Development of a methodology to estimate peak shear strength of large-scale natural and unfilled rock joints

FRANCISCO RÍOS BAYONA

Background

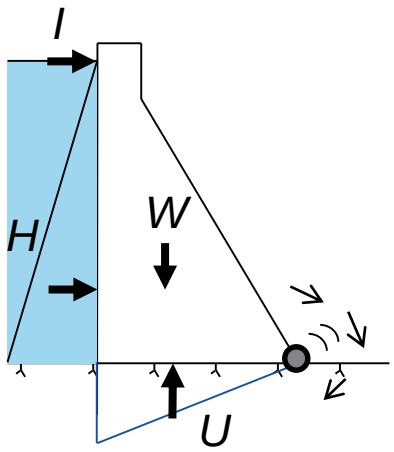
The determination of rock joint peak shear strength is a common problem in the stability analysis of dams.

Spillway at Krokströmmen arch dam (Photo: Fredrik Johansson).

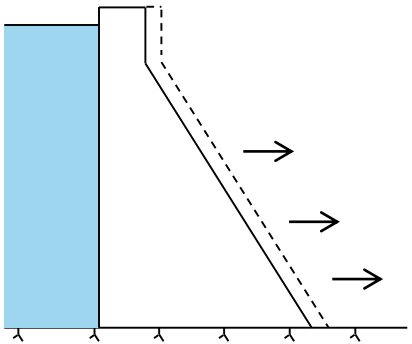
Spillway at Långbjörn concrete dam (Photo: Fredrik Johansson).

Background

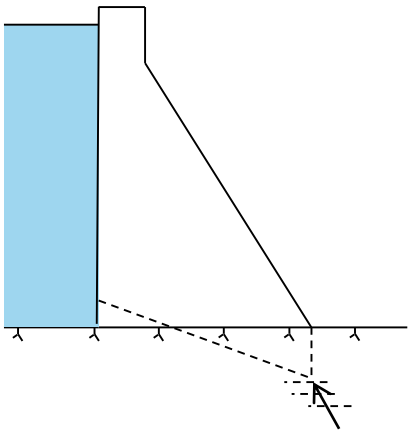
RIDAS – Stability analysis



- Overturning.



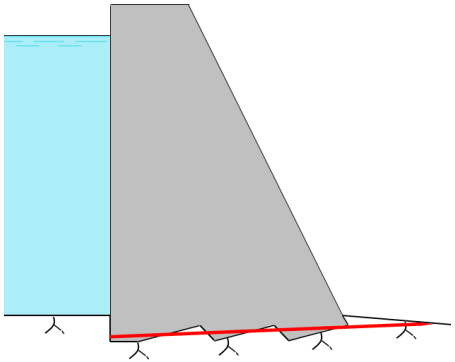
- Sliding.



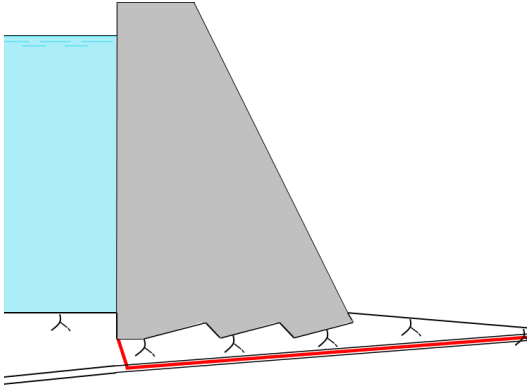
- Overstressing.

Background

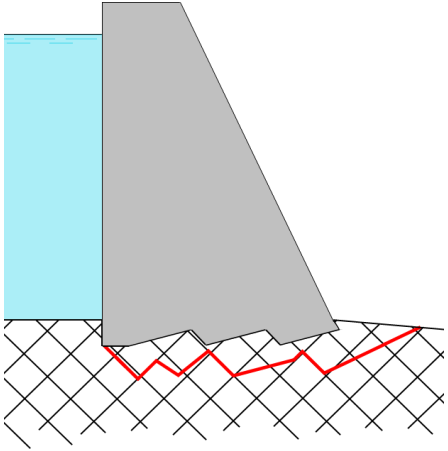
RIDAS – Sliding



- Concrete-rock interface.



- Along a rock joint below the dam foundation.



- In the rock mass.

➢ The weakest of these mechanisms determines where the failure occurs.

Background

RIDAS – Stability analysis for sliding failure in Sweden

- Sliding failure in the concrete-rock interface and along possible rock joints under the dam foundation is calculated with a friction coefficient, μ.

$$\mu = \frac{\sum R_{\mathrm{H}}}{\sum R_{\mathrm{V}}} \leq \mu_{\mathrm{target}} \begin{cases} \mu = \text{Calculated friction coefficient.} \\ R_{\mathrm{H}} = \text{Resultant of the forces parallel to the sliding plane.} \\ R_{\mathrm{V}} = \text{Resultant of the forces normal to the sliding plane.} \\ \mu_{\mathrm{target}} = \text{Allowed friction coefficient.} \end{cases}$$

- Recommended friction coefficients and safety factors according to RIDAS:

	Friction coeff.	Safety factor
Normal load case:	0.75	1.35
Exceptional load case:	0.90	1.10
Accidental load case:	0.95	1.05

Background

Guidelines in other counties

– In other countries such as USA, Canada and Norway the so-called Shear friction method is utilised and a total safety factor, SF, is calculated as

$$SF = \frac{c \cdot A + \sum R_{\mathrm{V}} \cdot \tan \emptyset}{\sum R_{\mathrm{H}}}$$

c = Cohesion

A = Total area

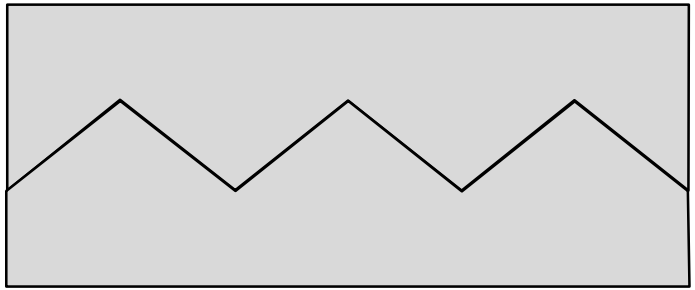
$\emptyset$ = Friction angle

- The calculations are relatively simple to perform.
- It is difficult to identify the potential failure mechanisms in the rock mass.
- Some parameters are difficult to estimate, due mainly to inherent large uncertainties (c, $\emptyset$).

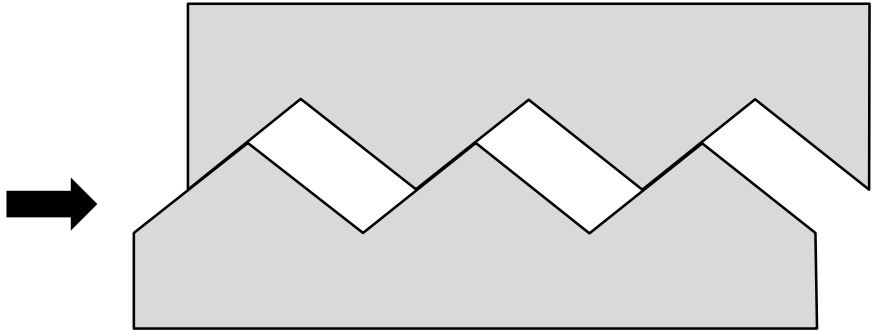
Background

Peak shear strength of rock joints is affected by different parameters:

- Normal stress
- Weathering, mineral coatings and infilling
- Roughness
- Scale
- Matedness



Perfectly mated rock joint.



Unmated rock joint.

Background

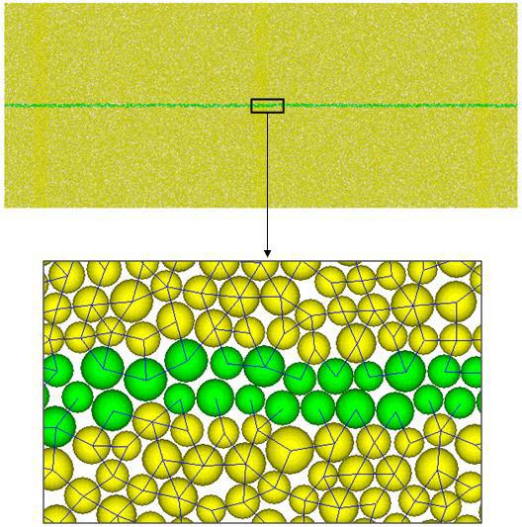
As a consequence, a number of empirical, analytical and semi-analytical shear strength criteria have been developed.

	Patton (1966)	Ladanyi & Archambault (1969)	Barton & Choubey (1977); Barton & Bandis (1982)	Zhao (1977) (After Barton & Choubey)	Grasselli & Egger (2003)	Johansson & Stille (2014)	Tang & Wong (2016)	Casagrande et al. (2018)
Roughness	(Yes)	(Yes)	Yes	Yes	Yes	Yes	Yes	Yes
Scale	No	No	Yes	Yes	No	Yes	No	Yes
Matedness	No	No	(Yes)	(Yes)	No	(Yes)	(Yes)	No

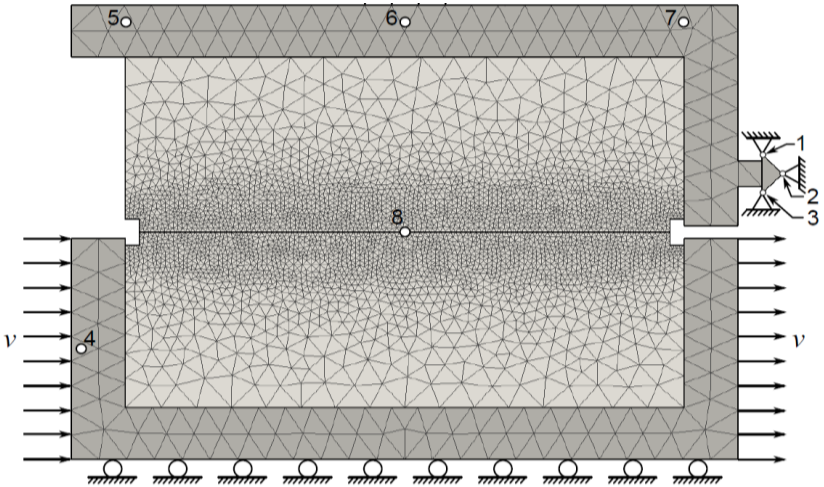
Background

Emergence of advanced software in recent years

- Discrete element method (DEM)
- Combined finite-element method (FDEM)



Numerical shear test in PFC^{2D} (Bahaaddini 2013).



Numerical shear test in Y-GEO (Tatone 2014).

Aim

Overall aim of this Research Project:

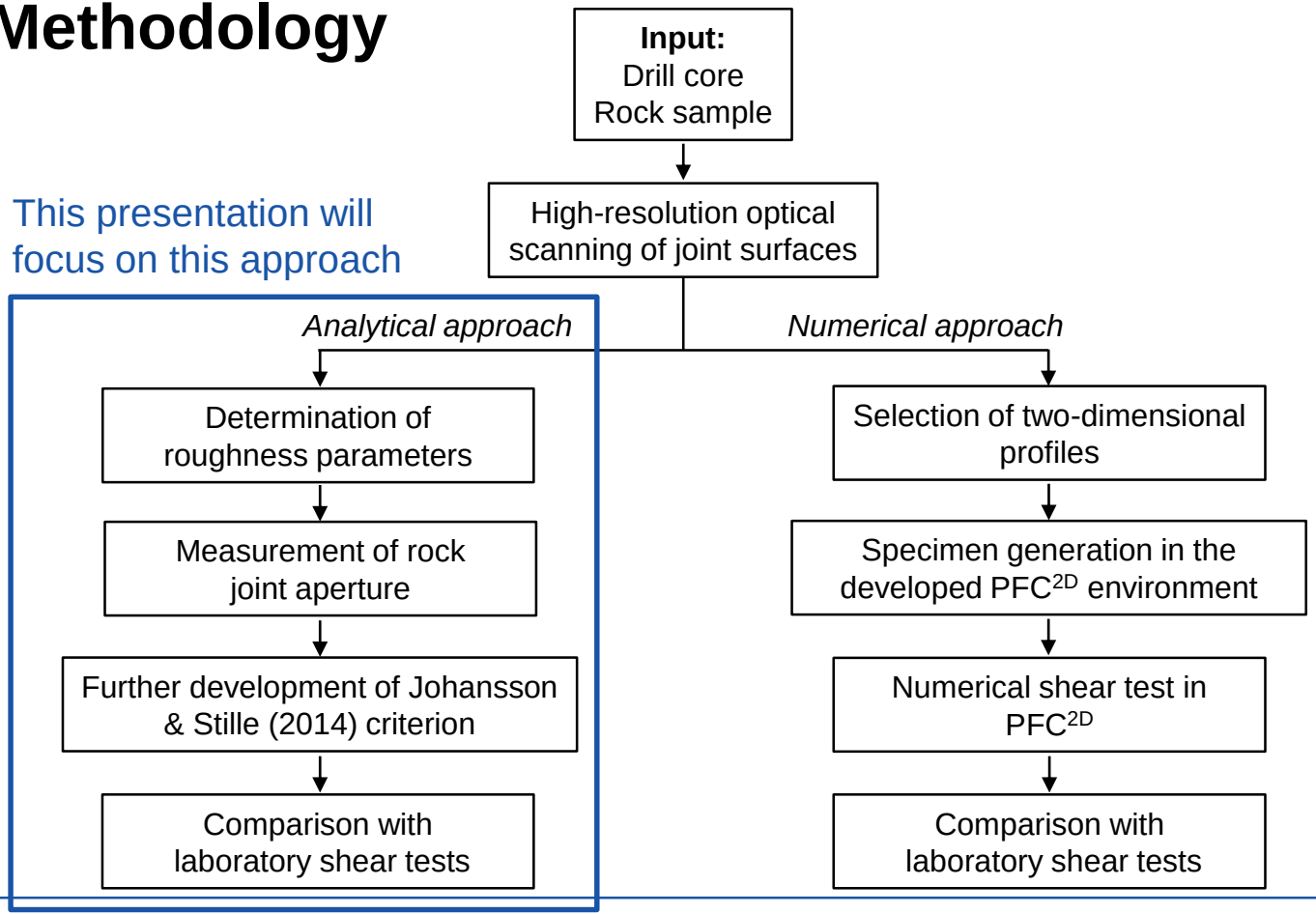
- To develop a methodology to estimate peak shear strength of natural and unfilled rock joints *in-situ* based on measurable parameters in the field.

This Licentiate Thesis:

- To investigate, develop and apply analytical and numerical techniques for estimation of peak shear strength of natural and unfilled rock joints.

Methodology

This presentation will focus on this approach



Use of aperture measurements in estimation of peak shear strength

Rock joint matedness plays an important role (e.g. natural rock joints).

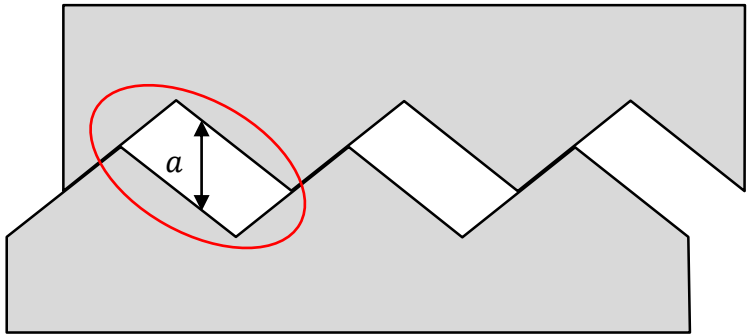
Difficult to estimate (e.g. Zhao 1997; Johansson & Stille 2014; Tang and Wong 2016)

- Visual inspections
- Initial shear displacement, u_{i}

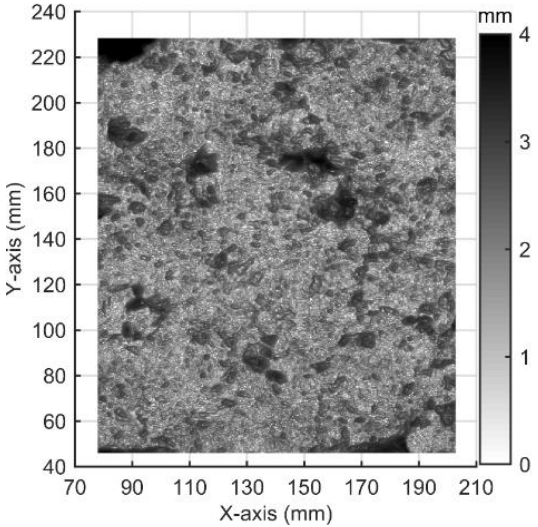
➢ No criterion exists that relates matedness with a measurable parameter in the field.

Aim

To develop a methodology to estimate peak shear strength based on measured average rock joint aperture, a, and roughness using high-resolution optical scanning.



Unmated rock joint.



Aperture measurements using information from high-resolution optical scanning.

Johansson & Stille (2014) criterion

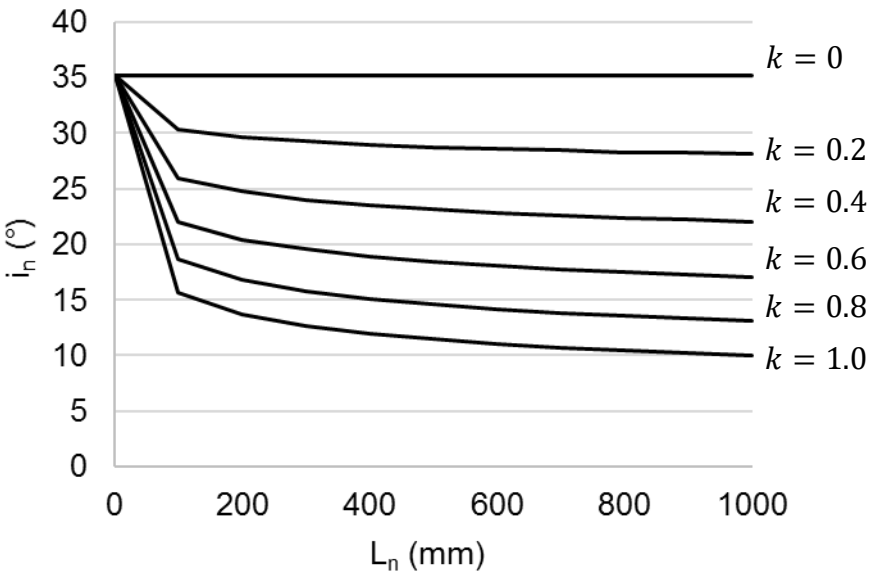
$$\emptyset_{\mathrm{p}} = \emptyset_{\mathrm{b}} + i_{\mathrm{n}}$$

in which

$$i_{\mathrm{n}} = arctan\left[\tan(i_{\mathrm{g}}) \cdot \left(\frac{L_{\mathrm{n}}}{L_{\mathrm{g}}}\right)^{kH-k}\right]$$

in which

$$i_{\mathrm{g}} = \theta^{*}_{\mathrm{max}}\left(1 - 10^{\left(\frac{\log\frac{\sigma_{\mathrm{n}}}{\sigma_{\mathrm{ci}}} - \log A_0}{C}\right)}\right)$$



Example of changes in the dilation angle at different degrees of matedness up to a scale of 1000 mm (Johansson 2009; Johansson & Stille 2014; Johansson 2016).

Johansson & Stille (2014) criterion

$$k = \frac{\log u - \log L_{\mathrm{asp,g}}/2}{\log L_{\mathrm{n}}/2 - \log L_{\mathrm{g}}/2}$$

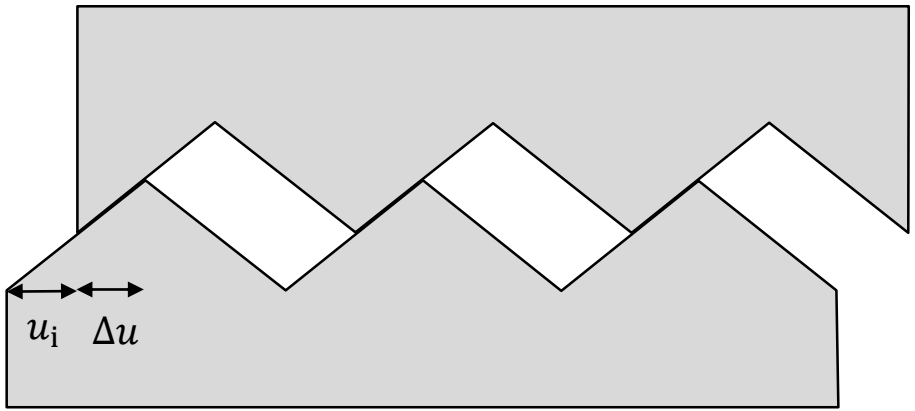
(From Johansson 2016)

$$u = u_{\mathrm{i}} + \Delta u \;\rightarrow u = 2 \cdot u_{\mathrm{i}}$$

u = total shear displacement at the peak

u_{i} = initial shear displacement prior the shear test

Δu = additional shear displacement to reach the peak

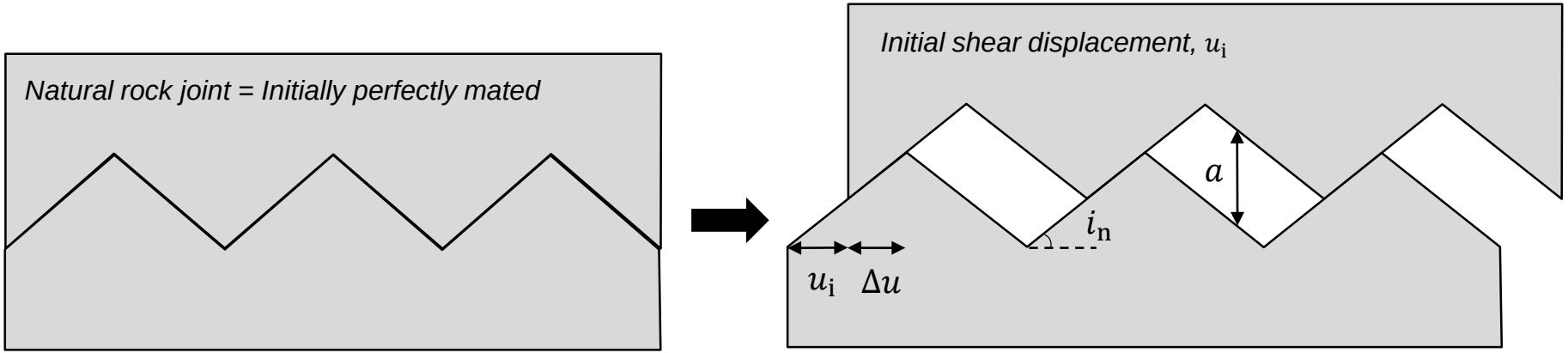


New approach

$$k = \frac{\log u - \log L_{\mathrm{asp,g}}/2}{\log L_{\mathrm{n}}/2 - \log L_{\mathrm{g}}/2}$$

$$u_{\mathrm{i}} = \frac{a}{\tan(i_{\mathrm{n}})}$$

$$u = u_{\mathrm{i}} + \Delta u \;\rightarrow u = 2 \cdot u_{\mathrm{i}} \rightarrow u = \frac{2\,a}{\tan(i_{\mathrm{n}})}$$

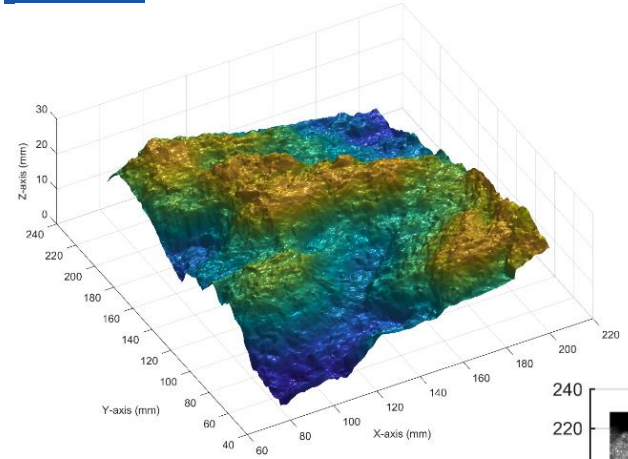


Methodology

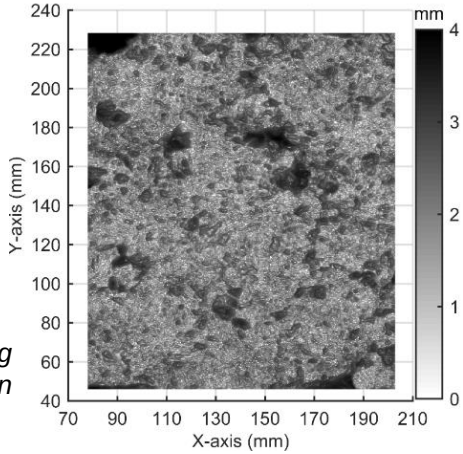
Overview of Storfinnforsen buttress dam (Photo: Uniper).

Picture taken during drilling through an existing rock joint adjacent to Storfinnforsen buttress dam (Photo: Carl-Oscar Nilsson).

Methodology



Digitised rock joint surface after high-resolution optical scanning.



Aperture measurements using information from high-resolution optical scanning.

Calculation of:

$$\theta^*_{\max}, A_0, C, \sigma_{\mathrm{ci}}, \sigma'_n \rightarrow \boldsymbol{i_g}$$

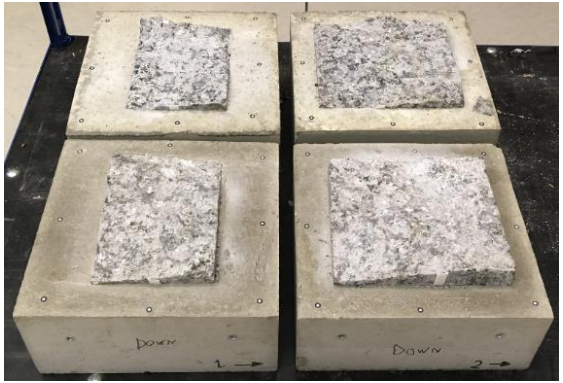
$$a \rightarrow \boldsymbol{k}$$

$$k,\ i_{\mathrm{g}}, L_{\mathrm{g}}, L_{\mathrm{n}}, H \rightarrow \boldsymbol{i_n}$$

$$\emptyset_{\mathbf{p}} = \emptyset_{\mathrm{b}} + i_{\mathrm{n}}$$

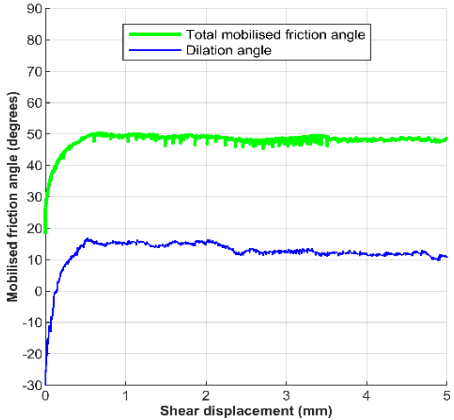
Methodology

8 laboratory shear tests
CNL with 1 Mpa



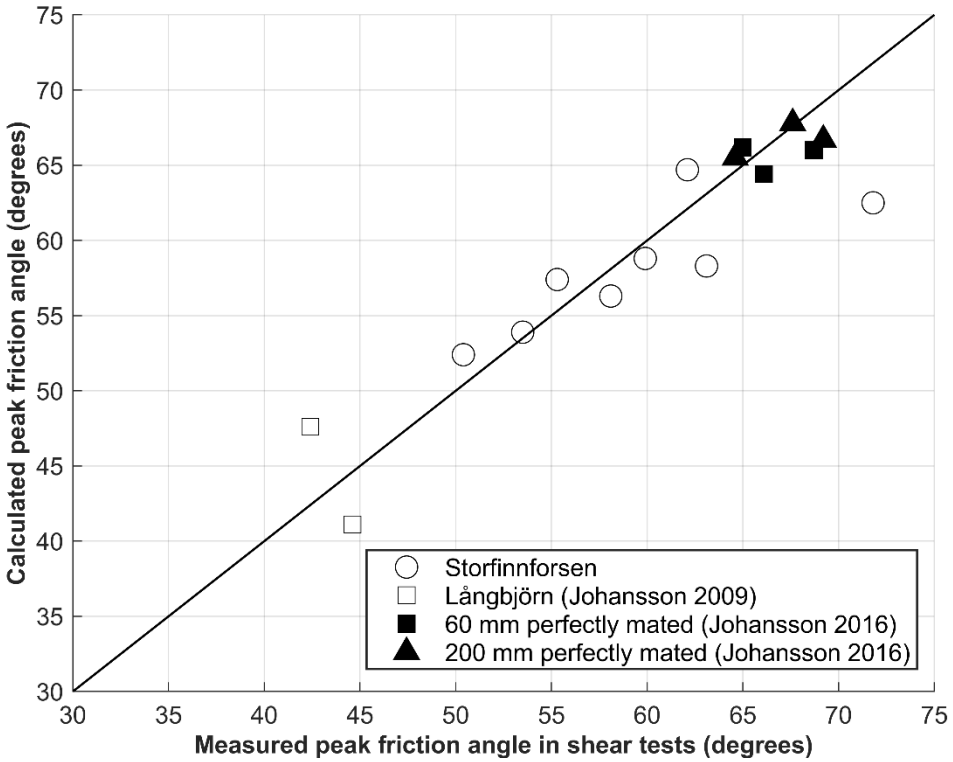
Picture of two analysed rock joint samples casted in concrete moulds (Photo: Francisco Ríos Bayona).

Picture of the utilised shear test machine at LTU, Luleå (Photo: Thomas Forsberg).

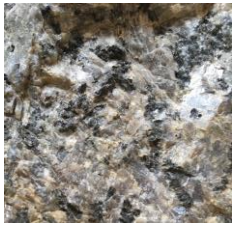


Registered data during of one of the conducted shear tests.

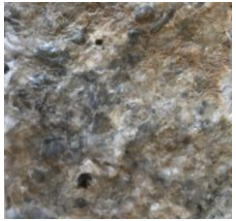
Results



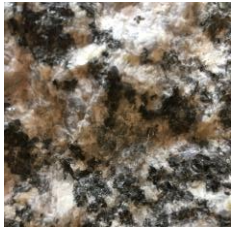
Comparison between calculated and measured peak friction angle in the laboratory.



Storfinnforsen.



Långbjörn.



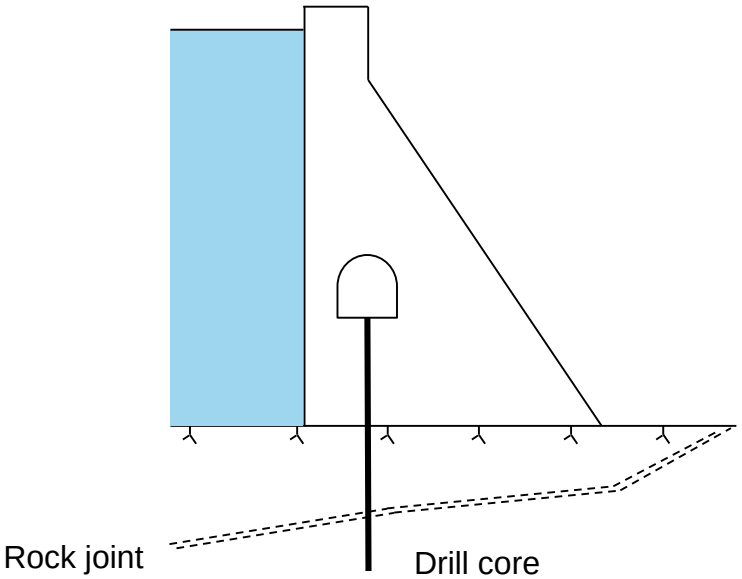
Perfectly mated.

Conclusions

- The results show a good agreement with the laboratory shear tests.
- Aperture measurements, a, can be used to estimate the matedness coefficient, k.
- Additional investigations are required for higher normal stresses (> 1 MPa) and the applicability of this approach in the field.
  - Extent of field investigations required to realistically account for the inherent uncertainties in the different parameters.

How could this approach be used in the field?

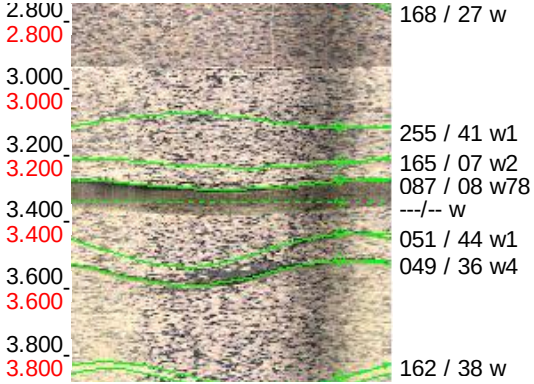
- A possible solution could be to perform drill cores to investigate rock joints under the dam foundation.



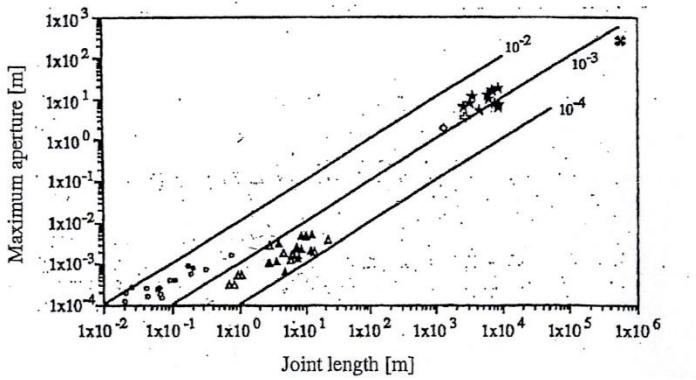
How could this approach be used in the field?

- BIPS-logging may be used to determine rock joint aperture.

- Some studies show that there exists a relationship between measured aperture and length of a rock joint.



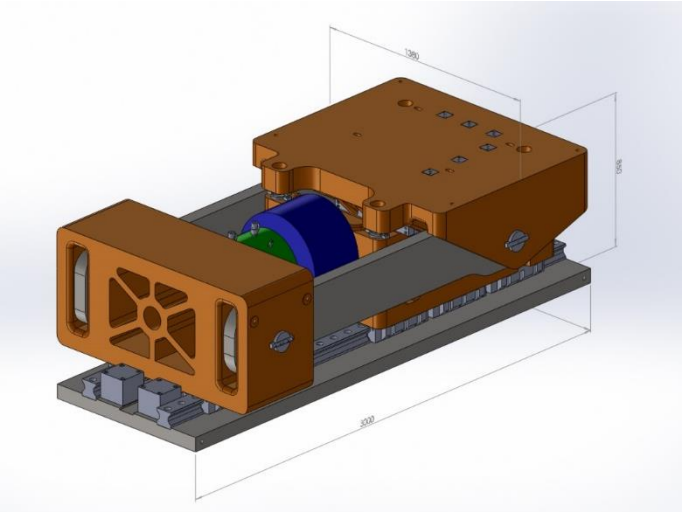
Example of a filmed drill core with an aperture of 78 mm.



Relationship between rock joint length and aperture (Vermilye & Scholz 1995).

How many field tests are required?

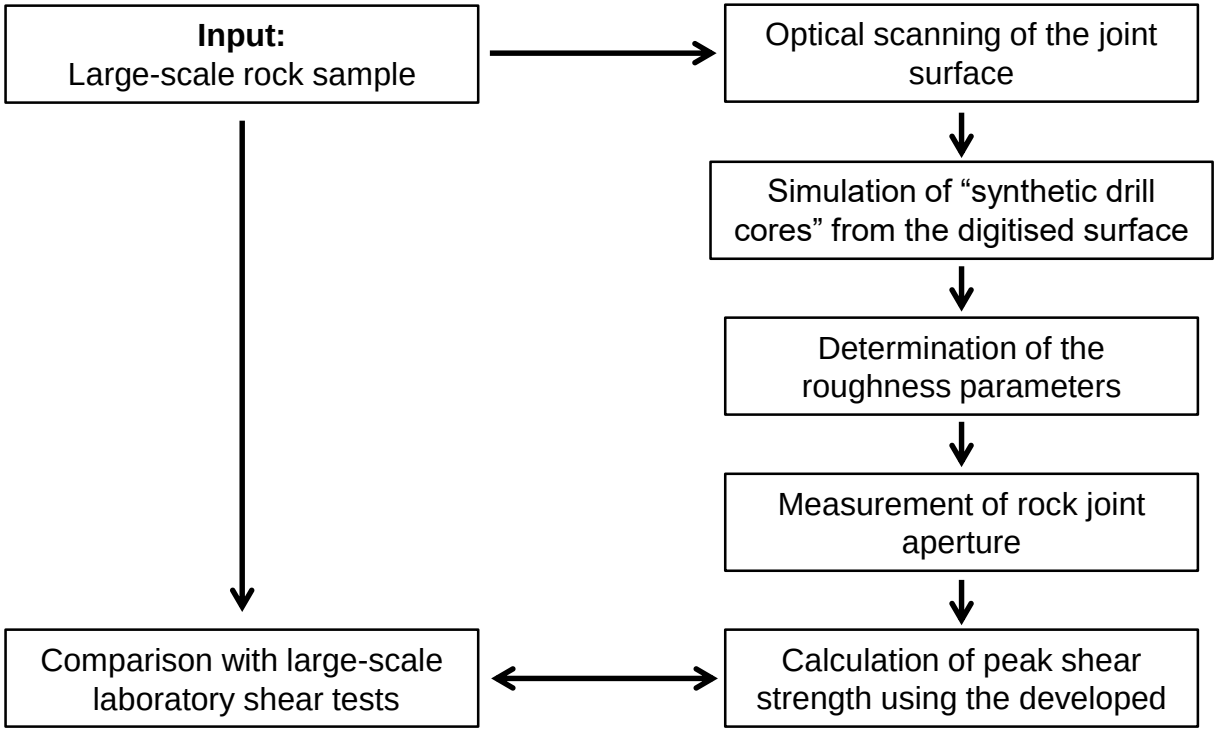
- Validate the proposed approach with the large-scale shear tests (SKB and RISE).



3D-model of the large-scale shear test machine currently being built at RISE in Borås (Jörgen Larsson).

Picture of a large-scale rock joint sample to be sheared in the new shear test machine (Photo: Francisco Ríos Bayona).

How many field tests are required?



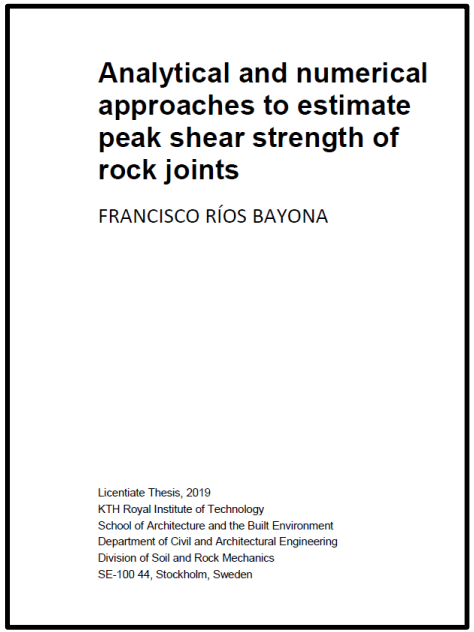
Acknowledgements

- Carl-Oskar Nilsson at Uniper for funding and providing with the analysed rock joint samples from Storfinnforsen.
- LTU for conducting the shear tests.
- Kenneth Strand at RISE for performing the high-resolution optical scanning.
- SVC and SKB for funding this research project.

Do you want to know more about this research?

- Ríos Bayona, F. (2019). Analytical and numerical approaches to estimate peak shear strength of rock joints (Licentiate Thesis). Stockholm. Available in DiVA.

- Email: frrb@kth.se


Analytical and numerical approaches to estimate peak shear strength of rock joints

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