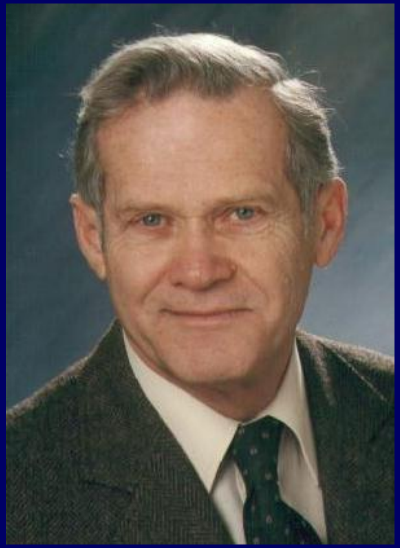
20th Gerald A. Leonards Lecture, Purdue University, April 12, 2024

Seismic Design Considerations for Tailings Dams

Jonathan D. Bray, PhD, PE, NAE

Faculty Chair in Earthquake Engineering Excellence
University of California, Berkeley
jonbray@berkeley.edu



Prof. Leonards Focused on Details

- **Depositional environment should be considered**
- **Thin layers can govern site performance**
- **Importance of continuous sampling**

“*Just one more FE analysis*,” which was #17. I performed 44 analyses before project was over to explore fully details that might matter

“*Students do not mind hard work if they feel they are learning something.*”
I learned much from Prof. Leonards.

Seismic Design Considerations for Tailings Dams

OUTLINE

1. Tailings Storage Facilities

2. Observed Performance of Tailings Dams

3. Flow Failure Potential

4. Seismic Slope Displacement

5. Summary

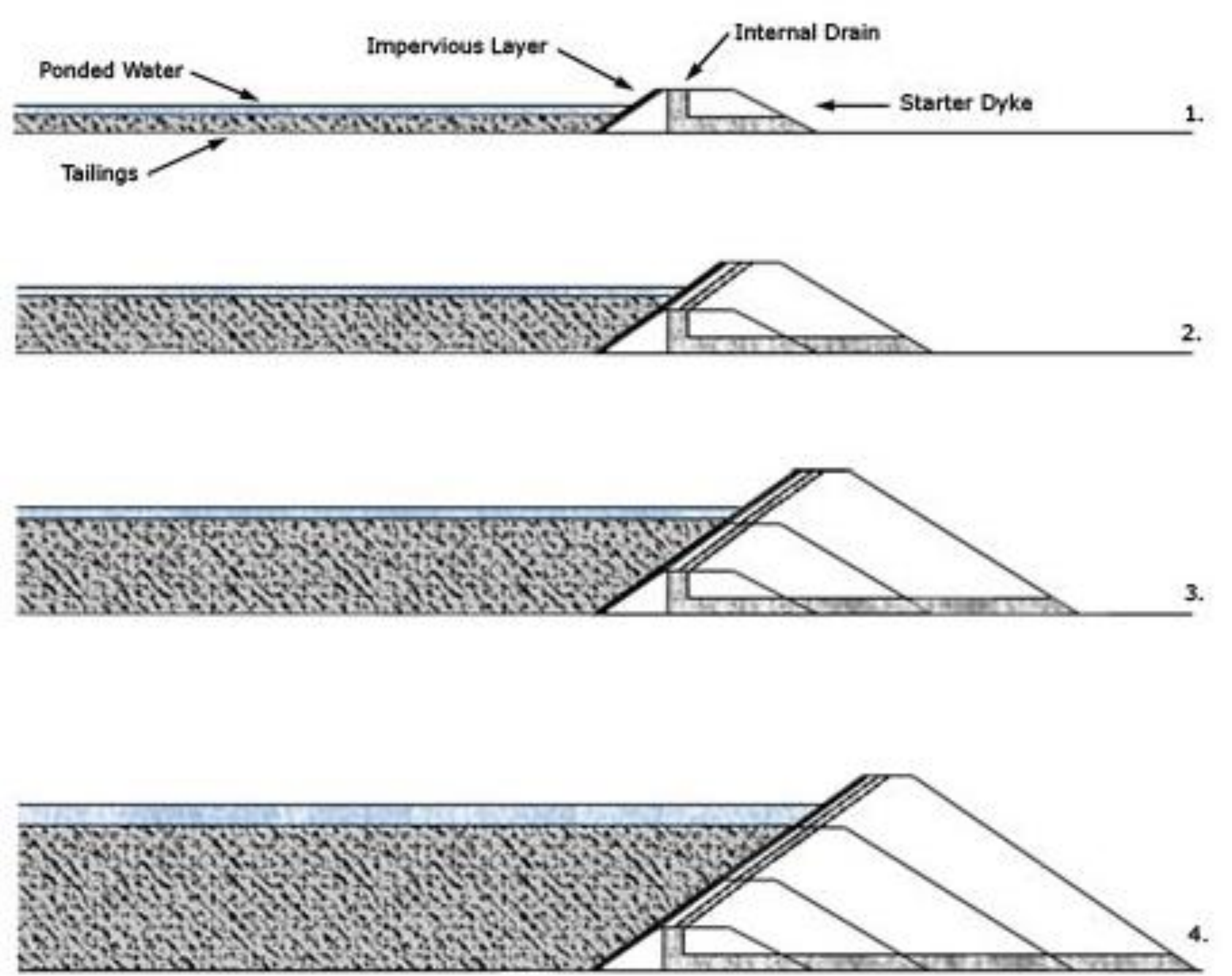
Tailings Storage Facility (TSF)

Akyem Mine TSF Cell 1 (background) and TSF Cell 2 (foreground) in Ghana

Photo courtesy of Kim Morrison, Newmont Corp.

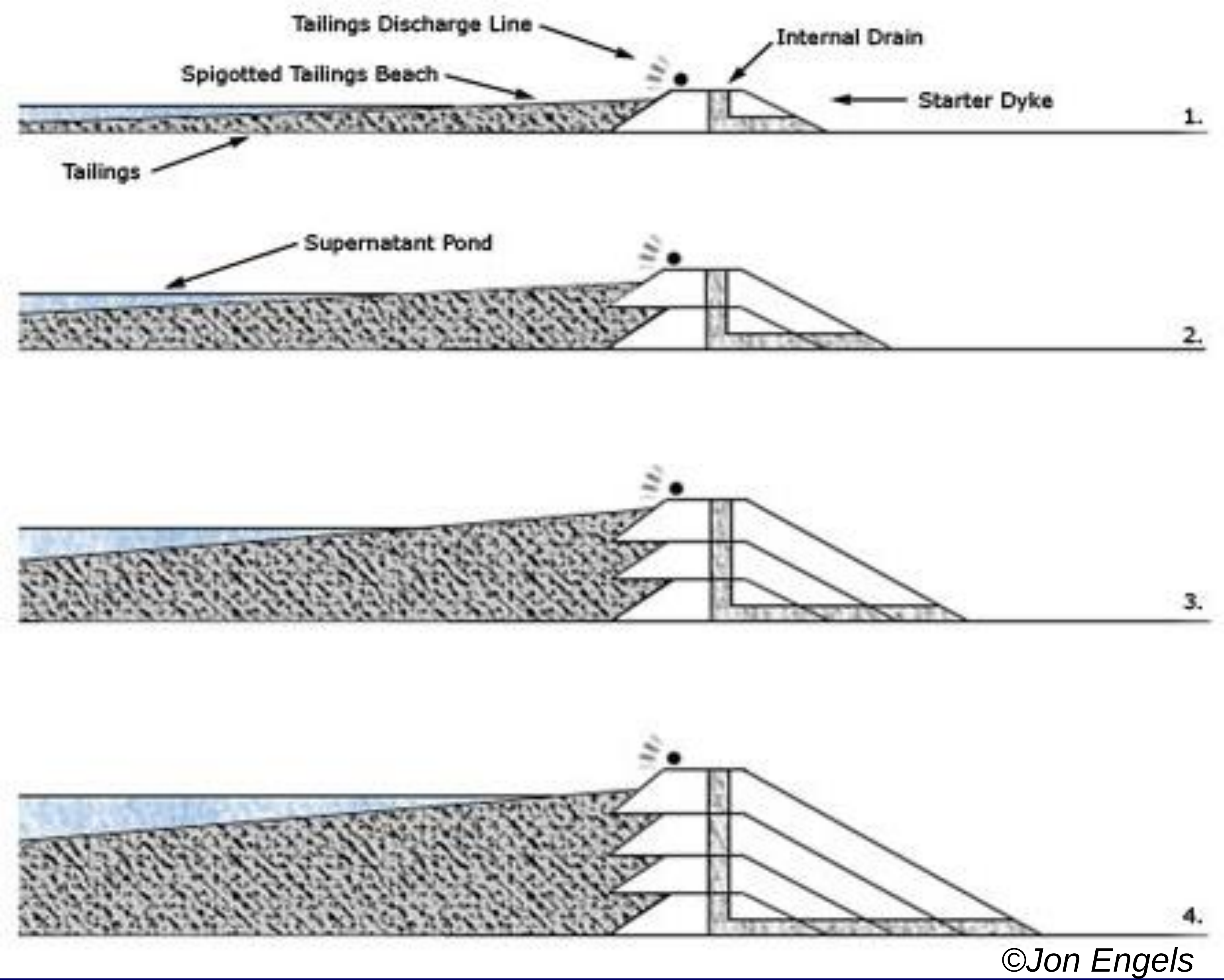
Types of TSF Design

- ***Downstream***
- *Centerline*
- *Upstream*



Types of TSF Design

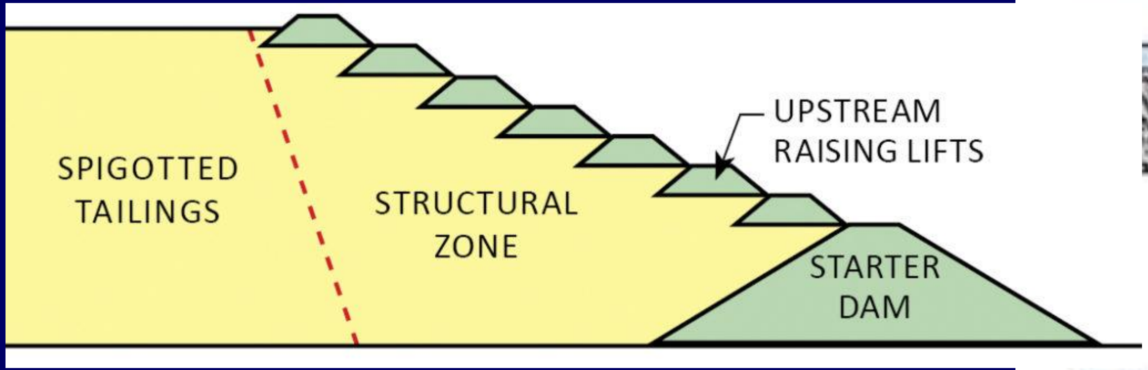
- *Downstream*
- ***Centerline***
- *Upstream*



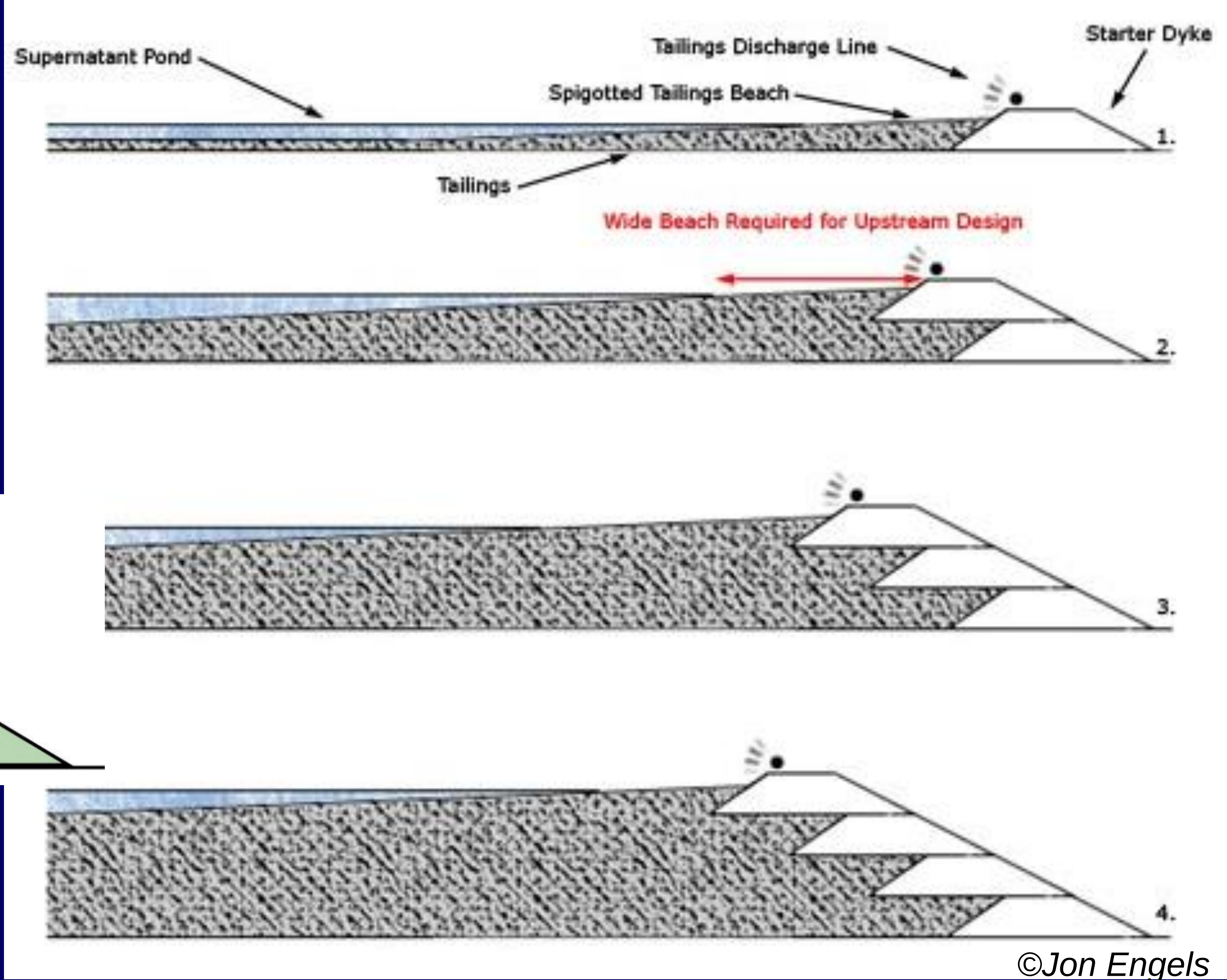
TAILENG

Types of TSF Design

- *Downstream*
- *Centerline*
- ***Upstream***



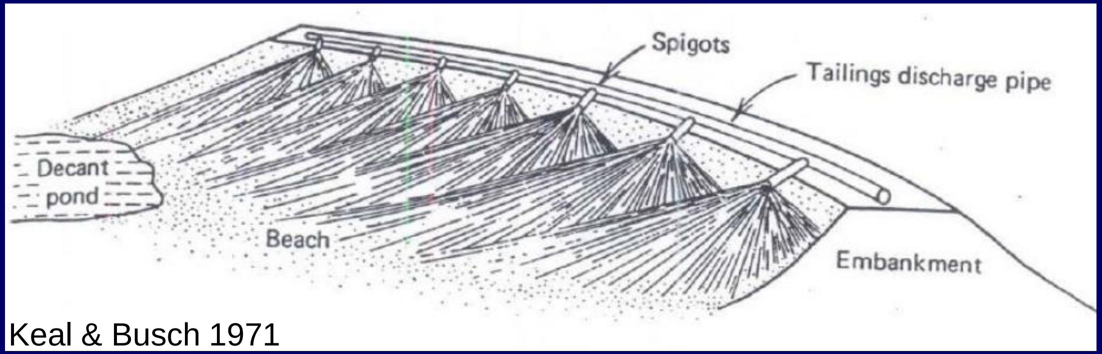
Best Practices for Tailings Dam Design - KCB (klohn.com)



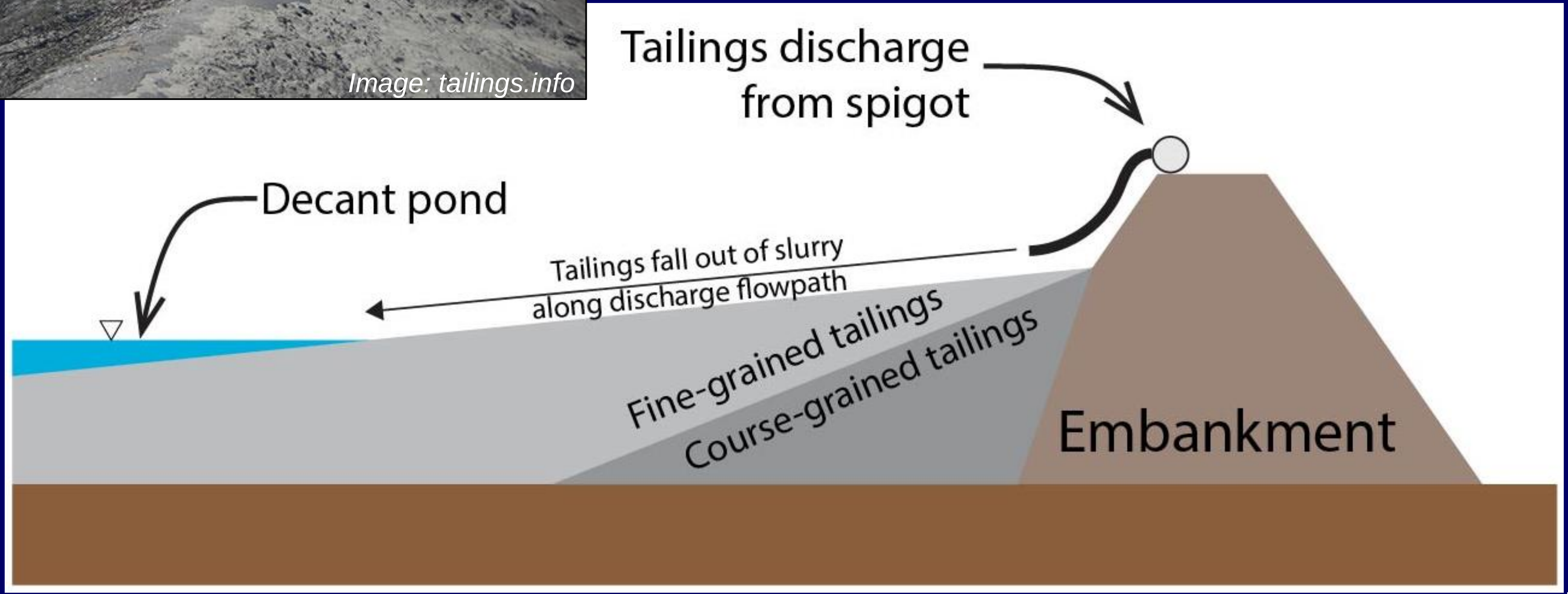
TAILENG

Spigot Discharge & Hydraulic Deposition


Image: tailings.info

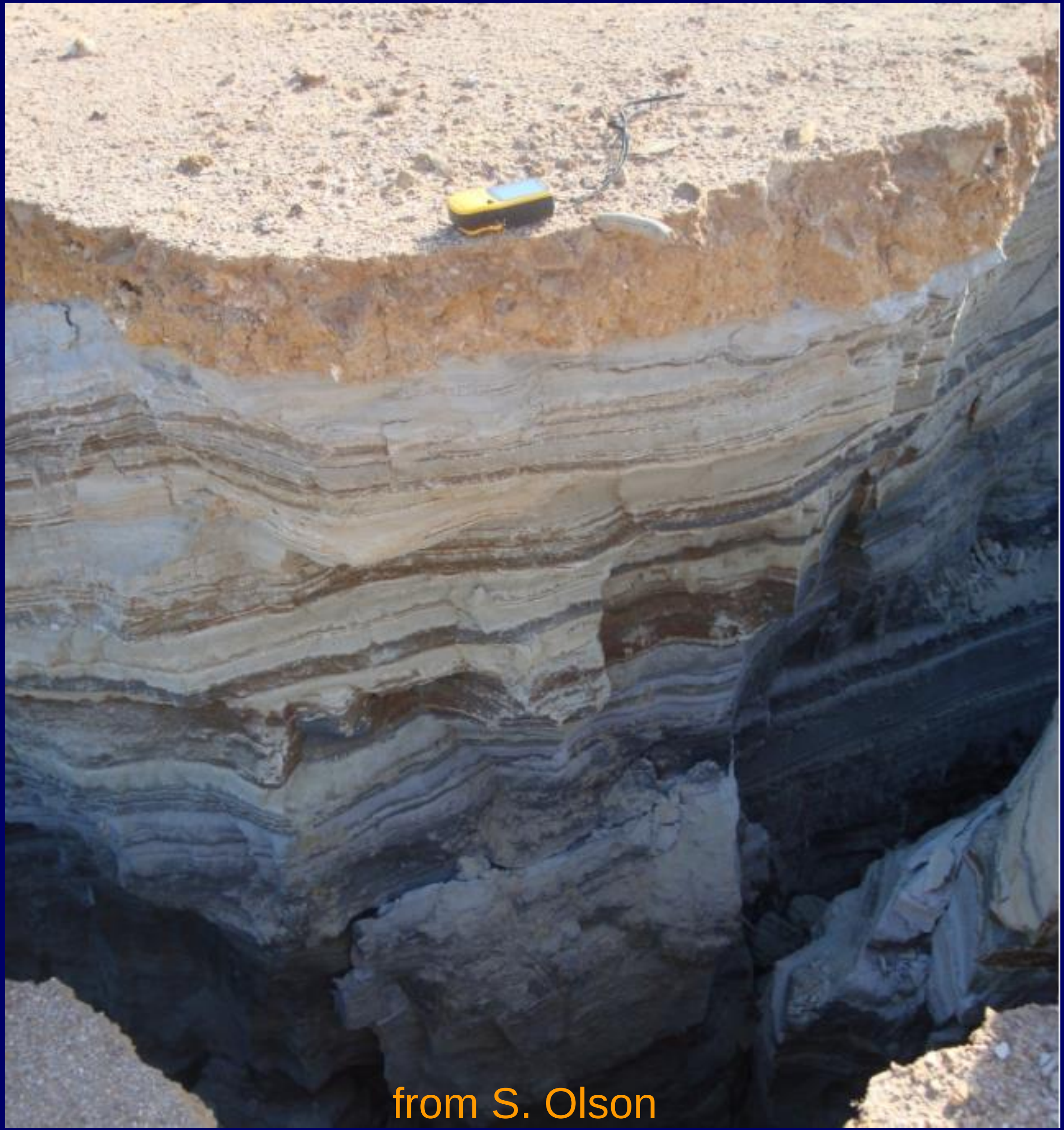


Keal & Busch 1971



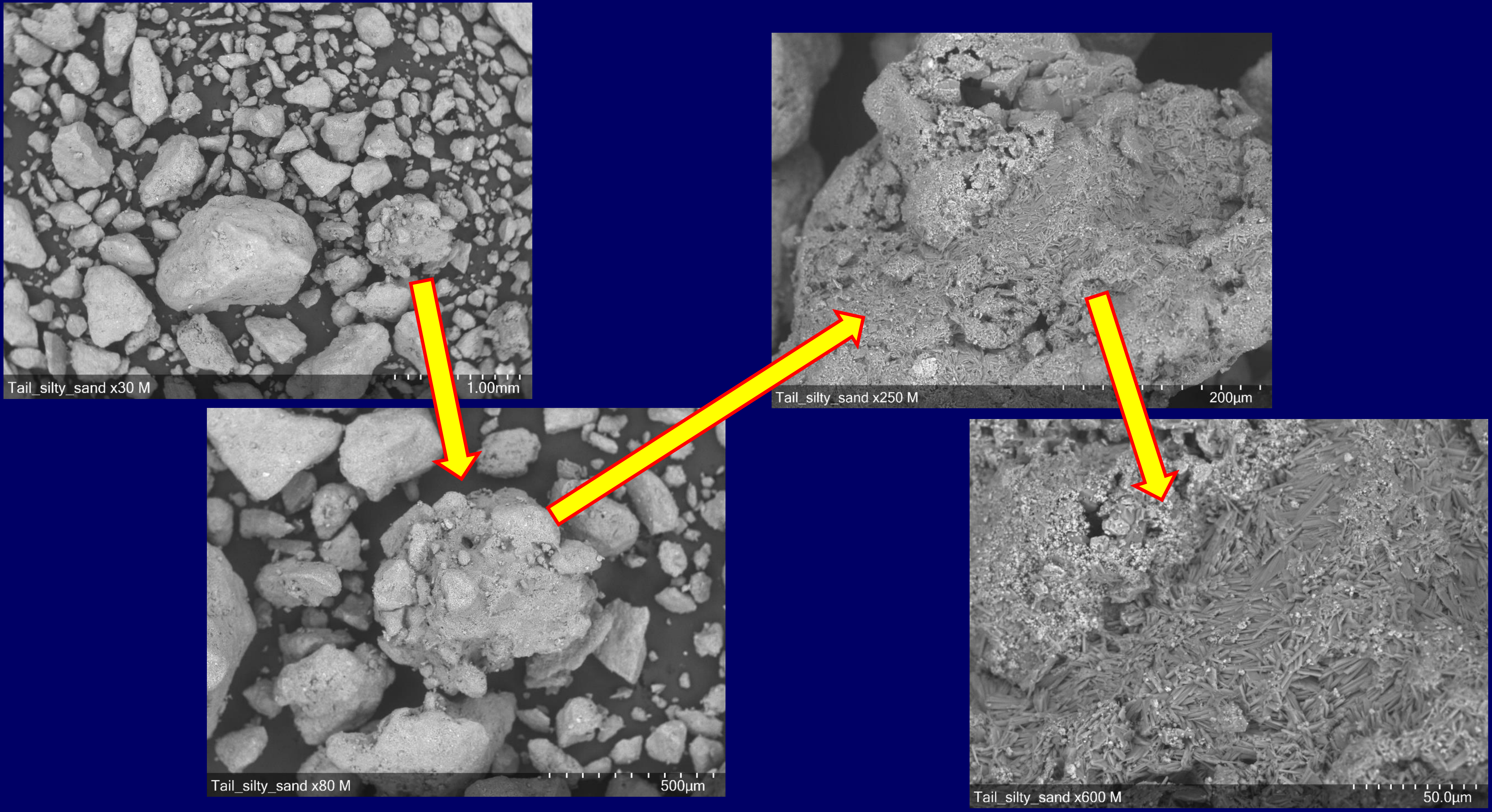
Hydraulic Filling Creates Layered System

- Composite response
- Anisotropic properties
- Drainage
- Instrumentation
- Calibration

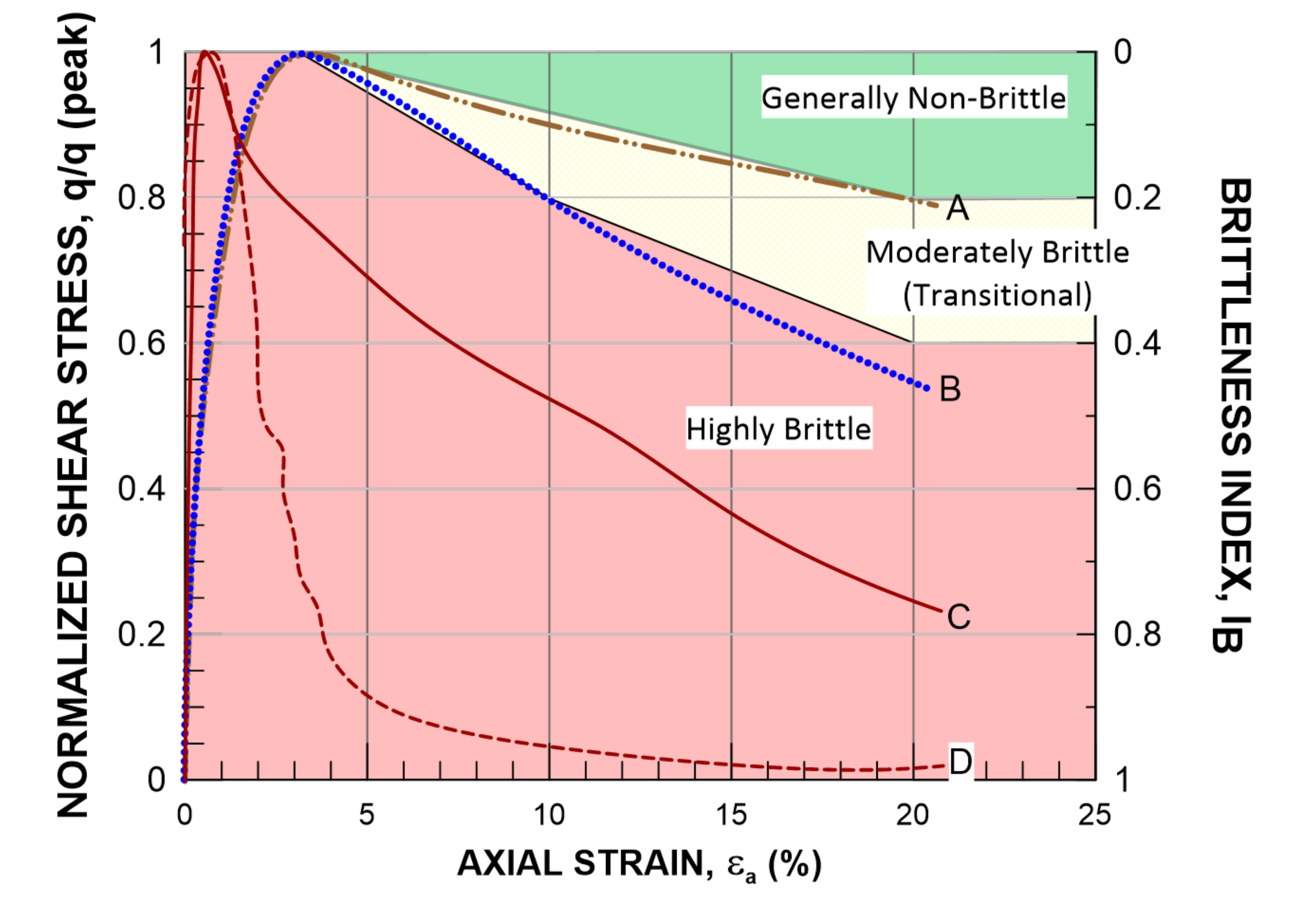


SEM Allows One to See Tailings Particles

(tailings material in Peru, Olaya & Bray, in progress)



Focus on Materials with Contractive Response with Brittle Strain-Softening



Brittleness Index, I_B
(Bishop 1967, 1973)

$I_B = 1 - S_r / S_{u\_peak} = 1 - 1 / S_t$

$S_t = S_{u\_peak} / S_r$

If $S_r = 0.2\ S_{u\_peak}$ **(i.e.,** $S_t = 5$ **)**

Then $I_B = 0.8$

Appendix B of *ICOLD Bulletin 194* (Herza, Ridlen, et al.)

2. Observed Performance of Tailings Dams

Feijao Tailings Dam 1 (H = 80 m)

(Robertson et al. 2019)

270 deaths

Recent Failures

Jagersfontein Tailings Dam Failure
South Africa, 11 September 2022

(after Torres-Cruz, 2022)

17 Fatalities

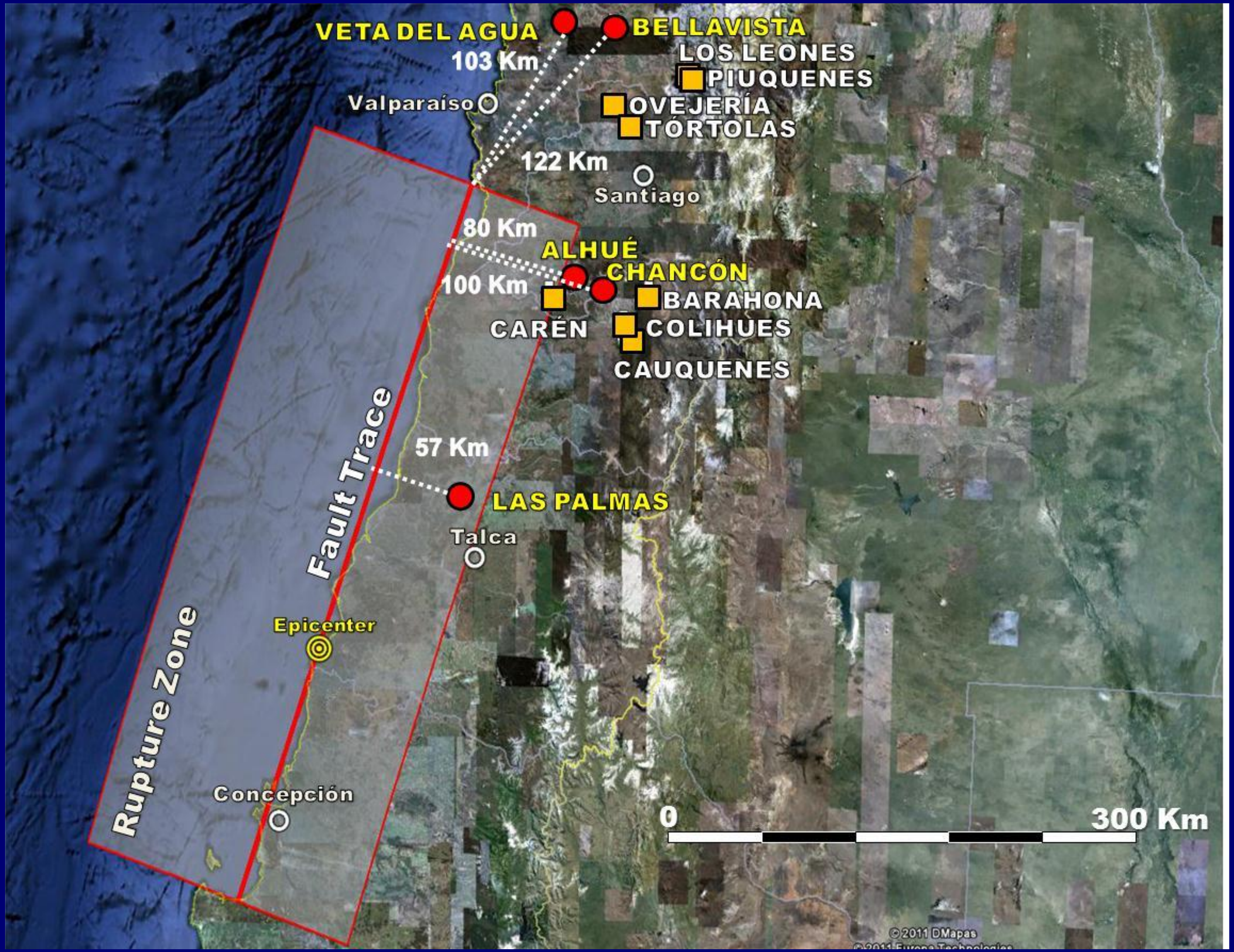
Copler Heap Leach Failure
Turkey, 13 February 2024

(from P. Repetto)

9 Fatalities

Observed Seismic Performance of Tailings Dams

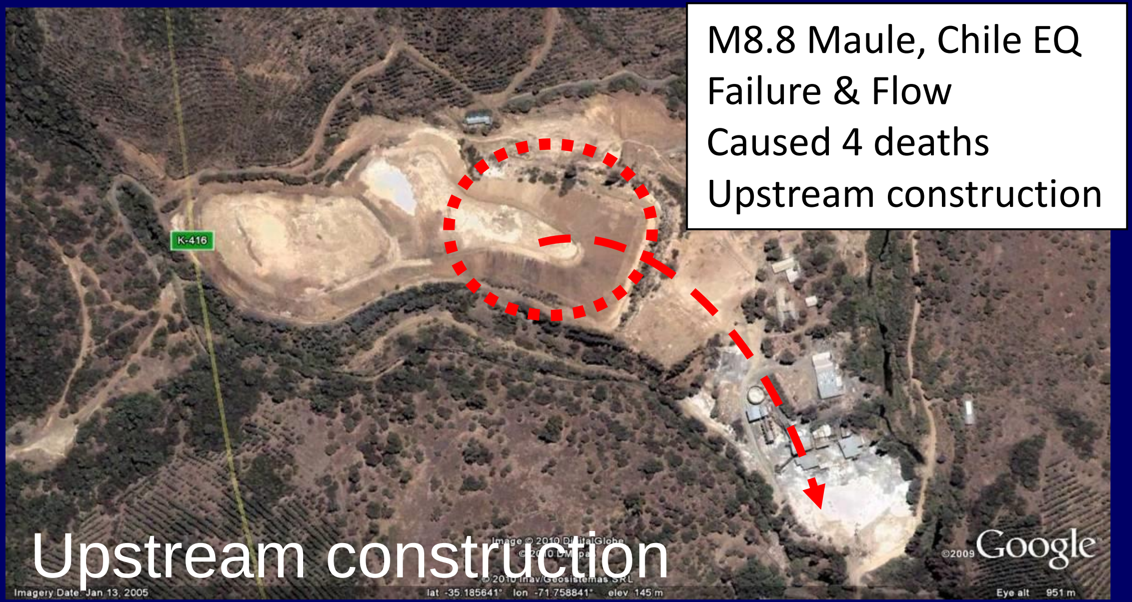
2010 M_w8.8 Maule, Chile EQ

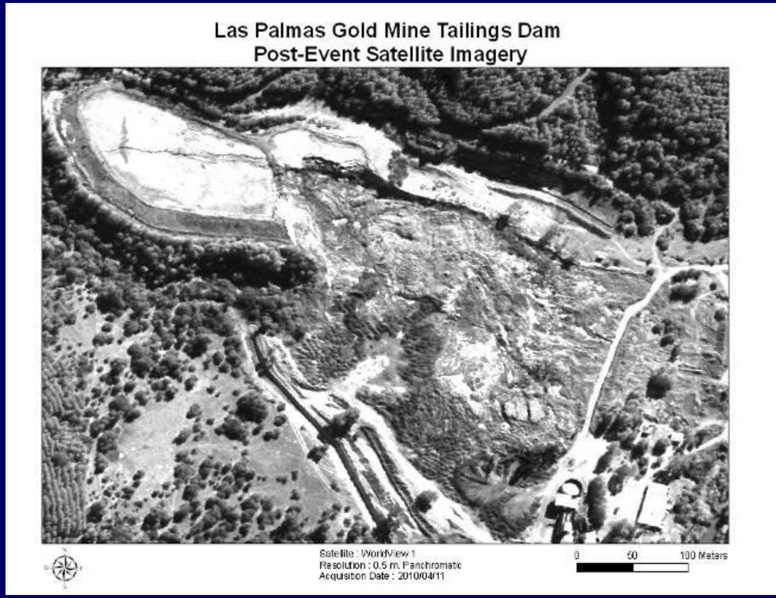


- Large tailings dams that performed well
- Tailings dams that performed poorly

Verdugo et al. 2012

Las Palmas Gold Mine Tailings Dam EQ-Induced Failure





Bray & Frost 2010

View across scarp

View from scarp looking downstream

Ejecta near toe of flow debris

Seismic Performance of Tailings Dams

(Upstream Construction Dams, M8.8 Maule, Chile EQ)

Bellavista
Dike No. 1
(Ramirez, 2010)

Veta del Agua
Dike No. 5
(Prof. R. Espinace)

Verdugo et al. 2012

3. Flow Slide Potential

Two Critical Issues

1. Are there materials that can lose significant strength due to cyclic loading?

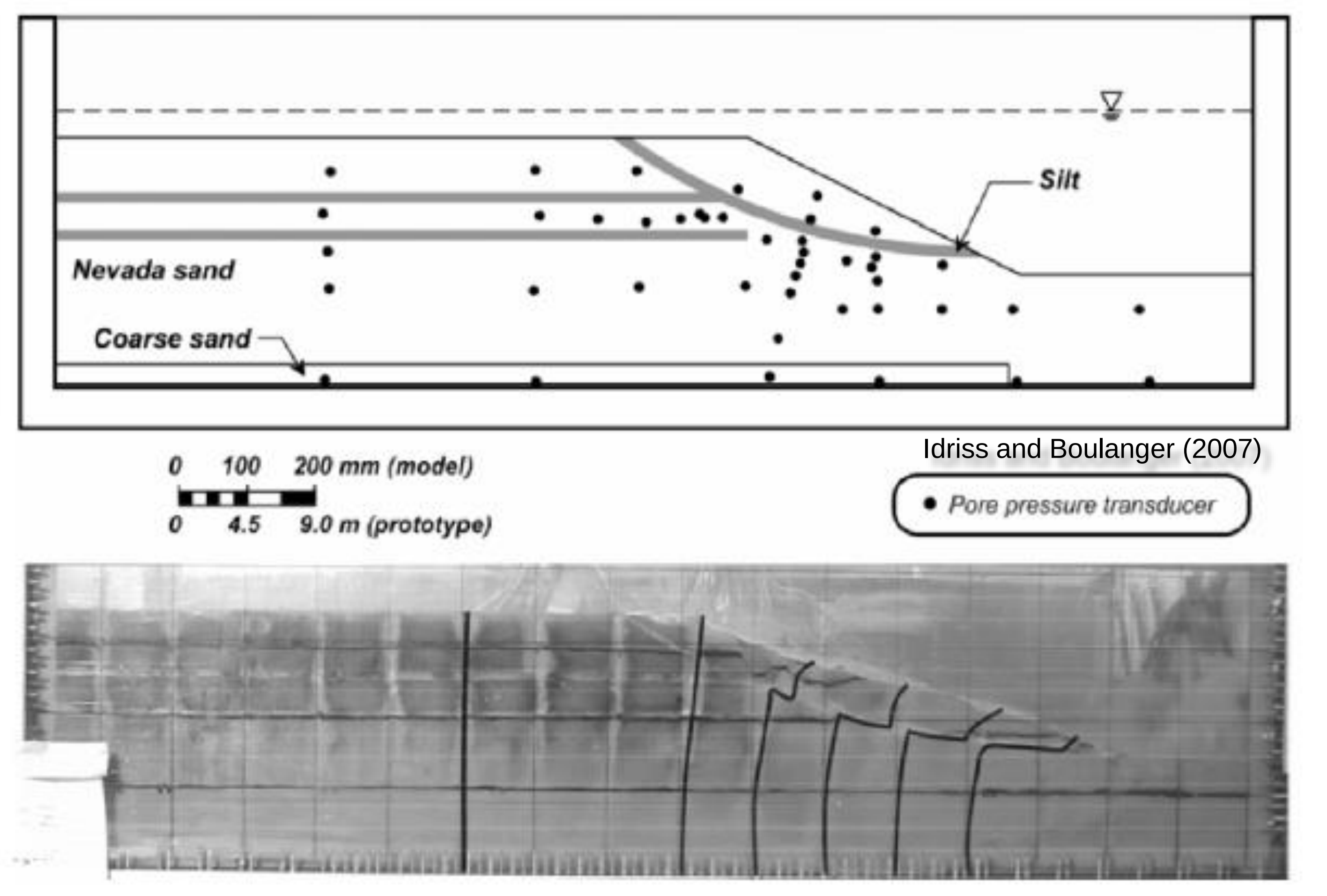
   If Post-Cyclic Static Slope Stability FS ≤ ≈ 1, Flow Slide is Possible

2. If not, will the system undergo significant deformations that may jeopardize its performance?

   If FS > 1, Estimate Seismic Slope Displacement

Post-Liquefaction Residual Strength (S_r) is a System Property

VOID REDISTRIBUTION



Idriss and Boulanger (2007)

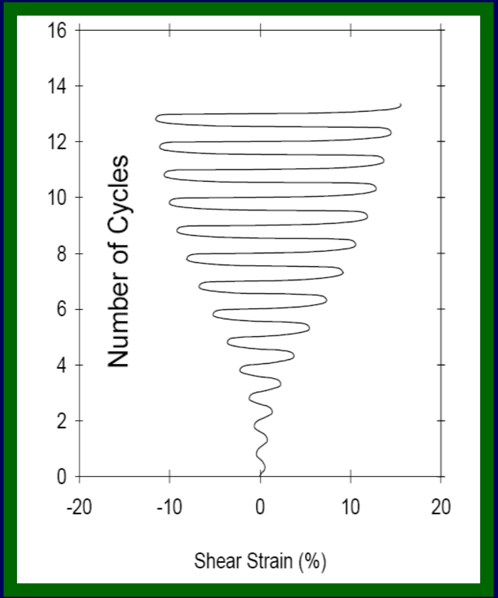
Porewater accumulated beneath silt layer

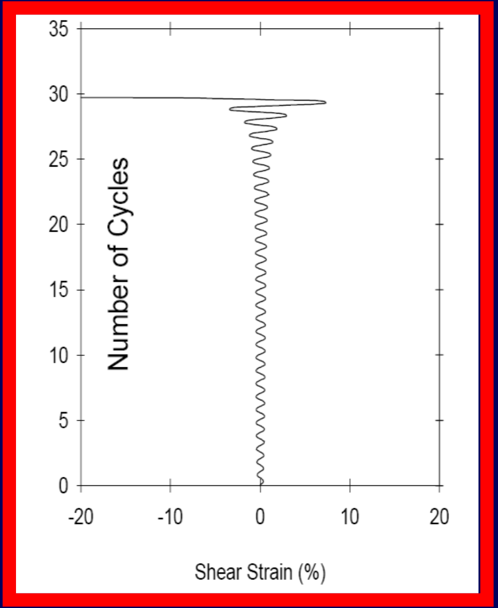
Local void ratio increases & strength decreases

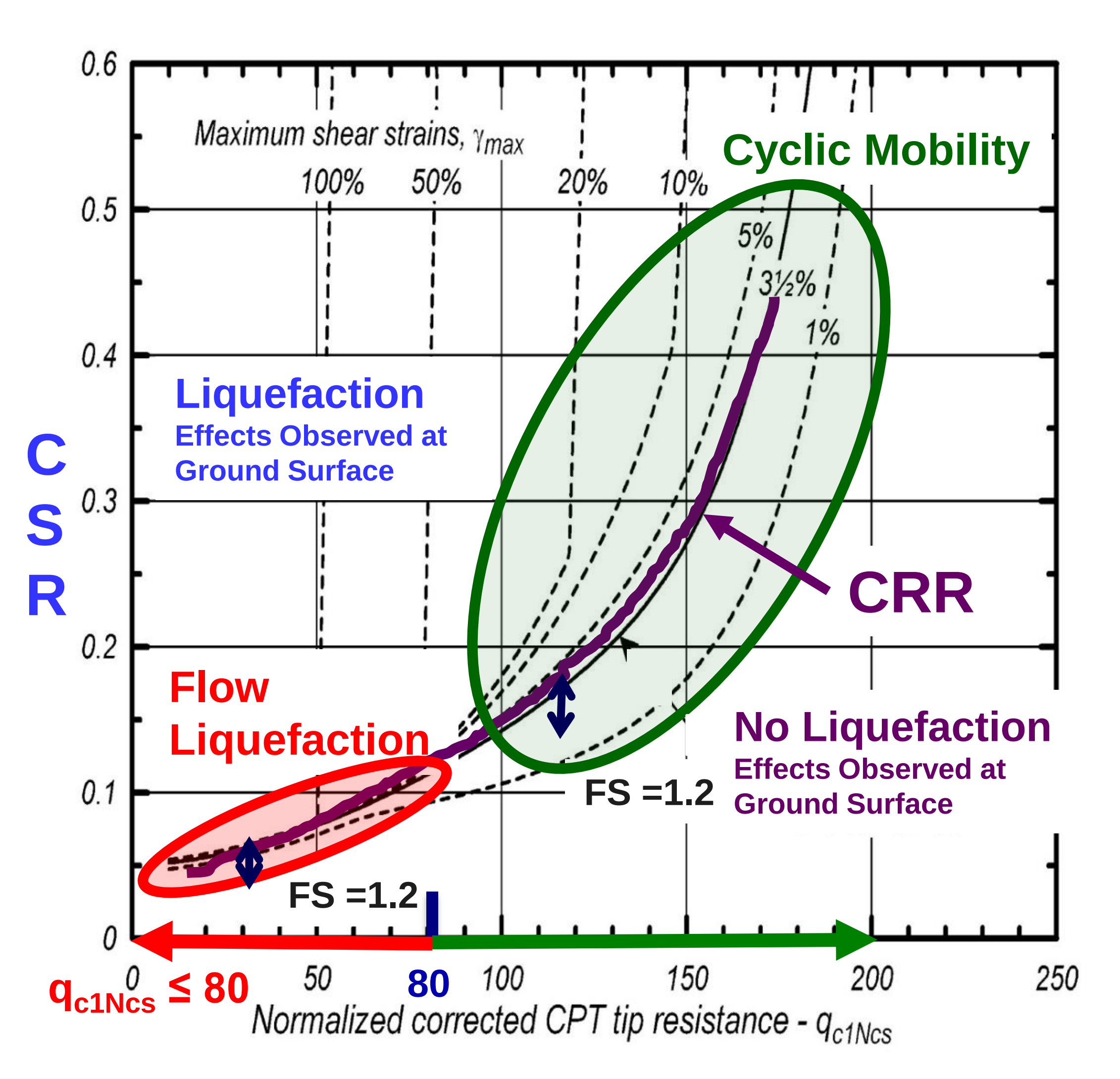
Failure occurred on discrete surface

Slope failed after shaking ended

LIQUEFACTION EFFECTS



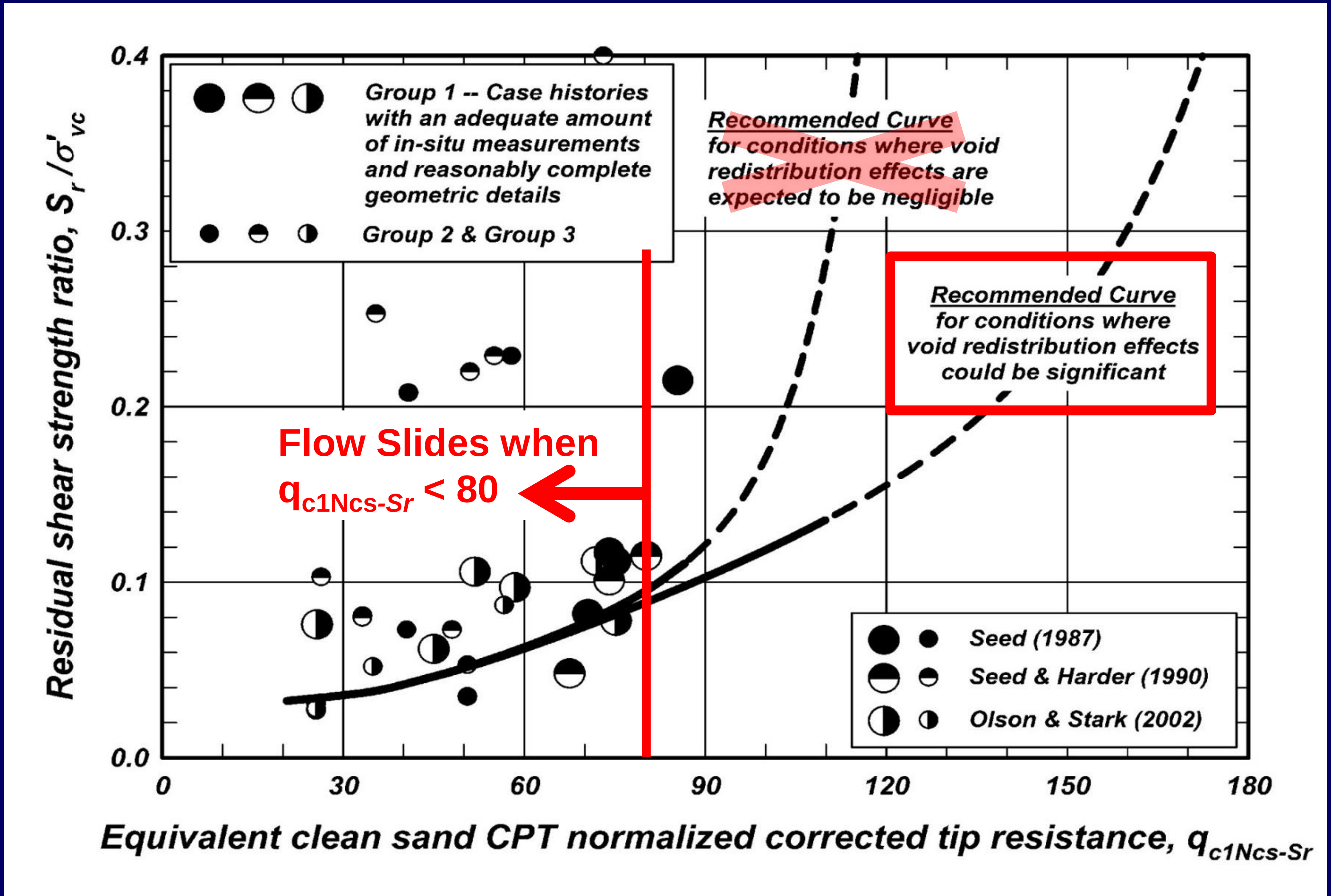




FS = CRR / CSR

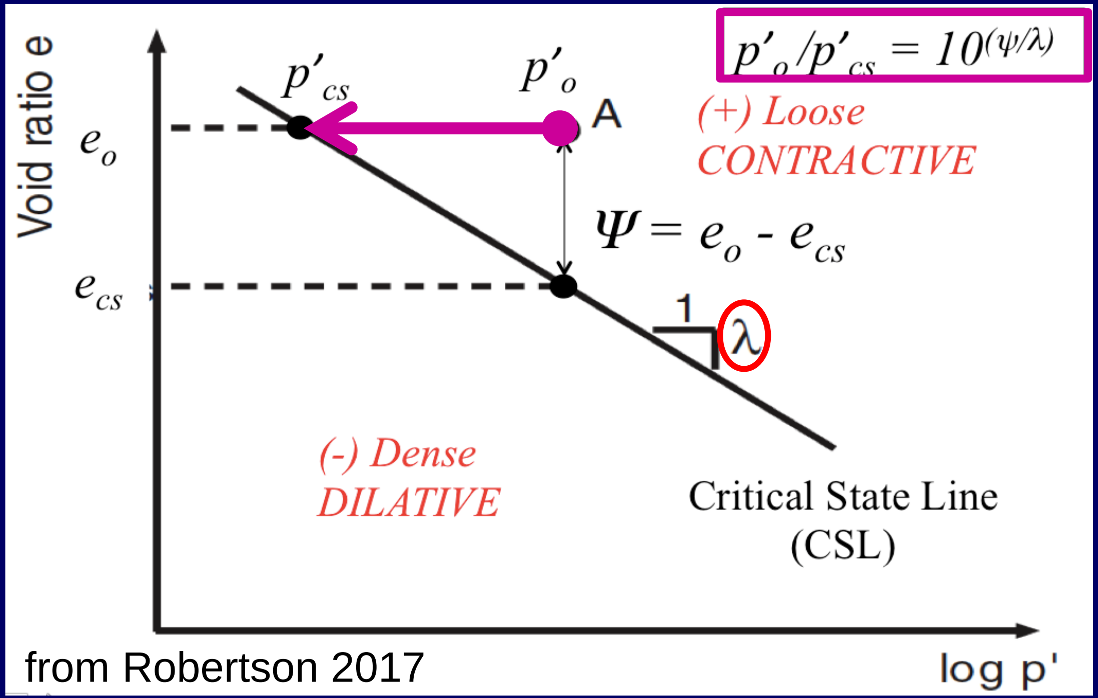
Idriss & Boulanger 2008

Post-Liquefaction Residual Strength



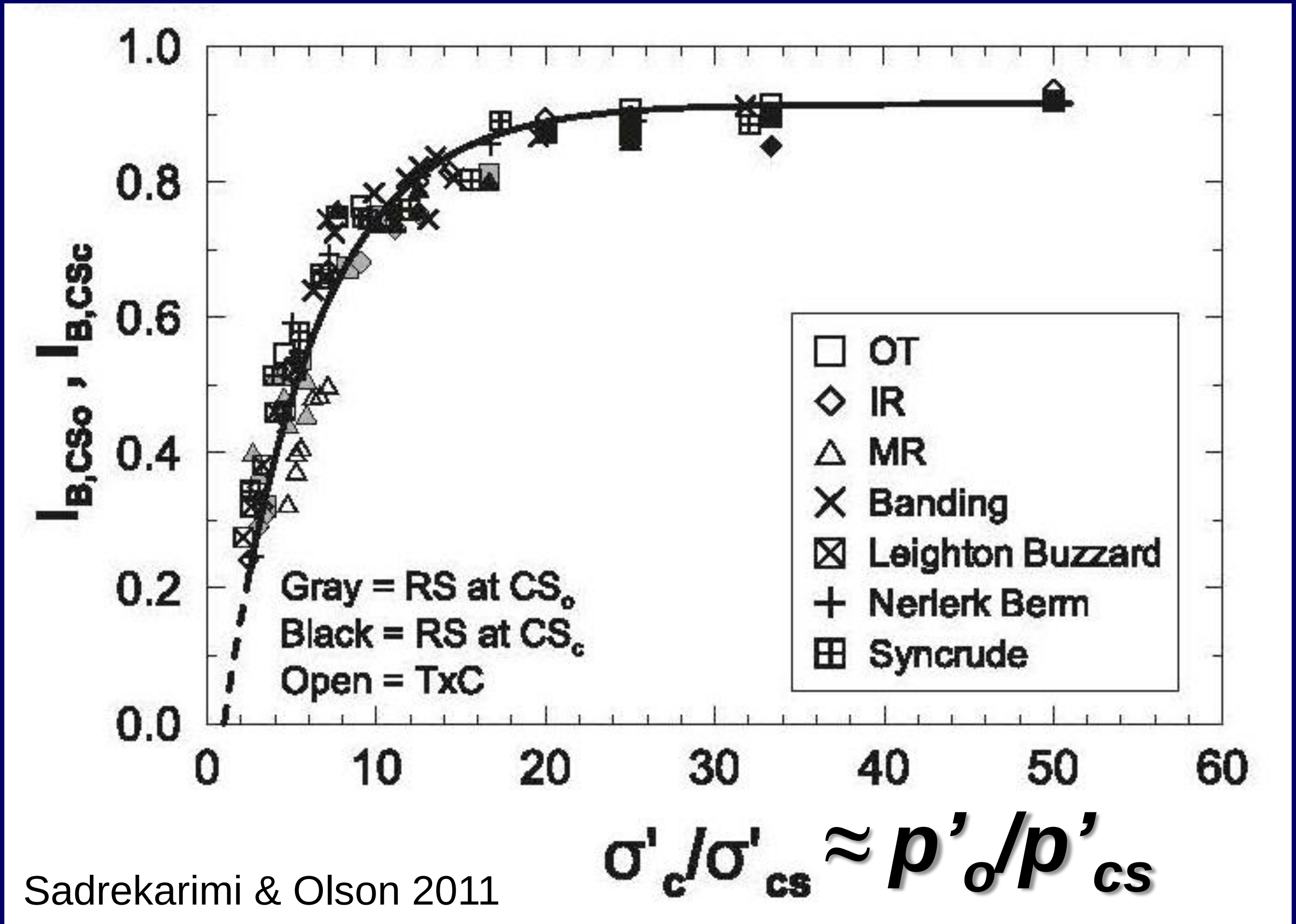
Idriss & Boulanger 2008

INITIAL STRESS RATIO (p'_o/p'_{cs})



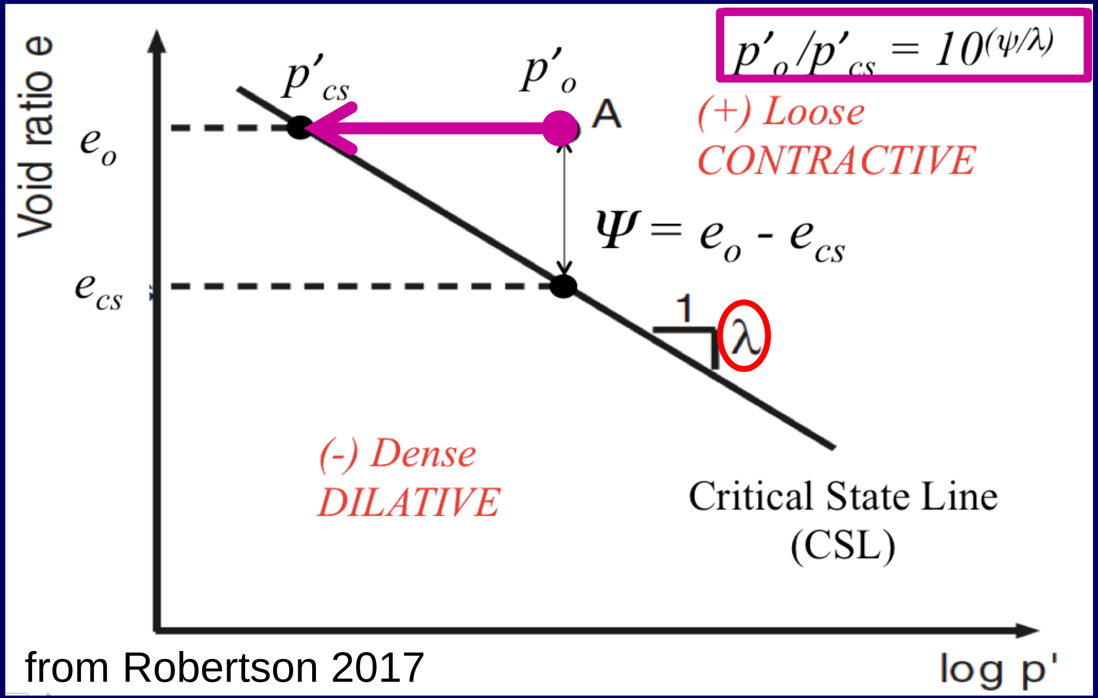
Brittleness Index (Bishop 1967):

$$I_B = 1 - S_r / S_{peak}$$



Brittleness increases as initial stress ratio increases

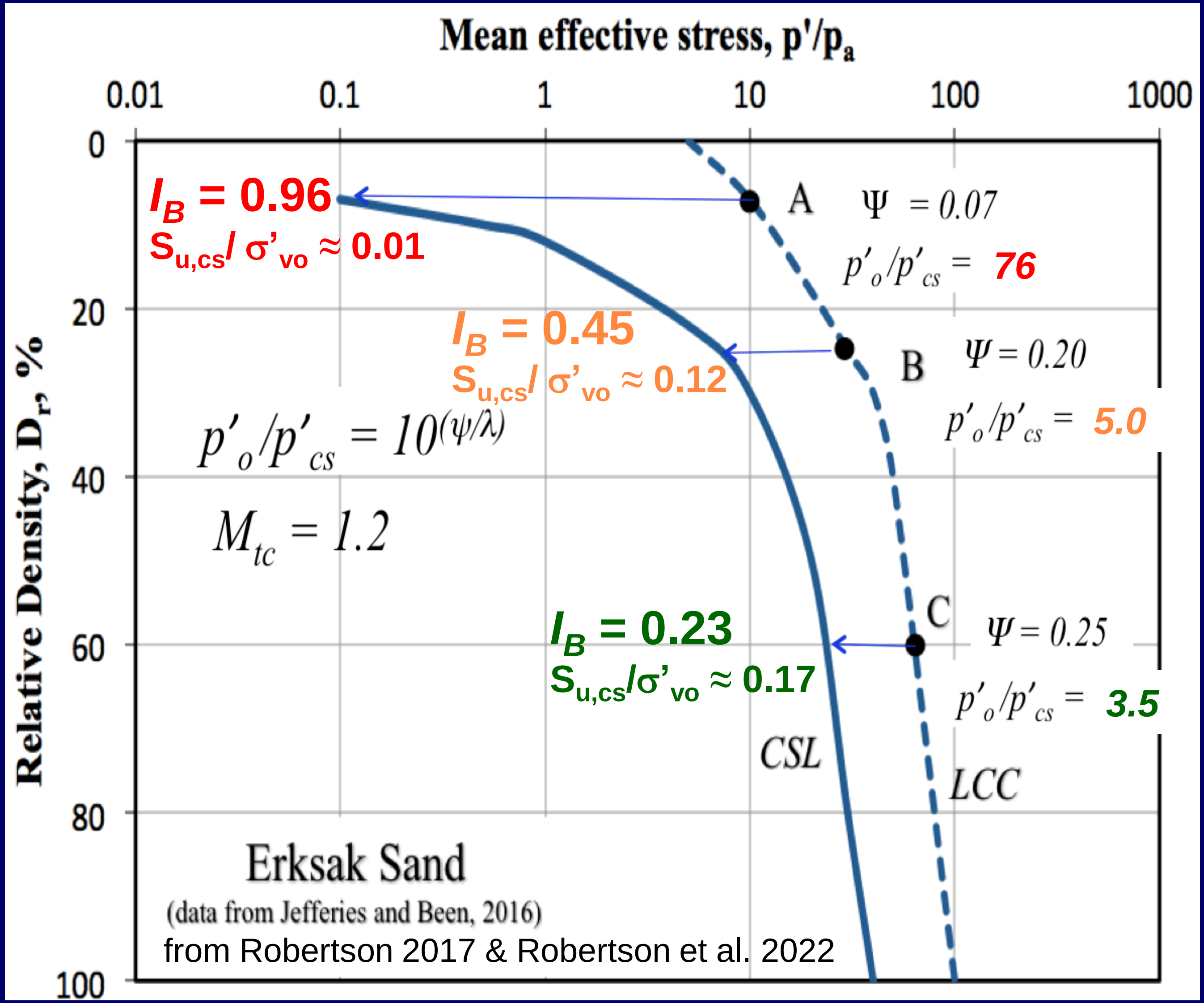
INITIAL STRESS RATIO (p'_o/p'_{cs})



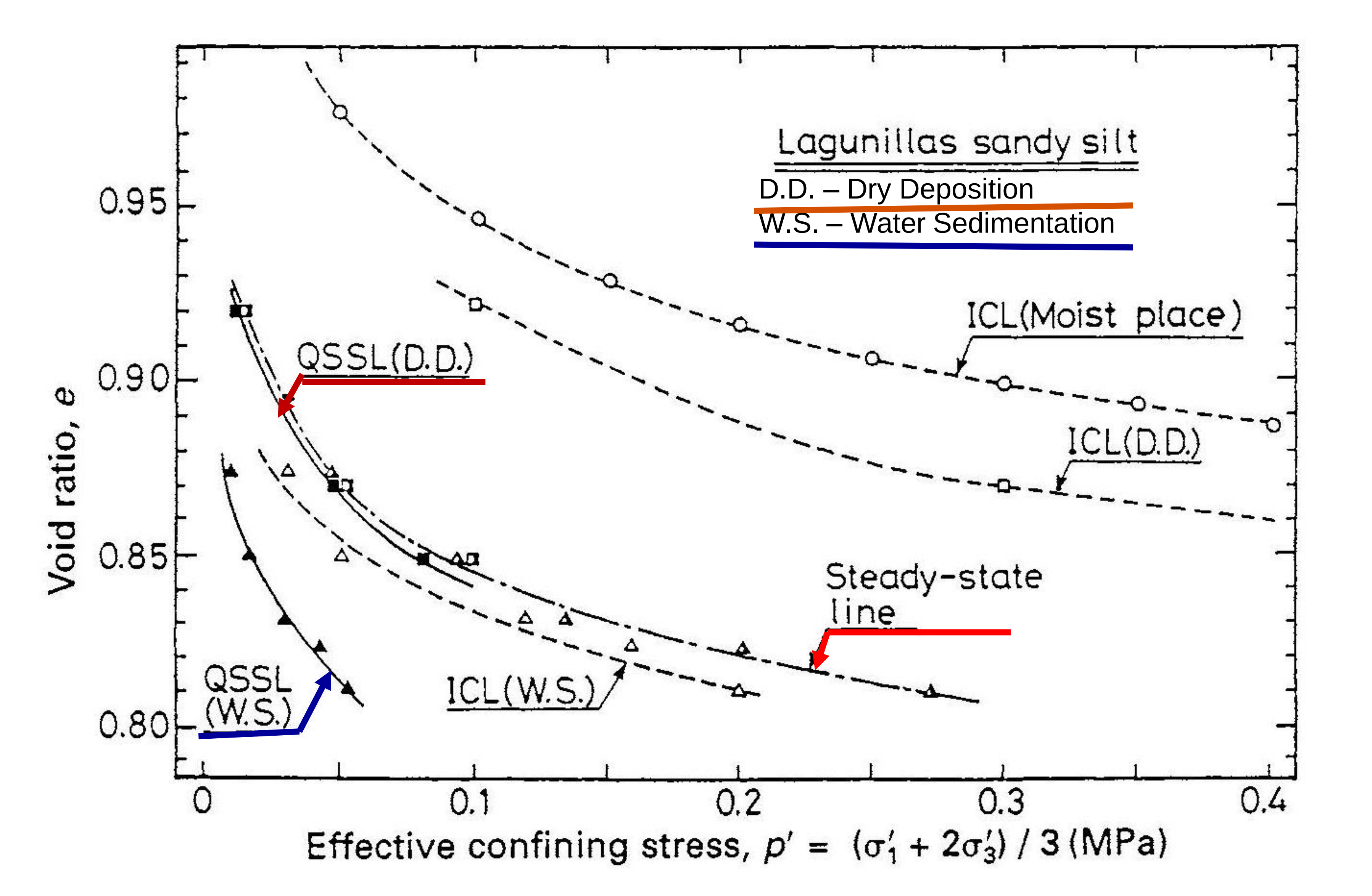
Brittleness Index (Bishop 1967):

$$I_B = 1 - S_r / S_{peak}$$

OVER LARGE STRESS RANGE



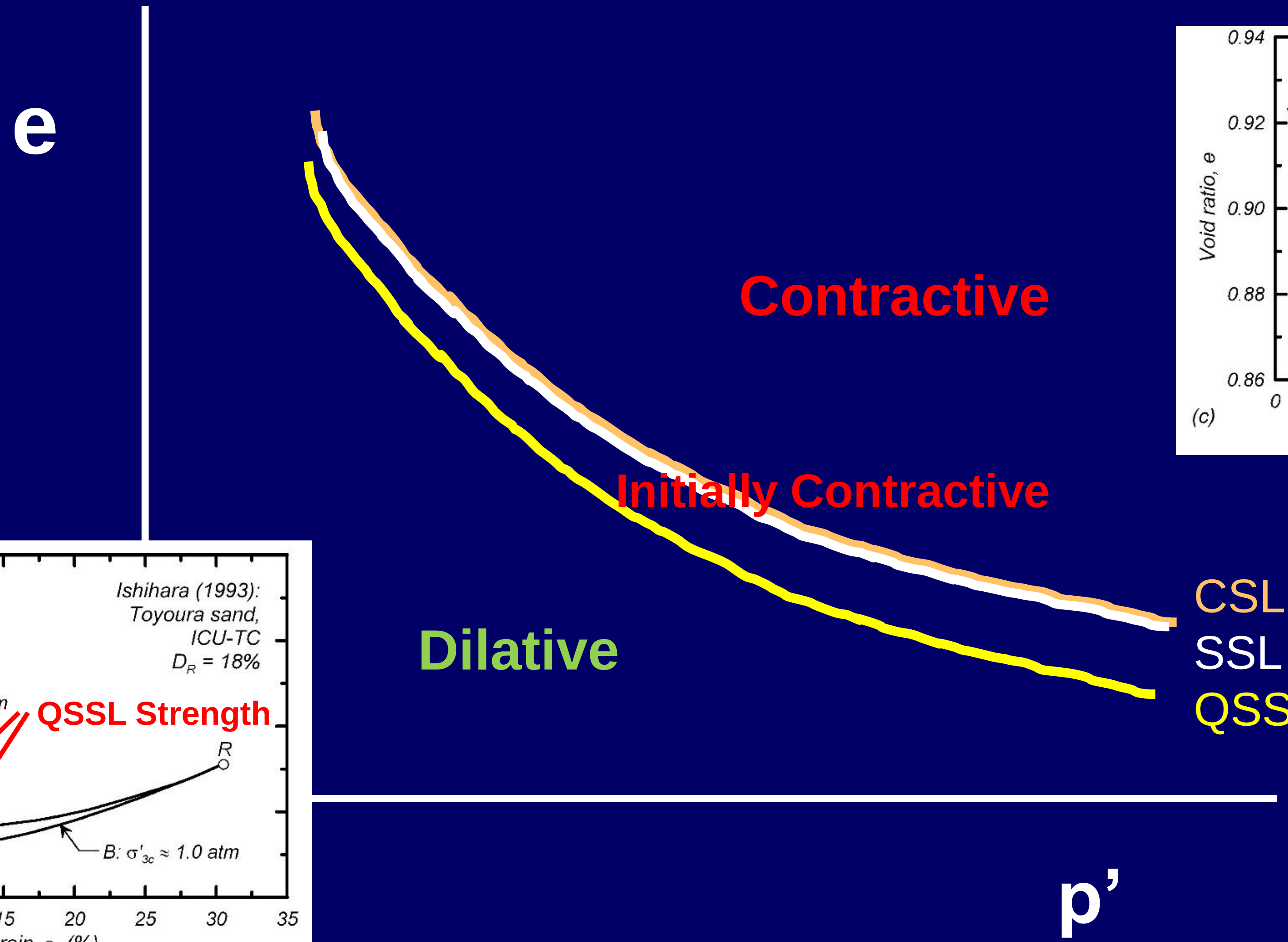
QSSLs & SSL with ICLs of Lagunillas Sandy Silt

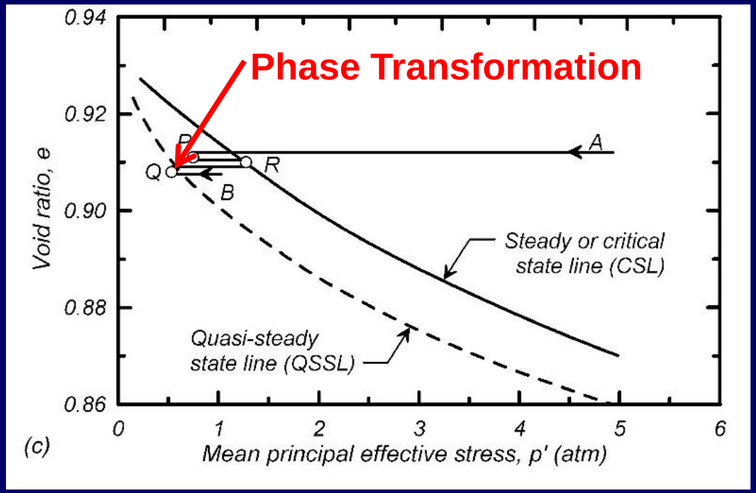


Ishihara 1996

QUASI-STEADY STATE LINE

(affected by soil fabric, i.e. depositional history)

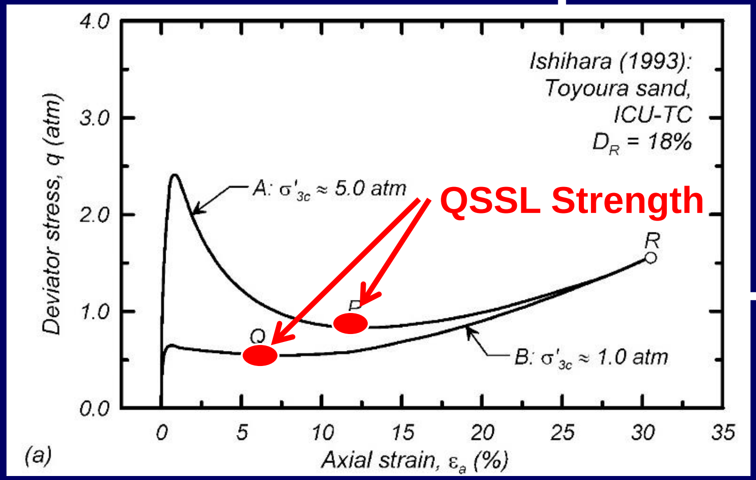




Data from Ishihara 1993

CSL
SSL } Independent of initial state or fabric

QSSL } Dependent on fabric



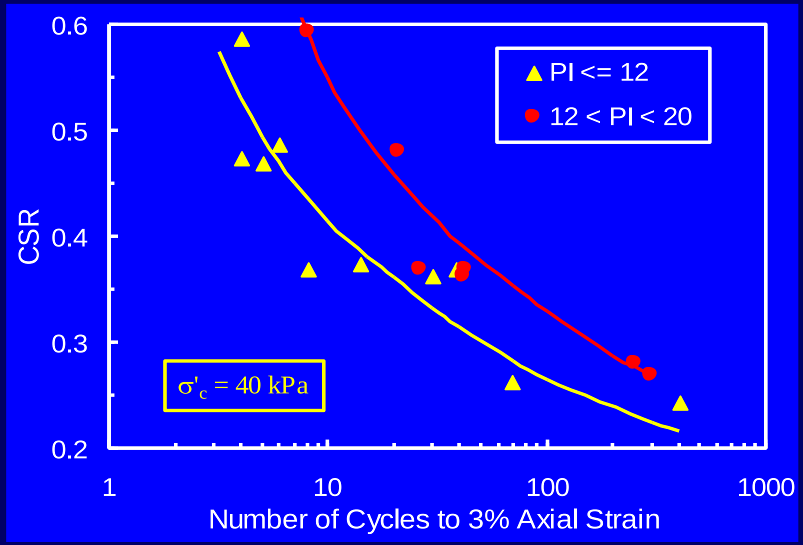
SILT LIQUEFACTION AFTER 1999 KOCAELI & CHI-CHI EQs

Silt can liquefy

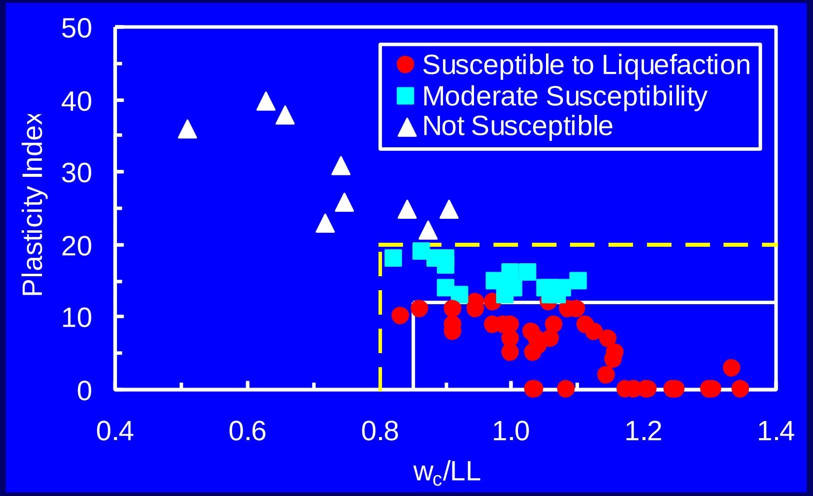
Do not use Chinese criteria because % clay-size criterion is not reliable

Focus on mineralogy & sensitivity:
Use PI ≤ 12 & w_c/LL ≥ 0.85

Under intense shaking, consider using:
PI ≤ 18 & w_c/LL ≥ 0.80

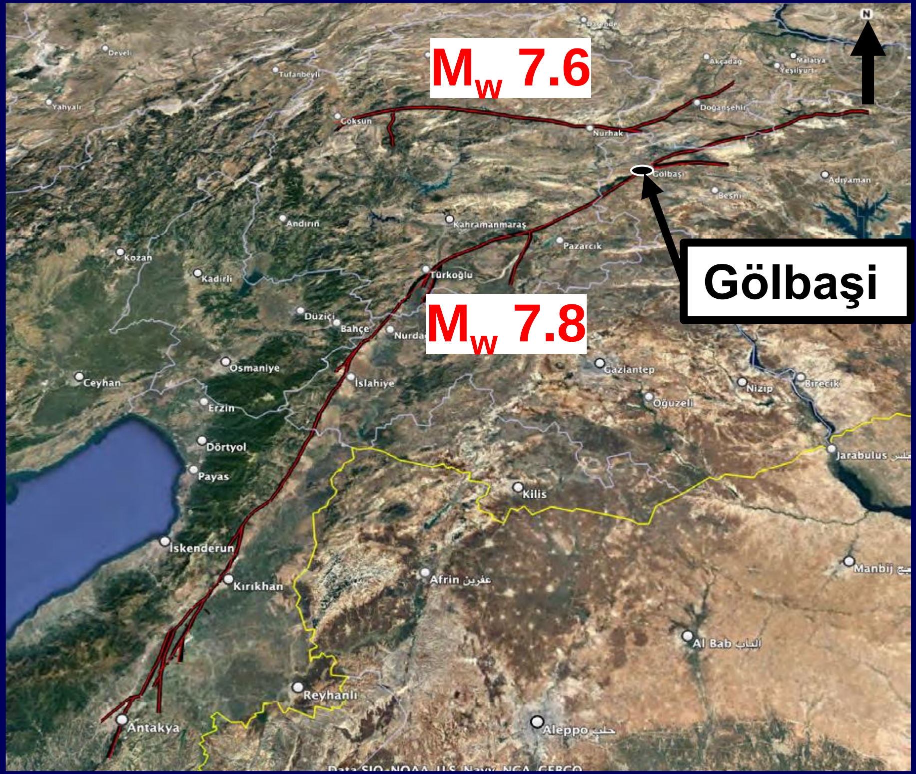


Silt CTX Testing (Bray & Sancio 2006)



Bray & Sancio 2006 Susceptibility Criteria

Sediment Ejecta in Gölbaşi – 2023 Turkey EQs



Ejecta (30MAR2023; 37.7877N, 37.6430E)

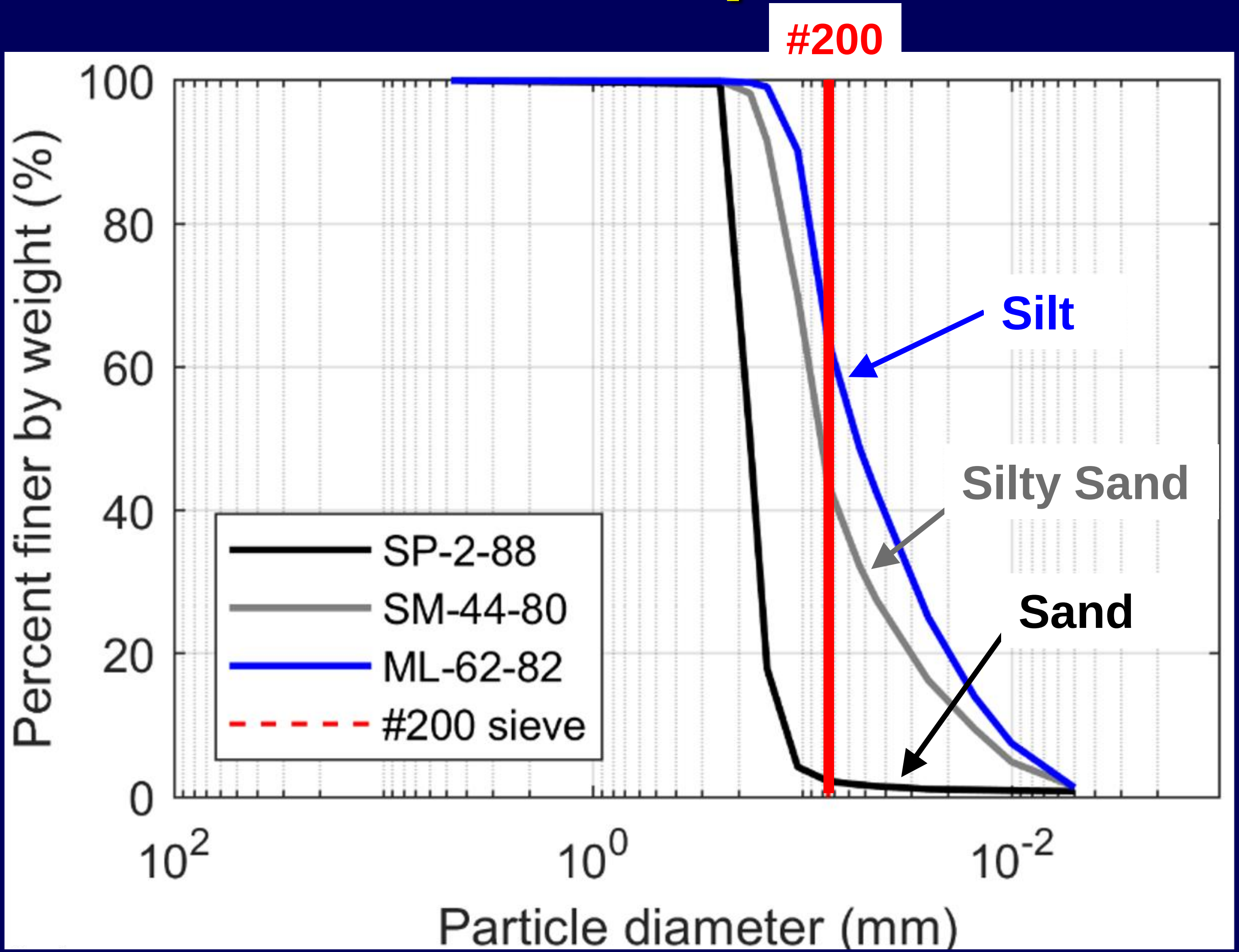
8 free-field ejecta samples collected after EQs

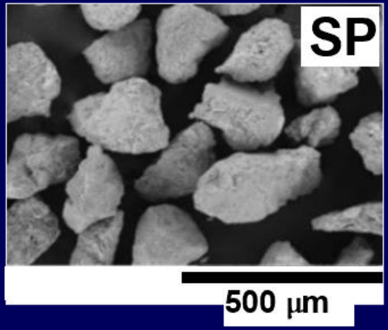
“Top-Down” procedure (Youd pers. com, 1999)

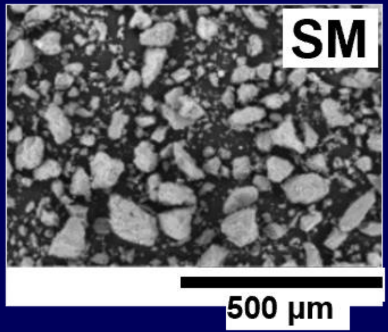
ASTM PI = 9 – 14

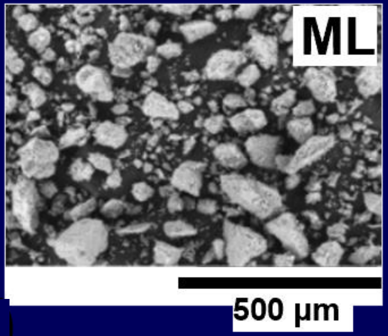
(Moug et al. 2023 GEER Report)

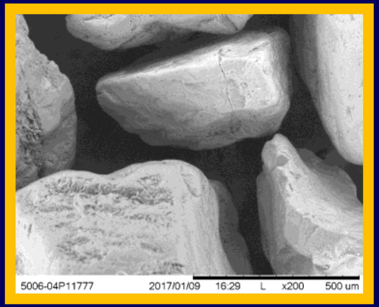
Grain-Size of Liquefiable Christchurch Soils











Classic Testing SP

Monterey 0/30
FC=0%
x200

Mijic et al. (2021)

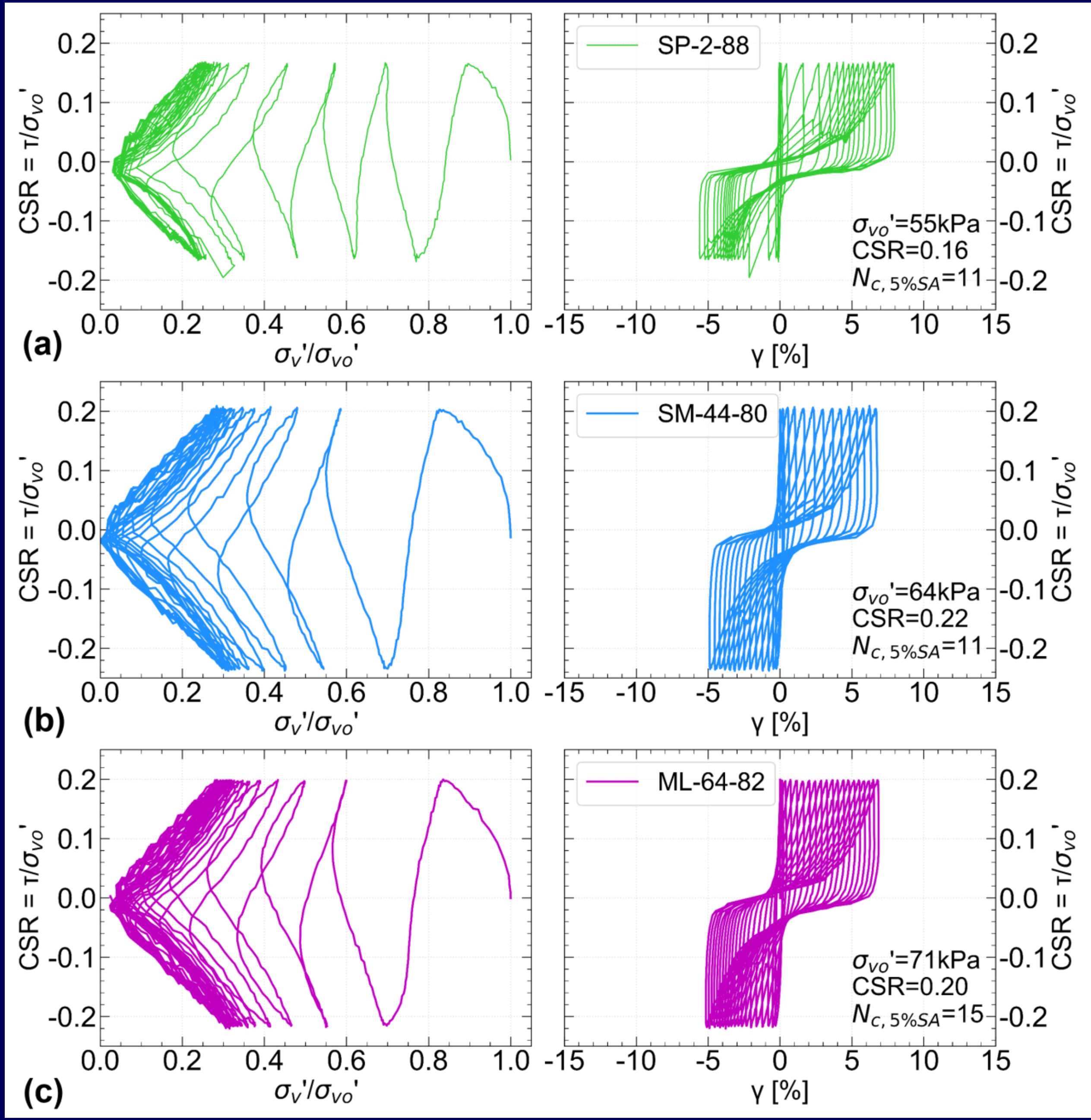
Does soil '*know*' the #200 sieve exists?

Cyclic Simple Shear Tests of “Undisturbed” Christchurch Soil

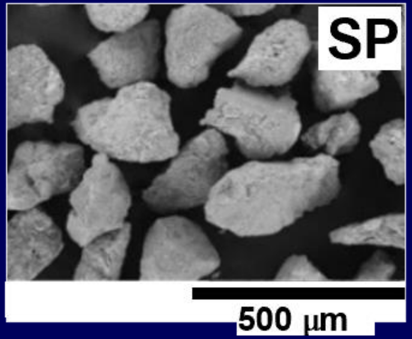
SP

SM

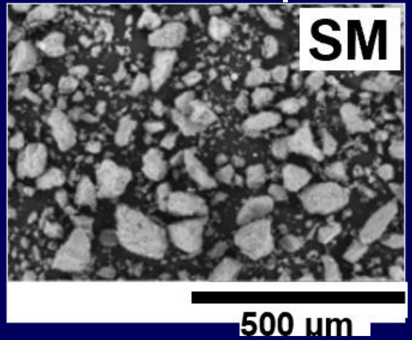
ML



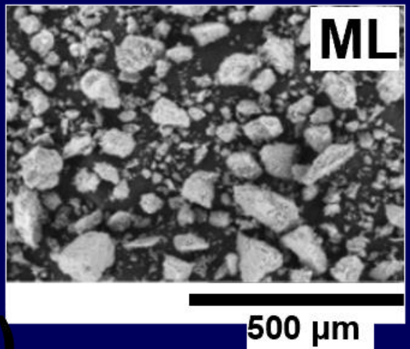
FC = 2%, D_r = 88%



FC = 44%, D_r = 80%

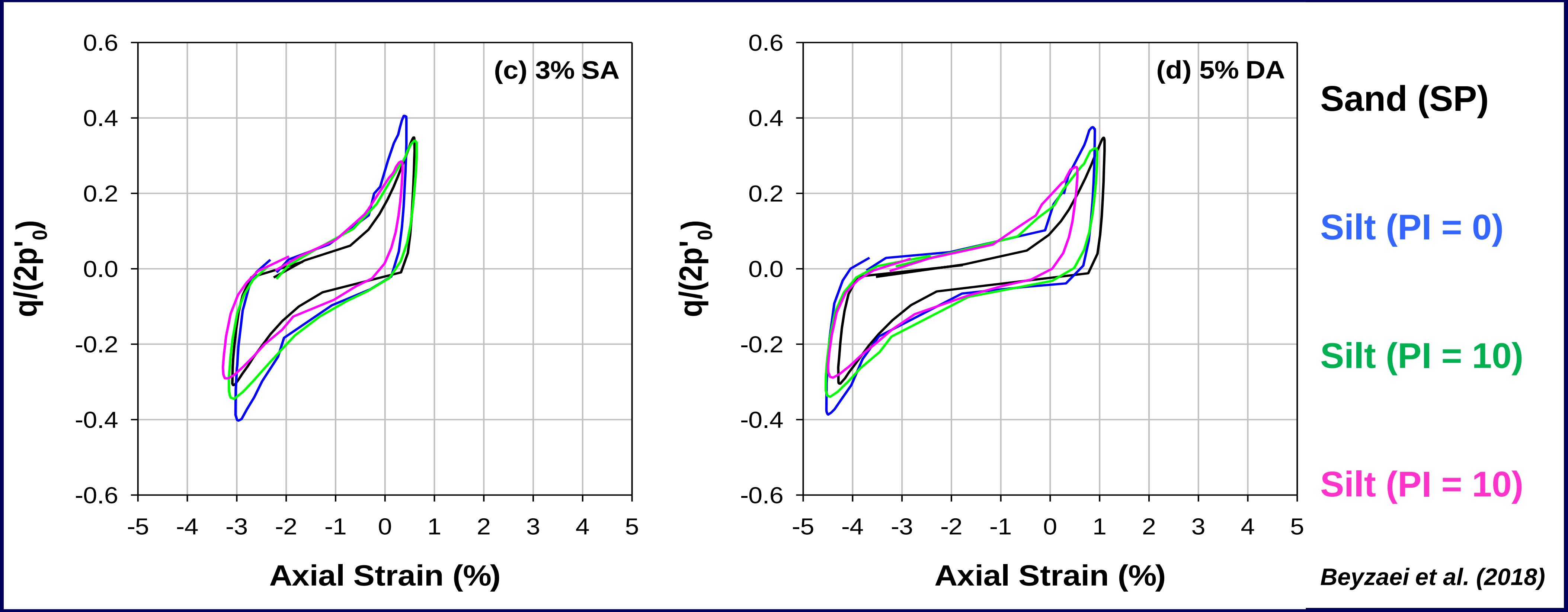


FC = 64%, D_r = 82%



Mijic et al. (2021)

Cyclic Triaxial Tests Performed on Christchurch Soil



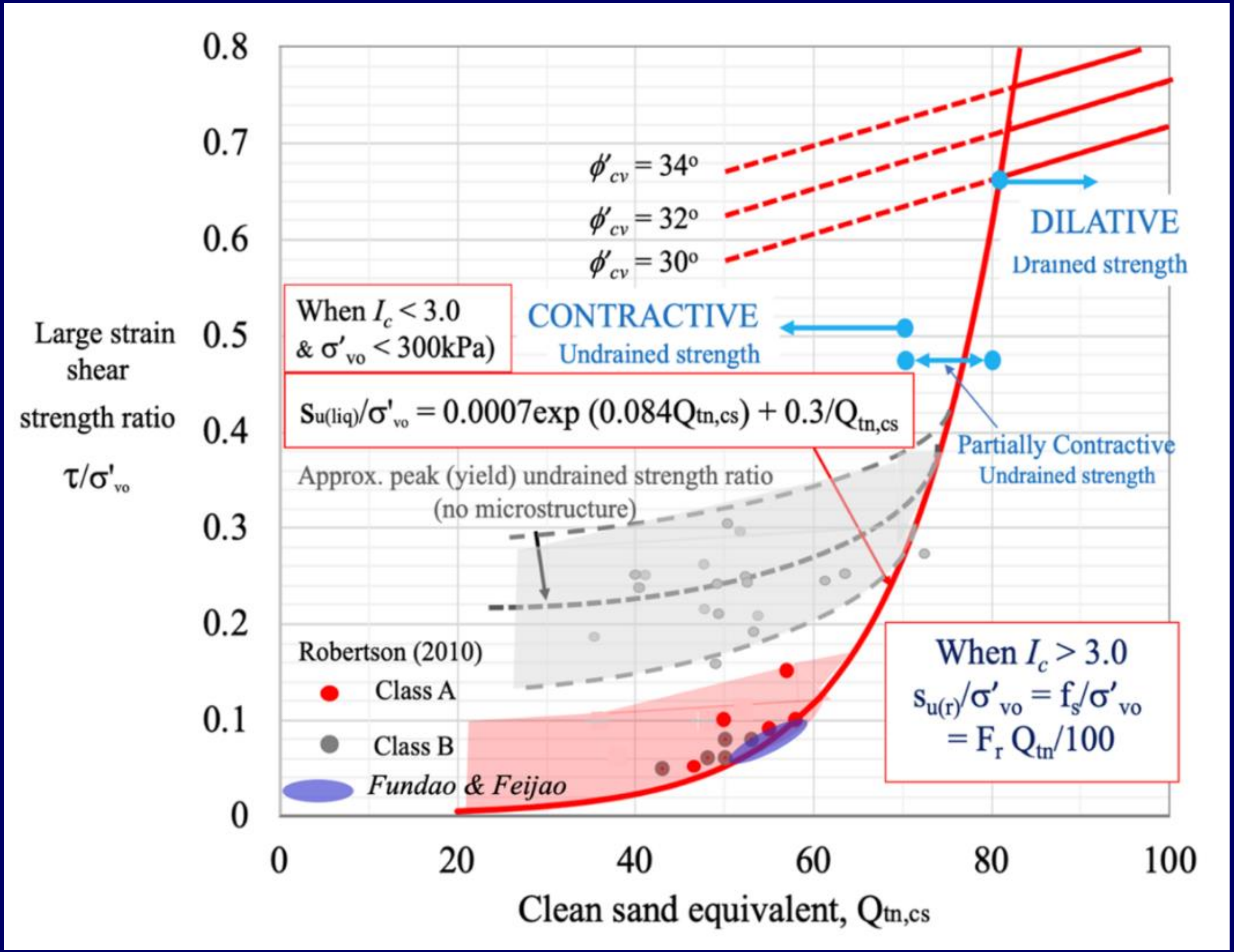
Bray & Sancio 2006 criteria based on engineering response & consequences of material

- "cyclic performance assessment" criteria

Perform cyclic testing on high FC soil to assess seismic response characteristics (they can be sampled effectively)

Sample & Test (Bray & Sancio 2006, 2008 and Boulanger & Idriss 2006, 2008)

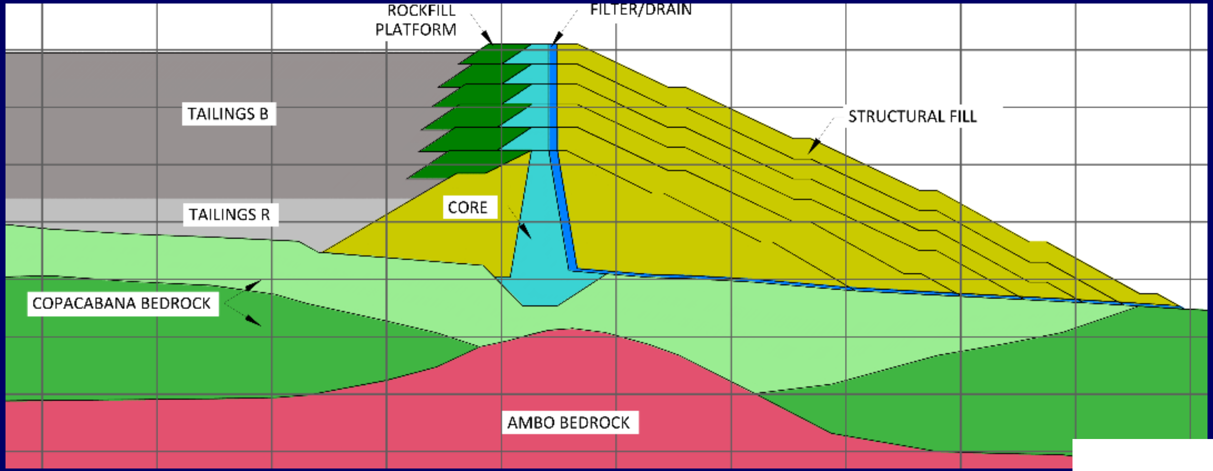
Post-Liquefaction Residual Strength

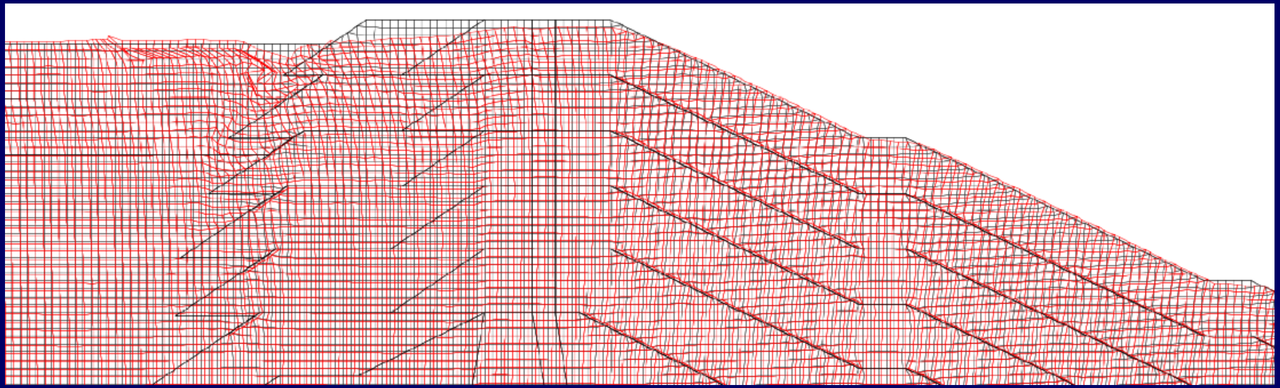


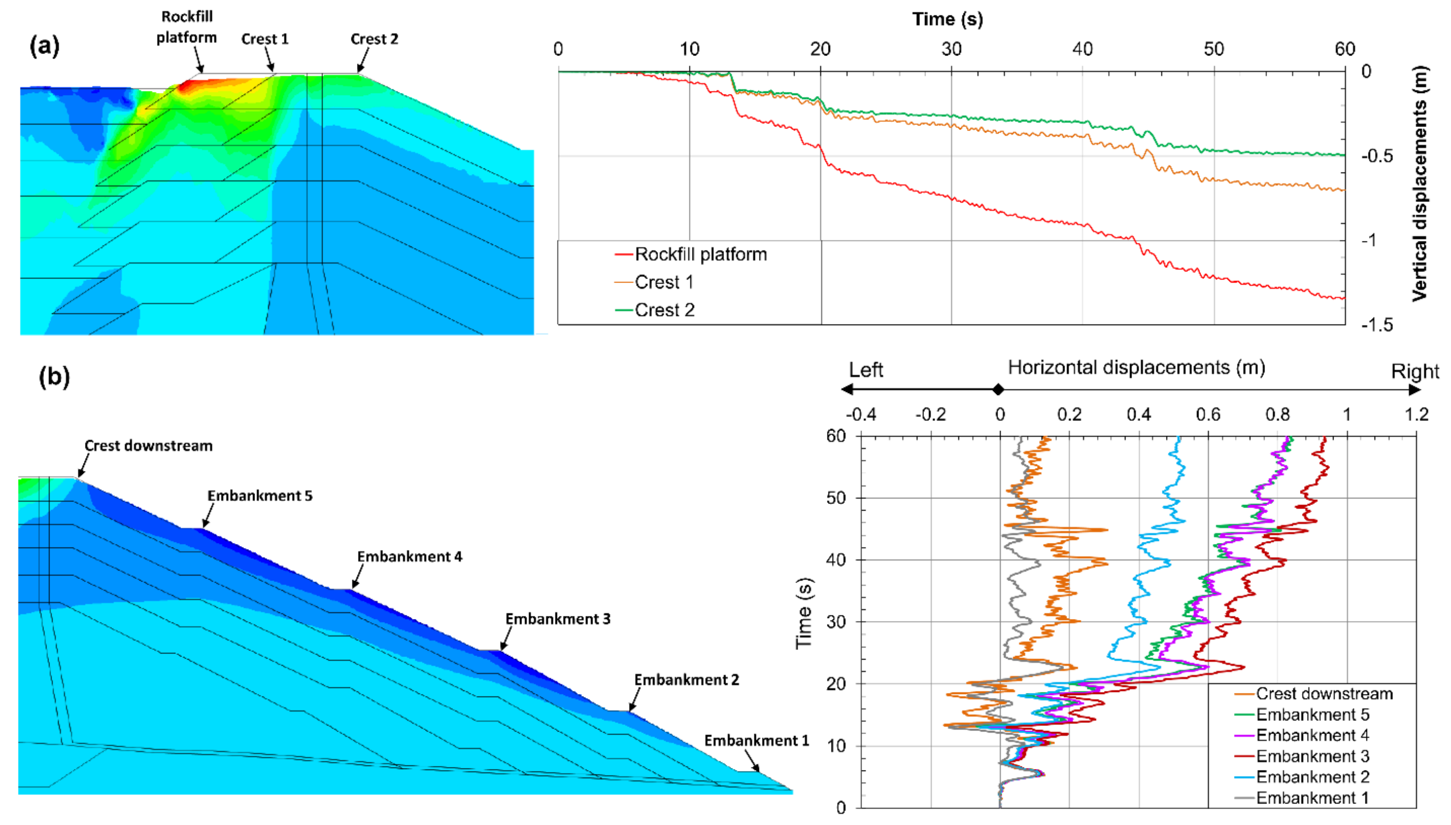
Robertson 2021

4. Seismic Slope Displacement

Finite Difference Analysis of a Centerline Tailings Dam







"Dynamic effective stress analysis of a centreline tailings dam under subduction earthquakes"

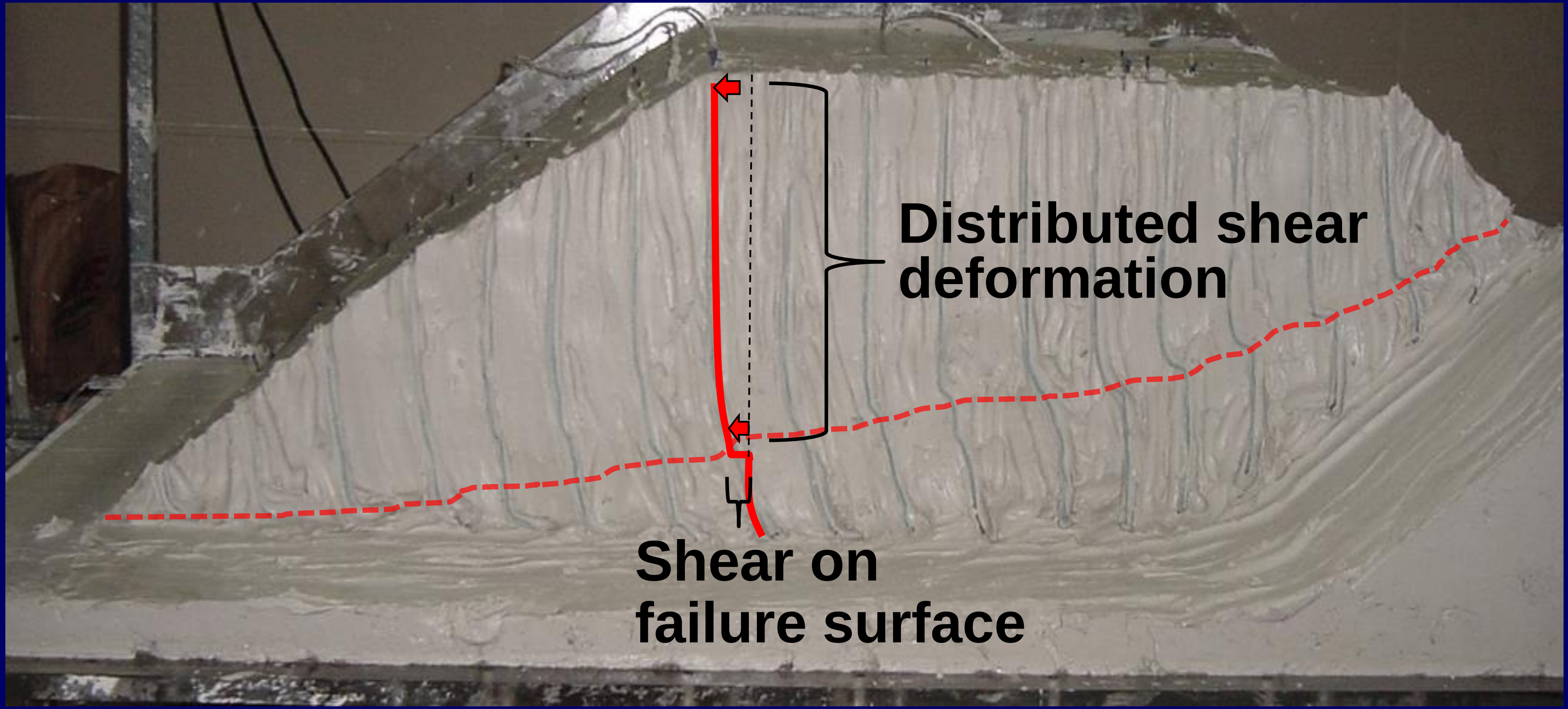
by Macedo et al. 2022

Seismic Slope Displacement

- **Shear on Failure Surface**
- **Distributed Shear Deformation**

} Newmark-type seismic displacement } **Shear**

- **Add Volumetric-Induced Deformation, when appropriate**



Key Components of Seismic Slope Displacement Analysis

a. Dynamic Resistance

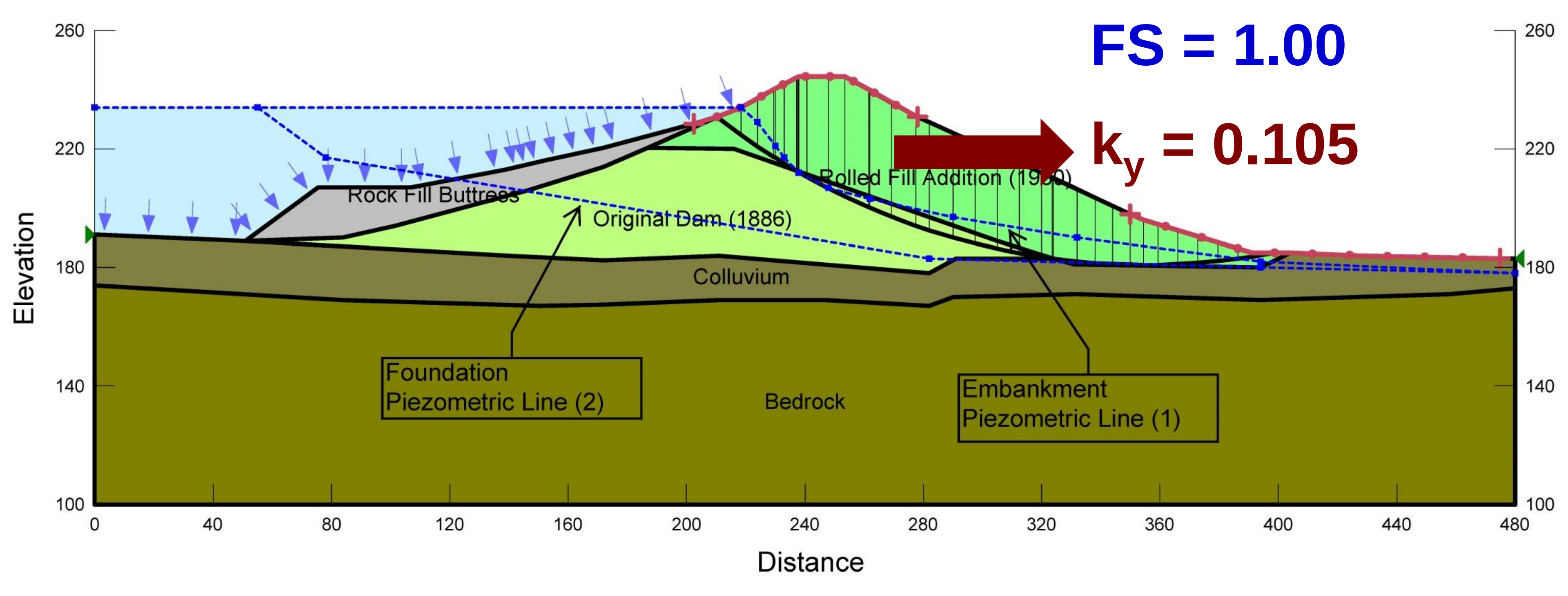
b. Earthquake Ground Motion

c. Dynamic Response

d. Seismic Displacement Calculation

a. Dynamic Resistance

Yield Coefficient (k_y): **seismic coefficient that results in FS=1.0 in pseudostatic stability analysis**

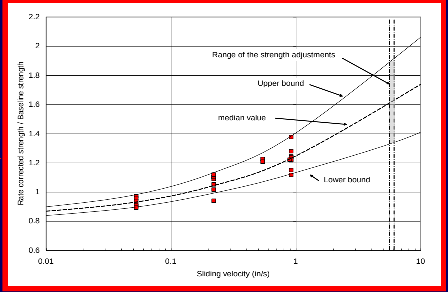


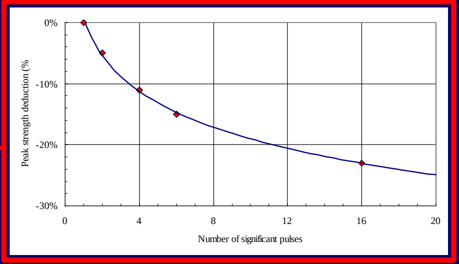
Use method that satisfies all three conditions of equilibrium and focus on soil strength, water pressures, and unit weight

Peak Dynamic Undrained Shear Strength of Clay

Chen et al. (2006)

- $S_{dynamic,\ peak} = S_{static,\ peak}\ (C_{rate})\ (C_{cyc})\ (C_{prog})\ (C_{def})$
- Rate of loading: $C_{rate} > 1$
- Cyclic Degradation: $C_{cyc} < 1$
- Progressive failure: $C_{prog} < 1$
- Distributed deformation: $C_{def} < 1$





Typical values often lead to:

$$S_{dynamic,\ peak} \approx S_{static,\ peak}\ (1.4)\ (0.85)\ (0.9)\ (0.9) \approx S_{static,\ peak}$$

But $S_{dynamic,\ peak}$ varies with loading, i.e., EQ motion:

Near-Fault Pulse: $S_{dynamic,\ peak} \approx S_{static,\ peak}\ (1.4)(1.0)(1.0)(0.9) \approx 1.2\ S_{static,\ peak}$

Long Duration: $S_{dynamic,\ peak} \approx S_{static,\ peak}\ (1.4)(0.7)(0.9)(0.9) \approx 0.8\ S_{static,\ peak}$

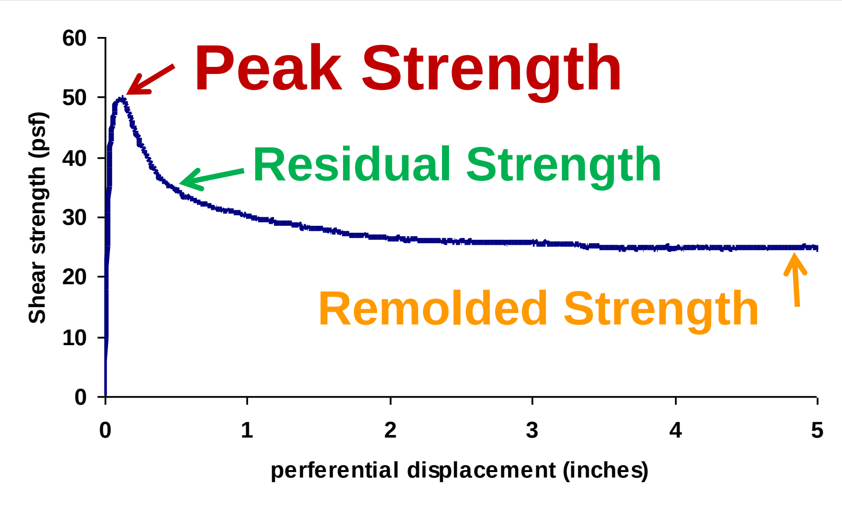
Dynamic Shear Strength of Clay

Chen et al. (2006)

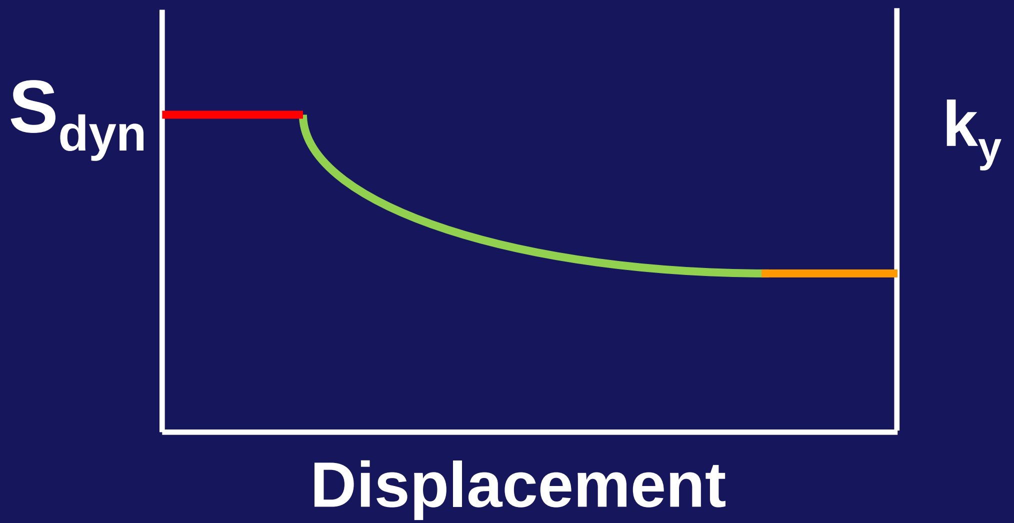
Peak dynamic strength is used for strain-hardening soil or limited displacement

As EQ-induced strain exceeds failure strain, dynamic strength reduces for strain-softening soil

Thus, $S_{dynamic}$ & k_y are also a function of displacement

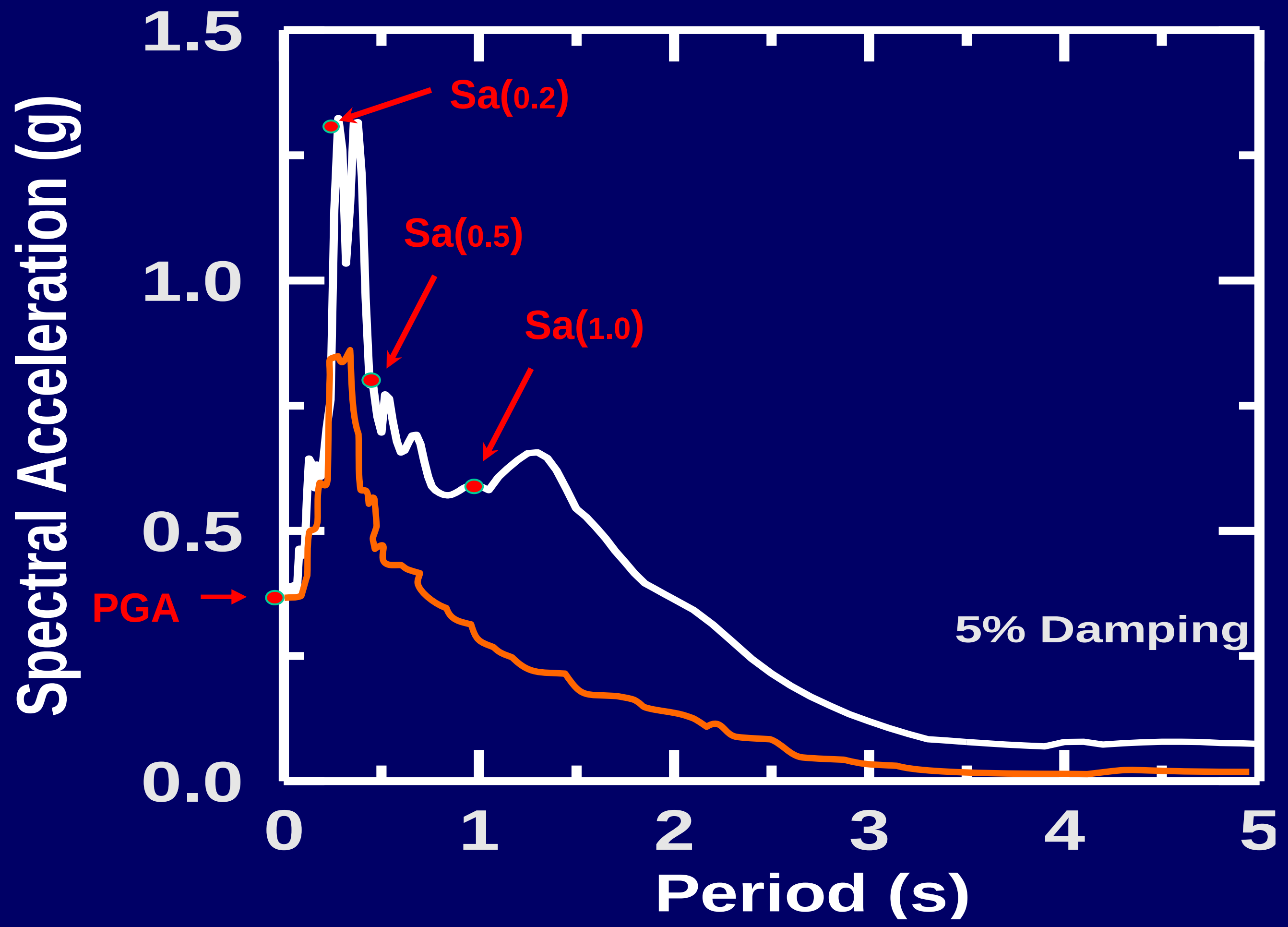


Field Vane Shear Test (FVST) [ASTM D2573]



b. Earthquake Ground Motion:

Acceleration Response Spectrum



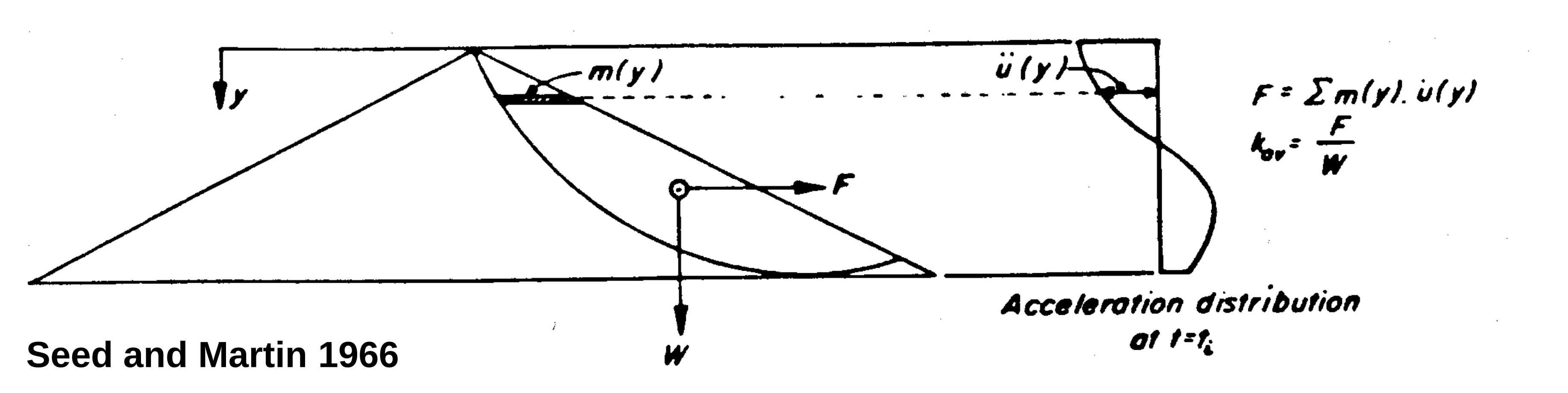
provides response of SDOF of different periods at 5% damping

indicates intensity and frequency content of ground motion below sliding mass

ground motion characteristics greatly affect slope displacement

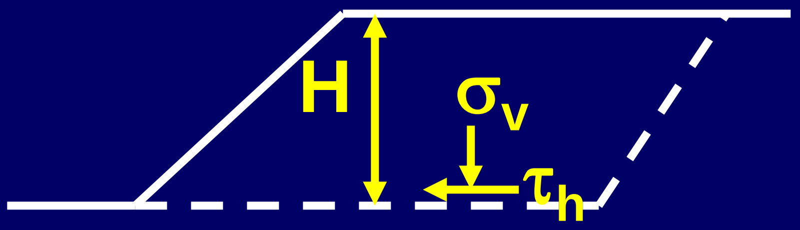
c. Dynamic Response of Sliding Mass

Equivalent Acceleration Concept

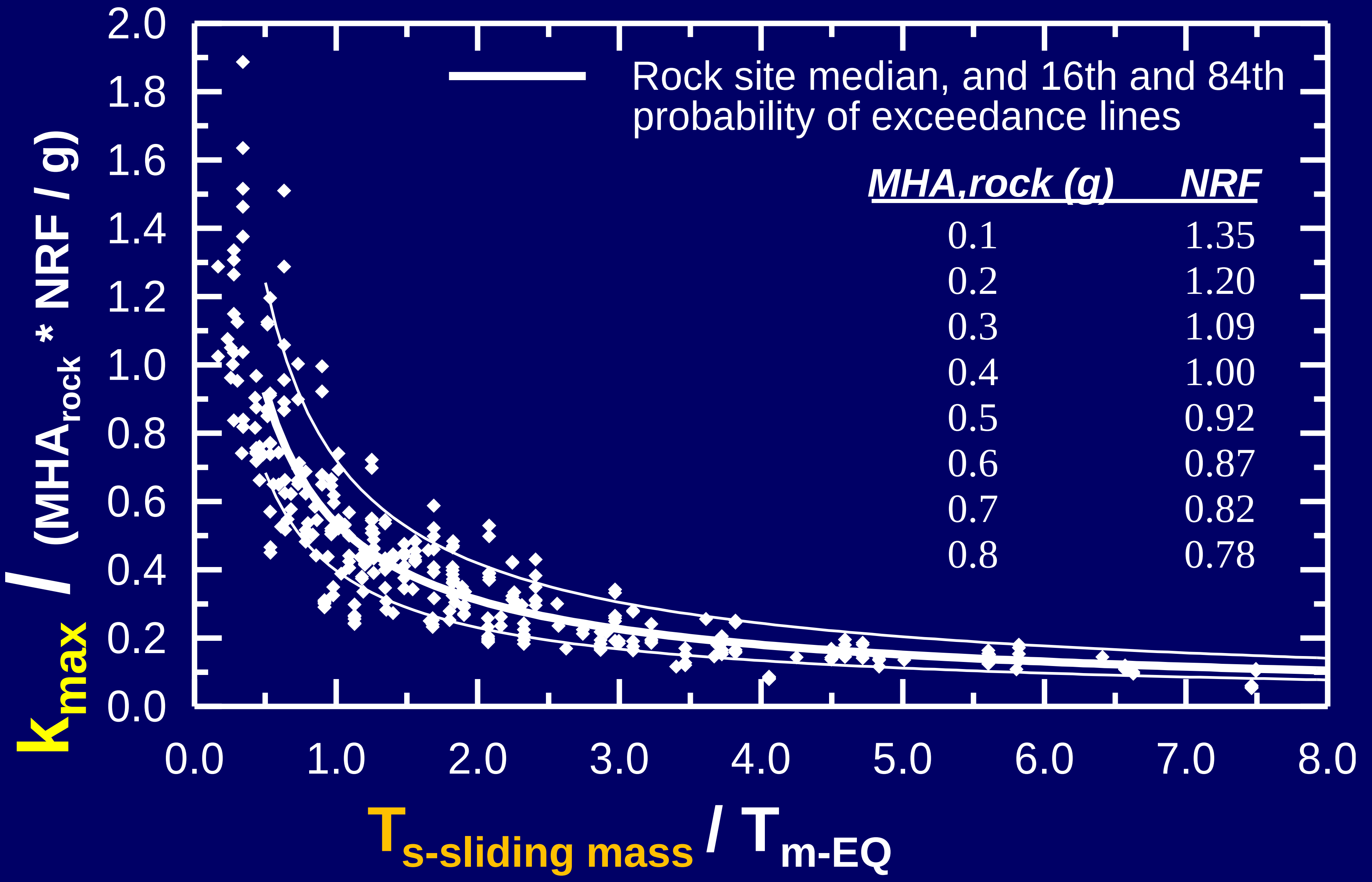


accounts for cumulative effect of incoherent motion in deformable sliding mass

- Horz. Equiv. Accel.: HEA(t) = $(\tau_h(t) / \sigma_v)$ g
- k_{max} = max. HEA / g



FACTORS AFFECTING MAXIMUM SEISMIC LOADING



(Bray & Rathje 1998)

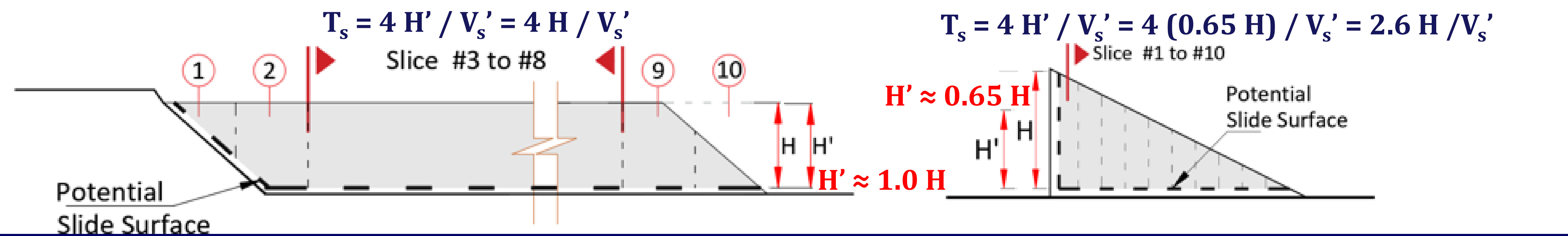
Fundamental Period of Sliding Mass (T_s)

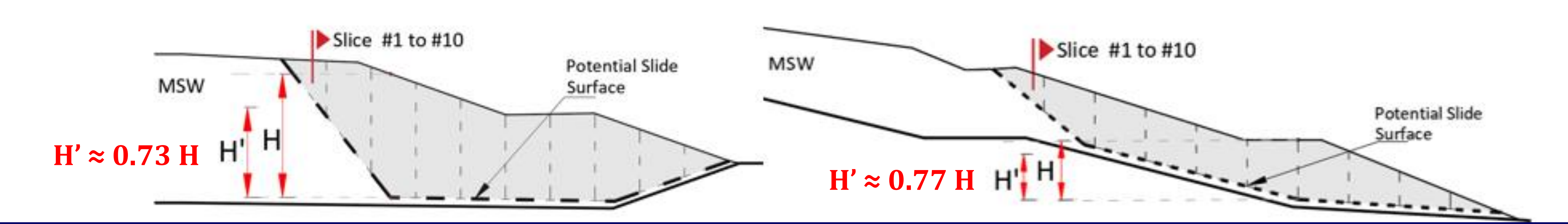
$$T_s = 4\,H' / V_s'$$

T_s = Initial Fundamental Period of Sliding Mass

V_s' = Average Shear Wave Velocity of Sliding Mass ($V_s' = \Sigma[(V_{si})(m_i)] / \Sigma(m_i)$)

H' = Effective Height of Sliding Mass ($H' = (\text{mass-weighted-}T_s)\, V_s' / 4$)





$H' \approx 0.65\,H$ to $1.0\,H$ (Bray & Macedo 2021)

Topographic Amplification of PGA for Shallow Sliding

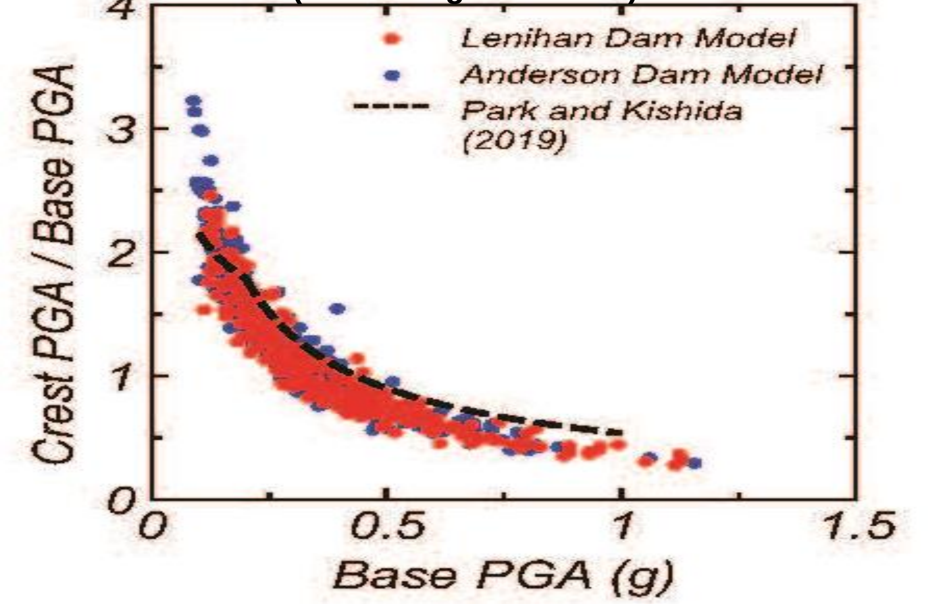
- **Steep Slope (>60º):** $PGA_{crest} \approx 1.5\ PGA_{1D}$
  (Ashford and Sitar 2002)

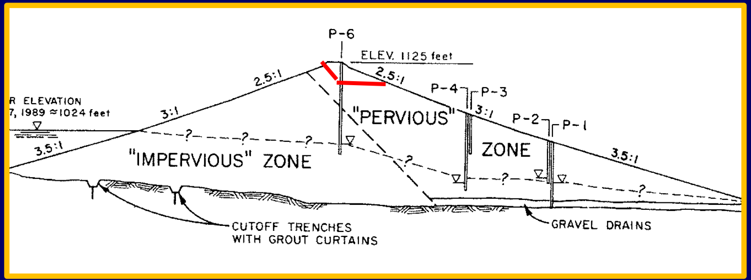
- **Moderate Slope (<45º) :** $PGA_{crest} \approx 1.3\ PGA_{1D}$
  (Rathje and Bray 2001)

In addition to 1D Site Effects

- **Dam Crest:** $PGA_{crest} \approx \exp(-0.62 + 0.254 \ln(PGA_{rock}))$ — $PGA_{rock} > 0.2\ g$
  (Park & Kishida 2019) $PGA_{crest} \approx \exp(0.147 + 0.731 \ln(PGA_{rock}))$ — $PGA_{rock} \leq 0.2\ g$

(Armstrong et al. 2020)



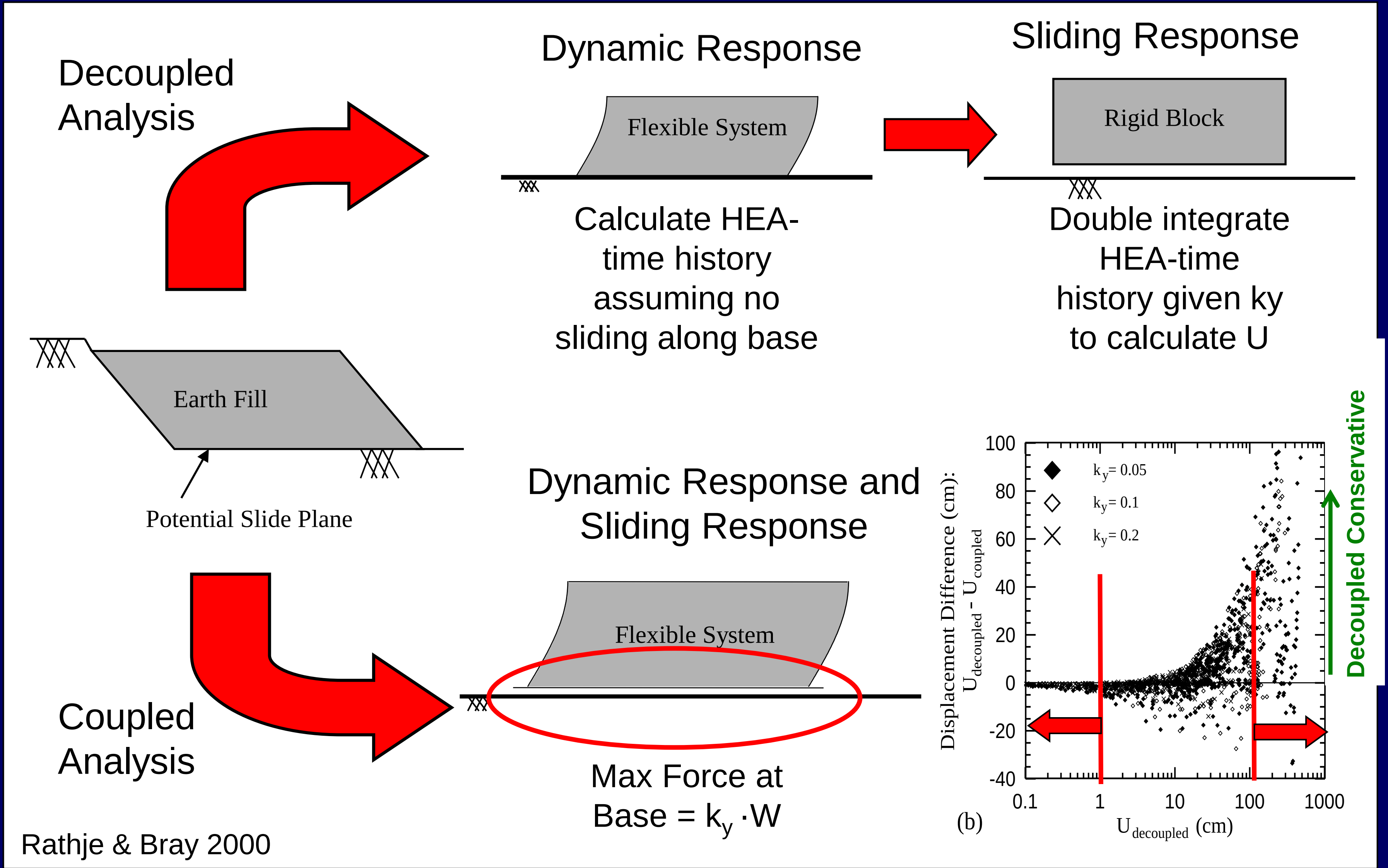


d. Seismic Displacement Calculation

Modified Newmark Sliding Block Analysis

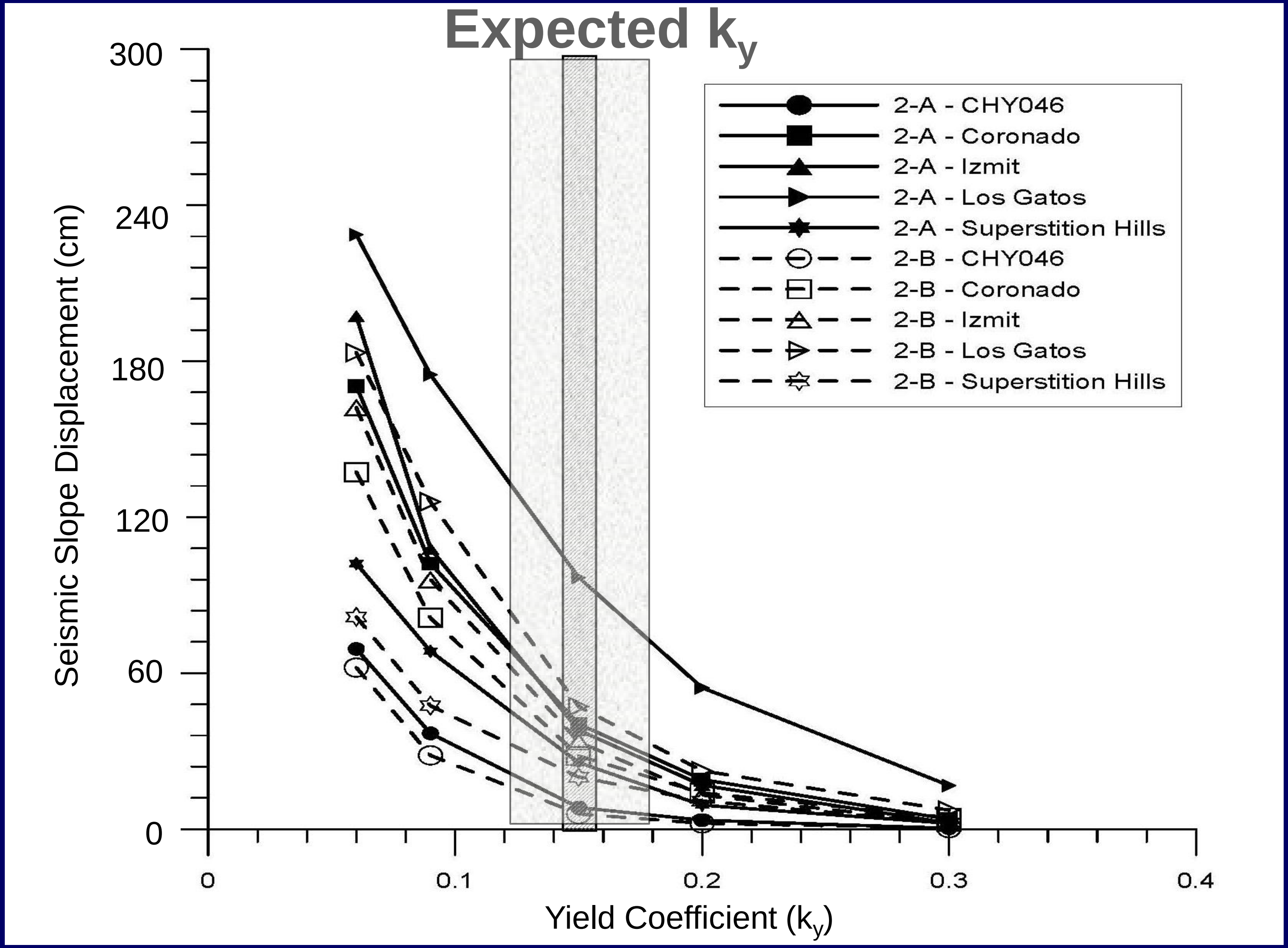
$FS_{static} > 1.0$

$k_y > 0$



Rathje & Bray 2000

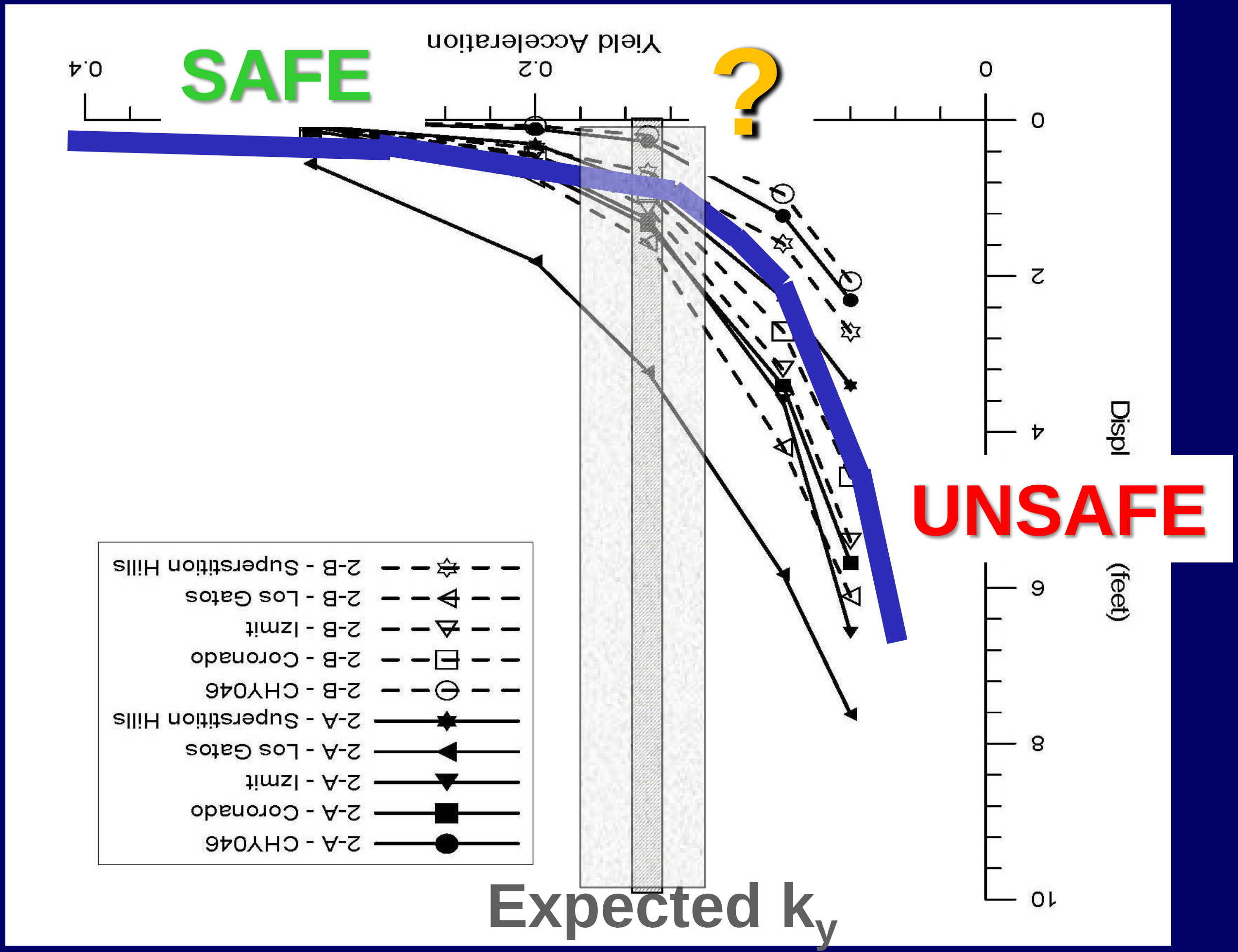
Calculated Seismic Slope Displacement (D)



Use programs such as SLAMMER by Jibson et al. (2013)

Think About It as a “Cliff”

Calculated Seismic Displacement is an *Index* of Performance



Evaluate Seismic Performance

Given seismic displacement estimates:

- Minor (e.g., D < 30 cm)
- Major (e.g., D > 1 m)

Evaluate the ability of the tailings dam to accommodate the estimated level of deformation

Consider:

- Brittleness of materials
- Consequences of failure and conservatism of hazard assessment and stability analyses
- Defensive measures that provide redundancy, e.g., filters, chimney drain, more freeboard, wider crest

Bray & Macedo (2019) Seismic Slope Procedure

update to Bray & Travasarou (2007) which was based on NGA-West-1

1. SLOPE MODEL

   nonlinear soil response

   fully coupled deformable stick-slip

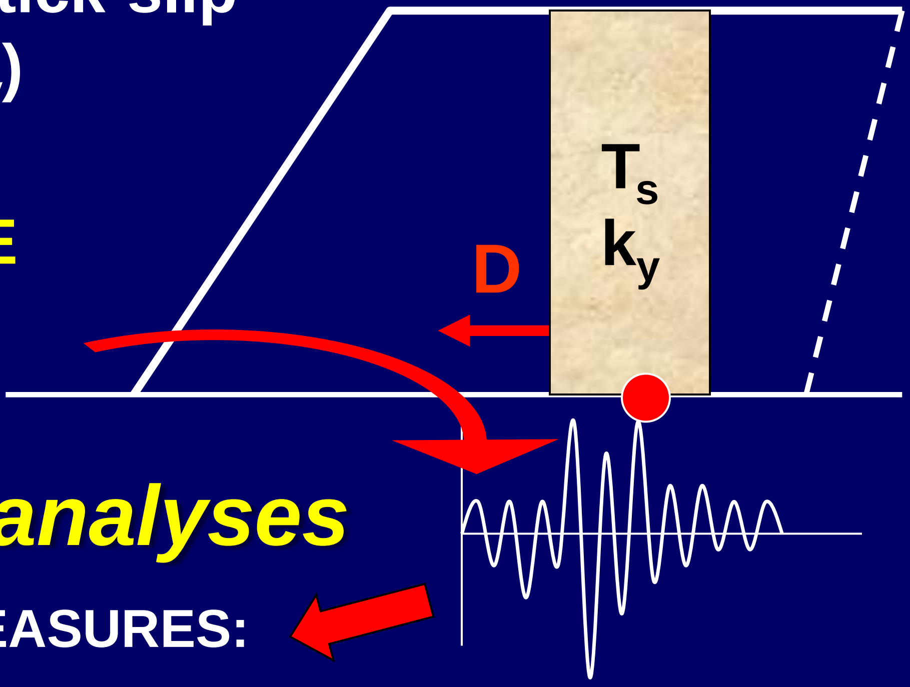
   stiffness (T_s) & strength (k_y)

   13 T_s values & 10 k_y values

2. EARTHQUAKE DATABASE

   6711 two-component records

   NGA-West-2: crustal EQs



Nearly 3000000 analyses

OPTIMAL INTENSITY MEASURES:

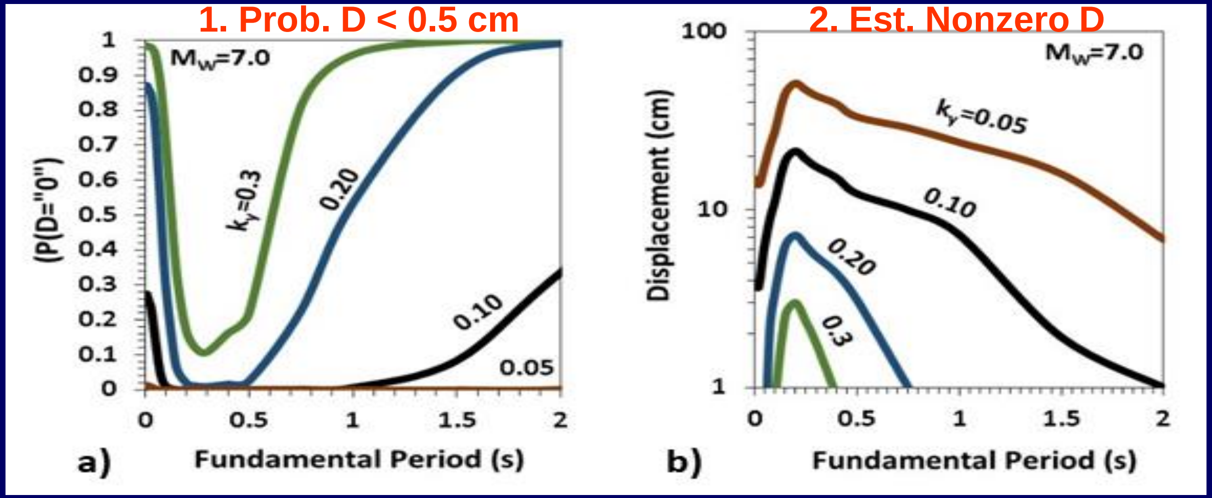
$S_a(1.3\ T_s)$ & M_w of outcropping motion below slide

3. VALIDATION

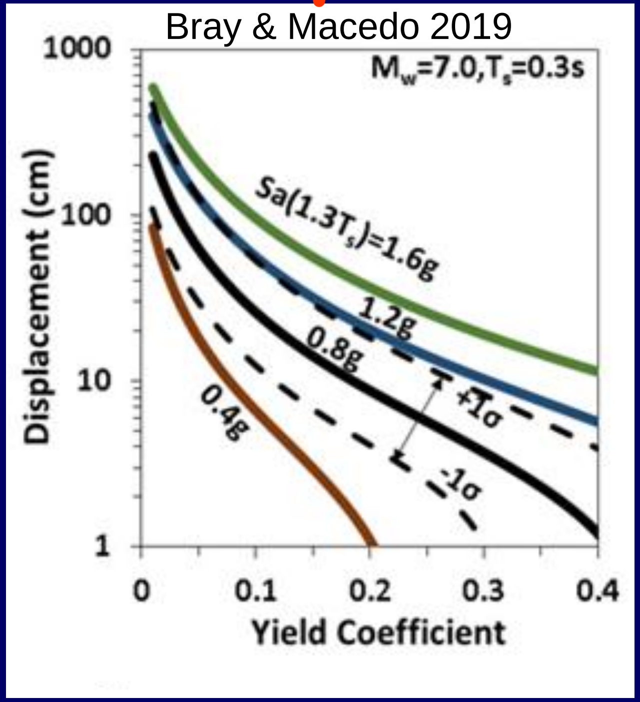
   13 case histories

Mixed Random Variable Approach

$P\,(D_0 = \text{'0'}) = f\,(k_y, S_a(1.3T_s), T_s)$

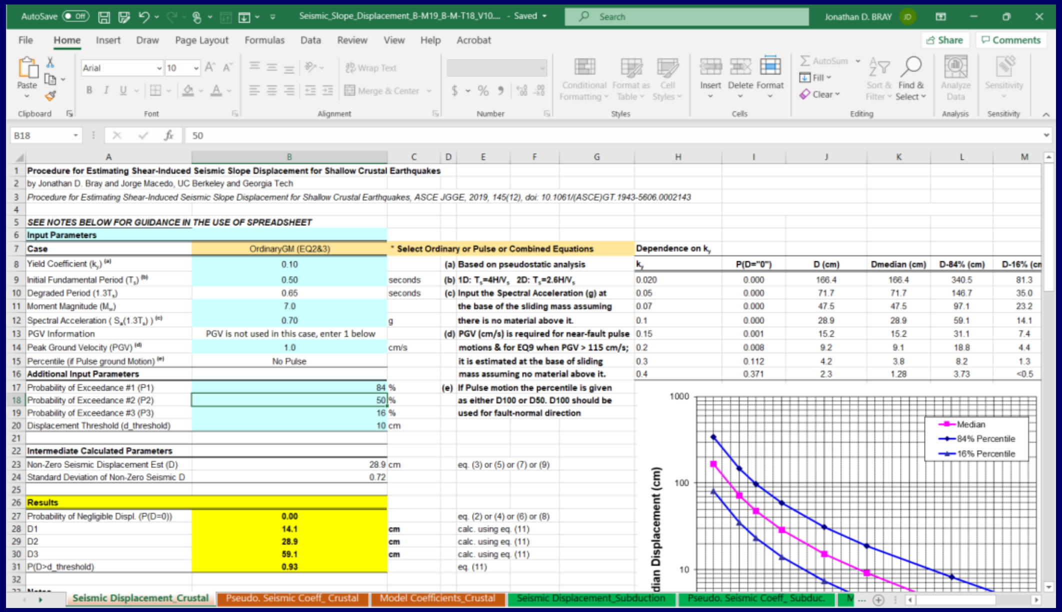


$D = f\,(k_y, S_a(1.3T_s), T_s, M_w) \pm \varepsilon$

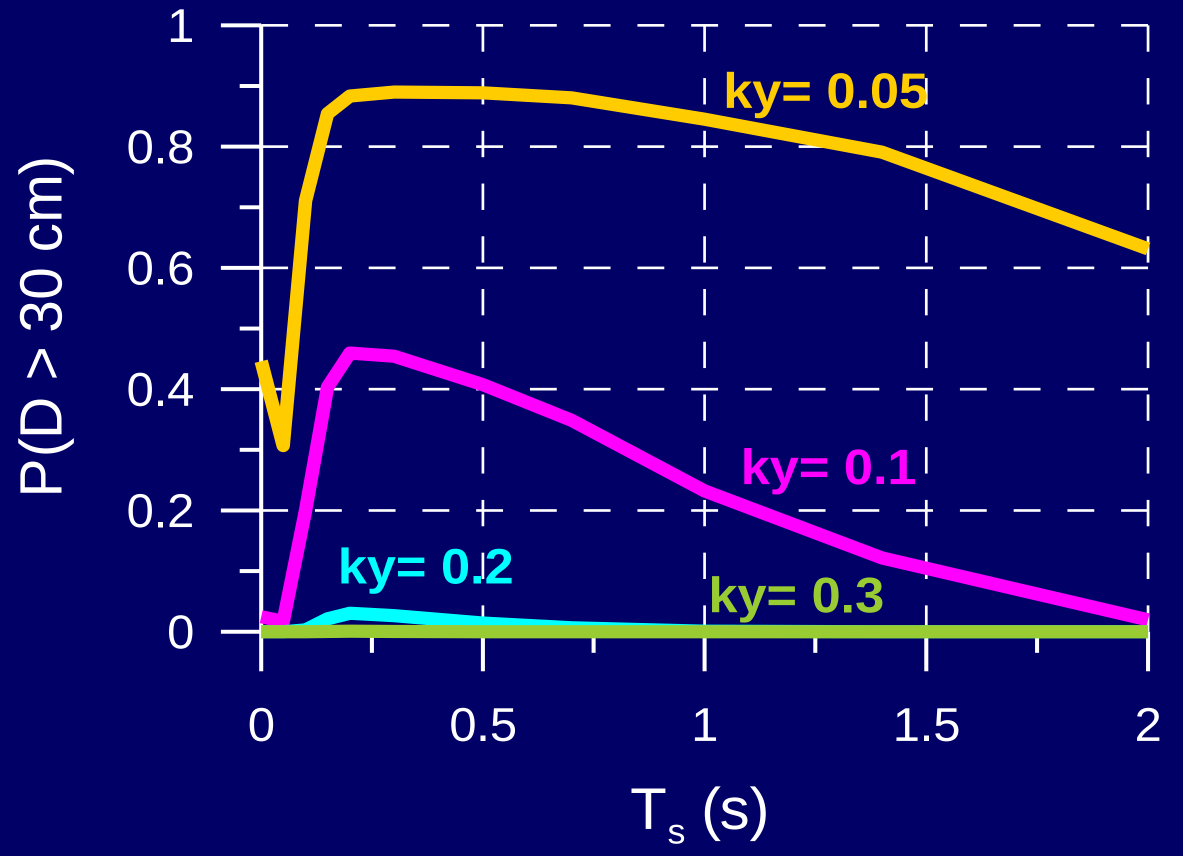


Use Spreadsheet:

https://ce.berkeley.edu/people/faculty/bray



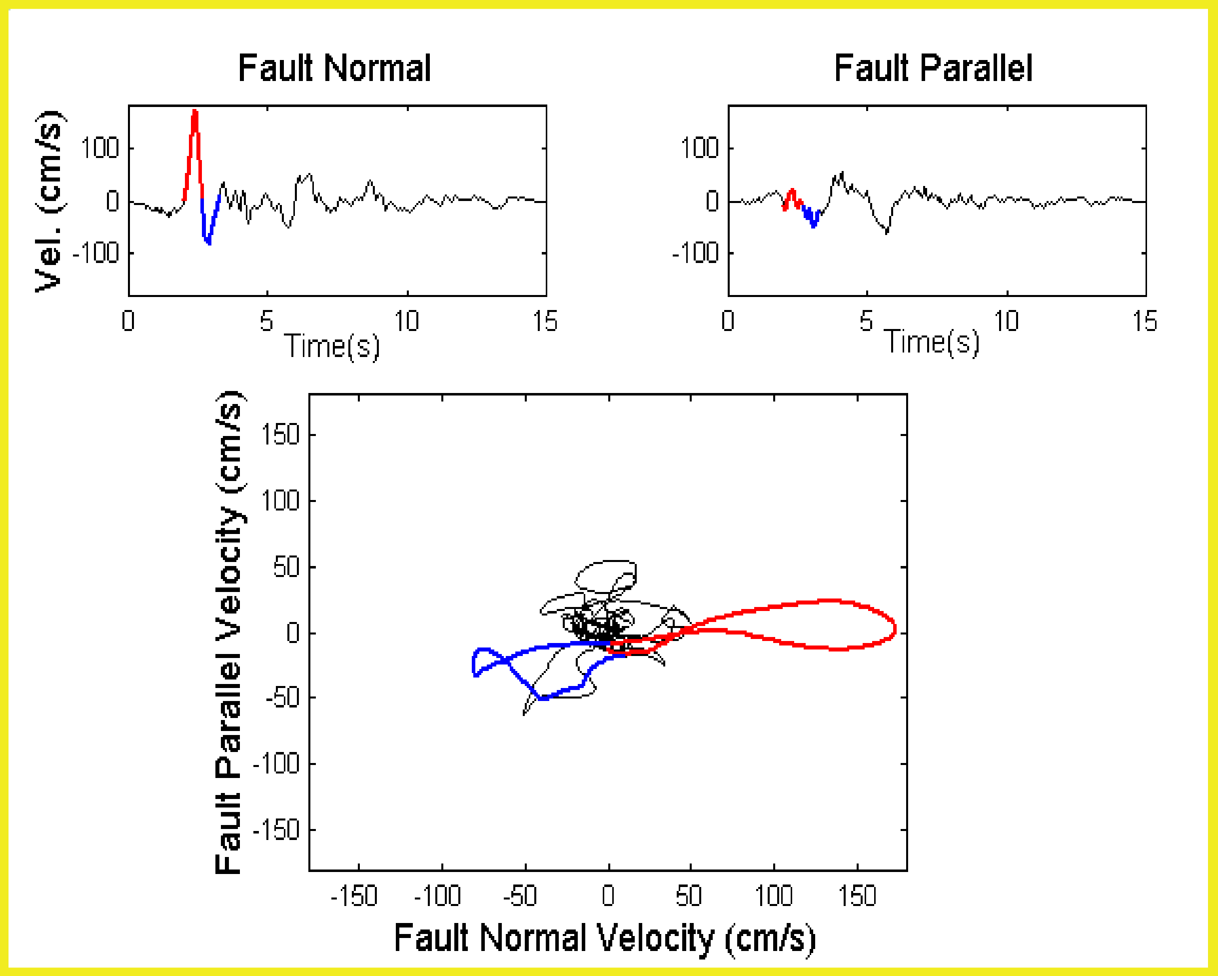
PROBABILITY OF EXCEEDANCE OF DISPLACEMENT THRESHOLD



Scenario Event: M 7 at 10 km “Soil” – SS fault

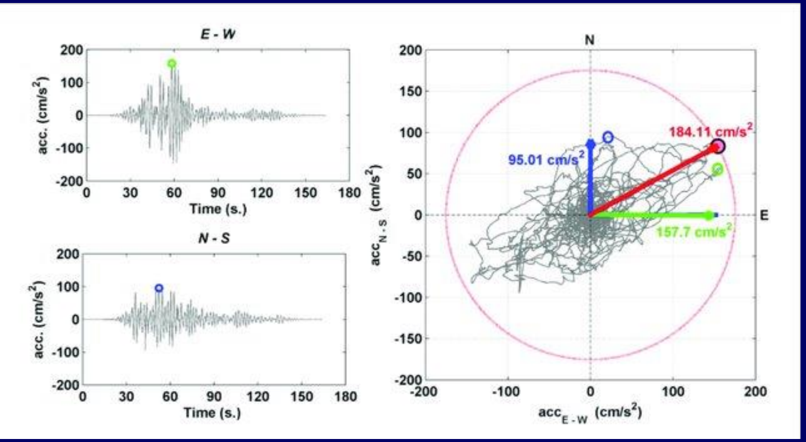
Forward-Directivity Fault-Normal & Fault-Parallel Velocity Pulses

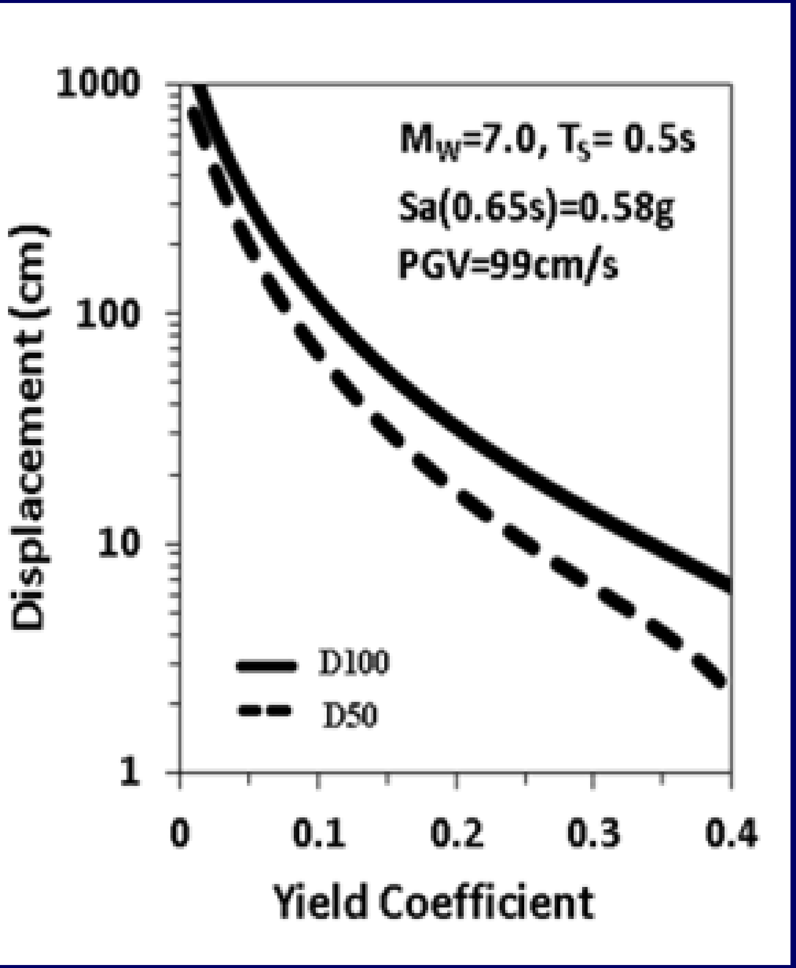
Rinaldi Receiving Station (1994 Northridge EQ)



Bray & Macedo (2019) Near-Fault Pulse Model

$$D = f\,(k_y, S_a(1.3T_s), T_s, M_w, PGV)$$





D100: Max D Component

D50: Median D Component

Horz. components of each near-fault recording rotated in 1º increments to calculate D100 & D50

Use D100 for Fault-Normal & D50 for Fault-Parallel Orientations

Validation of Bray & Macedo (2019) Simplified Procedure

System	EQ	Obs. D_{max} (cm)	Bray & Macedo 2019 P (D = "0")	Bray & Macedo 2019 Est. Disp (cm)
Guadalupe LF	LP	Minor	0.96	0
Pacheco Pass LF	LP	None	1.0	0
Austrian Dam	LP*	50	0.0	33 - 98
Lexington Dam	LP*	15	0.0	22 - 65
Chiquita Canyon D LF	NR*	30	0.0	15 - 44
Sunshine Canyon LF	NR*	30	0.0	17- 50

*Denotes Pulse Motion

Bray & Macedo (2019) used 13 well documented case histories in validation

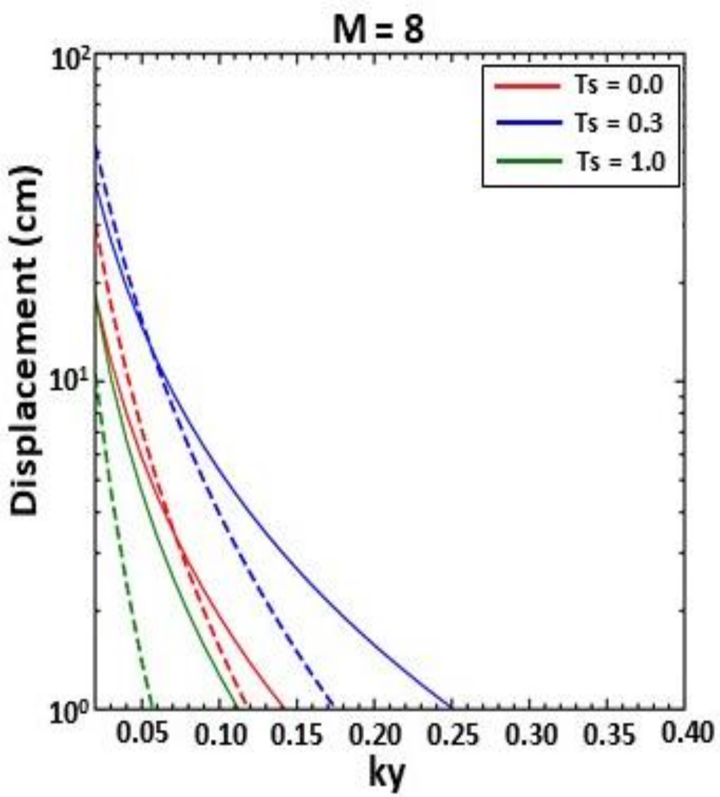
Subduction Zone Earthquakes

Macedo et al. (2023)

- 6240 Interface Subduction Zone EQ Two-Component Recordings (M_w from 4.8 to 9.1)

  Bray et al. (2018) used 810 two-component recordings (M_w from 7.0 to 9.1)

- 8299 Intraslab Subduction Zone EQ Two-Component Recordings (M_w from 4.0 to 7.8)

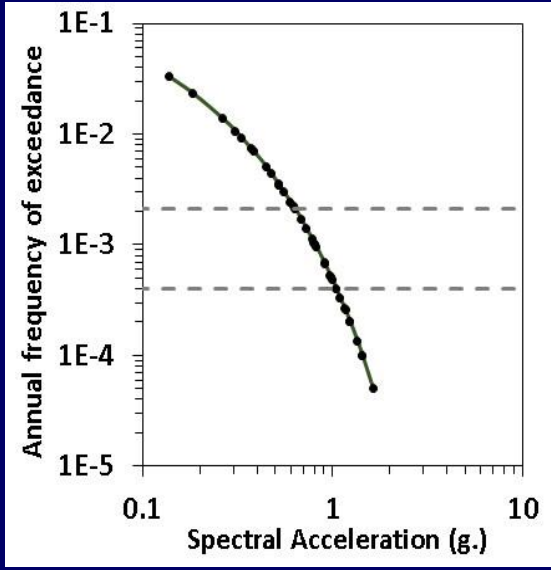


Solid Lines: Intraslab EQ Model

Dashed Lines: Interface EQ Model

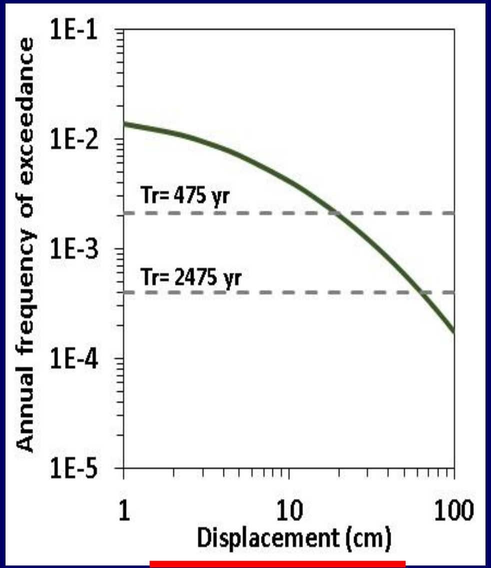
Ground motions processed uniformly
(PEER NGA-Sub Database, Bozorgnia & Stewart 2020)

Performance-Based Probabilistic Approach



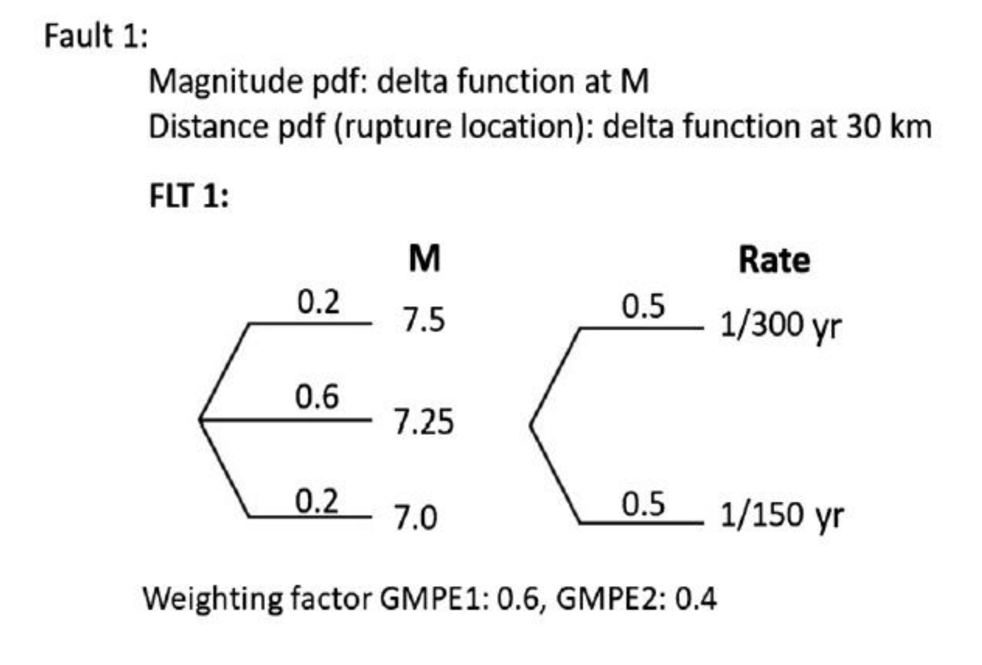
$$D = f\,(k_y\;\; S_a\;\; T_s\;\; M_w)$$

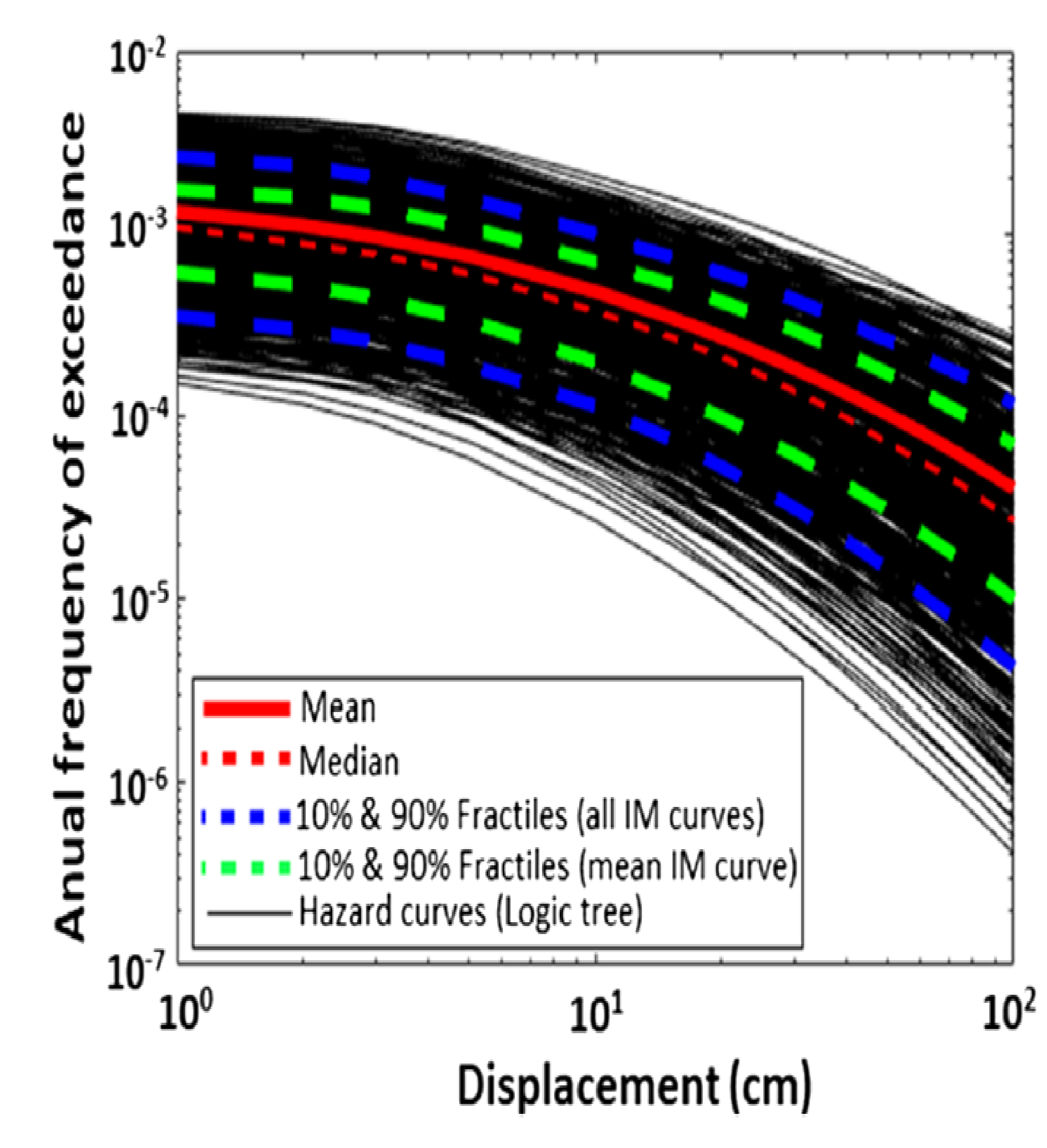
- *Include variability of S_a & D*
- *Include variability of k_y & T_s*



Mean Seismic Slope Displacement Hazard Curve

Capture Epistemic Uncertainty





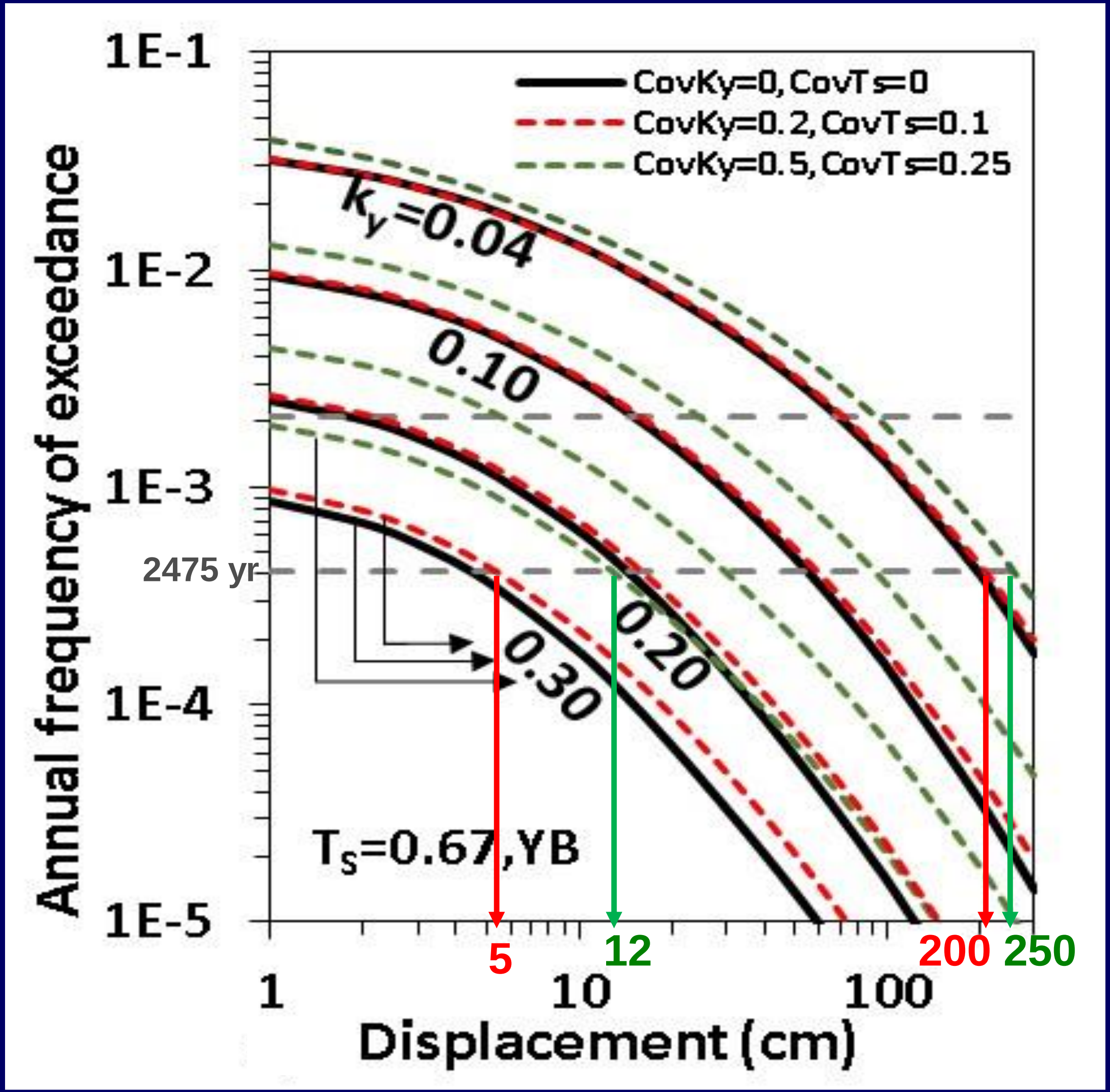
Logic Trees for:

M, R, Rate, GMMs &

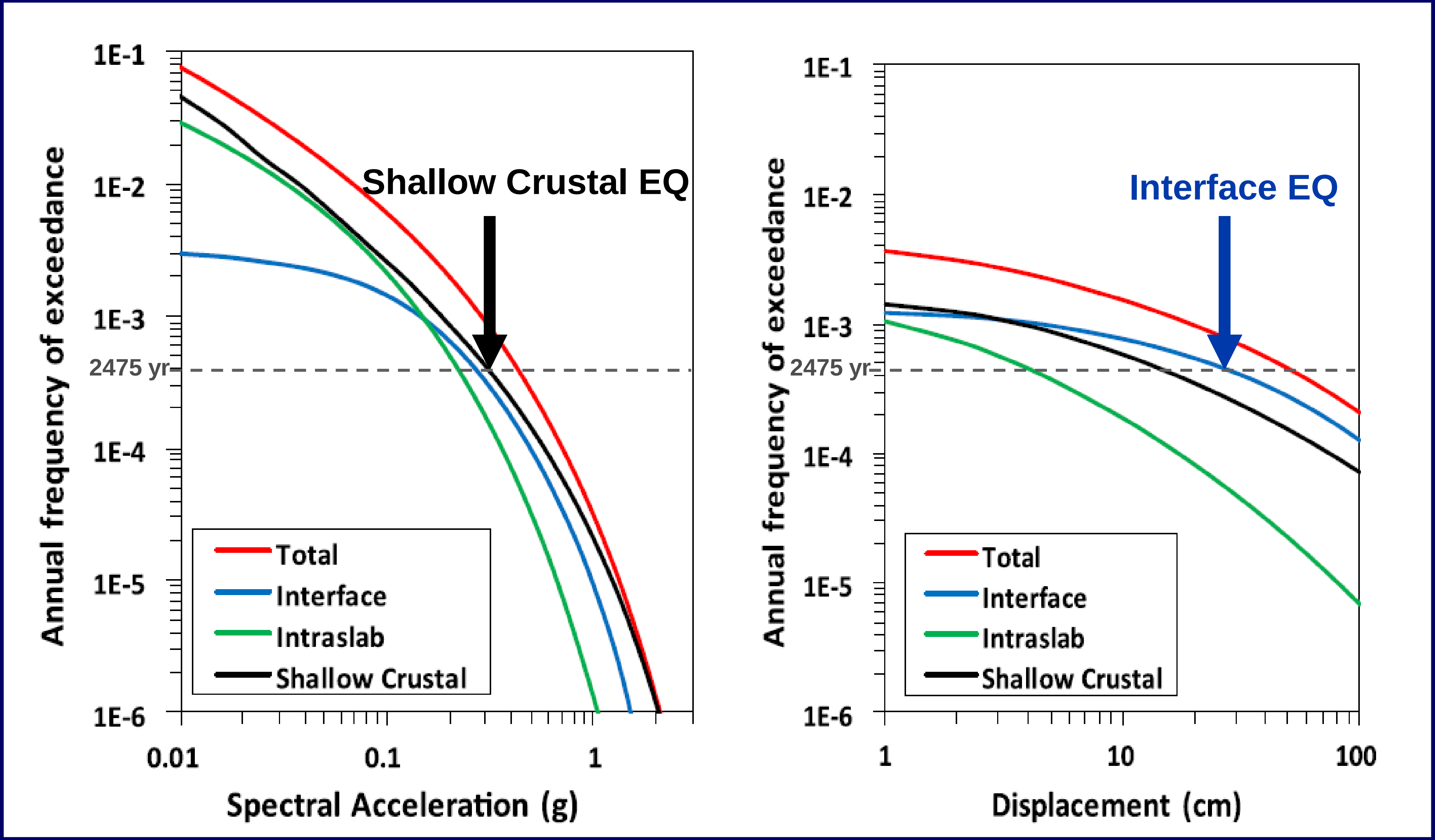
k_y, T_s, D-models

Macedo et al. (2018)

Comparison of Variability due to k_y & T_s



Contributions of Different Tectonic Settings (Seattle Site)



Macedo et al. (2018)

Summary

- First focus on severe strength loss potential: Flow Liquefaction
- Clayey Silt can liquefy - perform monotonic & cyclic tests
- Consider depositional environment (Fabric)
- Estimate S_r from back-analyses of flow slides - a system property
- Deformable sliding block displacement procedure provides useful insights when $FS_{static} > 1$; follow with FDA on high-risk dams
- Use Bray & Macedo (2019) for Shallow Crustal EQs and Macedo et al. (2023) for Interface & Intraslab Subduction Zone EQs
- PBEE seismic slope displacement approach captures uncertainty

References

Ashford, S.A. and Sitar, N. (2002) “Simplified Method for Evaluating Seismic Stability of Steep Slopes,” JGGE, ASCE, V. 128(2): 119-128.

Bray, J.D. “Chapter 14: Simplified Seismic Slope Displacement Procedures,” Earthquake Geotechnical Engineering, 4th ICEGE - Invited Lectures, in Geotechnical, Geological, and Earthquake Engineering Series, Vol. 6, Pitilakis, Kyriazis D., Ed., Springer, pp. 327-353, 2007.

Bray, J.D. and Rathje, E.R. (1998) “Earthquake-Induced Displacements of Solid-Waste Landfills,” J. Geotech. Geoenv. Engrg., ASCE, V124(3), 242-253.

Bray, J.D., Macedo, J. and Travasarou, T. (2018) “Simplified Procedure for Estimating Seismic Slope Displacements for Subduction Zone Earthquakes,” J. of Geotech. & Geoenv. Engineering, ASCE, V. 144(3): 04017124.

Bray, J.D., and Macedo, J. (2019) “Procedure for Estimating Shear-Induced Seismic Slope Displacement for Shallow Crustal Earthquakes,” J. Geotech Geoenv Eng, ASCE, V. 145(12),

Bray, J.D., and Macedo, J. (2021) “Closure to ‘Procedure for Estimating Shear-Induced Seismic Slope Displacement for Shallow Crustal Earthquakes,’” JGGE, doi.org/10.1061/(ASCE)GT.1943-5606.0002143.

Bray, J.D., and Macedo, J. (2023) “Performance-Based Seismic Assessment of Slope Systems,” Soil Dynamics and Earthquake Engineering J., V. 168, 10.1016/j.soildyn.2023.107835.

Chen, W.Y., Bray, J.D., and Seed, R.B. (2006) “Shaking Table Model Experiments to Assess Seismic Slope Deformation Analysis Procedures,” Proc. 8th US Nat. Conf. EQ Engrg., 100th Anniversary Earthquake Conf. Commemorating the 1906 San Francisco EQ, EERI, Paper 1322.

Macedo, J., Bray, J.D., Abrahamson, N., and Travasarou, T. (2018) “Performance-based probabilistic seismic slope displacement procedure,” Earthquake Spectra J., EERI, V. 34(2), 673-695.

Park, D.S., and Kishida T. (2019) “Seismic response of embankment dams based on recorded strong-motion data in Japan,” EQ Spectra 35(2): 955–976.

Rathje, E. M., and Bray, J.D. (2001) “One- and Two-Dimensional Seismic Analysis of Solid-Waste Landfills,” Canadian Geotechnical J., V38(4), 850-862.

Seed, H.B. (1979) “Considerations in the Earthquake-Resistant Design of Earth and Rockfill Dams,” Geotechnique, V. 29(3), pp. 215-263.

Bray, J.D. and Sancio, R.B. (2006) “Assessment of the Liquefaction Susceptibility of Fine-Grained Soils,” J. Geotech Geoenv Eng, V132(9), 1165-1177.

Bray, J.D. and Sancio, R.B. (2008) “Closure to ‘Assessment of the Liquefaction Susceptibility of Fine-Grained Soils,’” JGGE, ASCE, V134(7), 1031-1034.

Beyzaei, C.Z., Bray, J.D., van Ballegooy, S., Cubrinovski, S., and Bastin, S. (2018) “Depositional environment effects on observed liquefaction performance in silt swamps during the Canterbury earthquake sequence,” Soil Dynamics and Earthquake Engineering J., V. 107, 303-321.

Beyzaei, C.Z., Bray, J.D., Cubrinovski, S., Riemer, M., and Stringer, M. (2018) “Laboratory-Based Characterization of Shallow Silty Soils in Southwest Christchurch,” Soil Dynamics and Earthquake Engineering J., V. 110, 93-109, doi.org/10.1016/j.soildyn.2018.01.046.

Beyzaei, C.Z., Bray, J.D., Cubrinovski, S., Bastin, S., Riemer, M., Stringer, M., Jacka, M., van Ballegooy, S., and Wentz, R. (2020) "Characterization of Silty Soil Thin-Layering and Groundwater Conditions for Liquefaction Assessment," Canadian Geotechnical J., doi: 10.1139/cgj-2018-0287.

Bray J.D. and Olaya, F. (2023) “2022 H.B. Seed Memorial Lecture: Evaluating Liquefaction Effects,” J. Geotech Geoenv Eng, ASCE, V. 149(8), doi: 10.1061/JGGEFK.GTENG-11242.

Moug, D., Bassal, P., Bray, J.D., Cetin, K. O., Kendir, S.B., Sahin, A., Cakir, E., Soylemez, B., and Ocak, S. (2023) “February 6, 2023 Türkiye Earthquakes: GEER Phase 3 Team Report on Selected Geotechnical Engineering Effects,” GEER Report 082-S1, https://doi.org/10.18118/G6F379, June 30.