US-NZ-Japan International Workshop
Berkeley, CA – November 2-4, 2016

Liquefaction-induced flow slides governed by residual shear strength of liquefied soil

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Primary mechanisms involved in strength loss?

- *Physical models show void redistribution effects*

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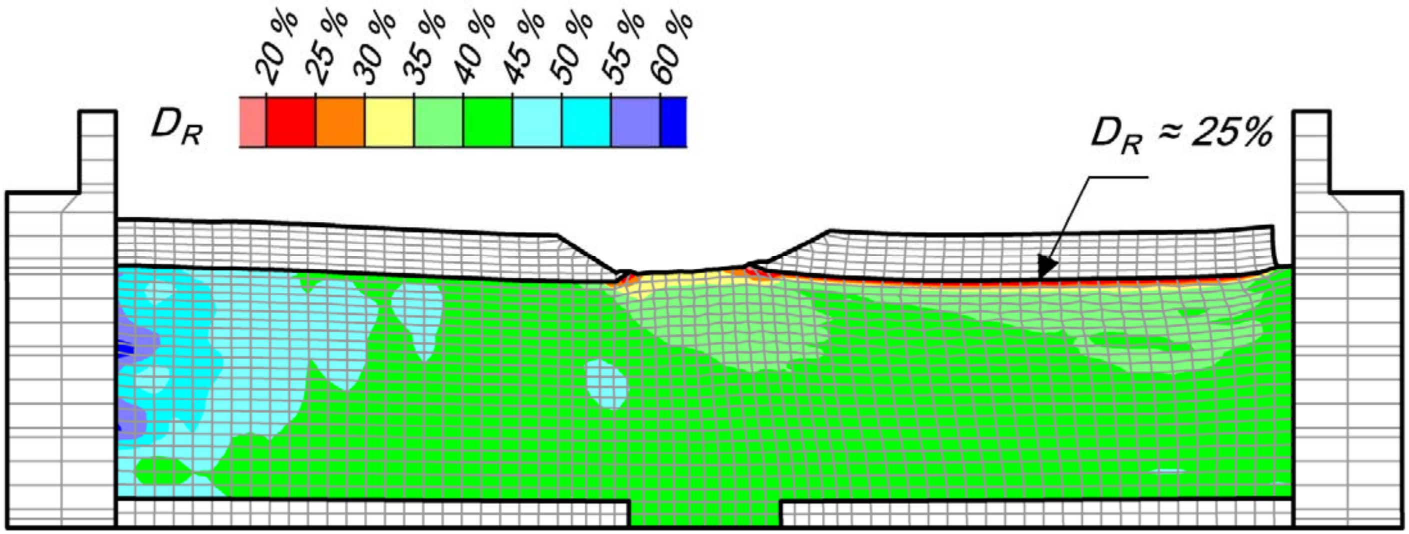
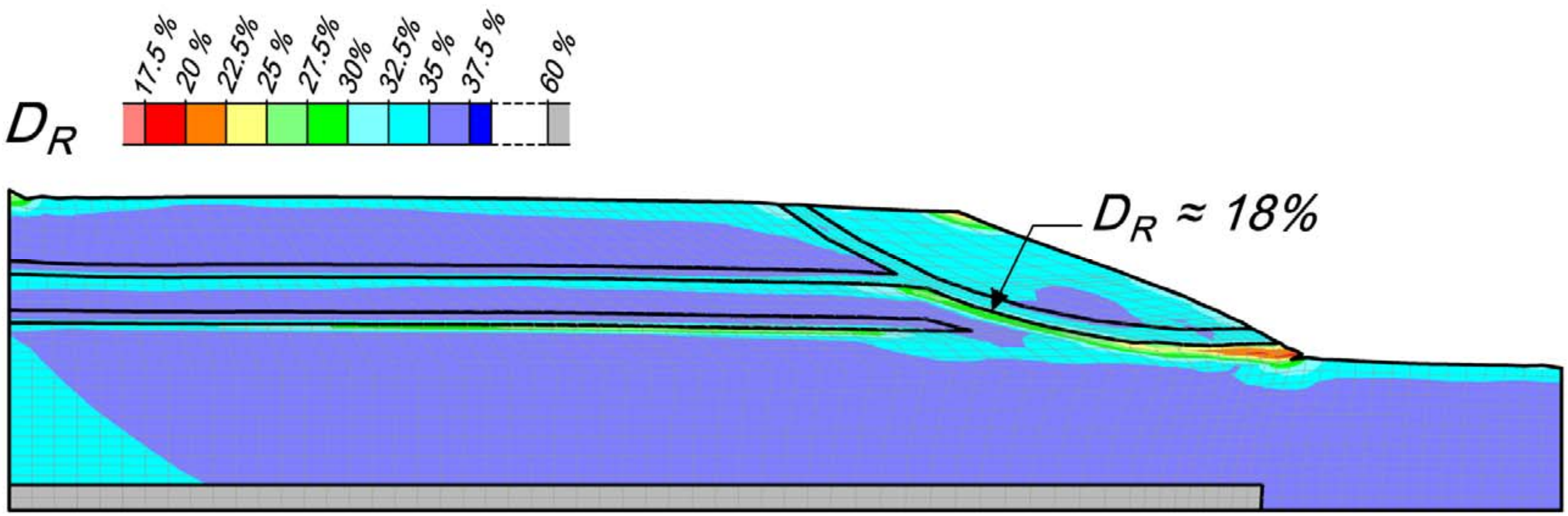
- *Numerical analyses show void redistribution effects*



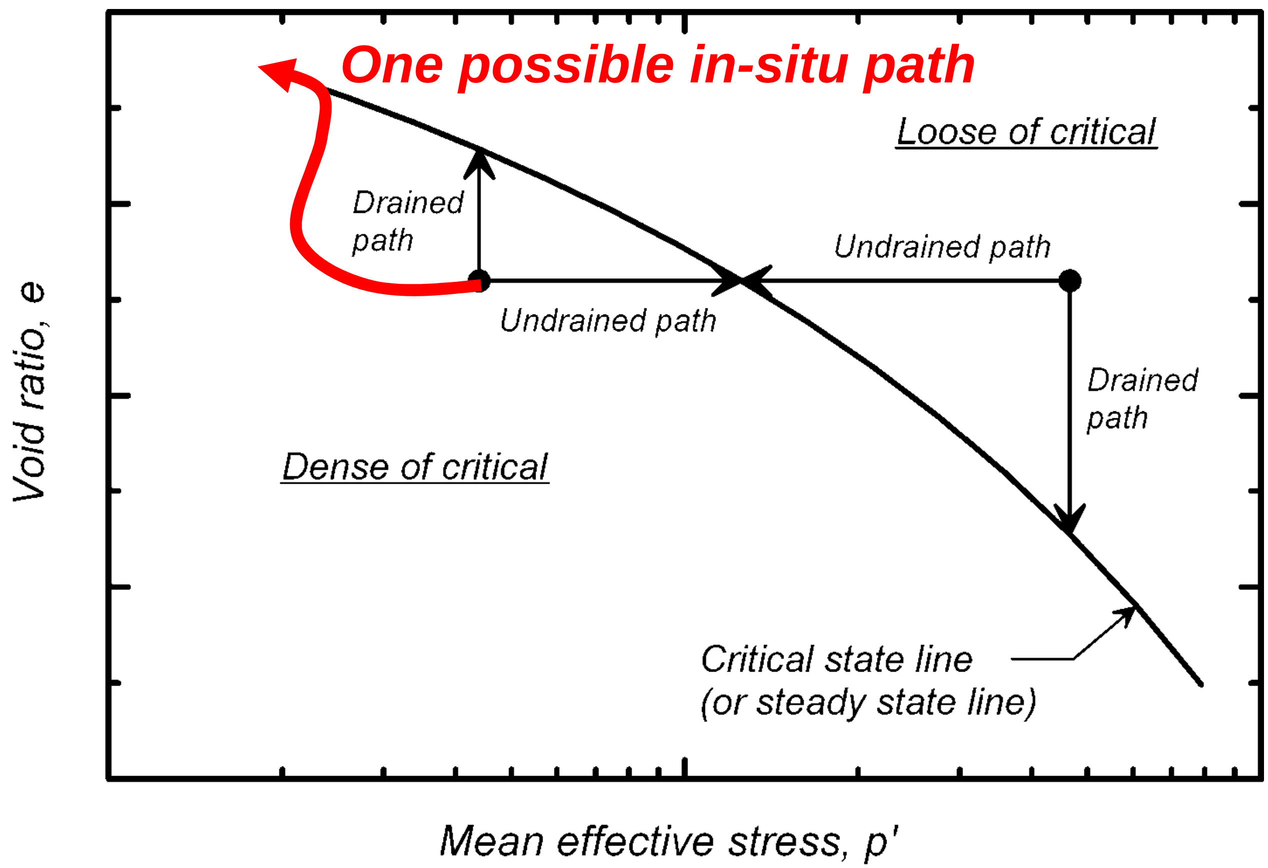


Primary mechanisms involved in strength loss?

- *Undrained response of cohesionless soils is reasonably understood*
  - *Critical state frameworks work*
  - *Dependence of stress-strain responses on consolidation stress & test type*
- *Void redistribution & diffusion effects are a key issue*
  - *Physical models show the mechanism, but most dramatic results have been limited to tests with adverse conditions*
  - *Numerical models show the mechanism, but there are challenges with mesh effects & localization scales*
  - *Field evidence is mixed*
    - *Effects on lateral spreading displacements or residual strengths are not clear in the case history databases*
    - *Possible cause of the post-shaking movements observed in various case histories*
  - *If void redistribution occurs, the field residual strength (S_r) is a system response rather than a soil property*

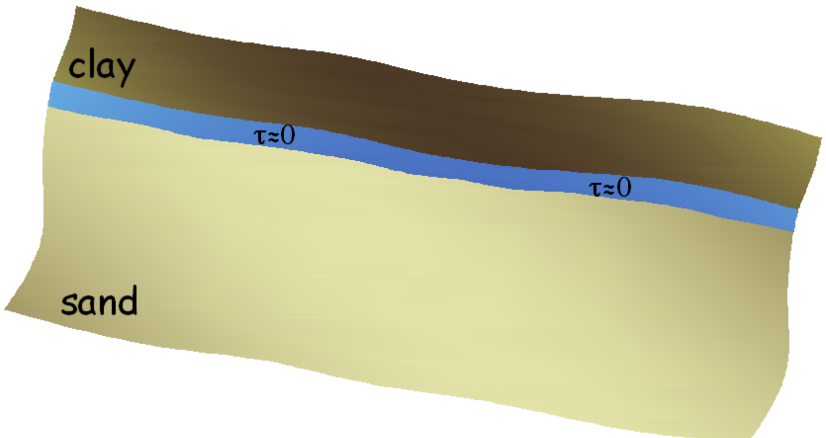
Primary mechanisms involved in strength loss?

- *Loading path not necessarily bounded by drained & undrained cases*

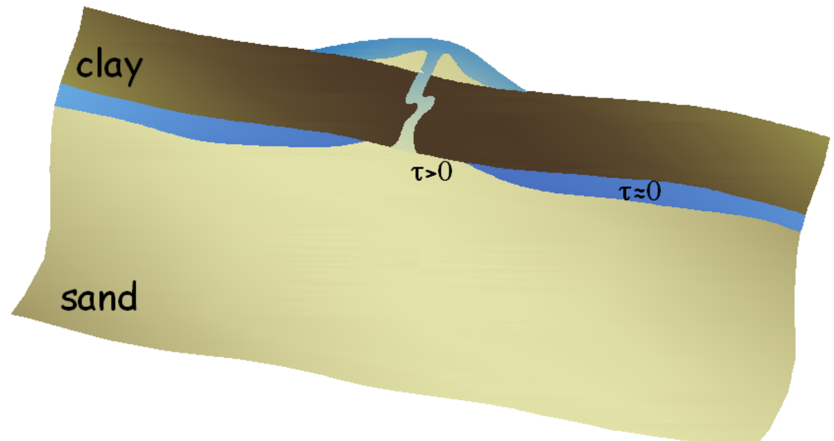


Key underlying geologic/placement processes?

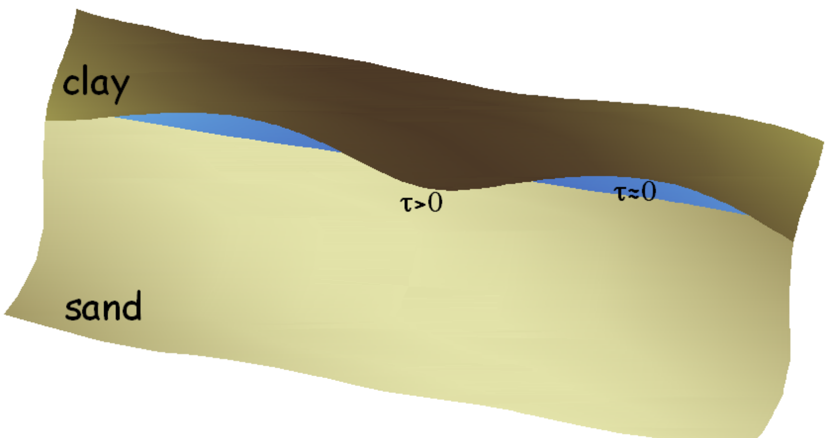
(modified after Naesgaard et al. 2006)



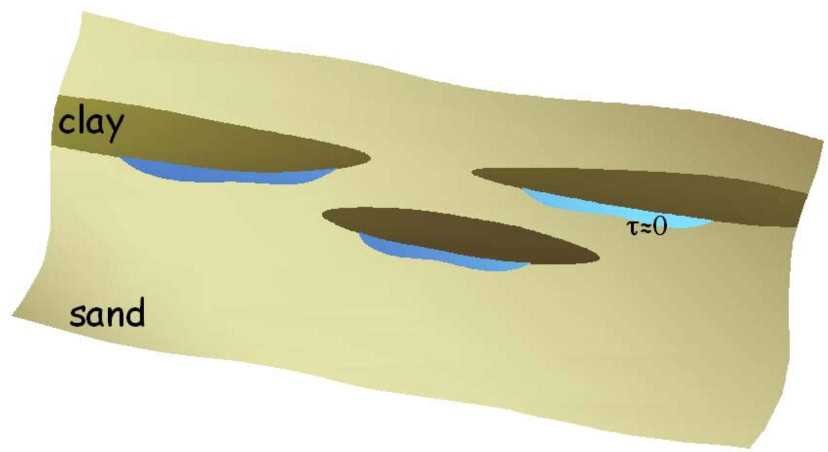
a) Continuous water film



b) Venting + collapse of water film



c) Undulating surface



d) Spatial discontinuity of barriers

Key underlying geologic/placement processes?

- *Sequence and characteristics of substrata / units*
- *Spreads versus slopes*
  - *Cracks & venting may form easily in lateral spreads*
  - *Cracks may not form easily at the larger depths under an embankment dam*

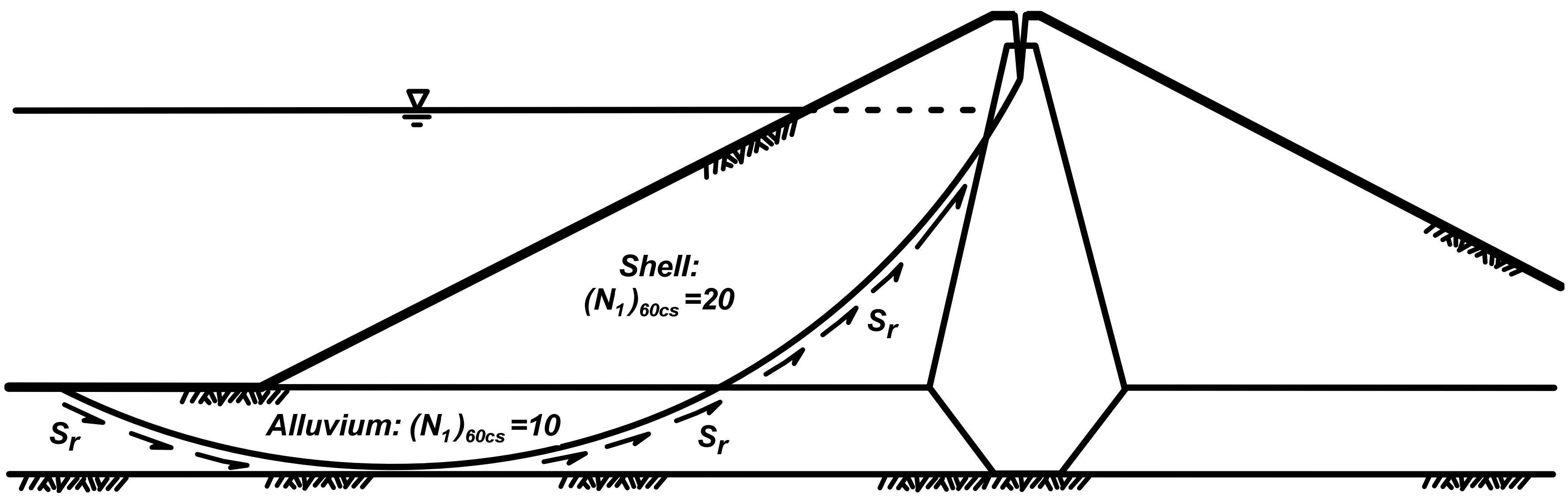
Dam shell (D. Serafini)

Fluvial deposit (R. Boulanger)

Hydraulic fill - USF (C. Davis, LADWP)

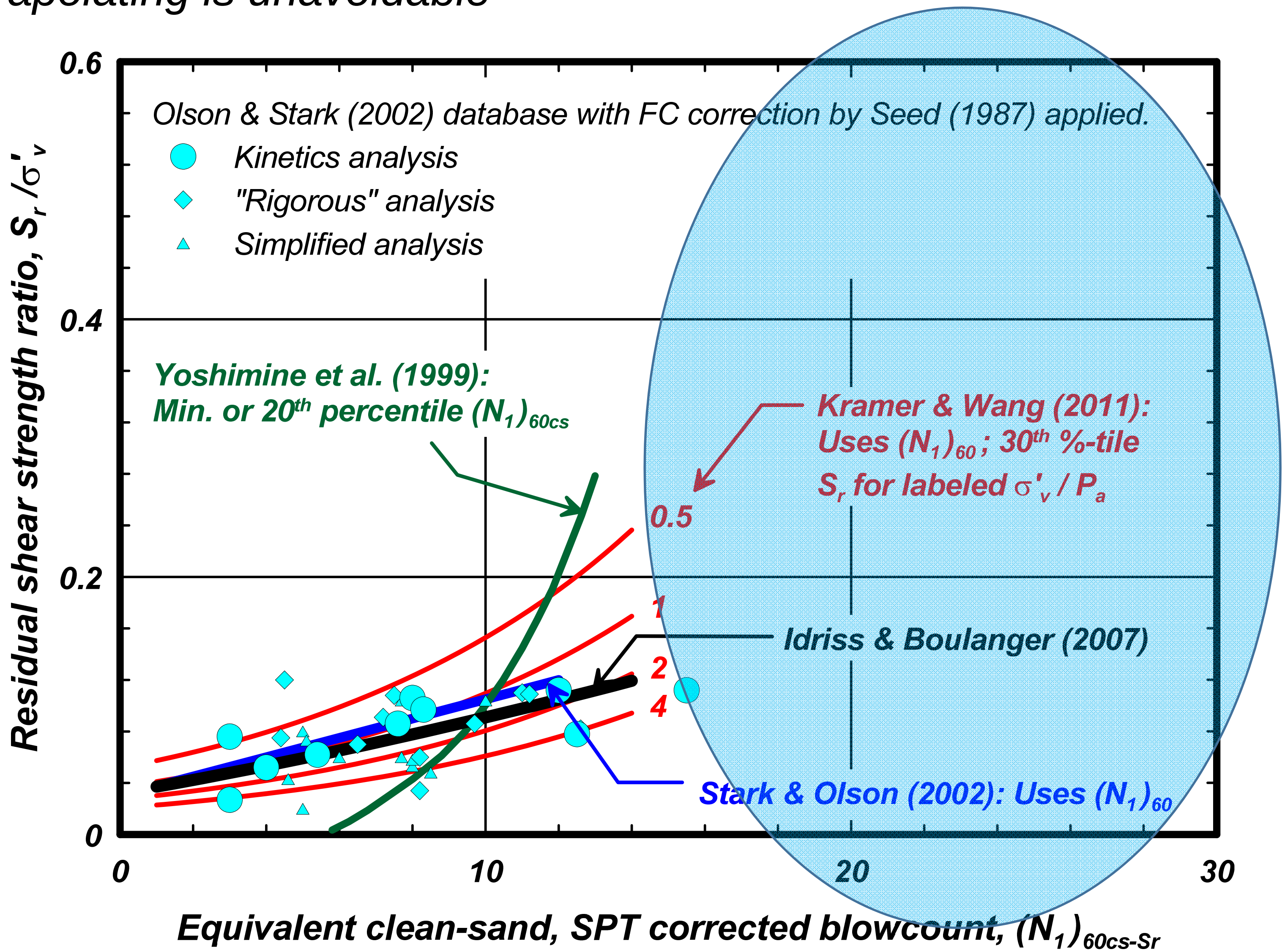
Current state-of-the-art?

- *What "residual" strengths do you use in a post-earthquake stability analysis?*
    - *If limiting r_u values are triggered in a slope, do you allow for any possible strength loss relative to the original drained conditions?*



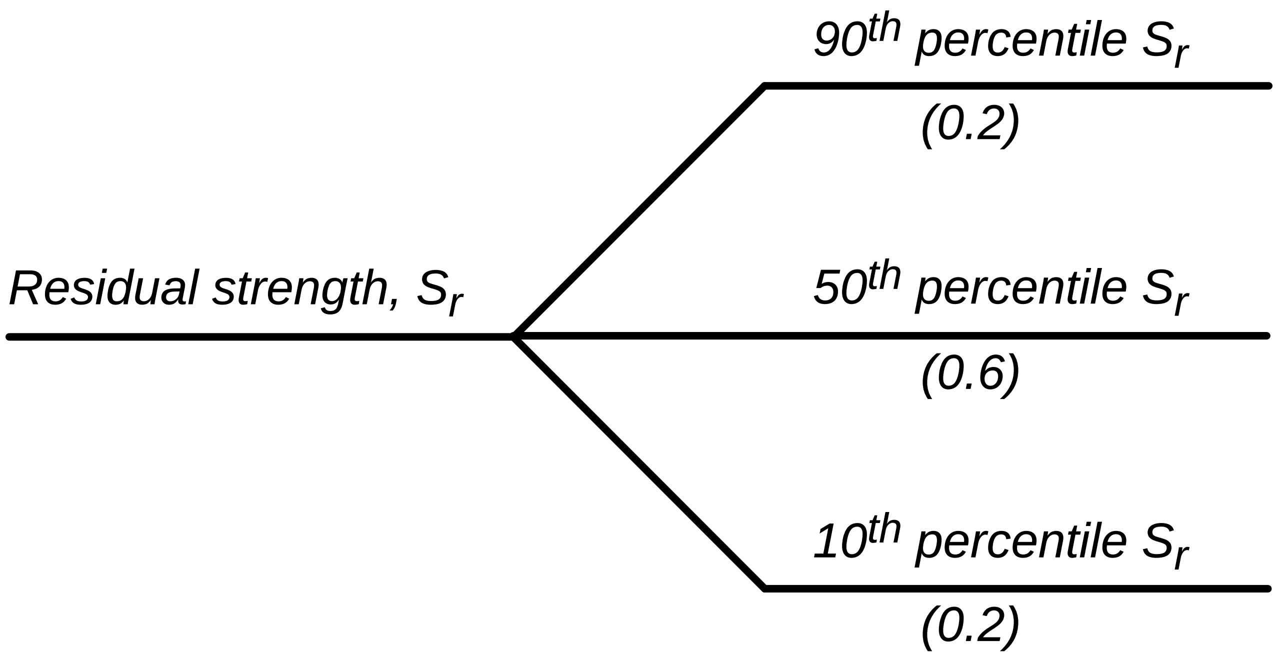
Current state-of-the-art?

- *Extrapolating is unavoidable*



Current state-of-the-art?

- *Event tree for a risk analysis*



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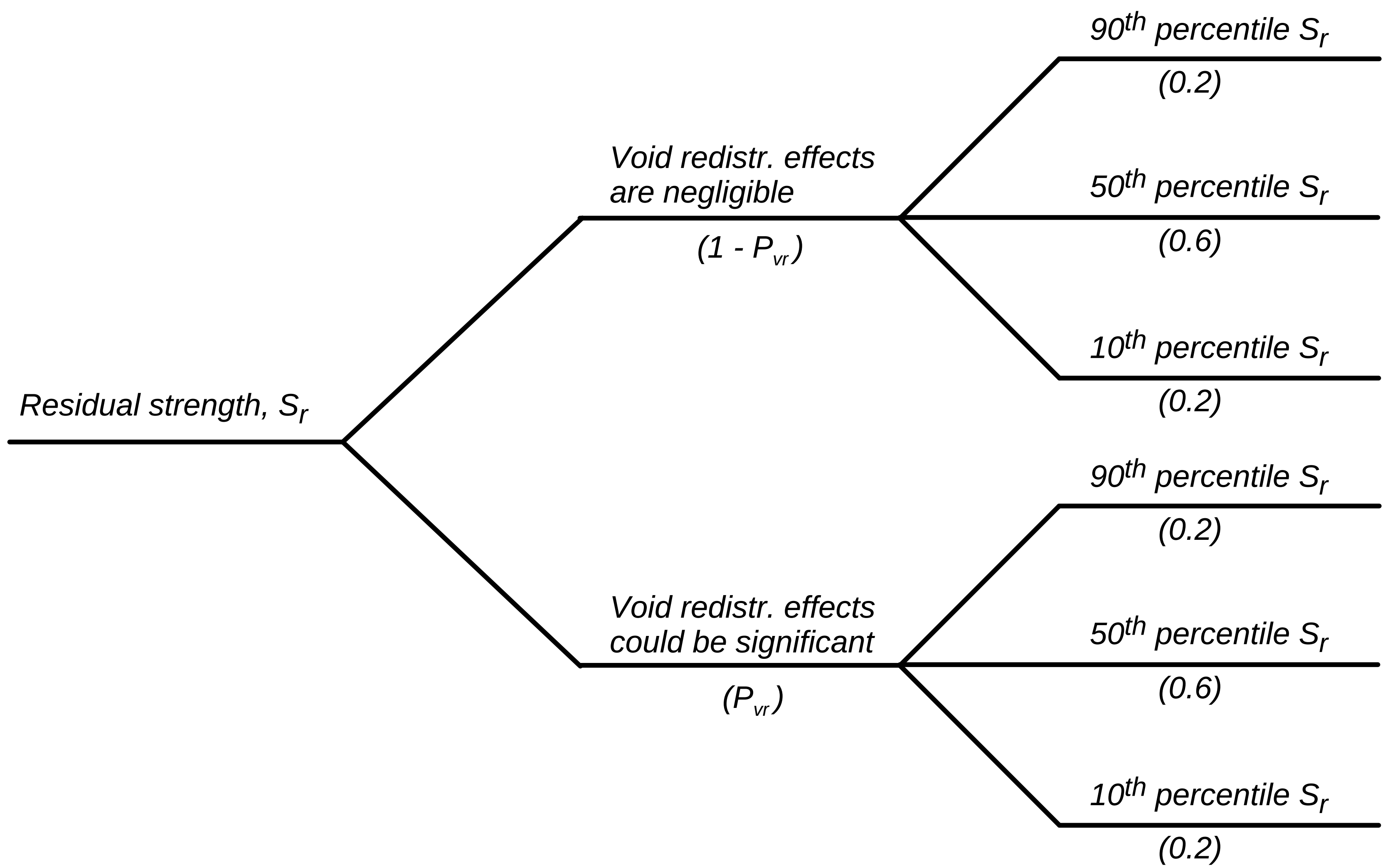
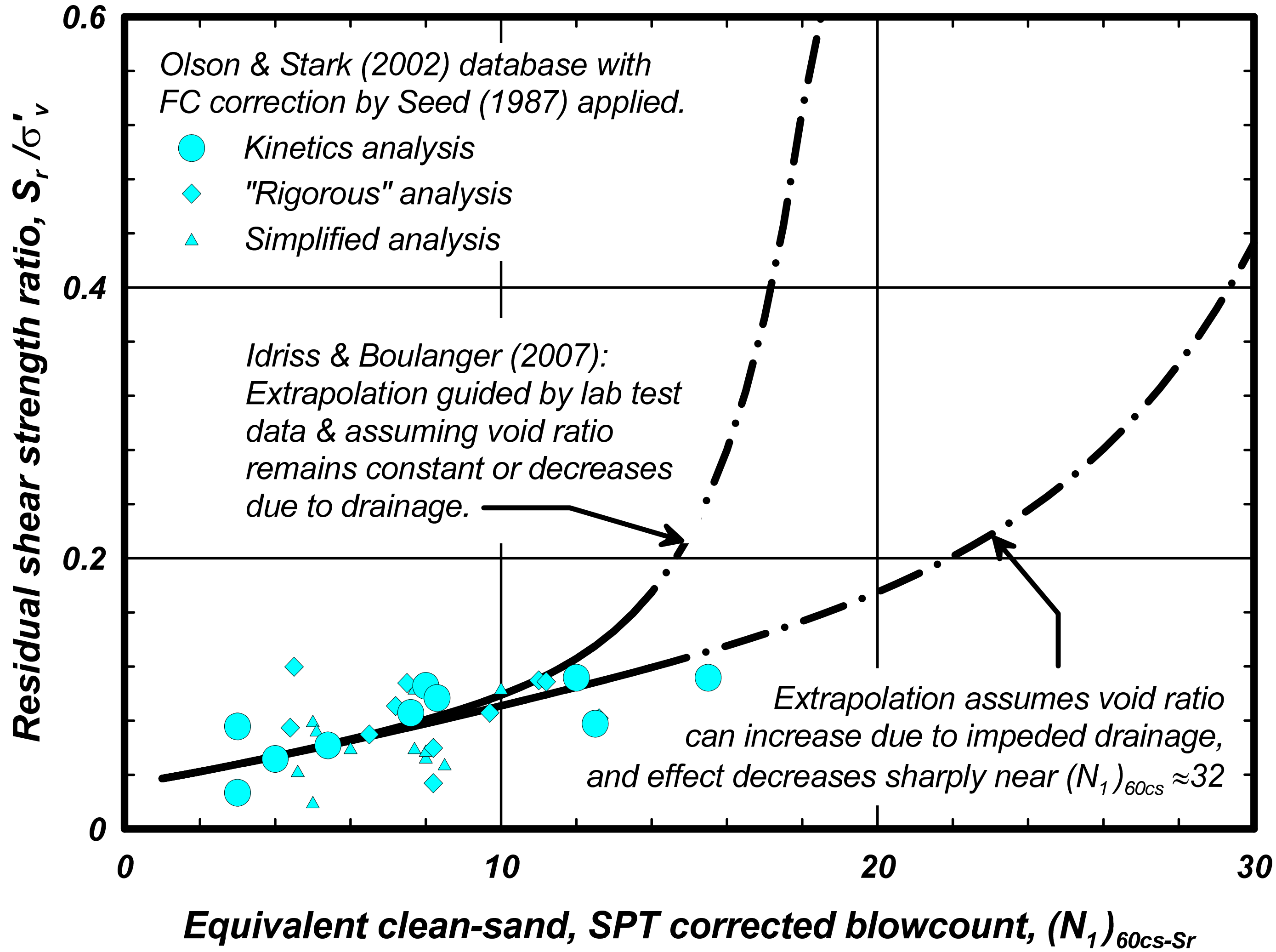


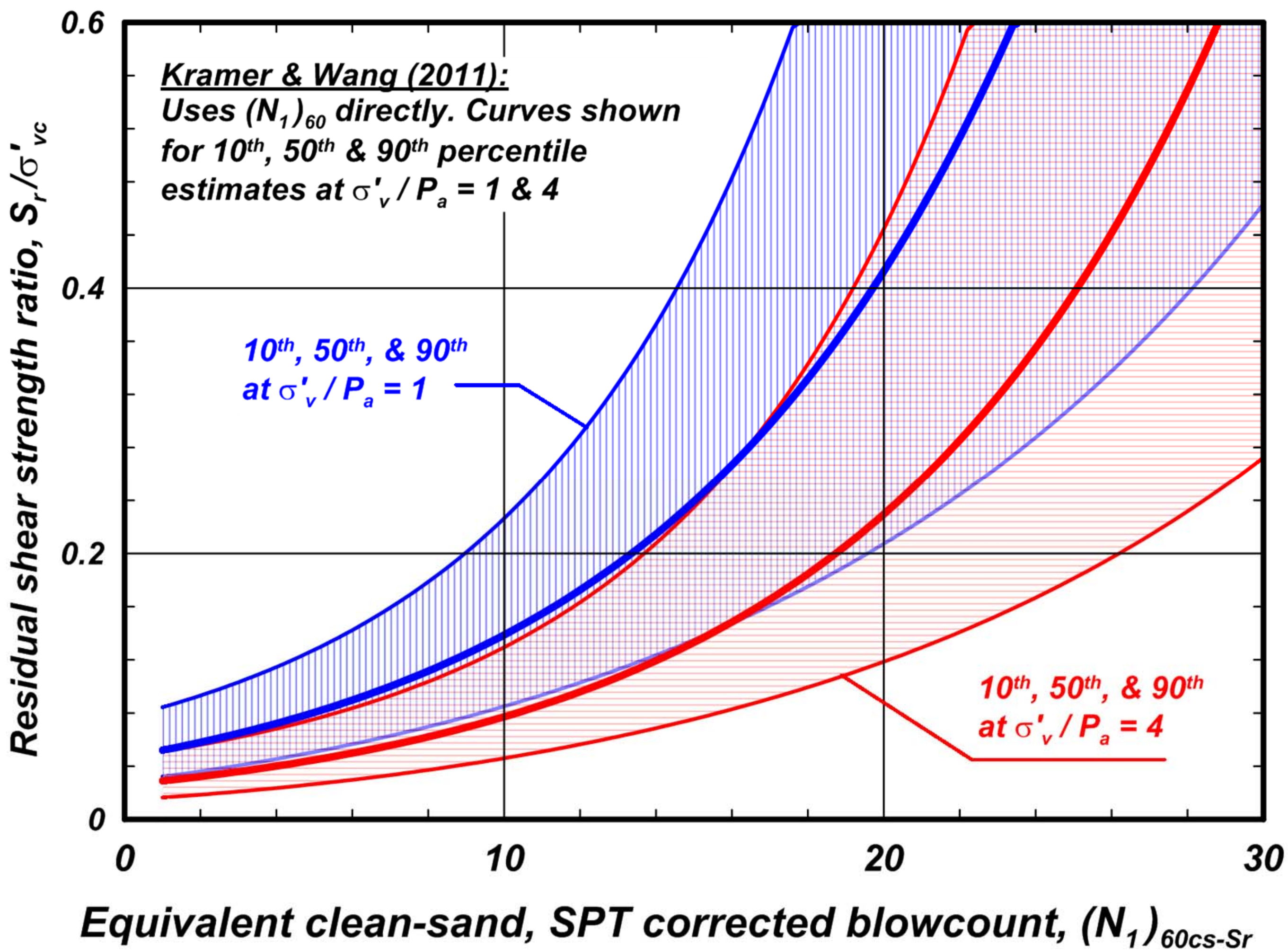
Current state-of-the-art?

➢ *Extrapolating – Idriss & Boulanger (2007)*



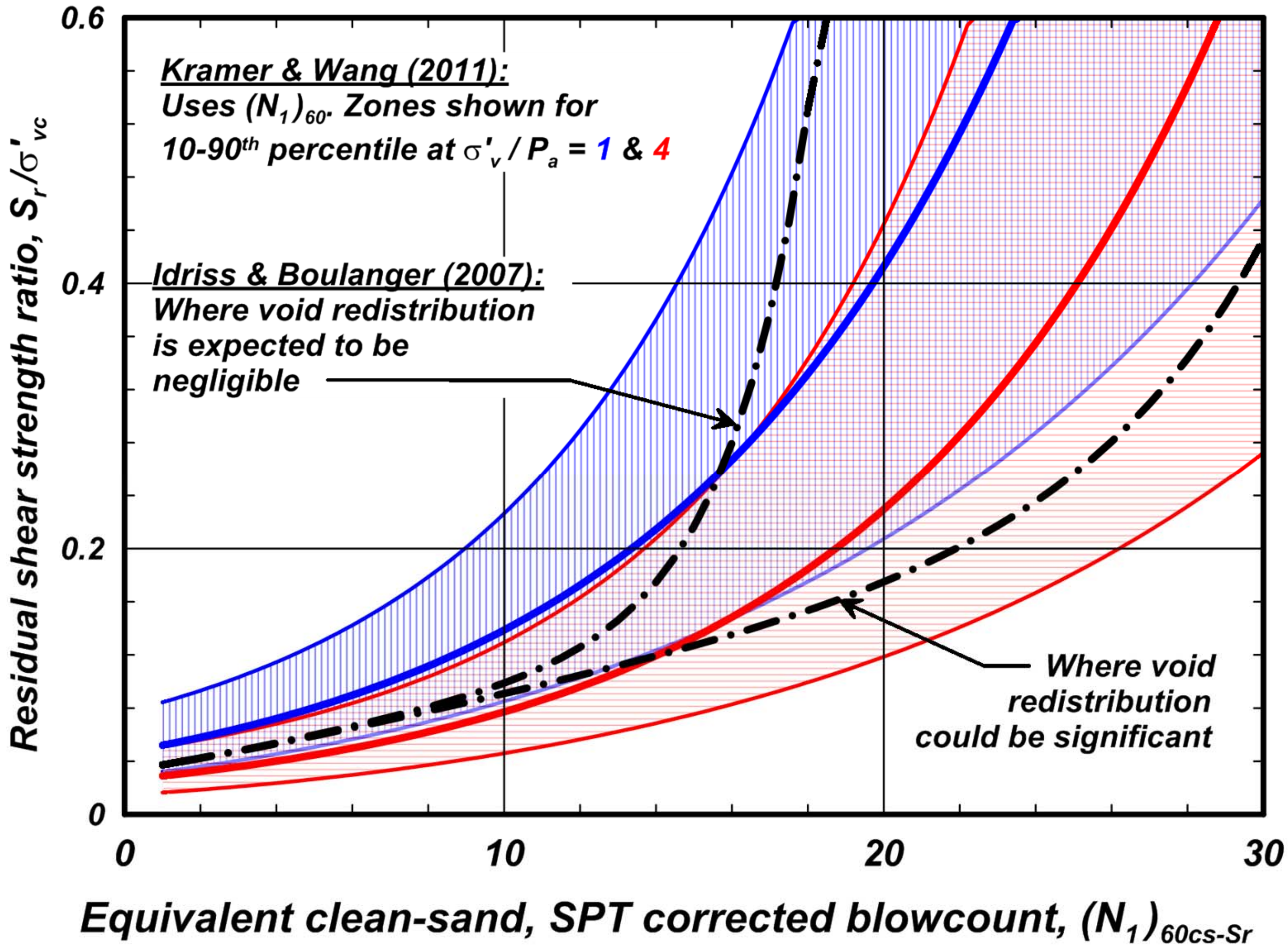
Current state-of-the-art?

- *Extrapolating – Kramer & Wang (2011)*



Current state-of-the-art?

- *Extrapolating – comparing ranges*



Challenges to better evaluation procedures?

- *Residual shear strength (S_r), and the deformations associated with void redistribution, can depend on:*
  - *pre-earthquake soil state (D_R, σ'_v) & properties,*
  - *physical geometry & stratigraphy,*
  - *permeability contrasts & interfaces characteristics,*
  - *ground motion characteristics.*

- *Pre-earthquake measures of the soil state [e.g., D_R, $(N_1)_{60}$] are insufficient for predicting the response.*

- *Numerical models have problems with localizations and we have problems defining all the initial conditions with confidence.*

- *Do the documented case histories bound the possible range of strengths we might see in future cases?*

Path forward for advancing understanding/procedures

- *Physical data*
  - *Large-scale physical model tests with more complex stratigraphy and dense arrays to locally measure responses.*
  - *Field instrumentation that can differentiate or identify roles of void redistribution & diffusion in future events*
- *Numerical models and theories that can:*
  - *Handle localizations more robustly*
  - *Simulate the void redistribution observed in various physical models and recreate delayed deformations*
  - *Simulate the absence of void redistribution in other physical models or cases*
  - *Parametric analyses that better separate the scenarios for improved guidance &/or understanding*
- *Validation of simulation tools:*
  - *Systematic evaluation of simulation tools against sets of physical data that did and did not develop localizations or water films – can we differentiate between these cases?*