Measurement of Surface Roughness of Rock Discontinuities

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ABSTRACT Roughness of a discontinuity may be an important factor influencing shear strength of the discontinuity. Traditionally, determining the roughness of a discontinuity surface and providing a numerical measure of the roughness has required considerable effort or specialised equipment. The development of new 3D imaging tools that are easy to use has provided effective fast and accurate means of creating 3D surface models from which roughness measurements can be readily obtained. These new techniques are versatile enabling a user to measure roughness along any desired profile and at any resolution up to the limit of the spatial subtense of a measurement on the discontinuity surface. This paper primarily reviews extensions to the use of 3D imaging that enable the measurement of roughness. Additionally we provide some examples of the measurements and examine some of the issues associated with extracting measures from the spatial data that will support estimation of shear strength.

1 INTRODUCTION

For objects in contact, their behaviour under the influence of any force is controlled by the geometry of the contact surfaces and the material properties of the objects. The 'geometry' of a surface can be considered to be comprised of two distinct components; one that may be referred to as the shape in terms such as waviness or curvature and a random component sometimes referred to as 'unevenness' (ISRM, 1978). The term 'roughness' has been used to describe both components. At fine scales roughness influences the shear strength of a discontinuity (ISRM, 1978) while at large scales roughness, or more precisely waviness, affects both the direction in which shearing occurs and the dilation of the discontinuity during relative motion of the surfaces, assuming that the components of the rock mass do not fail.

While methods of measuring the roughness of the surface of a discontinuity have been proposed (ISRM, 1978) there are now additional methods of measuring roughness. These methods include laser ranging (Rahman et al 2006) and 3D imaging using photogrammetry (Baker et al 2008). They provide data that is fundamentally different to the data acquired using previously defined methods and therefore the nature of the data generated by these devices and limitations on the use of these data must be fully understood.

A significant issue that arises from the measurement of surface geometry is the effect that measurement noise has on the characterisation of roughness. The presence of noise in measurements adds an additional component of random variation that will increase the apparent roughness as estimated from the raw data. Measurement noise is a significant issue in non-contact characterisation of roughness. Determination of the degree to which the roughness may be overestimated may be a critical limitation on the use of data obtained through a particular measurement process. Remote measurement of surface roughness has been demonstrated (Grasselli et al 2002, Rahman et al 2006, Haneberg 2006, Haneberg 2007, Baker et al 2008) and this work has described some methods of processing these data to deal with sensor noise.

This paper will address aspects of the measurement of surface coordinates used to estimate roughness in field situations at ranges that generally preclude the use of laboratory equipment and thus utilise laser ranging or photogrammetry techniques. The paper reviews some of the basic measurement concepts and describes a set of experiments that were conducted with the specific objective of assessing the degree of sensor noise for one of the laser sensors used in previous work as well as some theoretical analysis of the possible performance of photogrammetric systems in this role.

2 BACKGROUND

For interlocked surfaces such as unfilled joints the roughness of the surface influences the shear strength of the discontinuity and may be an important factor in the behaviour of the discontinuity under load. The dependence of shearing on the location and distribution of the three-dimensional contact area between two rock surfaces has been shown (Gentier et al., 2000) and a mathematical relationship between three-dimensional surface parameters and the shear strength of rock joints has been demonstrated (Grasselli and Egger, 2003).

'Roughness' is effectively a description of the geometry of a surface and the roughness of the surface of a discontinuity can be parameterised by measuring the deviation of the surface from 'smooth' or 'flat'. Estimates of roughness attempt to describe, in a single parameter, the complex surface topography of a discontinuity in a rock mass therefore the information embodied in these measurements must be properly understood in order to use them effectively.

The characterisation of roughness depends on the scale at which it is being considered. Since the roughness of a surface may influence the shear strength of a discontinuity the scale of the measurement as well as other measurement properties must be well understood.

Since the rock in which a joint forms is a natural material the unevenness of a joint exhibits randomness characteristic of many natural phenomenon. While the scale or degree of randomness may be small measurement of any natural phenomenon is often made difficult by such variability. Discussion of the spatial variability of roughness is beyond the scope of this paper.

It is important to capture the random variations of the geometry of a surface as measurements in a form that supports the use of the data in mathematical modelling or other applications in an appropriate manner. Thus consistent methodology applied to the measurement of surface characteristics is required to achieve consistency in the specification of roughness.

3 ESTIMATION OF THE JOINT ROUGHNESS COEFFICIENT

Roughness is an inferred parameter and the measurements that are used to characterise roughness must suit the models used to parameterise it. The measurement of the shape of a surface profile may be applied through the relationship (ISRM, 1978) between the peak friction angle, the compressive strength of a discontinuity (JCS) and the joint roughness coefficient (JRC) where:

$$\phi_{peak} = JRC \cdot \log_{10} \left(\frac{JCS}{\sigma_n} \right) + \phi_{residual}$$

To use this relationship the JRC must be estimated from measurements of the surface geometry. The estimation of roughness via mathematical expressions using the measurement data can be performed in a number of ways. Measures have been developed that include parameters based on surface lengths along profiles (Maertz et al., 1990), root mean square characterisation of local slopes (Tse and Cruden, 1979), surface topography (Grasselli et al., 2002), fractal dimensions (e.g. Baker et al., 2008) and spectral analysis of surface profiles. Maertz et al (1990) present a review of some measures. Methods of estimating the JRC from profile data include the Maertz and Tse and Cruden measures which are based on linear profiles. The use of linear profiles has produced what some workers have described as inconsistent results (Grasselli et al 2002). The Maertz and Tse and Cruden measures have been used to assess the effects of measurement noise using simulated linear profiles (Poropat 2008). The results of modelling the effects of measurement noise have supported the assessment that the use of such measures with linear profiles can produce inconsistent results. The measures are presented here to provide a context for the data presented in this paper.

In the following it is assumed that each profile is a set of N points in a plane normal to the plane of best fit to the 3D points defining the surface of the discontinuity. Each pair of points is separated by a distance Δs and has height z_i above plane of best fit to the 3D points. That is to say the points are represented as heights above a regular, uniformly spaced grid in two dimensions. A grid of this form is easily obtained from any general surface through resampling. The effects of the resampling process are expected to be second order effects and have not been considered her.

3.1 Surface length measurement

The JRC proposed by Maertz is based on an empirical correlation of the form:

$$JRC = c \cdot (R_n - 1) \tag{2}$$

where c is an empirical constant of the order of 400 and R_p is the roughness profile index which is defined as the ratio of the true profile length to the length of the projection of the profile on the plane that is the plane of best fit to the 3D points. That is

$$R_{p} \approx \frac{\sum_{i=1}^{N-1} \sqrt{\Delta s^{2} + (z_{i+1} - z_{i})^{2}}}{(N-1) \cdot \Delta s}$$
(3)

or

$$R_{p} \approx \frac{1}{(N-1)} \cdot \frac{\sum_{i=1}^{N-1} \sqrt{\Delta s^{2} + (z_{i+1} - z_{i})^{2}}}{\Delta s}$$
(4)

$$R_p \approx \frac{1}{(N-1)} \cdot \sum_{i=1}^{N-1} \frac{1}{\cos(\alpha_i)}$$
(5)

where α is the asperity angle.

Note that for equal intervals as associated with a regular grid, Δs , R_p is simply the average value of the secant of the asperity angle taken over all the segments. Since this increases without limit as α increases the range of applicability of this empirical relationship may be limited. The Maertz JRC has the benefit that as a surface approaches being perfectly smooth the JRC approaches 0.

3.2 Slope measurement

The JRC proposed by Tse and Cruden (1979) is the root mean square (RMS) estimate of the local slopes of the profile defined over the intervals between measured data points. It is expressed as:

$$JRC = 32.2 + 32.47 \cdot \log(Z) \tag{6}$$

where

$$Z = \sqrt{\frac{\sum_{i=1}^{N-1} (z_{i+1} - z_i)^2}{(N-1) \cdot \Delta s^2}}$$
(7)

For equal intervals, Δs , Z is

$$Z = \sqrt{\frac{\sum_{i=1}^{N-1} \frac{(z_{i+1} - z_i)^2}{\Delta s^2}}{(N-1)}}$$
(8)

For large N, Z approaches the standard deviation of the tangent of the asperity angles. Since this increases also without limit as α increases this limits the range of applicability of this relationship. In addition, at some low asperity angles the Tse Cruden estimate of the JRC may become negative.

3.2.1 *Two dimensional slope measurement*

A method that does not appear to have been described in the literature is a two dimensional analogue of the Tse Cruden relationship where the tangent of the asperity angles on a profile is replaced by the tangent of the deviations of the normals to the facets from the normal to a plane.

4 MEASUREMENT OF ROUGHNESS USING LINEAR PROFILING

Two of the methods described by the ISRM are 'physical methods' that require access to the surface of a discontinuity that will support measurements requiring contact with the surface. These are linear profiling and measurement of local surface orientation. Analysis of linear profiling using a contact measurement tool provides a useful basis for examining some of the issues associated with estimation of roughness.

Linear profiling can be performed by measuring the distance from the surface to a straight line defined by some physical means over the scale at which the measurement is to be made. In a laboratory situation this may be performed using specialist profile measurement tools. In the field this may be done using some form of straight edge as described by the ISRM that is often used with visual interpretation or using a profile gauge tool. A typical profile gauge is shown in **Figure 1**.

Linear profiling using a profile gauge provides a useful basis for introducing some of the issues associated with the measurement of roughness. Visual estimation is not discussed further.



Figure 1: Profile Gauge Tool

The profile gauge is essentially a sampling tool. Each measurement rod or element of the tool provides a single sample of the surface profile. The samples are usually uniformly spaced. Assuming that the ends of the elements are perfectly flat then, in the terms used in signal processing, this is a peak hold sampling system in which the measurement or sampling aperture is determined by the width of the elements of the profile gauge and the sample spacing is the spacing between rods. **Figure 2** illustrates the measurement process as would be observed using a profile gauge. Each of the vertical bars represents a measuring rod. Although the sampling aperture is the same as the sample spacing in this case in many measurement systems the sampling aperture may differ from the sample spacing. Examination of the case where the sample spacing and sampling aperture differ will not add anything further to the discussion here.

For a profiling tool the accuracy of the determination of the height of the measuring rods and the spacing of the measurements are the fundamental parameters that define the measurement data. With some limitations the simple measurement model provided by this tool can be extended to two dimensions and to other measurement instruments.



Figure 2: Peak hold sampled measurements of a profile

5 MEASUREMENT BANDWIDTH AND NOISE

It can be readily seen from the linear profiling example that there are small scale variations in the surface that cannot be measured using any given measurement system. Mathematically, the limits on the measurement in respect of the frequencies that can be measured are described by the Nyquist-Shannon sampling theorem which is a fundamental theorem in signal processing. However the character of a naturally occurring surface is not such that it cannot be described simply in terms of spatial frequencies. Discontinuous features such as small breaks exhibited in the data collected by Baker et al (Baker et al 2008) cannot be described simply in the frequency domain in a manner that supports estimation of roughness. If a surface is in fact random at all scales then the spatial frequency bandwidth of a surface profile of the surface at infinitesimally fine resolution would be infinite.

This essentially highlights the issue of the scale at which measurements of roughness are to be made. The spacing of the measurement rods of the profile gauge defines the smallest feature that can be measured by the tool and thus the scale at which roughness can be measured. The resolution at which the differences in height of the measurement rods can be determined defines the measurement noise. A standard result from probability theory is that if a measurement has a resolution of a then in the absence of any other effects the standard deviation of a random set of measurements from the mean when a sufficient number of measurements are made is (Papoulis 2001)

$$\sigma = \frac{a}{2 \cdot \sqrt{3}}$$

The combination of the scale at which the measurements are made and the 'noise' inherent in the determination of the height of the measurement rods will influence the estimation of roughness at the scale of measurement being used. This simple model can be applied to many measurement processes however, in the case of laser data, the very high resolution data collected may not be amenable to analysis using such a simple model. This issue is discussed in more detail later in this paper.

6 LABORATORY MEASUREMENTS OF SURFACE GEOMETRY

Grasseli et al (2002) used a topometric sensor to perform measurements of surface geometry at a distance of approximately 50 centimetres from a surface. They used a photogrammetric sensor that produced very detailed, high resolution three dimensional models of a surface. This sensor was reported as providing a measurement accuracy of $\pm 50 \ \mu\text{m}$. This figure may refer to the resolution of the sensor but precision of these measurements is not known.

In previously unreported work by the author a stereo camera system was used to determine the limits of measurement at slightly longer distances from the measured surface than reported by Grasselli et al. The sensor used comprised two Nikon D200 digital SLR cameras rigidly mounted relative to each other. A flat surface with a (flat) random intensity pattern imposed on the surface was used as a calibration target. In these experiments this system produced a surface model with a point-to-point root mean square deviation from flatness of approximately 100µm.

This result is consistent with the predicted precision of such as sensor where the term precision here is used (in the correct sense) as a measure of the random variation of the measured value of a parameter when a number of measurements are taken. Note that the term repeatability is sometimes used with precision or in the same context. The mathematics used to predict the performance of this sensor are beyond the scope of this paper but can be accessed in many publications on photogrammetry, for example the Manual of Photogrammetry 5th Edition (ASPRS 2004).

7 REMOTE MEASUREMENT OF ROUGHNESS / MEASUREMENT USING 3D POINT CLOUDS

A third method described by the ISRM is based on photogrammetry and is a remote sensing technique. Other remote measurement techniques include laser profilers and laser scanning systems that produce point clouds over a surface. Typical examples of these systems are produced by Optech (Canada), Maptek (Australia) and Riegl (Germany). Laser systems generate data in a form similar to that which can be obtained from 3D imaging systems that use photogrammetry such as the JointMetrix system (3G), the 3DM Analyst system (Adam Technology) or the Sirovision system (CSIRO).

A number of workers have obtained measurements of surface geometry using laser systems and photogrammetry (for example Baker et al 2008, Haneberg 2006, 2007, Rahman et al 2006).

7.1 Measurements using laser ranging

Rahman et al (2006) used a Riegl LMS-Z420i terrestrial laser scanner to acquire spatial coordinates on the surface of a rock face. The data were used to calculate the fractal dimension and a parameter defined as 'roughness amplitude' to characterise the surface geometry. In this work it was found that the fractal dimension and roughness amplitude were high for raw laser scan data and it was postulated that this was due to the range measurement error of the scanner.

The data acquired were obtained as measurements of the range from the sensor to natural rock surfaces and were smoothed using a scattered data interpolation technique based on the application of radial basis functions as interpolation kernels (Billings et al 2002). After interpolation and smoothing the fractal dimensions of the surfaces examined were typically of the order of 2.74.

7.2 Calibration of laser range data

To estimate the noise inherent in laser range measurements a set of experiments were conducted with a Riegl LMS-Z420i terrestrial laser scanner using a flat surface at a range of 100 metres. A section of the 3D point cloud obtained, covering the calibration target and part of the background, is shown in Figure 3 with a photograph of the target. The shadowing effect of the target can be clearly seen.



Figure 3: Laser scan data and image of calibration target and background



The 3D data for the calibration target itself is shown in detail in Figure 4.

Figure 4: The calibration target 3D point cloud

The plane of the calibration target was extracted from the 3D data and the measurement noise estimated. The variation in surface flatness of the calibration target was less than 0.5 millimetres peak to peak. The standard deviation of the measurement noise was determined to be 9 millimetres which is consistent with the manufacturer's specifications.

7.3 Measurements using photogrammetry

Baker et al (2008) and Haneberg (2006, 2007) have applied photogrammetry to the estimation of roughness and have shown that the data produced by such systems can be used to remotely characterise the geometry of a surface to estimate roughness.

Although the precision of the data acquired is not known the laboratory results reported earlier in this paper can be scaled up mathematically. The equations for estimating precision show that if the geometry is maintained the precision scales linearly with distance to the measurement surface. The previous estimate of precision (0.1 millimetre 4 metres) translates to a precision of 2.5 millimetres at 100 metres using a 24 millimetre focal length lens and approximately 1.0 millimetre at 100 metres using a 100 millimetre focal length lens. This level of performance has yet to be verified in the field.

7.4 Spatial Resolution

The Riegl LMS-Z420i can be used in a high resolution scanning mode that produces a spatial data point at approximately every 5 millimetres across a rock surface at 100 metres. However it should be noted that the beam divergence of the Riegl LMS-Z420i is 0.25 milliradians and thus the spot size at 100 metres is 25 millimetres. This is assumed to be to the 1/e points on the beam profile and as a result some 'averaging' of the structure occurs as a result. With a photogrammetry system as used a spatial point could, in principle, be generated every 6mm across a rock surface at 100 metres

7.5 Reduction in noise by data processing

It has been shown that, without smoothing, the estimation of the JRC using either the Maertz or Tse-Cruden formulae with linear profile data can produce quite large variations in the estimated JRC (Poropat 2008). The results reported by Rahman et al (2006) and the laser data presented here demonstrate that noise reduction or removal is critical for the estimation of roughness if the sensor noise is significant relative to the scale of the surface features being measured.

8 CONCLUSION

Estimation of roughness requires acquisition of detailed spatial data that defines the geometry of a surface combined with careful application of the data to infer roughness.

Previously published data and the results reported here indicate that further work is required to better understand the use of laser data and possibly photogrammetric data for characterising a surface in order to estimate roughness. Noting that the rock surfaces examined were not of the same type, in the work reported by Rahman et al (2006) the laser data produced estimates of fractal dimension that appear to significantly exceed those obtained using photogrammetry. Controlled experiments conducted on the same surfaces with different sensors are required to compare the effectiveness of these sensor systems for the measurement of roughness.

In addition, previously reported work clearly shows that some form of data smoothing is essential to the characterisation of roughness. Data smoothing changes the results of using the data to estimate roughness and since shear strength is a critical parameter the effect of various data smoothing process must be quantified and their suitability for use in the estimation of roughness validated.

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