Deriving roughness characteristics of rock mass discontinuities from terrestrial laser scan data

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Abstract: In this study, 3D terrestrial laser scan data have been used to quantify the surface roughness of rock mass discontinuities, to determine the roughness scale effect and to determine the influence of the range of precision. The Roughness-length method was applied to calculate fractal parameters (fractal dimension and roughness amplitude). The study showed that it is possible to calculate the fractal parameters from laser scan data of discontinuity surfaces. It has been found that the fractal dimension and roughness amplitude are very high for raw laser scan data, due to range measurement error of the used scanner.

The discontinuity surface has been reconstructed from the raw point data using a scattered data interpolation technique. The range measurement error can be removed using this data interpolation technique. The reconstructed surface visually resembles the actual discontinuity surface. The fractal parameters of the reconstructed surface have subsequently been calculated. By subtracting the fractal parameters of the raw data from the fractal parameters of the reconstructed surface, the range error of the laser scan data can be estimated.

The fractal parameters have also been calculated using different sample sizes. The fractal parameters show an increase with increasing sample size. This means that the roughness complexity of the discontinuity surface is also increasing with increasing sample size. From this observation it can be concluded that the roughness of discontinuity surfaces has a significant scale effect.

The maximum resolution of the laser scan data used in this study is 5 mm (1 point per 5 mm). The laser scan data with 5 mm resolution can only acquire roughness information from roughness features larger than 5 mm. Consequently, small-scale roughness (roughness features smaller than 5 mm) can not be obtained from the data. Therefore the resolution of the laser scan data (point density) needs to be increased to quantify discontinuity surface roughness accurately as a smaller scale.

Résumé:. Dans cette étude, des données de scanner laser 3D ont été utilisées pour quantifier la rugosité des discontinuités des masses rocheuses afin d'étudier l'effet d'échelle et l'influence du niveau de précision. La méthode de Rugosité-longueur a été appliquée pour calculer les paramètres fractaux (dimension fractale et amplitude de rugosité). L'étude a montré qu'il est possible de calculer les paramètres fractaux à partir des données de scanner laser des surfaces de discontinuité. On a trouvé que la dimension fractale et l'amplitude de rugosité sont très élevées pour les données de scanner laser brutes du à la plage des erreurs de mesure du scanner laser utilisé.

La surface de discontinuité a été reconstruite à partir des données brutes en utilisant la technique de l'interpolation des données dispersées. L'erreur de mesure peut être supprimée en utilisant cette technique d'interpolation. La surface reconstruite ressemble visuellement à la surface réelle. Les paramètres fractaux de la surface reconstruite ont ensuite été calculés. En soustrayant les paramètres fractaux des données brutes de ceux de la surface reconstruite, la plage d'erreur des données du scanner laser a été estimée.

Les paramètres fractaux ont aussi été calculés en utilisant différentes tailles d'échantillon. On a trouvé que les paramètres fractaux augmentent avec la taille de l'échantillon. Cela signifie que la complexité de la surface de discontinuité augmente aussi avec la taille de l'échantillon. De cette observation, on a conclu que la rugosité des surfaces de discontinuité a un effet d'échelle significatif.

La résolution maximale du scanner laser utilisé pour cette étude est de 5 mm (1 point tous les 5 mm). Les données de scanner laser d'une résolution de 5 mm peuvent seulement révéler des informations sur les caractéristiques des rugosités supérieures à 5 mm. Par conséquent, la rugosité à petite échelle ne peut pas être obtenue à partir de ces données. La résolution des données de scanner laser (densité de points) a besoin d'être augmentée pour quantifier la rugosité des surfaces de discontinuité à plus petite échelle.

Keywords: 3D models, discontinuities, remote sensing, rock description, data analysis, data visualisation.

INTRODUCTION

Shear strength, deformability and hydraulic conductivity of discontinuities largely depend on the surface roughness of discontinuities. It is also important to estimate the surface roughness of discontinuities accurately for a proper characterization and classification of a rock mass. Various attempts have been made to quantify the surface roughness of rock mass discontinuities. The existing roughness analysis methods are Joint Roughness Coefficient (JRC), ISRM suggested methods (ISRM, 1981), the roughness method used in the SSPC system (Hack, 1998), and methods using conventional statistical parameters and fractal dimension. However, the applicability and reliability of roughness analysis methods largely depends on the accuracy of the data acquisition. Roughness data acquisition techniques can be categorized as contact and non-contact approaches ranging from simple manual methods to mechanical profiling methods and highly sophisticated automatic optical methods (Feng et al, 2003). In this study the Roughness-length

method has been used as analysing method. The method that is used to acquire the geometric information of the discontinuity surface is 3D terrestrial laser scanning.

ROUGHNESS-LENGTH METHOD

The roughness of discontinuity surfaces has previously been characterized using the Roughness-length method by estimating the fractal dimension using laser scan data. The Roughness-length method was originally proposed by Malinverno (1990) and has later been modified by Kulatilake and Um (1999). Kulatilake and Um (1999) originally proposed this method for calculating fractal dimension of 2D profiles. Fardin et al. (2001; 2004) applied this method also to calculate the fractal dimension of 3D surfaces using 3D laser scan data of rock mass discontinuity surfaces. In this study the method used by Fardin is applied.

Fractals can be either self-similar or self-affine. Surface roughness of rock mass discontinuities are not self-similar fractals, but is considered as self-affine fractals. Therefore, only one parameter, D (fractal dimension), is not sufficient to quantify surface roughness accurately. Several researchers (Malinverno, 1990; Kulatilake and Um, 1999) proposed to include the amplitude parameter (A), which specifies variance or surface slope, along with the fractal dimension (D).

Main characteristics of the Roughness-length method

For a self-affine fractal, there is a power law relation between standard deviation of profile height and sampling window length of the profile (Malinverno, 1990). The relation is as follows (see also Figure 1):

Equation 1

$$S(w) = Aw^H$$

Equation 2

$$\log(S(w)) = \log_e A + H \log_e w$$

where:

S(w) = standard deviation of the profile height;
w = the spanning or window length of the profile;
H = the Hurst exponent and H = E – D (where E is the Euclidian dimension, E = 2 for a profile and E = 3 for a surface);
A = a proportionality constant defined as a measure of the amplitude of the profile.

The parameters H and A can be estimated from the slope and intercept, respectively (Figure 2), if plot between log(S(w)) and log(w) gives an acceptably straight line.

In Equation 1, when w = 1, the equation will be S(w) = A. Therefore, different units (mm, cm, m, km) can be used to represent w. As a result, different A values are possible for the same profile depending on the unit used for w. The value of A depends on the used scale. It means that A has the capability of capturing the effect of scale on roughness amplitude. From Figure 2, it can be observed that different roughness profiles may have same fractal dimension (D), but not same roughness amplitude (A). For example, if both D and A are the same for two roughness profiles, the roughness of the two profiles will be the similar. In case D is similar, but A is different for two profiles, the roughness of both profiles is also different. Therefore, it is not possible to estimate surface roughness using only the fractal dimension (D).

S(w) is calculated as the root mean square (RMS) value of the profile height residuals on a linear trend fitted to the sample points in a window of length w according to the following equation (see also Figure 2):

Equation 3

$$S(w) = RMS(w) = \frac{1}{n_w} \sum_{i=1}^{n_w} \sqrt{\frac{1}{m_i - 2} \sum_{j \in wi} (z_j - \bar{z})^2}$$

where:

n_w = the total number windows of length w
m_i = the number of points in window w_i
z_j = the residuals on the trend and
$\bar{z}$ = the mean residual in window w_i

This method has been used for calculating fractal parameters of not only 2D but also 3D rock discontinuity surface profiles. A power law relation between the standard deviation of the residual surface heights, S(w) and sampling window size, w, is defined for self-affine surface in the same form as Equation 1. The discontinuity surface is divided into a grid of squares as recommended by Kulatilake and Um (1999). The square grids or window sizes are between 4 % and 10 % of the total sample length. At least seven window sizes 4 %, 5 %, 6.66 %, 7.12 %, 8.31 %, 9.06 % and 10 % have selected within 4% and 10 % of the total sample. For each square, a local fitting plane is defined by least square-regression analysis. The residuals of asperity height, defined as the normal distance between the surface

asperity heights and their local fitting plane, and RMS(w) are then calculated for each square using Principal Component Analysis (PCA) of the 3D point (laser scan) data. In this method the global trend of the discontinuity surface is removed before calculation (i.e.: rotation of the surface to the horizontal X-Y plane).
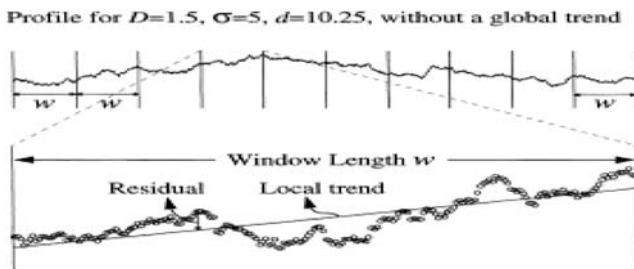
Figure 1. Main characteristics of the roughness-length method (Kulatilake et al., 1999).
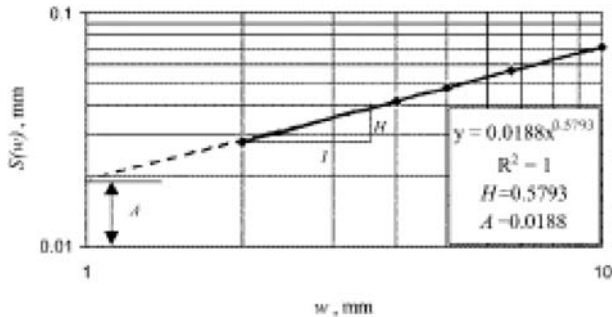
Figure 2. Log-log plot of standard deviation of reduced asperity height, S(w) versus profile length, w (after Fardin et al., 2001).

Requirement for accurate quantification of roughness using Roughness-length method

Roughness of rock mass discontinuity surfaces can be quantified by estimating the fractal parameters (fractal dimension and roughness amplitude) using the Roughness-length method. Kulatilake and Um (1999) proposed the following prerequisites for accurate quantification of roughness of natural rock joint profiles using the roughness length method:

- Data density (the number of data points per unit length) between 5.1 and 51.23;
- Fractal dimension, D between 1.2 and 1.7;
- Window sizes between 2 % and 10 % of the total sample length;
- At least seven window sizes need to be selected within the suitable minimum and maximum range of window sizes.

For example, the data density is 5.1 per unit length and window length is 2.5 %, 510 points are necessary for 100 units and 13 points are necessary in each window length. The data density is 51.23 per unit length and window length is 10 %, 5123 points are necessary for 100 units and 512 points are necessary for each window length. Therefore for accurate quantification of roughness using roughness length method data points between 510 and 5123 for 100 units or data points between 13 and 512 in each window length are required.


TERRESTRIAL LASER SCANNING

Terrestrial laser scanning technique has been used for data acquisition of rock mass discontinuities. Surfaces of discontinuous rock mass outcrops have been scanned using a terrestrial laser scanner. Large rock mass outcrops can be scanned easily without coming into contact with the rock masses using terrestrial 3D laser scanner. A terrestrial laser scanner collects a large number of 3D coordinate measurements of the scanned surface as a dense point cloud in a very short time. During scanning the reflection intensity of the reflecting surfaces of the rock masses has also been recorded. Five data sets collected from various rock mass outcrops using two types of terrestrial laser scanner have been used in this research.

DISCONTINUITY SURFACE RECONSTRUCTION

The laser scan data are resulting in a dense point cloud. The scattered point cloud data need to be interpolated to reconstruct the surface roughness of discontinuities. There are several surface reconstruction techniques such as 2D Grid, 3D Delaunay triangulation, FastRBF (RBF for Radial basis Function) etc.
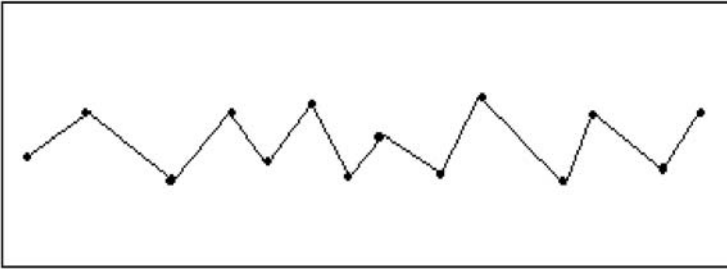
**Figure 3.** Figure 3.5: Delaunay triangulation technique.
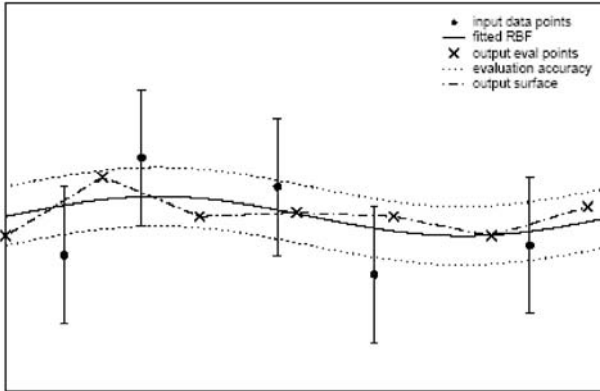
Figure 4. Figure 3.6: Fitting accuracy and evaluation accuracy (FastRBF Toolbox, 2004).

In Delaunay triangulation technique every point of the point cloud needs to be connected to reconstruct the discontinuity surface. It has the ability to describe the surface at different level of resolution. The problem with the type of laser scan data that is used in this study is that the spatial resolution is almost as large as the range error. The range error is caused by the limited precision with which the scanner can measure the range of the scanner to the object. It falls outside the scope of this study to elaborate on this. However, if the data resolution is for example in the order of 1 cm and the range error is also in the order of +/- 1 cm, then the reconstructed surface, using Delaunay, will be strongly influenced by the scatter produced by the range error, since it will only connect adjacent points (see also Figure 3). The "roughness" of a Delaunay-based surface, will therefore reflect more the noise or range error of the data, rather than the actual roughness of the surface. It is therefore better to use a parametric surface reconstruction technique that looks at regional trends, rather than connecting adjacent points.

The FastRBF scattered data interpolation technique creates a smooth surface from the scattered data using a mathematical function that is very close to the actual surface (Figure 4). The FastRBF interpolation technique has been used in this study. Radial Basis Functions (RBFs) is an interpolation technique to interpolate scattered data. Radial Basis Functions do not require that the data lie on any sort of regular grid. In a large-scale comparison of methods for interpolating scattered data in two dimensions, Franke (1982) identifies radial basis functions as "often giving the most accurate results of all tested methods" and producing surfaces that are "usually pleasing and very smooth." Hardy (1990) listed a large number of areas where Radial Basis Functions have been employed, usually with better results than competing techniques. These applications include geodesy, geophysics, signal processing, and hydrology.

DATA PREPARATION

Lustin, Belgium is famous for its stone quarry. The Tailfer rock is situated in the centre of a large synclinal structure (Syncline of Walgrappe), which forms the Northern border of the Dinant Synclinorium. The general geology of the site is well known; because the Meuse River and later the quarry activities have completely exposed the Frasnian and Famennian (Middle-Upper Devonian- bedded limestone). The rock types of scanned discontinuity surfaces consist of laminated stromatopores. It is part of the so-called Lustin Formation. The Lustin Formation is a part of the Middle Frasnian and consists of shallow water calcareous deposits (Da Silva and Boulvain, 2004).
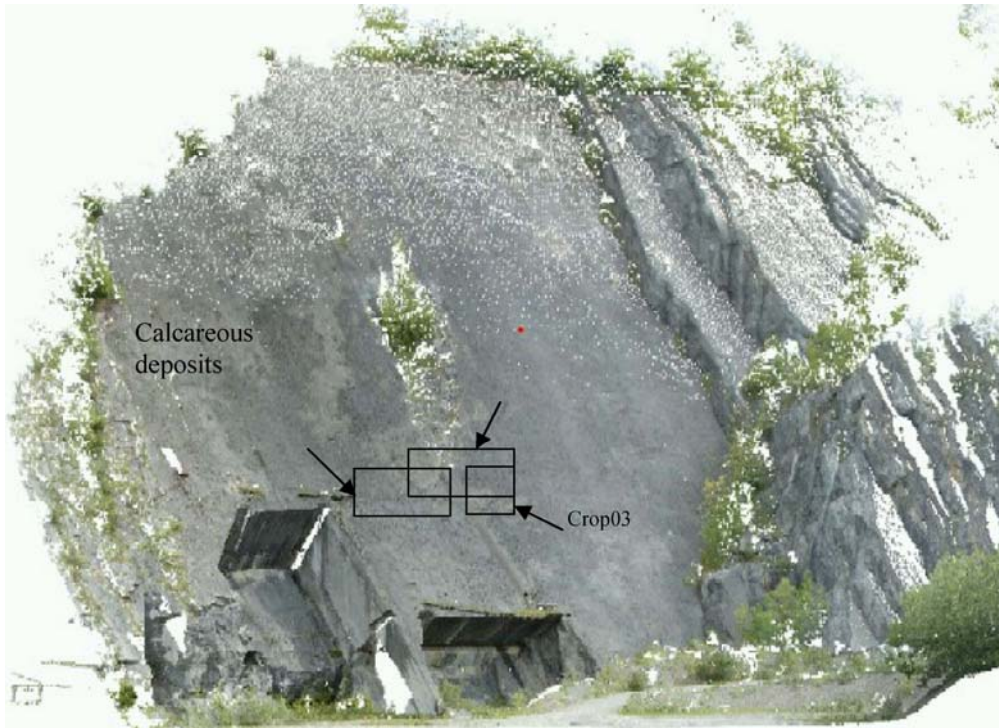
Figure 5. Overview of the laserscan of a large bedding surface taken by Riegl 3D -LMS-Z420i (site Lustin, Roche Tailfer, Belgium). The approximate locations of cropped samples (Crop01, Crop02 and Crop03) are indicated.

Part of the quarry was scanned using a Riegl LMS-Z420i terrestrial laser scanner. This scanner has a digital camera attached that takes pictures of the object that is scanned. The colour information from the digital imagery can be used to colour the point cloud generated by the laser survey. Figure 5 shows part of the quarry, showing the dipslope of the limestone bedding planes from which the 3 test surfaces have been selected. Note that Figure 5 is <u>not</u> a picture, but an actual 2D rendering of the 3D coloured point cloud.

ROUGHNESS QUANTIFICATION

Fractal parameters of the raw data

First, sample nr.01: Lustin_ScanPos01_Scan002 has been selected for analysis. Three rectangular samples, indicated as Crop01, Crop02 and Crop03, have been taken from the same discontinuity surface of this sample. The xyz coordinates and dimensions of these samples are given in Table 1.

Table 1. The xyz coordinates and dimensions of Crop01, Crop02 and Crop03 from Lustin_ScanPos01_Scan002

Sample nr.	Sample name	Minimum (m)			Maximum (m)			Dimension (m x m)
		x	y	z	x	y	z	
1.1	Crop01	-55.00	-11.00	13.55	-50.00	-6.00	21.10	6.4 x 6.1
1.2	Crop02	-55.02	-5.02	10.50	-49.98	-1.32	17.14	4.2 x 7.8
1.3	Crop03	-58.00	-8.00	13.13	-53.00	-1.42	21.59	6.5 x 7.8

The following procedures have been applied to analyze the raw data of Crop01, Crop02 and Crop03 from Lustin_ScanPos01_Scan02:

- The raw samples were not in a horizontal position. It is necessary to remove the global trend of the discontinuity surface to calculate the fractal parameters using the Roughness-length method. Therefore, the sample needs to be rotated a in a horizontal position. The samples are first rotated around the Z- axis along the strike to align along the X-plane. Subsequently, the samples are rotated around the X-axis along the dip to align with the Z-plane (projected to the XY plane). From the sample projected to the XY plane, a square sub-sample size of 1 m2 has been taken for analysis from each initial sample.
- The square sub-sample (size: 1 m2) has been divided into square grid or windows. The window sizes vary between 4 % and 10 % of the total sample size (Table 2) according to Roughness-length method.
- For each square window, a local fitting plane is defined by a least square-regression analysis using Matlab's Principal Component Analysis (PCA) function. The residuals of asperity height (standard deviation), defined as the normal distance between the surface asperity heights and their local fitting plane, are calculated for each square window from the trend surface of the least square-regression.

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- The standard deviations of all points in each window are calculated in Matlab. The results are subsequently exported to Excel. The standard deviations of all windows in each sub-sample are added together and the average standard deviation per window is calculated (Table 3).
- Window sizes and corresponding standard deviations of Crop01, Crop02 and Crop03 are plotted as X and Y-axis respectively as a double log graph, which generally show a linear trend (Figure 6).
- A best fitting line has been drawn using power law equations. In this analysis, the least square regression value (R^2) is more than 0.97 for every sample. Therefore the window sizes and the corresponding standard deviations show a strong correlation.
- In the double log graph the slope and intercept of the trend line are the Hurst exponent (H) and roughness amplitude (A) (Figure 6).
- From the Hurst exponent (H), the fractal dimension (D) can be calculated using the following equation: D = E - H; where, E is the Euclidian dimension, E = 3 for (3D) surfaces and E = 2 for (2D) profiles and H are 0 < H < 1 (Table 4).

Table 2. Procedure of dividing the sample into windows. Sample size: 1 m2

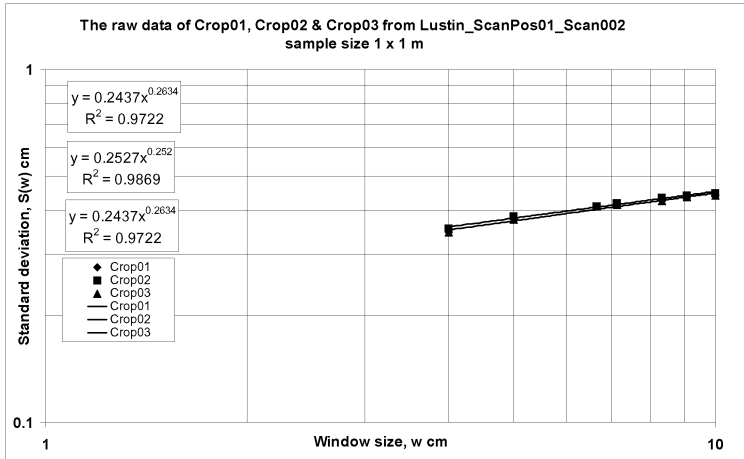| Window size (%)	Grid cells	Total # windows	Area/window (cm2)
4	25 x 25	625	4.0
5	20 x 20	400	5.0
6.66	15 x 15	225	6.66
7.12	14 x 14	196	7.12
8.31	12 x 12	144	8.31
9.06	11 x 11	121	9.06
10	10 x 10	100	10.0

The fractal dimensions and roughness amplitudes of Crop01, Crop02 and Crop03 can be found in Table 4. The parameters of these samples are close but not similar. This means that the roughness of the discontinuity plane changes slightly. Kulatilake and Um (1999) suggested that the fractal dimension of a rock mass discontinuity profile could vary between 1.2 and 1.7. For surfaces, it can be between 2.2 and 2.7. However, the fractal dimension estimated using the raw data is more than 2.7. This high value of fractal dimension should be mainly contributed to the range measurement error of the scanner. Therefore it is necessary to remove the range measurement error of the laser scan data to calculate the fractal dimension for accurate quantification of the surface roughness of discontinuity.

Table 3. Table 5.4: Window sizes and corresponding standard deviations of the raw data of Crop01, Crop02 and Crop03. he raw data of Crop01, Crop02 and Crop03 from Lustin_ScanPos01_Scan002, sample size: 1 m2

Window size, w (cm)	Crop01	Crop02	Crop03
	Std dev, S(w) (cm)	Std dev, S(w) (cm)	Std dev, S(w) (cm)
4.0	0.353	0.353	0.345
5.0	0.386	0.387	0.375
6.66	0.422	0.409	0.411
7.12	0.431	0.418	0.414
8.31	0.443	0.432	0.425
9.06	0.456	0.440	0.435
10.0	0.466	0.446	0.439

Table 4. Table 5.5: Fractal dimensions and roughness amplitudes of the raw data of Crop01, Crop02 and Crop03. The raw data of Crop01, Crop02 and Crop03 from Lustin_ScanPos01_Scan002, sample size: 1 m2

Sample nr.	Sample name	Hurst exponent, H	Fractal dimension, D (D = 3 -H)	Roughness amplitude, A (cm)
1.1	Crop01	0.2634	2.7366	0.2437
1.2	Crop02	0.2520	2.7480	0.2527
1.3	Crop03	0.2634	2.7366	0.2437

The raw data of Crop01, Crop02 & Crop03 from Lustin_ScanPos01_Scan002
sample size 1 x 1 m

$y = 0.2437x^{0.2634}$
$R^2 = 0.9722$

$y = 0.2527x^{0.252}$
$R^2 = 0.9869$

$y = 0.2437x^{0.2634}$
$R^2 = 0.9722$

◆ Crop01
■ Crop02
▲ Crop03
— Crop01
— Crop02
— Crop03

Standard deviation, S(w) cm

Window size, w cm

Figure 6. Log-log plot of window size versus standard deviation of the raw data of Crop01, Crop02 and Crop03, sample size: 1 m2.

Data interpolation for surface reconstruction

An attempt was made to remove the range measurement error from the raw data using the FastRBF interpolation techniques. After removing the range measurement error, the procedures that were applied for the raw data have been used to calculate the fractal parameters. The raw data of Crop01, Crop02 and Crop03 from Lustin_ScanPos01_Scan002 are used to remove the range measurement error.

### Visualization of the reconstructed surface

The filtered and unfiltered reconstructed surface data exported as Wavefront 'obj' files can be visualized in Deep Exploration or most 3D visualisation program. The unfiltered reconstructed surface data are showing artefacts (unwanted spikes) due to noise or range measurement error of the scanner, for example, unfiltered and filtered reconstructed surface data of Crop02 (Figure 7 and Figure 8). The filtered reconstructed surface data are not showing much artefacts; this means that most of the noise contributed due to the range measurement error of the scanner have been removed.

### Fractal parameters of the reconstructed surface

The unfiltered and filtered reconstructed surface data of Crop01, Crop02 and Crop03 have been analyzed on the basis of the Roughness-length method using the Matlab script. The unfiltered and filtered reconstructed surface data are loaded as text files separately in Matlab. The analyzing procedures are the same as the procedures that have been used for the raw data. The window sizes and corresponding standard deviations are given in Table 5 for unfiltered reconstructed surface data and in Table 6 for filtered reconstructed surface data. The window sizes and corresponding standard deviations are plotted on the X and Y-axis, respectively, in double graphs for both the unfiltered and filtered data (Figure 9 and Figure 10). Both plots show a linear trend. A least square regression trend line is drawn using power law regression analysis. The R2 (least square regression) values are more than 0.99 for both unfiltered and filtered data. The fractal dimension and the roughness amplitude for unfiltered and filtered data are shown in Table 7 and Table 8, respectively.

It has been found that the fractal dimension of the unfiltered reconstructed surface data is lower than that of the raw data and higher than that of the filtered reconstructed surface data (filter width 1 cm). It means that the fractal dimension has decreased from the raw data to the filtered data. The roughness amplitude of the surface has also decreased from the raw data to the filtered data for Crop01, Crop02 and Crop03 (Figure 11, Figure 12 and Figure 13).

It seems likely to assume that the fractal dimension and roughness amplitude of the raw data are high due to the inherent noise of the raw data. This, in turn, can to a large part be contributed to the range measurement error of the scanner. An attempt was taken to remove the inherent noise from the raw data using the FastRBF 'fitting plane' and '3D iso-surface' functions. Therefore, the fractal dimension and roughness amplitude of the raw noisy data are less than that of the reconstructed surface data. After interpolation of the data in this manner the roughness information is assumed to be more representative to the actual roughness of the discontinuity surfaces (Figure 8). The fractal dimension and roughness amplitude of the smoothed or filtered data of 1 m2 discontinuity surface from Crop01, Crop02 and Crop03 are given Table 8). It has been observed that the fractal parameters of three different areas (1 m2) of the same discontinuity surface are very close, but not similar. It means that the roughness of the discontinuity surface is not the same anywhere on the discontinuity surface.

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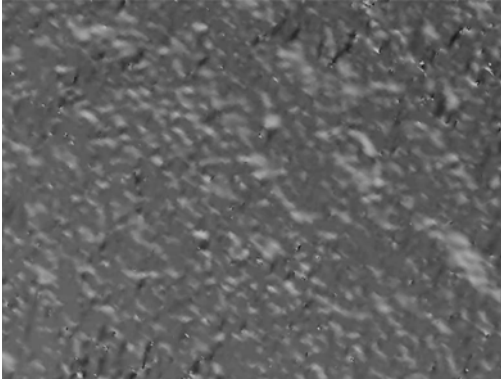
Figure 7. Figure 5.9: Example of <u>unfiltered</u> reconstructed surface data of Crop02 from Lustin_ScanPos01_Scan002, mesh resolution 1 cm, without filtering.
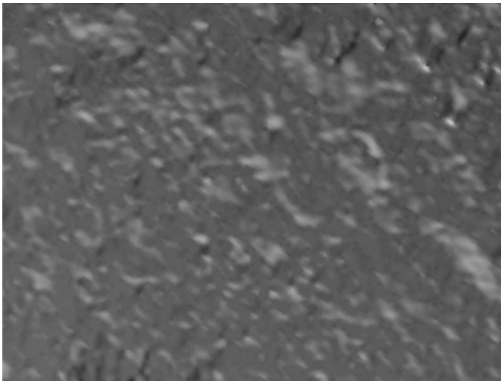
Figure 8. Figure 5.10: Example of <u>filtered</u> reconstructed surface data of Crop02 from Lustin_ScanPos01_Scan002, mesh resolution 1 cm, filter width 1 cm.

The resolution of this laser scan data is 1 cm. Therefore, the roughness features less than 1 cm are not captured in this laser scan data. Consequently, fractal dimension and roughness amplitude of discontinuity surfaces are calculated using roughness features greater than 1 cm.

It is necessary to choose a unit of measurement (scale) to calculate fractal parameters of a natural rock joint profile. Roughness measurement units need to be less than 1 mm for complete acquisition of roughness information of rock mass discontinuity surfaces. The data density (resolution) between 5.1 and 51.23 per mm is necessary for the rock mass discontinuity profile (Kulatilake and Um, 1999). Therefore, the minimum data points are 25 per square mm and a maximum of 2625 data points per square mm are needed for surfaces. The data density of 25 points per square mm can be achieved but data density of 2625 points per square mm may be still impractical.

The resolution of laser scan Lustin_ScanPos01_Scan002 is 1 cm. For this data, the measurement unit of roughness needs to be 5 cm. This means at least 5 points per 5 cm are necessary to fulfil data density requirement that proposed by Kulatilake and Um (1999). Therefore, the minimum window length needs to be 2.5 % of the total sample size (12.5 cm) and the maximum window length needs to be 10 % of the total sample size (50 cm) for sample length of 100 units. This means that a minimum sample length 5 m is necessary. For surface, minimum sample size 25 m2 is required. In this study a minimum sample size is taken of 1 m2. The minimum window size is taken 4 % of the total sample size. 4 % of the total sample size means that minimum window size for 1 m2 sample size is 4 cm2. The maximum window size is taken 10 % of the total sample size; this means that maximum window size for 1 m2 is 10 cm2. The minimum window size of 4 cm2 and maximum window size 10 cm2 of this sample do not fulfil the requirements of minimum window size and maximum window size. However, log-log plot of window sizes and corresponding standard deviations give an acceptable linear trend. The least square regression value (R2) of the trend line is more than 0.99 (Figure 9 and Figure 10). Kulatilake and Um (1999) suggested that R2 more than 0.81 could be acceptable.
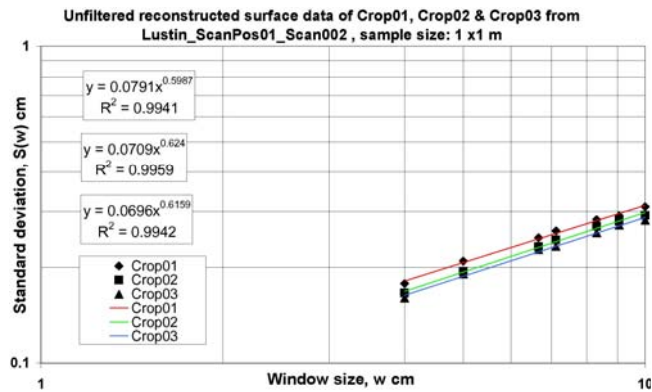
Table 5. Window sizes and corresponding standard deviations of unfiltered reconstructed surface data of Crop01, Crop02 and Crop03. Unfiltered reconstructed surface data of Crop01, Crop02 and Crop03 from Lustin_ScanPos01_Scan002, <u>without filtering</u>, sample size: 1m2
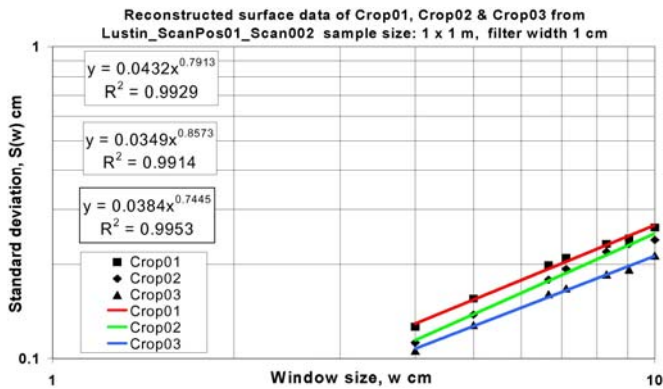
Window size, w (cm)	Crop01	Crop02	Crop03
	Std dev, S(w) cm	Std dev, S(w) cm	Std dev, S(w) cm
4.0	0.178	0.166	0.160
5.0	0.210	0.194	0.191
6.66	0.248	0.233	0.228
7.12	0.261	0.244	0.233
8.31	0.283	0.269	0.257
9.06	0.291	0.280	0.272
10.0	0.311	0.292	0.282

Table 6. Window sizes and corresponding Standard deviation of filtered reconstructed surface data of Crop01, Crop02 and Crop03. Filtered reconstructed surface data of Crop01, Crop02 and Crop03 from Lustin_ScanPos01_Scan002, <u>Filter width 1 cm</u>, sample size: 1m2

Window size, w (cm)	Crop01	Crop02	Crop03
	Std dev, S(w) cm	Std dev, S(w) cm	Std dev, S(w) cm
4.0	0.126	0.113	0.106
5.0	0.155	0.138	0.128
6.66	0.199	0.179	0.161
7.12	0.210	0.193	0.168
8.31	0.232	0.220	0.186
9.06	0.242	0.232	0.193
10.0	0.262	0.240	0.213

Figure 9. Log-log plot of window size versus standard deviation of Crop01, Crop02 and Crop03, without filtering.

Figure 10. Log-log plot of standard deviation versus window size of Crop01, Crop02 and Crop03, with filter width of 1cm.

Table 7. Fractal dimensions and roughness amplitudes of unfiltered reconstructed surface data of Crop01, Crop02 and Crop03. Unfiltered reconstructed surface data of Crop01, Crop02 and Crop03 from Lustin_ScanPos01_Scan002, <u>without filtering</u>, sample size: 1m2

Sample nr.	Sample name	Hurst exponent (H)	Fractal dimension, D (D = 3 -H)	Roughness amplitude, A (cm)
1.1	Crop01	0.5987	2.4013	0.0791
1.2	Crop02	0.6240	2.3760	0.0709
1.3	Crop03	0.6159	2.3841	0.0696

Table 8. Fractal dimensions and roughness amplitudes of filtered reconstructed surface data of Crop01, Crop02 and Crop03. Filtered reconstructed surface data of Crop01, Crop02 and Crop03 from Lustin_ScanPos01_Scan002, <u>Filter width 1 cm</u>, sample size: 1m2

Sample nr.	Sample name	Hurst exponent (H)	Fractal dimension, D (D = 3 -H)	Roughness amplitude, A (cm)
1.1	Crop01	0.7913	2.2087	0.0432
1.2	Crop02	0.8573	2.1427	0.0349
1.3	Crop03	0.7445	2.2555	0.0348

Table 9. Fractal dimension (D), roughness amplitude (A), least square regression value (R2) of the <u>raw data, unfiltered and filtered reconstructed surface data</u> of Crop01, Crop02 and Crop03. Crop01, Crop02 and Crop03 from Lustin_ScanPos01_Scan002, sample size: 1 m2

Sample nr.	Sample name	Data type	Fractal dimension, D	Amplitude, A (cm)	Least square regression value, R2
1.1	Crop01	Raw data points	2.7366	0.2437	0.9722
		Gridded data point without filtering	2.4013	0.0791	0.9941
		Gridded data point 1 cm filter width	2.2087	0.0432	0.9929
1.2	Crop02	Raw data points	2.7480	0.2527	0.9869
		Gridded data point without filtering	2.3760	0.0709	0.9959
		Gridded data point 1 cm filter width	2.1427	0.0349	0.9914
1.3	Crop03	Raw data points	2.7366	0.2437	0.9722
		Gridded data point without filtering	2.3841	0.0696	0.9942
		Gridded data point 1 cm filter width	2.2555	0.0348	0.9953
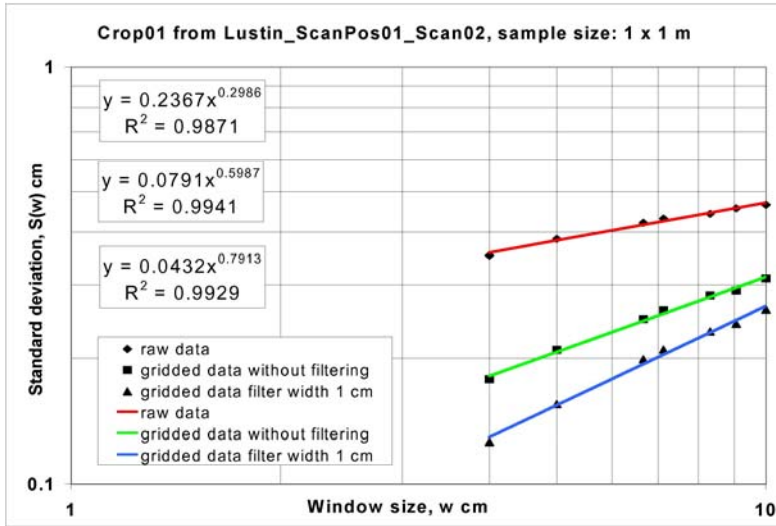
Figure 11. Comparison of fractal dimensions, roughness amplitudes of the raw data, unfiltered reconstructed surface data and filtered reconstructed surface data of Crop01.
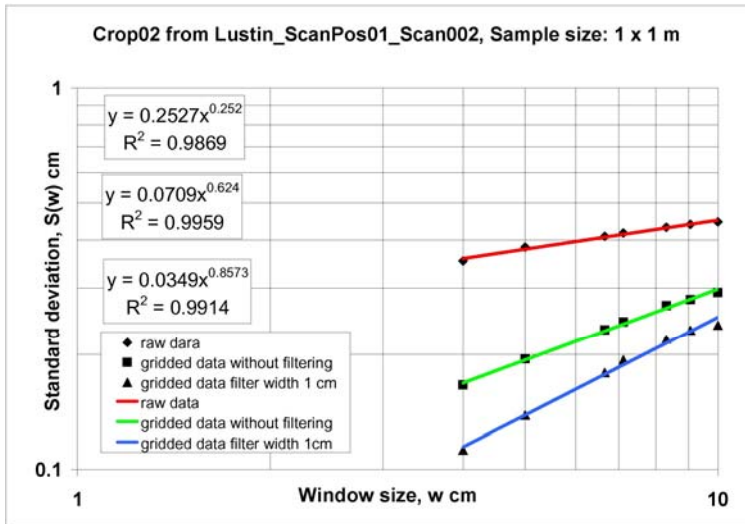
Figure 12. Comparison of fractal dimensions, roughness amplitudes of the raw data, unfiltered reconstructed surface data and filtered reconstructed surface data of Crop02.
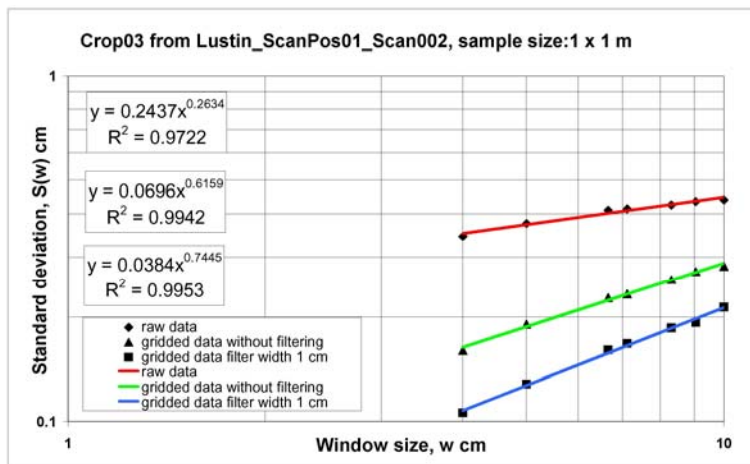
Figure 13. Figure 5.15: Comparison of fractal dimensions, roughness amplitudes of the raw data, unfiltered reconstructed surface data and filtered reconstructed surface data of Crop03.

CONCLUSIONS

On the basis of this study, the following conclusions can be made:

Terrestrial laser scan data have been used to quantify the surface roughness of rock mass discontinuity surfaces. Surface roughness of rock mass discontinuity has been estimated using fractal parameters (fractal dimension and roughness amplitude). The roughness-length method has been used to determine the fractal parameters. The fractal dimension and amplitude parameter are very high for the raw laser scan data. The fractal parameters of the raw data are high due to the range measurement error of the scanner. The range measurement error can however be removed using the FastRBF data interpolation and smoothing techniques. The fractal parameters of the interpolated data are lower than that of the raw data. If the fractal parameters of the Roughness-length method are calculated using, for example, data resolution of 1 cm, the roughness of the discontinuity surface that can be quantified covers the feature sizes only more than the 1 cm.

The fractal parameters of the raw laser scan data are higher than that of the interpolated data. In the interpolated data the range measurement error from the laser scan data is removed. Therefore the fractal parameters of the interpolated data are considered more representatives to the roughness of the discontinuity surface. By subtracting the fractal parameters of the raw data from the fractal parameters of the interpolated data, the error of the laser scan data can be estimated.

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