Flow Failure Assessment for Dams and Embankments with Examples

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Queensland Tailings Group
Brisbane, Australia

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Outline

- Recent Flow Failures
- Liquefied Strength
- Flow Failure Susceptibility
  - Contractive/dilative boundary
  - State parameter
- Five Step Procedure
- Application Examples
- Summary

2022 South African Flow Failure

https://www.youtube.com/watch?v=k3kaQKl0h1E

September 11, 2022

30-40 mph (40-60 km/hour)

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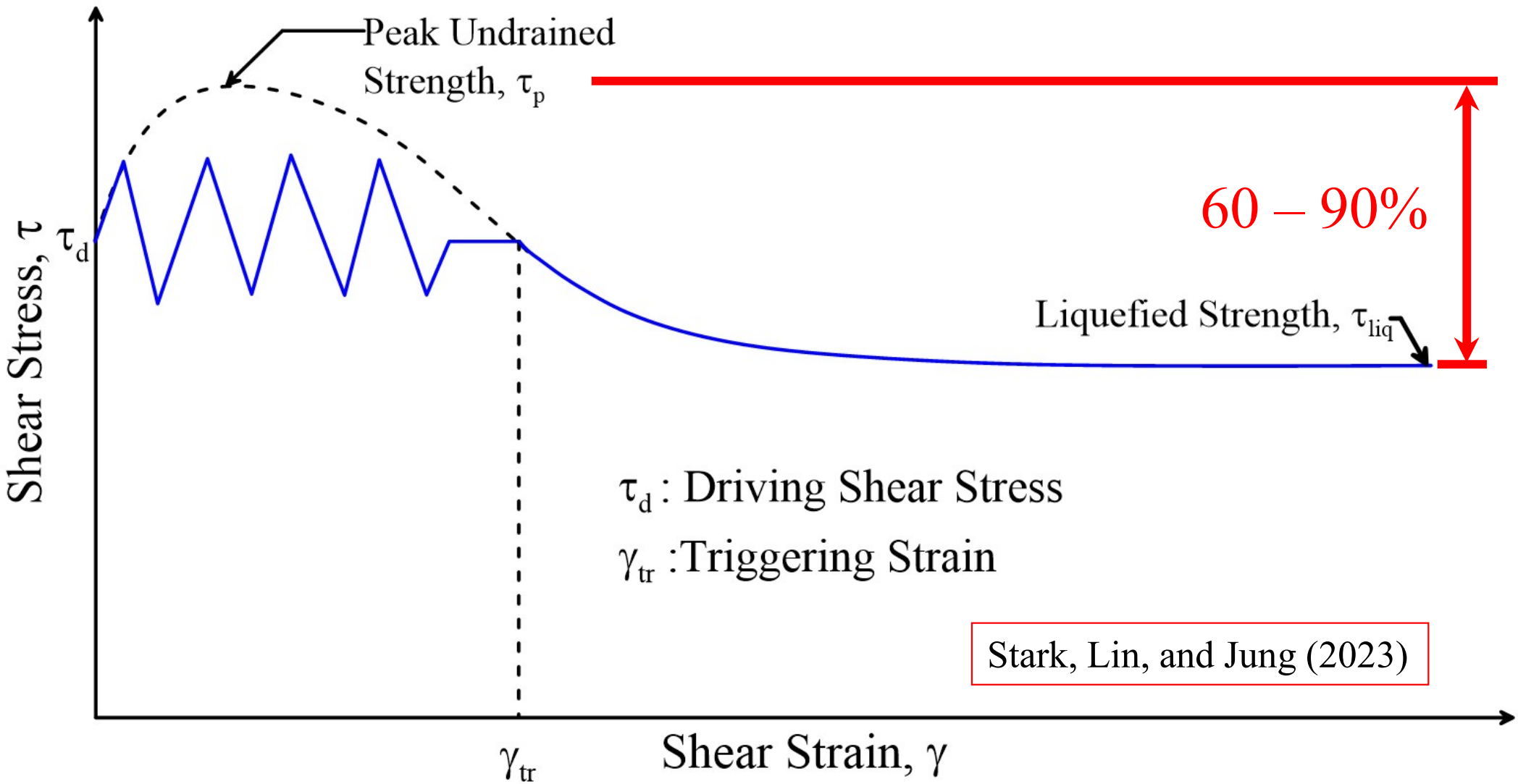
Yield & Liquefied Strengths



- Depends on in-situ density and effective stress: State Parameter

Unknown Trigger=?

- Trend of assuming unknown trigger (no mechanism identified)
- Assumes soil liquefies
- All saturated, contractive soil is assigned liquefied strength
- Will result in $FoS_{flow} << 1.0$
- Does not match field observations
- Liquefied strength ~ 1/3 yield => FoS_{flow} 0.3 to 0.4
- Retrofit 2,584 upstream tailings dams worldwide (Stark et al., 2022)

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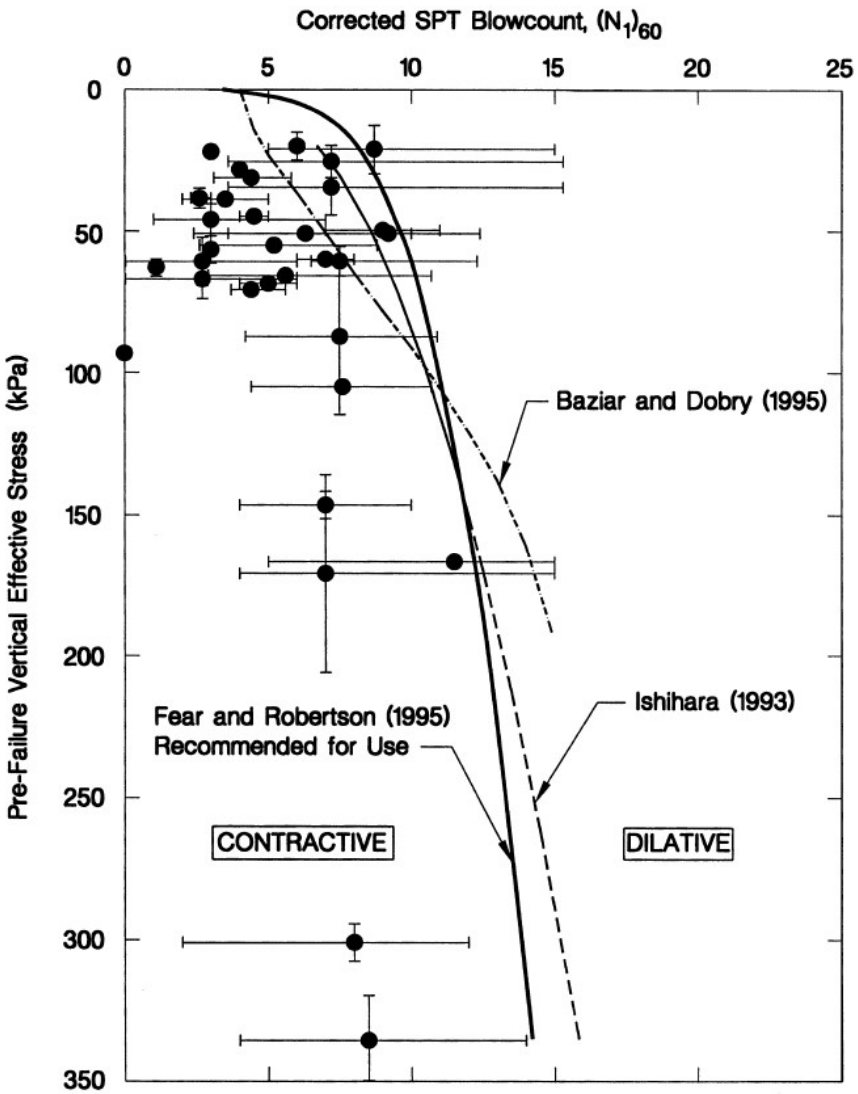
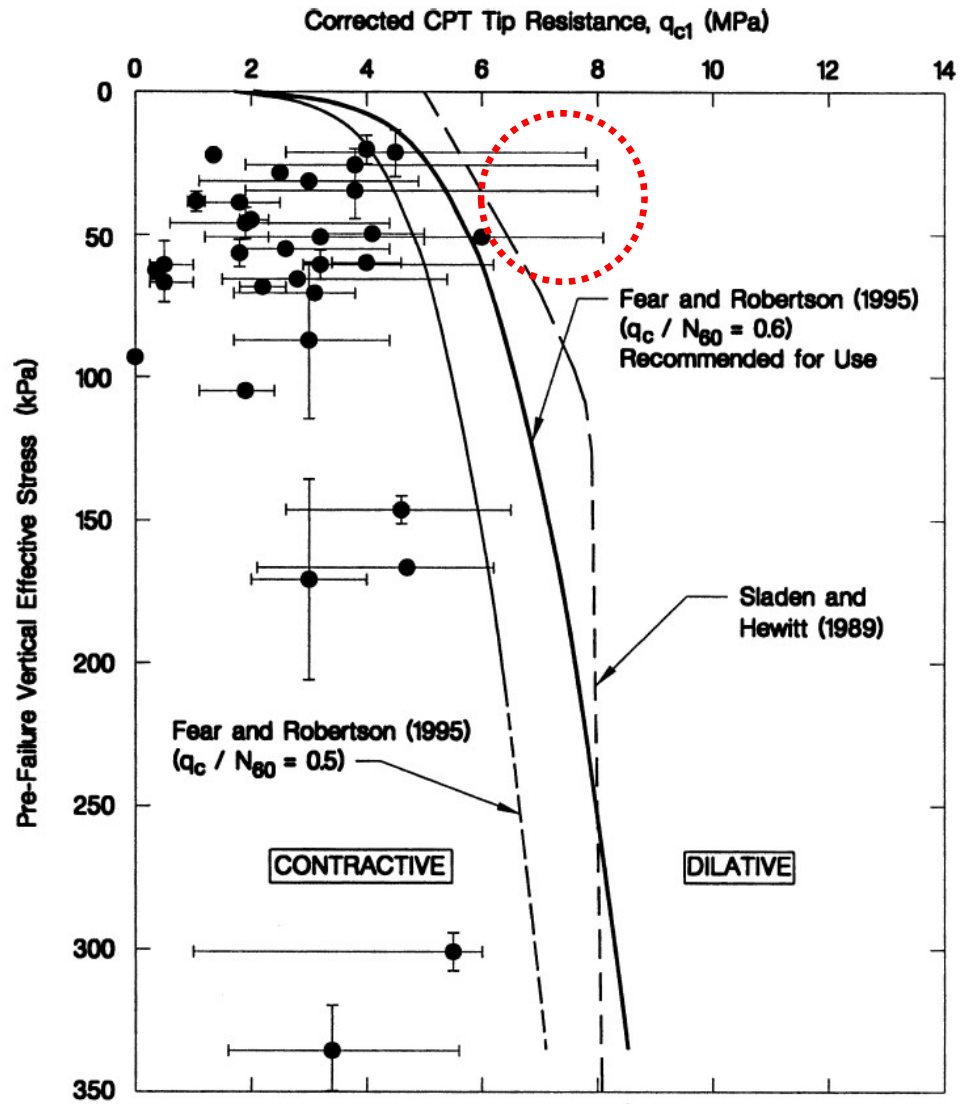
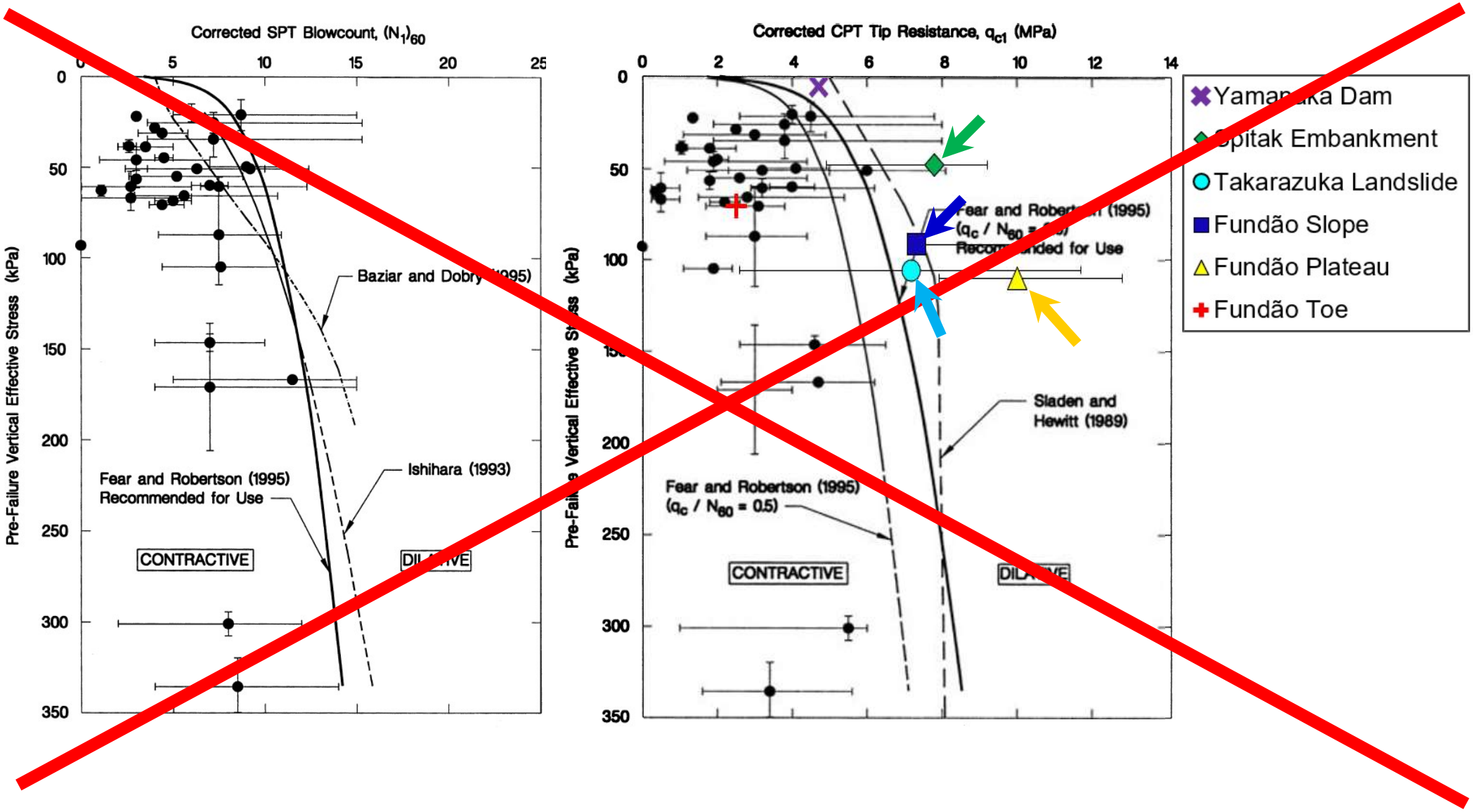
Contractive/Dilative Boundary





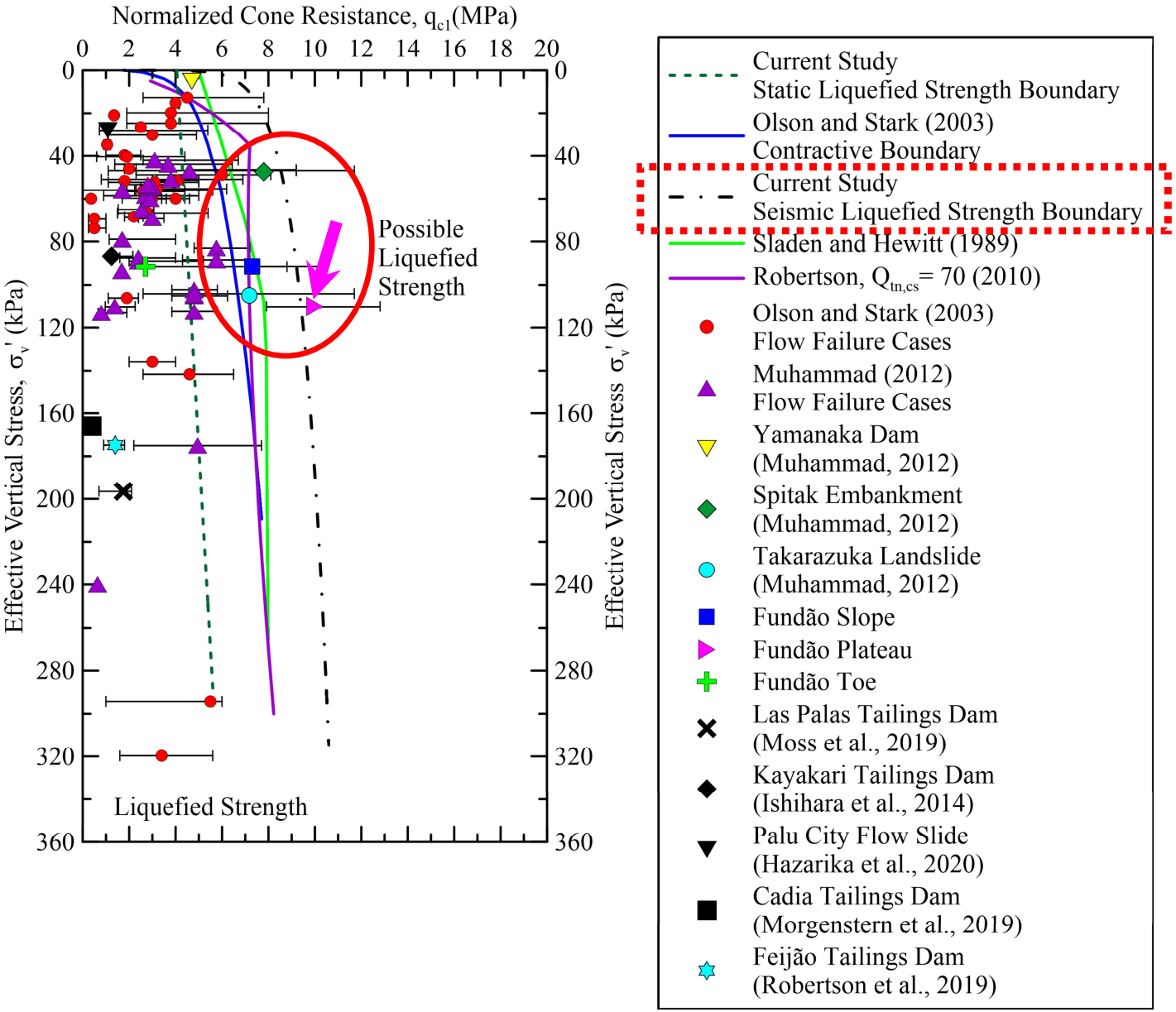
Olson and Stark (2003)

Contractive/Dilative Boundary



Olson and Stark (2003)

Contractive/Dilative Boundary



1 tsf = 0.1 MPa

Stark et al. (2023)

- Use liquefied/possible liquefied not contractive/dilative

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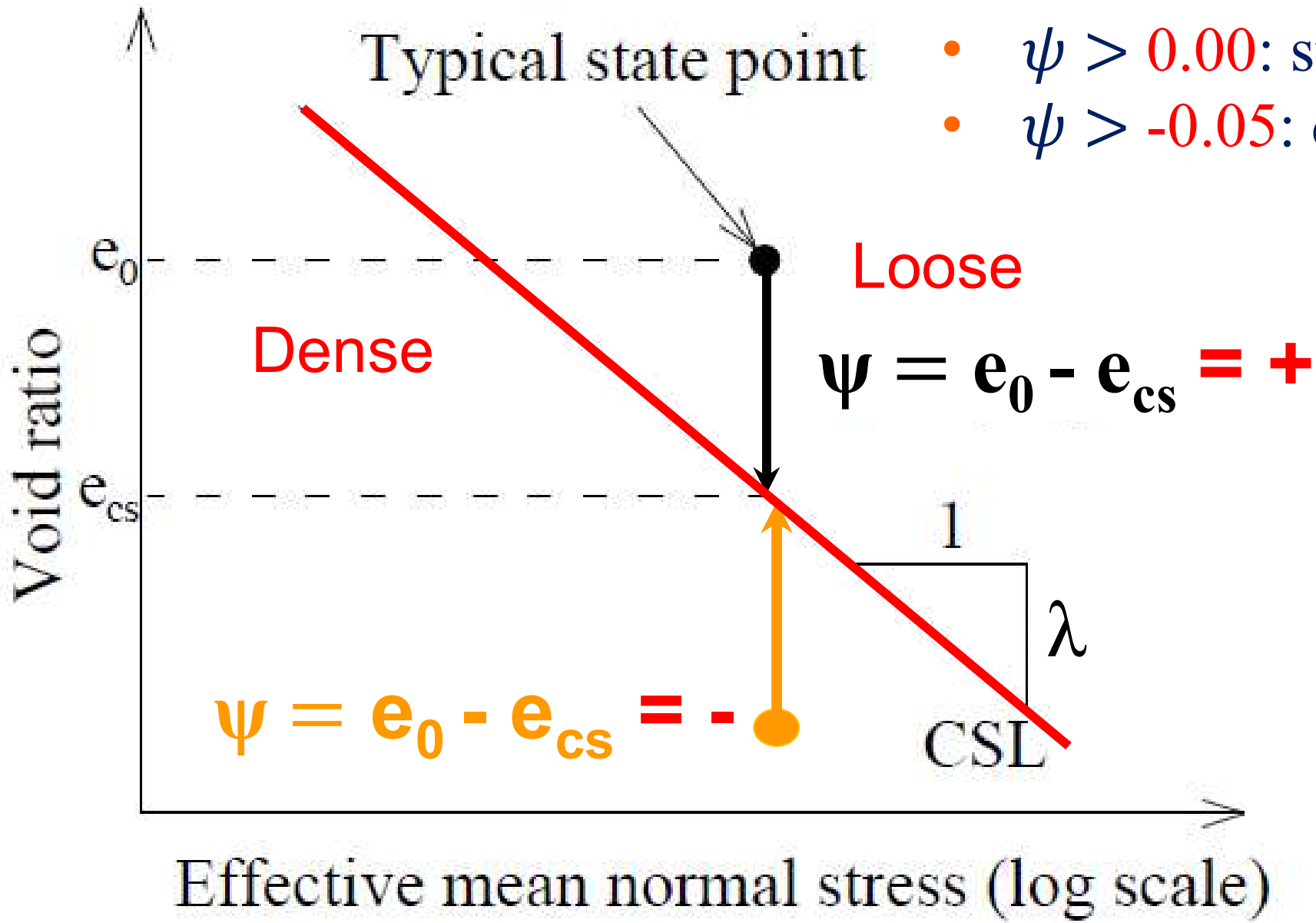
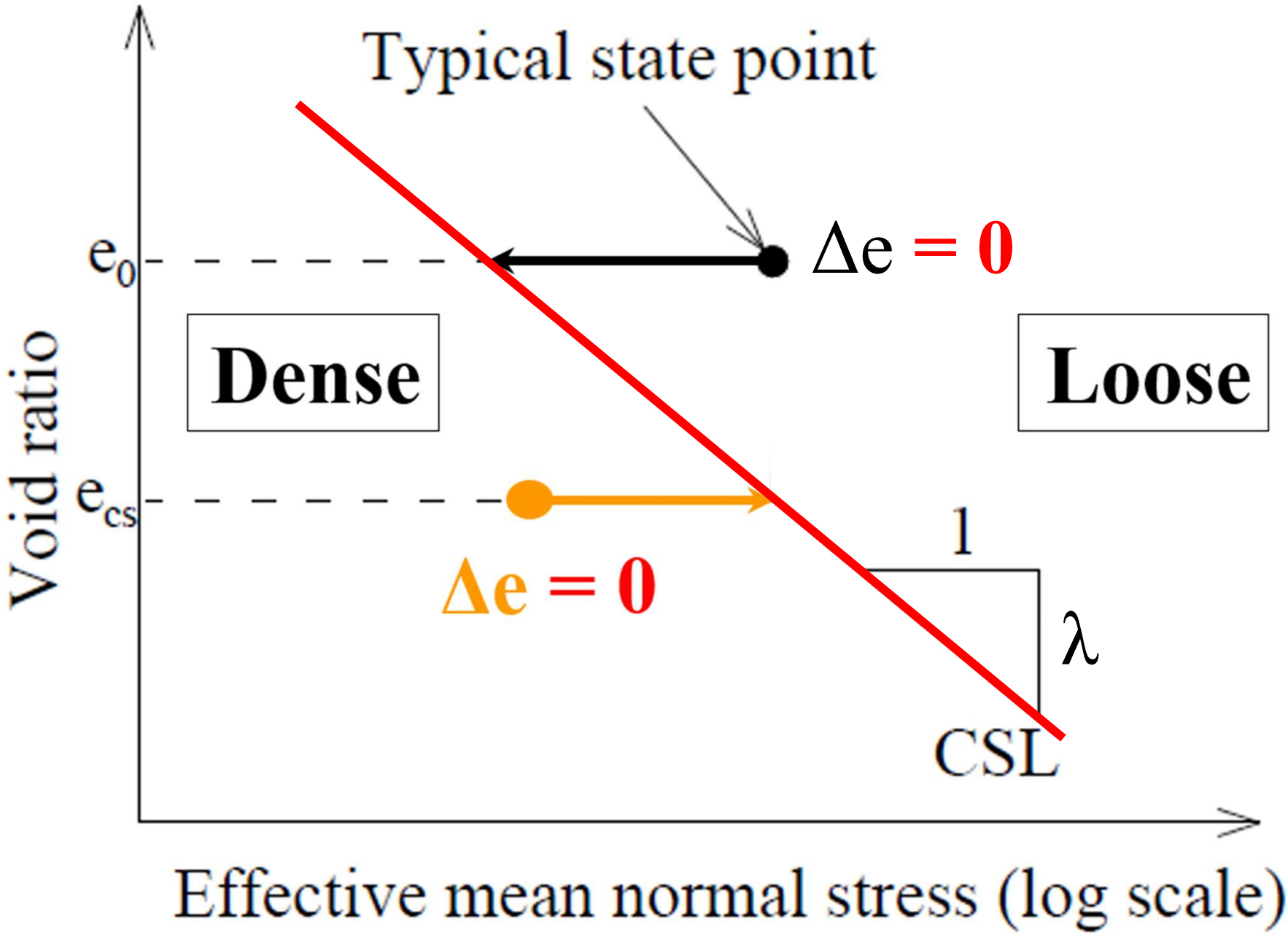
Drained Shear

- $\psi > 0.00$: static
- $\psi > -0.05$: dynamic



Undrained Shear



State parameter

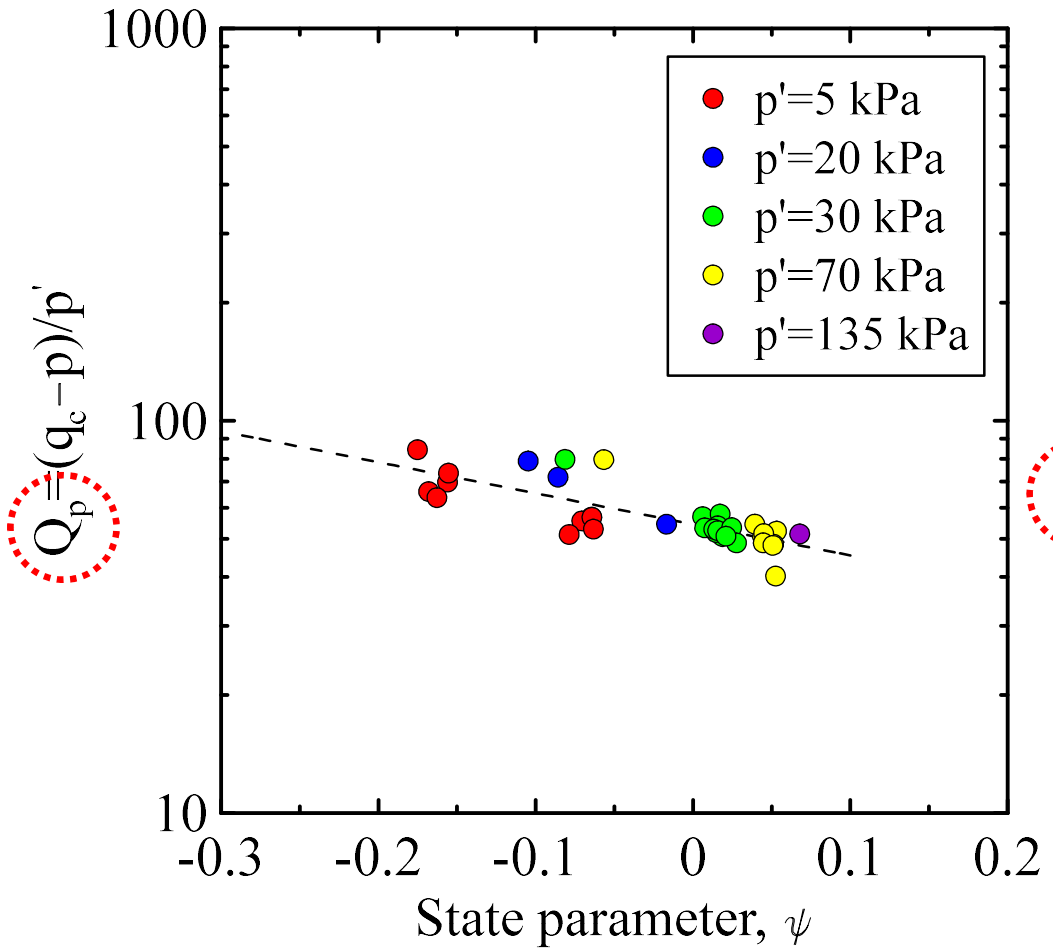
- Critical state framework
- $\psi > 0.00$: static liquefaction triggering
- $\psi > -0.05$: dynamic liquefaction triggering (Fourie et al., 2022)

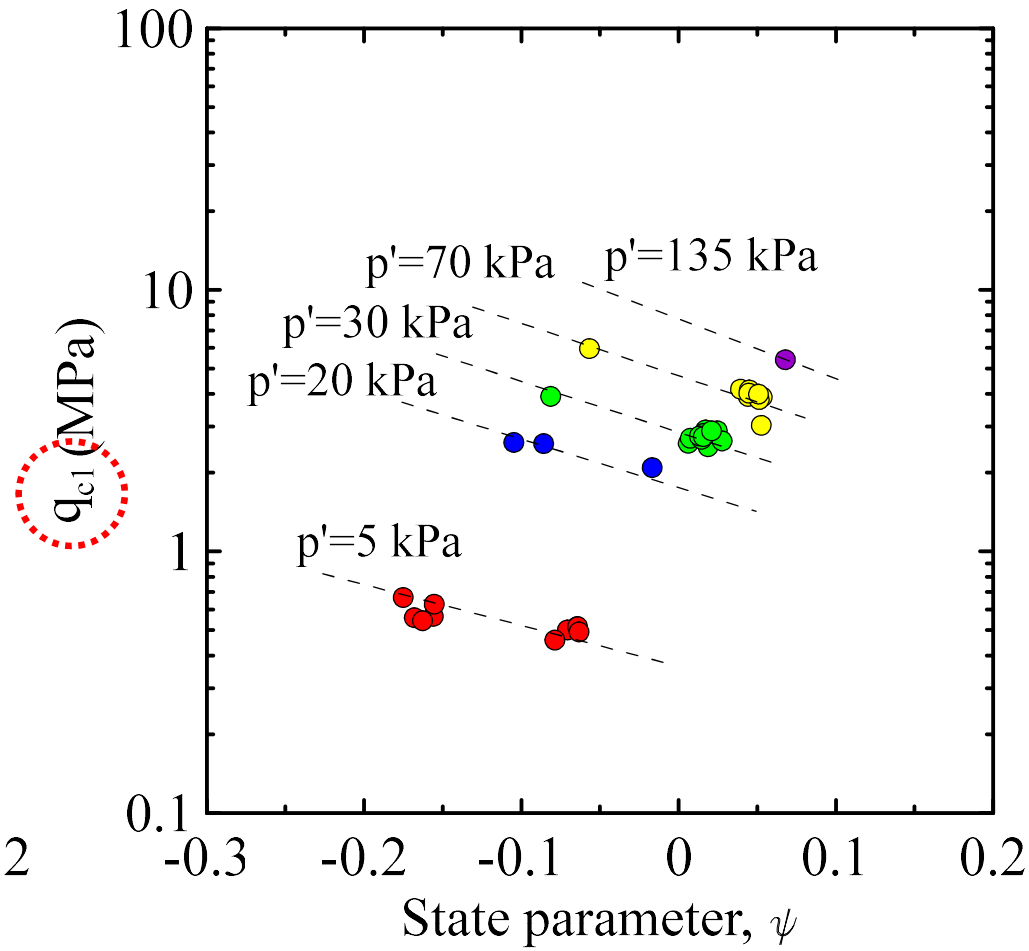
- Strong correlation with Q_p
- Verify with calibration chamber data

$$Q_p = \left(\frac{q_c - p_o}{p'_o}\right) \approx \left(\frac{q_c}{p'_o}\right)$$

- p_0 = mean σ
- p'_0 = mean σ'

Develop ψ & CPT Correlation



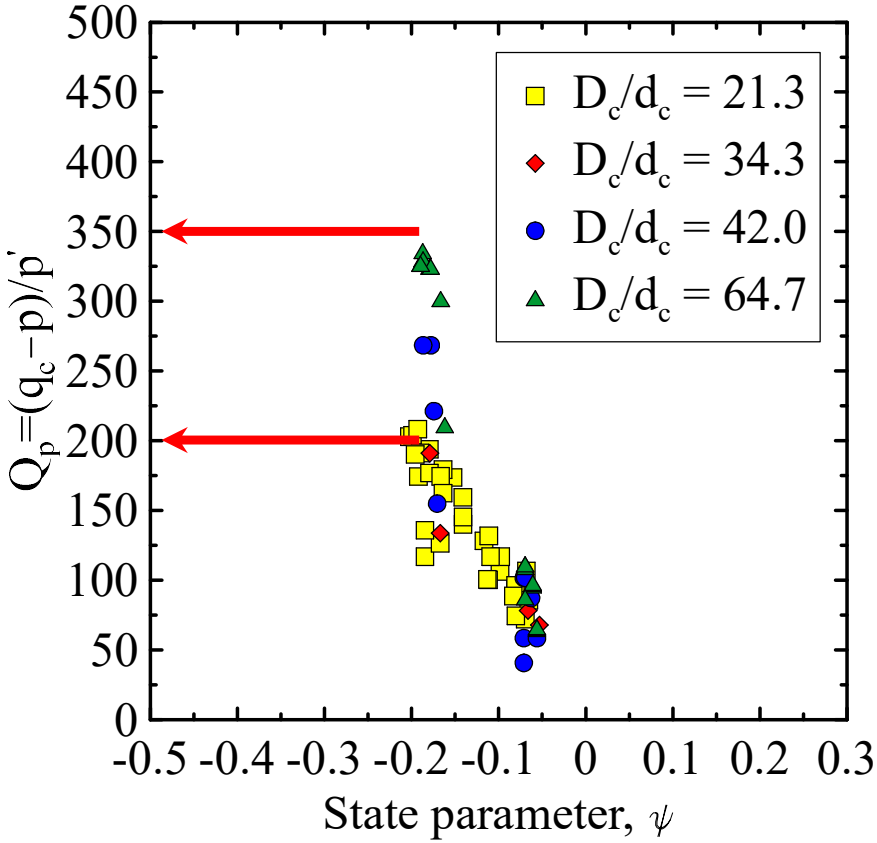


- Use $Q_p = (q_c - p_0)/p_0'$ for stress level normalization

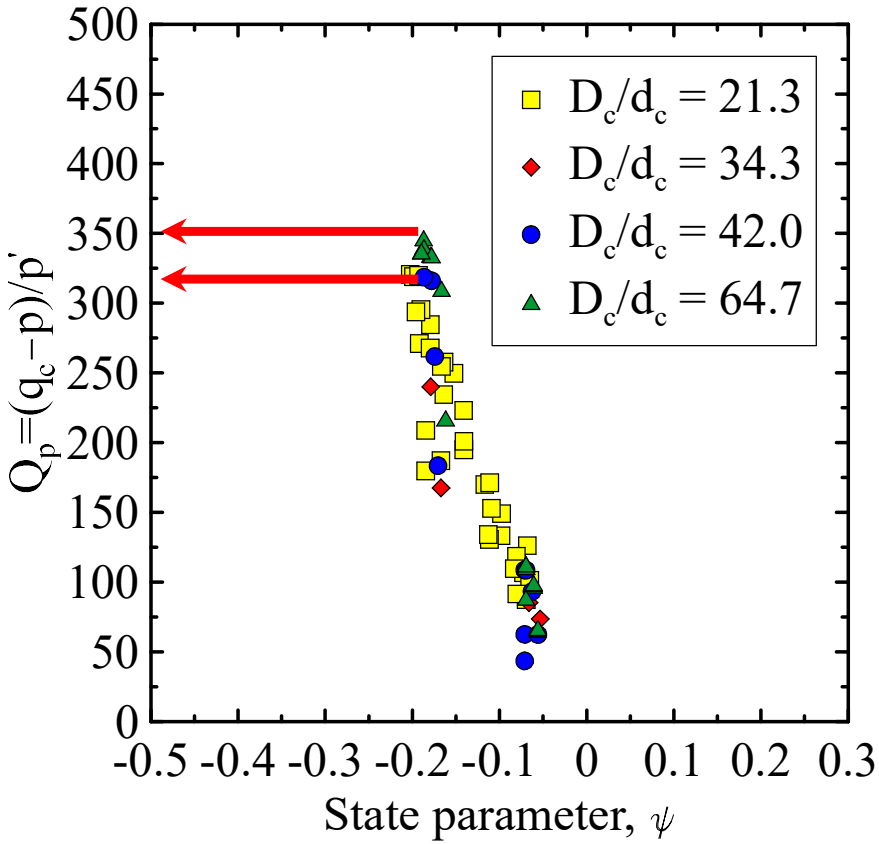
Calibration Chamber Correction

- Boundary effect correction
- $C_f = \left[\frac{(D_c/d_c)-1}{70}\right]^{-D_r/200}$ (D_c: chamber diameter; d_c: cone diameter)

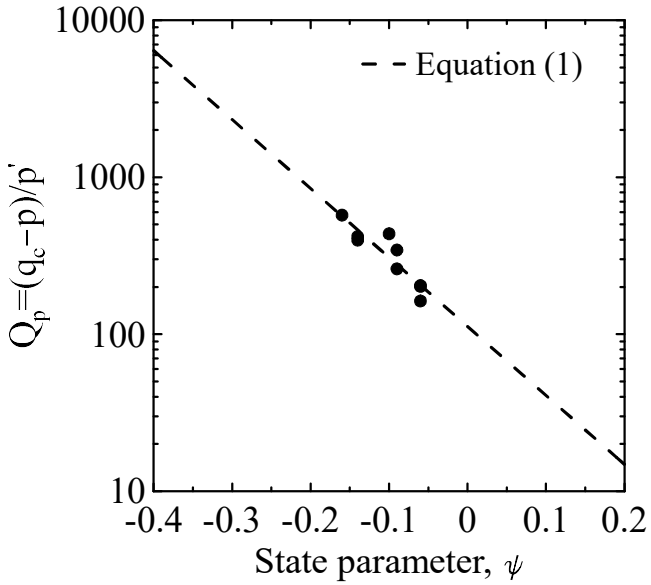
Uncorrected



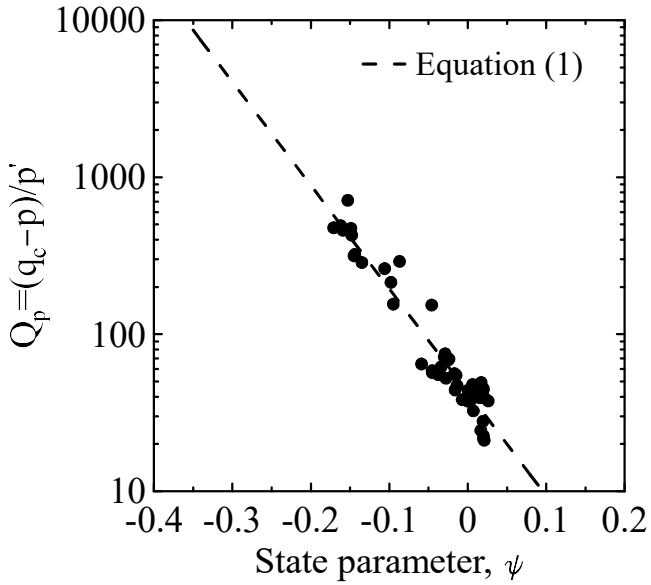
Corrected



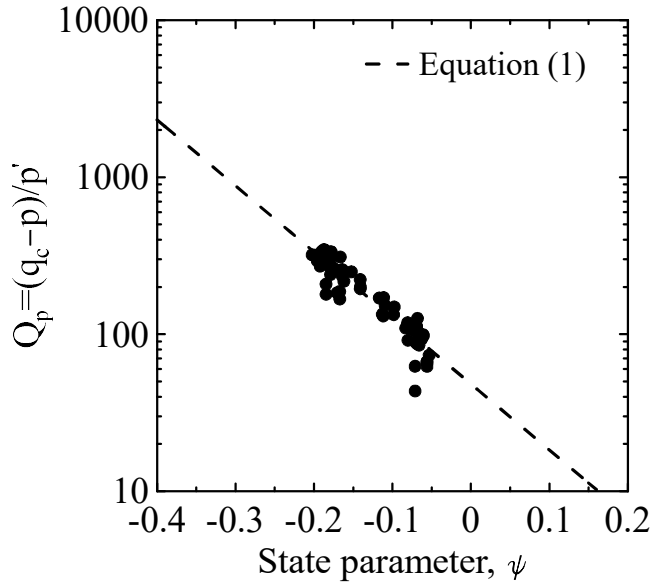
ψ & CPT Correlation – 18 sands



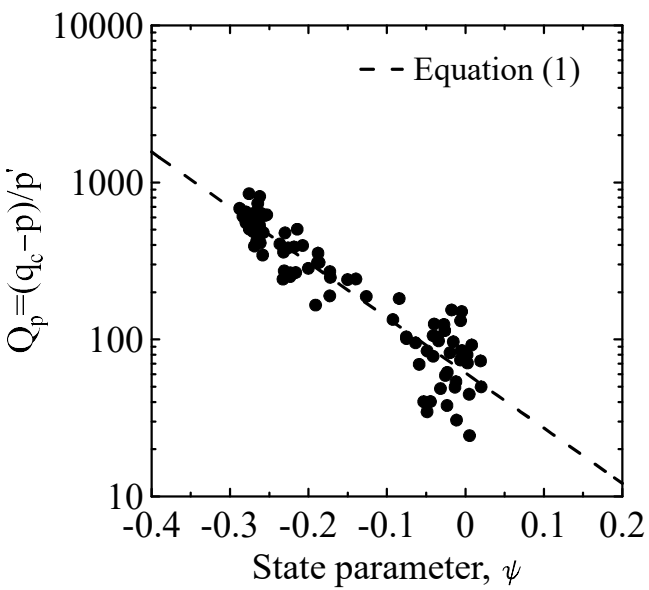
Quebec Sand ($\lambda = 0.021$)



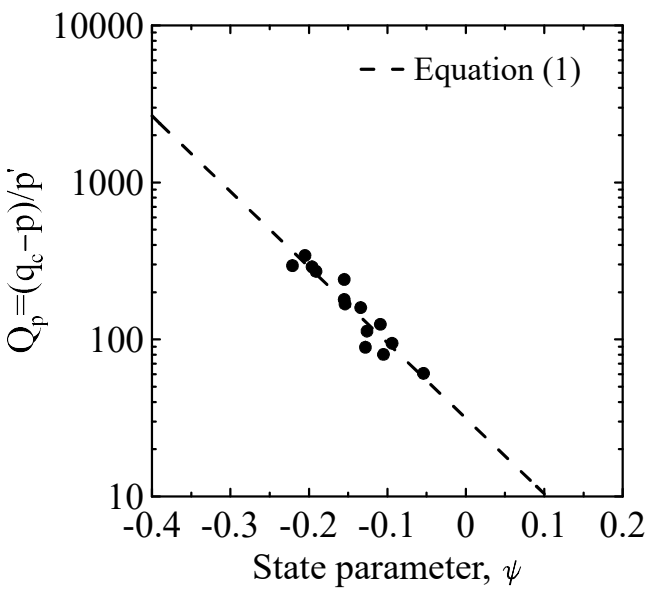
Ottawa Sand ($\lambda = 0.028$)



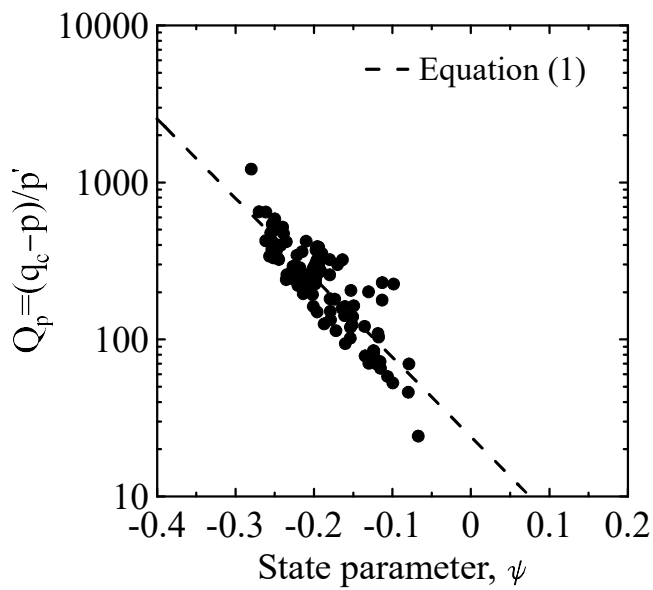
Monterery #0 Sand ($\lambda = 0.029$)



Hokksund Sand ($\lambda = 0.054$)

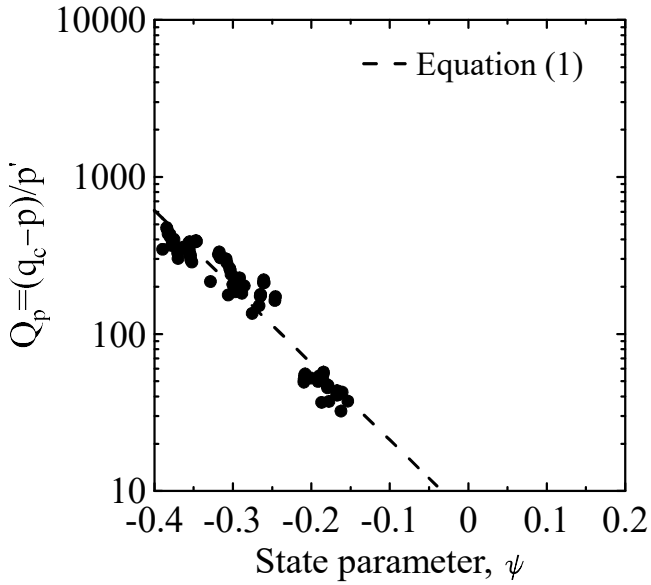


Erksak Sand ($\lambda = 0.054$)

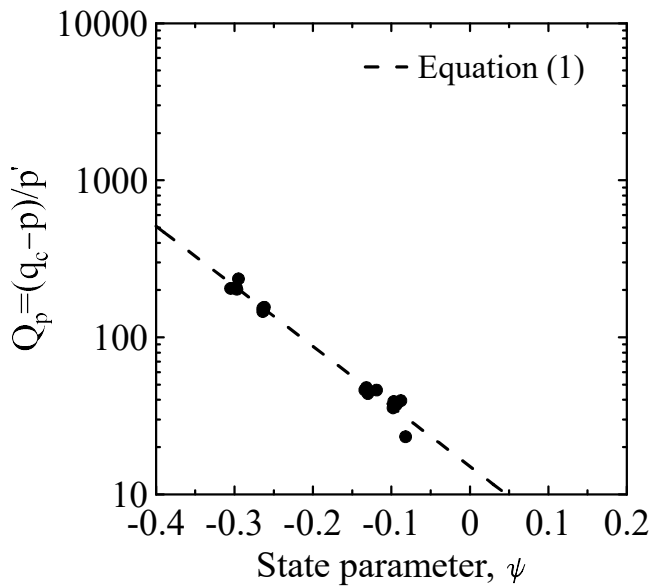


Ticino Sand ($\lambda = 0.056$)

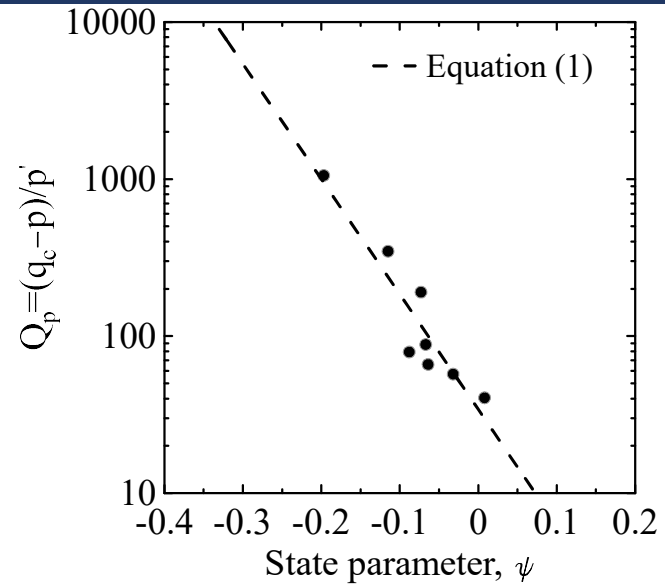
ψ & CPT Correlation – 18 sands



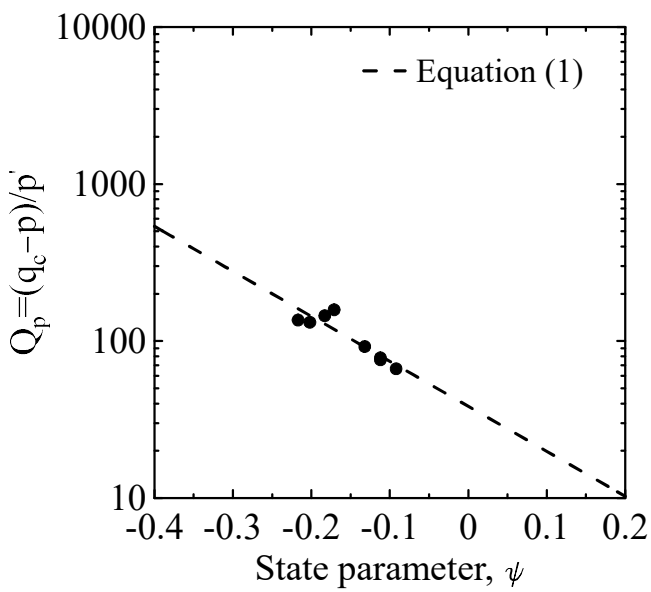
Leighton Buzzard Sand ($\lambda = 0.060$)



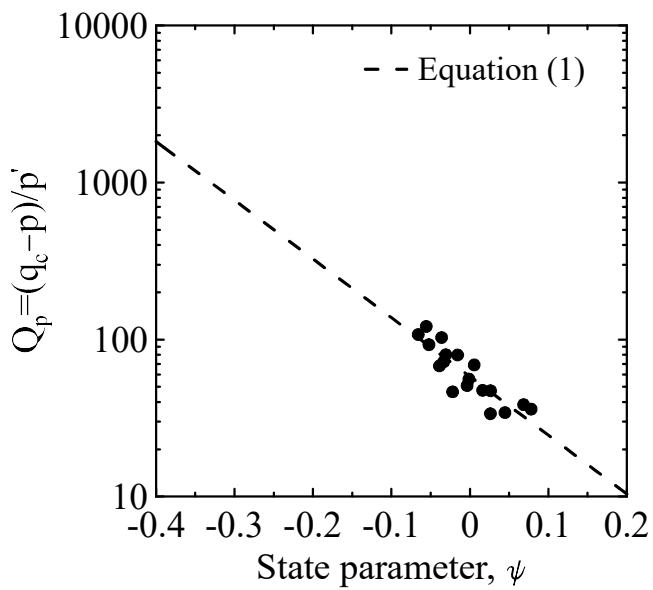
Reid Bedford Sand ($\lambda = 0.065$)



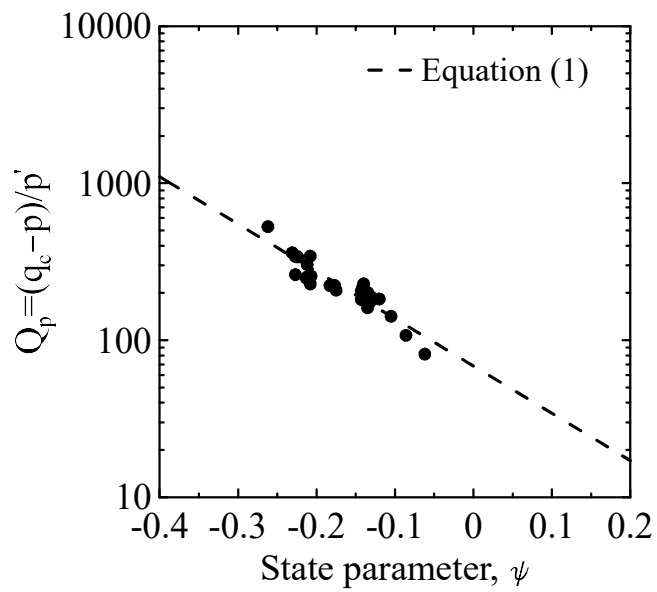
Syncrude Tailings ($\lambda = 0.065$)



Sydney Sand ($\lambda = 0.066$)

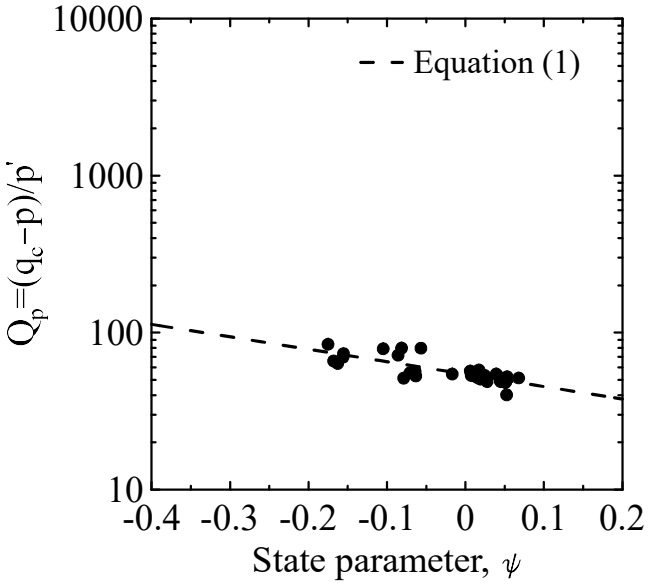


West Kowloon Sand ($\lambda = 0.080$)

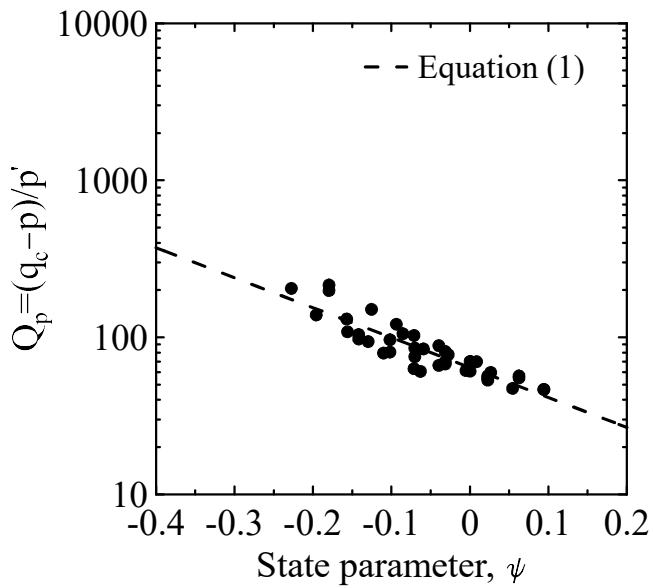


Toyoura Sand ($\lambda = 0.085$)

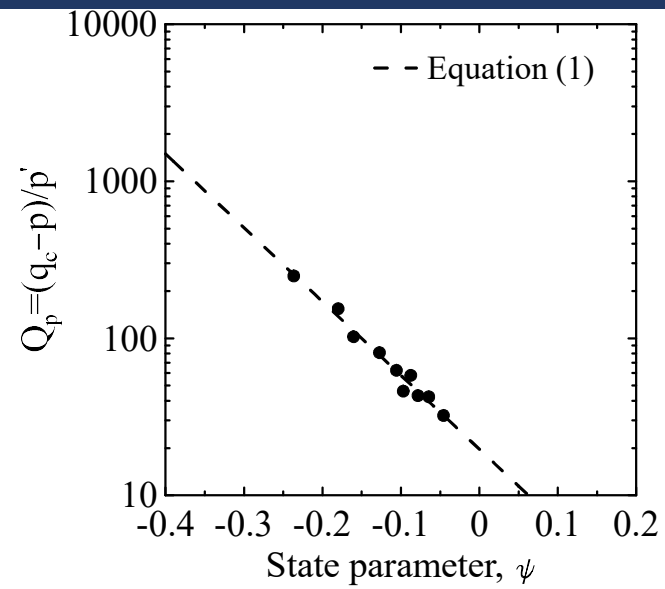
ψ & CPT Correlation – 18 sands



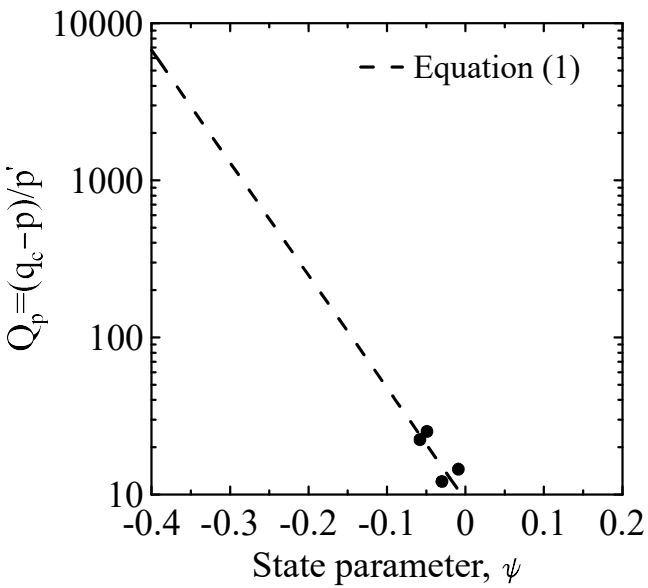
Light Castle Sand ($\lambda = 0.060$)



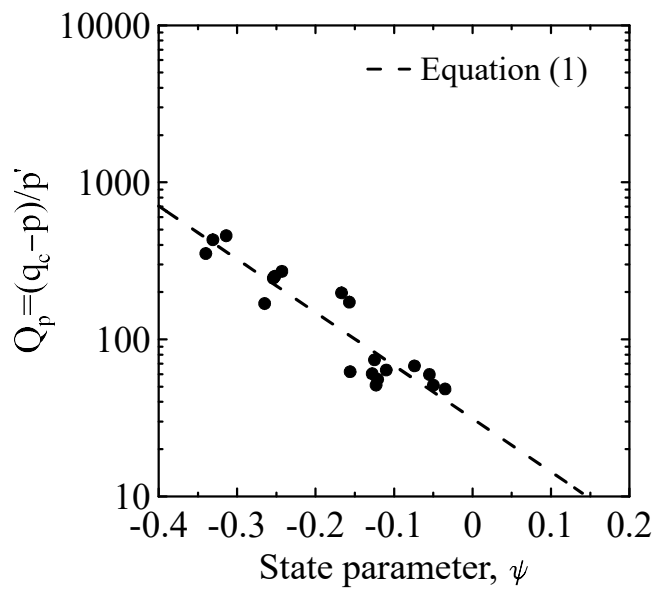
Mai Lao Sand ($\lambda = 0.115$)



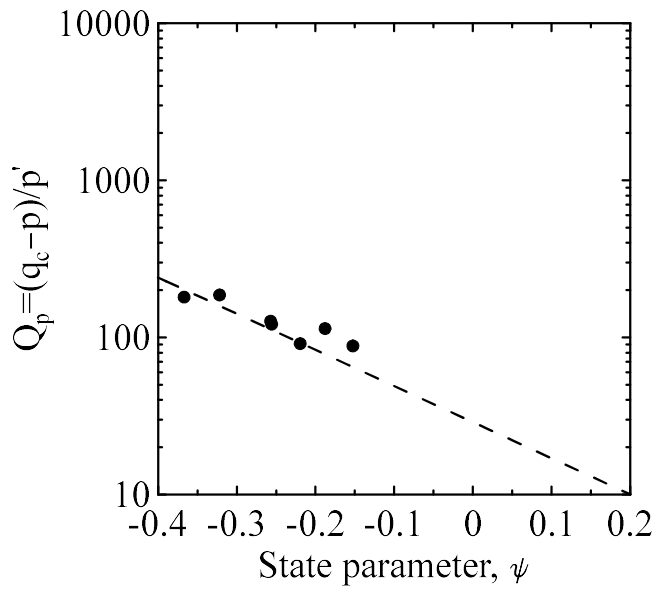
Check Lap Kok Sand ($\lambda = 0.130$)



Yatesville Silty Sand ($\lambda = 0.066$)

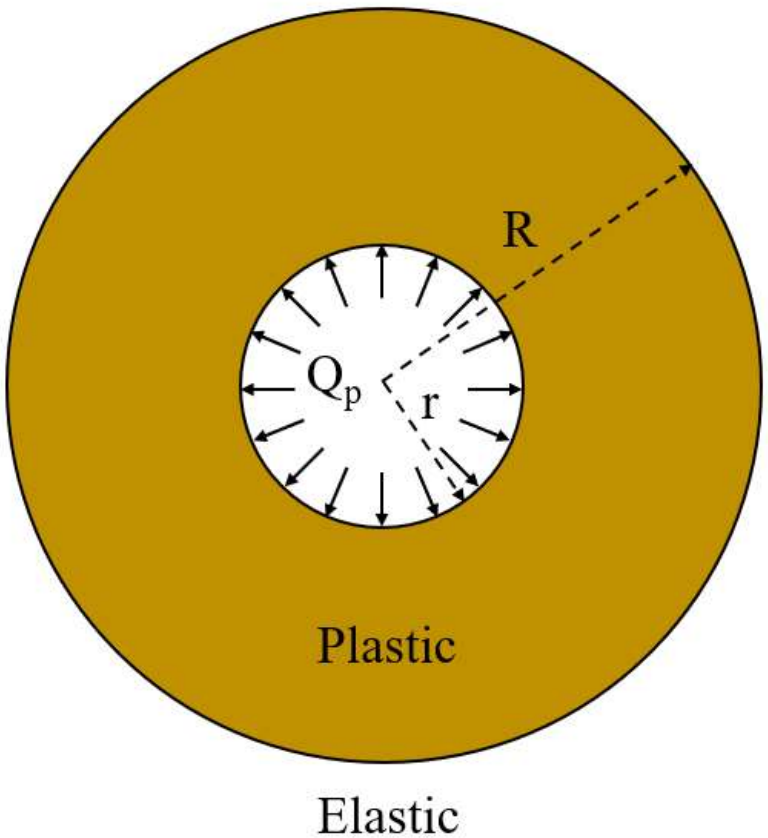


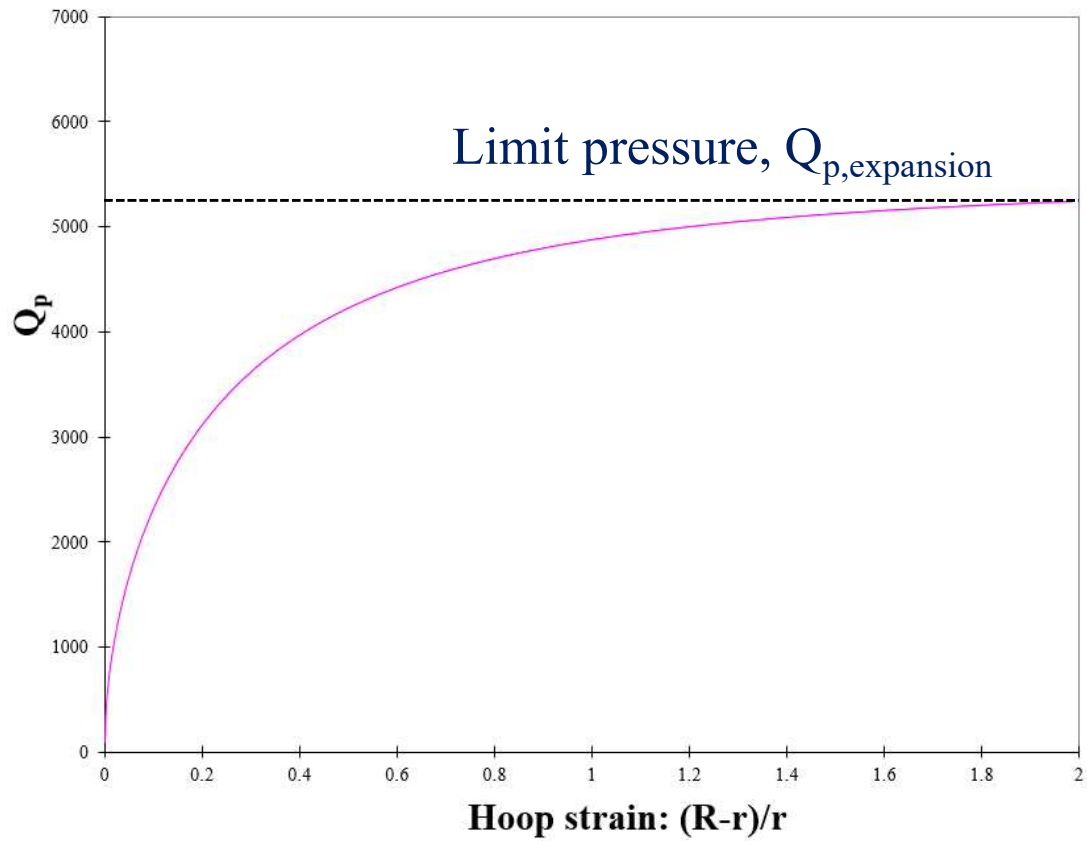
Hilton Mines Tailings ($\lambda = 0.170$)



Saemangeum Sand ($\lambda = 0.290$)

Cavity Expansion Analysis

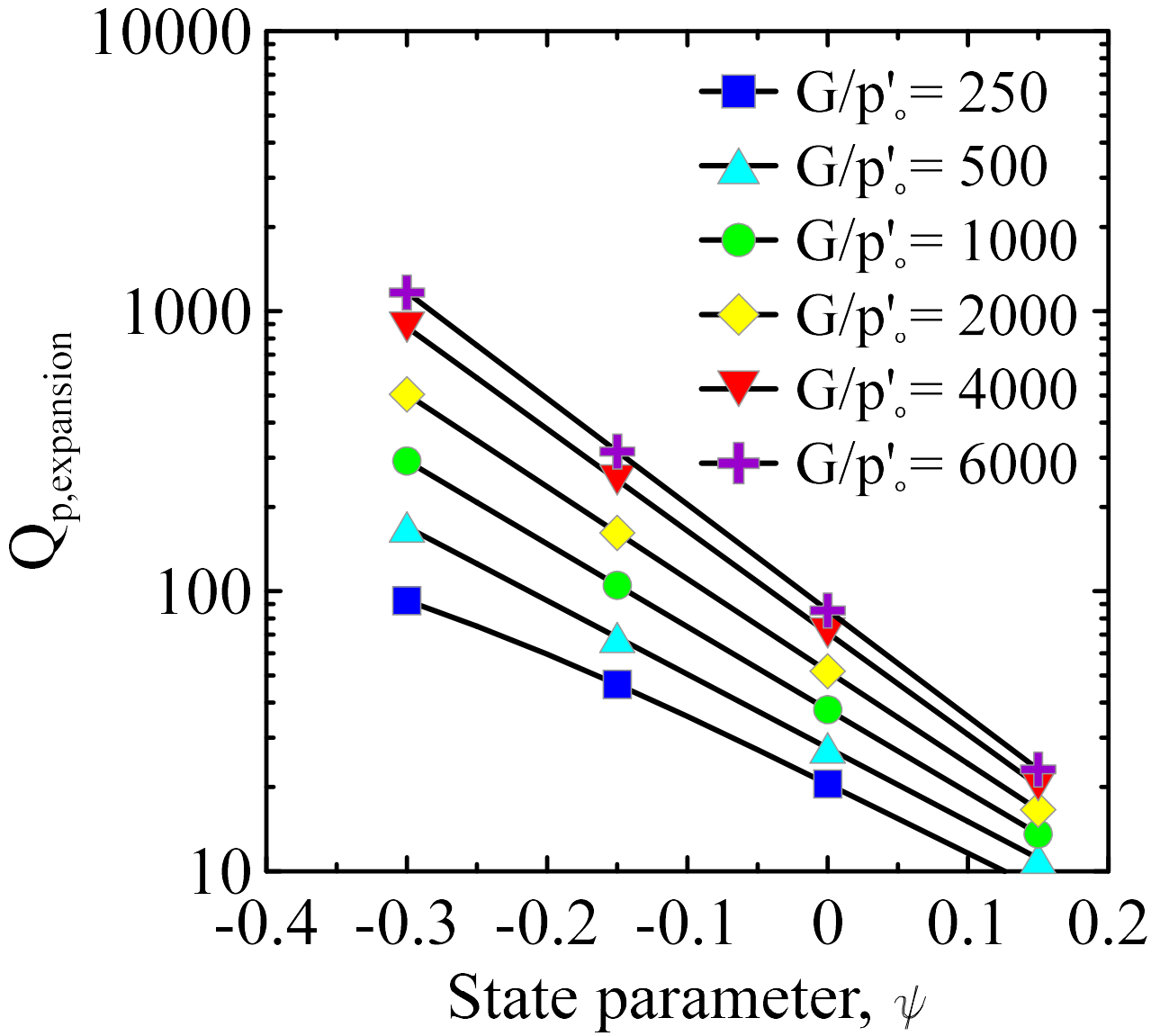




- Model CPT as expansion of a cavity
- Calculate $Q_{p,expansion}$

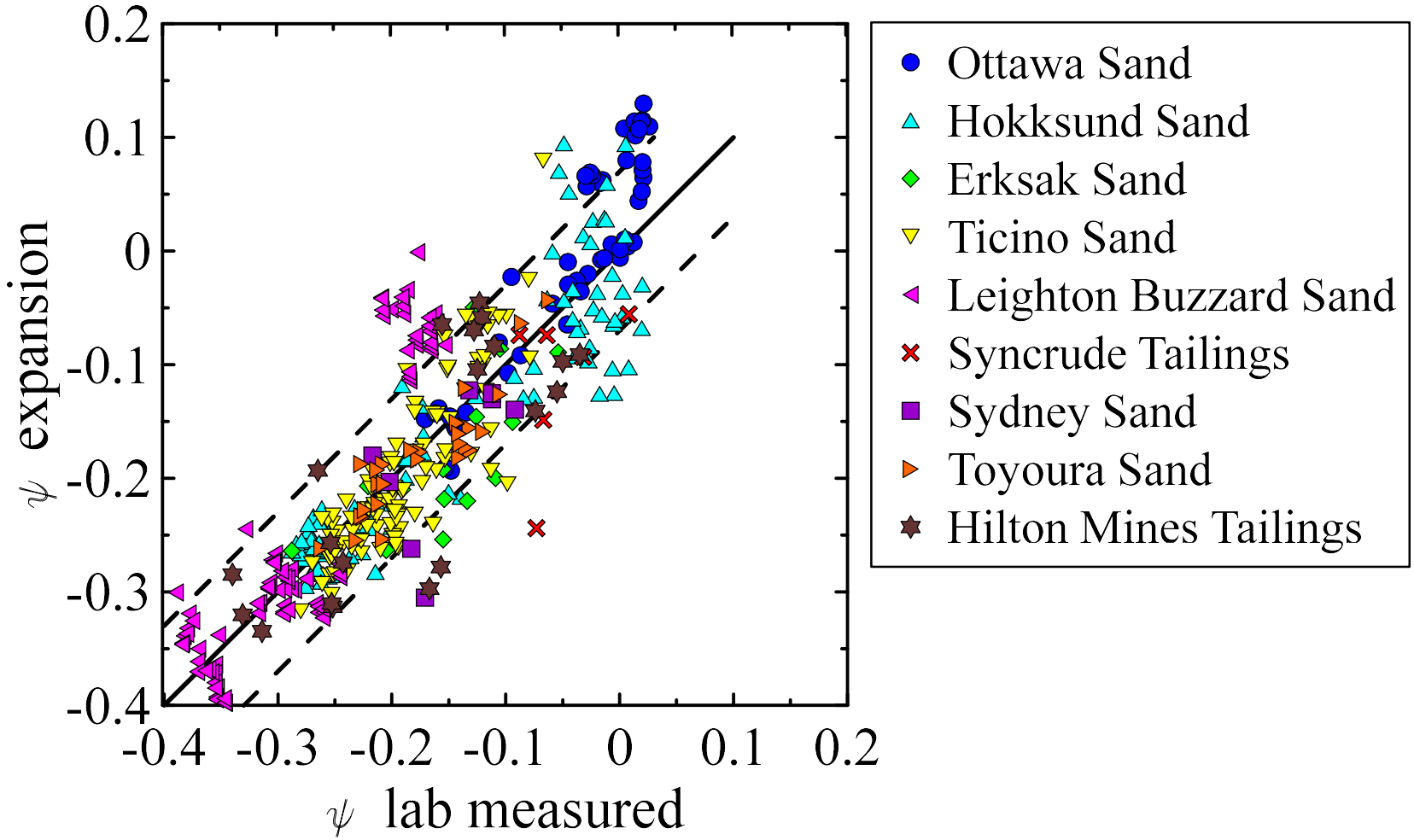
$$\psi_{expansion} = -\ln\left(\frac{Q_{p,expansion}}{1.64 * (G/p'_o)^{0.45}}\right) * \frac{1}{2.27(G/p'_o)^{0.16}}$$

ψ from Cavity Expansion



- G = shear modulus

Ψ Validation



$$\Psi_{expansion} = -\ln\left(\frac{Q_{p,expansion}}{1.64 * (G/p'_o)^{0.45}}\right) * \frac{1}{2.27(G/p'_o)^{0.16}}$$

- Excel Spreadsheet

ψ Spreadsheet

Estimating ψ_{field} from field CPT measurements - January 20, 2024

(Use this Worksheet when G and λ_{10} are not available)

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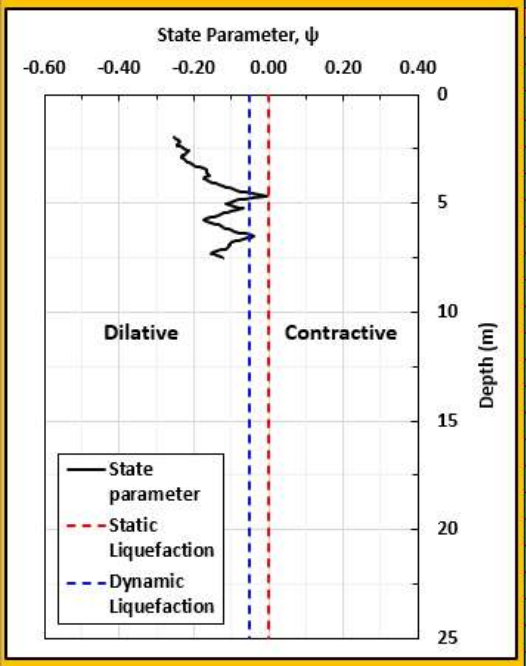
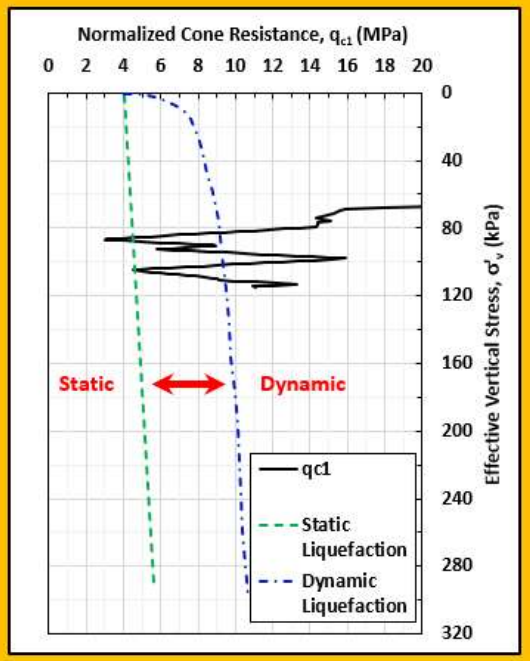
Input		
γ_{sat} (kPa)	Water depth (m)	K_o
20	4	0.5

Depth (m)	q_c (MPa)	Fr (%)	σ'_v (kPa)	p' (kPa)	Q_p	I_c	G/p'	λ_{10}	ψ_{field}	q_{c1} (MPa)
2.00	25.2	0.9	40.0	26.7	943.3	1.4	4742.9	0.11	-0.25	37.9
2.05	24.7	1.0	41.0	27.3	903.0	1.4	4777.9		-0.25	36.9
2.10	24.2	1.1	42.0	28.0	864.6	1.4	4860.0		-0.24	35.9
2.15	25.5	1.2	43.0	28.7	888.4	1.5	5184.2		-0.24	37.5
2.20	27.0	1.2	44.0	29.3	918.2	1.5	5398.5		-0.24	39.3
2.25	28.4	1.2	45.0	30.0	946.7	1.5	5389.5		-0.24	41.1
2.30	29.9	1.1	46.0	30.7	974.0	1.4	5364.9		-0.25	42.9
2.35	29.4	1.1	47.0	31.3	937.5	1.4	5075.6		-0.25	41.9
2.40	28.6	1.2	48.0	32.0	892.0	1.5	5177.8		-0.24	40.4
2.45	27.7	1.3	49.0	32.7	848.3	1.5	5287.0		-0.23	38.9
2.50	26.9	1.5	50.0	33.3	806.3	1.6	5363.1		-0.22	37.5
2.55	26.1	1.7	51.0	34.0	766.0	1.6	5410.8		-0.22	36.0
2.60	25.2	1.8	52.0	34.7	727.3	1.7	5433.8		-0.21	34.6
2.65	28.6	1.8	53.0	35.3	809.0	1.6	5804.0		-0.22	38.9
2.70	30.1	1.6	54.0	36.0	835.6	1.6	5696.5		-0.22	40.7
2.75	30.1	1.5	55.0	36.7	820.4	1.6	5361.3		-0.23	40.4
2.80	30.1	1.3	56.0	37.3	805.7	1.5	5025.2		-0.23	40.1
2.85	30.1	1.2	57.0	38.0	791.5	1.5	4686.2		-0.23	39.8
2.90	30.1	1.1	58.0	38.7	777.9	1.5	4552.5		-0.23	39.5
2.95	30.1	1.2	59.0	39.3	764.7	1.5	4674.9		-0.23	39.2
3.00	30.1	1.3	60.0	40.0	751.9	1.5	4788.0		-0.23	38.9
3.05	30.1	1.4	61.0	40.7	739.6	1.6	4892.7		-0.22	38.7
3.10	30.1	1.5	62.0	41.3	727.6	1.6	4989.8		-0.22	38.4
3.15	27.6	1.6	63.0	42.0	655.5	1.6	4719.5		-0.21	34.9
3.20	25.0	1.5	64.0	42.7	584.8	1.7	4281.7		-0.21	31.4
3.25	22.4	1.5	65.0	43.3	516.3	1.7	3861.5		-0.20	28.0
3.30	19.8	1.4	66.0	44.0	449.9	1.7	3457.1		-0.19	24.6





- 3 input parameters – γ_{sat} = 16-21 kPa
- Graph shows liquefiable layers
- ψ > 0.00 & -0.05 = Contractive

- Procedure Steps 1 & 2

$$\psi_{field} = -\ln\left(\frac{Q_{p,field\ cpt}}{1.64 * (1.49 - \lambda) * (G/p'_o)^{0.45}}\right) * \frac{1}{2.27(G/p'_o)^{0.16}}$$

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Flow Failure Assessment Procedure

Five Step Procedure (Stark et al., 2023):

1) Assess static liquefaction potential of segments along failure surface,
2) Assess dynamic liquefaction triggering of segments,
3) If liquefaction not triggered, assess shear-induced pore-water pressure due to small vibrations along failure surface,
4) Assign liquefied strength or ratio to segments, and
5) Conduct post-triggering stability analysis to assess flow failure potential.

Flow Failure Assessment Procedure

Step 1a: Assess static liquefaction potential of segments using ψ

- $$Q_p = \left(\frac{q_c - p_o}{p'_o}\right) \approx \left(\frac{q_c}{p'_o}\right)_p$$

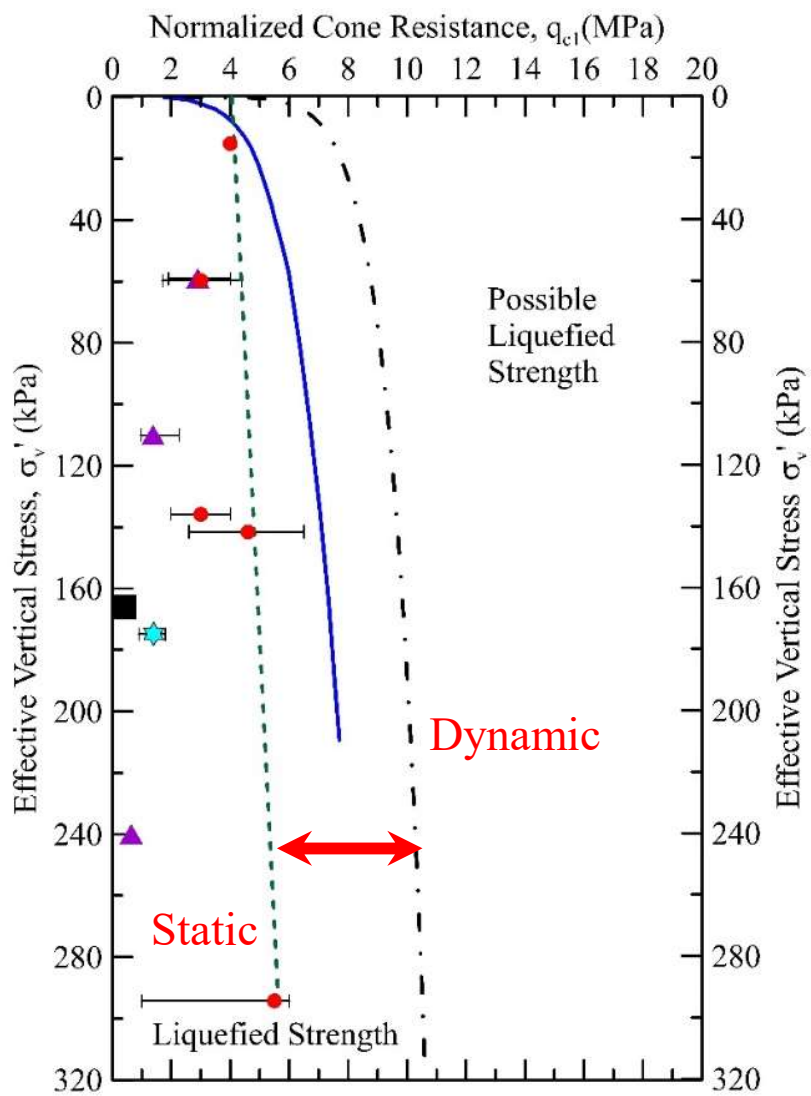
- $$\psi_{field} = -\ln\left(\frac{Q_{p,field\ cpt}}{1.64*(1.49-\lambda)*\left(G/p'_o\right)^{0.45}}\right) * \frac{1}{2.27\left(G/p'_o\right)^{0.16}}$$

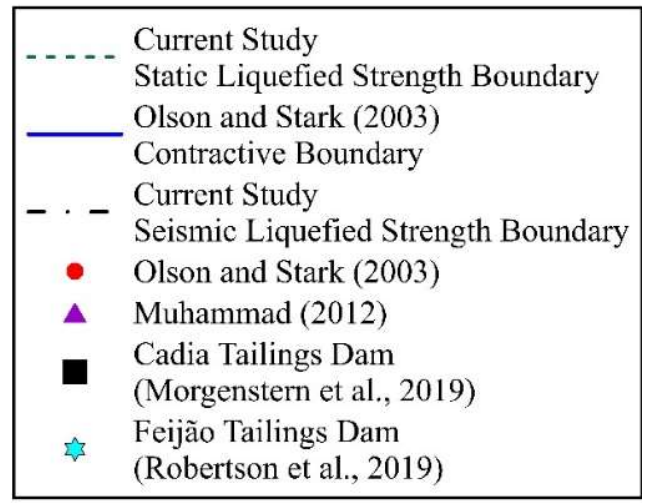
- Use spreadsheet
- $\psi > 0.00$: apply liquefied strength

Flow Failure Assessment Procedure

Step 1b: Assess static liquefaction potential of segments using q_{c1}

- Not Contractive & Dilative





$$q_{c1} = q_c * C_q = q_c * \frac{1.8}{0.8 + (\sigma'_{vo}/P_a)}$$

Flow Failure Assessment Procedure

Step 2a: Assess dynamic liquefaction potential of segments using ψ

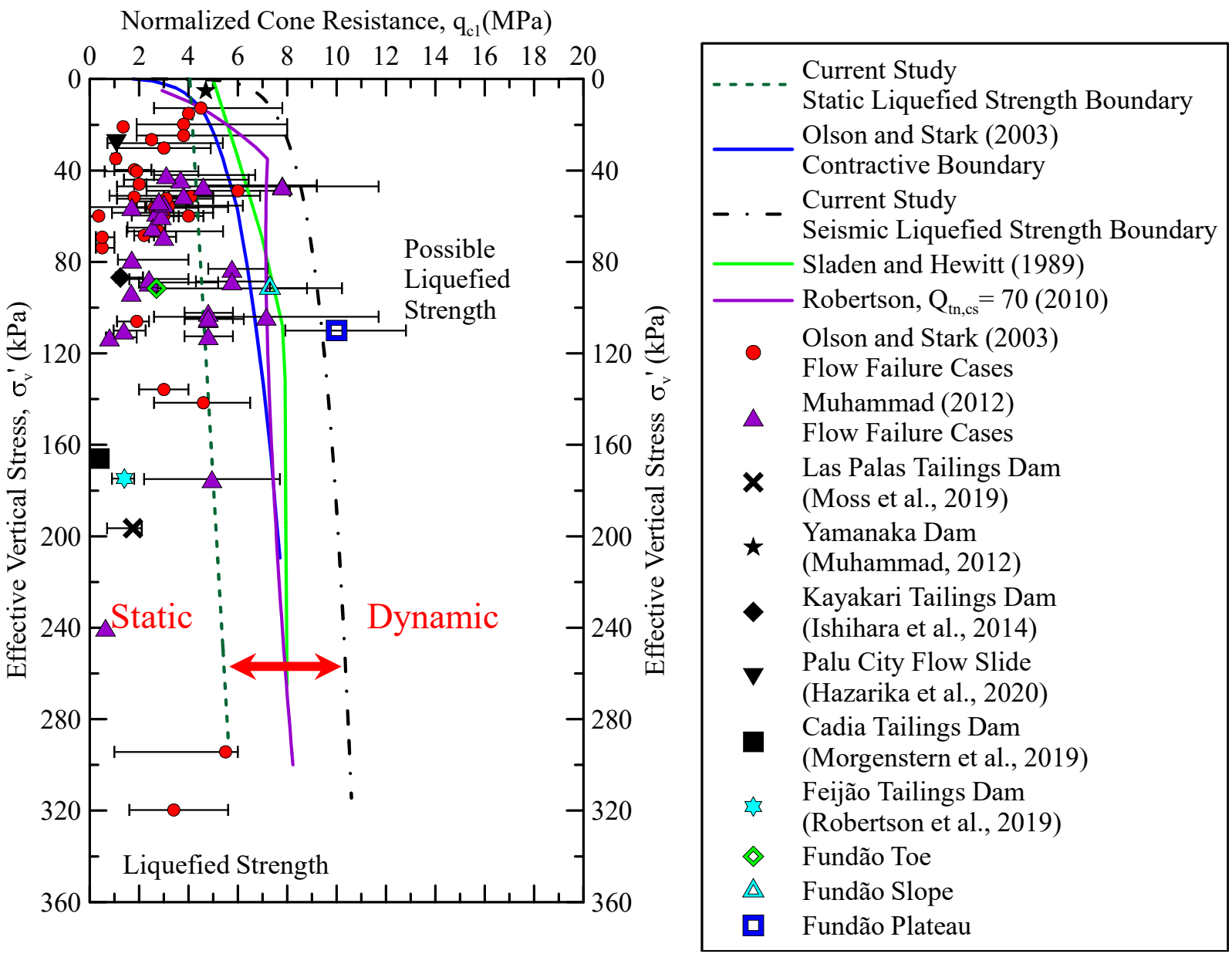
- $$Q_p = \left(\frac{q_c - p_o}{p'_o}\right) \approx \left(\frac{q_c}{p'_o}\right)_p$$

- $$\psi_{field} = -\ln\left(\frac{Q_{p,field\ cpt}}{1.64*(1.49-\lambda)*\left(G/p'_o\right)^{0.45}}\right) * \frac{1}{2.27\left(G/p'_o\right)^{0.16}}$$

- Use spreadsheet
- ψ > -0.05: apply liquefied strength

Flow Failure Assessment Procedure

Step 2b: Assess static liquefaction potential of segments using q_{c1}



Flow Failure Assessment Procedure

Steps 1 & 2: Static and Dynamic liquefaction triggering analysis using ψ

Estimating ψ_{field} from field CPT measurements - January 20, 2024

(Use this Worksheet when G and λ_{10} are not available

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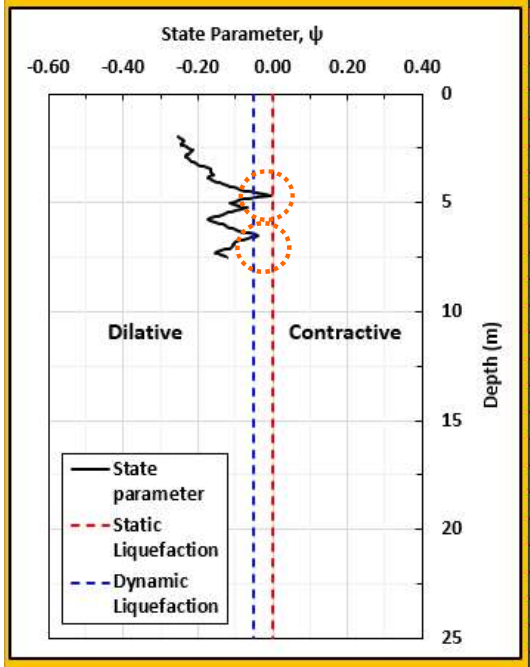
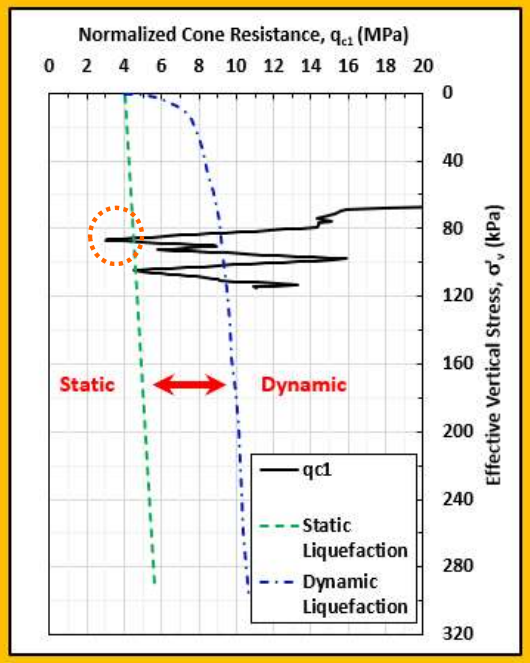
ILLINOIS
www.tstark.net

Input		
γ_{sat} (kPa)	Water depth (m)	K_o
20	4	0.5

Depth (m)	q_c (MPa)	Fr (%)	σ'_v (kPa)	p' (kPa)	Q_p	I_c	G/p'	λ_{10}	ψ_{field}	q_{c1} (MPa)
2.00	25.2	0.9	40.0	26.7	943.3	1.4	4742.9	0.11	-0.25	37.9
2.05	24.7	1.0	41.0	27.3	903.0	1.4	4777.9		-0.25	36.9
2.10	24.2	1.1	42.0	28.0	864.6	1.4	4860.0		-0.24	35.9
2.15	25.5	1.2	43.0	28.7	888.4	1.5	5184.2		-0.24	37.5
2.20	27.0	1.2	44.0	29.3	918.2	1.5	5398.5		-0.24	39.3
2.25	28.4	1.2	45.0	30.0	946.7	1.5	5389.5		-0.24	41.1
2.30	29.9	1.1	46.0	30.7	974.0	1.4	5364.9		-0.25	42.9
2.35	29.4	1.1	47.0	31.3	937.5	1.4	5075.6		-0.25	41.9
2.40	28.6	1.2	48.0	32.0	892.0	1.5	5177.8		-0.24	40.4
2.45	27.7	1.3	49.0	32.7	848.3	1.5	5287.0		-0.23	38.9
2.50	26.9	1.5	50.0	33.3	806.3	1.6	5363.1		-0.22	37.5
2.55	26.1	1.7	51.0	34.0	766.0	1.6	5410.8		-0.22	36.0
2.60	25.2	1.8	52.0	34.7	727.3	1.7	5433.8		-0.21	34.6
2.65	28.6	1.8	53.0	35.3	809.0	1.6	5804.0		-0.22	38.9
2.70	30.1	1.6	54.0	36.0	835.6	1.6	5696.5		-0.22	40.7
2.75	30.1	1.5	55.0	36.7	820.4	1.6	5361.3		-0.23	40.4
2.80	30.1	1.3	56.0	37.3	805.7	1.5	5025.2		-0.23	40.1
2.85	30.1	1.2	57.0	38.0	791.5	1.5	4686.2		-0.23	39.8
2.90	30.1	1.1	58.0	38.7	777.9	1.5	4552.5		-0.23	39.5
2.95	30.1	1.2	59.0	39.3	764.7	1.5	4674.9		-0.23	39.2
3.00	30.1	1.3	60.0	40.0	751.9	1.5	4788.0		-0.23	38.9
3.05	30.1	1.4	61.0	40.7	739.6	1.6	4892.7		-0.22	38.7
3.10	30.1	1.5	62.0	41.3	727.6	1.6	4989.8		-0.22	38.4
3.15	27.6	1.6	63.0	42.0	655.5	1.6	4719.5		-0.21	34.9
3.20	25.0	1.5	64.0	42.7	584.8	1.7	4281.7		-0.21	31.4
3.25	22.4	1.5	65.0	43.3	516.3	1.7	3861.5		-0.20	28.0
3.30	19.8	1.4	66.0	44.0	449.9	1.7	3457.1		-0.19	24.6



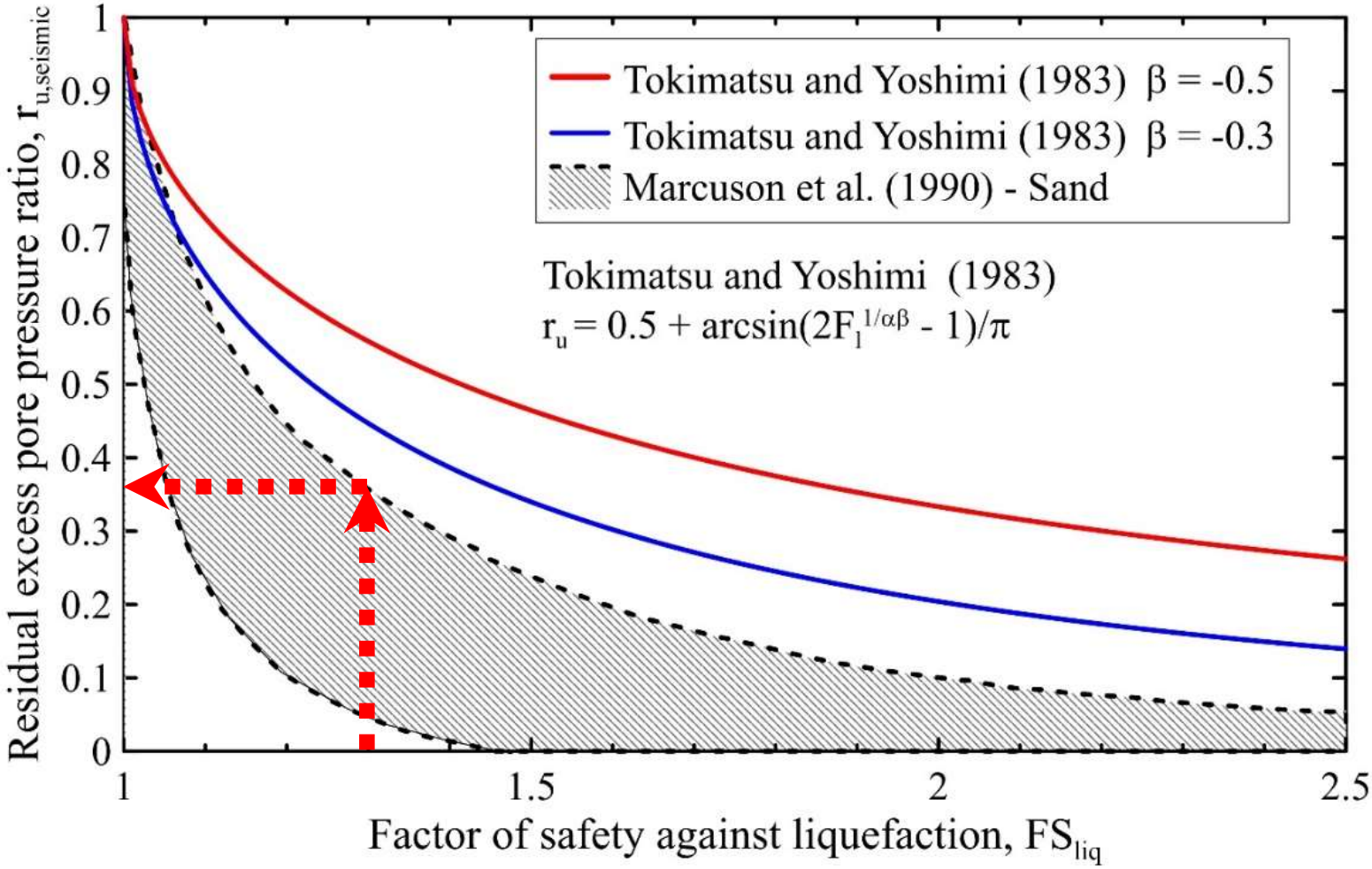


- Use graphs in spreadsheet

Flow Failure Assessment Procedure

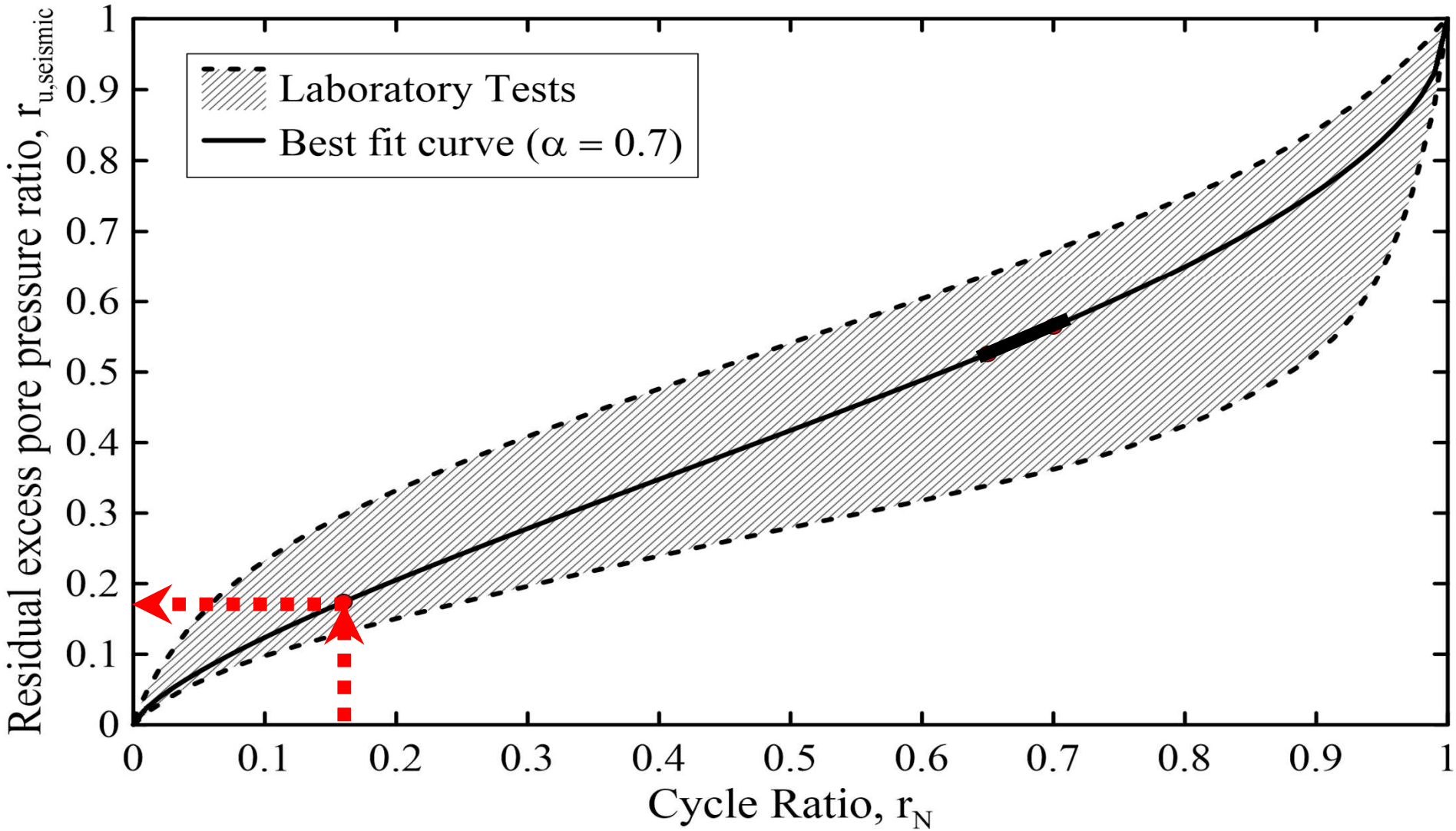
Step 3: If No triggering, estimate shear-induced pore-water pressures or effective mean stress reduction

- $r_{u,total} = r_{u,static} + r_{u,dynamic}$



Excess Pore Pressure Ratio

Step 3: If No triggering, estimate shear-induced pore-water pressures or effective mean stress reduction



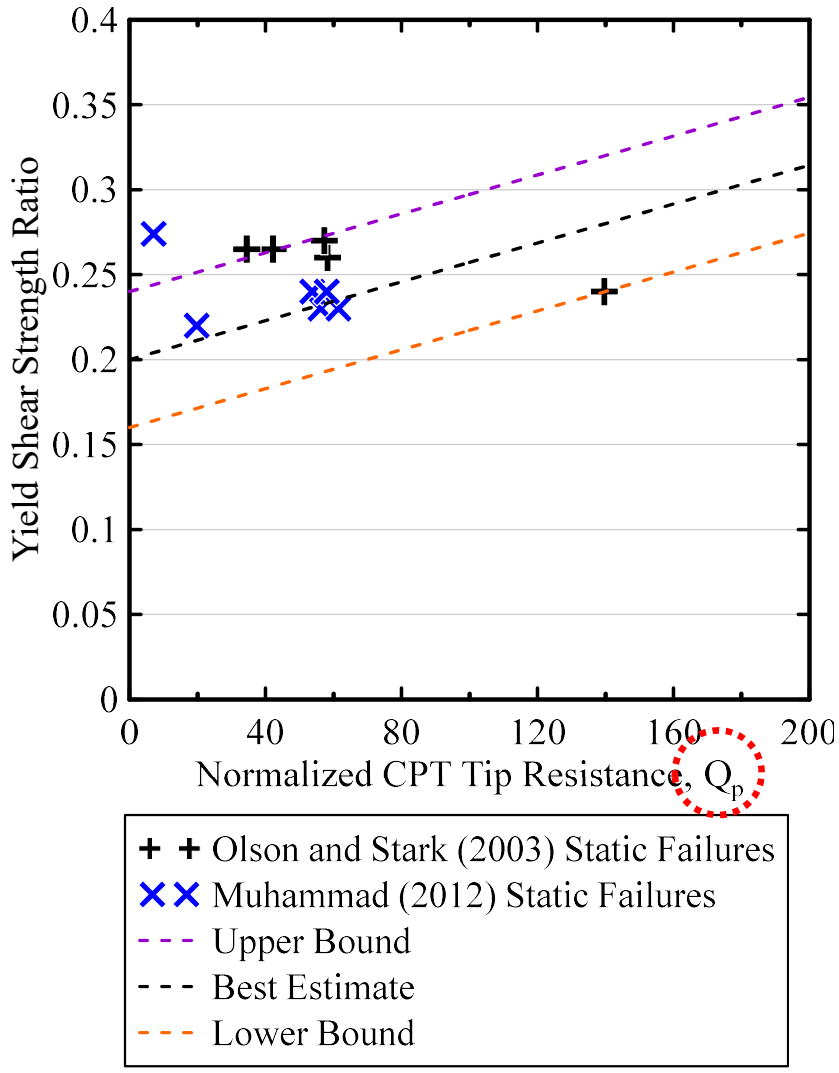
Seed et al. (1976). "Pore-water pressure changes during soil liquefaction." *J. Geotech. Engrg.,* 102(4), 323-346.

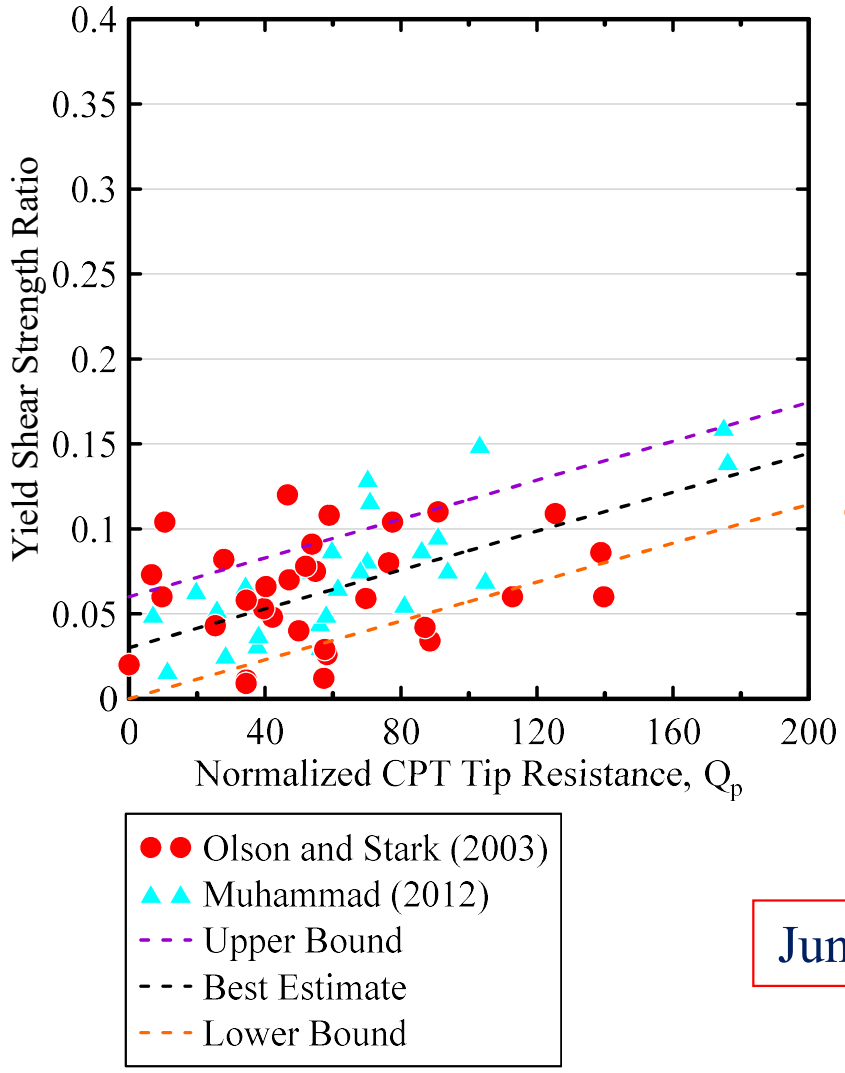
Flow Failure Assessment Procedure

Step 4: Assign a liquefied strength (ratio) to segments if:

- Static liquefaction chart – Left of trend line
- $FoS_{\mathrm{Liq}} \leq 1.0$
- Effective stress left of CSL
- $r_u \geq 0.7$

Yield & Liquefied Strengths





- ~10-30%

Jung et al. (2024)

$$Q_p = \left(\frac{q_c - p_o}{p'_o}\right) \approx \left(\frac{q_c}{p'_o}\right)$$

- p'_0 = mean σ'

Flow Failure Assessment Procedure

Step 5: Perform post-triggering stability analysis

- $FoS_{\text{Flow}} \leq 1.0$ => flow failure
- $FoS_{\text{Flow}} = 1.0$ to 1.1 => permanent deformations, if

  $\text{Fo}S_{\text{Triggering}} < 1.1$ segments => assign liquefied strength & calc FoS_{Flow}
- $1.2 < FoS_{\text{Flow}} < 1.3$ => calculate permanent deformations
- $FoS_{\text{Flow}} > 1.2$ to 1.3 => no action required

Olson and Stark (2003)

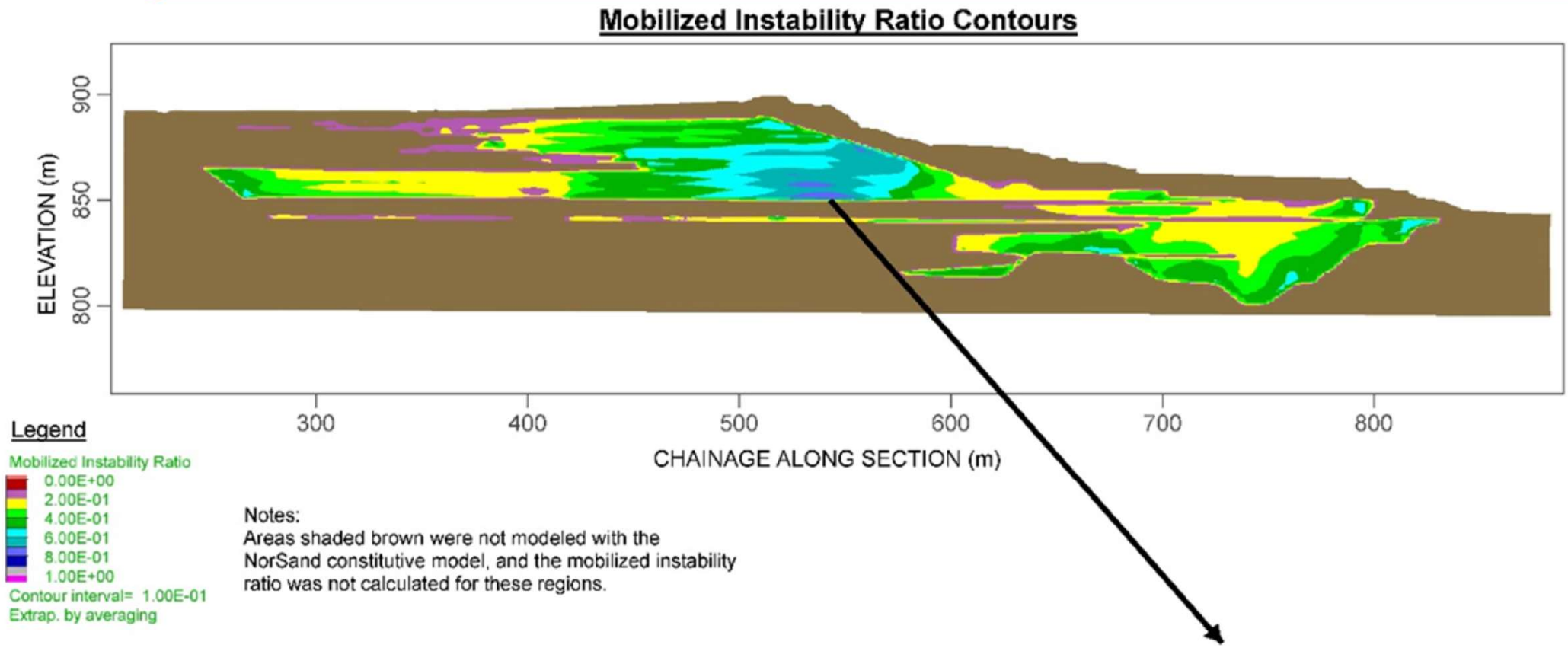
Outline

- Recent Flow Failures
- Liquefied Strength
- Flow Failure Susceptibility
  - Contractive/dilative boundary
  - State parameter
- Five Step Procedure
- Application Examples
- Summary

Application Examples

- Case 1 – Lateral Extrusion
- Case 2 – Static/Drilling Pressure
- Case 3 – Low Shaking
- Case 4 – High Shaking

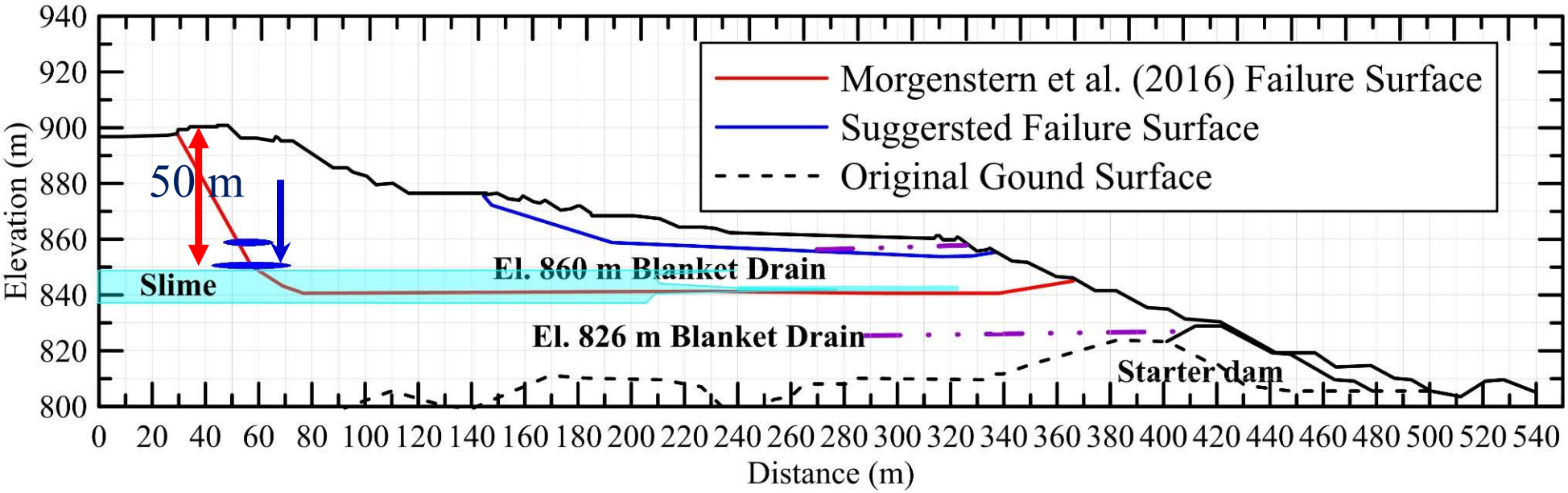
Case 1 – Lateral Extrusion



Response of Sand Tailings at Interface between Sand and Slimes Throughout Dyke Construction

- Soft slimes underlying saturated loose tailings (50 m depth)
- Decreases horizontal confining pressure
- No available CPT measurements of slimes

Case 1 – Lateral Extrusion

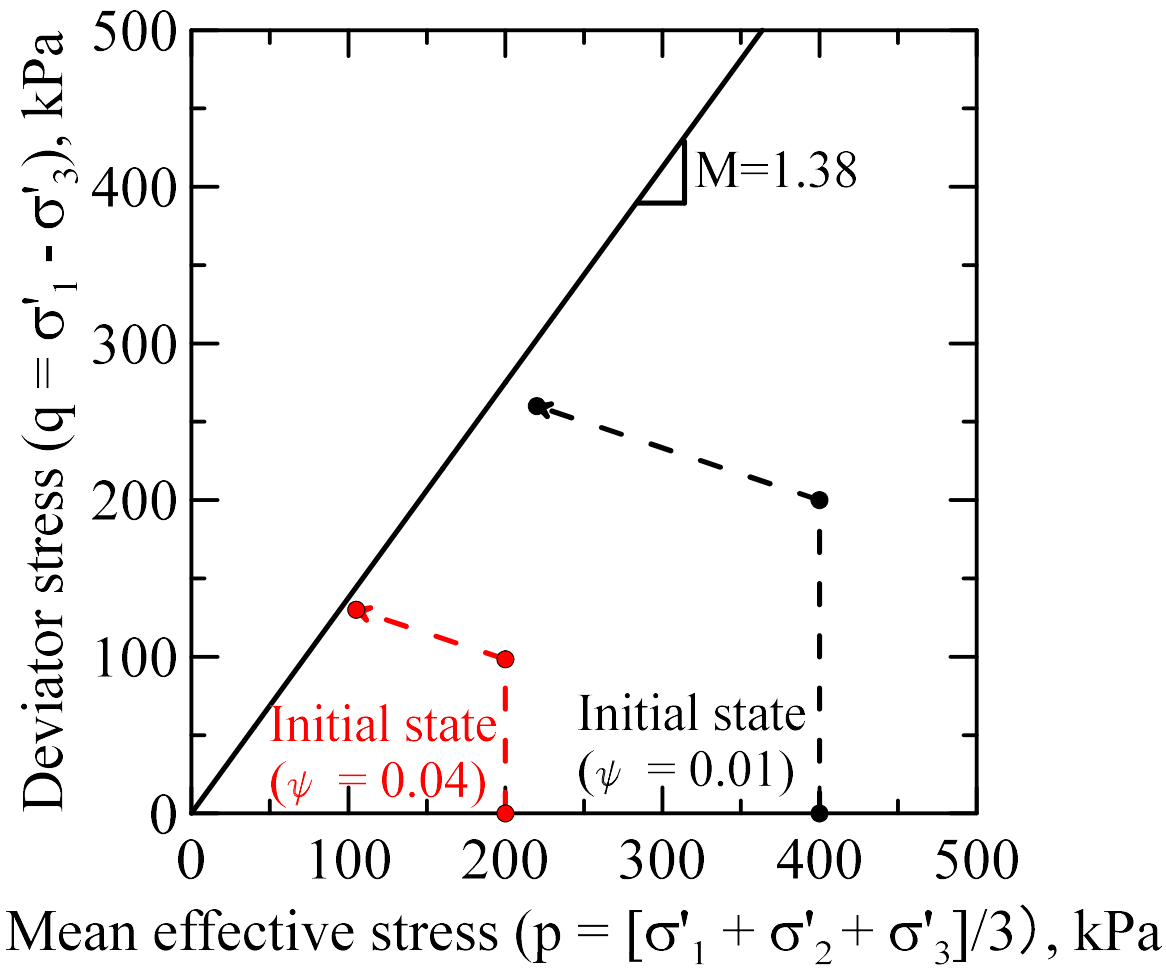


Case 1 – Lateral Extrusion

Steps 1&2: Assess static & dynamic liquefaction triggering of segments

- No CPT so no ψ

Step 3: Estimate mean effective stress reduction due to lateral extrusion



Case 1 – Lateral Extrusion

Step 4: Assign a liquefied strength (ratio) if

- Static liquefaction chart – Left of trendline
- $FoS_{\text{Liq}} \leq 1.0$
- Effective stress left of CSL
- $r_{\text{u-total}} \geq 0.7$

ψ = 0.04	**ψ = 0.01**
Possible Liquefied Strength	Possible Yield Strength
Effective stress at CSL	No triggers

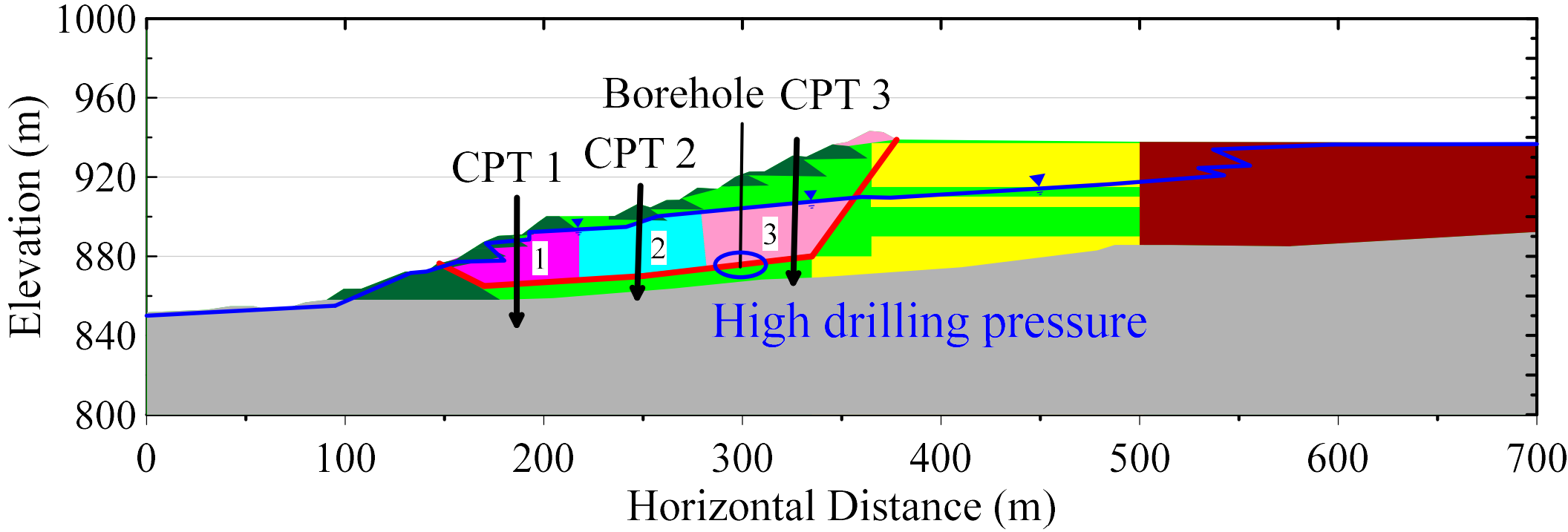
Step 5: Perform post-triggering stability analysis

- $FoS_{\text{Flow}} \sim 1.0$
- if $FoS_{\text{Flow}} \leq 1.0$ => flow failure

Application Examples

- Case 1 – Lateral Extrusion
- Case 2 – Static/Drilling Pressure
- Case 3 – Low Shaking
- Case 4 – High Shaking

Case 2 – Static/drilling pressures

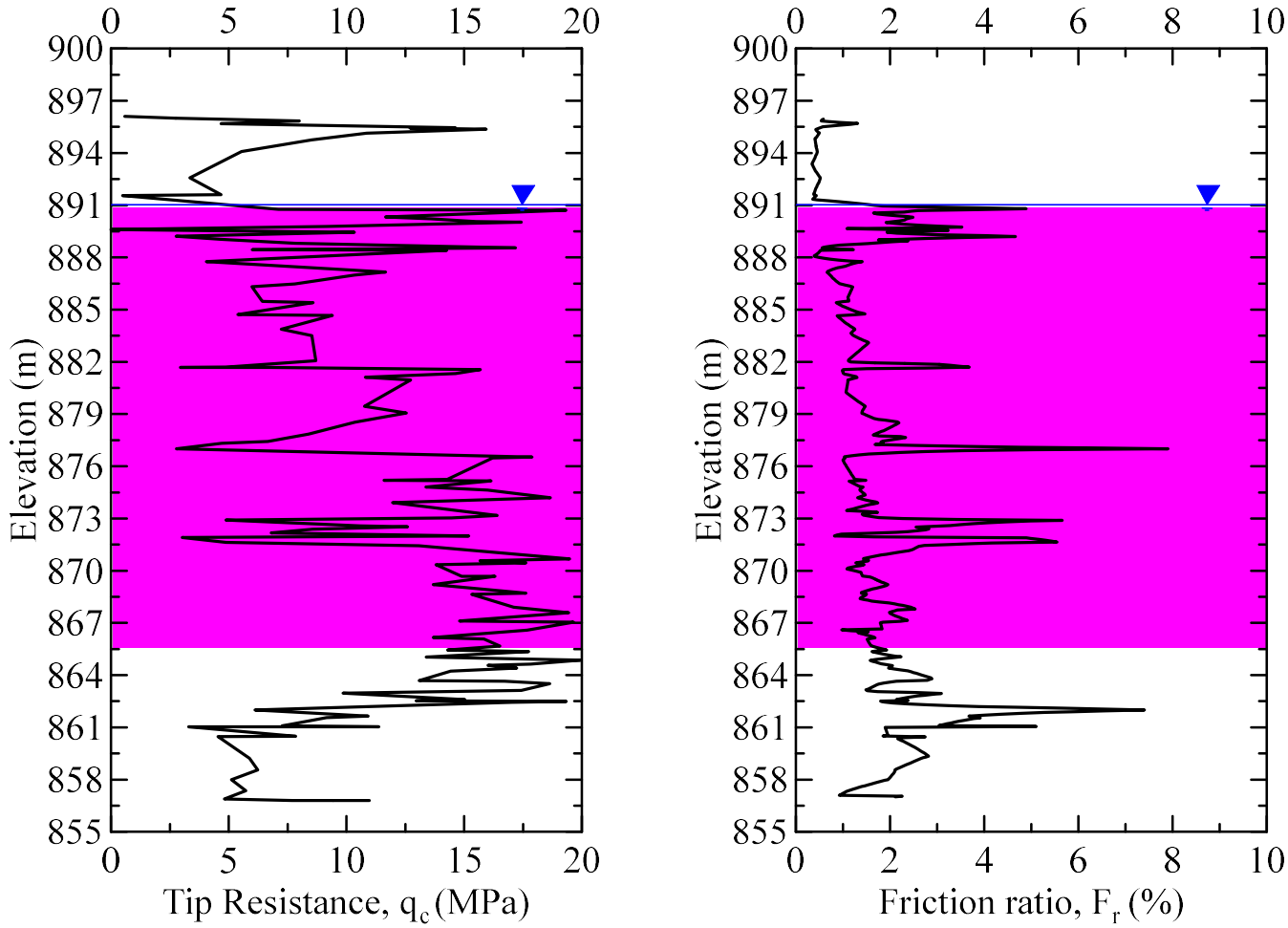


- Divide failure surface into several segments
- Local liquefaction near borehole overpressure
- Propagates throughout segment 3

Case 2 – Static/drilling pressures

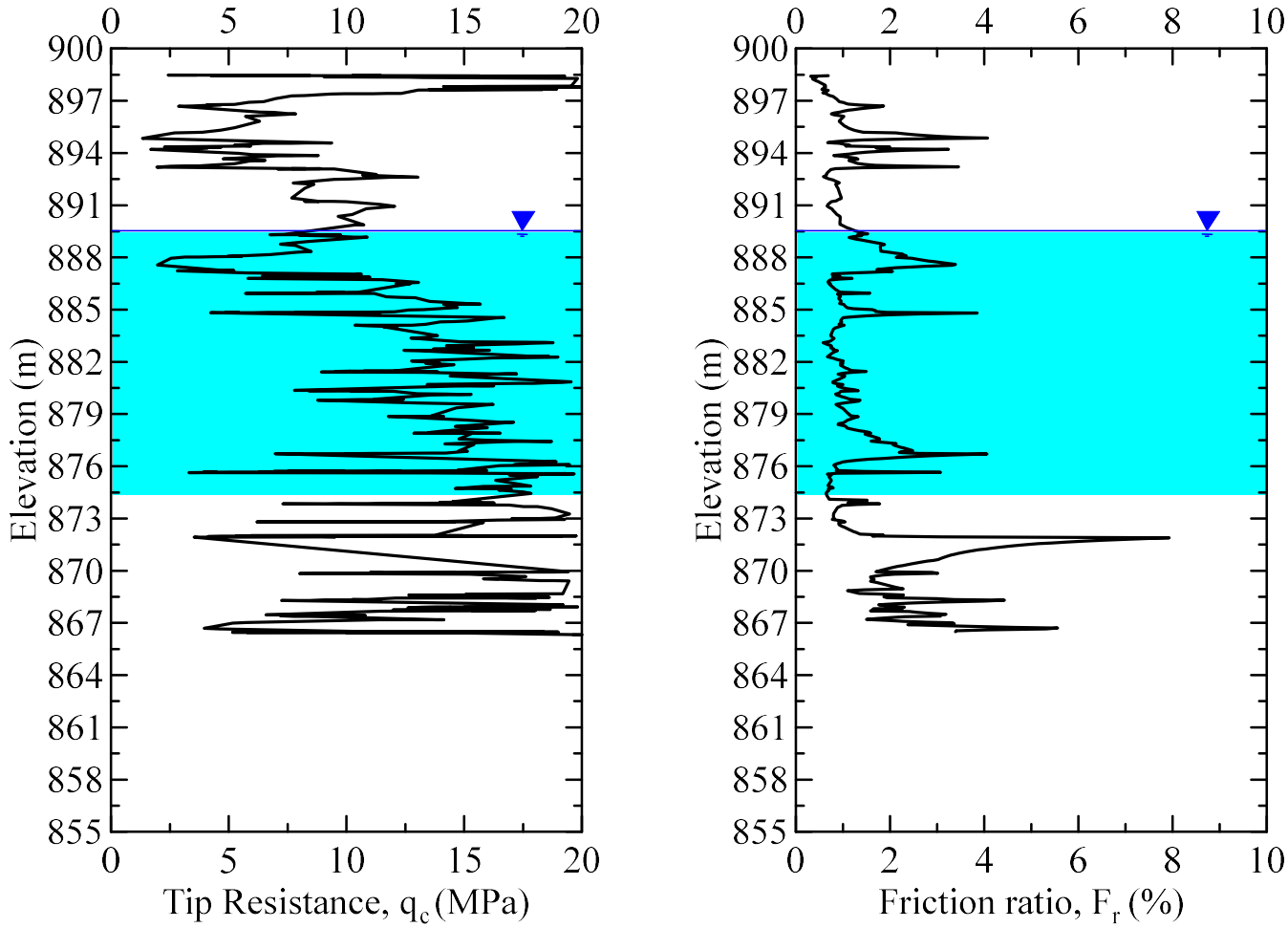
- CPT measurements (CPT-1)

Need q_c & F_r for ψ



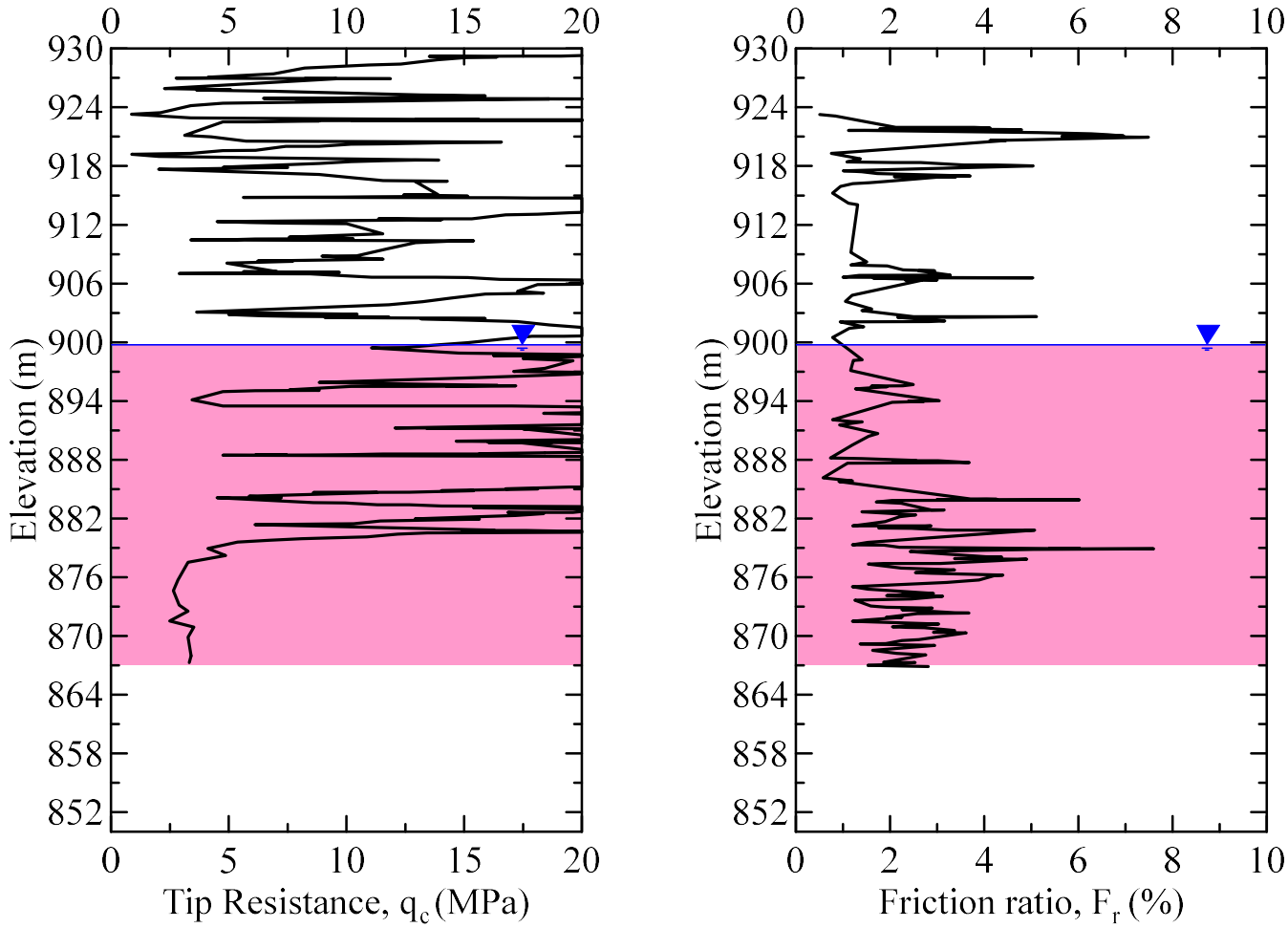
Case 2 – Static/drilling pressures

- CPT measurements (CPT-2)



Case 2 – Static/drilling pressures

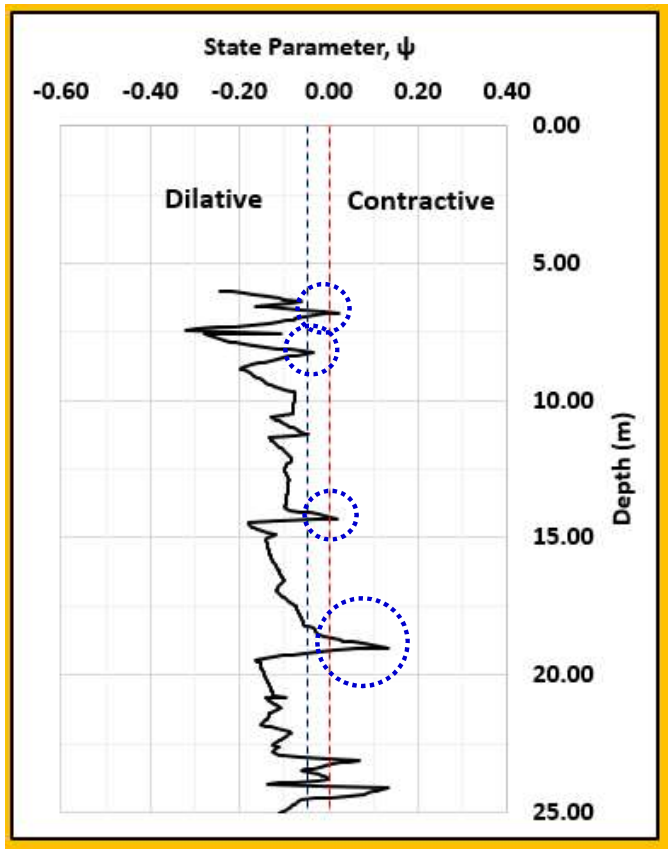
- CPT measurements (CPT-3) – Segment 3



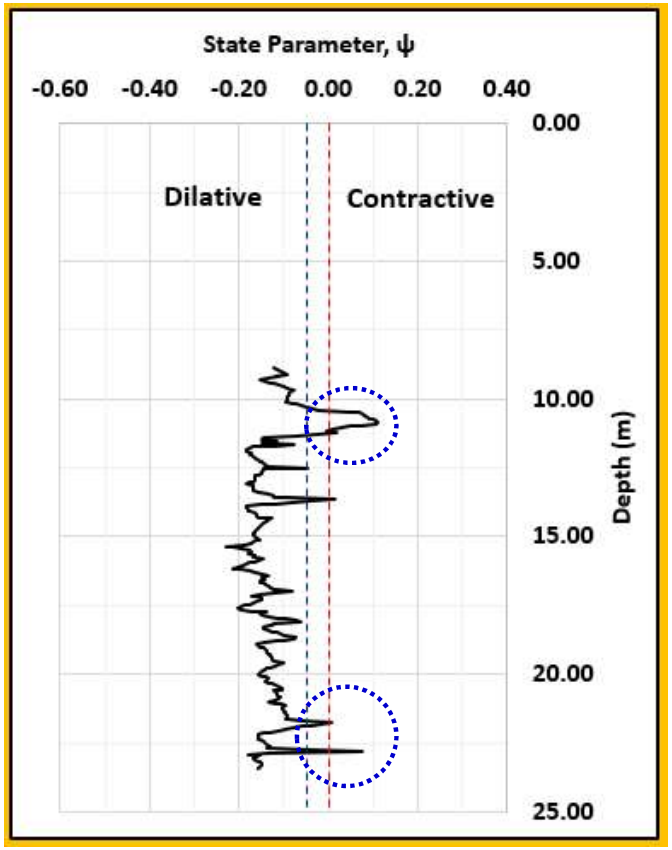
~30 m deep

Case 2 – Static/drilling pressures

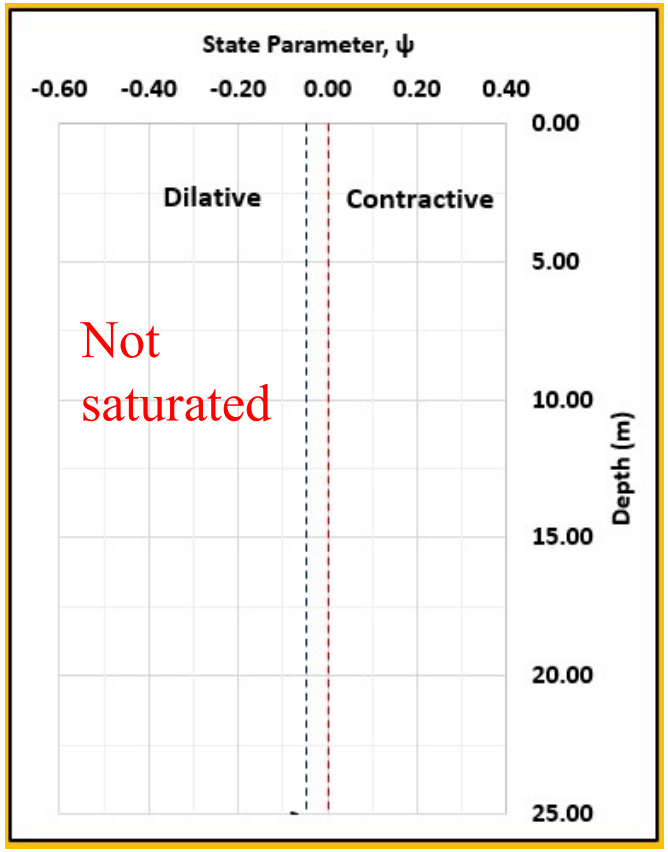
Steps 1&2: Static and dynamic liquefaction triggering analysis using ψ
– Mostly ψ < 0.00, not liquefiable



CPT-1



CPT-2

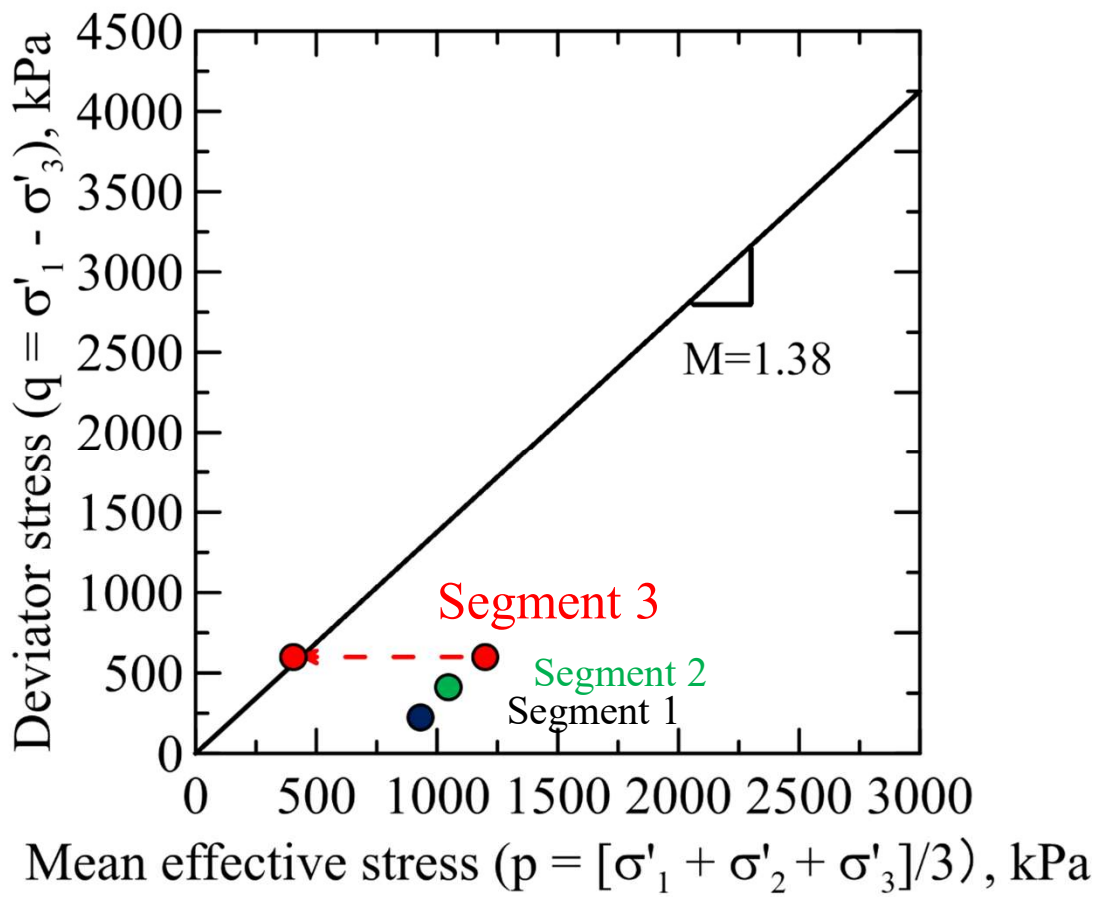


CPT-3

- Use spreadsheet

Case 2 – Static/drilling pressures

Step 3: Estimate drilling-induced excess pore-water pressures
- Assign liquefied strength to Segment 3



Decrease mean effective stress due to drilling pressures

Case 2 – Static/drilling pressures

Step 4: Assign a liquefied strength (ratio) if

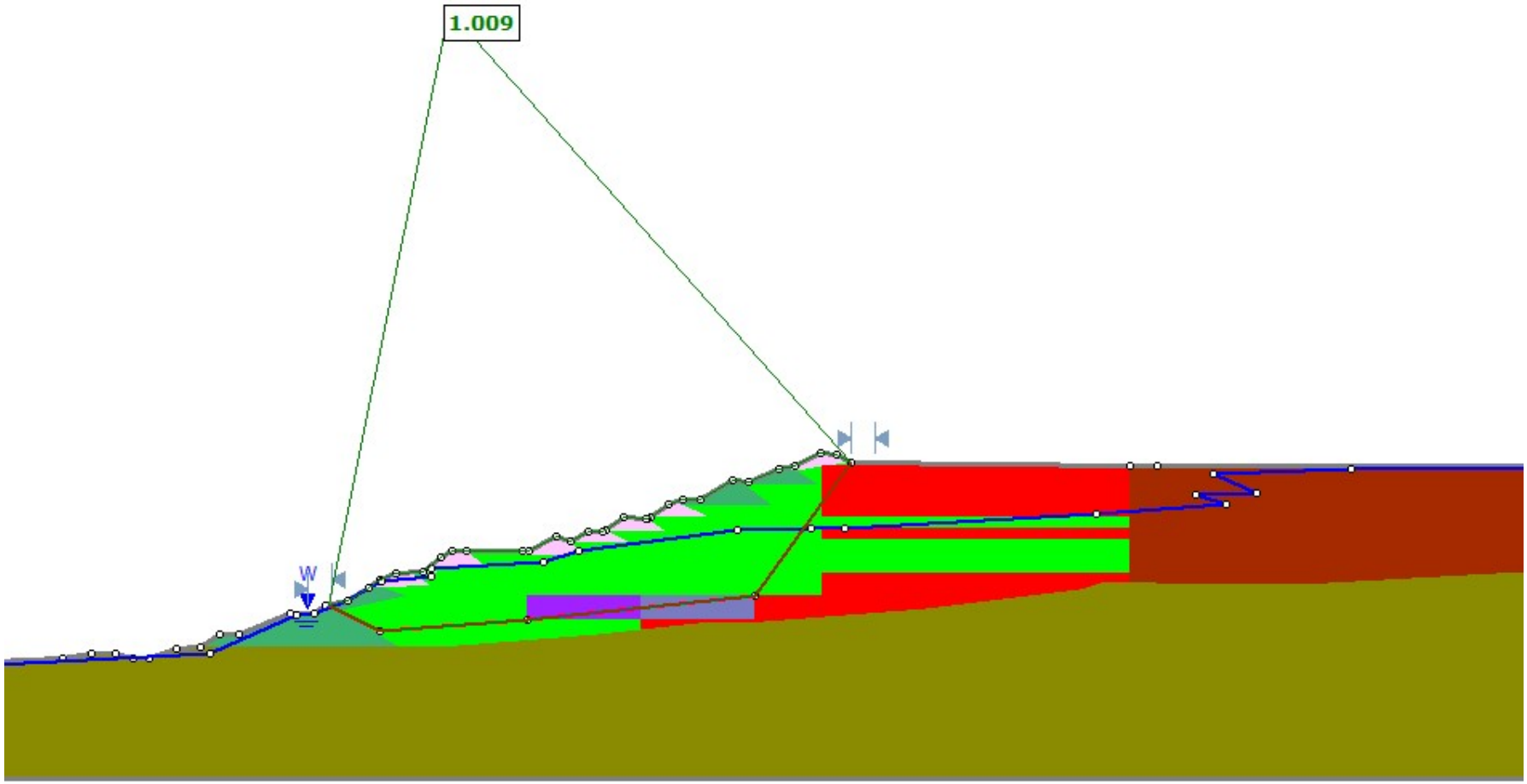
- Static liquefaction chart – Left of trendline
- $FoS_{Liq} \leq 1.0$
- Effective stress left of CSL
- $r_{u\_total} \geq 0.7$

Segment 1	Segment 2	Segment 3
Yield Strength	Yield Strength	Liquefied Strength
No trigger	No trigger	Effective stress left of CSL

Case 2 – Static/drilling pressures

Step 5: Perform post-triggering stability analysis

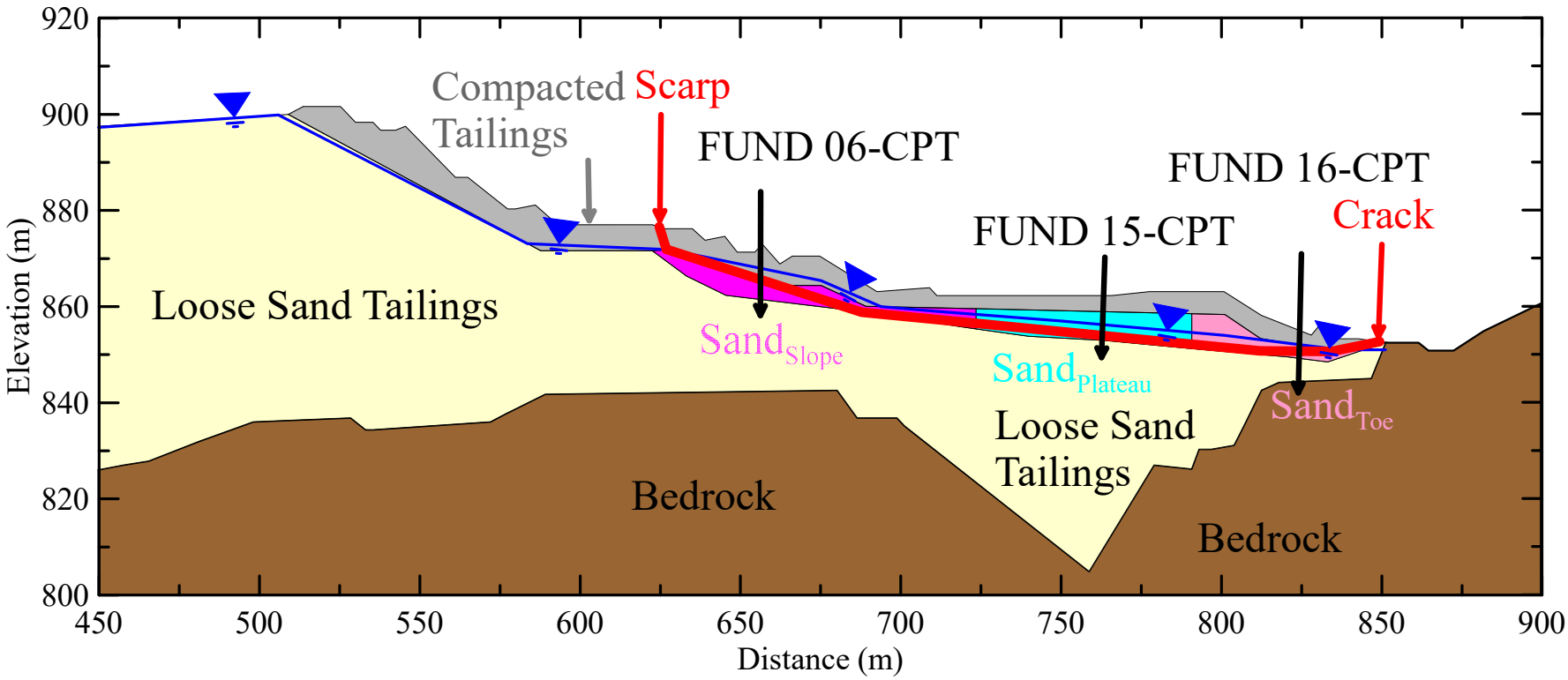
- $FoS_{\text{Flow}} \sim 1.0$
- $FoS_{\text{Flow}} \leq 1.0$ => flow failure

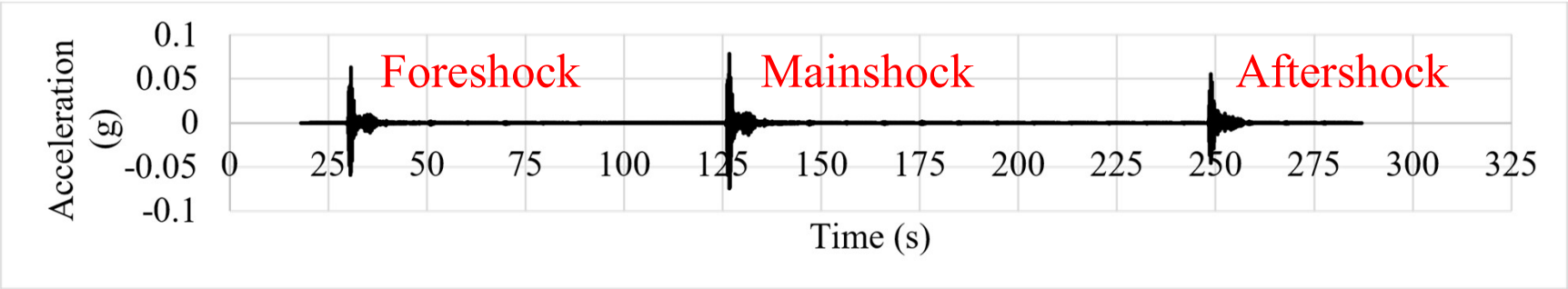


Application Examples

- Case 1 – Lateral Extrusion
- Case 2 – Static/Drilling Pressure
- Case 3 – Low Shaking
- Case 4 – High Shaking

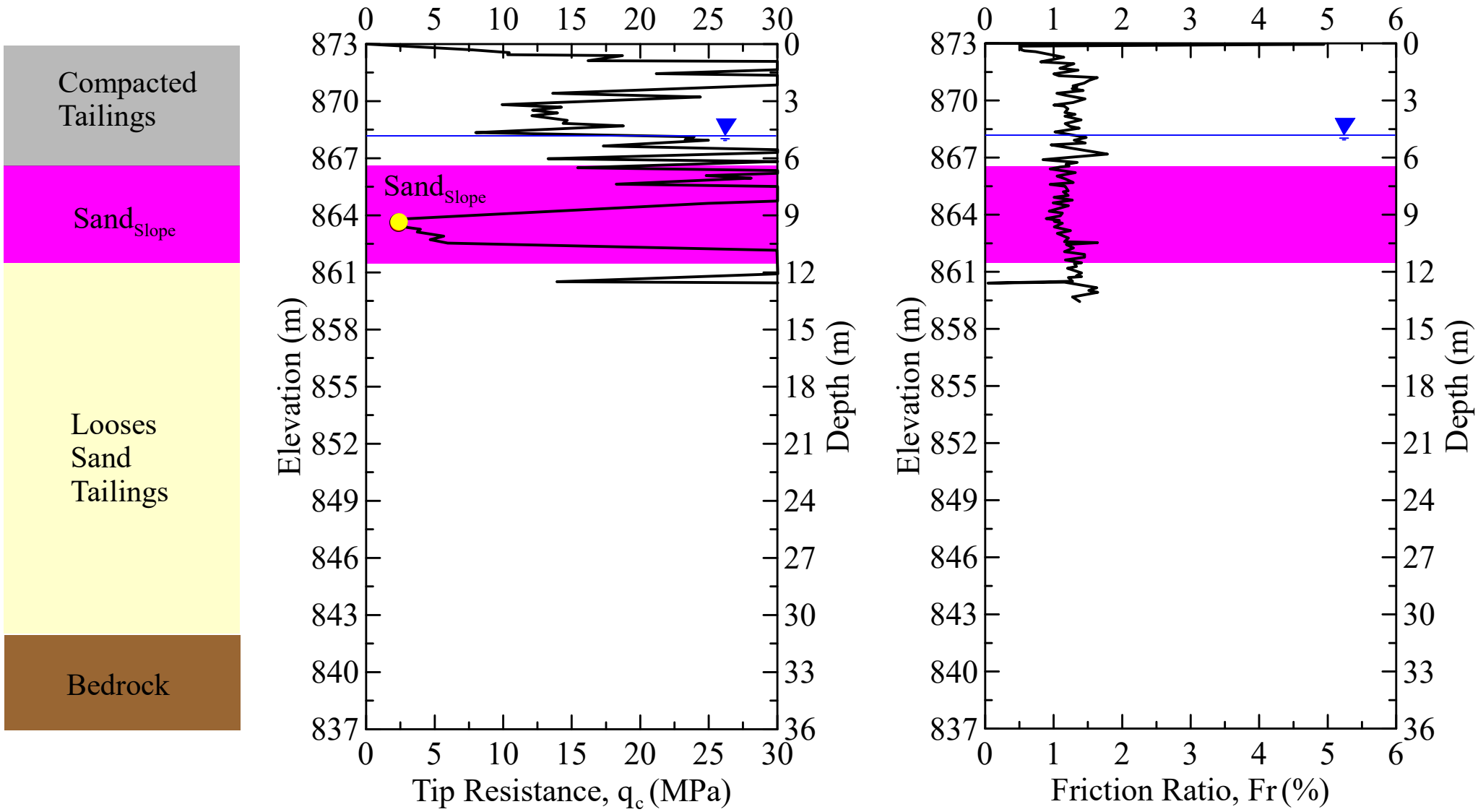
Case 3 – Low Shaking



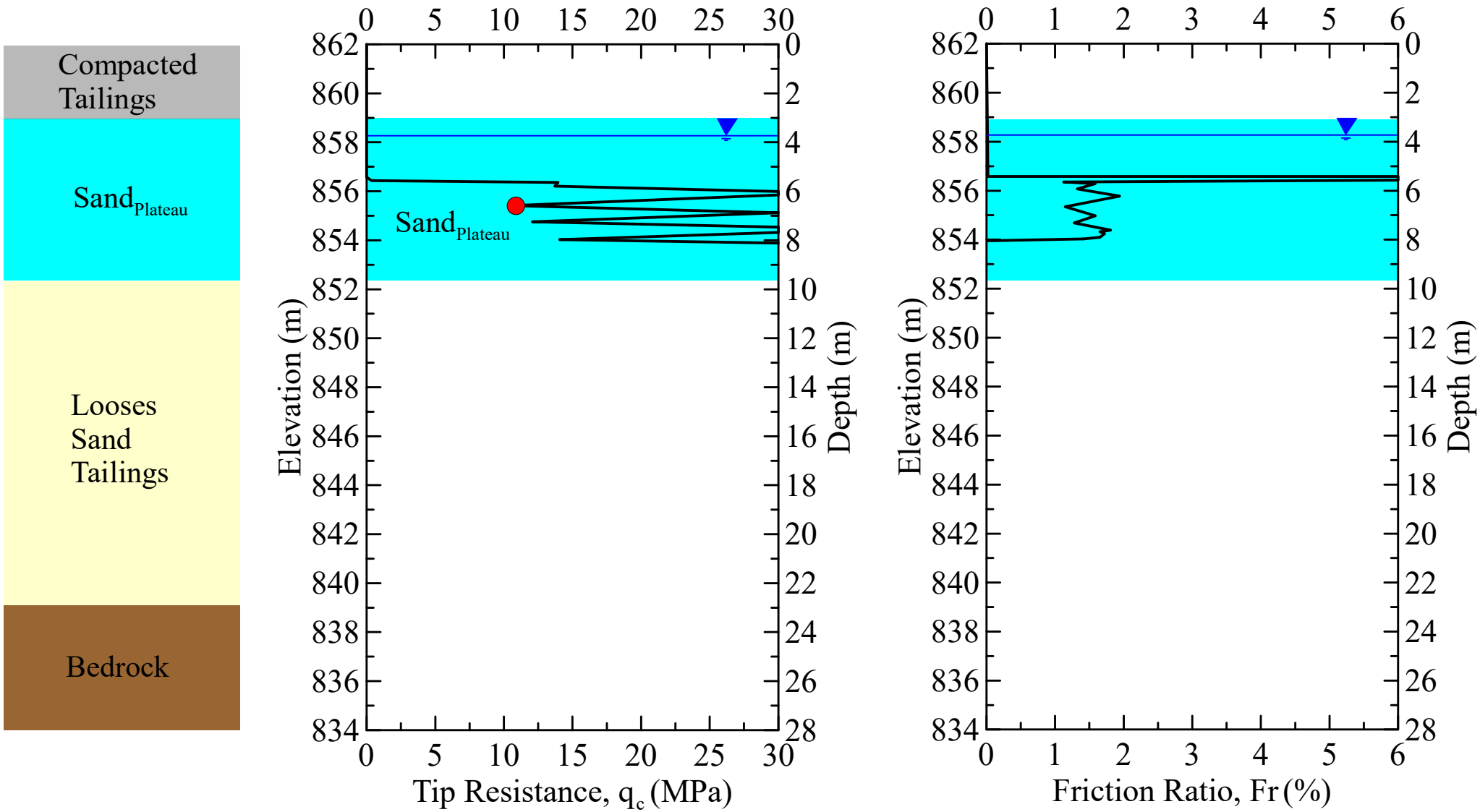


(Stark et al., 2022)

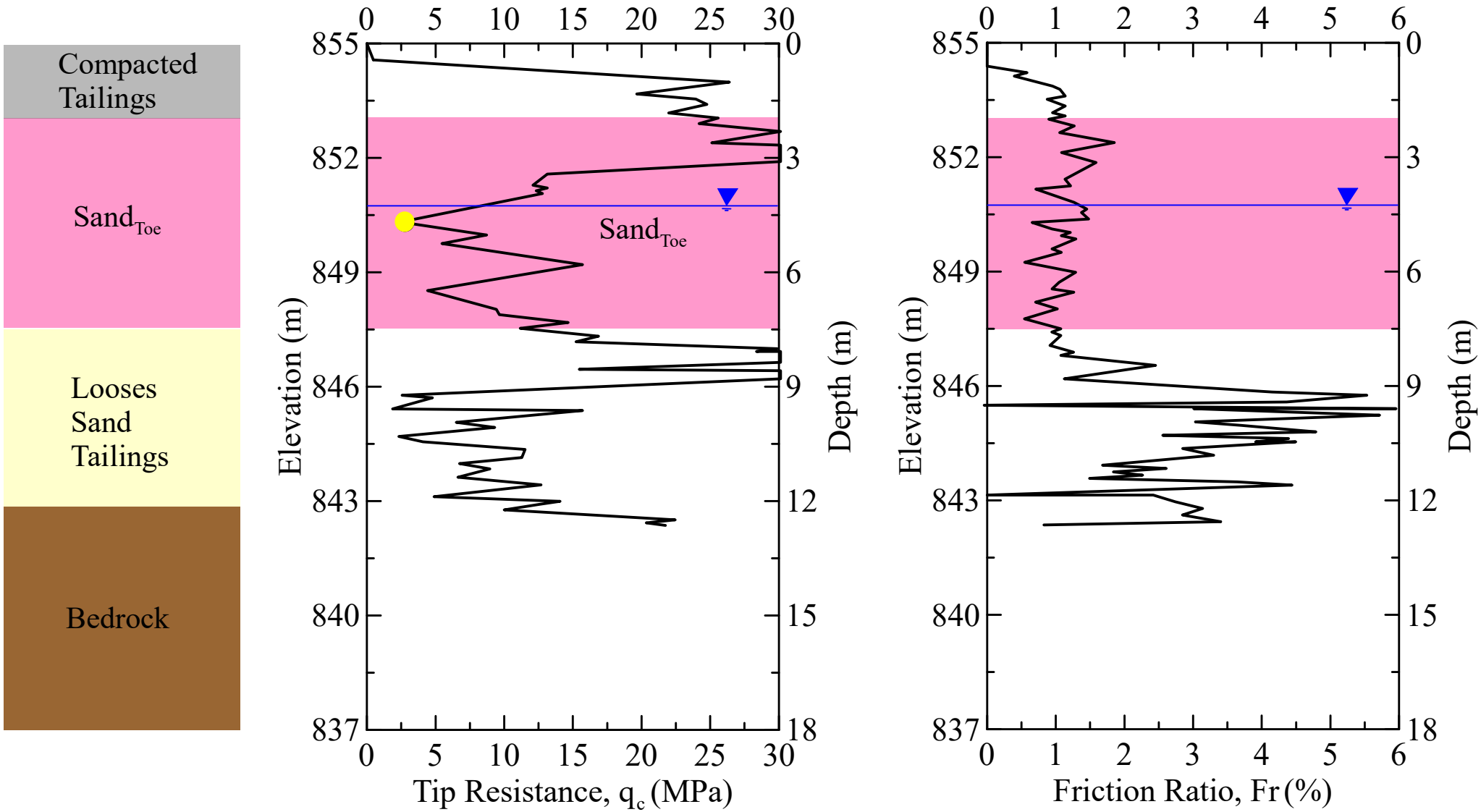
CPT measurements - $Sand_{Slope}$



CPT measurements - Sand$_{Plateau}$

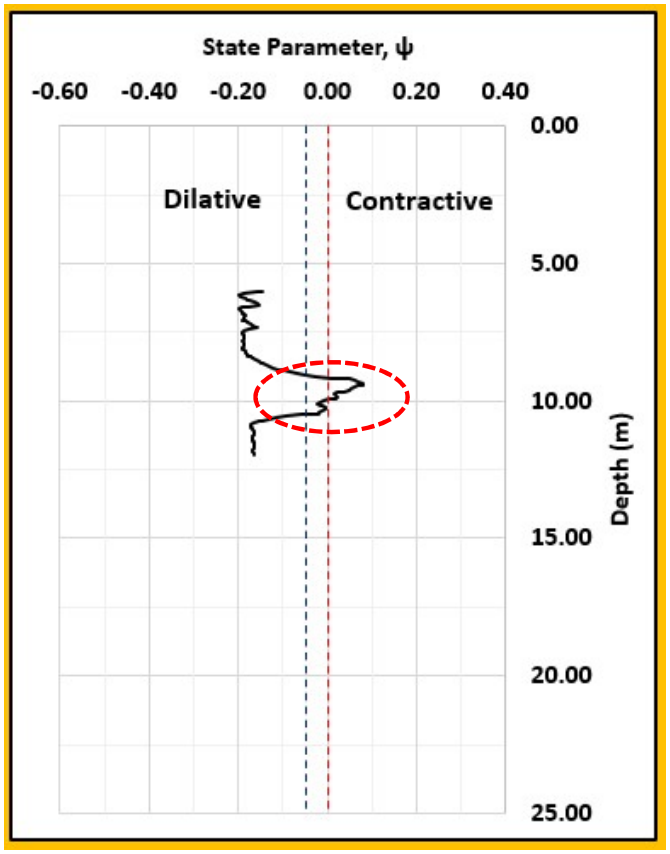


CPT measurements - $Sand_{Toe}$

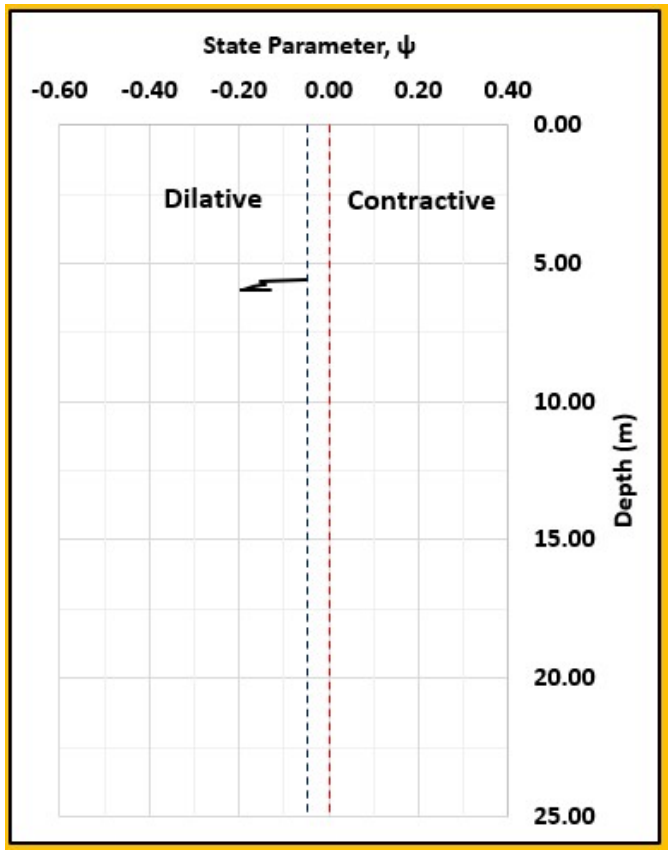


Case 3 – Low Shaking

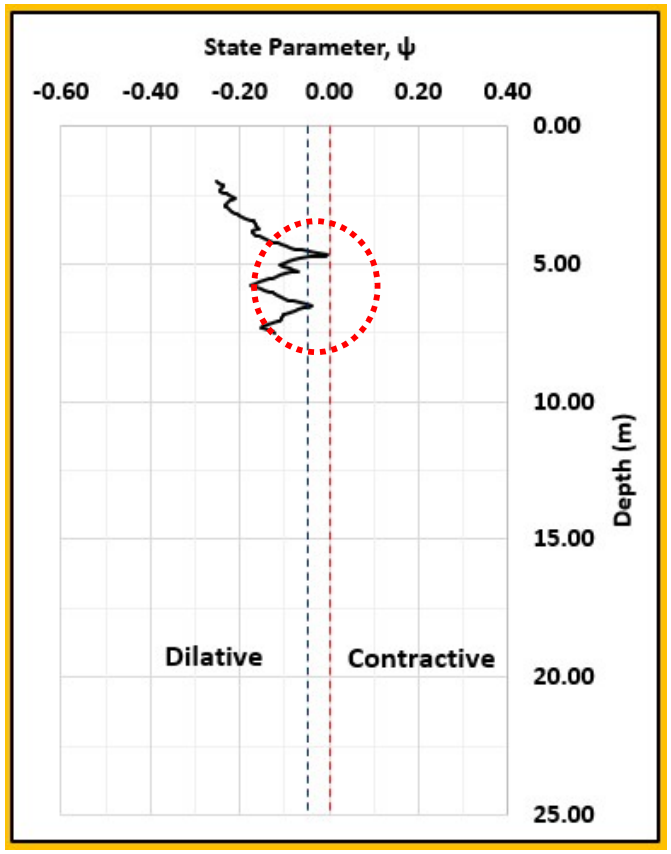
Steps 1&2: Static and dynamic liquefaction triggering analysis using ψ
- Assign liquefied strength to $Sand_{Slope}$ & $Sand_{Toe}$



$Sand_{Slope}$



$Sand_{Plateau}$

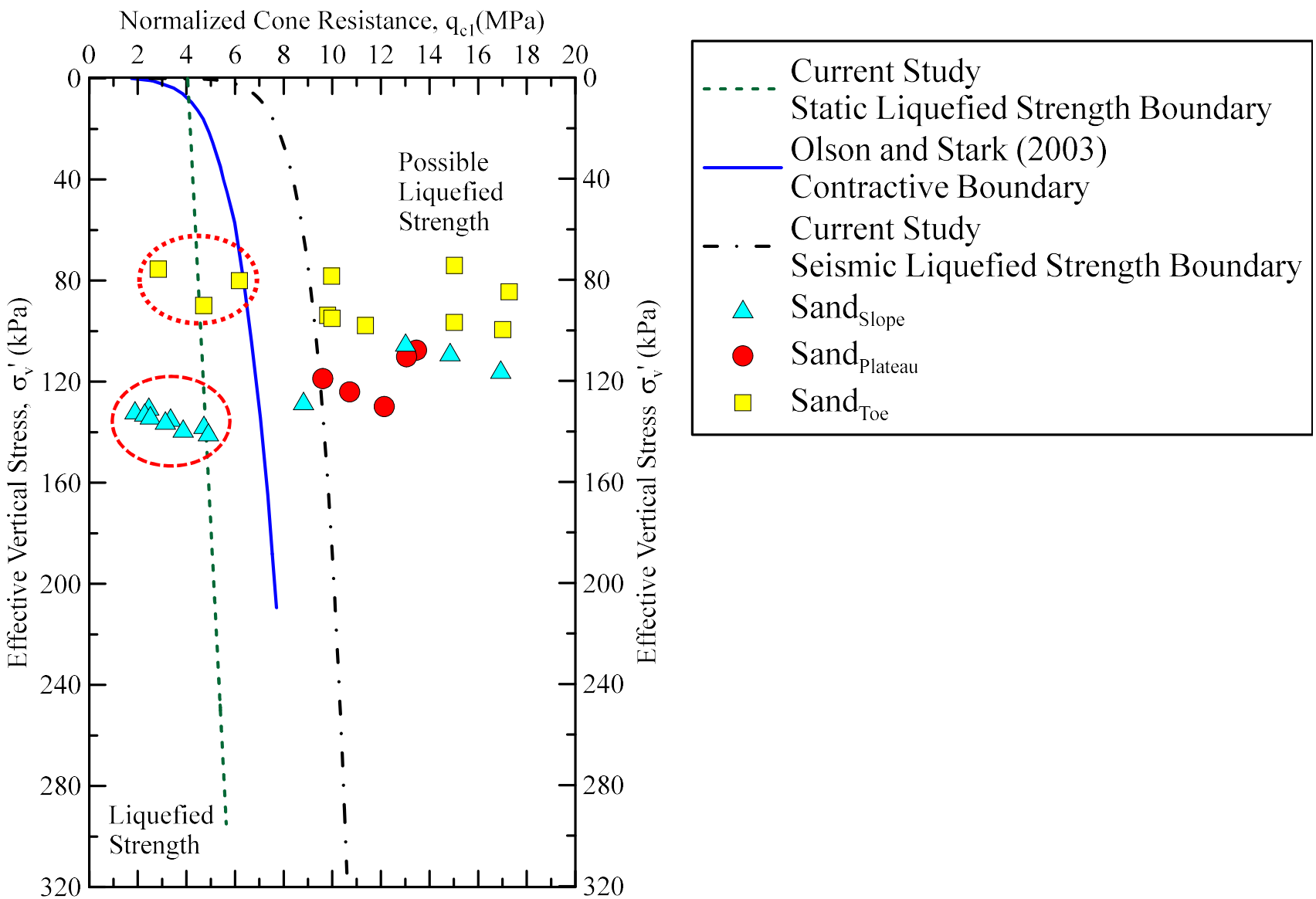


$Sand_{Toe}$

- Use spreadsheet

Case 3 – Low Shaking

Steps 1&2: Static and dynamic liquefaction triggering analysis using q_{c1}
- Assign liquefied strength to $Sand_{Slope}$ & $Sand_{Toe}$

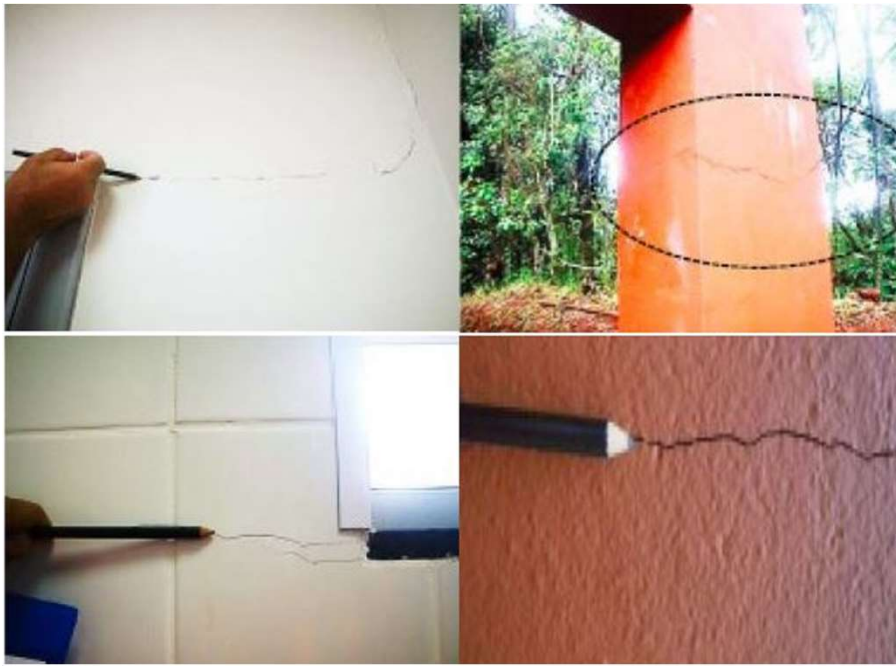


Pre-Failure Earthquakes

Step 3: If No triggering, estimate shear-induced pore-water pressures

Pre-failure earthquakes on November 5, 2015 (Atkinson, 2016)

Local Time	Moment Magnitude Mw	Distance from Fundao	Event
2:12:15 pm	2.2	<2 km	earthquake (foreshock)
2:13:51 pm	2.6	<2 km	earthquake (main shock)
2:16:03 pm	1.8	<2 km	earthquake (aftershock)
2:36-2:46 pm	Dam Failure		

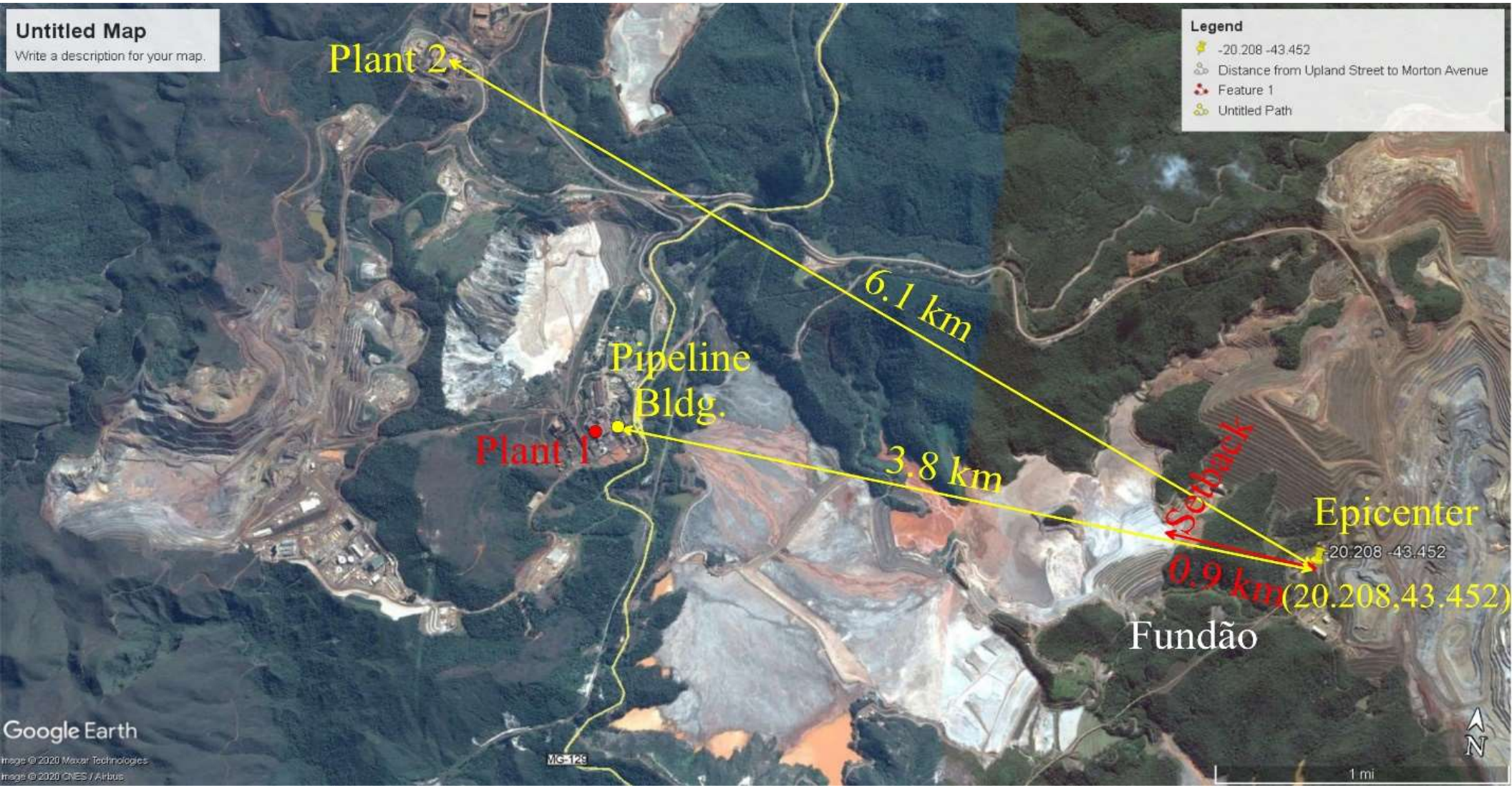


Eyewitness Accounts:

- Shaking strong enough to cause computer to fall from tabletop and minor structural cracking (Morgenstern et al., 2016)
- Viviane Rezende – 2nd eqk shook truck on dam
- Daviely Silva – Desk shaking & broken glass
- **MMI ~ 5 to 6**

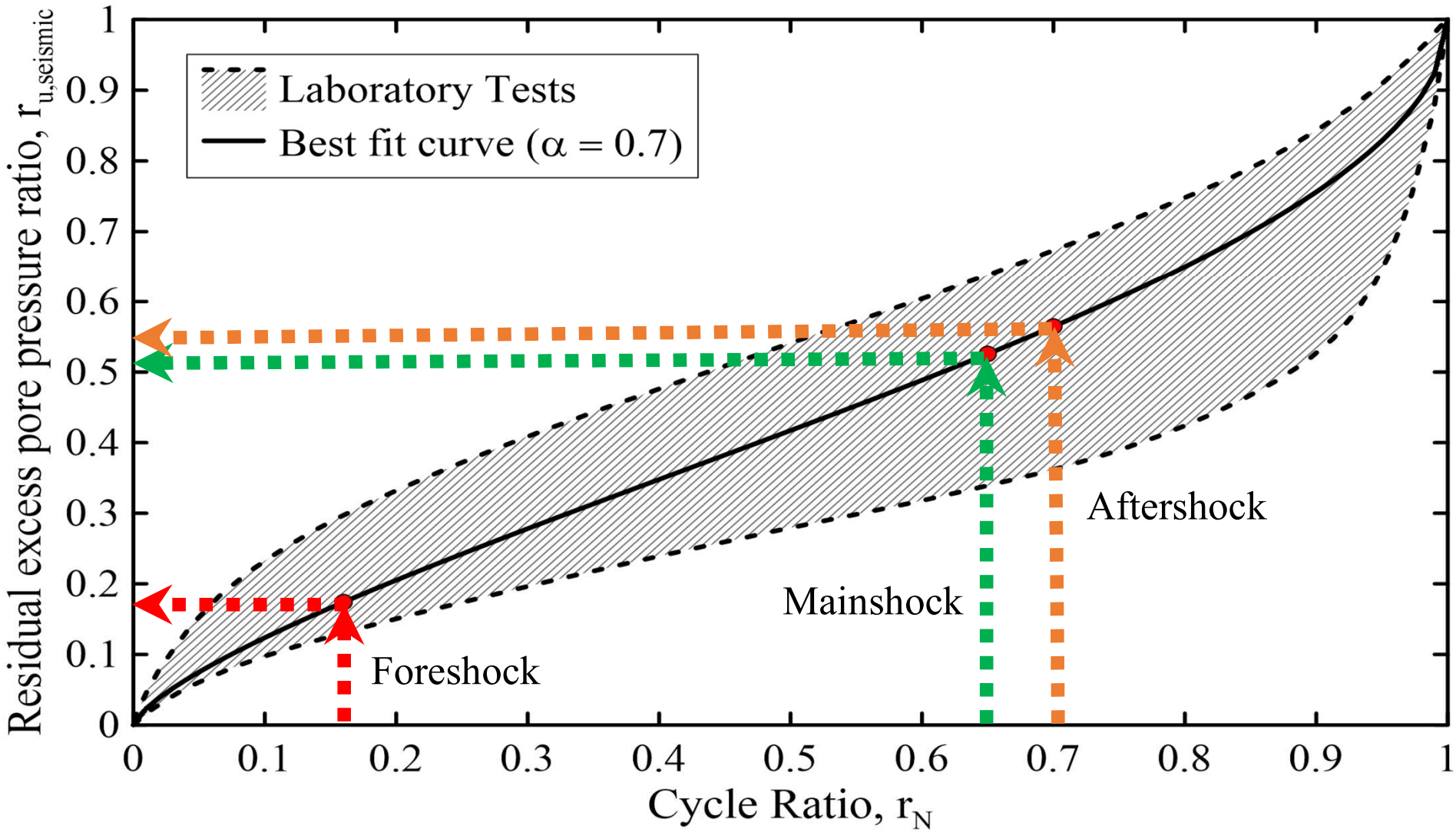
Pre-Failure Earthquakes

Ciardelli and Assumpacao (2019) Epicenter coordinates



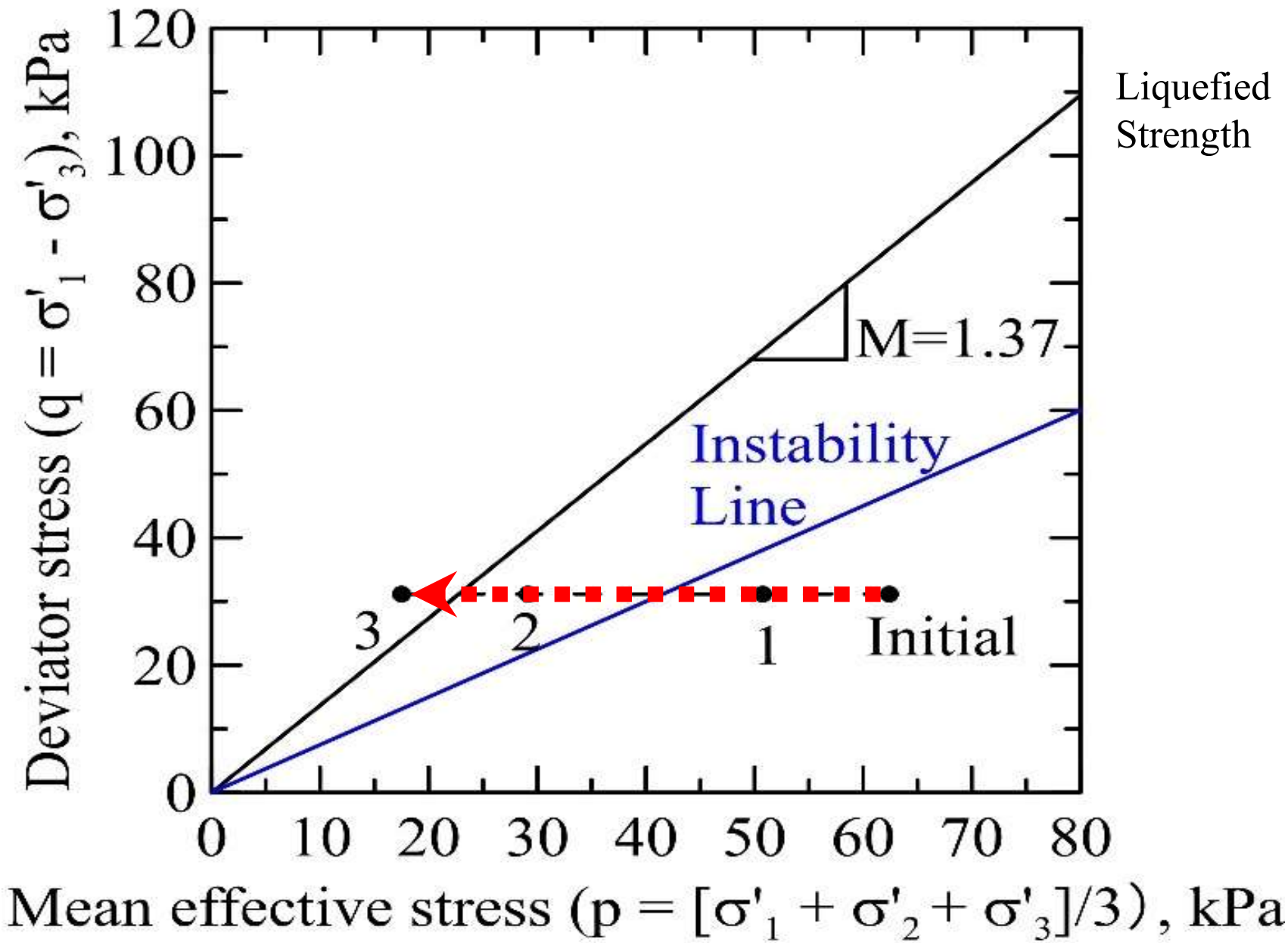
Excess Pore Pressure Ratio

Step 3: If No triggering, estimate shear-induced pore-water pressures

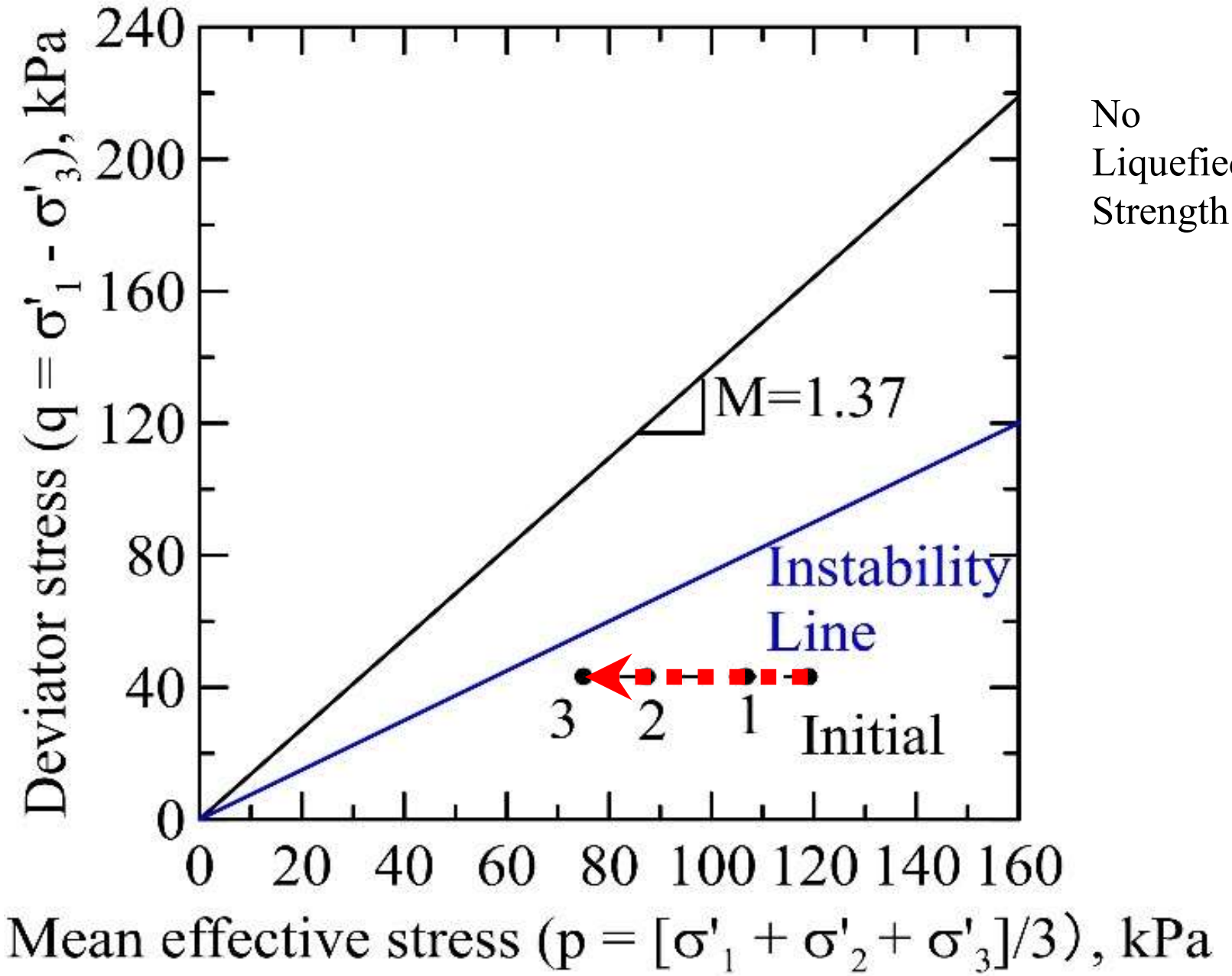


Seed, H.B., Martin, P.P., and Lysmer, J. (1976). "Pore-water pressure changes during soil liquefaction." *J. Geotech. Engrg.*, 102(4), 323-346.

Critical state line – $Sand_{Slope}$

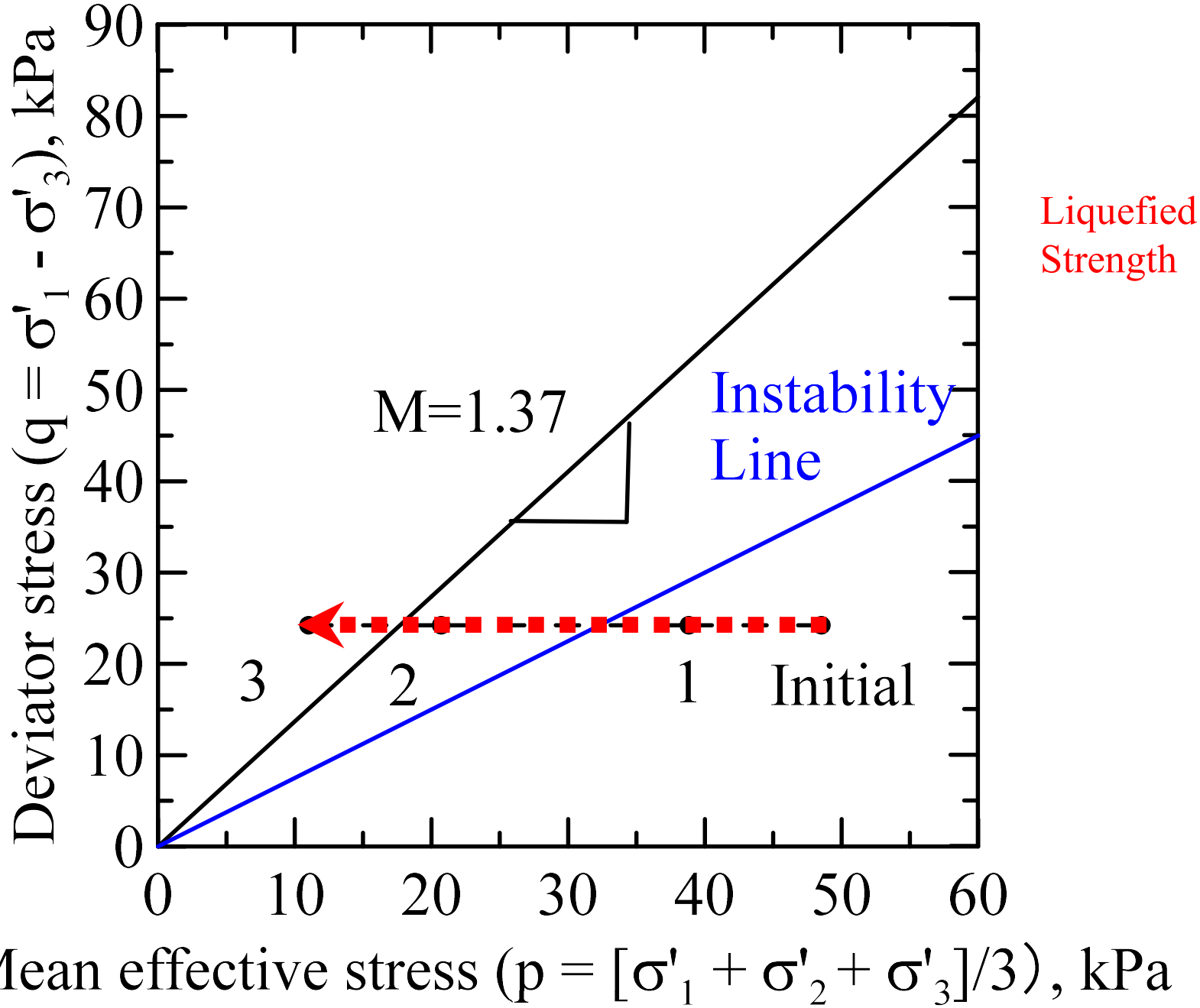


Critical state line – Sand$_{Plateau}$



No Liquefied Strength

Critical state line – $Sand_{Toe}$



Case 3 – Low Shaking

Step 4: Assign a liquefied strength (ratio) if

- Static liquefaction chart – Left of trendline
- $FoS_{Liq} \leq 1.0$
- Effective stress left of CSL
- $r_{u\_total} \geq 0.7$

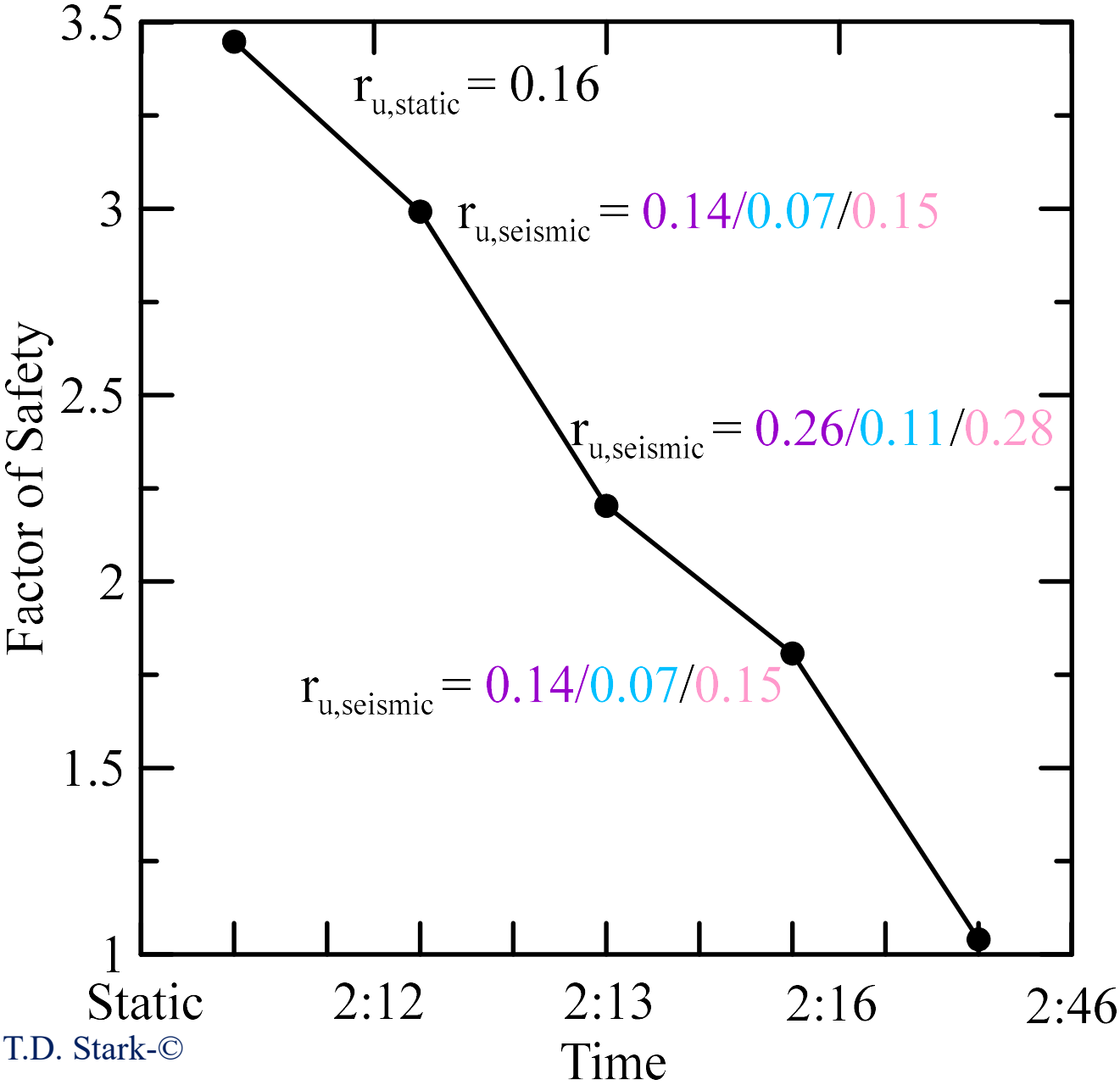
$Sand_{Slope}$	$Sand_{Plateau}$	$Sand_{Toe}$
Liquefied Strength	Yield Strength	Liquefied Strength
Left of trendline	No trigger	Left of CSL

Step 5: Perform post-triggering stability analysis

- $FoS_{Flow} \sim 1.0$
- if $FoS_{Flow} \leq 1.0$ => flow failure

Slope Stability Analyses

Step 5: Perform post-triggering stability analysis



Initial Condition:
r_u=0.16

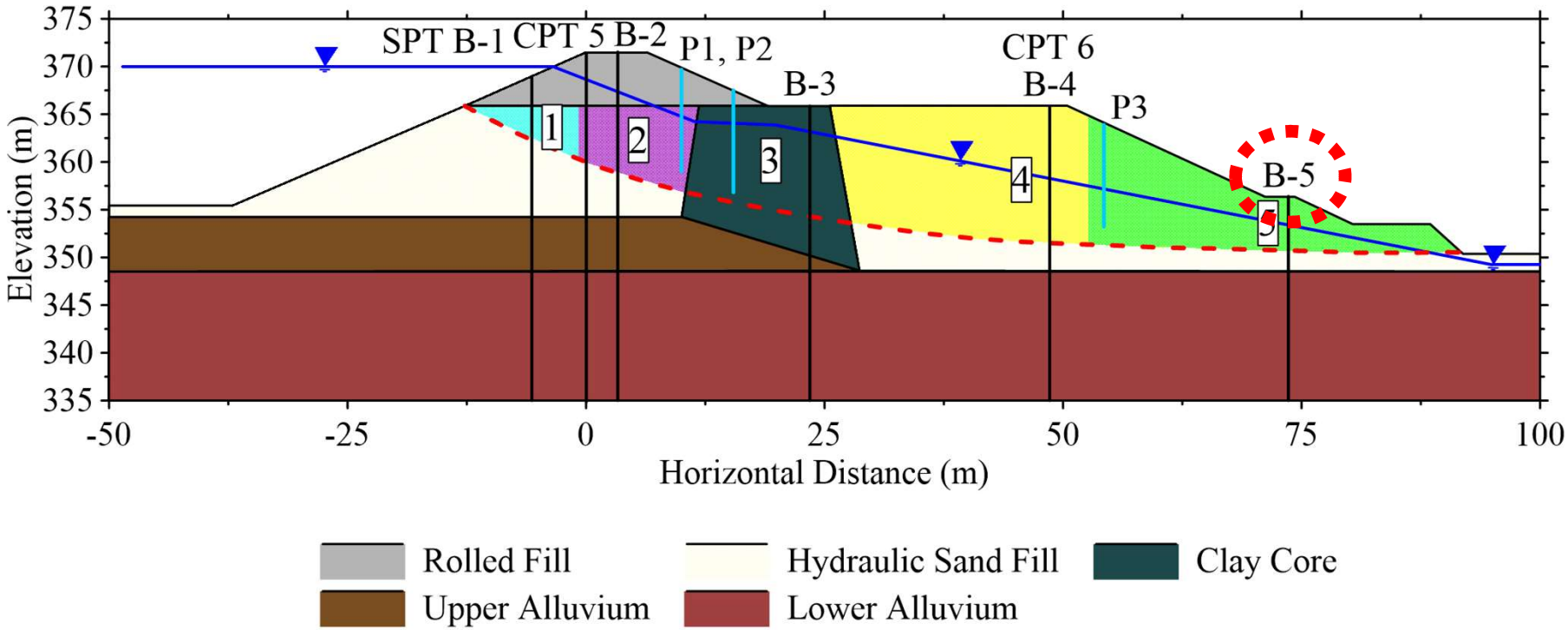
Final States:
r_u = 0.65/0.37/0.68
Slope/Plateau/Toe

Application Examples

- Case 1 – Lateral Extrusion
- Case 2 – Static/Drilling Pressure
- Case 3 – Low Shaking
- Case 4 – High Shaking

Case 4 – High Shaking

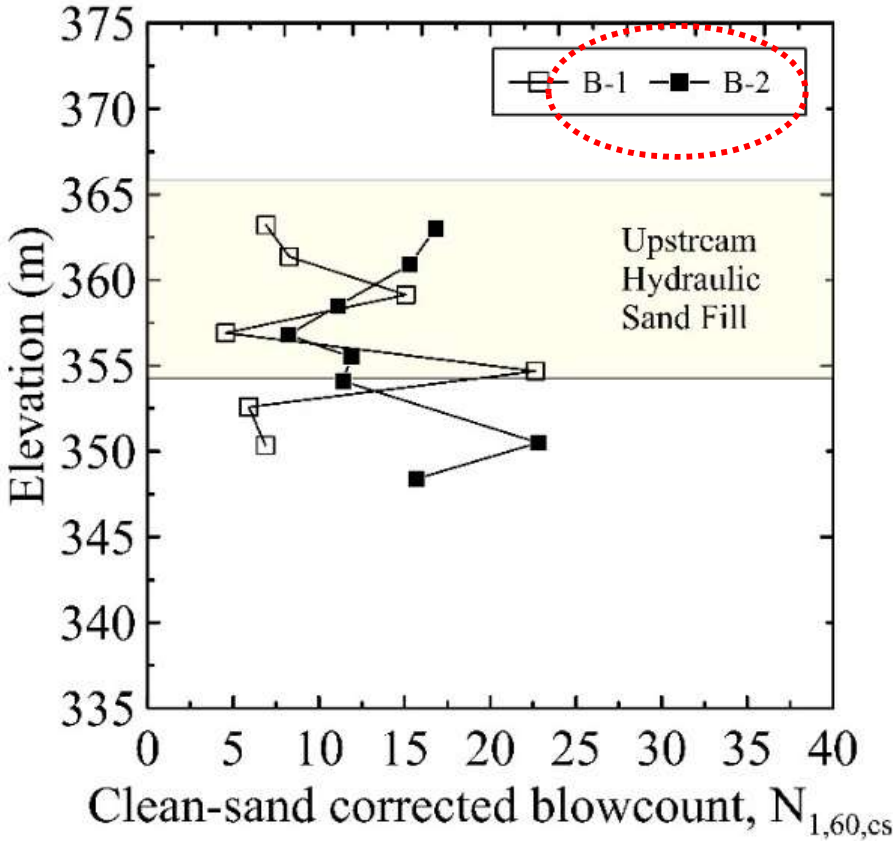
- 1971 Upper San Fernando Dam

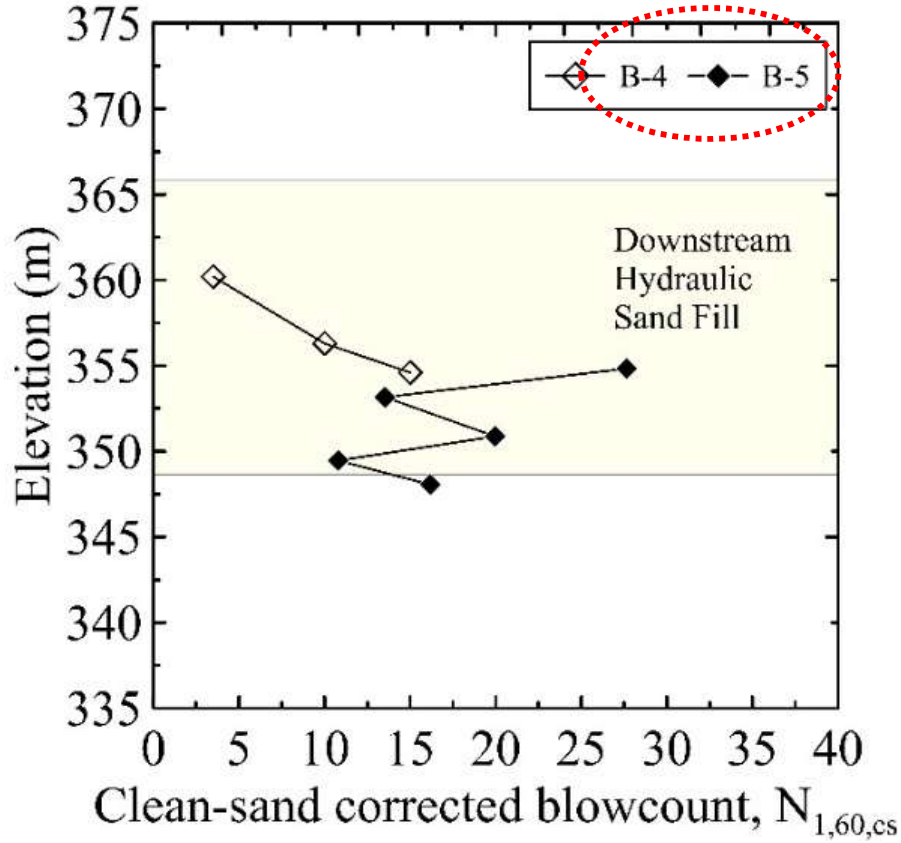


- San Fernando earthquake (M_w = 6.1), PGA = 0.6 g
- Small liquefaction-induced deformations

Case 4 – High Shaking

- SPT measurements

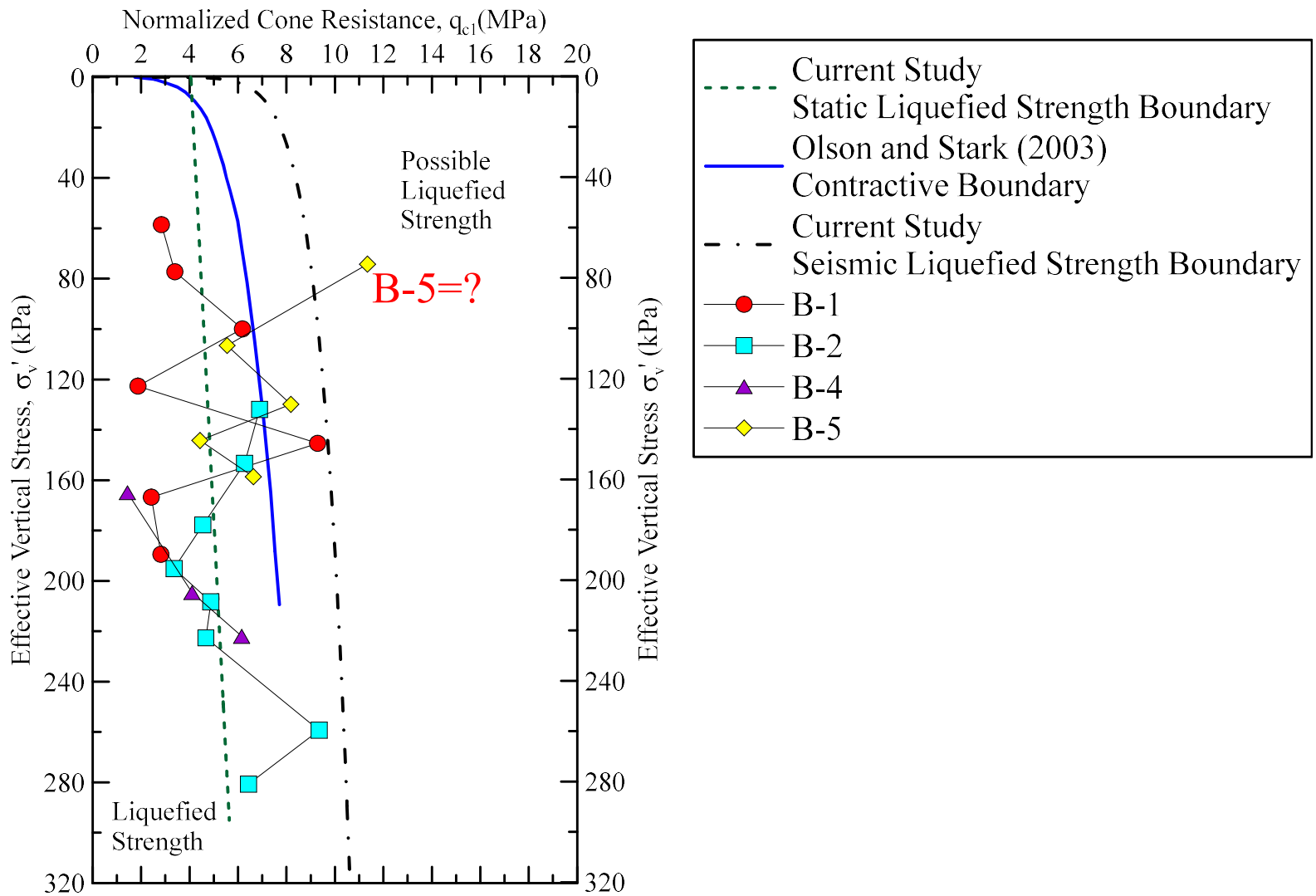




- Use q_c/N_{60} relationship (Stark and Olson, 1995)
- No available F_r data –liquefied/possible liquefied boundary

Case 4 – High Shaking

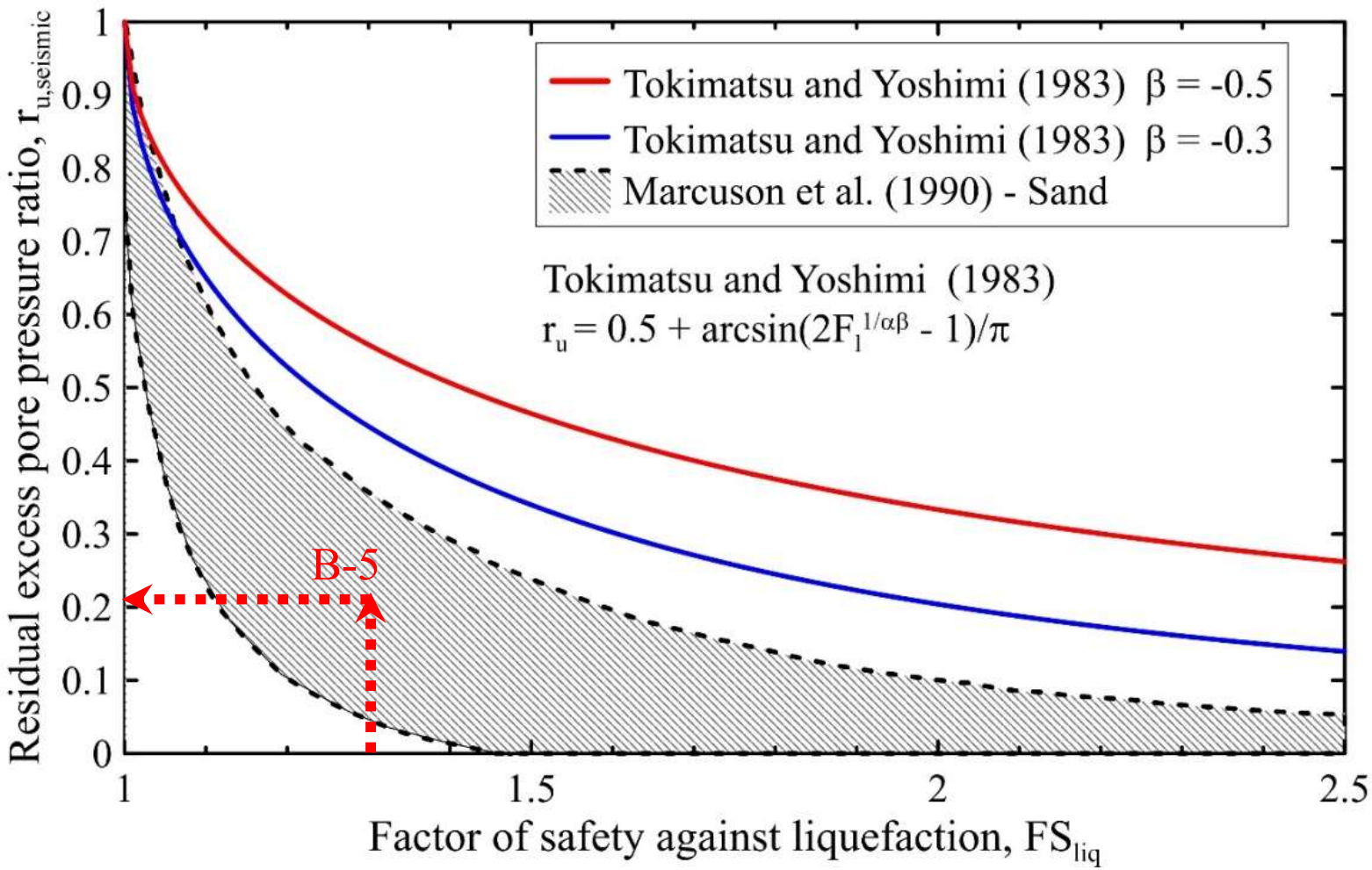
Steps 1&2: Assign liquefied strength to B-1, B-2 and B-4



- B-1, 2, and 4 = liquefied strength

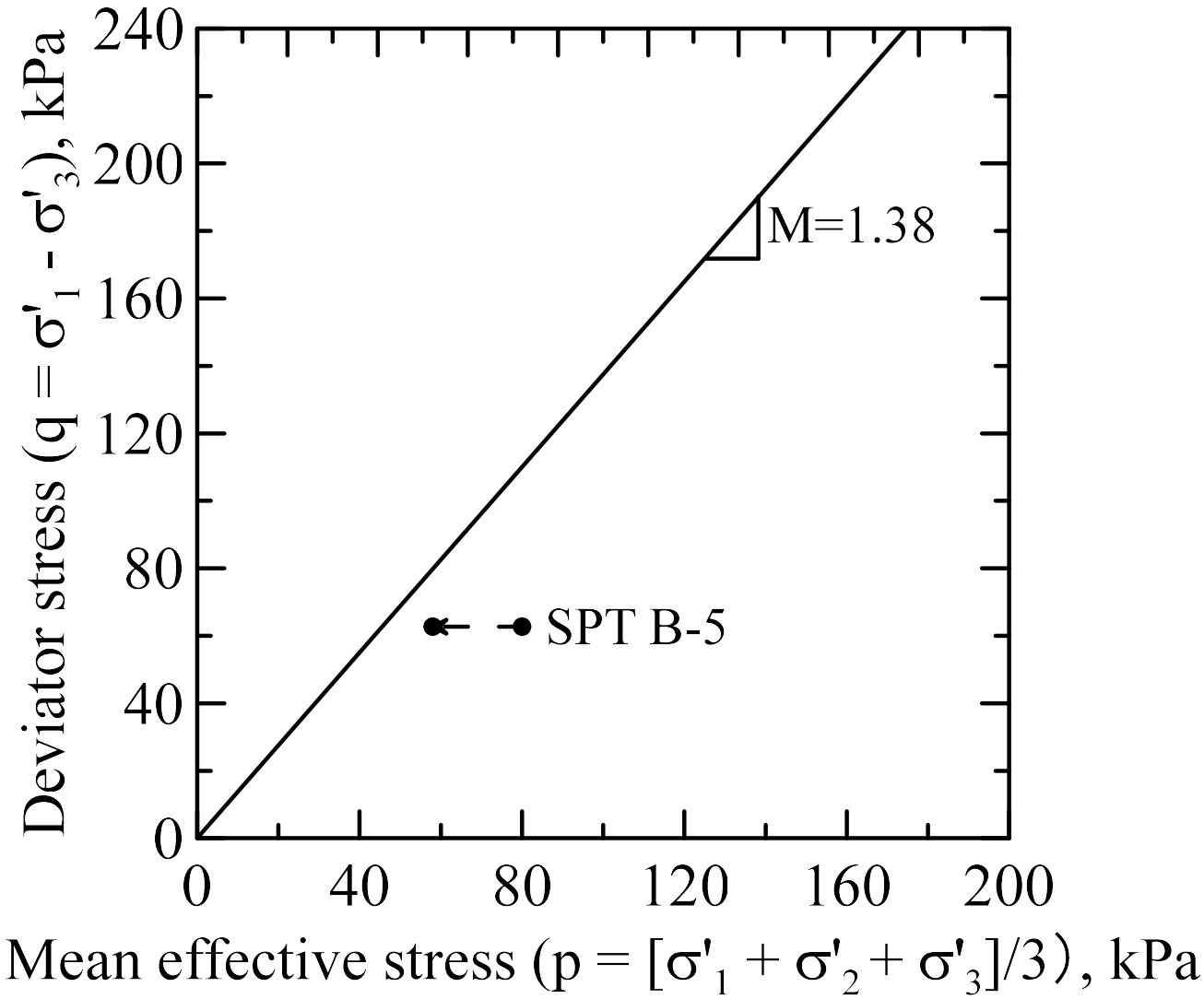
Case 4 – High Shaking

Step 3: Estimate earthquake-induced excess pore-water pressures



Case 4 – High Shaking

Step 3: Estimate earthquake-induced excess pore-water pressures



- B-1, 2, and 4 = liquefied strength

Case 4 – High Shaking

Step 4: Assign a liquefied strength (ratio) if

- Static liquefaction chart – Left of trendline
- $FoS_{Liq} \leq 1.0$
- Effective stress left of CSL
- $r_{u\_total} \geq 0.7$

B-1	B-2	B-4	B-5
Liquefied Strength	Liquefied Strength	Liquefied Strength	Yield Strength
Left of trendline	Left of trendline	Left of trendline	No trigger

Step 5: Perform post-triggering stability analysis

- FoS_{Flow} = 1.0 to 1.1 => observed field permanent deformations

Outline

- Recent Flow Failures
- Liquefied Strength
- Flow Failure Susceptibility
  - Contractive/dilative boundary
  - State parameter
- Five Step Procedure
- Application Examples
- Summary

Summary

- Don't use contractive/dilative boundary
- Assess static and dynamic triggering
- Estimate shear-induced pore pressures & mean effective stress reduction
- Assign liquefied strength:
  - Static liquefaction chart – Left of trend line
  - $\psi > 0.00$ or
  - Effective stress left of CSL
  - $r_u > 0.7$
- Conduct post-triggering stability analysis

Flow Failure Assessment for Dams and Embankments with Examples

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