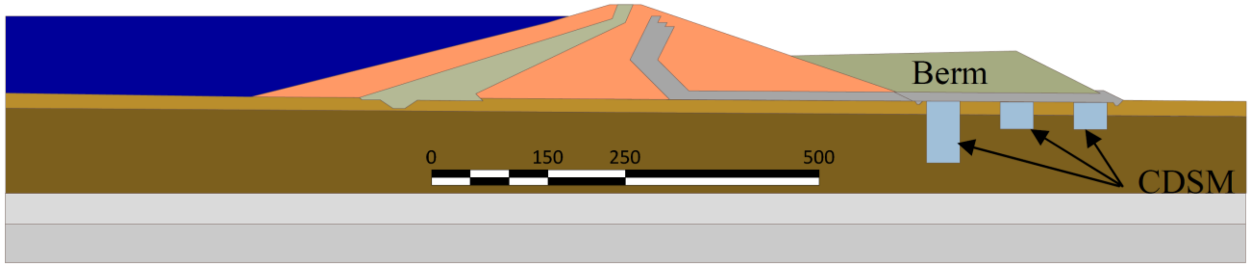


Example 2: Soil cement grids in embankment dams

- *Several US dams remediated with soil-cement walls/grids.*
  - *Common analysis approach is a 2D section with composite properties in treatment zone*
  - *Questions about how cracking affects performance and adequacy of 2D analyses*



Clemson Diversion Dam (Wooten & Foreman 2005)

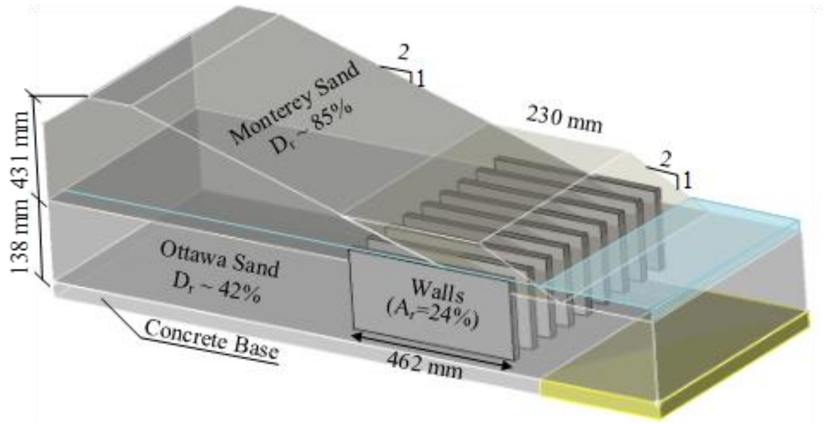


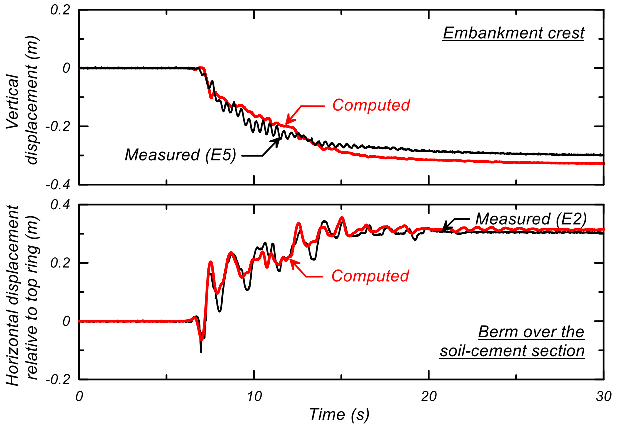
Perris Dam (Friesen & Balakrishnan 2012)

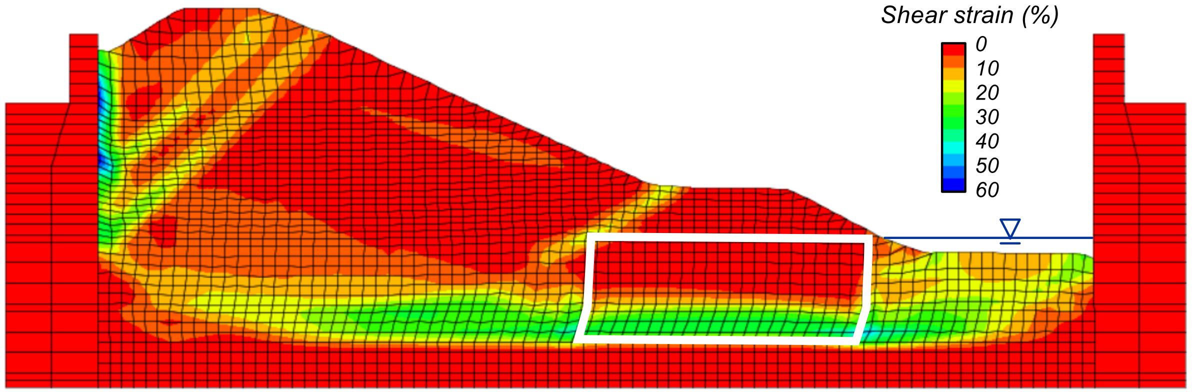
Test sections at San Pablo Dam (TNM 2007)

Example 2: Soil cement grids in embankment dams

- *Centrifuge models examined performance of soil-cement walls under shaking with limited and extensive cracking. UC Davis is a shared-use NHERI facility – all data at DesignSafe!*
- *2D NDAs were in reasonable agreement with the responses recorded in the centrifuge model, despite not accounting for a number of complex mechanisms evident in the test data*

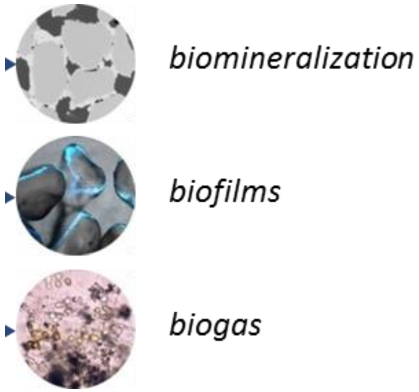


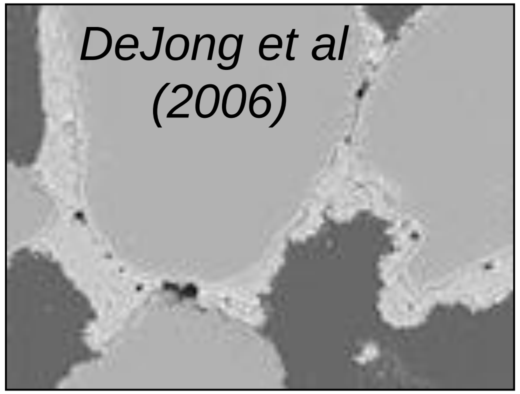


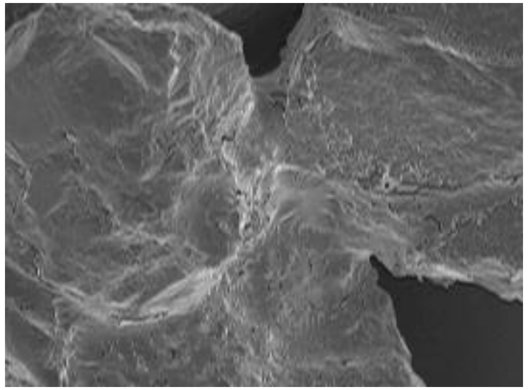


Example 3: Bio-mediated processes

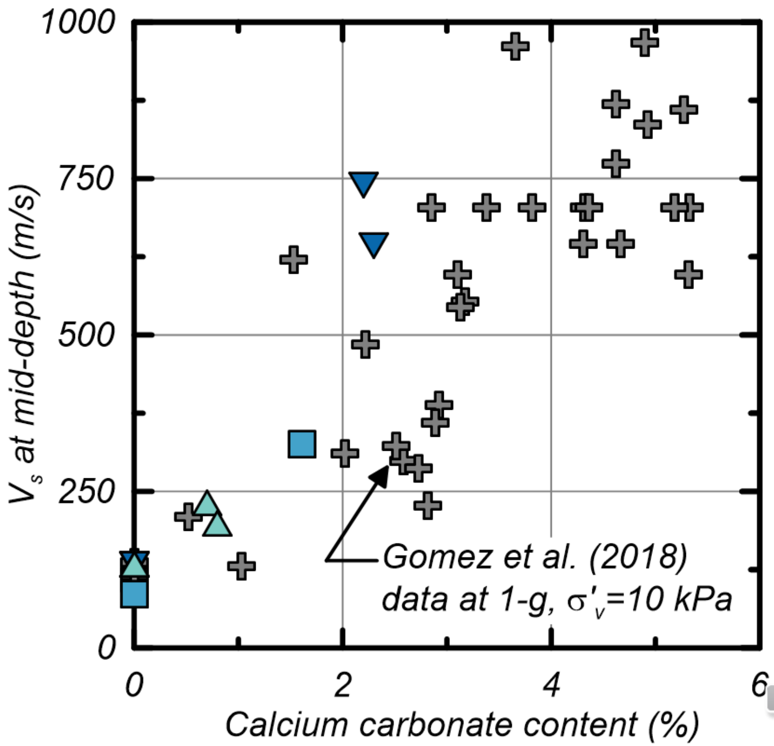
- Center for Bio-inspired and Bio-mediated Geotechnics (CBBG) advancing a number of alternative mitigation process (e.g., biocementation, biofilms, biogas)
- Example: Biocementation techniques (MICP, EICP, MIDCP) getting ever more effective and efficient with advances in the science and deployment procedures at different scales







MICP of Ottawa sand
(Darby et al 2019)



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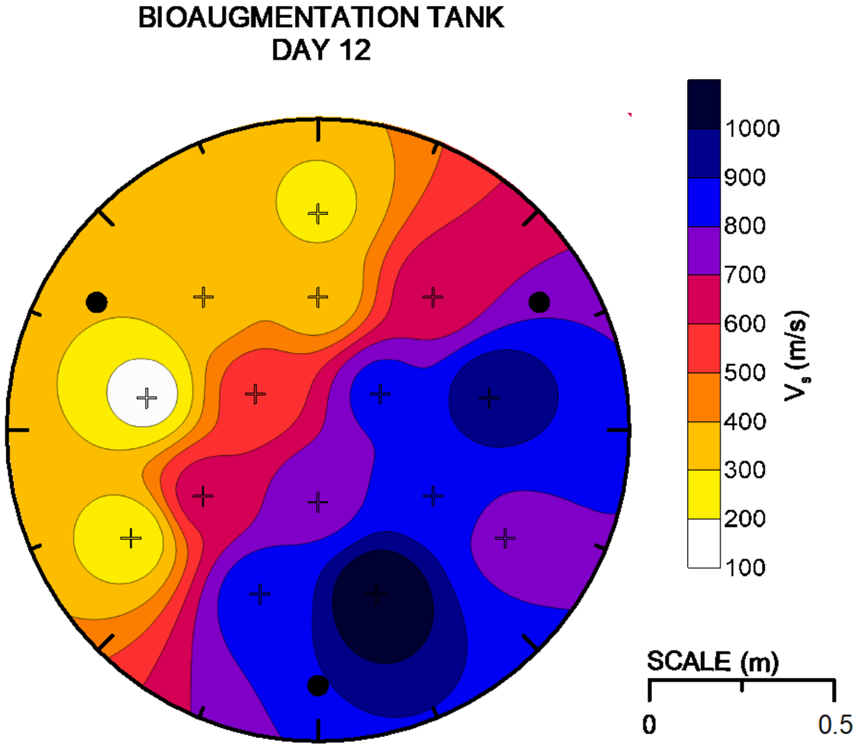
Gomez et al 2015



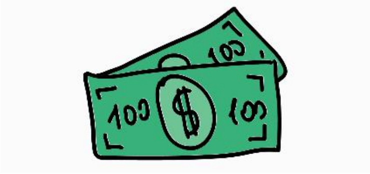
Remediation – Further evolution of tools and procedures

- *Remediation tools and techniques are always evolving*
  - *Complex mechanisms pose challenges for refined designs*
  - *Opportunity for improved economy if we can more confidently design these systems, particularly to reduce deformations rather than preclude them*
- *Advancing remediation tools and design procedures*
  - *Numerical modeling of these complex mechanisms*
  - *Large scale physical modeling (NHERI) to quantify mechanisms and validate numerical modeling procedures*
  - *Many remediation problems are well suited to coordinated team efforts (or a pooling of funds) that bring together the necessary range of expertise and capabilities*
  - *Rapid advancement of bio-mediated techniques are an example of the value of center-based group efforts (CBBG ERC).*

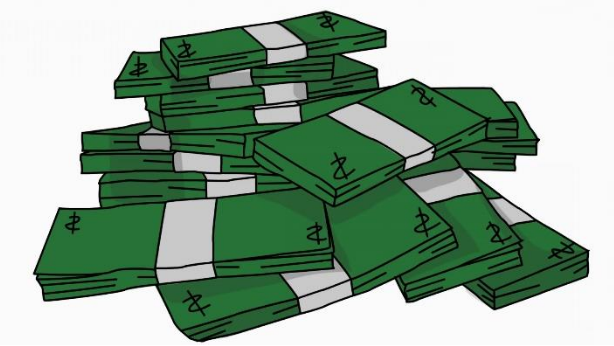
Risk management approaches

Risk management and performance-based engineering for liquefaction

- *Hierarchy of tools*
  - *Experiences and frameworks: nuclear facilities, dams, PEER, ports, construction, others*
  - *Tiers of rigor: from qualitative to SHAC-levels 3 & 4*
  - *Tiers of effort: weeks to years*
- *Attributes that appear to influence adoption rates across different industries*
  - *Stakeholder arrangements and their perceptions of risk*
  - *Transition from standards-based to risk-based thinking*
  - *Uniqueness of each geotechnical, soil-structure, or lifeline system requires development of project-specific system response curves*
  - *Secondary modes of damage can be system-specific and complicate event trees*
  - *Simpler systems may have clearer decisions, no obvious life safety issues, or less economic advantage to performing a risk evaluation*

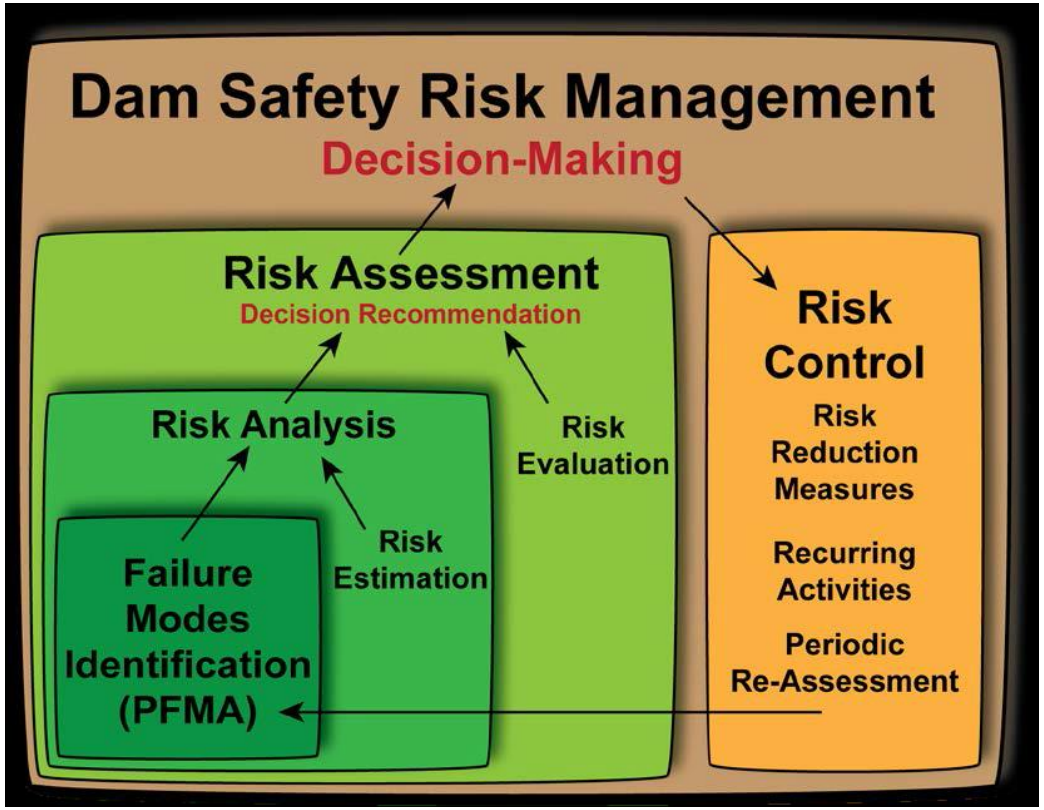






Example: Seismic risk management for dams

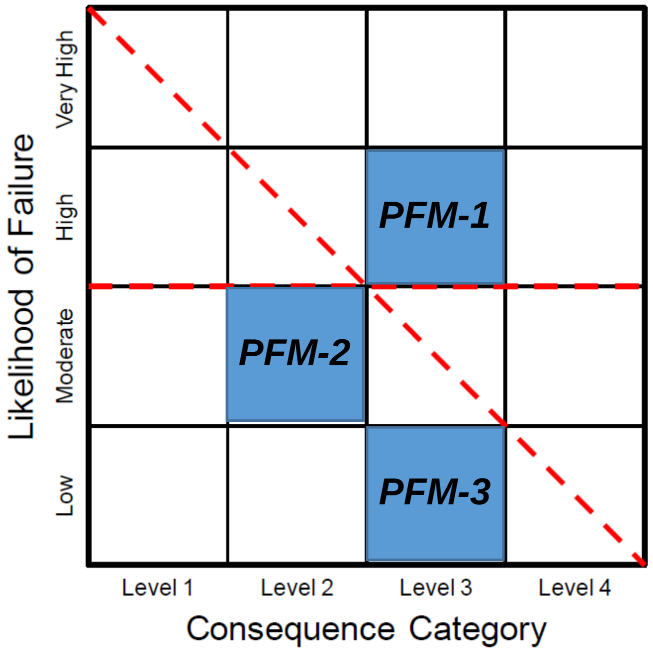
- *USBR/USACE risk management guidelines (e.g., 1997 - 2015) have evolved with experience*
  - *Risk used at facility and portfolio levels*
  - *Include qualitative, semi-quantitative, and quantitative analyses*
  - *Probabilistic procedures reflect pragmatic choices for applications to dams*

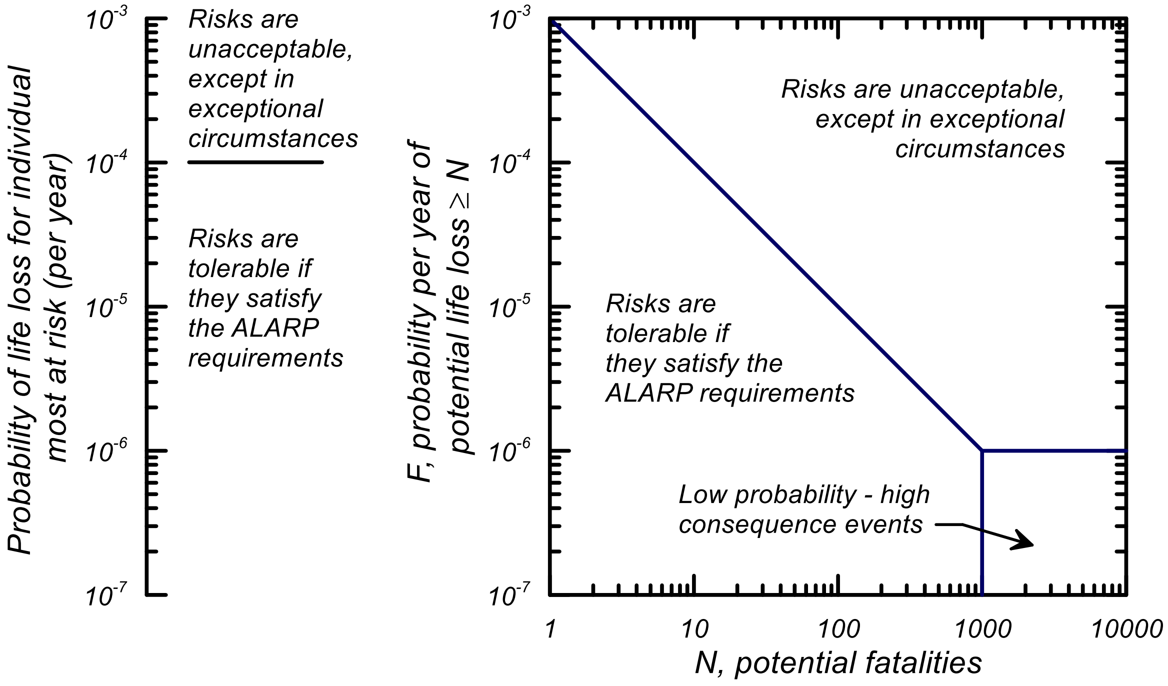


Reclamation-USACE (2015)
/www.usbr.gov/ssle/damsafety/risk/methodology.html

Example: Seismic risk management for dams - Effort

- *Typical applications per informal survey of a few dam colleagues (NS, DG, JH, …)*
  - *Every dam has unique system response curves, interdependent failure modes, etc.*
  - *Qualitative or semi-quantitative: Team of several people for 1-2 weeks; maybe $25-50k*
  - *Quantitative: Larger team for months to years; maybe $100-250k extra costs*
  - *Costs go up steeply if results trigger need for additional explorations, updated PSHA, etc.*



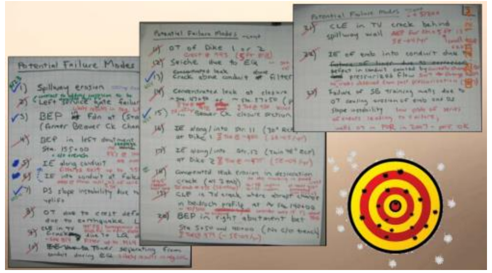
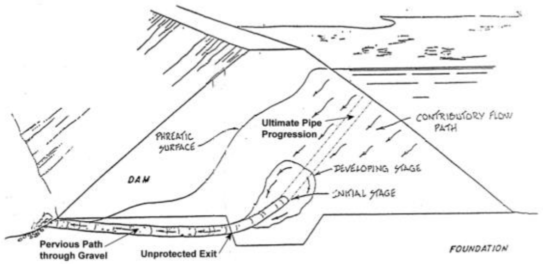


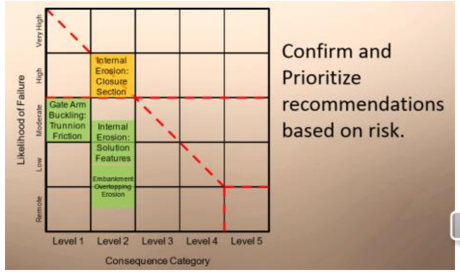
Figures after Reclamation-USACE (2015)

Example: Seismic risk management for dams - PFMA

- *First step is a "potential failure modes analysis" or PFMA*
  - *Facilitated meeting of people with required expertise/knowledge: geologic, geotechnical, hydrologic, structural, operations, inspections, …*
  - *Identify potential failure modes: initiator, progression, impacts*
  - *Adverse and favorable factors*
  - *Consequence review*
  - *Value of additional information or interim risk reduction measures*
- *New adopters generally see strong benefits from a PFMA at reasonable cost*
  - *Enhanced communication across groups and disciplines*
  - *Identification and focus on key risk drivers*
  - *Improvements in monitoring and characterization efforts*
  - *Identification of efficient risk reduction measures or emergency action plan improvements*

"Best practices" Reclamation-USACE (2015)

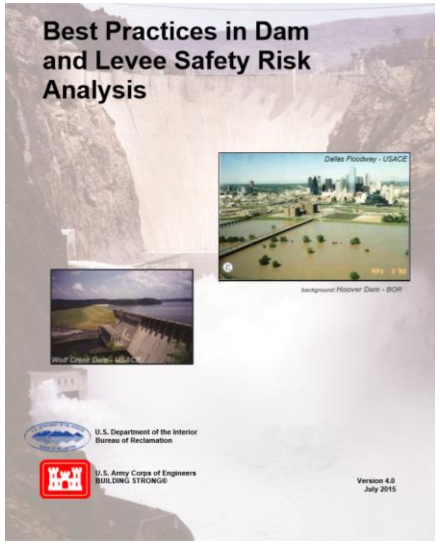



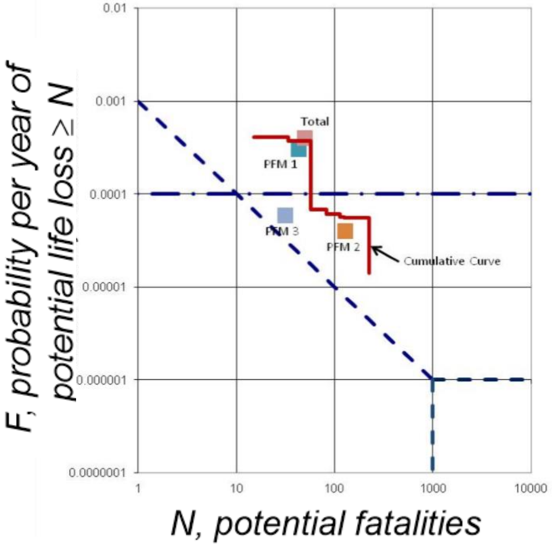



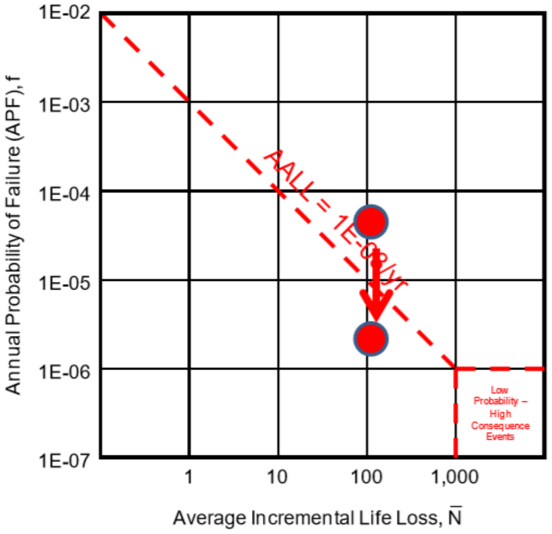
Example: Seismic risk management for dams – Analyses & ALARP

- *Risk analysis (qualitative or quantitative)*
  - *Ranking of different failure modes (including different hazards/loadings)*
  - *Evaluating mitigation alternatives at the system level*
  - *Prioritizing work efforts at system and portfolio level (i.e., different facilities)*
- *As low as reasonably practicable (ALARP)*
  - *Identify actions that could reduce risks for reasonable cost and effort*
  - *Judgment based on risk levels, cost effectiveness, good practices, societal concerns, …*
- *Sometimes the process is more important than the product*

"Best practices" Reclamation-USACE (2015)

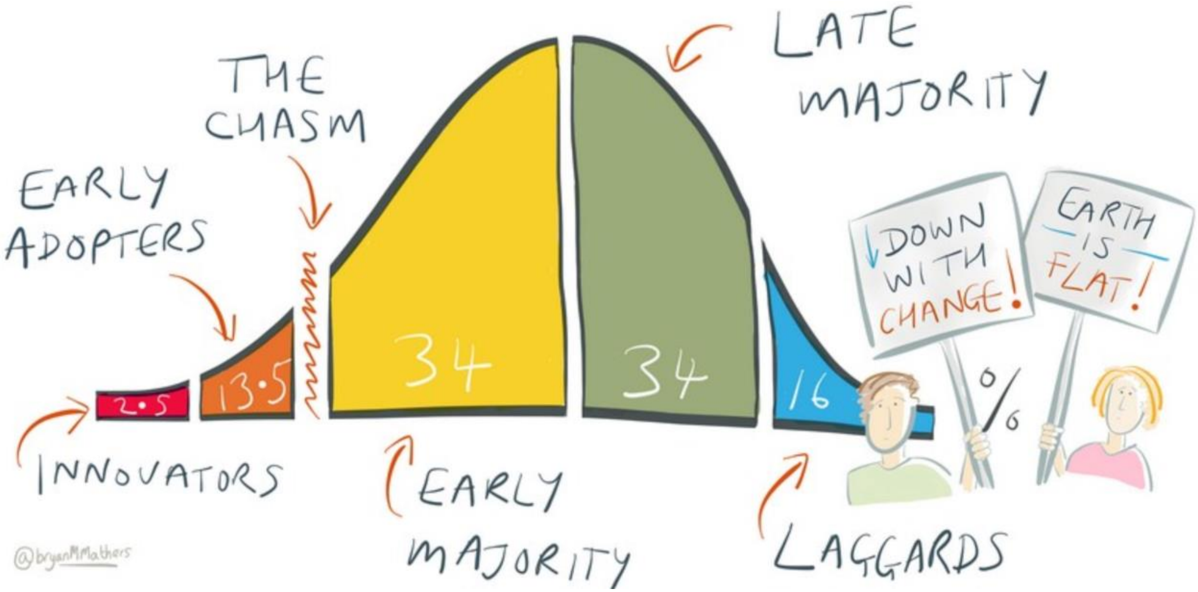


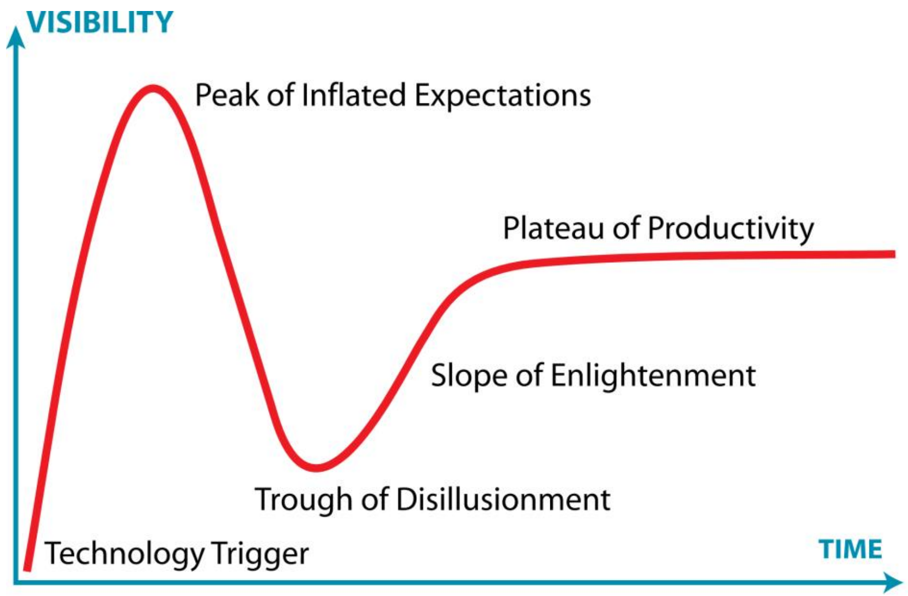




Broadening use of risk management

- *Broadening use of risk management (with or without liquefaction hazards)*
  - *Need qualitative or qualitative procedures that are tailored to different types of infrastructure via appropriate pragmatic simplifications*
  - *"Best practice" guidelines and tool boxes that reduce costs and training barriers*
  - *Need informed clients and pioneering projects that demonstrate improved decision making*





Risk management – Pervasive liquefaction hazards

- *Special case of pervasive liquefaction hazards*
  - *Widespread damages mean risk for everyone is greater than the cumulative risk for individual sites*
  - *Policies should consider community risks and promote risk reduction efforts/changes, considering potential impacts of rare, high consequence events*

Christchurch (courtesy T. O'Rourke)

Urayasu (Google maps)

Risk management – Pervasive liquefaction hazards

- *Functional recovery: A conceptual framework (EERI white paper, 2019)*
  - *Safety & recovery should be equally important measures for design codes & guidelines*
  - *Communities should be explicit about expected time to recover functionality*
  - *Must consider interdependencies between buildings and lifeline infrastructure systems*
- *Humility in resilience engineering (Berne 2019)*
  - *Acknowledge possibility of unforeseen consequences & need for plural viewpoints*
  - *Consider social inequality in the distribution of risks and benefits*

Christchurch (courtesy T. O'Rourke)

Urayasu (Google maps)

Concluding remarks

Liquefaction: Lessons, challenges and opportunities

- *Half century of research*
  - *Tremendous advances in the science, practices and policies related to liquefaction*
- *Future directions*
  - *Need to address knowledge gaps and practice limitations that hinder our effectiveness and progress in certain situations*
  - *Presented several lessons, challenges, or opportunities toward that goal*
- *Achieving progress*
  - *Bigger challenges call for coordinated team efforts (e.g., as facilitated by PEER, CBBG,…)*
  - *Large-scale experimental facilities have a strong role to play (e.g., NHERI)*
  - *New technologies & capabilities (discrete elements, sensing, AI, bio-geotechnics,…)*
  - *Community based strengthening of our standards of practice*
  - *Sustained risk reduction efforts and policies that promote them*
- *Exciting opportunities for another generation*

Acknowledgments

- *Influence of numerous friends and colleagues*
  - *UC Davis colleagues (IMI, JTD, BLK, DWW, KZ, AM) and friends (JDB)*
  - *NHERI/NEES, CBBG, PEER*
  - *International community (e.g., US-NZ-Japan workshop 2017)*
  - *Colleagues and clients on various projects*
  - *Many others*
- *EERI for this opportunity*