A Stochastic Approach for Discontinuity Shear Strength (StADSS)

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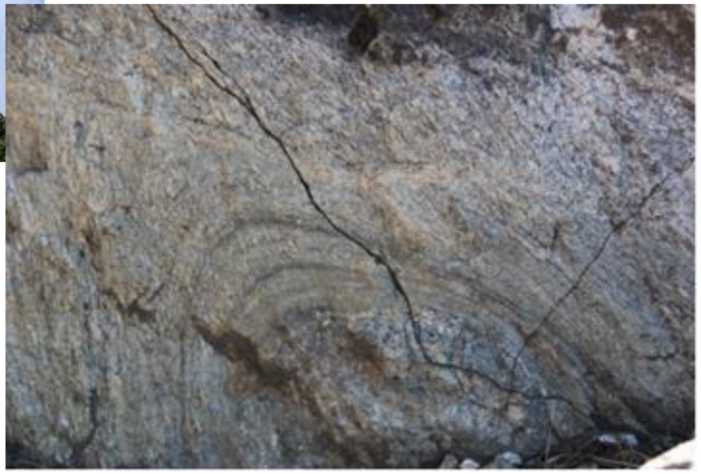
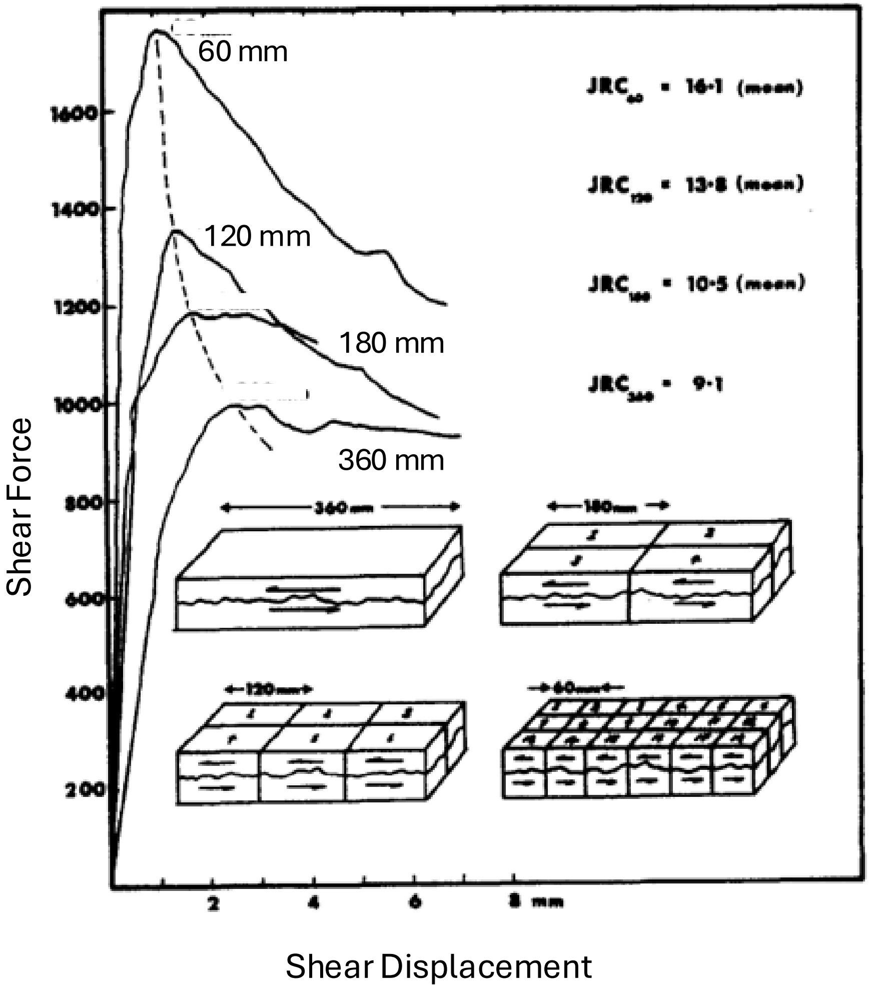
Introduction

- Rock discontinuities strongly affect the hydromechanical response of rock masses, including stability
- Estimating the shear strength of large in situ discontinuities is challenging:
    - Measurement of roughness is non-trivial (scale dependent, scale descriptor?)
    - Full discontinuity morphology not typically accessible



Barton and Bandis (1980)



Introduction

- Pioneer shear model by Barton (1976) and co-workers is the most common method used in practice

$$\tau_p = \sigma_n \tan\left(JRC \cdot log\left(\frac{JCS}{\sigma_n}\right) + \phi_r\right)$$

- Since 1970s, much research has been conducted on rock joints (experimental and numerical) but often not practical enough to be used by industry or applicable to large scale in situ discontinuities.

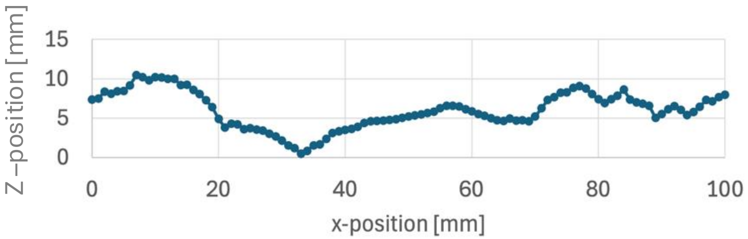
- JRC model has a simple mathematical form, so very easy to use….but:
  - JRC is sometimes non-trivial to assess
  - Scale effect is prescribed as “Positive” – strength reduces as scale increases
  - There is evidence in the literature of positive, negative and neutral scale effect (Pratt, 1974)

$$JRC = JRC_o \left(\frac{l}{l_o}\right)_o^{-0.02 \cdot JRC_o}$$

Can we develop a practical approach that :

1. Eliminates subjective or ill-defined roughness descriptors,
2. Is based on a mechanistic shear model to predict peak and residual shear strength,
3. Resolves the scale effect,
4. But does not require complicated constitutive modelling?

StAdss – Principle



Input

Statistical characterization of seed trace (available 2D data)

⇓

N synthetic surfaces created from seed trace using rigorous random field model (**RFM**)

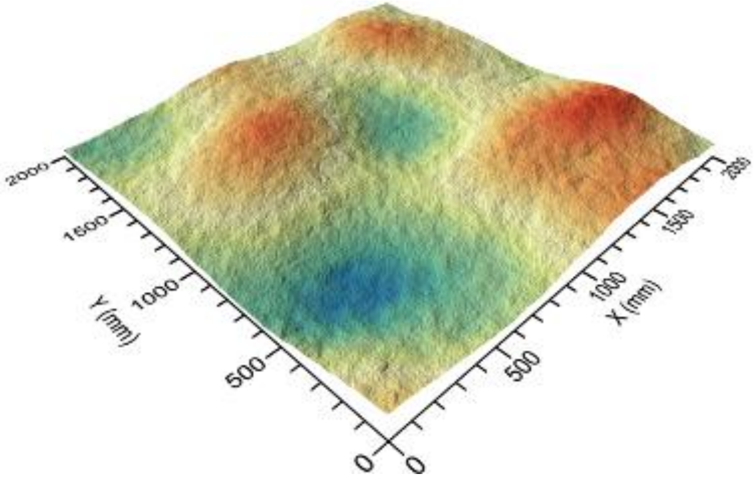
⇓

Monte Carlo simulations of shear strength on the *N* synthetic surfaces using **NDSS* Shear model**

⇓

Distribution of shear strength of the discontinuity

Shear strength is a 3D process!



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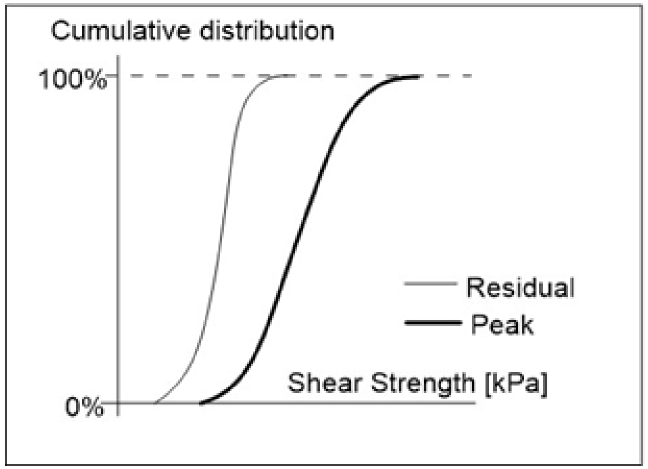
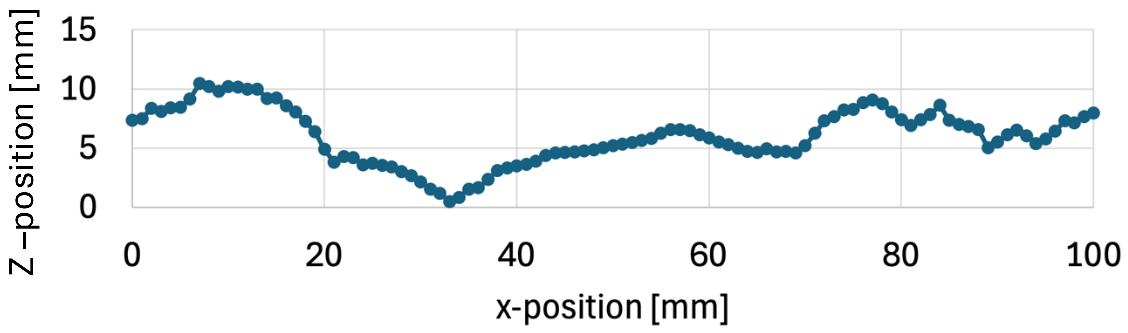


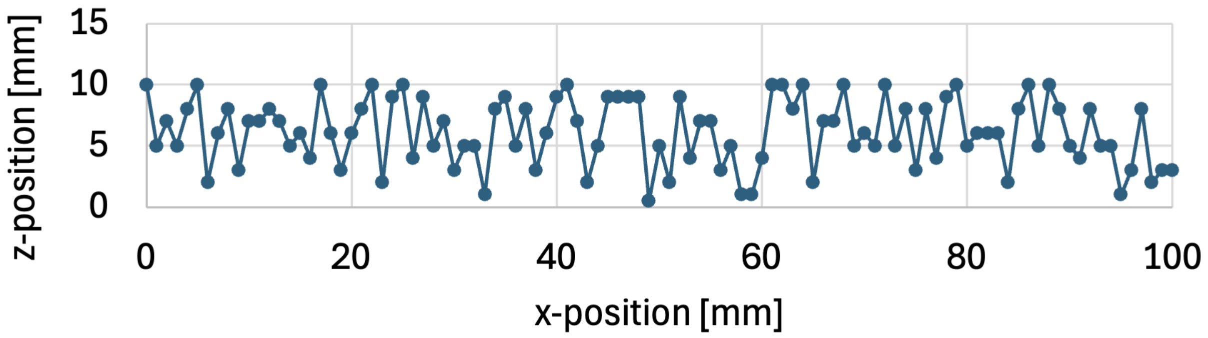
Output

*NDSS: Newcastle Discontinuity Shear Strength

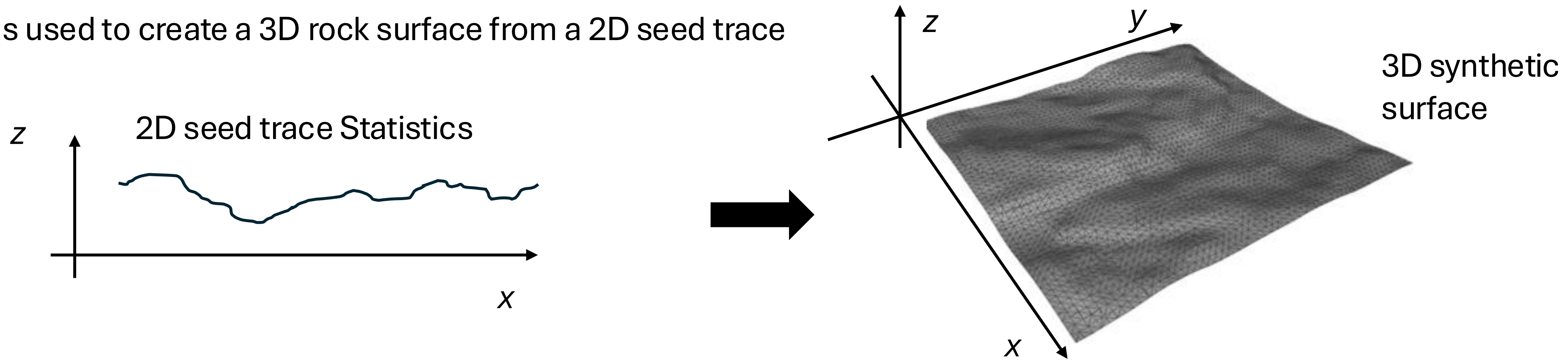
Random Field Model (RFM)

- RFM = random number generator (specify distribution type, mean, standard deviation) **with a correlation function**





- RFM is used to create a 3D rock surface from a 2D seed trace

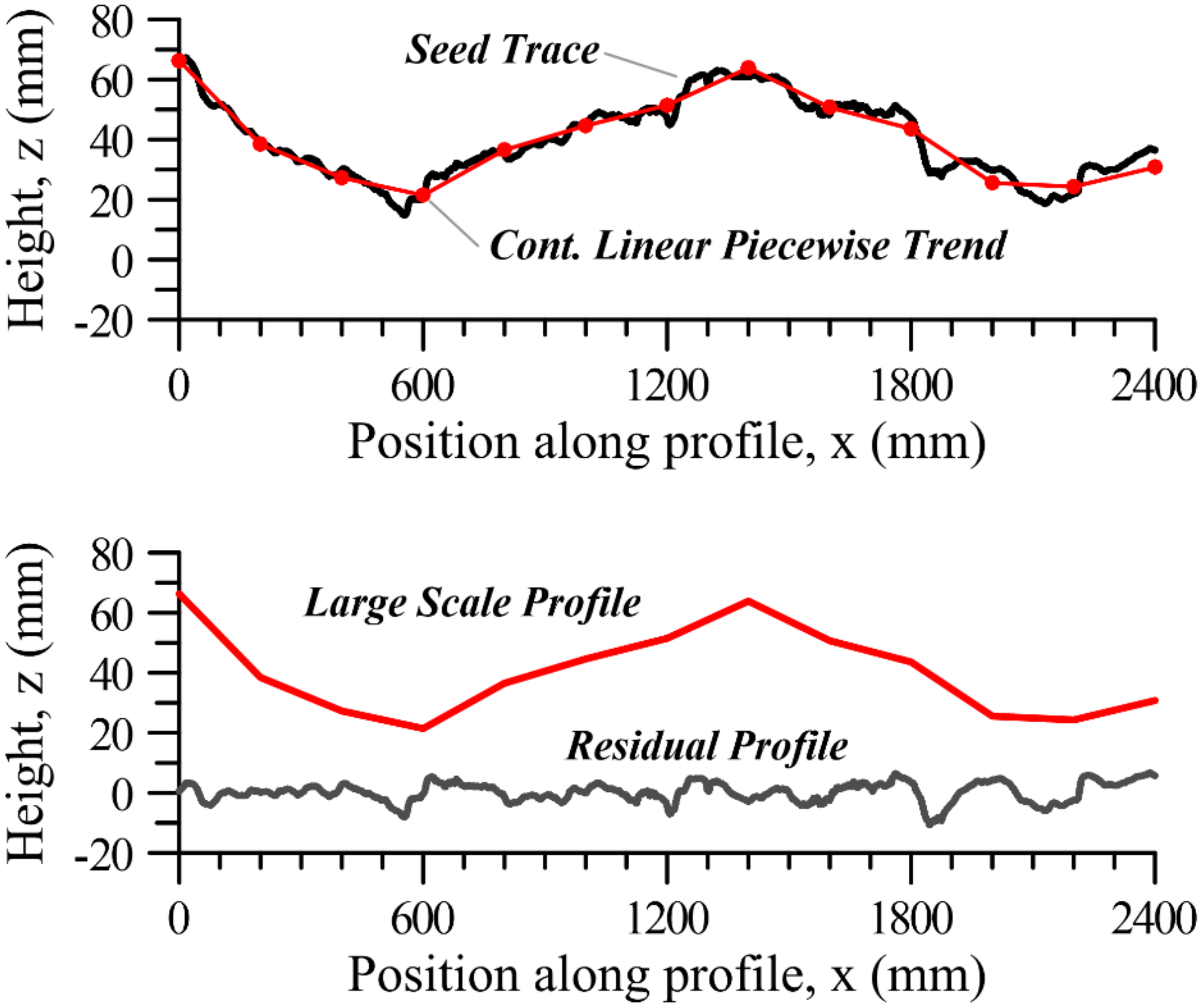


- RFM = rigorous statistical tool => Statistics of the 3D surface = Statistics of the 2D seed trace
- Shear is a 3D process, but we have 2D information (trace)

Random Field Model: decoupling process

- To produce more realistic large rock surface with different levels of roughness scale, we introduce a decoupling/recoupling process (Jeffery et al., 2021)

- Step 1: decouple the seed trace into 3 sub-traces (daughter traces) – curve fitting process



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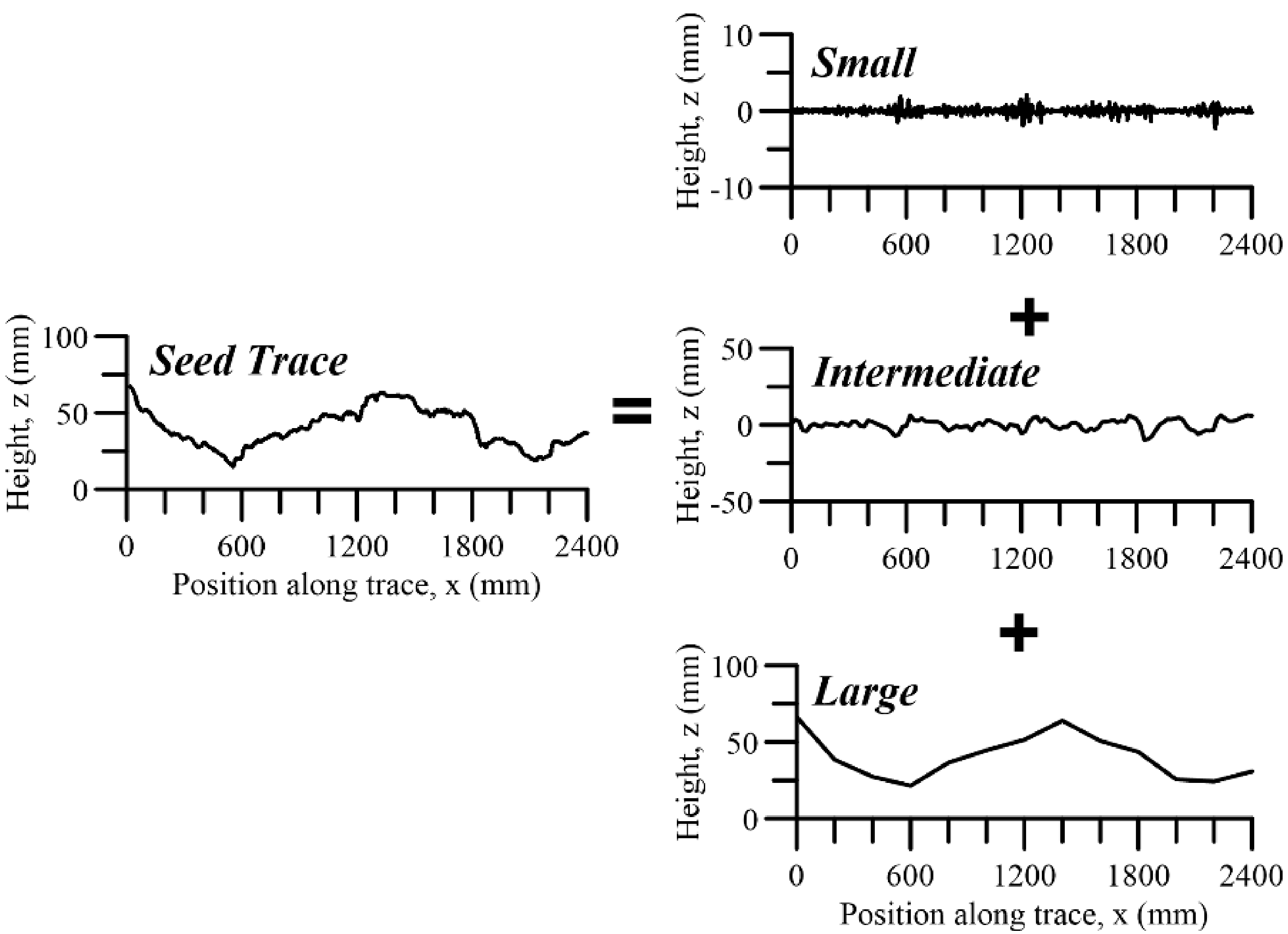
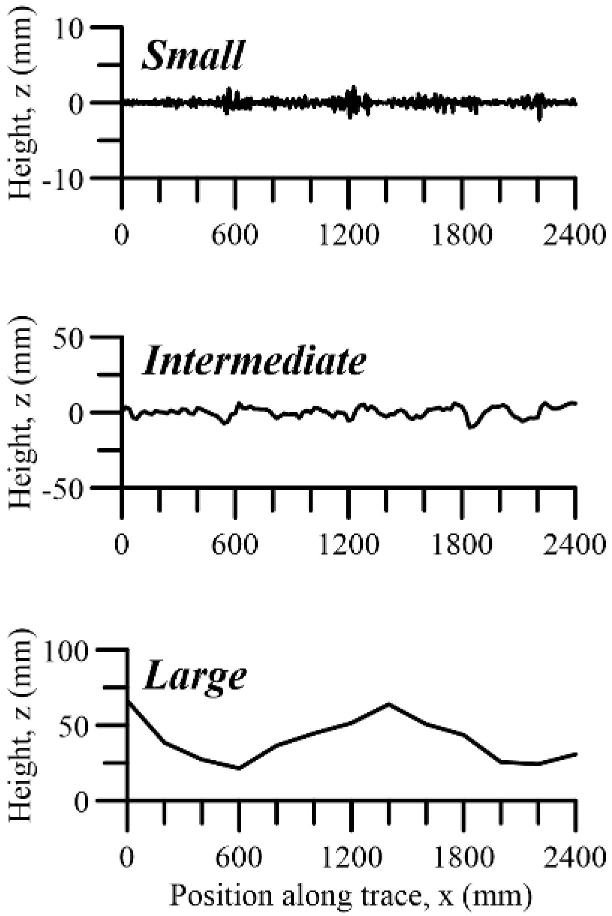


Random Field Model: decoupling process

- Step 2: produce a surface at each level from the statistics of the daughter traces



Trace statistics + **RFM** =

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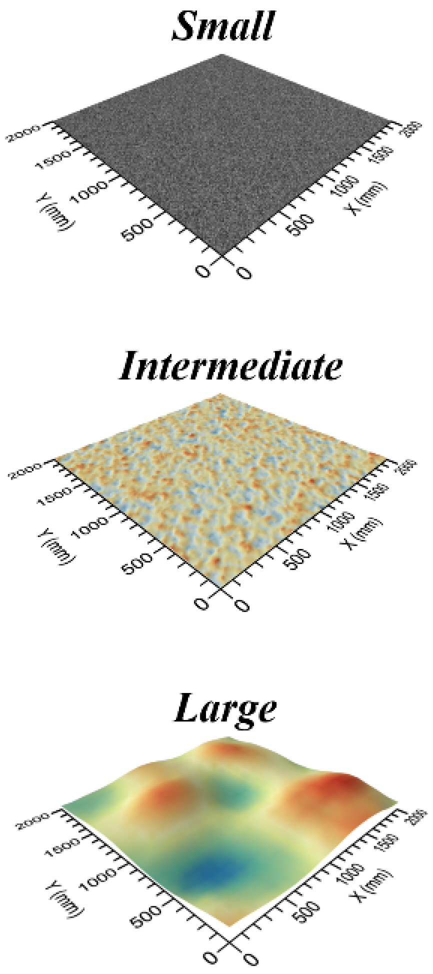
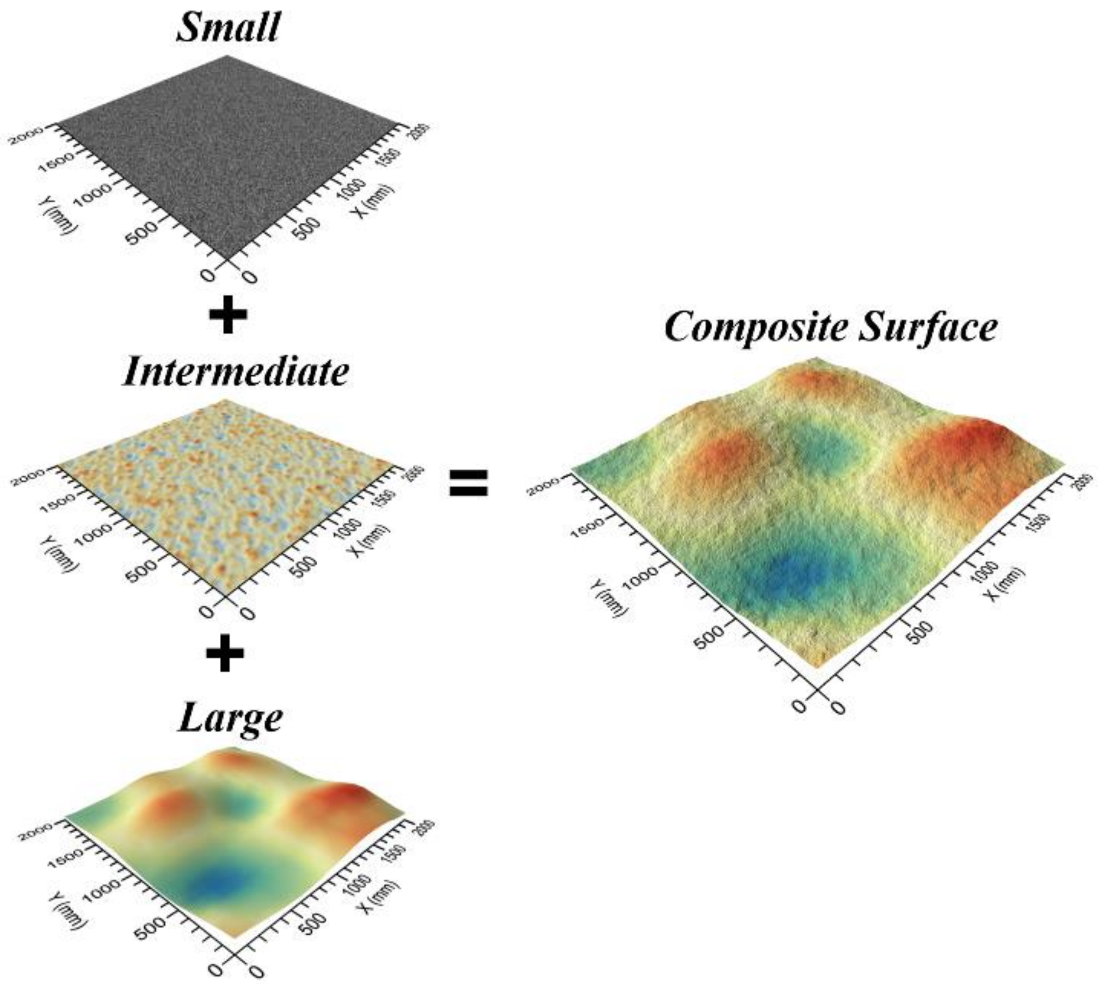


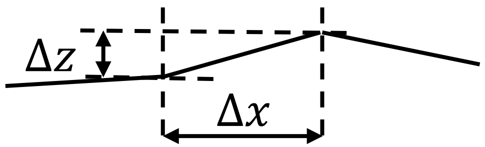
Random Field Model: decoupling process

- Step 3: Combine the 3 surfaces to produce a composite surface



Important note: roughness of traces/surfaces is here quantified via the standard deviation of gradients (sd_i)

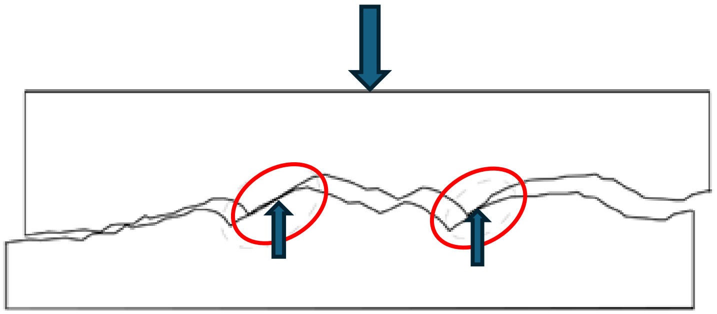
$$i = \Delta z / \Delta x$$

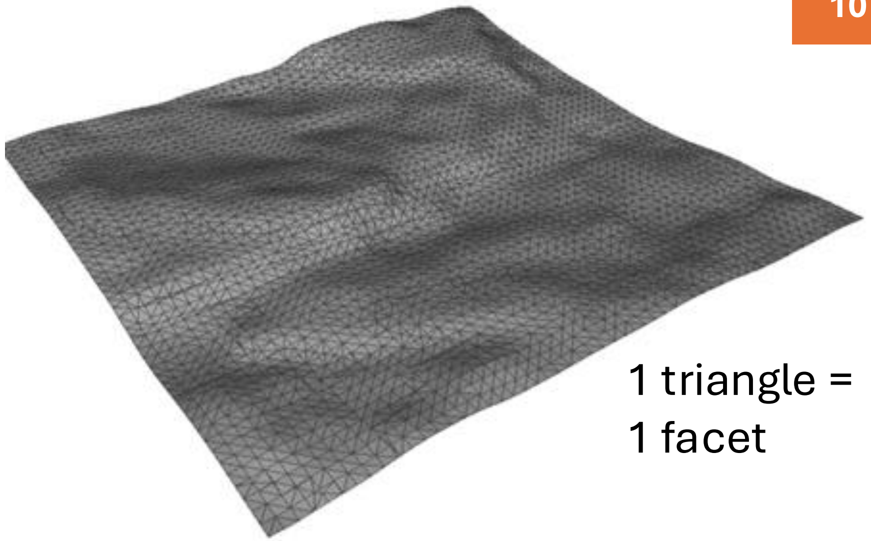


Newcastle Discontinuity Shear Strength Model (NDSS)

Inputs:

- 3D triangulated and grided surface
- Strength parameters (HB, ϕ_b)
- Shear direction
- Normal effective stress





1 triangle = 1 facet

Mechanics of the model (see Casagrande et al., 2018):

- Surfaces are perfectly matching and normal stress is constant
- Joint is assumed to dilate along steepest facets during shearing (=> facets contributing to shear resistance)
- Normal stress concentration occurs as joint dilates
- On each contributing facet, compute stress required to shear single facet and slide over facet
- If sliding stress > shearing stress => facet is sheared (angle is reduced)
- Iterations stop when sliding stress = shearing stress

Outputs:

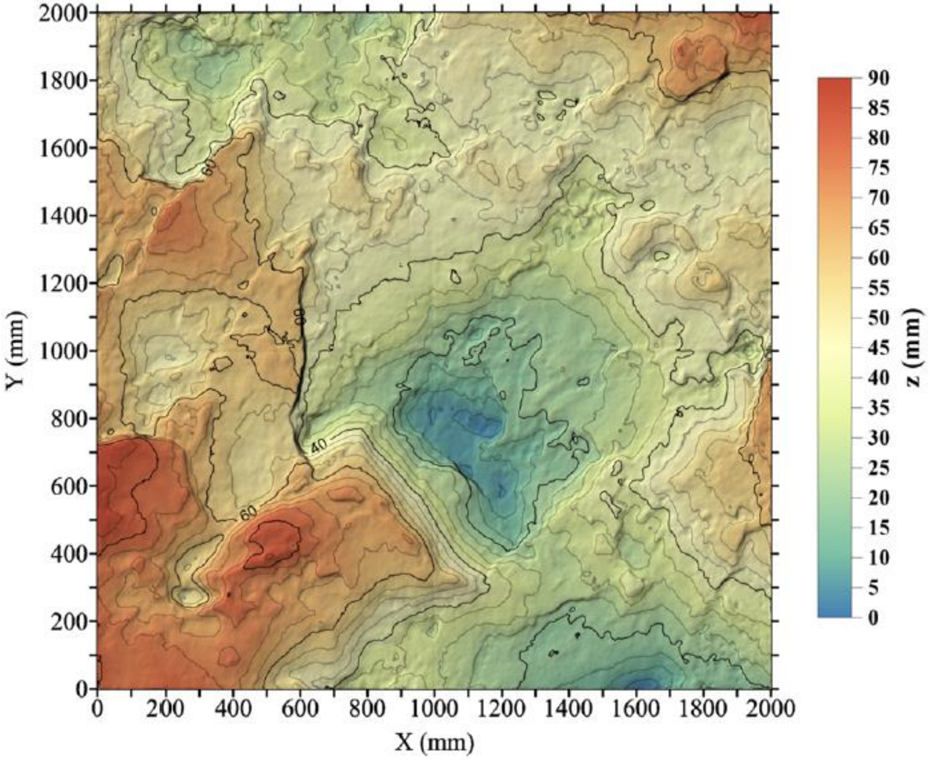
- Sheared areas
- Inclination of sheared facets β

$$\boxed{\tau_p = \sigma_n' \tan(\phi_b + \beta)}$$

$$\boxed{\tau_r = \tau_p - \frac{Sheared\ Area}{Total\ Area} cohesion}$$

Large scale applications – Lab testing

- NDSS model was extensively validated in the lab on small scale specimens, but what about large scale?
- We built a large shear box for 2m per 2m discontinuities (Jeffery et al., 2022, GTJ)
- Tested mortar replicas of a real discontinuity
- Mortar strength was characterised ($\sigma_{ci} = 67.8\ MPa, m_i = 8.5, \phi_b = 36.2^o$)

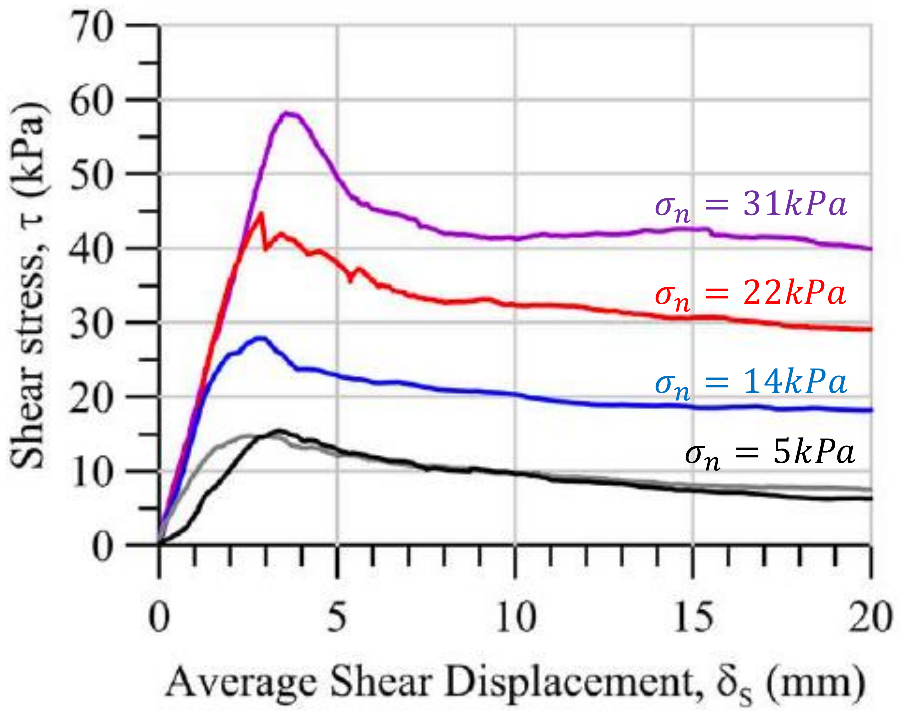


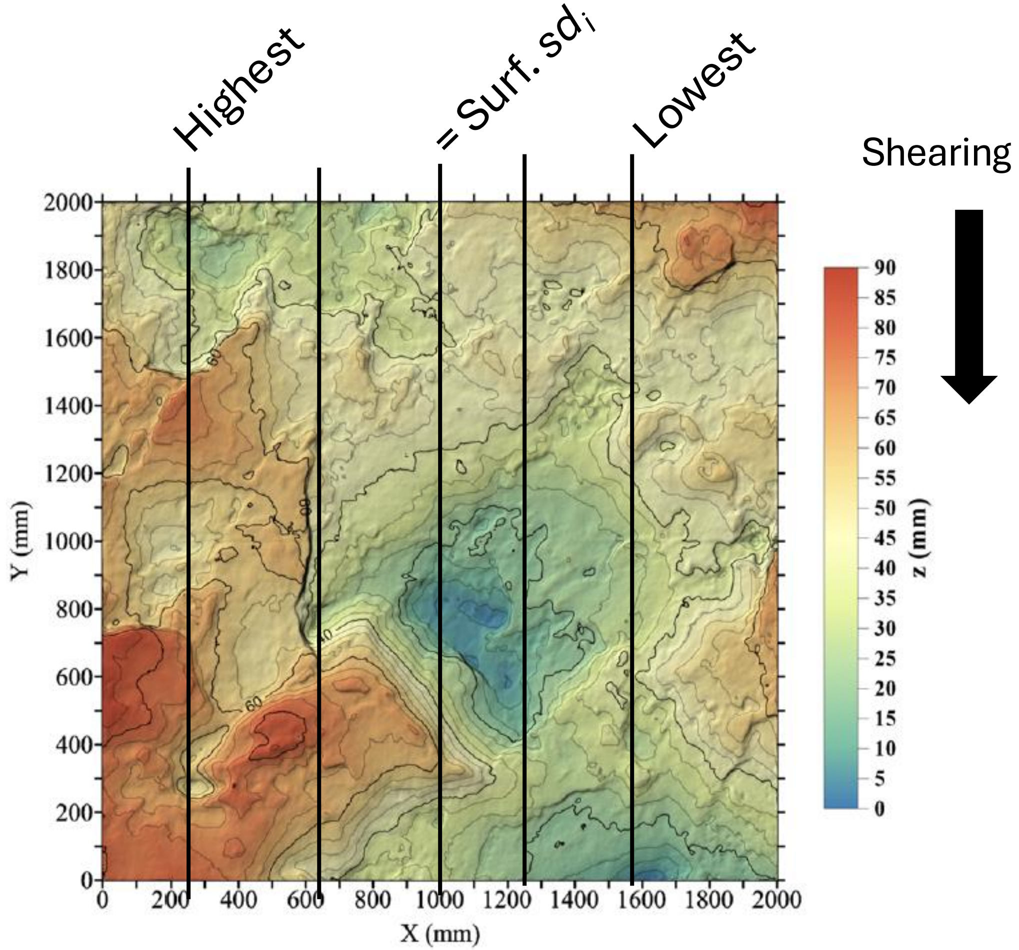
Top/Bottom

Bottom wall

Large scale applications – Lab testing

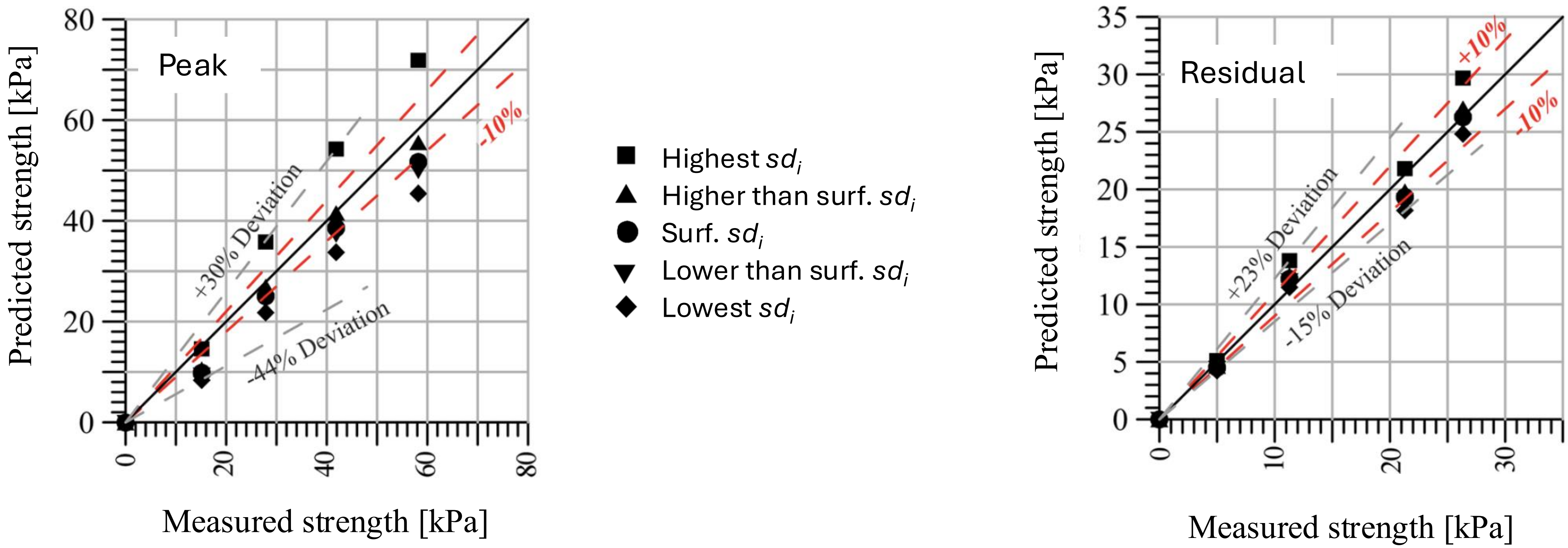
- Evolution of shear stress with tangential displacement below:
  - Max shear displacement ~300 mm
  - Peak at <5mm (<1% of surface length)
  - Different seed traces selected to apply StADSS (RFM+NDSS)





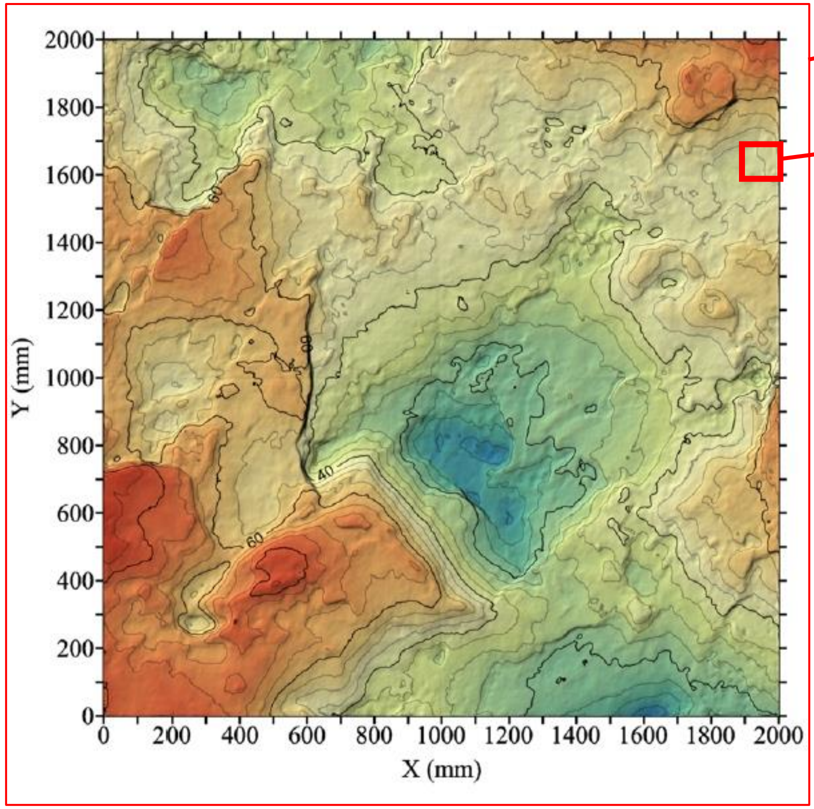
Large scale applications – Lab testing

- Strength prediction (average values from distributions) depends on roughness of seed trace (expected)
- Peak strength: predictions are within -44% to +30% of experimental value (maximum error values)
- Residual strength: -15% to 23% error i.e., less sensitive to seed trace roughness
- On that surface, for ~70 % of traces, relative error on residual shear strength is < ±8% (Jeffery et al., 2023)



Scale effect – what about residual strength?

- It is known that scale affects peak shear strength, but residual strength is considered scale independent
- It is common practice to infer a residual friction angle from rock cores and apply to a large discontinuity
- Residual state = residual roughness, so scale could matter!
- Scale effect on residual strength was investigated using the NDSS model



Residual strength of large surface (NDSS) ($\tau_r(\sigma_n)$)

Residual strength of 400 sub-surfaces (100mm per 100 mm, NDSS)
($\tau_{r-min}(\sigma_n)$, $\tau_{r-average}(\sigma_n)$, $\tau_{r-max}(\sigma_n)$)

Minimum Strength ratio: $\frac{\tau_{r-min}(\sigma_n)}{\tau_r(\sigma_n)}$

Average Strength ratio: $\frac{\tau_{r-average}(\sigma_n)}{\tau_r(\sigma_n)}$

What is measured in the lab on a core

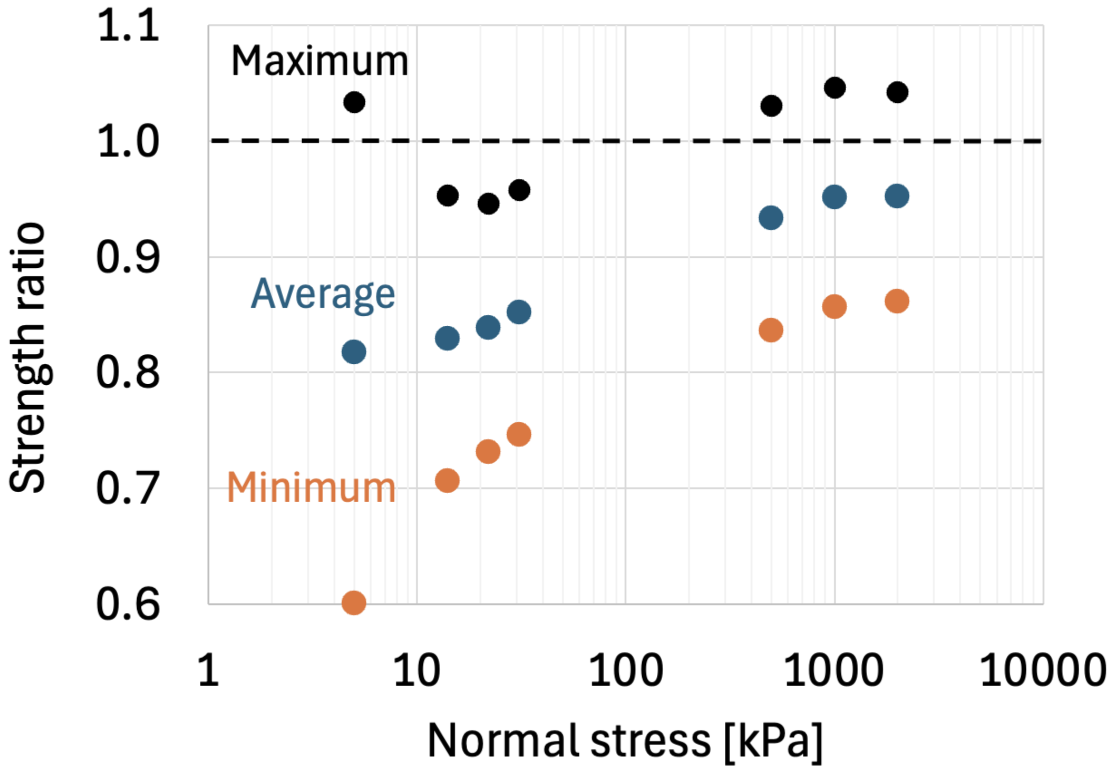
Strength of full surface

Maximum Strength ratio: $\frac{\tau_{r-max}(\sigma_n)}{\tau_r(\sigma_n)}$

Scale effect – what about residual strength?

- Strength ratio is stress dependent
- Underestimation of residual strength can be quite large, especially at low stresses

⇒ it is best to estimate the residual strength of the large surface at full scale

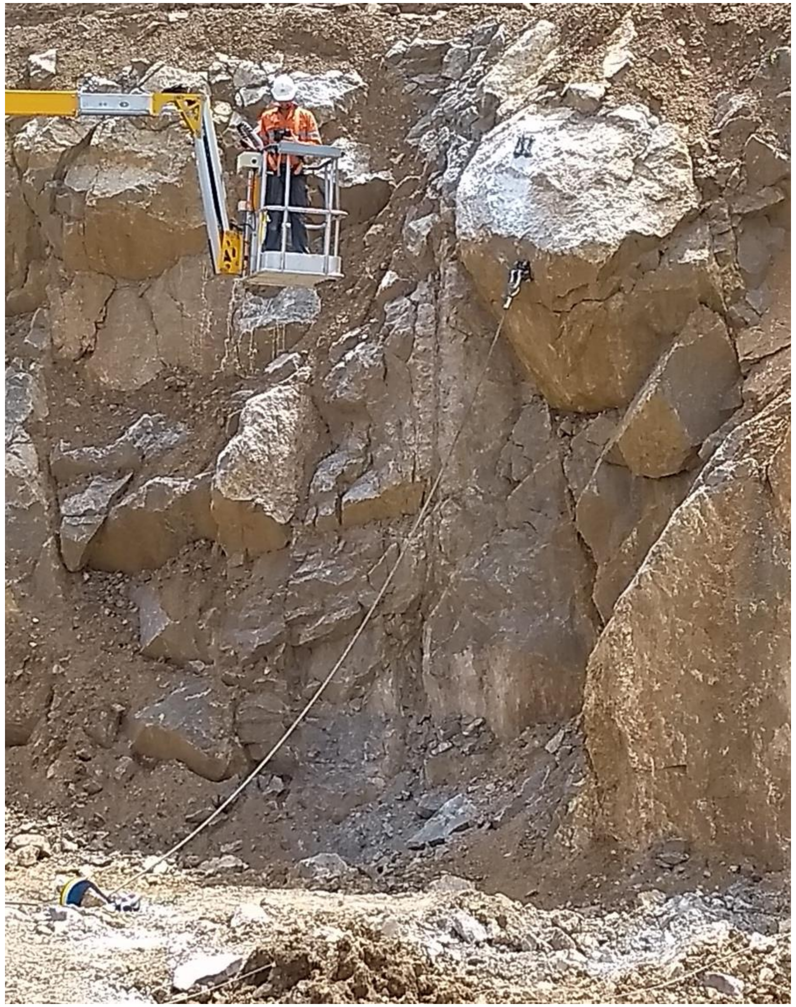


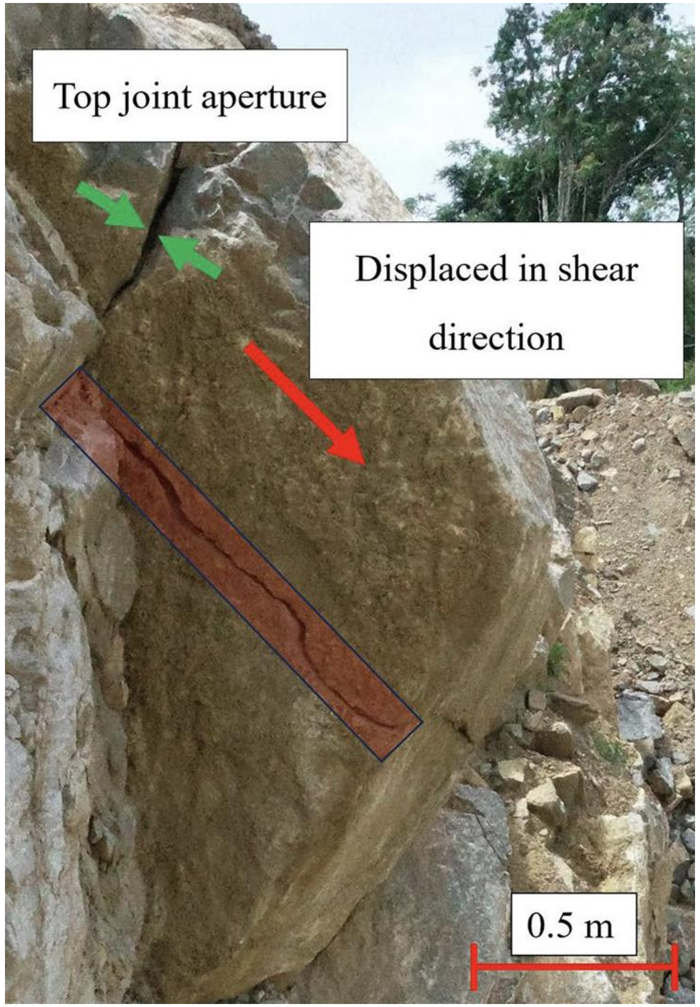
Strength ratio < 1 means that the residual strength of the full surface is underestimated

For more on the scale dependence of residual strength, check our upcoming (?) AGS paper (Conference special issue)

Large scale applications – In situ pull out test

- An in situ pull test was performed in a limestone quarry in NSW (Butcher et al., 2024)





Large scale applications – In situ pull out test

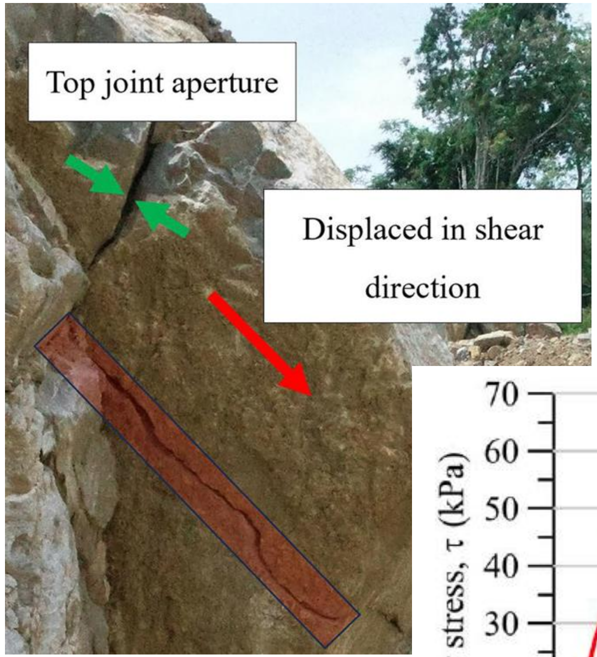
- Two visible traces were surveyed - surface is very rough (*sd_i* = 0.74 m/m and 0.84 m/m => JRC ~30)
- “Tangent” models cannot return a sensical shear strength
- Rock cores were tested ($\sigma_{ci} = \sim 97\ MPa, m_i = 8.8, \phi_b = 37.4^o$)

- Strength prediction returns:
  - Peak shear strength of ~450 kPa ($\Phi_p \sim 88^o$)
  - Residual shear strength of 16 kPa ($\Phi_r \sim 50^o$)

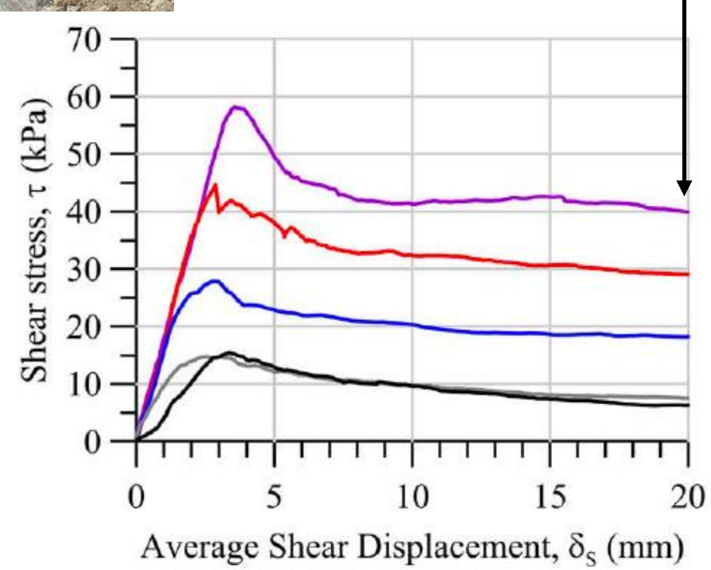
- Stress required to move the top block: ~ 27 kPa ($\Phi_m \sim 64^o$)

- How to make sense of this result: $\tau_p \gg \tau_m > \tau_r$?
  - Top joint aperture of ~20mm (~1% length)
  - Peak strength has already been mobilised
  - Validation of peak strength inconclusive…

- Block was stable:
  - Mobilised strength > Predicted Residual Strength
  - **Residual strength prediction makes sense!**



1% length

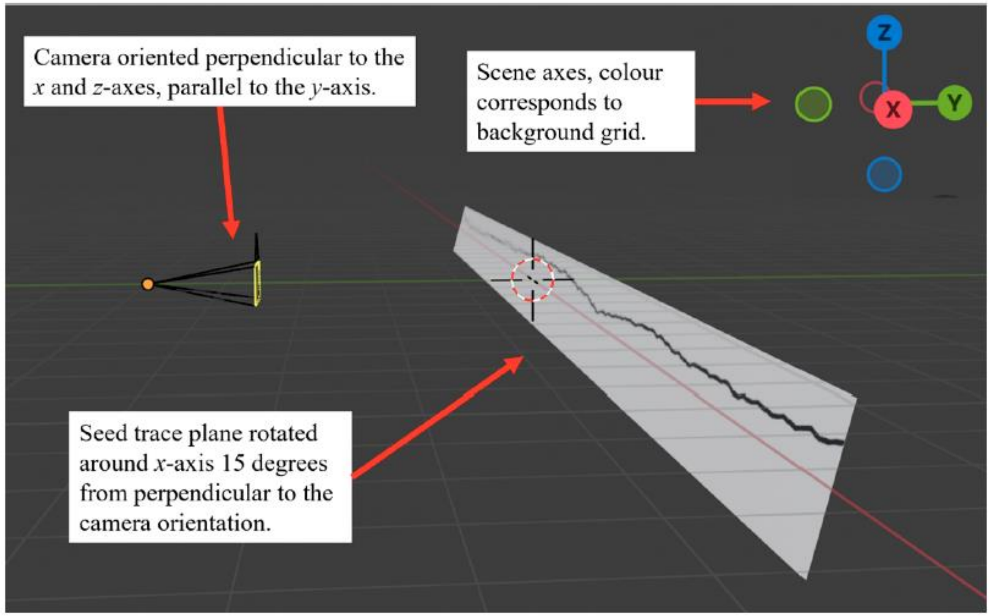


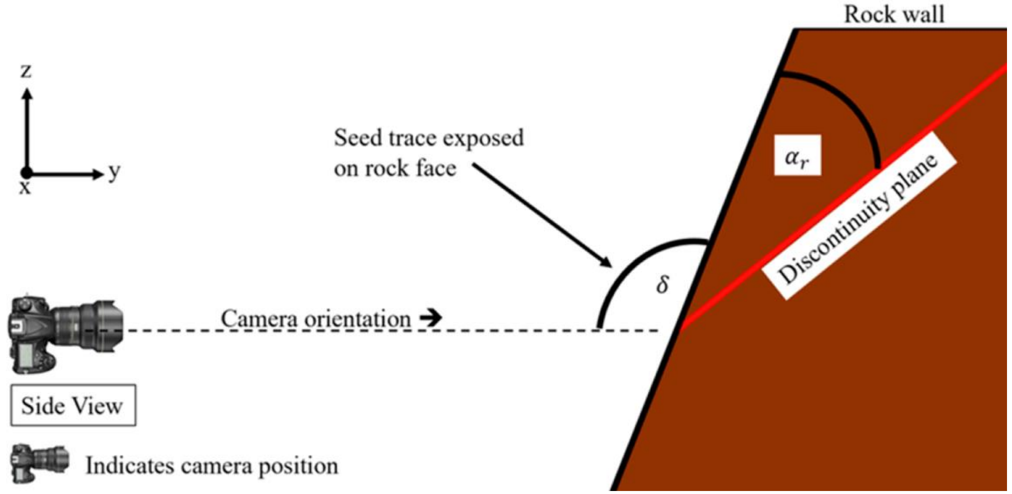
Practical considerations – errors associated with in situ survey

- Ideally, perfect photo is taken on site: high resolution, perpendicular to the rock face, planar rock face.
- Reality: resolution might be inadequate, camera may be slightly rotated.
- How does this affect shear strength prediction?

- We used Blender software and 3 rough profiles (sd_i of 0.31, 0.71, 1.12 m/m) to assess:
  - Effect of distance on roughness measurement (and error)
  - Effect of camera position on roughness measurement (and error)

- Objective is to correlate error on roughness and error on strength prediction





Butcher et al. (2025), Remote Sensing

Practical considerations – errors associated with in situ survey

Figure shows relative error on **residual** strength with relative error on roughness (smoothest surface)

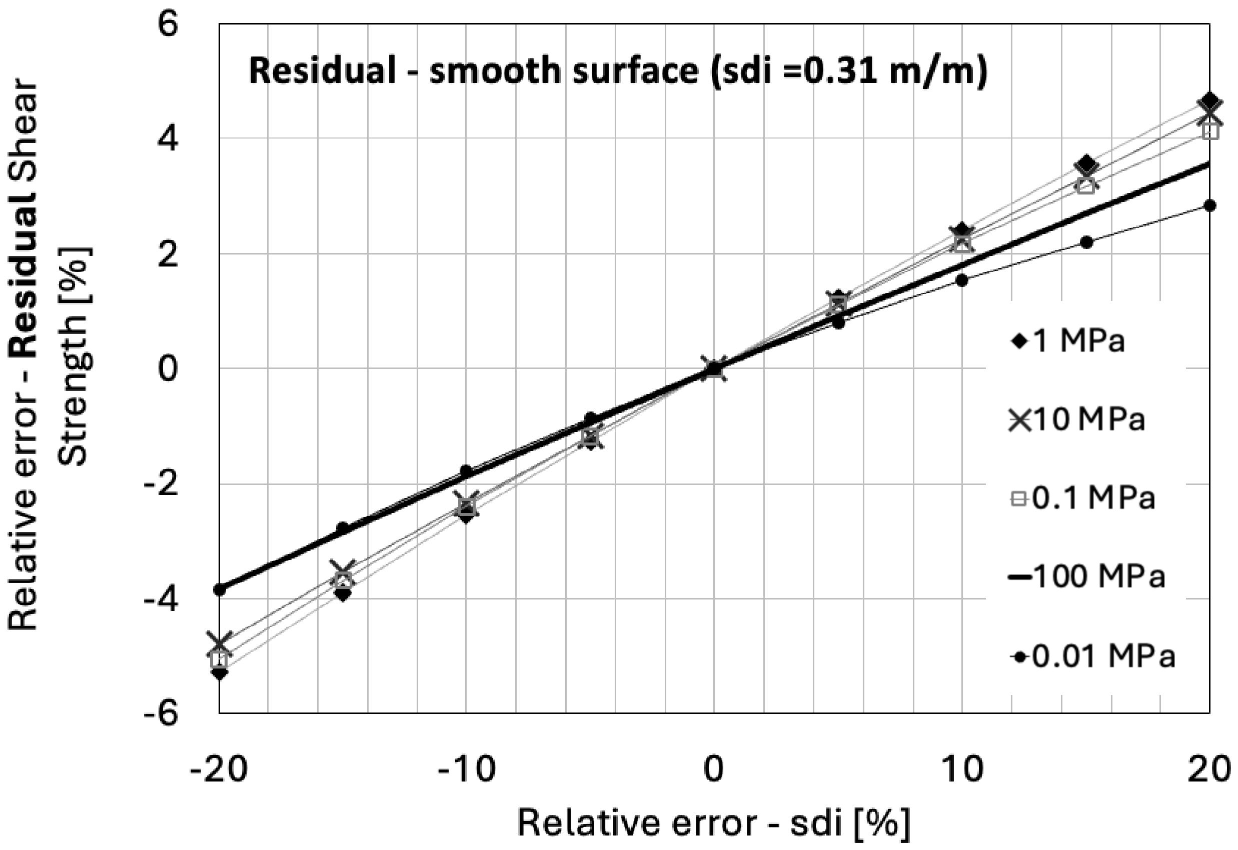
- The higher the error on roughness (sd_i), the higher the error on strength prediction
- 20% of error on sd_i generates less than 6% relative error on residual strength
- Not much effect of normal stress
- Not much effect of surface roughness

For **peak** strength, strong effect of normal stress and surface roughness:

- Normal stress ↘, error on strength ↗
- For the roughest surface => Max error ~ 300%

Recommendations to limit sd_i error to less than 20%:

- Resolution of 7 to 8 pixels/mm
- $\pm 15^o$ deviation from orthogonality (around vertical and horizontal axis)



Conclusions

- StADSS is a new approach to estimate shear strength (peak and residual) of large in situ rock discontinuities
- StADSS is based on rigorous statistics (RFM) and is mechanistic in nature (NDSS), not empirical.
- StADSS does not rely on ill-defined, single roughness descriptor but on statistical profile data
- StADSS inputs: high resolution photographs of traces + rock testing (cores, UCS, TX)
- Because roughness data is surveyed at project scale, StADSS bypasses (solves) the scale effect
- Very important because scale effect affects both peak and residual shear strength
- StADSS requires some complicated implementation, but we can run the simulations, happy to explore more validation cases.
- For more information you can visit the StADSS website: www.stadss.com.au or contact me.
- Future developments: water pressure effects, mismatching, rock bridges…

Acknowledgement of financial support

Thanks to PSM and Australian Research Council for their financial support