Capturing the roughness of discontinuity traces in the field with high accuracy: the effect of photograph resolution

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ABSTRACT: The recently developed stochastic approach to discontinuity shear strength (StADSS) avoids scale effects by predicting peak and residual shear strength using full scale discontinuity data. StADSS has been applied to mortar replicas of perfectly matched specimens in the laboratory, but application to large in situ discontinuities is yet to be undertaken. Paramount to the in-situ application of StADSS is the adequate collection of discontinuity roughness information. This paper presents an approach to digitize the seed trace of in-situ discontinuities. Several identical images of a seed trace with varying pixel densities were analyzed to determine what pixel to millimeter ratio was sufficient to enable a Gaussian distribution of gradients to develop. It was found that a pixel density of 6-7 pixels per millimeter of seed trace length was sufficient to develop the parameters of a suitable Gaussian distribution of gradients, which could then be used for further statistical analysis.

Keywords: Discontinuity, Roughness, Scale Effect, Shear Strength.

1 INTRODUCTION

The stochastic approach to discontinuity shear strength (StADSS) assumes that the profile of a discontinuity exposed on a rock face (referred to as the "seed trace") is representative of the roughness contained with the rock mass. This new stochastic approach bypasses the scale effect that plagues shear strength predictions (both peak and residual) by using full scale discontinuity roughness data and avoiding scale dependent roughness descriptors (Buzzi & Casagrande, 2018; Buzzi et al., 2017; Casagrande, 2018; Casagrande et al., 2018; Jeffery, 2021; Jeffery et al., 2021; Jeffery et al., 2018).

The approach was validated in the laboratory by series of direct shear tests at small scale (100mm per 100 mm, Casagrande (2018)) and large scale (2m per 2m, Jeffery (2021)). After large scale validation under controlled conditions, Jeffery (2021) recommended large scale, in-situ application of StADSS for proper field validation. To enable large scale application of StADSS in the field, a seed trace digitization methodology must be developed. Ideally, seed trace data must be digitized at high resolution (≤ 1 mm intervals) to gain enough data to characterize roughness at full scale (Buzzi

& Casagrande, 2018; Buzzi et al., 2017; Casagrande, 2018; Casagrande et al., 2018; Jeffery, 2021; Jeffery et al., 2021).

An underpinning component of StADSS is to generate a distribution of shear strengths by virtually shearing a set of unique 3D synthetic surfaces containing roughness representative of the real discontinuity. The 3D synthetic surfaces generated by a random field model, are required to exhibit a Gaussian distribution of gradients, an observed characteristic of natural discontinuity surfaces (Buzzi & Casagrande, 2018; Casagrande et al., 2018). Hence, in geotechnical engineering, and more specifically StADSS, a Gaussian correlation function is usually adopted to estimate the correlation length for the random field model (Griffiths & Fenton, 2007; Jeffery, 2021). Enabling this process requires the seed trace input data to exhibit a Gaussian distribution of gradients, also. So, whilst seed trace data must be input at 1 mm intervals, the resolution of the captured seed trace data from an image must be sufficient to allow realistic gradient values, and enough variation for a Gaussian distribution of gradients to develop.

This paper presents a preliminary application of a seed trace digitization method to a discontinuity specimen in Gloucester, NSW, within Martin's Lime Quarry. The specimen investigated was approximately a 2.4 m^3 block of limestone dipping out of a highwall at approximately 46.5° as shown in Figure 1. The objective of the study is to establish how the number of pixels in high resolution photograph may affect the characterization of seed trace roughness statistics.

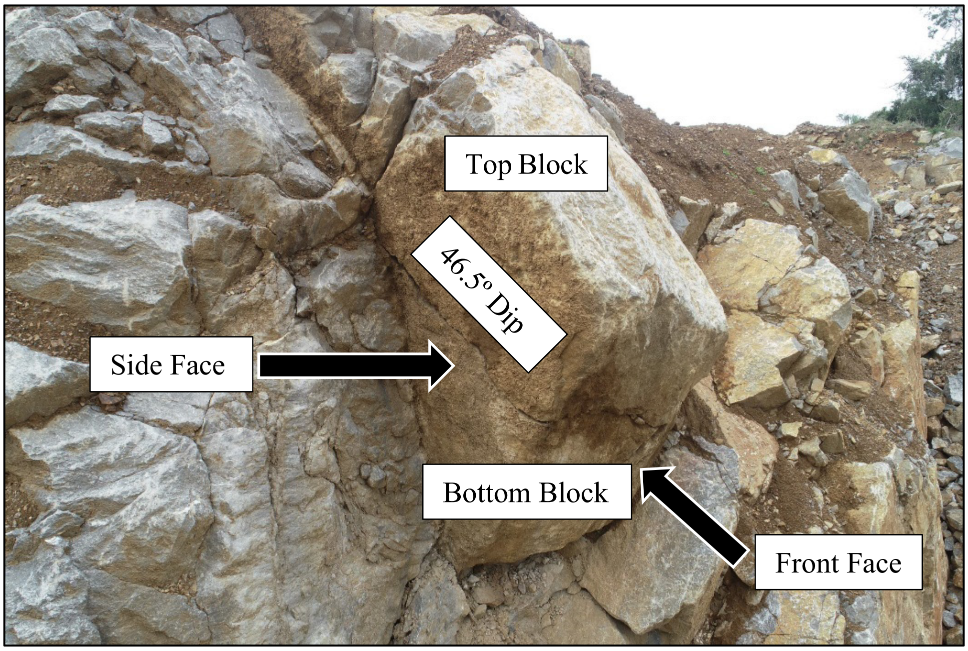

Figure 1. Limestone case study specimen located at Martin's Lime Quarry, Gloucester, NSW, Australia.

2 DATA COLLECTION AND EXTRACTION

Potentially unstable rock blocks, requiring a shear strength prediction and stability assessment, are often in an elevated position and deemed unsafe for physical inspection. This is the case of the specimen of Figure 1, located about 6 m above ground level. Considering this, a remote methodology to capture seed trace data must be developed. A Phantom 4 Drone with a 20-megapixel (M) camera used to capture the image discussed in this publication. The effective pixel resolution of the images was approximately 18M.

The seed trace selected for this preliminary application comes from the front view, with a photograph taken perpendicularly to the rock face (Figure 2a). The digitization of the seed trace was achieved by manually coloring the pixels contained within the seed trace white, and the remainder of the rock mass in black. Each seed trace was thicker than a single pixel, so a top and bottom seed trace was able to be extracted.

The coordinates of the top and bottom traces within the image were extracted using a Python script. Ground control points (GCPs) were also recorded to allow the scale of the data to be determined (pixels/mm). The GCPs were identifiable features on the rock mass and were surveyed using a total station during the field investigation. The raw seed trace image is shown in Figure 2a, and the processed seed trace is shown in Figure 2b.

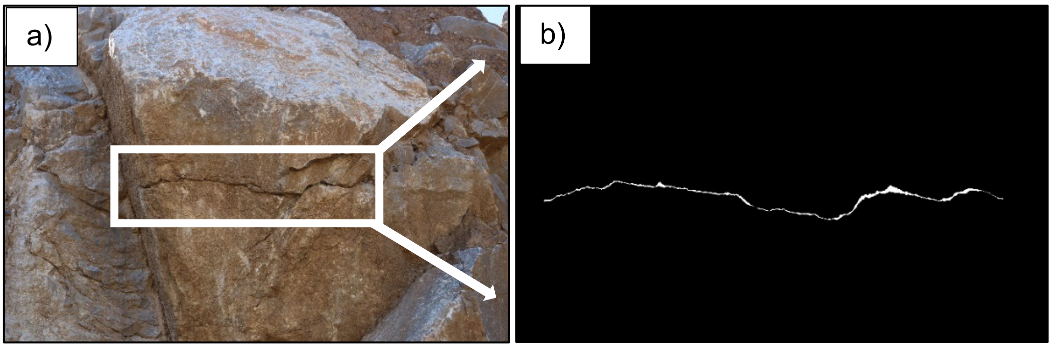

Figure 2. a) The original image of the seed trace (contained within the white box). b) The processed seed trace corresponds to the seed trace in Figure 2a.

An example of the extracted seed trace data from the processed image is presented in Figure 3.

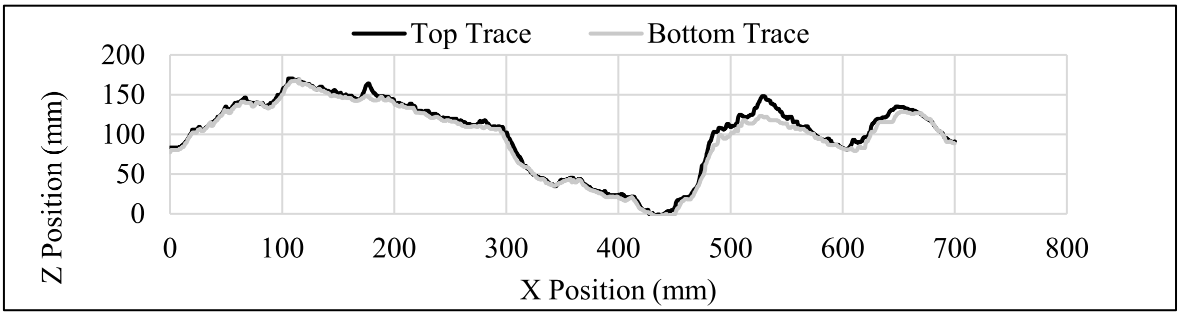

Figure 3. Digitized top and bottom seed trace data.

2.1.1 *Seed Trace Analysis*

The original image of the seed trace depicted in Figure 2a, had pixel dimensions of 5,184 pixels wide and 3,456 pixels high. The pixel density was then increased using the up-sampling algorithm in Photoshop (Adobe, 2023) to create four different pixel density scenarios (ST1 – ST4). This methodology adds pixels to an image whilst maintaining edge data using the ‘nearest neighbor’ interpolation method to designate color values for new pixels. The dimensions and details of each image scenario are summarized in Table 1.

Table 1. Summary of image resolution scenarios.

Scenario ID	Width [pixels]	Height [pixels]	Approximate Sampling Ratio [pixels/mm]	Comment
ST1	5,184	3,456	1.63	Original image
ST2	10,368	6,912	3.33	Doubled pixel dimensions
ST3	20,736	13,824	6.67	Quadrupled pixel dimensions
ST4	30,000	20,000	9.80	Maximum dimensions (RAM limitations)

Although the random field model required to apply StADSS produces a field of asperity heights, research by the authors has shown that the standard deviation of gradients greatly influences peak shear strength (Jeffery, 2021). As such, it is essential to adequately characterize the distribution of gradients. The importance of extracting a seed trace from an image with sufficient pixel density is highlighted when the distribution of gradients at varying pixel densities are observed. The gradient distribution for the top seed trace extracted from the original image (ST1) and the doubled pixel density image (ST2) is shown in Figure 4. The distribution of gradients for the higher pixel density images (ST3 and ST4) are respectively shown in Figure 5.

As seen in Figure 4, the gradients at 0°, and approximately ±30° occur more frequently due to there being less than 2 - 4 pixels per millimeter respectively, to trace the gradient of the seed trace. In this case, the gradients are clearly not normally distributed based on visual inspection. Where the pixel density scale exceeds 6-7 pixels per millimeter of seed trace length, sufficient detail is available to allow more precise characterization of gradients during processing. A near Gaussian distribution of gradients is visually identifiable at the pixel densities of ST3 and ST4 as shown in Figure 5.

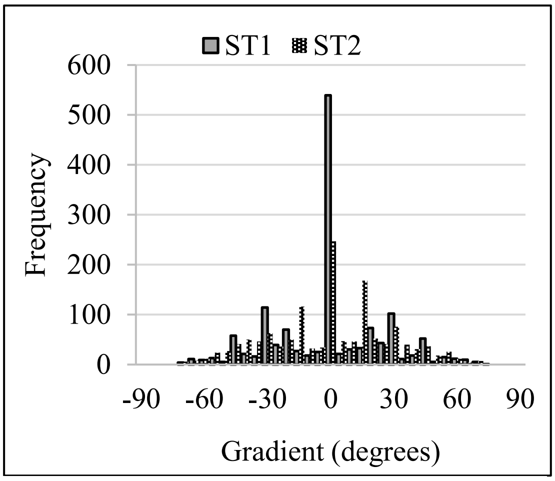

Figure 4. Distribution of gradients from the seed trace extracted from the original image with 18 M pixels (ST1) and 72 M pixels (ST2).

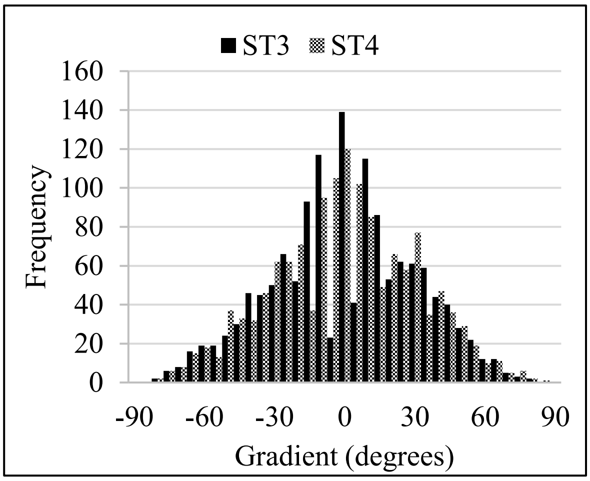

Figure 5. Distribution of gradients from the seed trace extracted from a processed image with 286 M pixels (ST3) and 600 M pixels (ST4).

2.2 *Kolmogorov-Smirnov Goodness-of-Fit Test (K-S Test)*

The K-S test can be used to statistically determine how close a distribution of data is to being normally distributed (Chakravarti et al., 1967). The K-S test statistic (D_n) is defined by Equation 1.

$$D_n = \max_{1 \le i \le N} \left(F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_i) \right) \tag{1}$$

where, *F* is the theoretical cumulative distribution of the distribution being tested, Y_i is the i^{th} ordered data point in the distribution, and *N* is the number of data points in the distribution.

A critical threshold value ($D_{n,\alpha}$) may be calculated from the K-S tables depending on the number of data points, and the significance level (α). If the K-S test statistic (D_n) is greater than the critical value ($D_{n,\alpha}$), then the hypothesis of normal distribution is rejected (Chakravarti et al., 1967). There were 1400 data points in each data set and a significance level of $\alpha = 0.001$ was adopted to determine whether the distributions are Gaussian. The relative error was calculated as the percentage of difference between D_n and $D_{n,\alpha}$, relative to $D_{n,\alpha}$. The K-S test for each data set (ST1 – ST4) is summarized in Table 2.

Table 2. Summary of K-S test to determine distribution of gradients normalcy.

Scenario ID	Critical Value - $D_{n,\alpha}$	K-S Test Statistic - D_n	Relative Error	Comment
	[-]	[-]	[%]	
ST1	0.052	0.189	263	Not normally distributed.
ST2	0.052	0.066	29	Not normally distributed.
ST3	0.052	0.055	5	Nearly normally distributed.
ST4	0.052	0.050	-	Normally distributed.

The test confirmed that a normal distribution of gradients was closely formed (±10% relative error) where the pixel density exceeded 6-7 pixels per millimeter (ST3 and ST4).

2.3 *Implication for Random Field Model*

Table 3 reports the values of standard deviation of gradients, and estimated correlation length from the seed traces with varied pixel density. The correlation length is a parameter that is required to produce the synthetic rock surface via the random field model (Jeffery, 2021). The standard deviation of gradients and correlation length both initially increase with pixel density; a reflection of the progressively widening distributions with increasing pixel density shown in Figure 4 and Figure 5.

Table 3. Summary of varying seed trace statistics and resulting correlation length estimations depending on image resolution.

Scenario ID	Mean Gradients	Standard Deviation of Gradients	Correlation Length *
	[degrees]	[degrees]	[mm]
ST1	-0.21	26.4	164.1
ST2	0.04	29.0	168.3
ST3	0.34	33.1	175.2
ST4	-0.17	30.4	175.5

* Note: that the correlation length was determined using a Gaussian auto-correlation function on the plain seed trace without decoupling it into different scales of roughness as per Jeffery et al. (2021).

An inadequate characterization of the roughness profile because of low pixel density is likely to result in an incorrect estimation of the correlation length. This is shown in Table 3 where the standard deviation of gradients decreased from ST3 to ST4, whereas the correlation length slightly increased. Hence, data should be checked to be normally distributed to reliably estimate correlation length.

3 CONCLUSION

The preliminary application of the seed trace digitization methodology indicates that an image containing 6-7 pixels per millimeter of seed trace length, is the minimum resolution required to satisfy the requirements of StADSS. Where the resolution of the image is less than 6-7 pixels per millimeter, only a non-Gaussian distribution of gradients is possible to extract due to insufficient options to characterize changes in gradients. The standard deviation of gradients, and the estimated correlation length was observed to be relative to the pixel density of the captured image. Hence, to reliably generate synthetic surfaces using a random field model, seed trace data must exhibit a Gaussian distribution of gradients to correctly estimate correlation length, mean and standard deviation, inputs of the random field model. It is acknowledged that the influence of pixel density on correlation length for the presented trace was relatively minor, however, a relationship was established and should be checked for future seed traces where the influence may be far greater. Further investigation is required to determine how seed trace resolution influences predictions of peak and residual shear strength by StADSS. Additional future development will possibly encompass characterization of aperture, mismatch, openings, and persistence.

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