Contactive v. Dilative: Is it black and white?

Presented by:

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Presented to:

Queensland Tailings Group

Brisbane, Australis

June 9, 2022

Fundao Failure Outline

- 5 November 2015 Failure
- Field observations
- Subsurface investigation
- Effect of blasting and earthquakes
- Slope stability analyses
- Time of Failure
- Summary
- Olson & Stark (2003) Update

Piezometric Levels

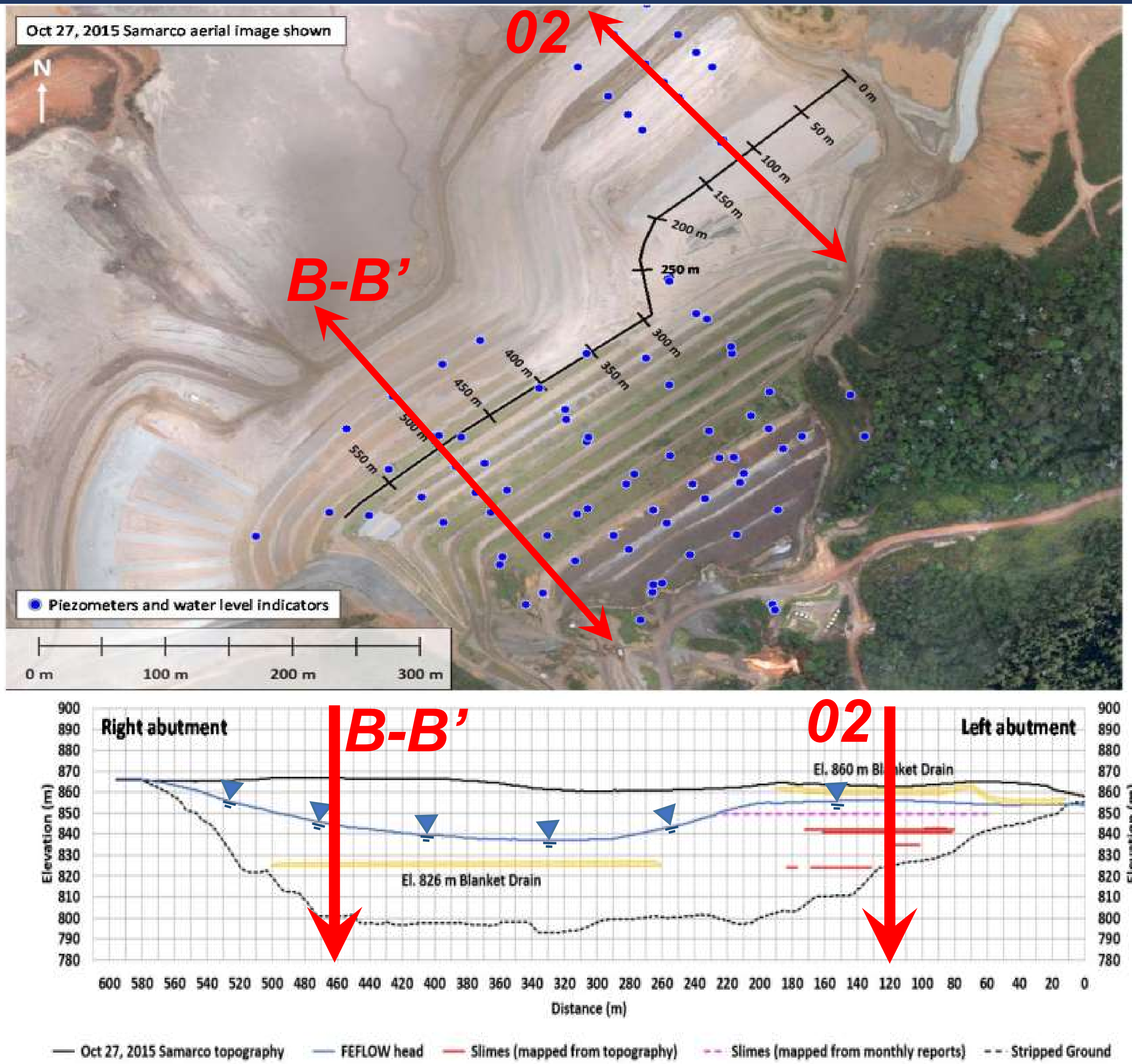

Figure B6-12 Longitudinal section from left to right abutment ***(Morgenstern et al., 2016)***

Witness Location and Description

#9: Avalanche of mud-like tailings cascaded down. The starter dam had no movement

#5: Crack open up along crest of left abutment setback and propagating in both direction

(Morgenstern et al., 2016)

Outline

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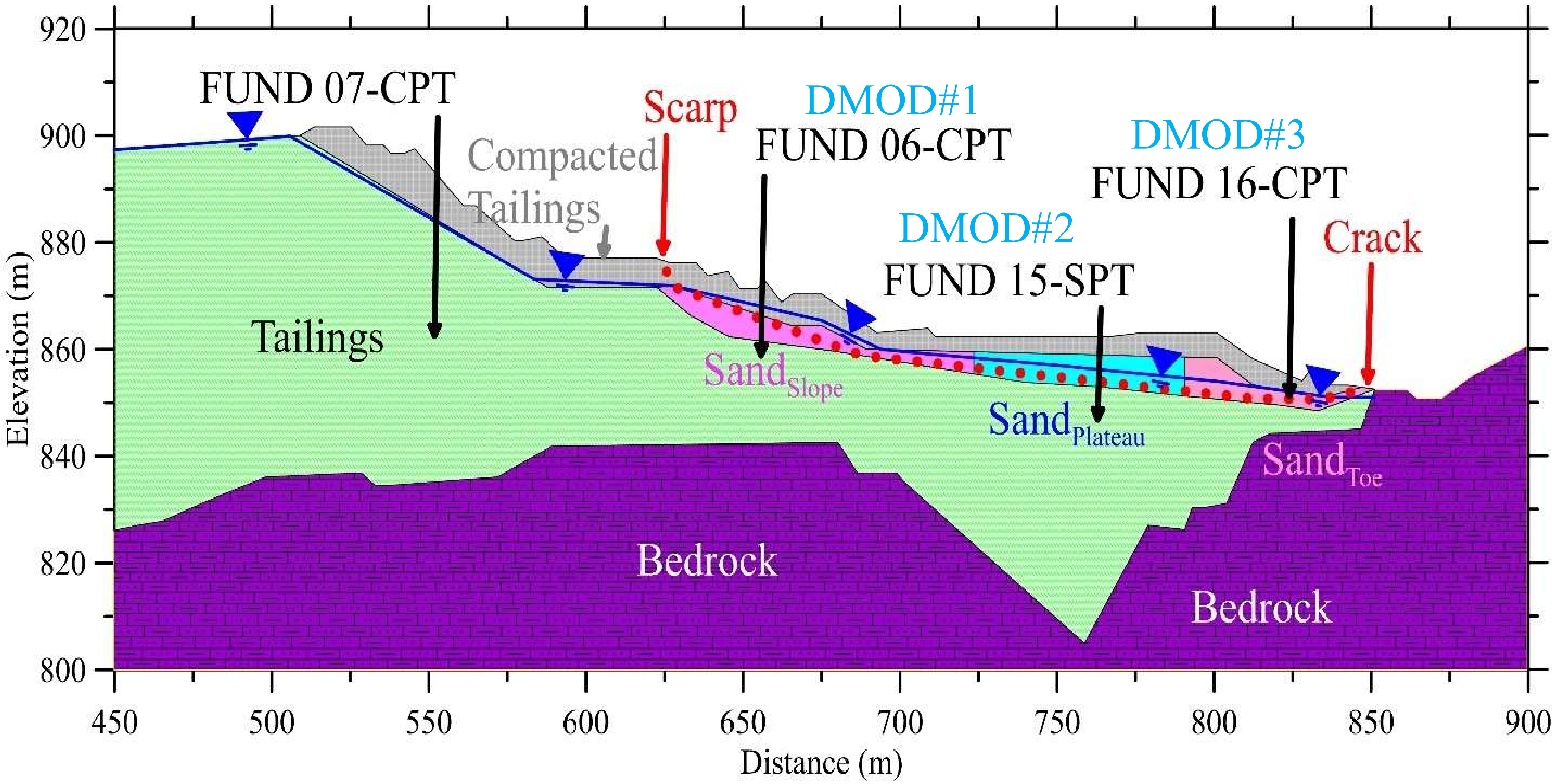
Pre-Failure CPT and SPT locations

(Morgenstern et al., 2016)

Cross-Section 02– Left Abutment



Cross-Section 02– Left Abutment

Sand tailings and slime particle distribution

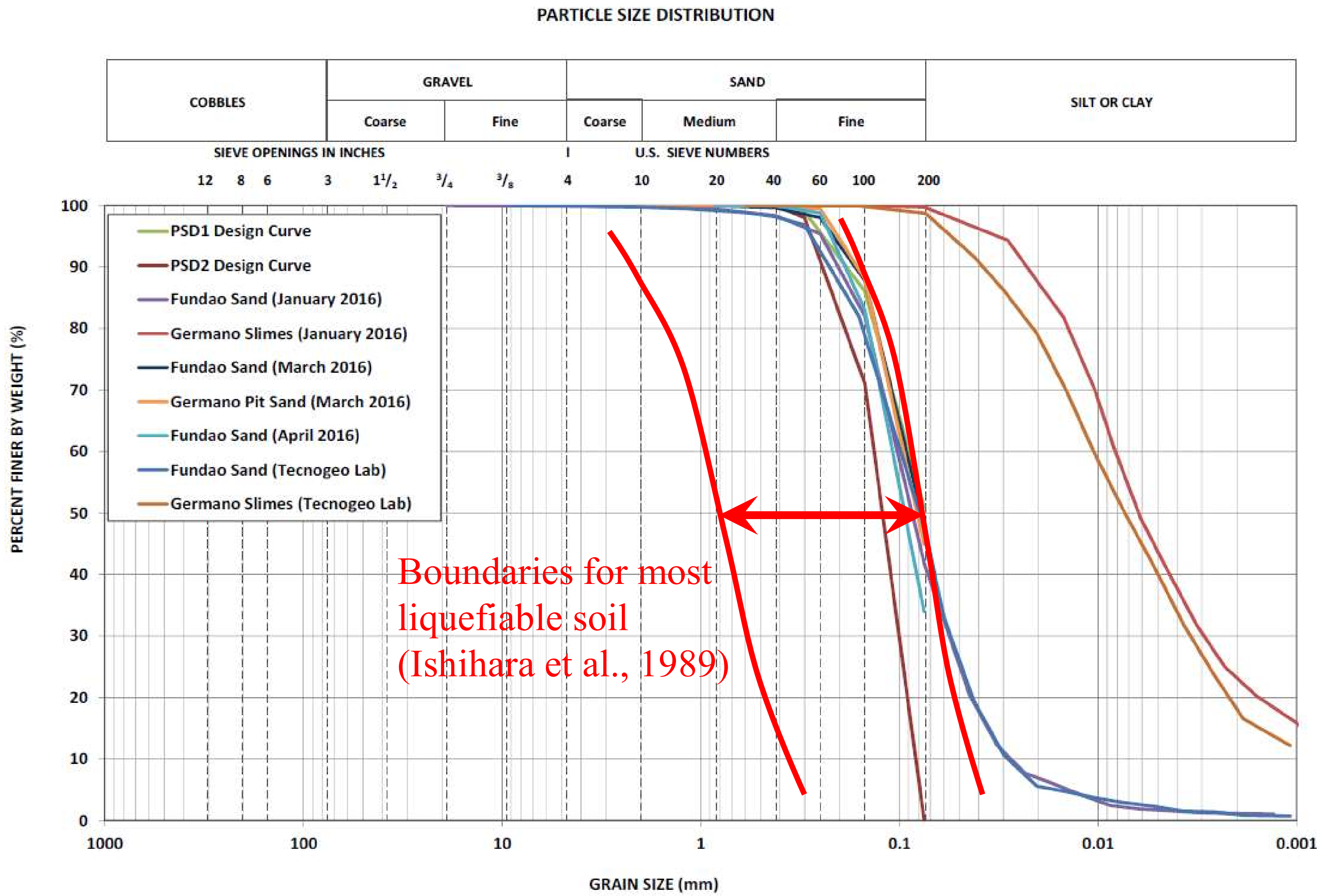
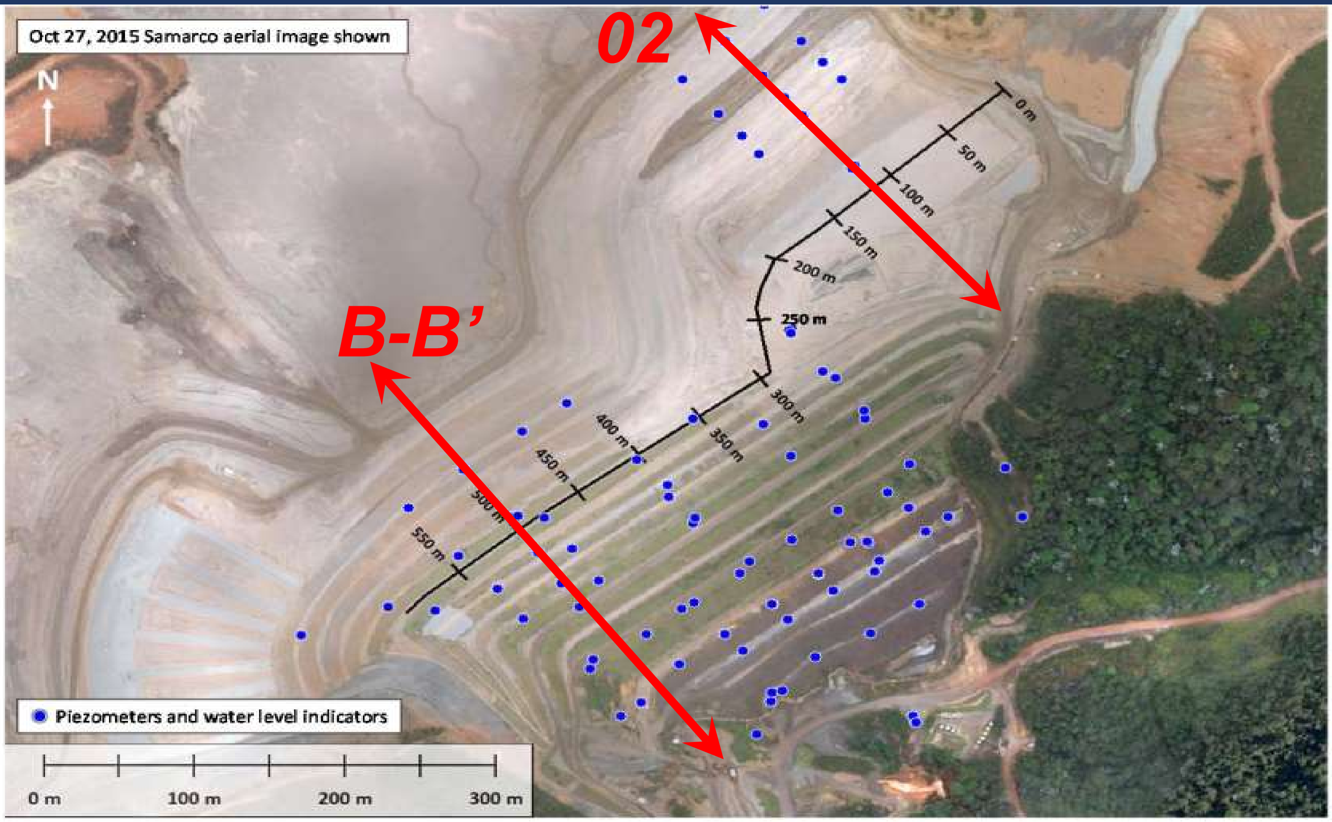


Figure D4-1 Particle size distribution of field sand tailings and slimes samples

2015 Fundao Tailings Dam Failure

Piezometric Levels



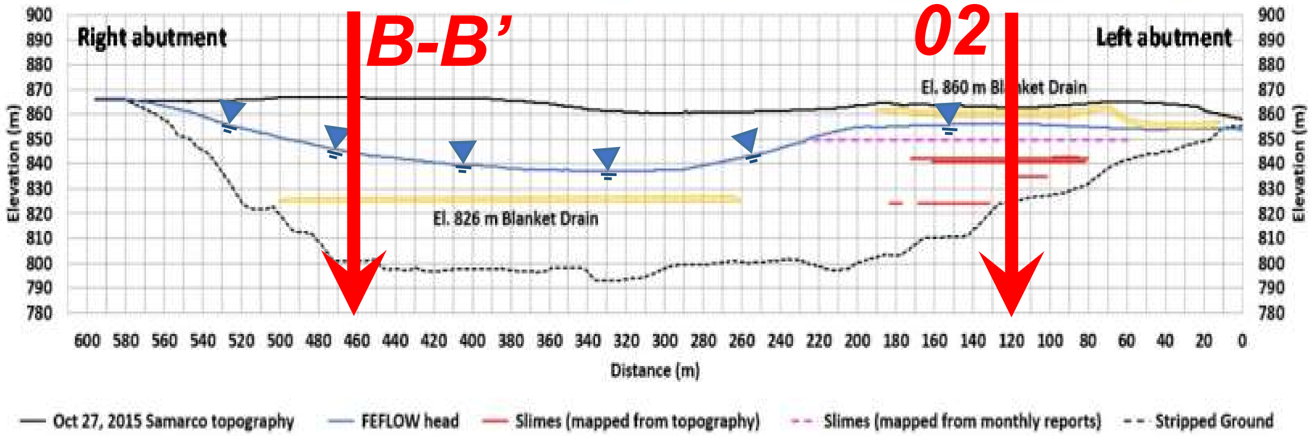


Figure B6-12 Longitudinal section from left to right abutment *(Morgenstern et al., 2016)*

Pre-Failure Earthquakes

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

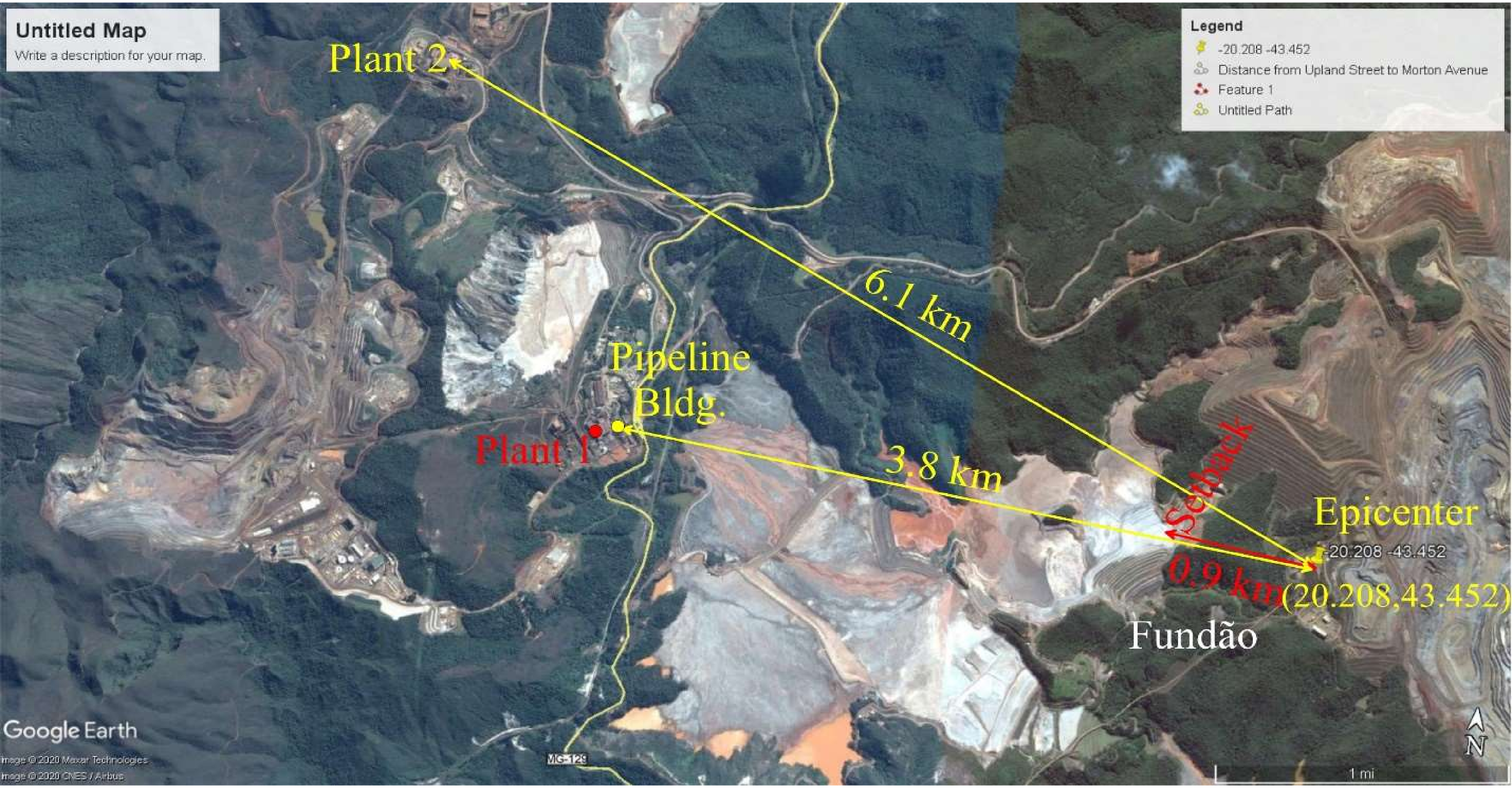
Local Time	Moment Magnitude Mw	Distance from Fundao	Event
2:12:15 pm	2.2	<2 km	earthquake (foreshock)
2:13:51 pm	2.6	<2 km	earthquake (main shock)
2:16:03 pm	1.8	<2 km	earthquake (aftershock)
2:36-2:46 pm	Dam Failure		

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



Pre-Failure Earthquakes

Eyewitness Accounts of 11/5/15 Earthquakes:

- 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**
- **M ~ 4 to 5**

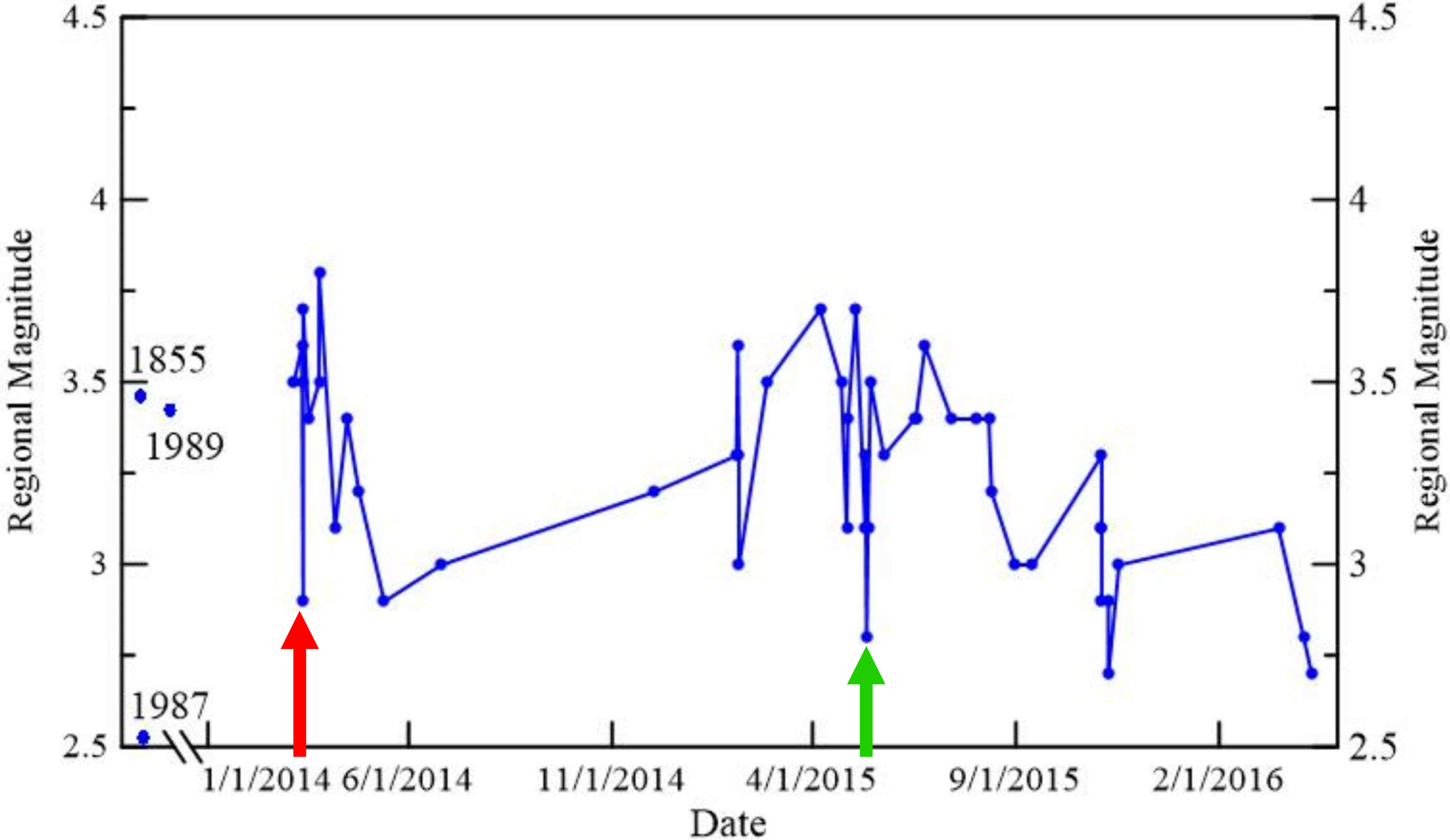
Modified Mercalli Scale

I.	Not felt.
II.	Felt by persons at rest, on upper floors, or favorably placed.
III.	Felt indoors. Vibration like passing of light trucks.
IV.	Vibration like passing of heavy trucks.
V.	Felt outdoors. Small unstable objects displaced or upset.
VI.	Felt by all. Furniture moved. Weak plaster/masonry cracks.
VII.	Difficult to stand. Damage to masonry and chimneys.
VIII.	Partial collapse of masonry. Frame houses moved.
IX.	Masonry seriously damaged or destroyed.
X.	Many buildings and bridges destroyed.
XI.	Rails bent greatly. Pipelines severely damaged.
XII.	Damage nearly total.

Richter Magnitude	Earthquake effects
0-2	Not felt by people
2-3	Felt little by people
3-4	Ceiling lights swing
4-5	Walls crack
5-6	Furniture moves
6-7	Some buildings collapse
7-8	Many buildings destroyed
8-Up	Total destruction of buildings, bridges and roads

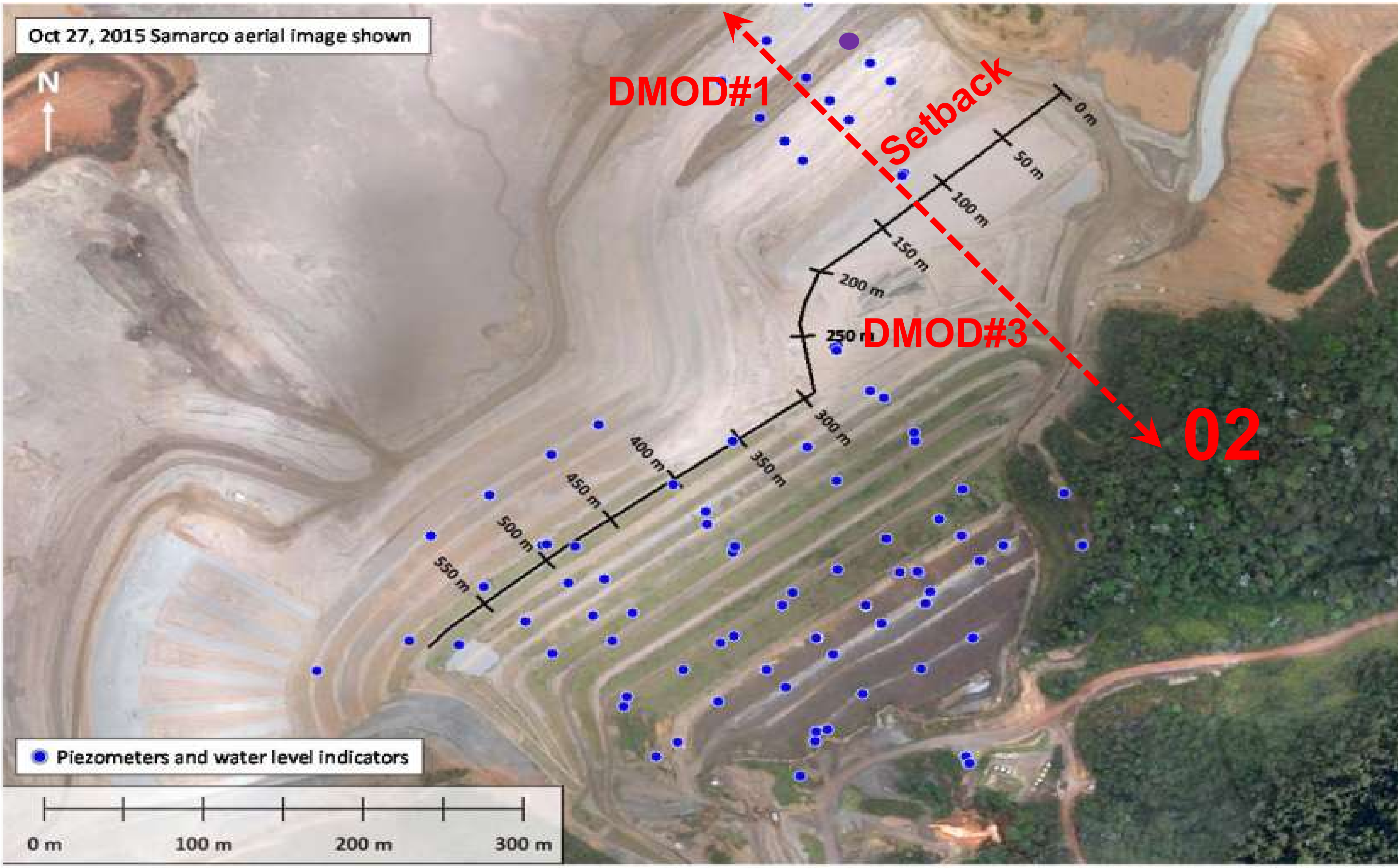
https://earthquakenepal2015.weebly.com/the-richter-scale-and-modified-mercalli-intensity-scale.html

Seismic History

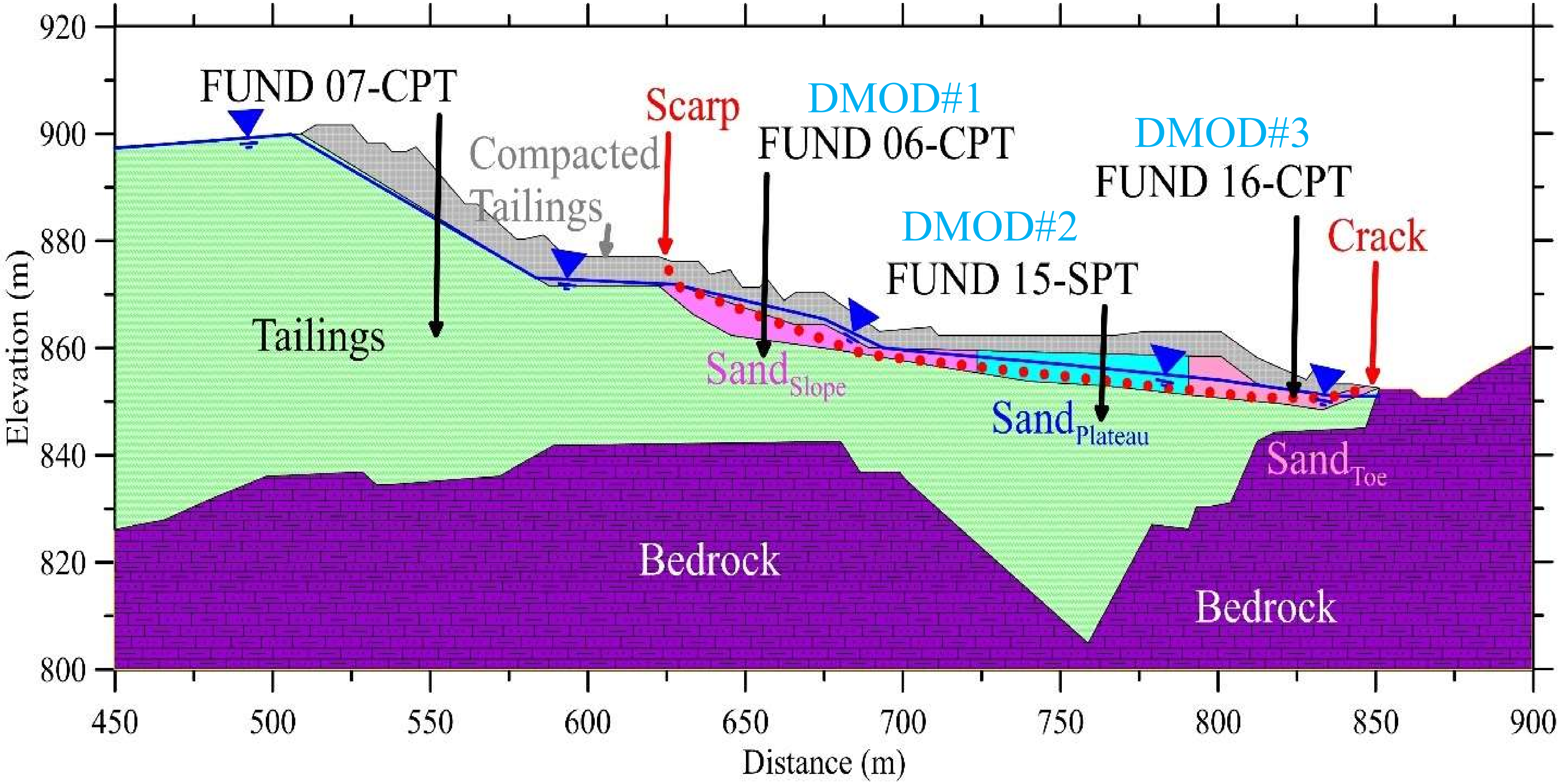


Reference: Atkinson, G. (2015). Ground Motion Prediction Equation for Small-to-Moderate Events at Short Hypocentral Distances, with Application to Induced-Seismicity Hazards. Bull. Seism. Soc. Am., **105**, doi: 10.1785/0120140142

Cross-Section 02– Left Abutment

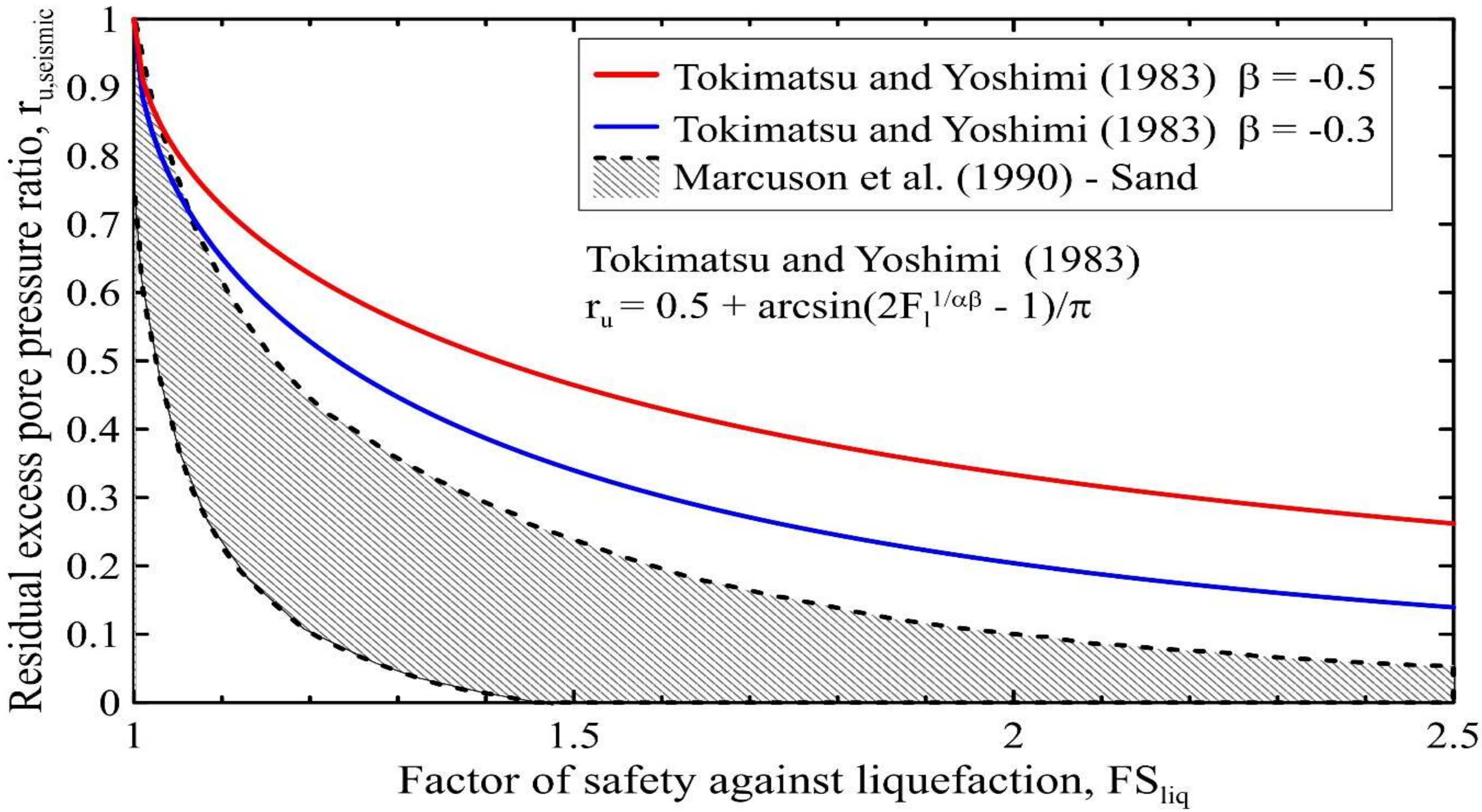


Cross-Section 02– Left Abutment



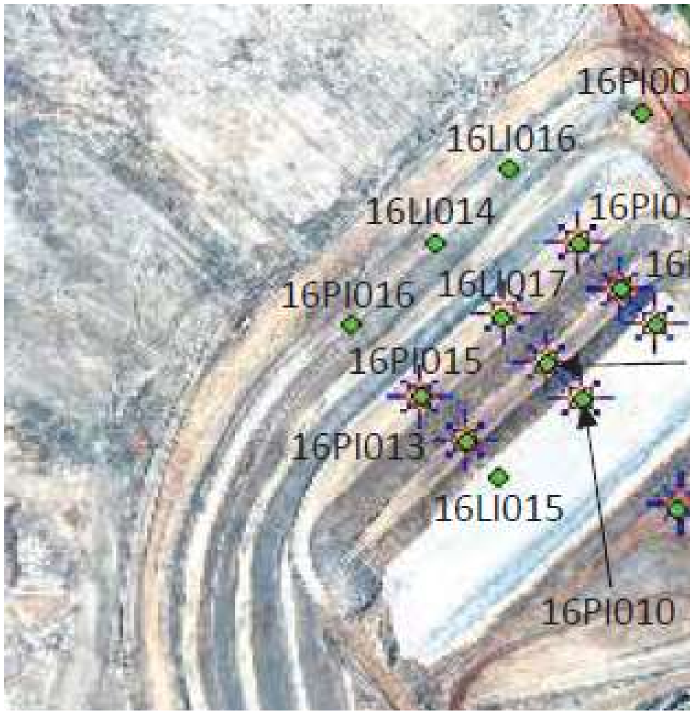
Cross-Section 02– Left Abutment

Excess Pore Pressure Ratio



Modified from Marcuson et al. (1990)
Stark et al. (2021) Pore-Water Pressure Generation During Closely Spaced Earthquakes: Fundão Dam (in publishing)

Pre-Failure CPT Data-FUND 06-CPT



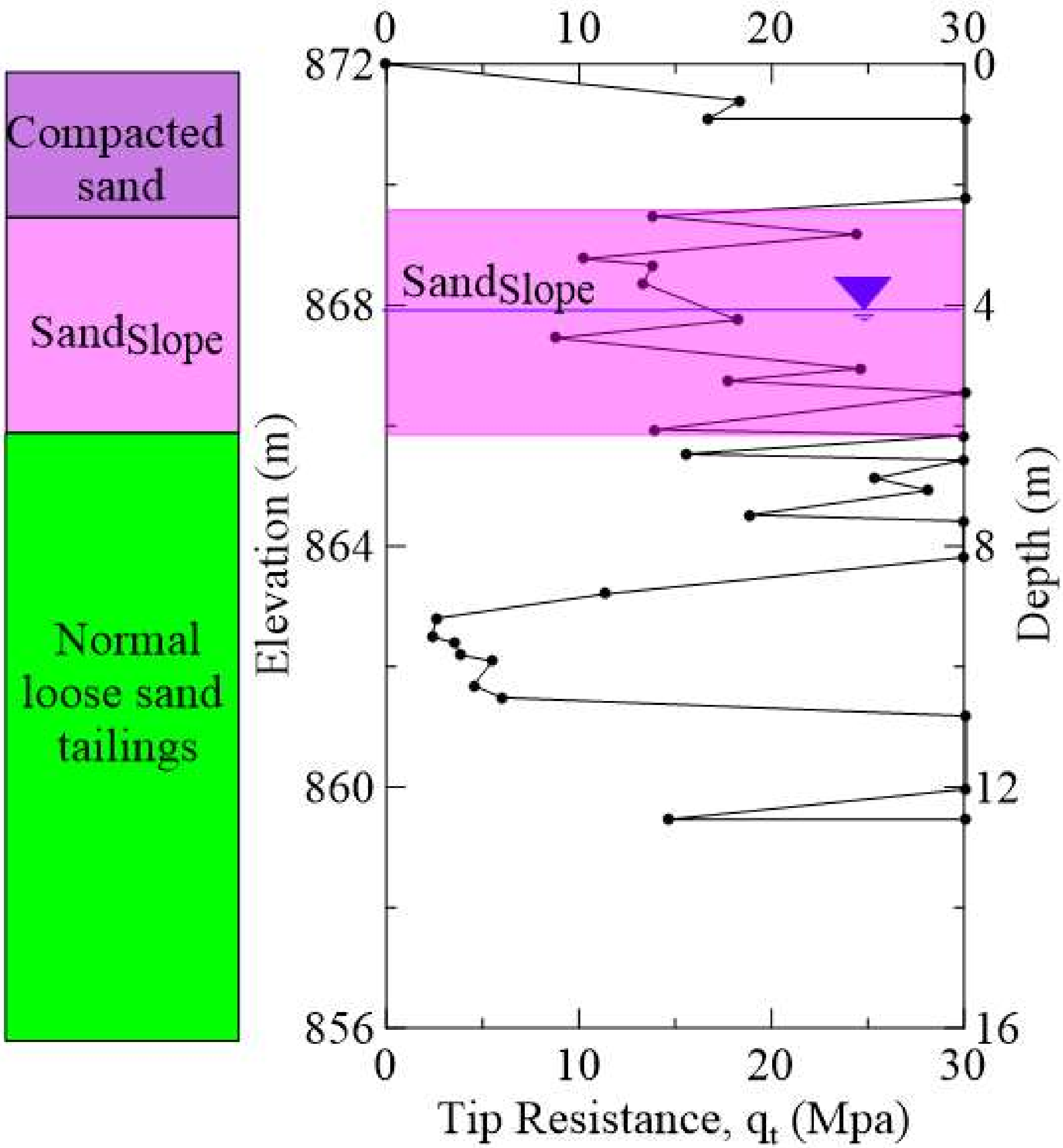
(Morgenstern et al., 2016)

Tailings Sand$_{\text{Slope}}$:

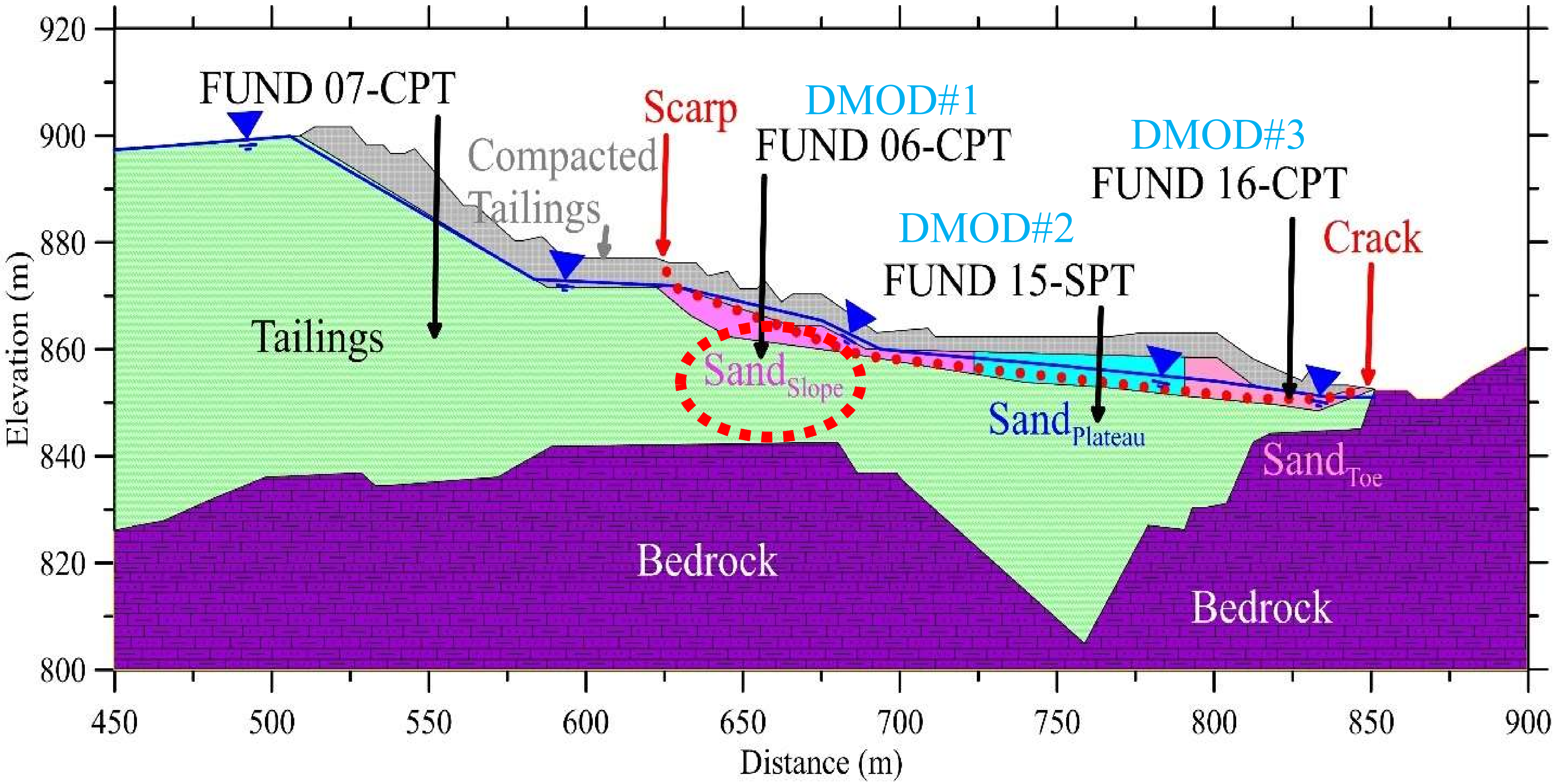
Depth = 4.25 m

Pre-Failure CPT Data-FUND 06-CPT

Tailings Sand$_{Slope}$:
Depth = 4.57 m



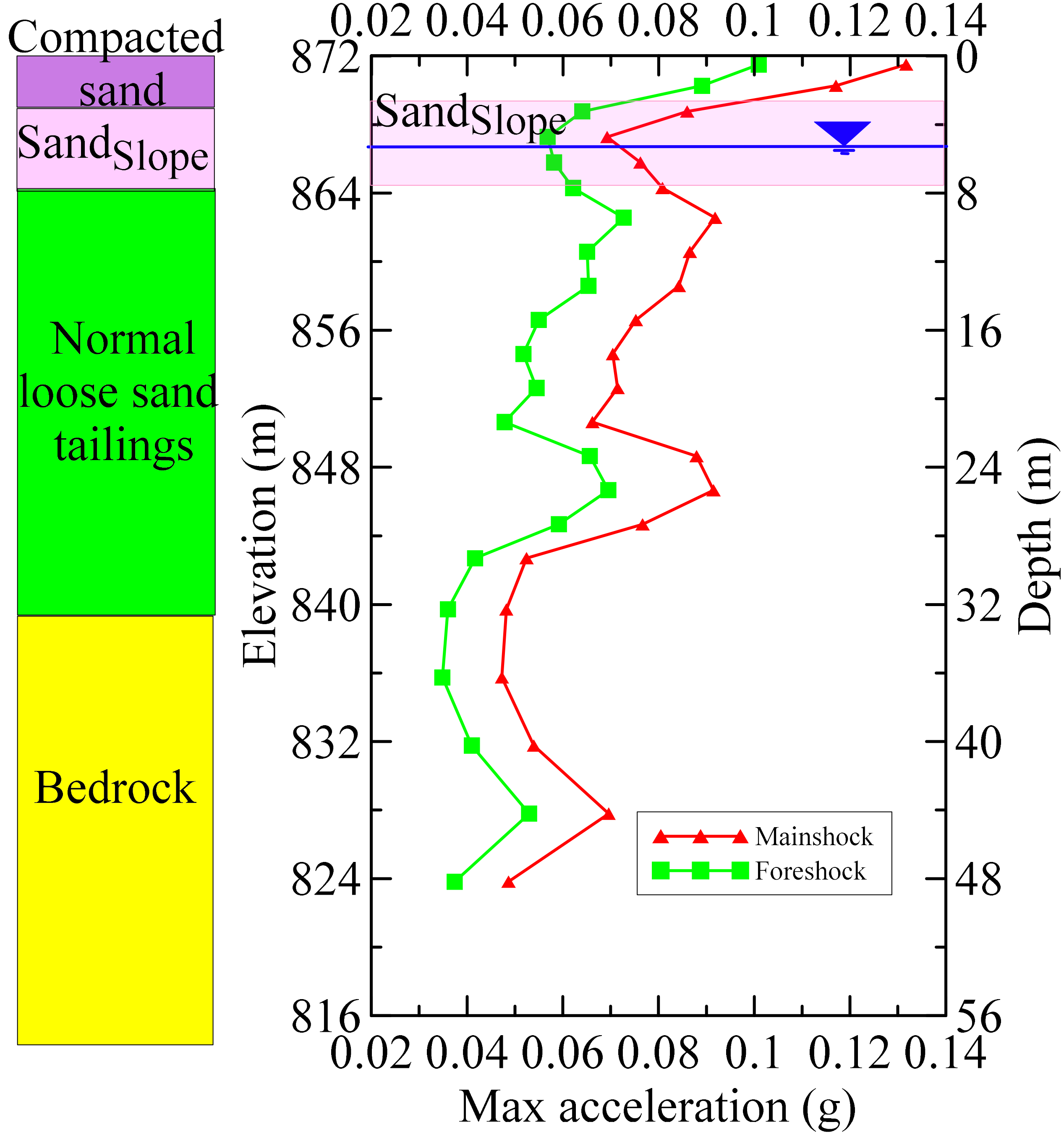
Pre-Failure Site Response Analysis



Cross-Section 02– Left Abutment

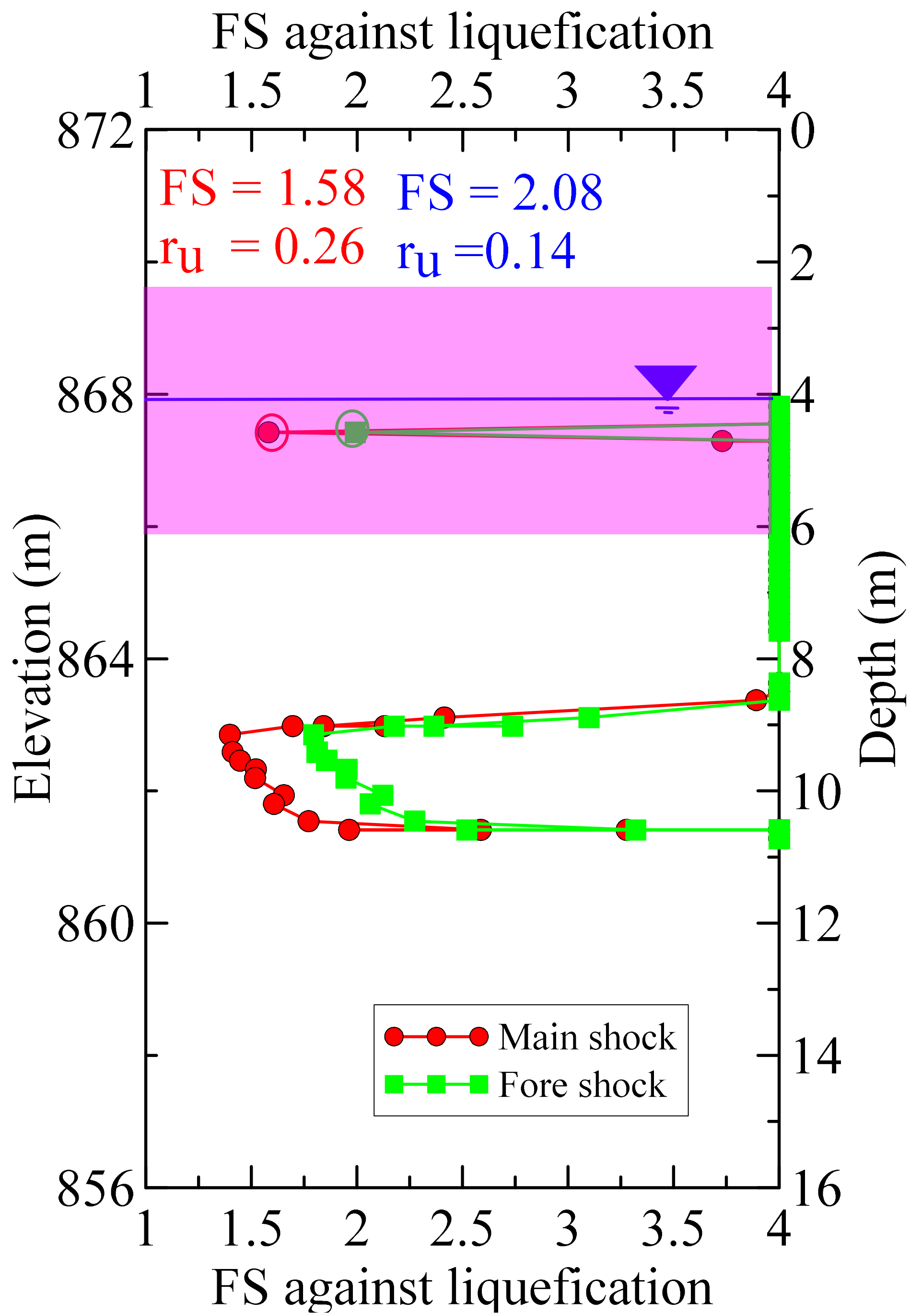
Pre-Failure Site Response Analysis

Tailings Sand$_{Slope}$:
Depth = 4.57 m

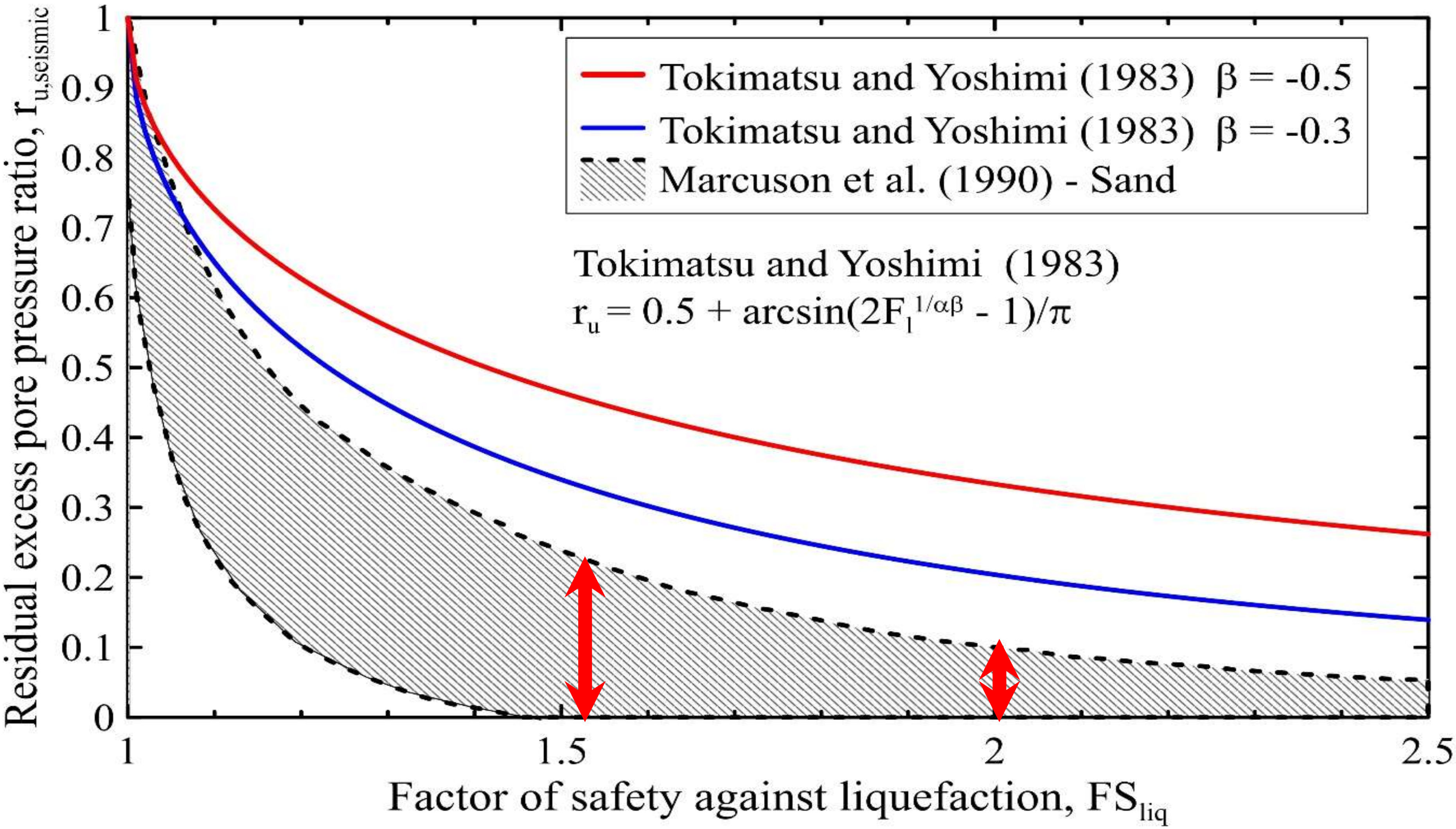


Pre-Failure CPT Data-FUND 06-CPT

Tailings Sand$_{Slope}$:
Depth ~ 4.57 m
FS<2.1



Excess Pore Pressure Ratio



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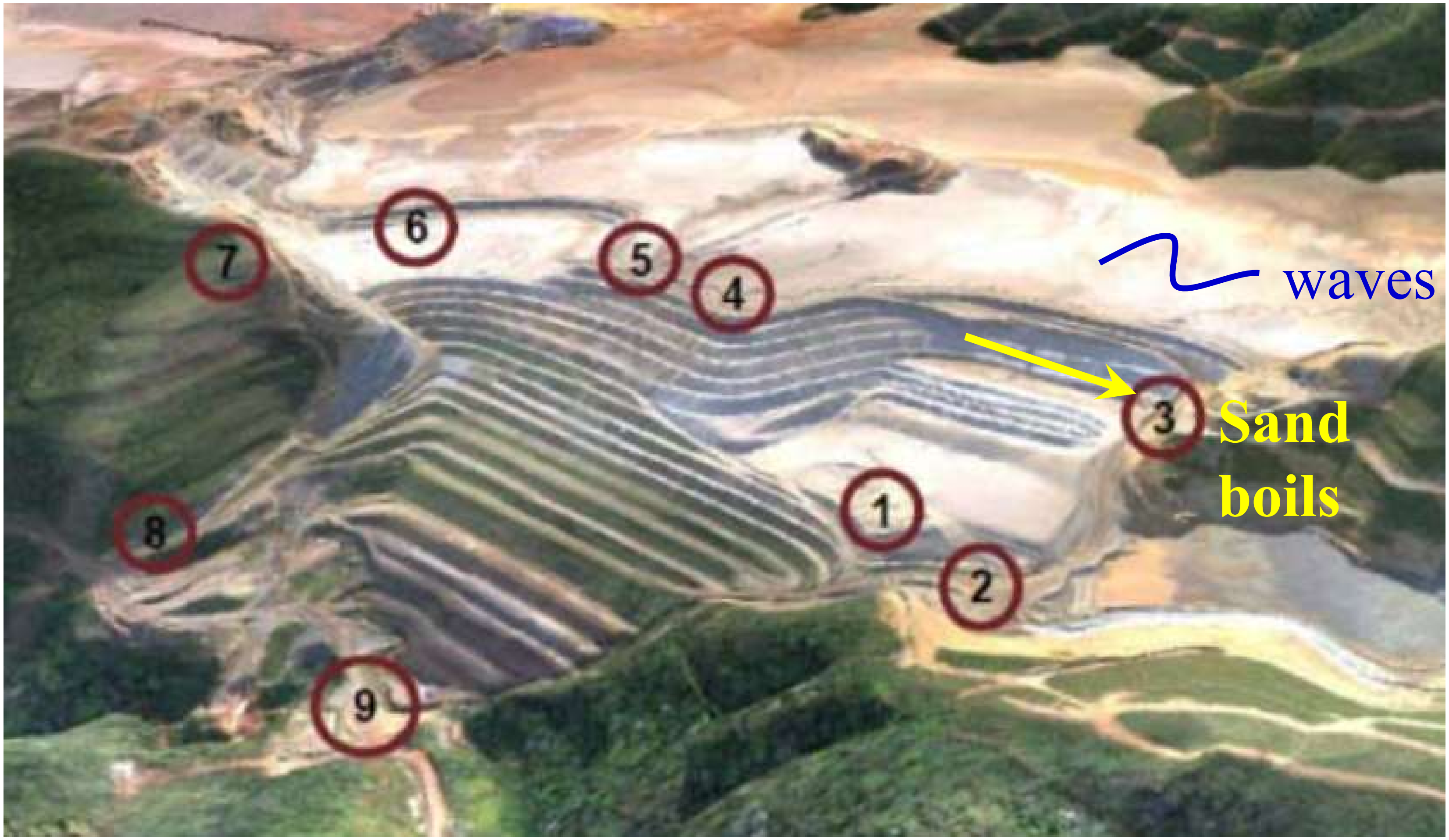
Stark et al. (2021) Pore-Water Pressure Generation During Closely Spaced Earthquakes: Fundão Dam (in publishing)

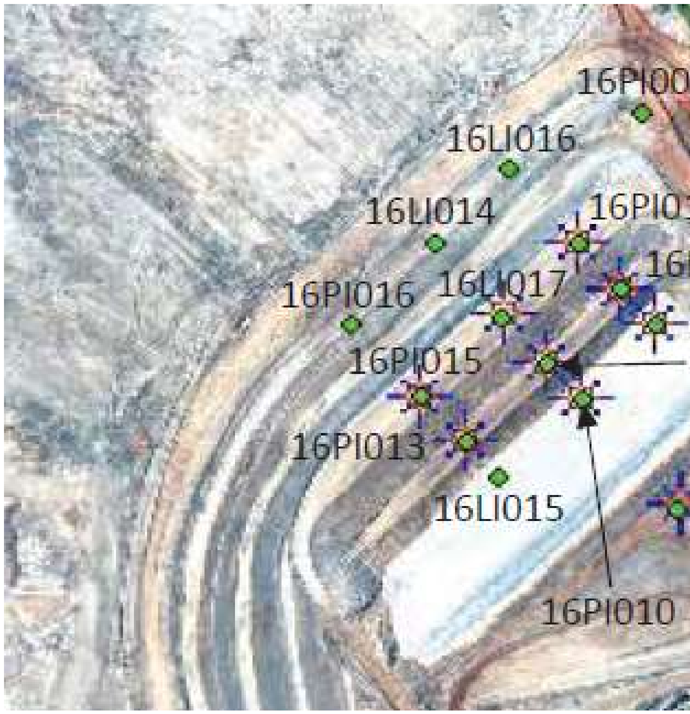
Witness Location and Description



#4: waves developed in the central portion of the reservoir, accompanied by cracks forming on the left side and blocks of sand moving up and down on the left abutment setback

(Morgenstern et al., 2016)

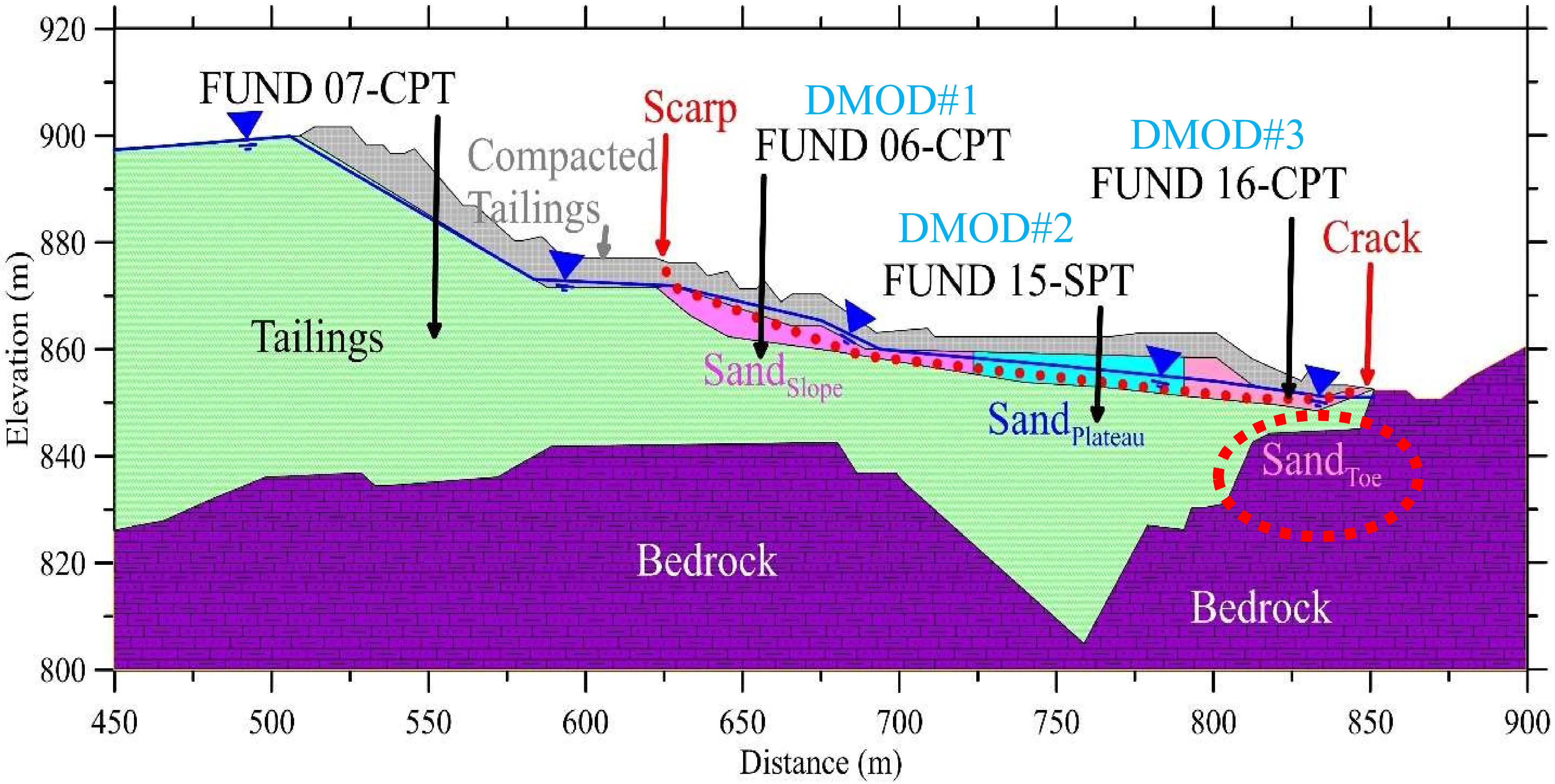
Pre-Failure CPT Data-FUND 16-CPT



Tailings Sand$_{\text{Toe}}$:

- Apparent fines content ~ 10% & Depth = 3.76 m

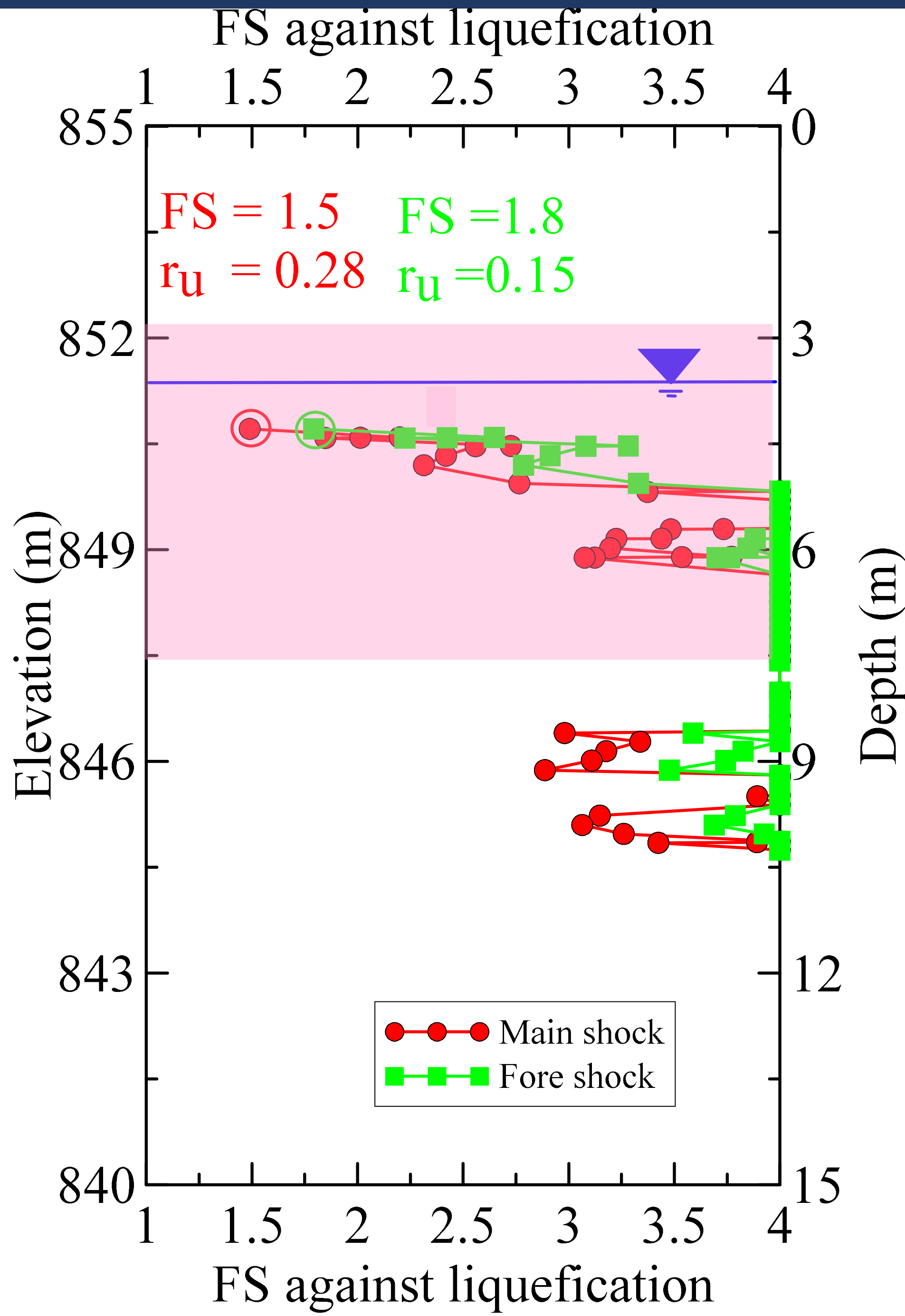
Cross-Section 02– Left Abutment



Cross-Section 02– Left Abutment

Pre-Failure CPT Data-FUND 16-CPT

Sand$_{Toe}$
Depth = 3.8 m
FS<1.5



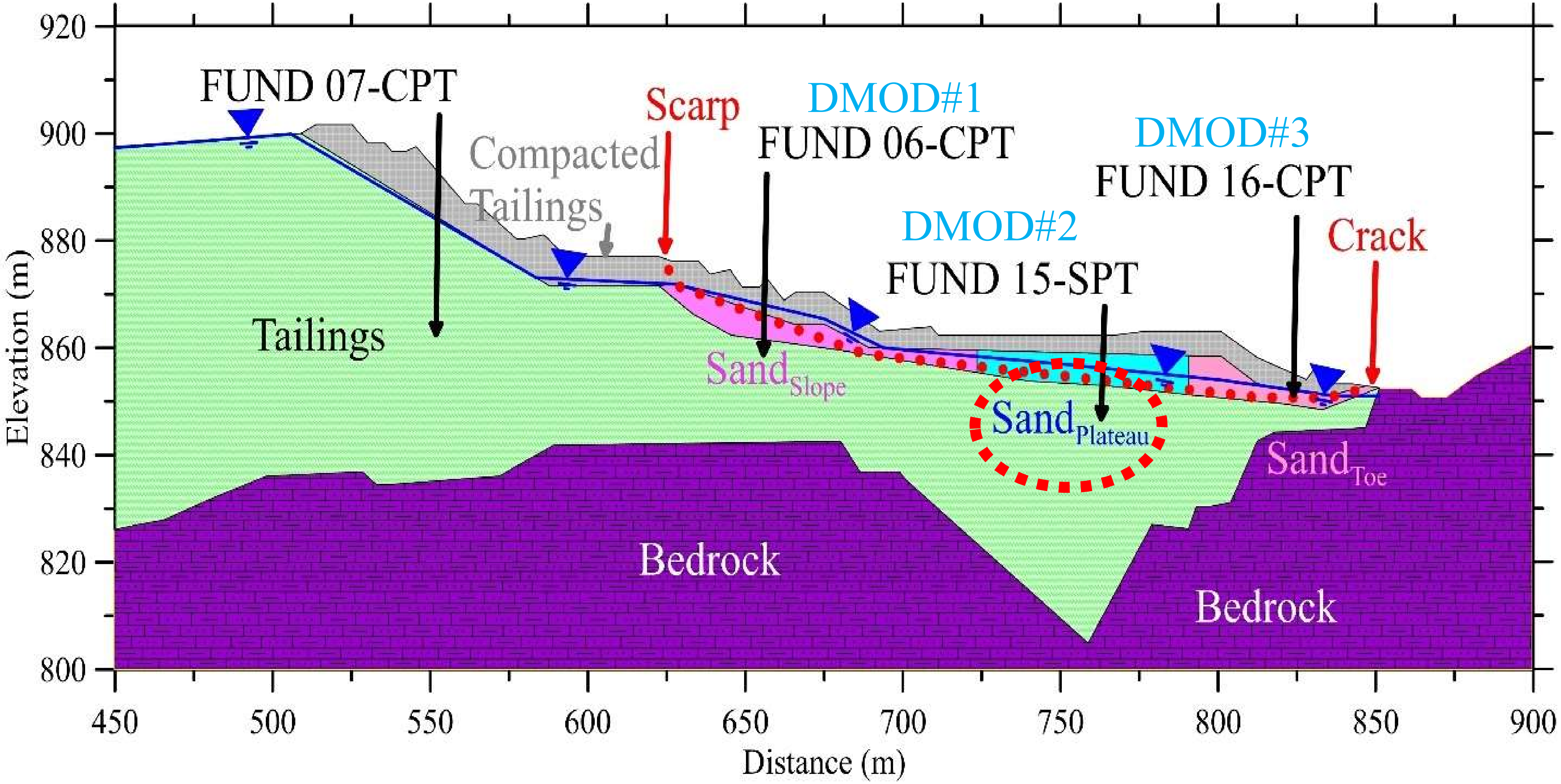
Pre-Failure SPT Data-FUND 15-SPT

Tailings Sand$_{\text{Plateau}}$:

- Apparent fines content ~ 10%
- Clay size fraction < 2% (Morgenstern et al., 2016)
- Silt deposit has no cohesion

(Morgenstern et al., 2016)

Cross-Section 02– Left Abutment



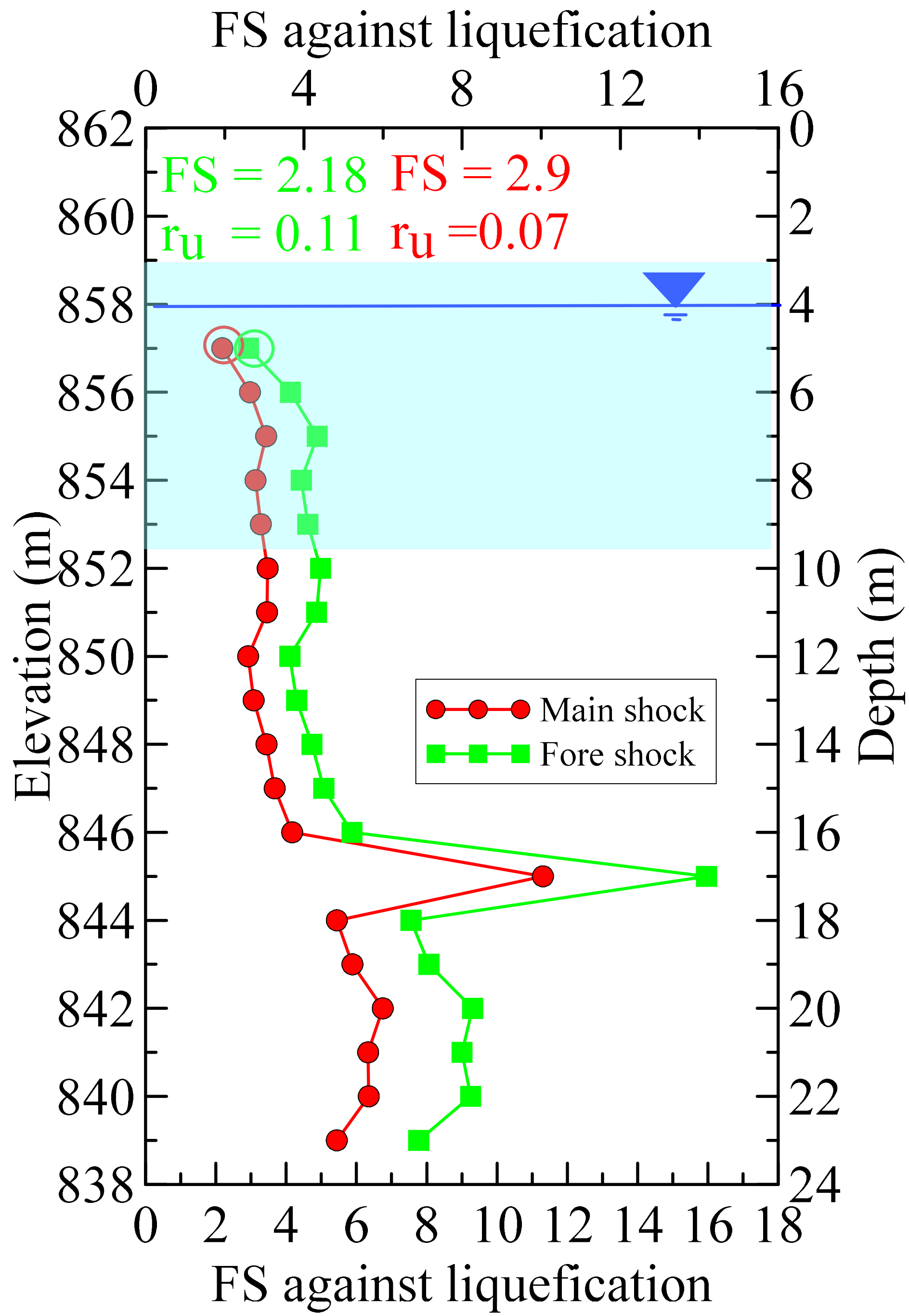
Cross-Section 02– Left Abutment

Pre-Failure SPT Data-FUND 15-SPT

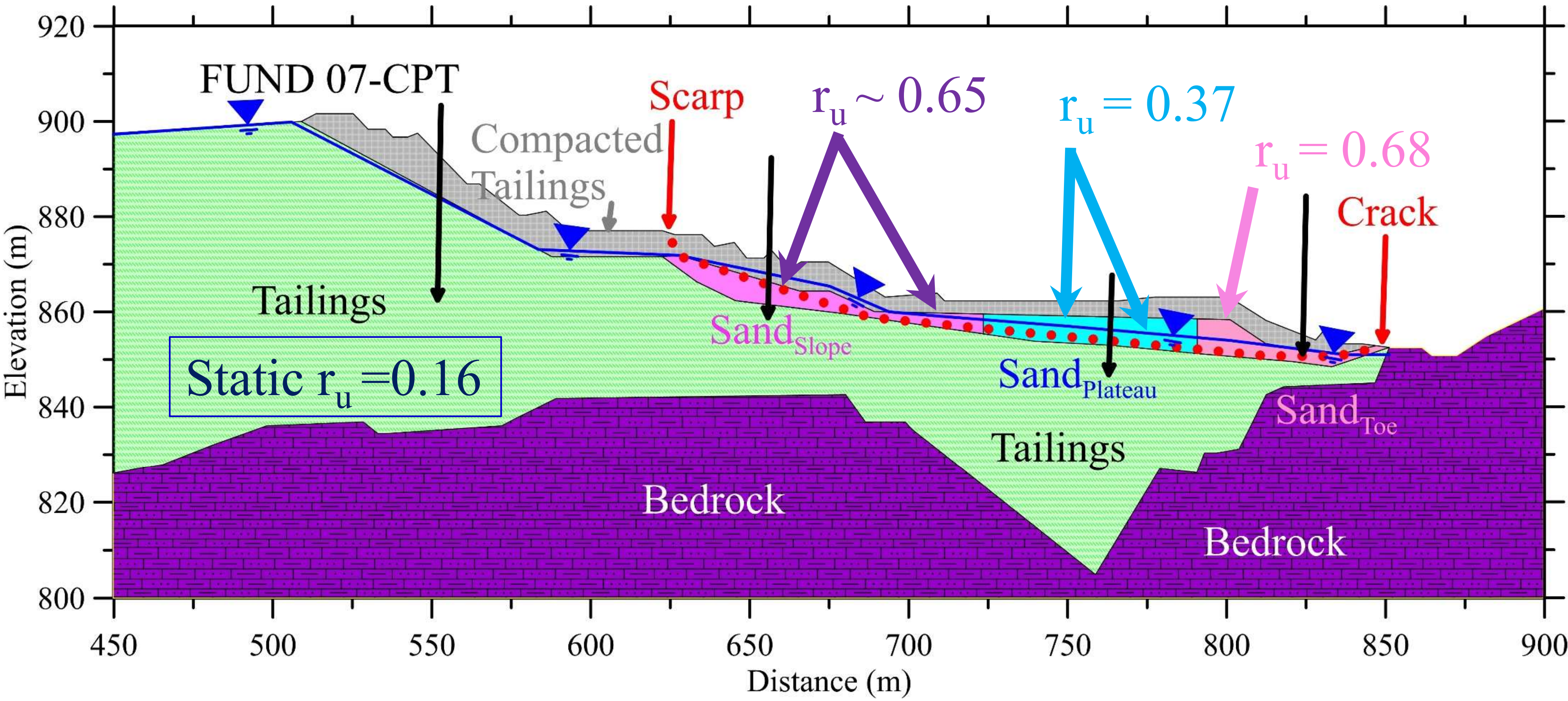
Sand$_{Plateau}$

Depth = 5.0 m

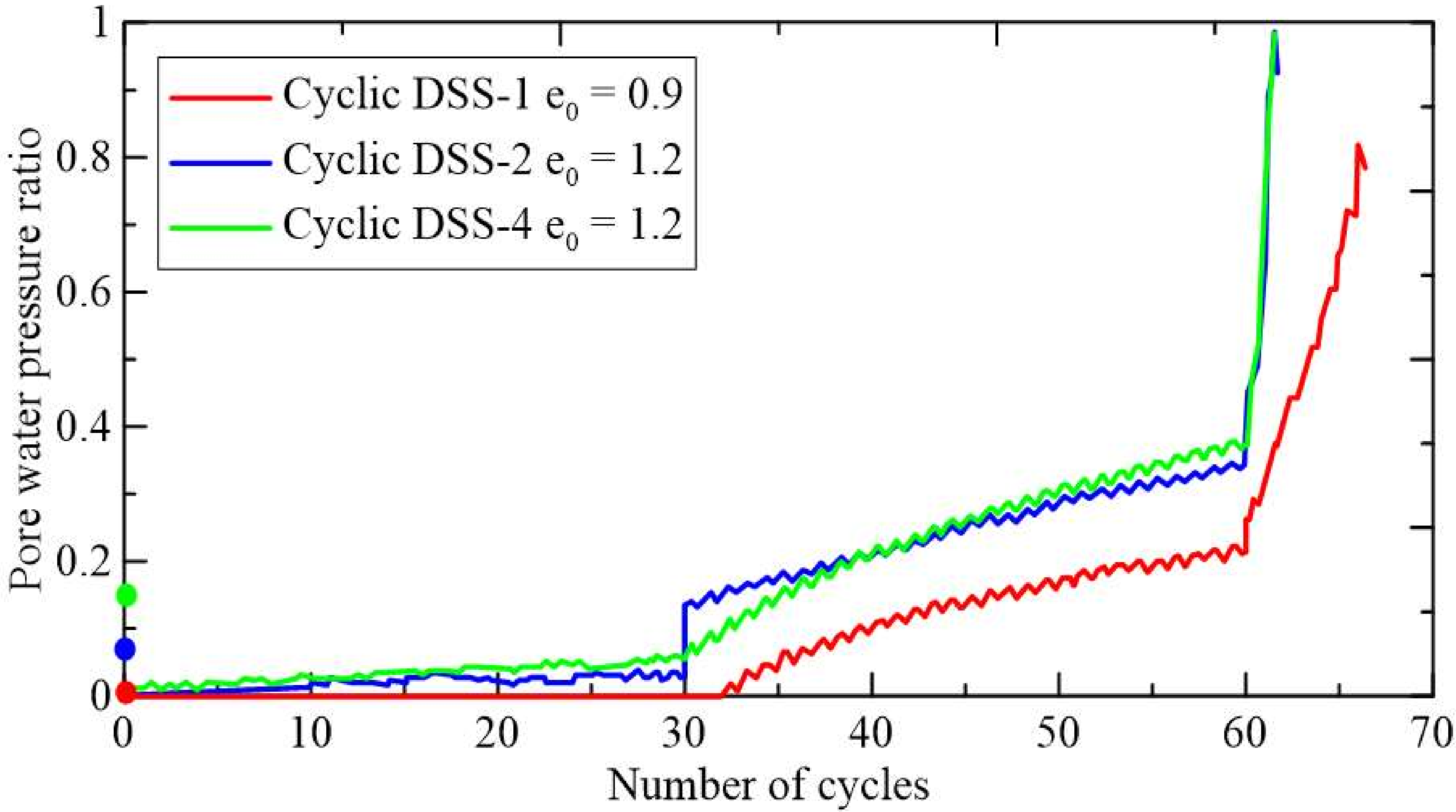
FS>1.5



Cross-Section 02 – Total r_u Values

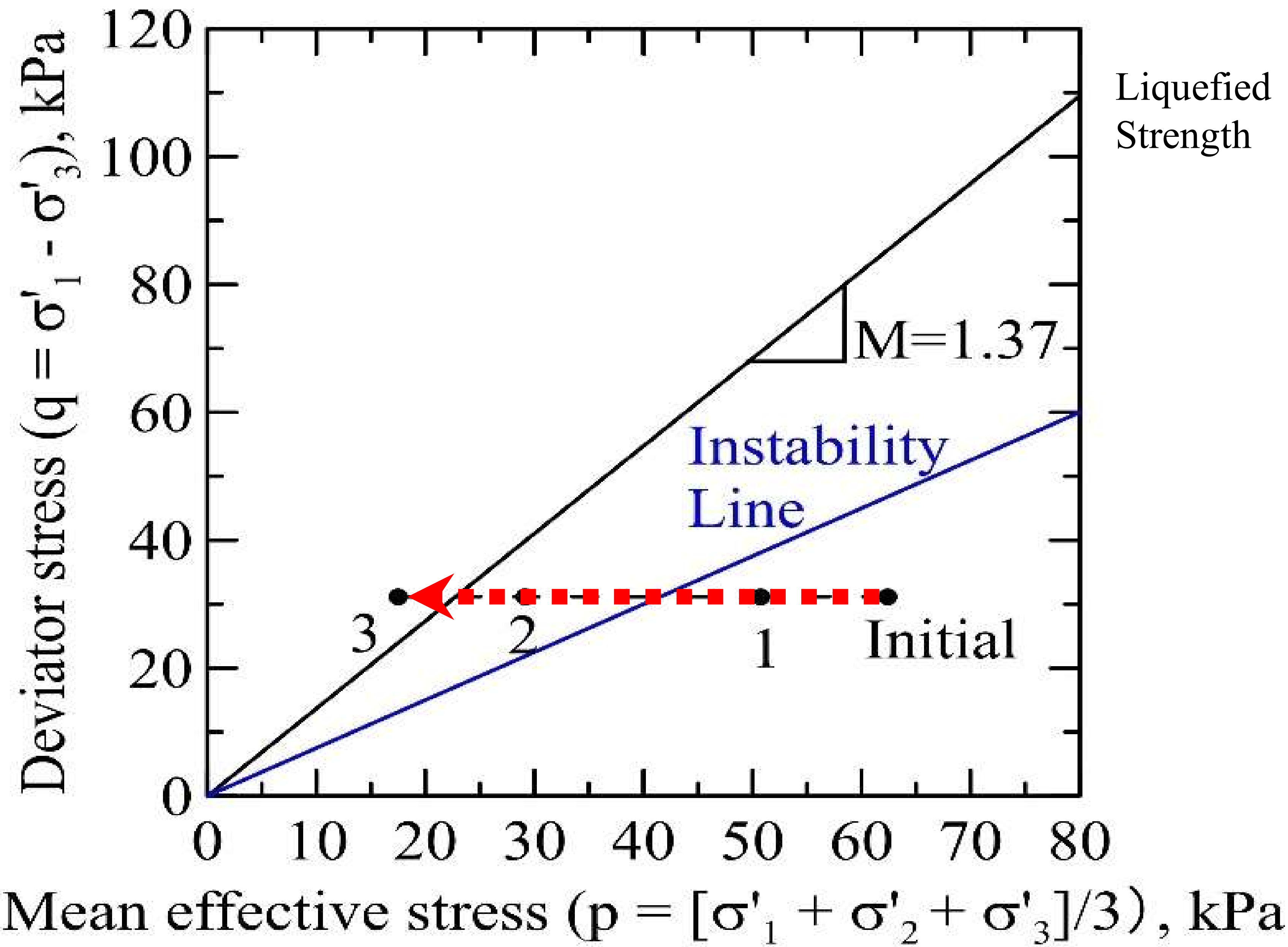


Cyclic Direct Simple Shear Testis – Attachment D5

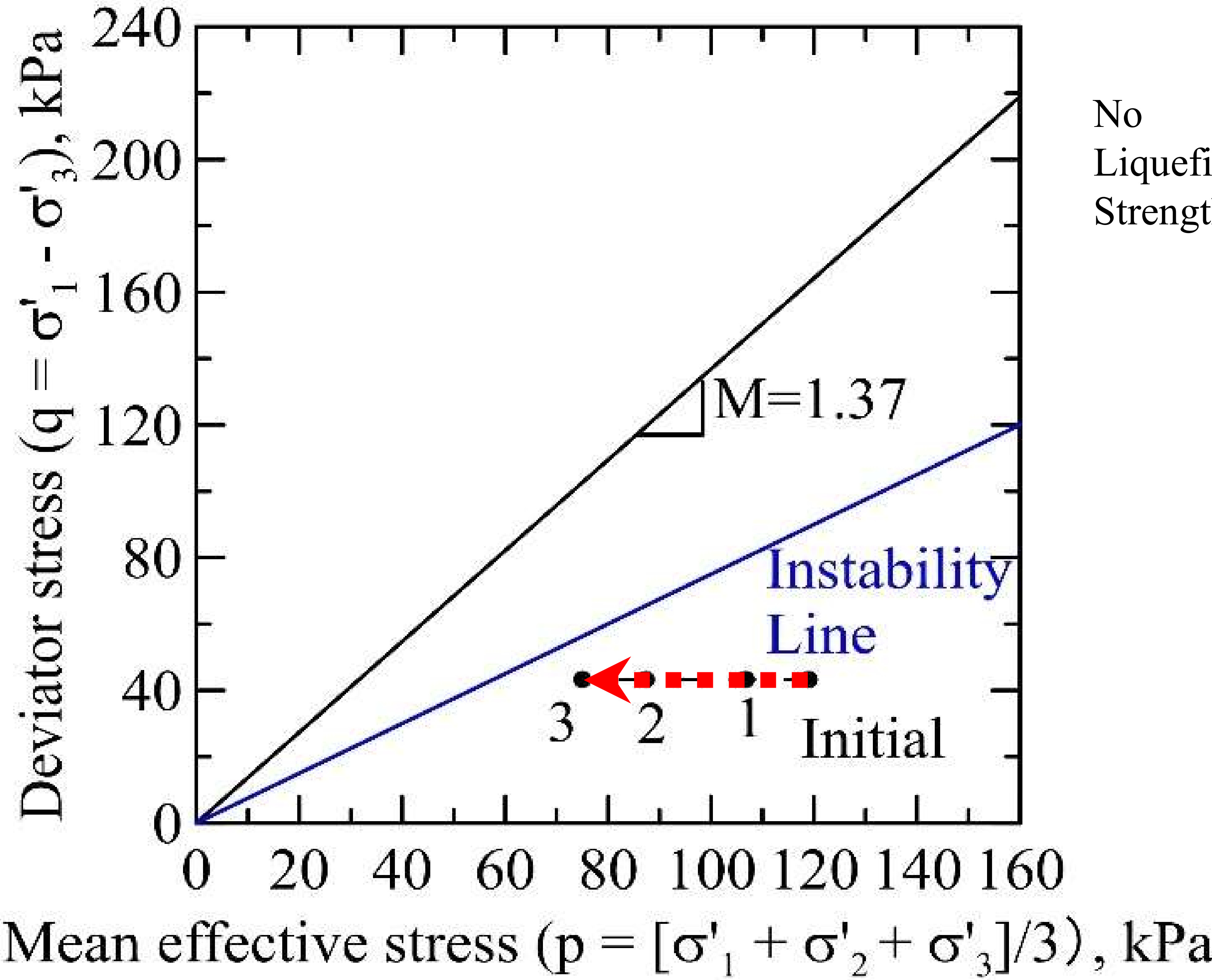


- 0 to 30 cycles – CSR = 0.01 = 10*CSR at Slimes
- 30 to 60 cycles – CSR = 0.05 ~ CSR at Left Abutment Setback
- 60 to 90 cycles – CSR = 0.1 ~ Panel CSR

Critical state line – Sand$_{\text{Slope}}$

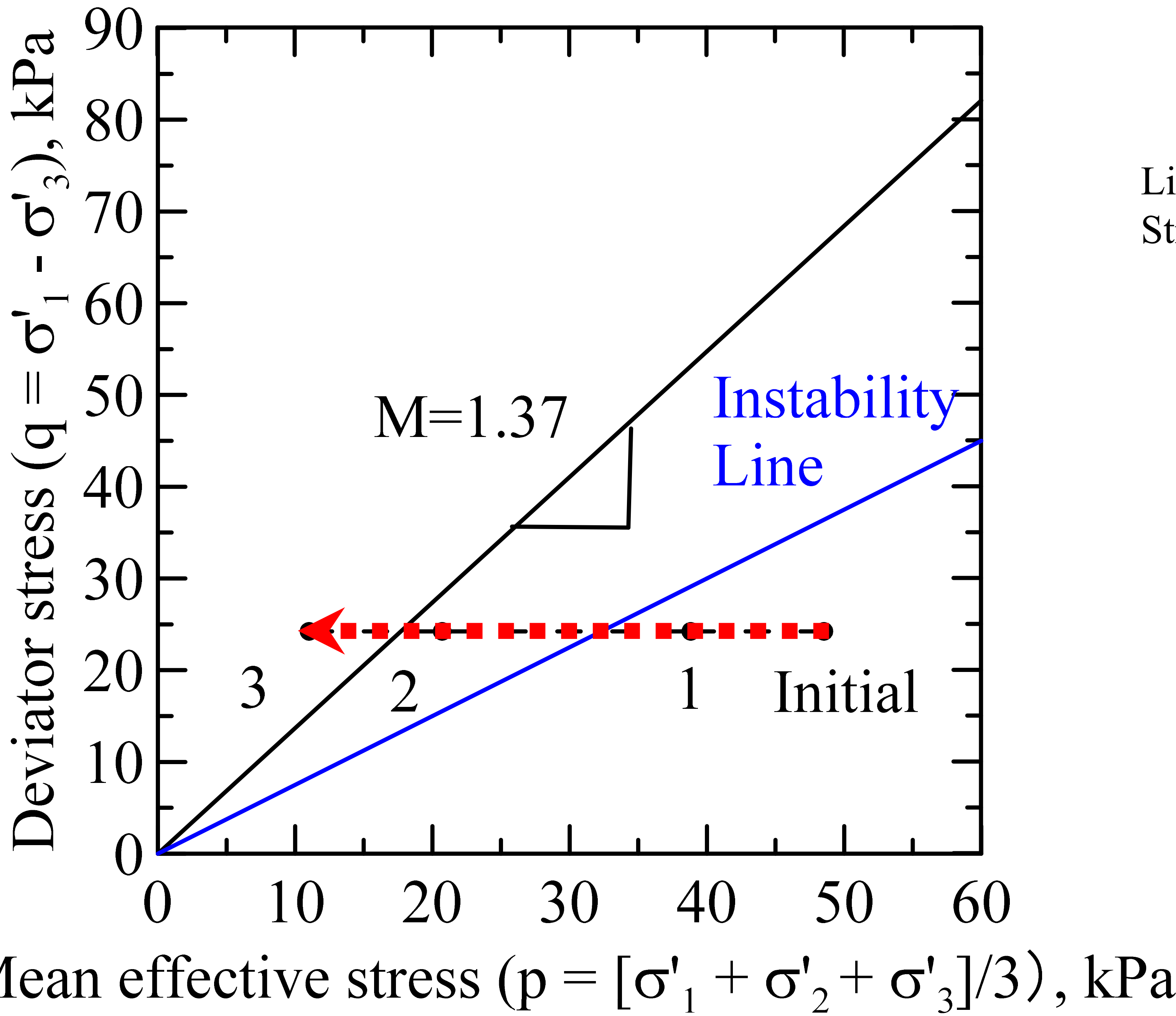


Critical state line – Sand$_{Plateau}$



No Liquefied Strength

Critical state line – Sand$_{Toe}$



Liquefied Strength

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- 5 November 2015 Failure
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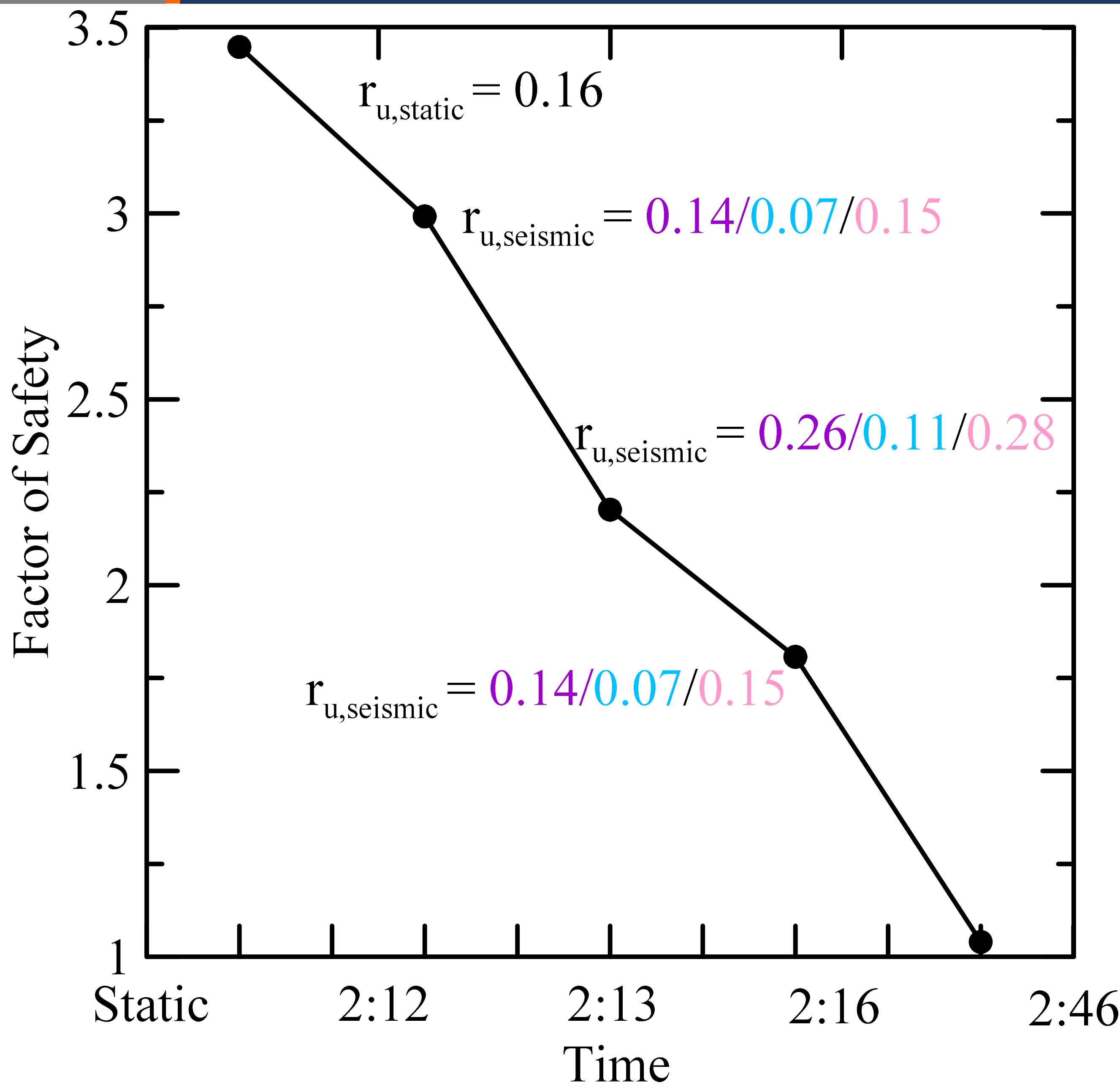
Slope Stability Analyses



Each dynamic event generates excess pore water pressure that reduces shear resistance along left abutment

Initial Condition:
r_u=0.16

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

Limit Equilibrium Input Parameters

Material Type	Color	Strength Type	Effective cohesion, c' (kPa)	Effective friction angle, ϕ' (°)	Liquefied s_u/σ_v' Ratio	r_u
Sand Tailing		Mohr-Coulomb		33		
Compacted Sand		Mohr-Coulomb	5	35		
Foundation		Mohr-Coulomb		40		
$Sand_{Toe}$		Mohr-Coulomb		22	0.03	
$Sand_{Plateau}$		Mohr-Coulomb		22		0.42
$Sand_{Slope}$		Mohr-Coulomb		22	0.03	

Total Unit Weight = 22.0 kN/m^3

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Time of Failure After Earthquakes

Eyewitness Accounts:

- Rodrigues-Silva at Plant 2 – travels to dam w/in 15 to 20 min – failed
- Silverio-Silva's email to *University* of Brasilia Seismology Department, - 15 min
- Failure within 30 min of shaking

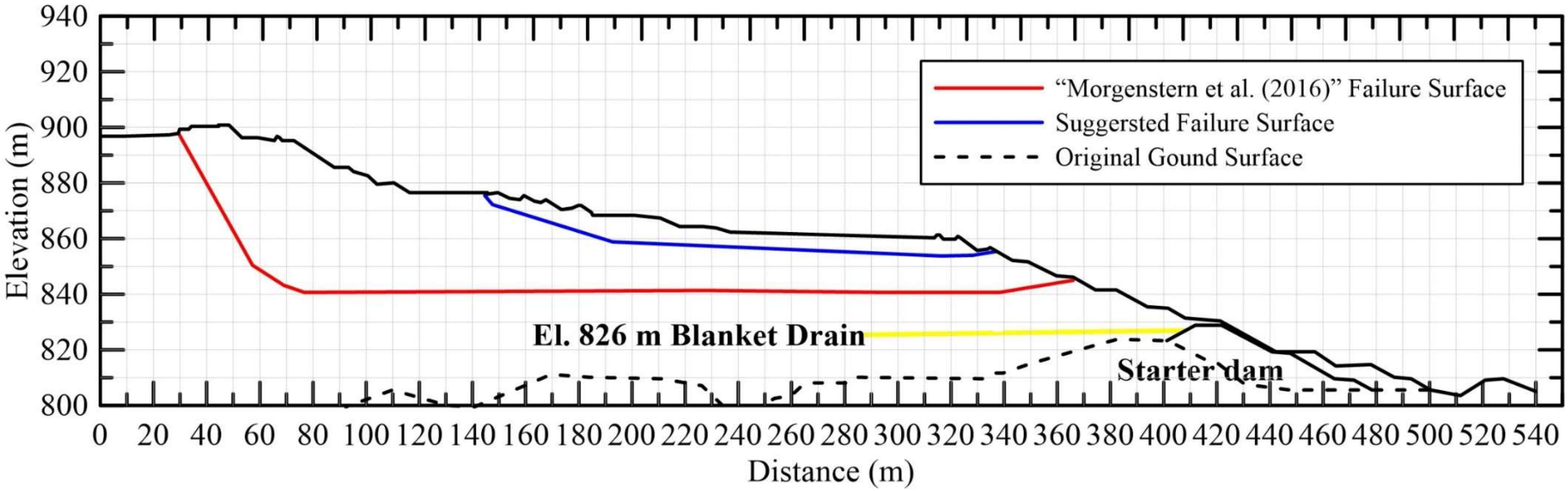
Failure after Shaking

- 1971 Lower San Fernando Dam Slide– minutes after shaking – Seed et al. (1973)
- 1978 Mochikoshi Tailings Dam Failure – 24 hours after shaking – Ishihara (1984)
- 2018 Palu, Indonesia Flowslide – two to three minutes after shaking – Mason et al. (2018)

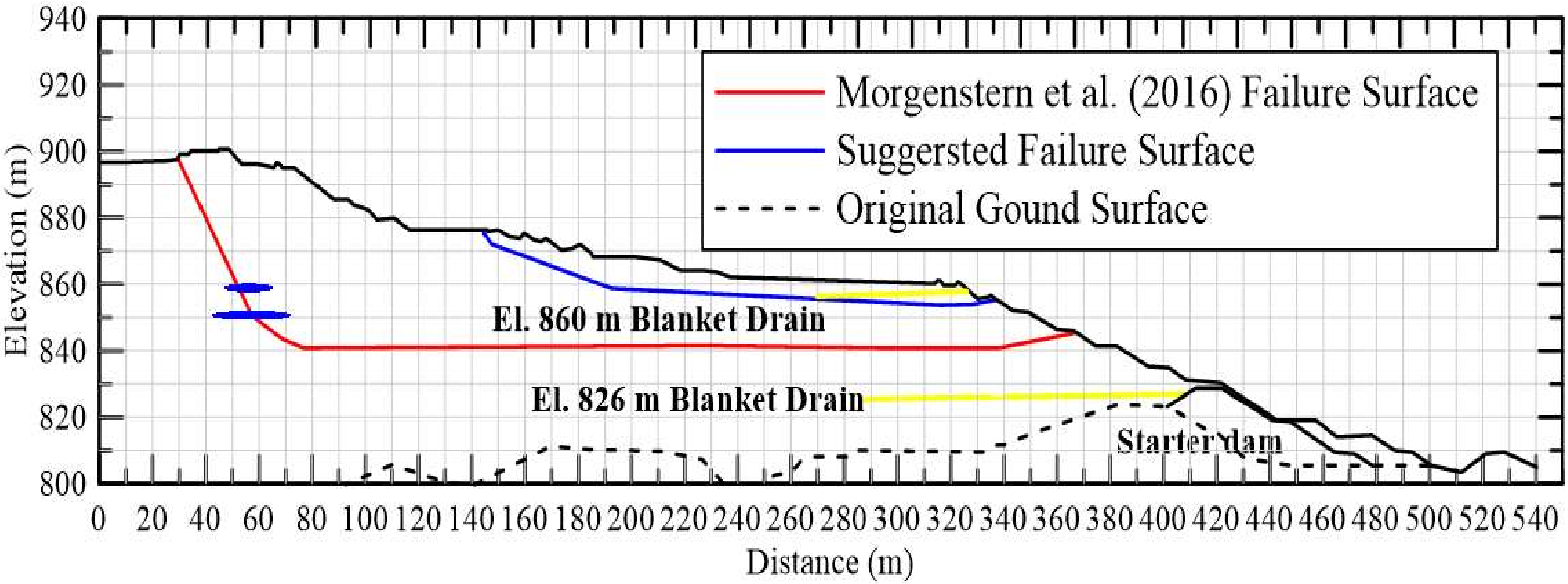
Summary

- **Tailings dam stability**
  - **consider dynamic loads**
- **Fundao Tailings Dam Failure**
  - **accumulation of excess pore-water pressures**
  - **not at large depths**
- **Tailings Dam Failure usually results in an Environmental Problem**

Cross-Section 02– Left Abutment



Comparison of Failure Surfaces



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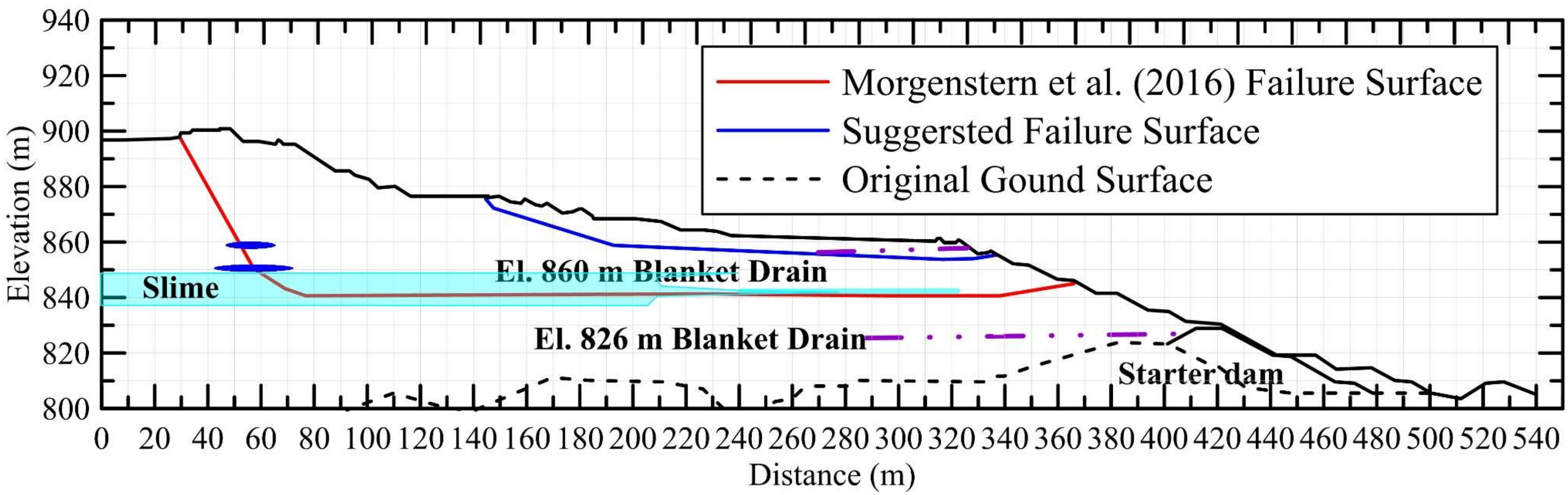


Liquefied Strength Ratio

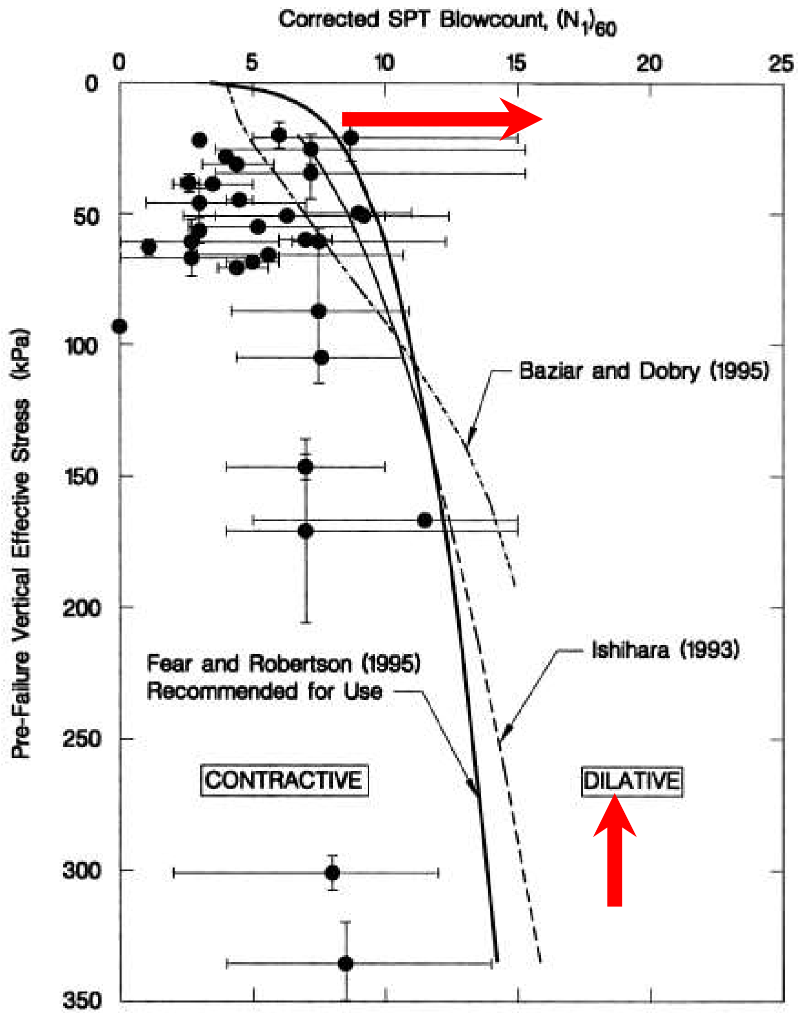


Fig. 7. Relationships separating contractive from dilative conditions using flow failure case histories and corrected SPT blowcount (bars indicate ranges of penetration test values and prefailure effective stresses)

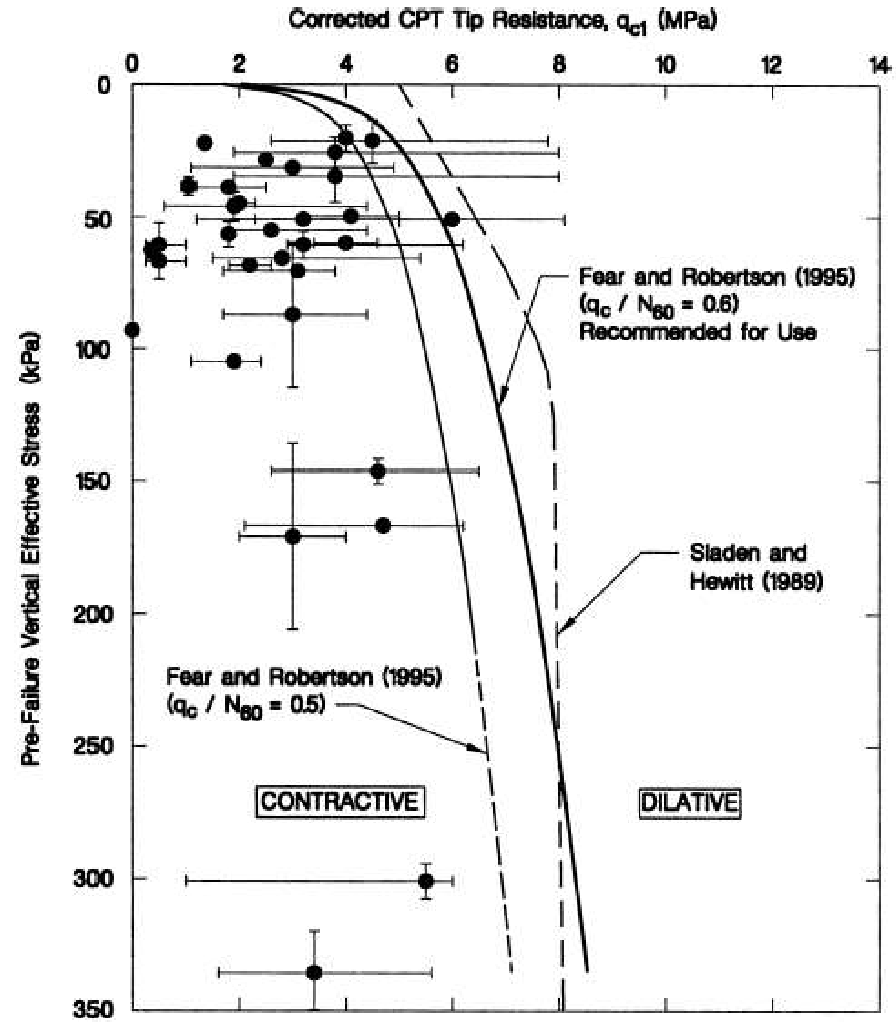


Fig. 8. Relationships separating contractive from dilative conditions using flow failure case histories and corrected CPT tip resistance (bars indicate ranges of penetration test values and prefailure vertical effective stresses)

Liquefied Strength

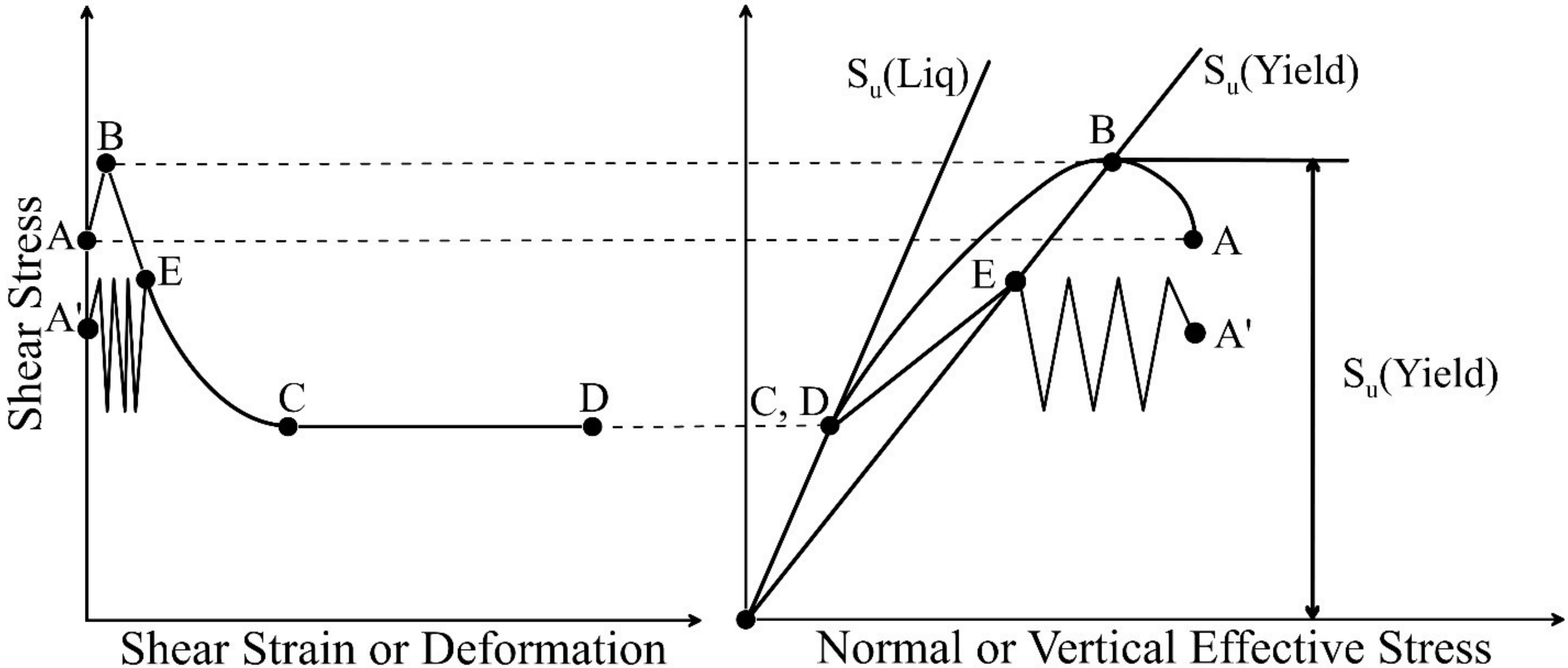


Fig. 1. Schematic undrained response of saturated sandy soil subjected to static and dynamic loads.

Stark and Lin (2022)

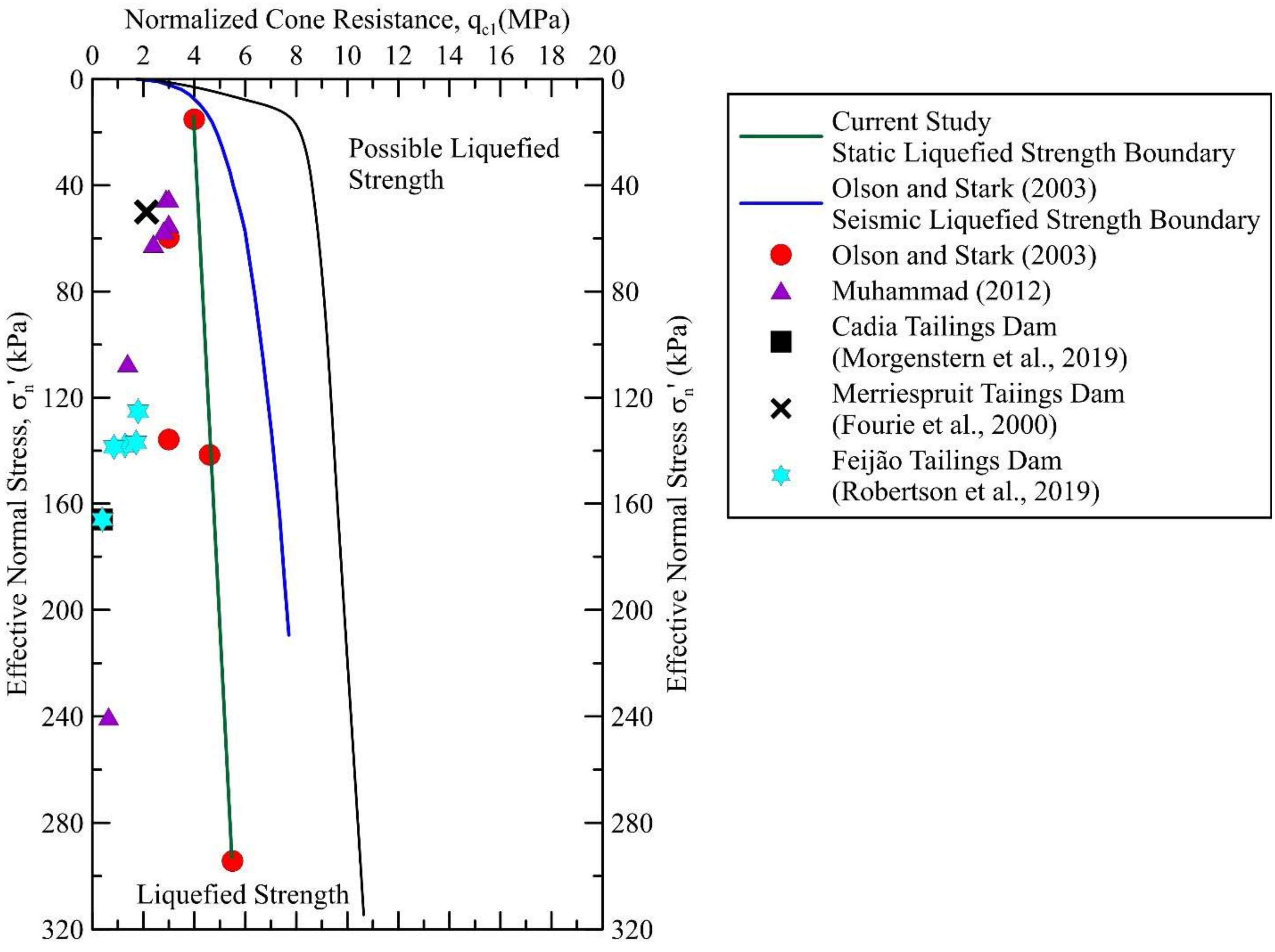
Five Step Process:

1) Assess static liquefaction potential,
2) Perform liquefaction triggering analysis,
3) If liquefaction not triggered, assess shear-induced pore-water pressure due to small vibrations,
4) Assign yield and liquefied strength, and
5) Conduct post-triggering stability analysis to assess flow failure potential

Stark and Lin (2022)

Step 1: Assess static liquefaction potential of Segments
- Not Contractive & Dilative

4 MPa

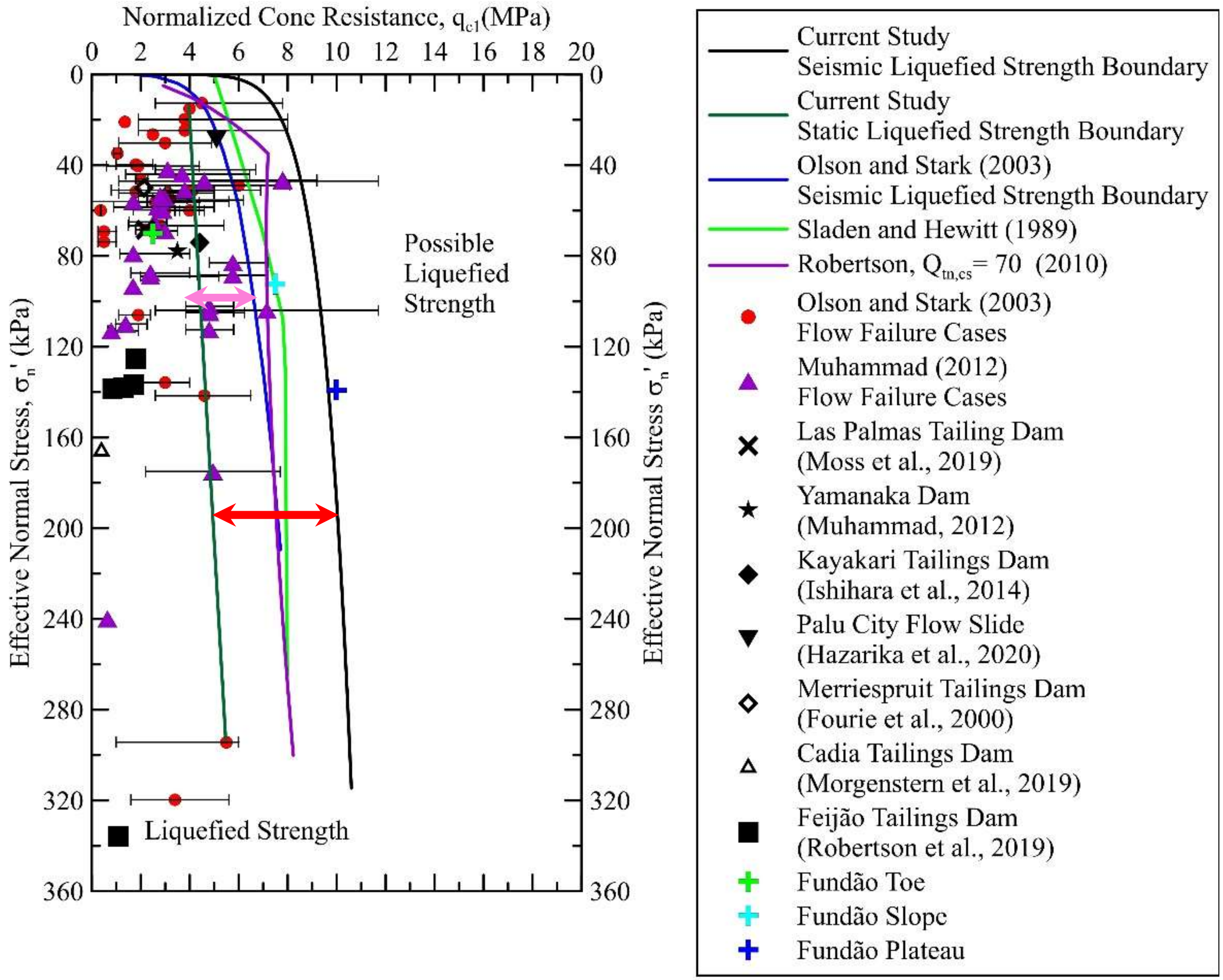


Stark and Lin (2022)

Step 2: Liquefaction triggering analysis

- Not Contractive & Dilative &
- Olson & Stark (2003) – Mean not upper bound

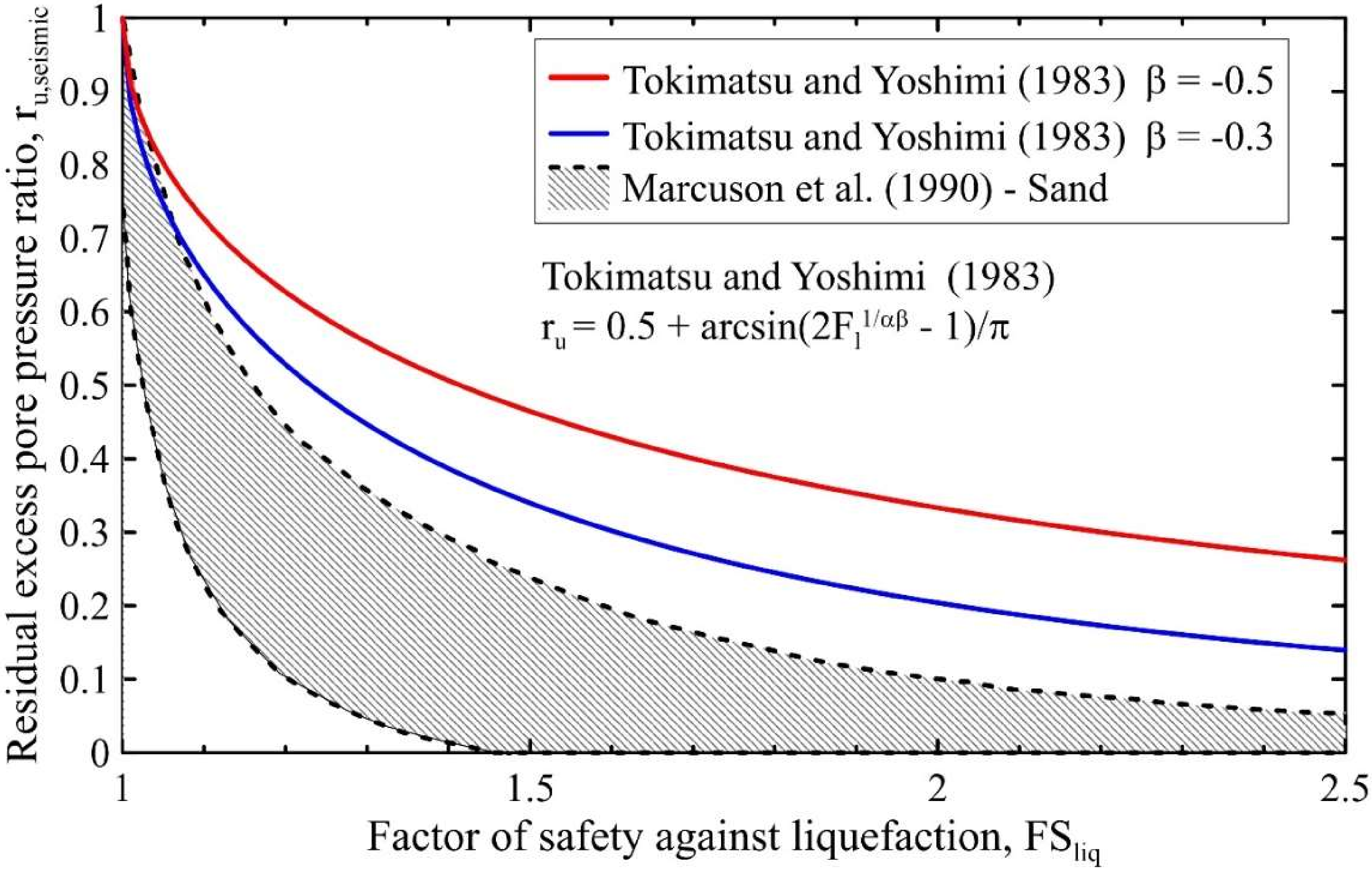
$$\sigma_n' = 3.01 \times 10^{-7} \times q_{c1}{}^{8.796}$$



Stark and Lin (2022)

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

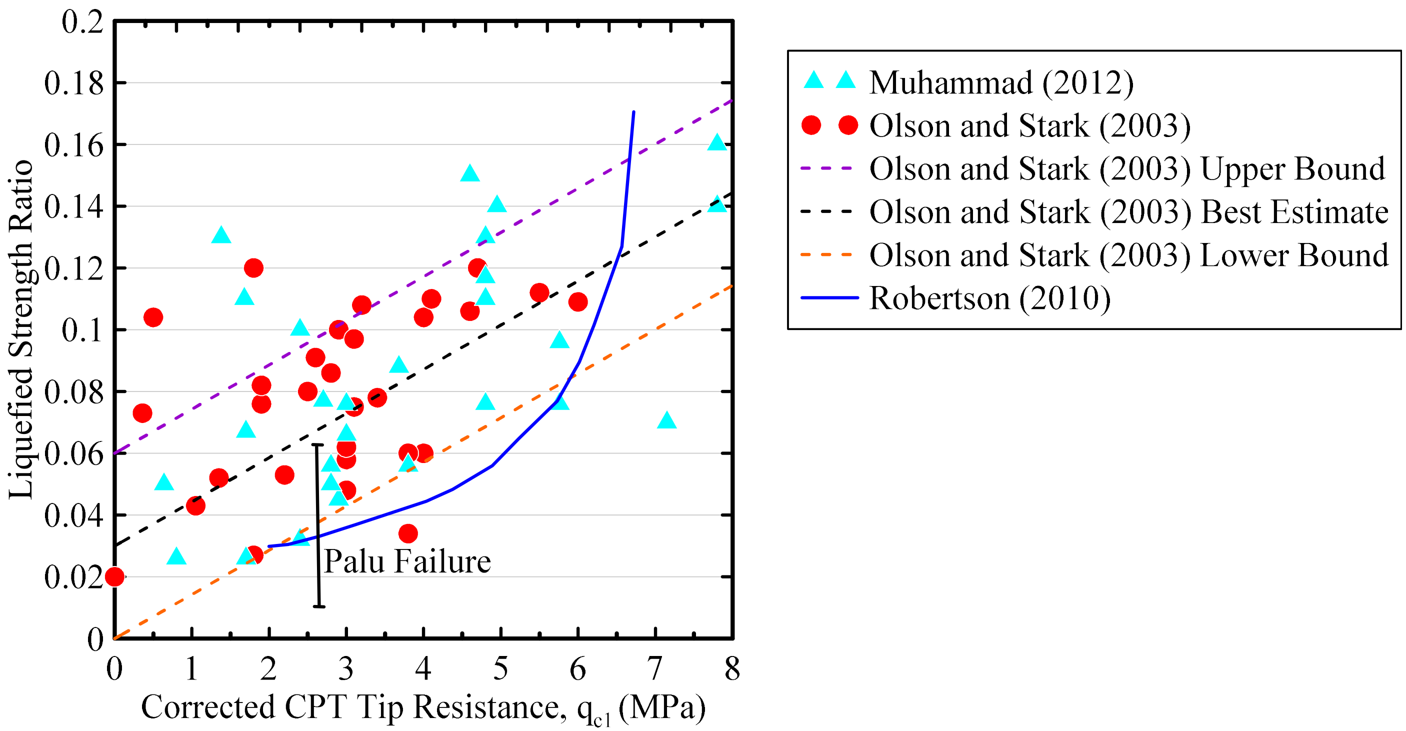
- $r_{u\ total} = r_{u\ static} + r_{u\ dynamic}$



Stark and Lin (2022)

Step 4: Assign yield and liquefied strengths

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



Stark and Lin (2022)

Step 5: Post-triggering stability analysis

- $FOS_{Flow} \leq 1.0$ => flow failure
- $FOS_{Flow} = 1.0$ to 1.1 => permanent deformations
- $FOS_{Flow} = 1.0$ to 1.1 => permanent deformations, if
  $\mathrm{FO}S_{Tiggering} < 1.1$ => assign liquefied strength & calc FOS_{Flow}
- $1.2 < FOS_{Flow} < 1.3$ => calculate permanent deformations
- $FOS_{Flow} > 1.2$ to 1.3 => no action

Contactive v. Dilative: Is it black and white?

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Brisbane, Australis

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