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.
Background

RIDAS – Stability analysis

- Overturning.
- Sliding.
- Overstressing.
Background

RIDAS – Sliding

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

• Concrete-rock interface.

• Along a rock joint below the dam foundation.

• In the rock mass.
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, $\mu$.

$$\mu = \frac{\sum R_H}{\sum R_V} \leq \mu_{\text{target}}$$

$\mu = \text{Calculated friction coefficient.}$

$R_H = \text{Resultant of the forces parallel to the sliding plane.}$

$R_V = \text{Resultant of the forces normal to the sliding plane.}$

$\mu_{\text{target}} = \text{Allowed friction coefficient.}$

– Recommended friction coefficients and safety factors according to RIDAS:

<table>
<thead>
<tr>
<th></th>
<th>Friction coeff.</th>
<th>Safety factor</th>
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<tbody>
<tr>
<td>Normal load case:</td>
<td>0.75</td>
<td>1.35</td>
</tr>
<tr>
<td>Exceptional load case:</td>
<td>0.90</td>
<td>1.10</td>
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<tr>
<td>Accidental load case:</td>
<td>0.95</td>
<td>1.05</td>
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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

$$SF = \frac{c \cdot A + \sum R_v \cdot \tan \phi}{\sum R_h}$$

- $c$ = Cohesion
- $A$ = Total area
- $\phi$ = 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 ($c$, $\phi$).
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.

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<td>(Yes)</td>
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<td>Yes</td>
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<tr>
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<tr>
<td>Matedness</td>
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<td>No</td>
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<td>No</td>
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</table>
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).

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.
This presentation will focus on this approach

**Methodology**

**Input:**
- Drill core
- Rock sample

- High-resolution optical scanning of joint surfaces

**Analytical approach**
- Determination of roughness parameters
- Measurement of rock joint aperture
- Further development of Johansson & Stille (2014) criterion
- Comparison with laboratory shear tests

**Numerical approach**
- Selection of two-dimensional profiles
- Specimen generation in the developed PFC\textsuperscript{2D} environment
- Numerical shear test in PFC\textsuperscript{2D}
- Comparison with laboratory shear tests
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.
Johansson & Stille (2014) criterion

\[ \phi_p = \phi_b + i_n \]

**in which**

\[ i_n = \arctan \left[ \tan(i_g) \cdot \left( \frac{L_n}{L_g} \right)^{kH-k} \right] \]

**in which**

\[ i_g = \theta_{\text{max}}^* \left( 1 - 10 \left( \frac{\log \sigma_{\text{cl}} - \log A_0}{c} \right) \right) \]

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

\[ k = \frac{\log u - \log L_{asp,g}/2}{\log L_n/2 - \log L_g/2} \]

\[ u = u_i + \Delta u \rightarrow u = 2 \cdot u_i \]

(From Johansson 2016)

- \( u \) = total shear displacement at the peak
- \( u_i \) = initial shear displacement prior the shear test
- \( \Delta u \) = additional shear displacement to reach the peak

\( u_i \) = initial shear displacement prior the shear test

\( \Delta u \) = additional shear displacement to reach the peak
New approach

\[ k = \frac{\log u - \log L_{\text{asp,g}}/2}{\log L_n/2 - \log L_g/2} \]

\[ u_i = \frac{a}{\tan(i_n)} \]

\[ u = u_i + \Delta u \rightarrow u = 2 \cdot u_i \rightarrow u = \frac{2a}{\tan(i_n)} \]

Natural rock joint = Initially perfectly mated

Initial shear displacement, \( u_i \)
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

Calculation of:

\[ \theta_{\text{max}}, A_0, C, \sigma_{\text{ci}}, \sigma'_{\text{n}} \rightarrow i_g \]

\[ a \rightarrow k \]

\[ k, i_g, L_g, L_n, H \rightarrow i_n \]

\[ \phi_p = \phi_b + i_n \]
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.
Comparison between calculated and measured peak friction angle in the laboratory.
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?

Input:
Large-scale rock sample

→ Optical scanning of the joint surface

→ Simulation of “synthetic drill cores” from the digitised surface

→ Determination of the roughness parameters

→ Measurement of rock joint aperture

→ Calculation of peak shear strength using the developed

Comparison with large-scale laboratory shear tests
Acknowledgements

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➢ LTU for conducting the shear tests.

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Do you want to know more about this research?


➢ Email: frrb@kth.se