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Remote Characterisation of Surface Roughness of Rock Discontinuities

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Abstract

The roughness of a discontinuity may be an important factor influencing shear strength of the discontinuity. Determining the roughness of a discontinuity surface and providing a numerical measure of the roughness generally requires considerable effort. The development of new, easily accessible tools for 3D imaging 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 enough to enable a user to measure roughness along any desired profile and at any resolution up to the limit of the spatial subtense of an image pixel on the discontinuity surface. This paper reviews the use of 3D imaging for the measurement of roughness and provides some examples of the measurements.

1 Introduction

In general terms the roughness of the surface of a discontinuity is a measure of the deviation from 'smooth' or 'flat' and depends on the scale at which it is being considered. At small scales roughness influences the shear strength of a discontinuity (ISRM, 1978) while at large scales roughness is referred to as waviness and will affect 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. For either small scale roughness or waviness the 'roughness' will contribute to the shear strength of a discontinuity. In both cases, estimates of roughness are an attempt to describe, in a single parameter, the complex surface topography of a discontinuity in a rock mass.

For interlocked features such as unfilled joints the roughness of the surface of a discontinuity is a component of 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 demonstrated (Grasselli and Egger, 2003).

The requirement for measures of roughness is readily seen in the relationship (ISRM, 1978) between the peak friction angle, the compression strength of a discontinuity, JCS, and the joint roughness coefficient, JRC, where:

$$\phi_{peak} = JRC \cdot \log_{10}\left(\frac{JCS}{\sigma_n}\right) + \phi_{residual} \tag{1}$$

The role of joint roughness in controlling the behaviour of a rock mass makes understanding the methods that can be used to estimate the joint roughness coefficient important. Traditionally, these methods have required considerable time and analytical effort. The development of three dimensional imaging techniques has, however, replaced these slow and potentially error prone methods with a new method that offers flexibility, and speed of data acquisition and accurate estimation of surface roughness.

Three methods of estimating roughness based on physical measurements of surface topography have been described by the ISRM (1978). More recently the use of laser scanners and photogrammetry to define the surface topography of a rock mass and estimate roughness have been described (Rahman et al., 2006; Haneberg, 2006, 2007; Baker et al., 2008). The measurement methods are discussed in this paper.

Of major significance to users of these new measurement methods are the limitations and potential problems that inevitably arise with the application of new techniques. This paper addresses some of those issues.

2 The mathematical background

Since the topography of the surface of a discontinuity in rock is an expression of a natural process it is subject to a range of variation. It is important to capture such variations in a form that supports the use in mathematical analysis. The mathematical expression of roughness depends on the approach taken. The measures that have been developed 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.

This paper will address remote characterisation using 3D point clouds including the Maertz and Tse and Cruden measures with a brief reference to fractal measures.

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. Such a grid is easily obtained from any general surface through resampling.

2.1 Surface length measurement

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

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

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:

$$R_p \approx \frac{\sum_{i=1}^{N-1} \sqrt{\Delta s^2 + \left(z_{i+1} - z_i\right)^2}}{(N-1) \cdot \Delta s} \tag{3}$$

or:

$$R_p \approx \frac{1}{(N-1)} \cdot \frac{\sum_{i=1}^{N-1} \sqrt{\Delta s^2 + \left(z_{i+1} - z_i\right)^2}}{\Delta s} \tag{4}$$

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

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 this may limit the range of applicability of this empirical relationship.

Obviously the Maertz JRC has the attraction that as a surface approaches being perfectly smooth the JRC approaches 0.

2.2 Slope measurement

The JRC proposed by Tse and Cruden (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:

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

For equal intervals, *Δs, Z* is:

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

Therefore, 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 may limit the range of applicability of this relationship.

In addition, at some low asperity angles the Tse Cruden estimate of the JRC may become negative.

An estimation method which 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 average normal to the plane.

2.3 Fractal measurement

The fractal dimension of a profile can be used as a measure of roughness (ISRM, 1978). To calculate the fractal dimension of a curve the length of the curve when sampled at different scales is compared (Barnsley, 1988). The fractal dimension is a limit calculated across all scales, but, in practice, the available data can rarely support calculations across all scales.

In some respects measuring the length of a surface profile is similar to measuring the length of a coastline, a topic addressed by Benoit Mandelbrot in his treatise on fractals (Mandelbrot, 1982). As the scale of the measurement is decreased ever finer structure becomes evident when measuring the coast and when determining the surface profile of an exposed discontinuity.

The relationship between the length of a coastal boundary, or any line, the fractal dimension and the scale size provides an estimate of the fractal dimension of the line. The relationship is:

$$\log[L(s)] = (1 - D)\cdot\log(s) + b \tag{9}$$

where *L(s)* is the length measured at scale *s* and *D* is the fractal dimension and *b* is a constant. A straight line has a fractal dimension of 1 since the measured length of the line cannot vary with the scale; any regular Euclidean object has a fractal dimension of 1.

The fractal dimensions of coastlines have been found to vary from as little as 1.04 for South Africa to as large as 1.24 for England. Since exposed discontinuities are generally of much simpler shape than coastlines, i.e. it is rare to see the equivalent of concave features such as bays, it can be reasonably expected that the fractal dimension of an exposed discontinuity would have a value towards the lower end of this range if not smaller than the lower limit here.

The standard deviation of profile height of a self-affine fractal and the sampling window length of the profile are related by a power law (Malinverno, 1990):

$$S(w) = A\cdot w^H \tag{10}$$

where *w* is the sampling window length and *H* is the Hurst exponent which is determined by the Euclidian dimension, *E*, (E = 2 for a line and E = 3 for a surface) through the relationship.

$$H = E - D \tag{11}$$

In order to use the fractal dimension, *D*, to estimate roughness *D* may have to be restricted to the range 1.2 to 1.7 (Kulitilake, 1999). However, other workers have reported profiles that showed fractal dimensions from

1.1 to 1.5 covering a range of self-similar and self-affine curves (e.g. Rahman et al., 2006). The results obtained may be significantly affected by the range measurement error of the sensor (Rahman et al., 2006). Factors such as this may influence the choice of technique used to measure roughness when the estimation is made using the fractal dimension of a surface.

2.4 Limitations

Both the Maetrz and Tse and Cruden measures will exhibit divergent behaviour as the roughness increases. In addition the Tse and Cruden measure may not be usable for very small values of roughness because it is inherently limited at low values and measurement errors may make this limit difficult to determine.

In addition all measures will be affected by measurement error and the degree to which these errors affect the measurements may be critical in determining the choice of measurement method and the relationship used.

3 Contact measurement of roughness

Two of the methods described by the ISRM are ‘physical methods’ that require access to the surface of a discontinuity that will support ‘contact’ measurements while the third, based on photogrammetry, is a remote sensing technique.

3.1 Linear profiling

Estimation of joint roughness from linear profiles requires the determination of 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, but, in the field, this is more conveniently undertaken using some form of straight edge as described by the ISRM. The limitations of this method are obvious and the details are left to the interested reader.

3.2 Measurement of surface orientation

This method requires the collection of a series of measurements of the local orientation of the rock mass surface at a range of scales (ISRM, 1978). Measurement is accomplished using a set of circular plates of various sizes being used to ‘define’ the local orientation at various scales by placing the plates against the surface. Measurements of dip and dip direction are then made and recorded at a minimum of 25 positions for the largest scale and at larger numbers of positions for smaller scales.

Each measurement is then plotted on an equal area net for each scale and contoured with the maximum roughness direction at each scale being estimated from the contours.

3.3 Limitations

Obviously these methods are limited in applicability due to the requirement for physical access to the surface of a discontinuity. In addition consistent estimation or use of the apparatus is required for measurements of roughness to be accurate.

The linear profiling method is recommended if the potential sliding direction is known (ISRM, 1978), but application of this method may require subjective assessment of the measurements to correlate the profiles with suggested values of JRC.

4 Remote measurement of roughness/measurement using 3D point clouds

4.1 Estimation from point data

In contrast to methods requiring physical contact with a surface the development of precise laser scanning systems and photogrammetry systems that both produce 3D point cloud measurements of the position of a point on a surface in 3D space enable the estimation of surface roughness in the field without physical contact with the surface.

These systems produce clouds of 3D points that are generally irregularly spaced in 3D space unless very specific geometrical constraints apply and such constraints almost always do not apply in field measurements. Since roughness is estimated in specific directions these point clouds must be transformed to an appropriate data structure or spatial basis.

The use of this transformation has been well documented in the literature (e.g. Baker et al., 2008; Haneberg, 2006, 2007) and specific details of the processing will not be discussed further here except where the following discussion warrants further examination.

The acquisition and use of point cloud data should be undertaken with due consideration of the accuracy, resolution and precision of the data. It should be noted that accuracy is less significant to the measurement of roughness than resolution and precision which may interact to some degree.

Three dimensional point clouds can support a range of methods for estimating roughness. With appropriate data transformation they can be used to estimate roughness using either linear profiles or two dimensional models and can be used to undertake estimation of roughness based on measurement of the local orientation of the rock mass surface at a range of scales as described previously (ISRM, 1978).

4.2 Measurement noise

A significant problem with the use of 3D point clouds in estimation of the JRC of an exposed discontinuity is the presence in the point cloud data of measurement errors which may be significant enough to overestimate the JRC. The principal measurement error that must be dealt with is the range from the sensor to a point on an exposed discontinuity. Range measurement noise is generally dominated by the resolution of the measurement system but may be significantly increased by other effects.

The effect of measurement errors is, in most cases, to increase the apparent roughness of a surface. For example Rahman et al. (2006) measured values of D greater than 2.7 for surfaces for which values of D in the range 2.2 to 2.7 were expected. The authors attributed the larger than expected values of D to the presence of range errors in the laser data that they used.

4.2.1 Range errors in laser data

Range errors in laser data arise from a number of effects which may include but are not limited to:

- Resolution limits in the range measurement.
- Timing jitter in the electronics used to measure time of flight.
- The effect of surface reflectivity changes.
- Atmospheric effects.

Laser range measurements are often obtained with some form of digital time measurement and, as with any digital measure, may be limited by the resolution of the time measurement system at some level. Resolution is sometimes confused with precision. However, while affecting precision it may not be the primary determinant and may be masked by factors such as measurement noise.

Range errors can be reduced with the application of some data processing techniques. One easily implemented technique is range averaging. It should be noted that the application of data processing may change the statistical distribution of the errors and this change may affect the choice of any preconditioning applied to the range data before roughness is estimated. For example, simple range averaging will change the error distribution due to resolution limits from uniformly distributed over a range defined by the resolution interval to a distribution that may approach that of a Gaussian distributed random variable if a sufficiently large number of samples is acquired.

4.2.1.1 Typical performance

The Riegl LMS-Z390i may be considered a typical laser scanning system for this sort of application. This system integrates a digital camera and has a maximum range of 400 metres. The maximum range can only be achieved with surface reflectivities of the order 0.8 and more typical operating ranges might be 200 metres to

250 metres. The quoted single shot precision for this device, equivalent to the range precision that might be achievable with a photogrammetric measurement system, is 4 millimetres. This system provides a signal processing function that averages a number of readings to achieve 2 millimetre precision.

4.2.2 Range errors in photogrammetry data

Range errors in 3D data obtained using photogrammetry may arise from a number of sources including:

- Resolution limits in the disparity measurement in images.
- Errors in the calibration of the cameras.
- The effect of image processing algorithms.
- Atmospheric effects.

For close range photogrammetry with low angles of convergence the effect of limited resolution in the disparity measurement in the images used may dominate. For example when using a Nikon D300 at a range of 250 metres with a 50 millimetre focal length lens and a convergence angle of 10 degrees a disparity measurement resolution of 1 pixel will result in a range measurement with an error in the range of ±30 millimetres.

This error is a uniformly distributed random variable and therefore the precision, the standard deviation, of this measurement is approximately 20 millimetres. The precision of the range measurement when the disparity resolution is one pixel is approximately the same as the pixel size projected on a rock face at that range which is 25 millimetres.

However, most photogrammetric systems measure disparity at the sub pixel level so the range measurement resolution, and thus the precision, is much smaller than this example indicates. It would be expected that measurement precision of less than 5 millimetres would be achieved at this range with this configuration in most cases. Some image processing systems claim correlation accuracies at 0.01 pixel resolution (equivalent to 0.2 millimetre precision), however, this is not considered a performance level that is likely to be achieved in mapping rock faces.

Range measurement resolution can also be reduced by increasing the focal length (almost a linear effect) or increasing the convergence angle. The effect of the latter is non-linear but can be approximated as linear over small changes. Photogrammetric systems should provide user aids that enable estimation of the range measurement resolution that can be achieved with a specified camera and geometry.

4.3 Measurement spread/localisation errors

A secondary effect arises from the localisation of the measurement. Since neither laser systems or photogrammetric systems produce true ‘point’ measurements the point at which a measurement is made may not be well defined.

Depending on the range at which the measurements are acquired this effect may be far more pronounced for laser measurement systems than for photogrammetric systems. For example, a laser system with a beam spread of 0.3 milliradians (the beam spread specification quoted for the Riegl ZLMS390i) will produce a spot size of 30 millimetres at 100 metres and 150 millimetres at 500 metres whereas the camera and lens combination referred to previously results in pixel sizes of 6 millimetres and 30 millimetres respectively.

4.4 Measurement scale

A further problem, which may be as significant, is that of the ‘scale’ of the measurements. The distance along a profile between the measurements of the profile will be one of the factors that determine the lower limit of the scale at which roughness can be measured.

For the configuration described previously the camera based photogrammetry system is theoretically capable of providing a spatial point at every pixel which would represent a spatial point every 25 millimetres at a range of 250 metres with a 50 millimetre focal length lens or every 12.5 millimetres with a 100 millimetre focal length lens.

The Riegl LMS-Z390i provides point measurements with a separation of 0.002 degrees (0.035 milliradians) and thus will provide a measurement every 10 millimetres on the rock face at 250 metres. However, it should be noted that this measurement spacing must be interpreted with care. The spot size at this range is 75 millimetres (0.3 milliradian beam spread) and if the signal averaging mode is used the position of the measurement is determined by the signal processing algorithm.

Since some form of signal conditioning must be applied either during the measurement process in the case of a laser scanner or during post processing in the case of both laser scanning systems and photogrammetric systems. Therefore the minimum measurement scale that can be reliably used will be dependent on the measurement spacing and the processing algorithm. Median filters are often used to remove random signals of the kind to be found in data of this form and with a typical window of 5 range measurements the minimum measurement scale can be easily calculated.

The laser system referred to here would have a measurement scale of approximately 50 millimetres and the D300 a measurement scale of 125 millimetres with a 50 millimetre focal length lens or approximately 60 millimetres with a 100 millimetre focal length lens.

These scales will vary linearly with the distance to the face being mapped.

5 Implementation of remote measurement of roughness

5.1 Acquisition of surface models

The primary goal of the data acquisition systems used to acquire data from which estimates of surface roughness may be derived is to acquire a sufficient number of measurements so that a usable model of the surface topography can be created. The two systems considered here both produce clouds of 3D points that are assumed to represent the surface being assessed, that is the point cloud is assumed to provide a digital surface model (DSM) representing the topography of the surface of the discontinuity.

5.1.1 Comparison of laser systems and photogrammetry systems

Both laser systems and photogrammetry systems produce point clouds that, when viewed from the position of the sensor, define a point in space by the measured range from the sensor and the angle of the measurement vector. For the purposes of the estimation of roughness small systematic errors in the measured angles are not critical since they will simply produce a rotational shift in the 3D models and that shift is generally negligible in comparison to the spread of the orientations in a set of discontinuities.

In most respects the data acquired by these systems is similar in format and can be processed similarly.

5.2 Creation of high resolution DSMs

A 3D point cloud is not a surface representation and the data acquired by laser systems and photogrammetry systems are generally not used as simple point clouds. When the points are assumed to lie on a common surface the first stage of processing to support roughness estimation is alignment of the data to a convenient spatial reference which is usually the XY plane with the line of steepest descent aligned to either the X or Y axes. The details of these processes are well covered in the literature.

However, the data are usually randomly scattered after alignment and for some forms of processing must be interpolated to create a regular grid. To undertake this step the data points are ‘linked’ to form a triangulated network that is used to interpolate the data to obtain data values at points on the required regular grid.

5.3 Signal conditioning

To reduce the effects of measurement noise some form of signal conditioning may be required. The range measurement errors discussed previously are usually uncorrelated and thus are suitable for filtering using any one of a wide variety of one dimensional or two dimensional processing algorithms. For uncorrelated data a common choice is the median filter which has the useful property of preserving edges while removing uncorrelated noise, sometimes referred to as ‘salt and pepper’ noise.

In the absence of range averaging as used, for example, in the Riegl LMS-Z390i scanner the range measurement data errors are uncorrelated because for both laser systems and photogrammetry systems each range measurement is an independent measurement. When averaging algorithms are applied with laser range data the filtering process may introduce correlation between range measurements and this assumption will not be valid. In that case the signal conditioning algorithm must be more carefully chosen but in the absence of information regarding the algorithms used in the scanning system this choice may be guesswork.

5.4 Estimation of roughness

Once the data have been aligned to a suitable measurement orientation interpolation of the data at the desired grid points can be completed using any one of a number of off-the-shelf software packages. The estimation of roughness is then an exercise in applying an algorithm which produces the chosen estimator based on the appropriate data.

6 Examples

To illustrate the application of some of these measures and the effects of measurement errors under controlled conditions some limited simulations of estimation of roughness from linear profiles using the Maertz and Tse/Cruden formulations for the JRC were undertaken.

A simulated profile of a surface was generated using 1000 data points (Figure 1). The vertical scale has been exaggerated for clarity. Visual comparison with the profiles published by the ISRM suggests that this profile is similar to that of a surface with a JRC of approximately 10.

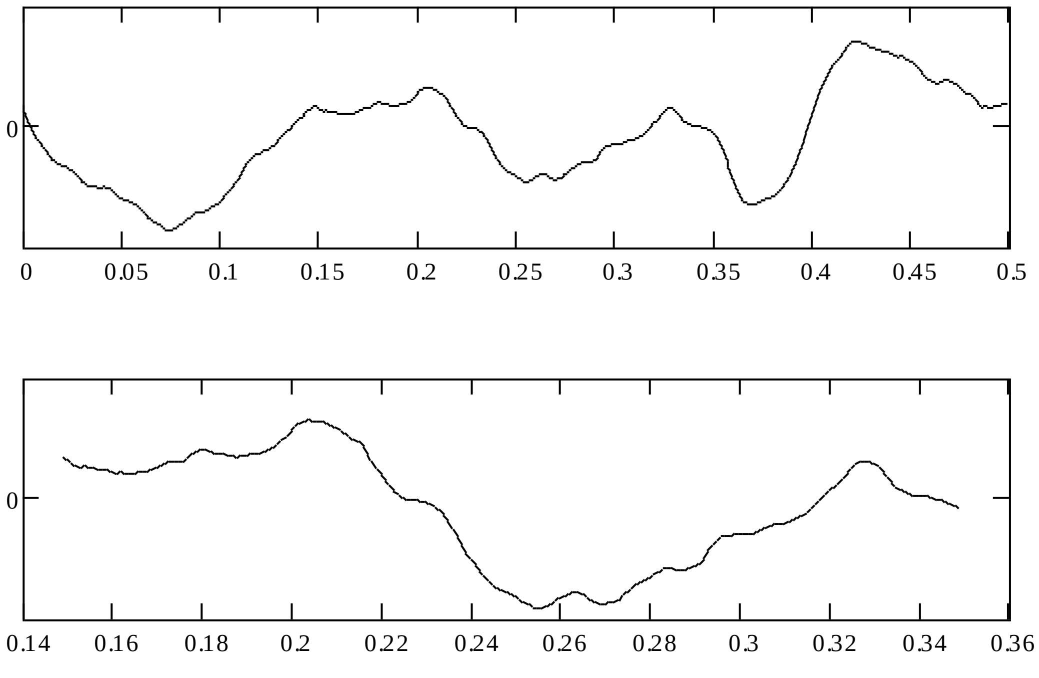

Figure 1 Simulated Surface Profile (full length and detail)

The JRC for this profile was estimated using the Maertz and Tse Cruden estimators. The surface was then corrupted with additive noise with a standard deviation of 0.0005. This corresponds to a measurement error standard deviation of 0.5 millimetres over a profile of one metre length sampled at 1 millimetre intervals. The resulting profile is shown in Figure 2. The vertical scale has been exaggerated for clarity.

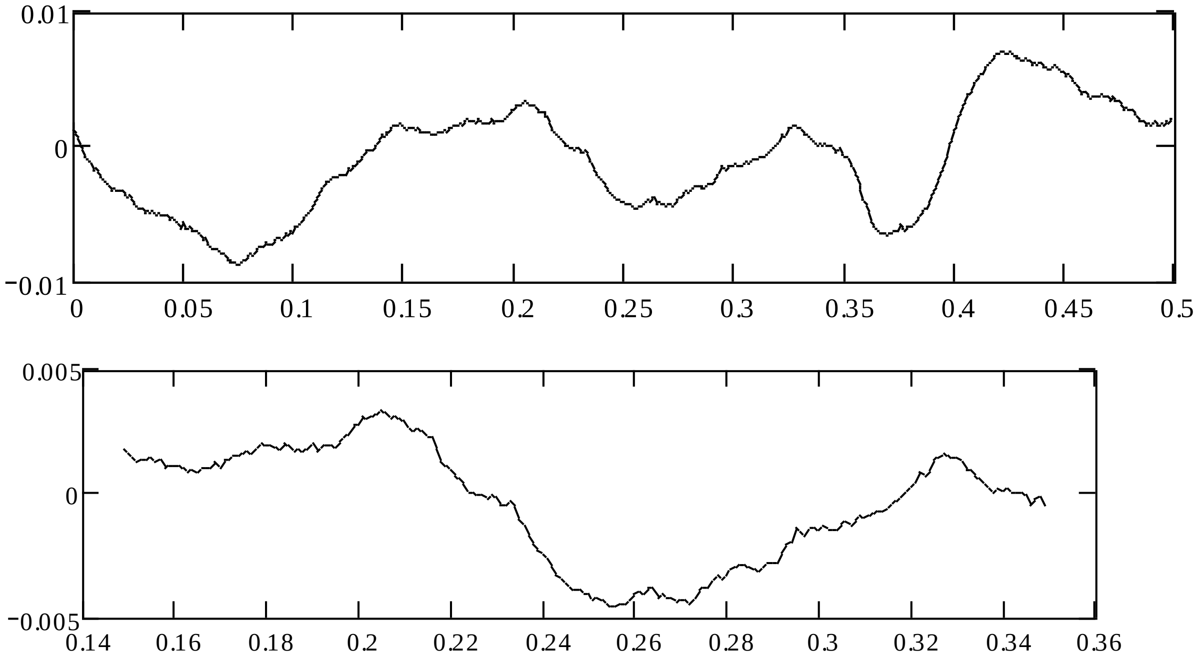

Figure 2 Surface profile corrupted with noise (full length and detail)

The noise corrupted profile was then filtered with three filters; an averaging filter with a window size of 5 pixels, a median filter with a window size of 3 pixels and a median filter with a window size of 5 pixels. Details of the filtered surface profiles are shown in Figure 3, Figure 4 and Figure 5. The excessive smoothing of the averaging filter is evident in these plots, especially in the regions (X axis) around 0.18 and 0.28.

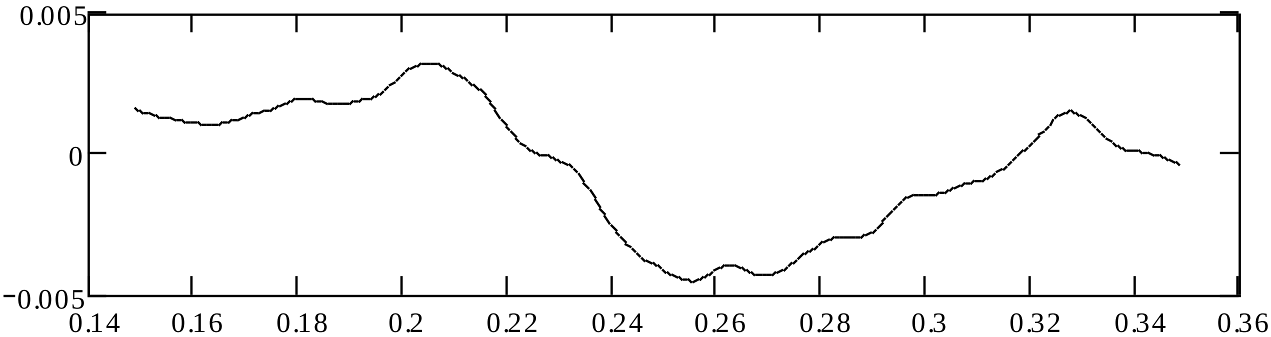

Figure 3 Detail of the surface profile filtered with a 5 pixel averaging filter

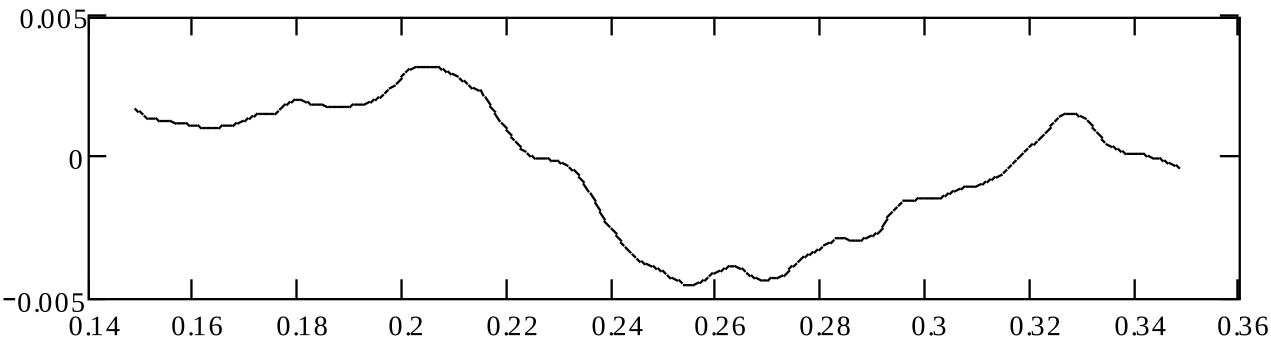

Figure 4 Detail of the surface profile filtered with a 3 pixel median filter

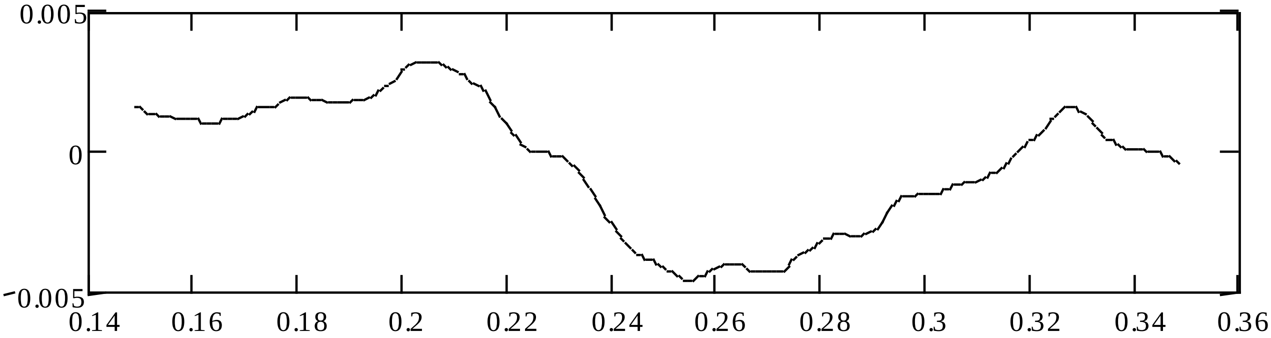

Figure 5 Detail of the surface profile filtered with a 5 pixel median filter

A summary of the results obtained using these data sets is provided in Table 1. This summary also includes the JRC calculated without noise but with the same filtering applied. This comparison data has been added as a control.

From the results obtained by filtering the noise corrupted data it would be tempting to assume that the averaging filter is the 'best' filter to use. However, this conclusion may be called into question when the JRC values for filtered data that has not been corrupted with noise are compared. In this case the averaging filter produces significantly lower estimates of the JRC and the median filters perform quite well. This is a consequence of the fact that the median filters are 'shape preserving' while the averaging filter blurs all details and thus makes the profile look smoother than it is.

The very clear message from this simulation is that if the measurement noise is significant in relation to the sample spacing these methods will over-estimate the JRC.

Table 1 Summary of JRC values for Noise to Sample Spacing of 0.5

Profile	Maertz JRC	Tse Cruden JRC
Simulated	7.03	8.59
Simulated + noise	82.95	27.52
Simulated + noise + 3 pixel median filter	24.78	18.24
Simulated + noise + 5 pixel median filter	15.39	14.68
Simulated + noise + 5 pixel averaging filter	10.36	11.43
Simulated + 3 pixel median filter	7.01	8.56
Simulated + 5 pixel median filter	6.97	8.53
Simulated + 5 pixel averaging filter	6.59	8.12

The question that arises is: When can these methods be safely applied?

Additional simulations were undertaken in which with corrupting noise had a smaller standard deviation. The analysis of these results showed that a noise standard deviation of approximately 0.1 times the sample spacing could be tolerated with improvements to the filtering algorithm. The results of these simulations are shown in Table 2.

Table 2 Summary of JRC values for Noise to Sample Spacing of 0.1

Profile	Maertz JRC	Tse Cruden JRC
Simulated Profile	7.03	8.59
Simulated + noise	11.11	11.91
Simulated + noise + 5 pixel averaging filter	6.71	8.24
Simulated + noise + 3 pixel median filter	8.75	10.24
Simulated + noise + 5 pixel median filter	8.44	9.98
Simulated + 2D 5 pixel averaging filter	6.57	8.11
Simulated + 2D 3 pixel rank filter	7.76	9.34
Simulated + 2D 5 pixel rank filter	7.16	8.75

These results are quite unambiguous. With measurement noise standard deviation of less than 10% of the sample spacing and an appropriate noise reduction filter, the shape of the profile is preserved and the JRC as estimated by the Maertz formulation or the Tse and Cruden formulation are estimated to within a close tolerance.

7 Conclusion

The development of methods of remotely determining the surface topography of rock mass discontinuities at a range of scales have enabled the estimation of the roughness of discontinuities with speed and precision that has not been hitherto achievable. These advances have spurred attempts to apply mathematical methods to characterise the roughness of a surface and use these estimates in analysing the behaviour of discontinuities in rock masses.

The data acquired by these systems must, however, be used with knowledge of the limitations of the data in the form of measurement errors as well as limitations in terms of sampling density and scale effects. This paper has reviewed some of the issues that may arise when acquiring data from a rock face remotely and attempting to use that data to estimate the roughness of a discontinuity surface.

Of major concern is the possibility that, if the measurement errors are nor properly understood and dealt with appropriately the surface roughness will be overestimated. The possibility of this outcome and the consequences that might arise from it suggest that careful assessment of the sensor system used to acquire the 3D point cloud is required.

A significant conclusion from the work reported here is that the relativity of the measurement error and the measurement scale is extremely important. When these are properly understood and controlled the use of remotely sensed 3D points clouds for the estimation of the JRC can be undertaken with confidence, but if measurements are used carelessly the JRC will be over-estimated.

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References

Baker, B.R., Gessner, K., Holden, E. and Squelch, A. (2008) Automatic detection of anisotropic features on rock surfaces, Geosphere; April 2008; Vol. 4, No. 2, pp. 418–428.

Barnsley, M.F. (1988) Fractals everywhere, Academic Press London, UK.

Egger, P. and Grasselli, G. (2003) Constitutive law for the shear strength of rock joints based on three-dimensional surface parameters, International Journal of Rock Mechanics and Mining Sciences 40, pp. 25–40.

Gentier, S., Riss, J., Archambault, G., Flamand, R. and Hopkins, D.L. (2000) Influence of fracture geometry on sheared behavior, International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 37, pp. 161–74.

Grasselli, G., Wirth, J. and Egger, P. (2002) Quantitative three-dimensional description of a rough surface and parameter evolution with shearing, International Journal of Rock Mechanics and Mining Sciences, Vol. 39, No. 6, pp. 789–800.

Haneberg, W.C. (2006) Measurement and Visualization of Directional Rock Surface Profiles Using Three-Dimensional Photogrammetric or Laser Point Clouds, Journal of Rock Mechanics and Mining Sciences 2006.

Haneberg, W.C. (2007) Directional roughness profiles from three-dimensional photogrammetric or laser scanner point clouds, Proceedings 1st Canada-U.S. Rock Mechanics Symposium, Vancouver, 27–31 May, pp. 101–106.

ISRM Commission on Standardization of Laboratory and Field Tests (1978) Suggested Methods for the Quantitative Description of Discontinuities, International Journal of Rock Mechanics and Mining Sciences and Geomechanics, Vol. 15, pp. 319–368.

Kulatilake, P.H.S.W. and Um, J. (1999) Requirements for accurate quantification of self-affine roughness using the roughness-length method, International Journal of Rock Mechanics and Mining Sciences, 36, pp. 5–18.

Maerz, N.H., Franklin, J.A. and Bennett, C.P. (1990) Joint roughness measurement using shadow profilometry, International Journal of Rock Mechanics and Mining Sciences and Geomechanics. Abstracts, 27(5), pp. 329–343.

Malinverno, A. (1990) A simple method to estimate the fractal dimension of a self-affine series, Geophysics Research Letters, Vol. 17, pp. 1953–1956.

Mandelbrot, B. (1982) The Fractal Geometry of Nature W.H Freeman

Rahman, Z., Slob, S. and Hack, R. (2006) Deriving roughness characteristics of rock mass discontinuities from terrestrial laser scan data, IAEG2006 Paper number 437.

Tse, R. and Cruden, D.M. (1979) Estimating joint roughness coefficients, International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts., 16, pp. 303–307.