A possible way forward to predict the peak shear strength of a natural, unfilled rock joint under concrete dams based on field data

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ABSTRACT: The prediction of a rock joint's peak shear strength becomes complex when its joint surfaces are not fully accessible, such as the rock foundation under an existing concrete dam. This paper presents a case study with the application of a newly developed methodology that uses objective observations of the 3D roughness and joint aperture from drill cores to predict the peak shear strength of large natural, unfilled rock joints. Eight rock joint samples obtained after core-drilling an existing rock joint adjacent to the foundation of Storfinnforsen dam in Sweden were used. The main benefit of this approach is that it enables the prediction of both the mean value and the statistical uncertainty of the peak shear strength under conditions of difficult access. This information may be of importance in order to assess the safety in the foundation of an existing concrete dam.

Keywords: Rock joints, peak shear strength, concrete dams, field observations, drill cores.

1 INTRODUCTION

The hydropower industry in Sweden is responsible for approximately 45% of the total energy production in the country. The fact that many of these dams have been in service for over 50 years may raise concern regarding their structural safety, due mainly to adaptation to new regulations and the impact of climate changes (Krounis 2016). In recent years, the safety evaluation of various existing concrete dams have presented some difficulties due to uncertainties associated to the assessment of the shear strength of horizontal or sub-horizontal rock joints present in their rock foundations (Johansson 2009).

The mechanical behavior of rock joints is complex and is affected by a number of different parameters that are difficult to estimate in the field (Ríos Bayona 2022). Various attempts have been made in recent decades to develop both empirical and analytical criteria to increase the understanding of how the roughness, matedness, and surface area of a rock joint interact and contribute to its peak shear strength (e.g., Barton & Choubey 1977; Barton & Bandis 1982; Johansson & Stille 2014; Johansson 2016; Casagrande et al. 2018). However, the majority of the proposed criteria fail to account for the complete interaction of the aforementioned parameters (Ríos Bayona 2022). Additionally, the application of available techniques to predict the peak shear strength in the field becomes complex when the rock joint surfaces are not fully accessible, such as the rock foundation under an existing concrete dam. In these cases, to reduce the uncertainties in the prediction of the peak shear strength, it requires that a representative number of observations of both 3D roughness and aperture characteristics are performed.

More recently, Ríos-Bayona et al. (2022) studied the possibility of predicting the peak shear strength of large-size rock joints based on information from joint surface roughness and aperture obtained from various small-size samples, such as drill cores. Their methodology is based on the hypothesis that drill cores contain all necessary information to predict the peak shear strength of large natural, unfilled rock joints in the field.

This paper presents a case study with the application of the methodology developed in Ríos-Bayona et al. (2022) to predict the peak shear strength of a large natural, unfilled rock joints. Eight rock joint samples obtained after core-drilling an existing rock joint adjacent to the foundation of Storfinnforsen dam in Sweden have been used. The prediction of the peak shear strength is based on observations of 3D roughness and surface aperture made from simulated drill cores on the digitised joint surfaces of the analysed samples.

2 METHODOLOGY

The methodology applied in this paper to predict the peak shear strength of a large natural, unfilled rock joint is based on the study by Ríos-Bayona et al. (2022). Ríos-Bayona and colleagues studied the possibility to predict the peak shear strength of two rock joint samples with a surface area of approximately 500 x 300 mm based on observations of the 3D roughness and aperture made at a smaller size. The aim of these small-size observations was to simulate core-drilling on the joint surfaces of the analysed large-size samples. The simulated drill cores on the tested samples had dimensions of 60 x 60 mm, and they were based on a subdivision of their digitised joint surfaces

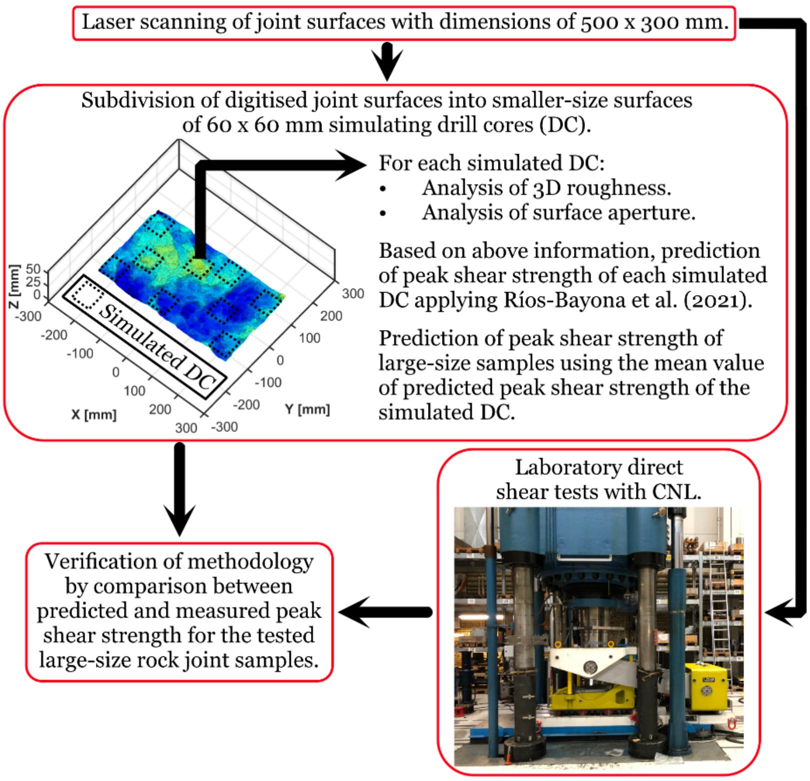

Figure 1. Flow chart with the main steps followed to investigate the use of drill cores to predict the peak shear strength of large-size rock joints (modified after Ríos-Bayona et al. 2022, CC BY 4.0, https://creativecommons.org/licenses/by/4.0/).

obtained through high-resolution laser scanning. Furthermore, each simulated drill core was considered as an independent component of a parallel system. The peak shear strength of each simulated drill core, based on measured 3D roughness and aperture, was predicted by applying the peak shear strength criterion by Ríos-Bayona et al. (2021). The peak shear strength of the tested large-size samples was predicted based on the mean value of the predicted peak shear strength of the simulated drill cores. The applied methodology was verified by comparison between predicted peak shear strength using the simulated drill cores, and measured peak shear strength in the laboratory direct shear tests. The main steps of the methodology developed by Ríos-Bayona et al. (2022) are illustrated in Figure 1.

3 THEORY

3.1 Peak shear strength criterion

The peak shear strength criterion by Ríos-Bayona et al. (2021) is a revised version of the criterion originally developed by Johansson and Stille (2014), further validated by Johansson (2016). The criterion is based on the adhesion theory of friction and assumes that sliding is the governing failure mode along the active asperities in contact. Furthermore, the criterion assumes that surface roughness can be described with self-affine fractal theory as a superposition of different asperities at different scales (Mandelbrot 1985). The criterion accounts also for the variation of the number and size of the active asperities in contact during the shearing process due to scale and matedness. The criterion can be expressed as

$$\phi_\mathrm{p} = \phi_\mathrm{b} + i_\mathrm{n}, \tag{1}$$

in which

$$i_\mathrm{n} = \operatorname{atan}\left[\tan(i_\mathrm{g})\left(\frac{L_\mathrm{n}}{L_\mathrm{g}}\right)^{k(H-1)}\right], \tag{2}$$

and

$$i_\mathrm{g} = \theta^*_\mathrm{max} - 10^{\left(\frac{\log_{10}\frac{\sigma_\mathrm{n}}{\sigma_\mathrm{ci}} - \log_{10} A_0}{C}\right)}\theta^*_\mathrm{max}, \tag{3}$$

where ϕ_p and ϕ_b are the peak and basic friction angles, respectively. i_n and i_g are the dilation angle at sample and grain scales, respectively. σ_n is the applied normal stress, σ_ci is the uniaxial compressive strength of the intact rock. A_0 and C are the maximum possible contact area ratio and a roughness parameter, respectively, and θ^*_max is the maximum apparent dip angle in the shearing direction. L_n is the length of the sample, L_g is the scale of the asperities associated with grain size, H is the Hurst exponent, and k is the matedness constant.

The equation for k is given by

$$k = \frac{\log_{10}\frac{2a_{50}}{\tan(i_\mathrm{n})} - \log_{10}L_\mathrm{asp,g}/2}{\log_{10}L_\mathrm{n}/2 - \log_{10}L_\mathrm{g}/2}, \tag{4}$$

where a_{50} is the measured median aperture between the rock joint surfaces at the beginning of the shearing process, and $L_\mathrm{asp,g}$ is the average length of the asperities in contact at grain size.

The parameter k directly associates a_{50} with both L_n and i_n. This theoretical association is based on the principles of self-affine fractal theory and that sliding is the predominant failure mode along the active asperities (Johansson & Stille 2014; Johansson 2016; Ríos-Bayona et al. 2021).

3.2 *Prediction of peak shear strength based on drill cores*

In the criterion by Ríos-Bayona et al. (2021), the peak shear strength is regarded as the result of a mean value-driven process to which each asperity in contact during the shearing process contributes. The criterion assumes that it is the size, number, and inclination of the active asperities in contact that determines the peak shear strength, rather than the total size of the tested samples. This can be seen from eqs. (2) and (4). This means that, under the same applied σ_{n} magnitude, the predicted value of ϕ_{p} with the criterion for rock joint samples of different sizes remains constant, given that their measured values of both surface roughness (i.e., A_0, θ^*_{max}, C, and H) and surface aperture (i.e., a_{50}) are the same. This theoretical assumption is connected to the possibility of describing surface roughness using self-affine fractal theory, which means that the roughness can be considered as a superposition of different asperities at multiple scales (Mandelbrot 1985).

Based on this interaction between surface roughness and aperture, Ríos-Bayona et al. (2022) assumed that $\tau_{\mathrm{p,L}} = \tau_{\mathrm{p,S}}$, where $\tau_{\mathrm{p,L}}$ and $\tau_{\mathrm{p,S}}$ are the peak shear stresses at large and small sizes, respectively. In addition, the total peak shear force of a large sample ($T_{\mathrm{p,L}}$) can be regarded as the sum of the peak shear forces of smaller samples, such as drill cores, given that they cover the entire joint surface area of the large sample. This can be expressed as $T_{\mathrm{p,L}} = \sum_{i=1}^{n} T_{\mathrm{p,S}_i}$, where n is the total number of drill cores over the complete surface, and $T_{\mathrm{p,S}_i}$ is the peak shear force from each individual drill core. By extension, $T_{\mathrm{p,L}} = \sum_{i=1}^{n} \tau_{\mathrm{p,S}_i} \cdot A_{\mathrm{p,S}_i}$. Furthermore, the peak shear strength can be regarded as a mean value-driven process, where each individual subarea can be seen as an independent component in a parallel system. Based on this assumption, $T_{\mathrm{p,L}}$ can be calculated as the product of the mean value of the predicted peak shear stress ($\mu_{\tau_{\mathrm{p,S}}}$) of the drill cores and the total area of the large sample (i.e., $T_{\mathrm{p,L}} = \mu_{\tau_{\mathrm{p,S}}} \cdot A$).

4 ROCK JOINT SAMPLES FROM STORFINNFORSEN

The methodology developed by Ríos-Bayona et al. (2022) was applied to eight rock joint samples obtained by over-drilling through an existing rock joint adjacent to the foundation of the Storfinnforsen dam. These rock joint samples consisted of grey coarse-grained granite and were scanned and tested in the laboratory under constant normal load conditions by Ríos-Bayona et al. (2021). The applied value of σ_{n} during the conducted direct shear tests was 1 MPa. The values of ϕ_{b} and σ_{ci} were estimated to be 31° and 110 MPa (Ríos-Bayona et al. 2021). The eight rock joint samples had a rectangular shape with dimensions that varied between approximately 130 mm to 210 mm. The measured values of 3D roughness and aperture derived from the performed high-resolution laser scanning on the joints' surfaces are available in Ríos-Bayona et al. (2021). The ϕ_{p} values of these eight samples measured in the direct shear tests varied between 50.5° and 71.8° with a mean value (μ) and standard deviation (σ) of 59.3° and 6.6°, respectively. The predicted ϕ_{p} values with the criterion by Ríos-Bayona et al. (2021) varied between 52.4° and 64.7° with values of μ and σ of 58° and 4.1°, respectively (Ríos-Bayona et al. 2021).

4.1 *Subdivision into smaller-size surfaces based on the scanning measurements*

As in the methodology by Ríos-Bayona et al. (2022), the digitised joint surfaces of the eight samples were subdivided into 60 smaller surfaces with dimensions of approximately 60 x 60 mm. Each of the surfaces at small size was considered as a simulated drill core obtained after borehole drilling. The ϕ_{p} value was predicted for each simulated drill core using the criterion by Ríos-Bayona et al. (2021) in eqs. (1) to (4), based on the observed 3D roughness and aperture. The ϕ_{p} value of the large natural, unfilled rock joint that contained the rock samples was calculated with the μ of the ϕ_{p} values of the simulated drill cores.

5 RESULTS

The information of 3D surface roughness and aperture captured in each of the 60 drill cores simulated on the eight samples from Storfinnforsen was used to predict their respective ϕ_p, based on the theoretical approach developed by Ríos-Bayona et al. (2022). The ϕ_p values predicted with the criterion by Ríos-Bayona et al. (2021) for the 60 simulated drill cores on the eight samples varied between 47.5° and 75.2° with values of μ and σ of 57.4° and 6.3°, respectively. The results are presented in Figure 2a. The μ value using the 60 simulated drill cores (57.4°) is in good agreement with the both values of measured ϕ_p in the laboratory (59.3°) and predicted ϕ_p (58°) with the criterion by Ríos-Bayona et al. (2021) using the eight samples.

The statistical uncertainty due to the number of simulated drill cores used to predict the ϕ_p of the large natural, unfilled rock joint from Storfinnforsen has been analysed using a Monte Carlo simulation. In this step, the ϕ_p value was predicted by randomly selecting 3, 8, and 20 simulated drill cores on the digitised surfaces of the eight rock joint samples, respectively. For each case, a total of 10,000 simulations were performed. The respective predicted ϕ_p in each simulation was calculated as the μ of the predicted ϕ_p of the randomly selected drill cores. The histograms of 10,000 Monte Carlo simulations are presented in Figure 2b, c and d. The results show that the ϕ_p in the Monte Carlo simulations using 3, 8, and 20 simulated drill cores have a similar μ as the one obtained using the 60 simulated drill cores (see Figure 2). However, the standard deviation of the mean values of predicted ϕ_p (σ_μ) decreases with increasing number of simulated drill cores. For instance, the σ_μ value obtained with 20 simulated drill cores is approximately 2.5° lower than the one obtained using 3 simulated drill cores.

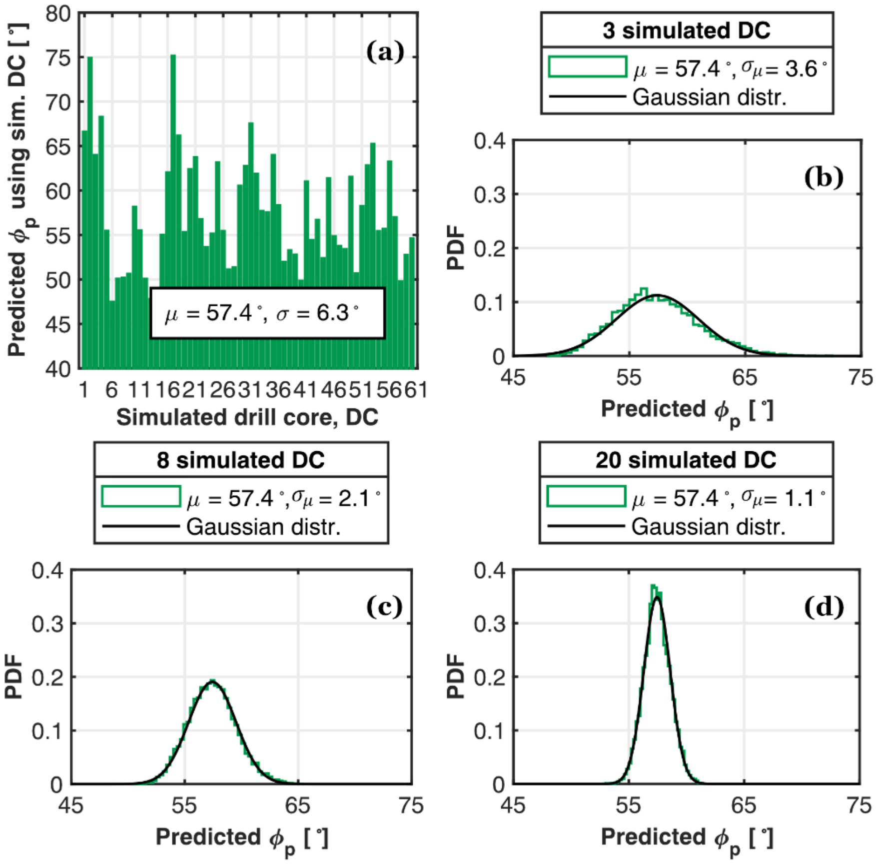

Figure 2. **a** Predicted ϕ_p values for the 60 simulated drill cores on the eight samples from Storfinnforsen. Histograms of 10,000 Monte Carlo simulations with predicted ϕ_p: **b** using 3 simulated drill cores; **c** using 8 simulated drill cores; **d** using 20 simulated drill cores. The continuous lines in each plot correspond to a Gaussian distribution with μ and σ_μ of the data set.

6 CONCLUDING REMARKS

This paper presents the application of a newly developed methodology in Ríos-Bayona et al. (2022) to predict the peak shear strength of large natural, unfilled rock joints. The peak shear strength of a large natural, unfilled rock joint adjacent to the foundation of the Storfinnforsen dam was predicted based on drill cores simulated on the digitised surfaces of eight samples. Based on the obtained results in Figure 2, it can be concluded that the methodology by Ríos-Bayona et al. (2022) can be of help to reduce the statistical uncertainty when predicting the peak shear strength of a natural, unfilled rock joint in the foundation of a concrete dam. The results of Mote Carlo simulation show that the statistical uncertainty decreased with increasing number of drill cores. However, the total uncertainty in the field assessment of the peak shear strength in the field may be influenced by other components, in addition to the σ_μ values presented in Figure 2. These sources of uncertainty associated with the prediction of the peak shear strength in the field are of significant importance when performing an engineering design applying a reliability-based methodology. Furthermore, the study by Ríos-Bayona et al. (2022) suggests that aperture measurements should be directly surveyed in the borehole at the actual level of applied σ_{n} to better predict the interaction between the active asperities in contact with the criterion by Ríos-Bayona et al. (2021).

The results of peak shear strength presented in this case study have not been verified in the laboratory with an actual large-size rock joint sample. Further efforts need to be focused on the field applicability of the suggested methodology in Ríos-Bayona et al. (2022) to predict the peak shear strength of large natural rock joints in the foundation under an existing concrete dam.

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