Application of Photogrammetry and Image Analysis for Rock Slope Investigation

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ABSTRACT: This study reviews the applications of close range photogrammetry (CRP) on modelling for rock slope stability analysis and weathering investigations focussing on the applicability of CRP to obtaining roughness characteristics. Current photogrammetric techniques have a potential to provide roughness profiles with dense measurement intervals. However, the quality of the roughness data is still questionable and the level of accuracy has not been sufficiently investigated. To advance the boundaries of the availability of CRP, this paper presents methodologies which can quantify the degree of accuracy for the obtained roughness data and to detect the data noise as an evaluation tool. Firstly, this study suggests an error model which measures the level of accuracy based on an ideal lab condition. The level of accuracy of rock joint roughness coefficient (JRC) obtained from CRP can be interpreted by using the developed error model. Secondly, this paper presents an image analysis workflow via a MATLAB image filtering code for the estimation of recession areas focussing on the variation of rock surface roughness. This post-process of CRP supports more reliable interpretation of photogrammetric roughness data. The developed error model and the combined image analysis with 3D photogrammetric models could compensate the limitations of the uses of both digital photographs and 3D surface models to obtain roughness characteristics and for quantifying weathering patterns.

Keywords: Photogrammetry, Rock surface roughness, Image analysis, MATLAB, Weathering.

1. INTRODUCTION

In rock slope investigation, the procedure of rock mass characterization is simple and relies on visual impression of the rock structure. Considering geological composition and joint surface conditions in small scale, visual assessment plays an important role for the determination of RMR and Q values in engineering purposes. As visual assessment is subjective, digital mapping methods and image analysis techniques have assisted the investigations to minimize human errors. Recently, terrestrial laser scanning (TLS) and close range photogrammetry (CRP) have been employed effectively to create 3D surface models and to generate the data of discontinuities with great accuracy. The obtained high-resolution images from these techniques can contain detailed geological composition of rock surfaces and the images are analysed using various analysis tools.

Close range photogrammetry (CRP) has been used in recent years to create 3D slope models for stability analysis in rock engineering (Ferrero et al., 2011; Firpo et al., 2011; Brideau & Stead, 2012). Recent high-end equipment in the field of digital photographing can create high resolution images and this technology has encouraged the spread of CRP to obtain surface features such as undulation and roughness which require higher degree of accuracy of 3D models. As a major research interest of the authors, the feasibility of CRP to investigate rock surface roughness has been actively studied focusing on the accuracy of 3D models within allowable distances (Kim et al., 2015b; Kim et al., 2016a). The idea from the previous studies developed a JRC (joint roughness coefficient) error model to interpret the errors of JRC values obtained from site photogrammetry surveys.

In rock engineering, roughness is a crucial factor in determining both the conditions of discontinuities and the weatherability of rock masses. Using the geological strength index (GSI) system, the roughness of rock joints can be quantified by using roughness parameters such as JRC and J_s (joint smoothness factor) relating to the friction characteristics of rock joints. In the case of weathering investigation, rock surface roughness has been employed to investigate the rate of weathering as the change of roughness can indicate the recession of rock surface by weathering (Meierding, 1993; McCarrorll and Nesje, 1996; White et al., 1998; Pope et al., 2002; Sancho et al., 2003). However, it should be noted that the roughness values are not the only possible parameter to explain the aspect of weathering because the products of weathering appear in different ways due to their geological formation.

In order to identify geological characteristics, digital images have been effectively interpreted by using various image analysis techniques. For example, McEwan et al. (2000) introduced an image analysis technique to assess ground erosion. As another example, Trauth (2010) studied individual grain sizes of deposits and geological settings by analysing digital images. Microscopic images were also employed to investigate the degree of weathering with a quantitative image analysis technique (Puente et al., 2006). However, it is inadequate to analyse recession areas by image analysis technique itself. Also, combining the data obtained from both the colours of 2D images and the changes of 3D surface model is complicated. The limitations of the application of photographs to quantify degradation areas by weathering was also discussed by Ortiz et al. (2013). Nonetheless, digital images effectively characterize the localized roughness on the surface of rocks using the information on the adjacent pixels of images. If the features of interest on a rock surface are simple and its colour is fairly uniform, the changes of undulation and roughness can be more precisely detected by the change of regional brightness. Thus, the correlations between the brightness and the asperities obtained from 3D images may compensate the limitations of both methodologies.

In this paper, the degree of accuracy of CRP to obtaining roughness data is widely discussed and the relevant errors are interpreted by using a photogrammetric JRC error model. Also, this study suggests a workflow of image analysis combining the images of 3D models and the changes of roughness data focussing on the relationships between roughness variation and colour information. To enhance the reliability of photogrammetric roughness data, the data of roughness heights are processed with relative brightness integers obtained from its greyscale images and a MATLAB image analysis technique is employed to filter the images.

2. ROCK SURFACE INVESTIGATION USING CLOSE RANGE PHOTOGRAMMETRY

2.1 Image resolutions in close range photogrammetry

Photogrammetry is a science to obtaining precise three dimensional models using two or more images. Close range photogrammetry (CRP) can be defined by the camera distance from the object of interest. CRP can be simply separated by the camera-to-object (c-to-o) distance of less than around 300 metres from the basic principles of aerial photogrammetry (Matthew, 2008). In order to investigate rock surface roughness, the ranges of c-to-o distances are much closer than the guideline as the targets of surveys are focussed on the detailed features of rock surfaces. It can be defined as an appropriate range of c-to-o that produces high resolution 3D images with small pixel sizes to such an extent as to generate roughness of rock surfaces.

In field conditions, the resolution of 3D models depends on the scale at which it is being considered combined with the field conditions. In the case of large scale photogrammetry surveys (point interval > 10 mm), several examples of achieved point intervals with different photogrammetry setups are presented in Table 1. With regard to the determination of image resolution, the point intervals of images are controlled by the following three parameters; camera sensor size, lens focal length and camera-to-object distance. These parameters should be mutually adjusted in photogrammetry setups to obtain the intended resolutions of 3D images.

Table 1 Examples of camera setups and image resolutions

authors	device/ software	① no. effect. pixels	② c-to-o dist. (m)	③ lens FL (mm)	④ point spac. (mm)
ADAM Tech	Nikon D2x /3DM Analyst	12e6	600	180	74
ADAM Tech	Nikon D2x /3DM Analyst	12e6	1200	400	66
Gaich et al., (2006)	Nikon D70s /ShapeMetriX3D	6e6	30	35	25 ~70
Voyat et al., (2006)	Nikon D100 /Virtuozo	6e6	-	18	50
Poropat, (2008)	Nikon D300 /Sirovision	12e6	100	100	60

①: number of effective pixels, ②: camera-to-object distance, ③: focal length of lens, ④: point cloud spacing

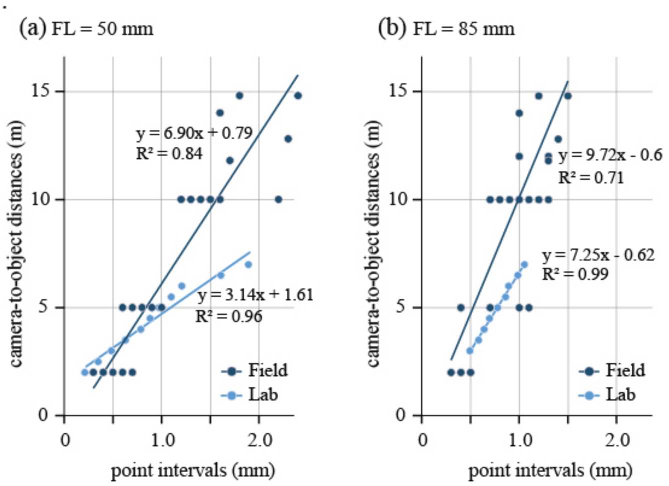

Figure 1 Relationships between camera-to-object distances and point intervals in fields and laboratory conditions; FL = 50 mm (a), FL = 85 mm (b)

For the case of small scale photogrammetry survey (e.g. point interval < 10 mm), some experimental data of point intervals are presented in Figure 1. The data in the figure were collected over six site investigations and under a laboratory condition, and obtained by using a Nikon D7000 digital camera (sensor resolution: 4,928 × 3,624 pixels) with fixed focal length lenses (Nikon Nikkor, FL = 24, 50, 85 mm). Relevant test data are well presented in the authors' previous study (Kim et al., 2016a). The data distributions show that the point intervals increase linearly. In the field conditions, the point intervals show rather scattered patterns (R^2 = 0.71 ~ 0.84) compared to those obtained under laboratory conditions (R^2 = 0.96 ~ 0.99). It is clearly demonstrated in the data distribution that a combination of a distance (around 5 metre) with a focal length lens (FL = 50 mm) was able to achieve a range of point intervals in high resolution ranges (e.g. less than 1.0 mm).

2.2. Application of CRP in rock engineering

2.2.1 Photogrammetric modelling

In rock engineering, photogrammetry has been effectively used to provide detailed information about the discontinuities of rock masses for various geotechnical and hydrogeological issues (Sturzenegger & Stead, 2009; Ferrero et al., 2011; Firpo et al., 2011; Brideau et al., 2012). The scales of the objects in photogrammetry surveys are various from a large open pit to individual rock blocks. In a large scale survey, 3D models provide detailed structural information which can be integrated into broader structural systems obtained through a GIS based geological map and a terrain digital elevation model. On slope stability issues, 3D surface models obtained from closer c-to-o distances have been used to construct model geometries for creating numerical models for various analyses such as landslides and rock falls. CRP has produced satisfactory results in the detection of joint sets and in the accuracy of the corresponding data for the joint orientations.

Figure 2 is an example of small scale CRP models. This model was created for a natural slope located along a drive road in the Tamborine Mountain area, Gold Coast, Australia (Kim et al., 2015a). The photogrammetry survey was to obtain measurements of the orientations of the joint sets of the slope and the shape and size of rock blocks at the inaccessible slope. Two images were captured at two camera positions using a Nikon D7000 camera with a 24 mm focal length lens with 33 metres of c-to-o distance. The model was created by using a photogrammetry program Sirovision (CSIRO, 2012). Based on the exposed joint sets of the 3D model, it was estimated that the rock mass consisted of polygonal blocks with the average volume being in the range of 0.4 ~ 1.8 m^3.

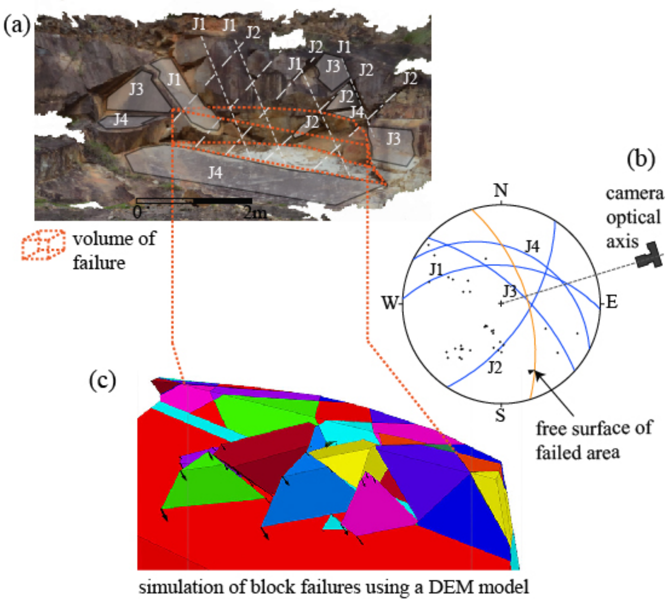

Figure 2 Photogrammetric model for a failed rock slope (a); stereonet projection of main joint sets (b); a 3DEC model at a sliding step (c) (Kim et al., 2015a)

As shown in Figure 2, structural mapping of joint sets was performed by a stereonet projection method using the obtained joint data. The 3D model was also utilized to obtain JRC values to assess a range of friction angles of the joint sets for stability analysis. However, the required extent of resolution of 3D images for the estimation of JRC values can be an issue because the accuracy of photogrammetric JRC values has been insufficiently established. The camera setup in this case study created a 3D image with 2.9 mm of an average pixel size. This value may be included in a sufficient range of density for structural mapping of joint sets. Considering the typical size of profile gauge for measurement of joint roughness (1mm interval), the resolution of the 3D image may lead to a range of errors in the estimation of JRCs.

2.2.2 Measurement of rock surface roughness

Based on the advantages of various visual information obtained from images and the feasibility of photogrammetry for creating 3D surface models, many researchers have employed photogrammetry for characterizing surface roughness (Jessell et al., 1995; Cravero et al., 2001; Lee & Ahn, 2004; Unal et al., 2004; Bistacchi et al., 2011; Sturzenegger & Stead, 2009; Nilsson et al., 2012). The applications of photogrammetry have been also found in wide ranges from archaeological to scientific purposes. Due to the importance of the use of roughness data, the feasibility of photogrammetry for the roughness investigation has been steadily studied. Recent studies just covered basic issues for the applicability of photogrammetry to estimate JRC (joint roughness coefficient) values (Haneberg, 2007; Baker et al., 2008; Poropat, 2008). These previous studies addressed the issues of the extent of accuracy of CRP with the image scales.

Evaluation of the accuracy and precision of CRP is difficult because of the uncertainty of photogrammetric data derived from various factors. The influencing factors can be introduced by both inaccuracies in camera system and bad planning of camera network geometry. For example, lens distortion is one of the most significant factors that can lead to systematic errors and needs to be taken into account for any photogrammetry applications. Also, depth accuracy is a factor which is related to planning of camera network. These influencing factors are well identified and discussed in various references on photogrammetry.

Considering the various influencing factors, statistical approaches have been employed to investigate the accuracy of photogrammetry. To measure the accuracy of continuous variables, the root-mean-squared-error (RMSE) and the mean absolute error (MAE) are commonly employed. RMSE has been widely used to identify the accuracy of data due to its high correlation between the predicted values and the observed values. In a photogrammetry standard, the accuracy of geospatial data obtained from photogrammetry has been classified using the RMSE of data coordinates (ASPRS, 2014). As a natural measure of average error magnitude, advantages of MAE have also been also reported (Willmott & Matsuura, 2005; Chai & Draxler, 2014).

Kim et al. (2015b) showed a quadratic function between the obtained errors from photogrammetry and camera-to-object distances based on a set of ideal laboratory tests. The proposed quadratic functions which are correlations between the difference of JRC values and the normalized JRC values showed upward parabolic curves with different widths according to the employed focal length of lens. The photogrammetric JRC values were distributed in both over estimation and under estimation ranges. Since the laboratory data were predominantly plotted in the range of underestimation, the quadratic regression curves were partly lack of correlations in the range of overestimation. Considering the balance of data, it is reasonable that the data can be interpreted by dividing the data range into underestimation and overestimation categories. The proposed error functions have been then improved as shown in Figure 3 (a). With the use of absolute values, the basic form of the MAE of JRC is simpler than the RMSE form as given in Eq. (1).

$$MAE_{JRC}=\sum_{i=1}^{n}|JRC_{o,i} - JRC_{p,i}| / N \quad (1)$$

The error models have been verified by using sets of field data (See Figure 3 (b) (Kim et al., 2016a). The results showed that the most influential of all the factors on the accuracy of roughness data was the point interval of 3D models. The results also showed that the oblique angles of the optical axis to the pole can significantly affect the accuracy of roughness data. The errors of photogrammetric JRC values obtained from field surveys are plotted in Figure 3 (b). The point intervals of roughness profiles in the graph was less than 1 mm.

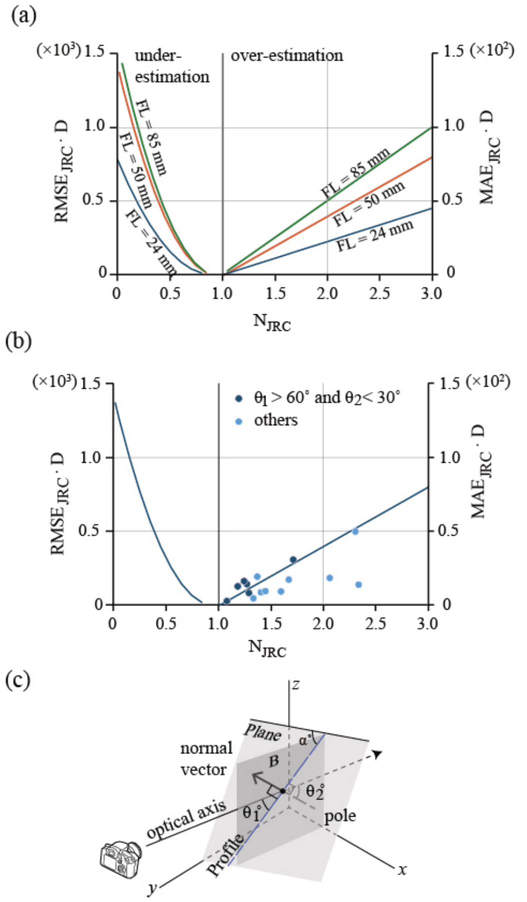

Figure 3 Photogrammetric JRC error models (a), an example of RMSE and MAE of JRC values obtained from field photogrammetry survey (FL = 50 mm) (b), camera oblique angle and normal vector of a section of interest (c) (Kim et al., 2016a)

Within the range of the dense point interval (e.g. less than 1 mm), the errors could be interpreted using the developed error models with close correlations. Figure 3 (b) also shows that the effect of the photograph angles on the accuracy of roughness data within the range of high oblique angles (e.g. $\theta_1 > 60°$ and $\theta_2 < 30°$). The relevant angles are identified by using a simplified figure (Figure 3 (c)). The experimental study showed that the accuracy of asperity heights and roughness parameter such as JRC values obtained from field photogrammetry surveys can be verified by comparing the values with the developed error model.

2.3 Investigation for weathering

As an indicator of the degree of weathering, rock surface roughness has been employed to investigate weathering states (McCarroll &

Nesje, 1996; White et al., 1998; Gómez-Pujol et al., 2006; Pinho et al., 2006). McCarroll & Nesje (1996) showed that roughness is a useful indicator to quantify the degree of weathering through a set of measurement of roughness profiles using profile gauges. Combined with modern survey techniques, weathering investigation has been expanded to the use of 3D digital surface models. Using the triangulate point clouds obtained from a laser scanning method, Medapati et al. (2013) attempted to use the γ-value, which is the angle from the vertical axis to the normal vector, for identifying the rock surface roughness in different weathering conditions. As high density photogrammetry 3D models allow for characterizing the detailed features of rock surfaces, any variations of the surfaces relating to erosion, roughness and damages of rock surfaces from weathering and excavation can be detected by performing long-term photogrammetry surveys.

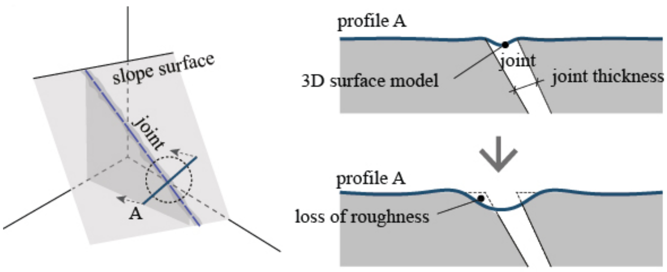

Figure 4 Changes of 3D model presenting loss of roughness by weathering in the intersection of joints

If a rock is vulnerable to weathering, the variations of roughness on the exposed rock surfaces can be observed at the intersections of the exposed joints within the surface areas of slopes in a relatively short period. Depending on the geological components of rocks, the roughness alterations will produce different forms of weathering products. Figure 4 shows an example of the features of weathering. In this case, the weathering products can be dominantly founded from the edges of joints. Profiles including the intersection of joints will be changed and the loss of roughness between the exposed joint edges leads to a decrease of their roughness indices. To investigate the trend of roughness variation, statistical methods can be usefully employed. Medapati et al. (2013) showed that roughness data can form specific distributions according to their weathering conditions.

An experimental case study was investigated by performing annual photogrammetry surveys (Kim et al., 2016). In this case study, the roughness variation due to weathering was quantified by using the changes of JRC values. The study slope is composed of the alternate bedding structures of sandstone and shale. Through the annual photogrammetry surveys, JRC values were obtained from 3D surface models for sandstone and shale sections at two yearly intervals. The JRC values were calculated by a function of 'Sirovision' in four radial directions (0˚, 90˚, 180˚ and 270˚). The JRC data were formed with scattered patterns for both shale and sandstone zones. This case study introduced a JRC variation rate (JVR) to quantify the roughness variations by weathering process as presented in Eq. (2). The results showed JVR can reflect the geological structural characteristics of the rock material as well as its durability.

$$JVR\ (JRC\ variation\ rate) = ((JRC_{t2} - JRC_{t1}) / JRC_{t1}) / year \qquad (2)$$

where, JRC_{t1} is the previously measured value in a particular year and JRC_{t2} is a measured value at present. If the JVR values are negative, the JRC values have been decreased during the specific periods. The estimated JVR data showed different shapes of distribution curves depending on the structure and durability of rock material. Figure 5 demonstrates that the JVR values are distributed forming skewed curves. In the shale zone, the surface of the selected area has considerably changed due to the exfoliations controlled by the textural properties of the shale bedding structures. The JVR values of the shale zone indicate higher average values than those of the sandstone data. The JVR data indicate different measures in the data distributions according to their geological bases.

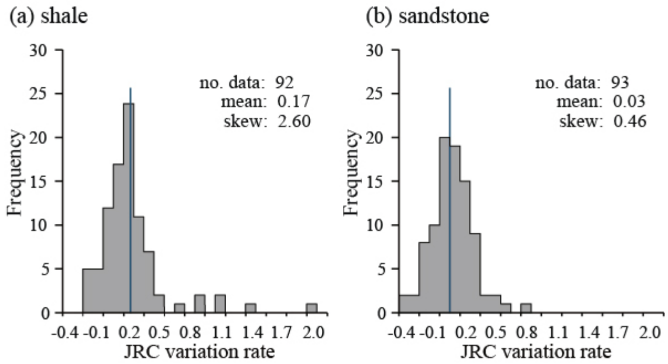

Figure 5 Data distributions of JVR obtained using Tse & Cruden function for shale (a) and sandstone (b) sections

3. IMAGE ANALYSIS

3.1 Use of photogrammetric greyscale images

A digital image can be regarded as a group of discrete pixels, each of which has various ranges of colour and brightness information. Colour images with various geological features can be more complex to be analysed than greyscale images. In the case of a greyscale image, it carries only intensity of brightness and can simplify the image structures. For example, each pixel of an 8 bit greyscale image has a luminance value which can be measured on a scale from black (0) to white (255). If the colour formations and textures of rocks are simple, the differences of the brightness between the compared stages of surveys can be regarded as an important factor arising from the different reflection of light. Using the brightness information of rock surface, the authors reported an application of image analysis comparing between before and after shearing stages in direct shear tests of rocks (Kim et al., 2014). The case study showed the applicability of image analysis to obtain the roughness variation form simple 2D greyscale images which are obtained in the same photographing conditions. However, it is worth mentioning that the differences of the extent of brightness between the surveys in a variety of field conditions, may produce misleading results.

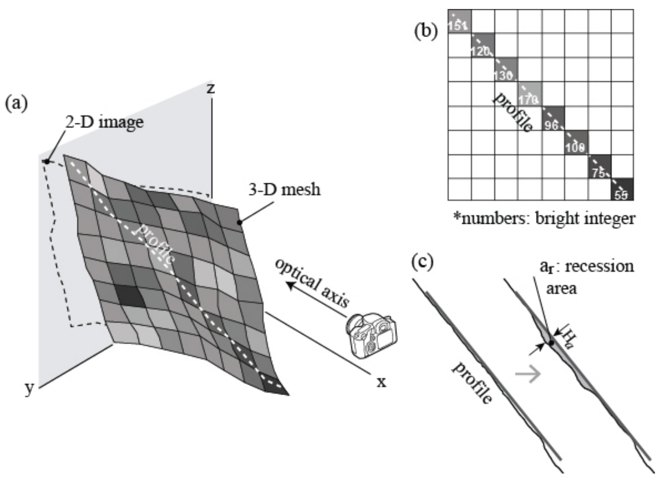

Figure 6 The use of a greyscale image of 3D model to investigate surface recession by weathering; surface model in pixels in 3D space (a), bright integers (b) changes of profile (c), (Kim et al., 2016b)

In the case study, for the same study slope in Section 2.3, the 3D images obtained from the annual photogrammetry surveys were analysed by using their greyscale images. As a distinct advantage of 3D images, extended meshes which cover all the areas of interest in a rock slope in orthogonal directions can be obtained as shown in Figure 6 (a). The 3D images present the bright information of geological features as well as the coordinates. This enables an analysis of the integer values of pixels combined with the 3D roughness data. As shown in Figure 6 (b), the changes of intensity values of greyscale 3D images are interpreted with the changes of asperity heights obtained from photogrammetric profiles. The results are used to estimate the recession areas during the time interval. This methodology can compensate the use of roughness indices for quantifying weathering considering the geological textural properties of rocks.

3.2 Procedure of image analysis

MATLAB® (The Mathworks Inc.) has been used as the main code to rotate 3D point clouds and extract roughness profiles. In photogrammetry analysis codes, their algorithms have been improved by developing better codes to produce an accurate simulation of objects and a user-friendly graphic interface (Madeira et al., 2010; CSIRO, 2012). Also, MATLAB® is a well-suited platform for analysing colour images using various image analysis tools. Further, these tools provide effective functions to visualize 3D images. This advantage enables researchers to approach the analyses of rock surface features considering the colour data of pixels of images and their 3D coordinates.

The procedure of the image analysis for the quantification of weathering is classified by the following three main categories as demonstrated in Figure 7. The first phase is to collect roughness data by performing photogrammetry in the same site. Secondly, the original RGB images are converted to greyscale with 8 bit pixel depth to simplify the image data. Thirdly, the variations of brightness integers (I) obtained from greyscale 3D images are correlated with the changes of asperity heights. Using an image thresholding technique of MATLAB®, the pixels of the greyscale images are filtered within the obtained guide ranges of (I) values from the profile analysis.

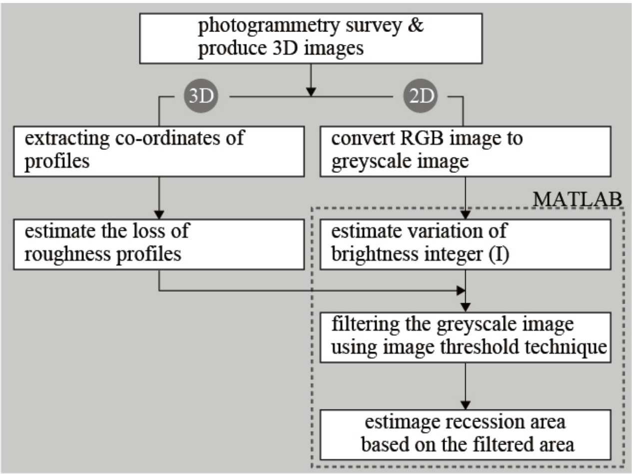

Figure 7 Workflow of roughness investigation combined with image analysis

3.3 Case study

In this study, the proposed image analysis is investigated through a case study. The geological condition of the study slope is composed of the alternate bedding structures of sandstone and shale in the Nerangleigh-Fernvale beds. The texture of sandstone is medium to coarse grained and joint sets are frequently found from the slope surface. The texture of shale is fine and has a laminated structure, and the orientations of the beddings are steeply inclined. The texture was observed using digital images taken by an 8 megapixel microscope camera from collected rock samples, as shown in Figure 8 (a).

Photogrammetry surveys were carried out for the study slope within a two year time period from 2012 to 2014. The digital images were created using a DSLR with 16.2 million effective pixels in an image and a 24 mm focal length lens. The pixel sizes of the 3D images varied with their camera setups as presented in Table 2. Stereo photographs were taken at two camera positions and the annual photographs were taken at the same positions. In the geo-referenced 3D images, two sections of both shale and sandstone zones were selected for the image analysis. The dimensions of the selected areas and the density of the 3D images are summarized in Table 2.

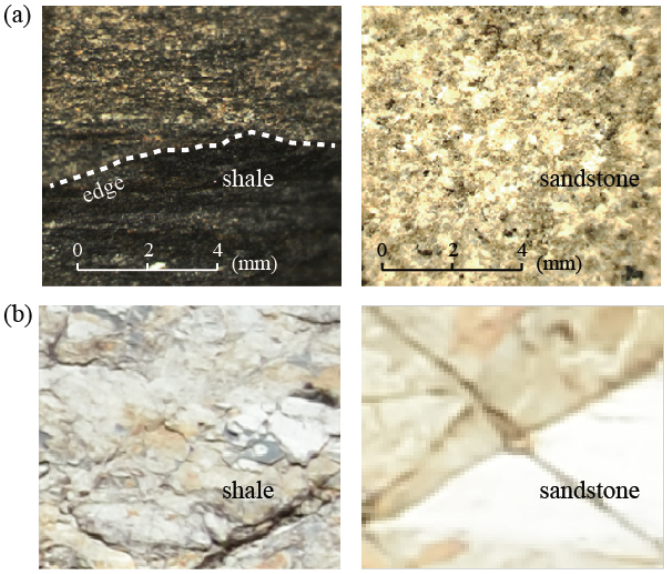

Figure 8 Images of the sampling areas on rock surfaces of the study slope; micro scale images of the collected rock (a), images of the sections of interest (b)

Table 2 Details of the 3D images in the sampling areas

camera setup & image size		shale	sandstone
c-to-o distances (m)		17.0	17.0
image size (mm)	width	332 ~ 667	427 ~ 523
	height	678 ~ 1,123	427 ~ 513
Image scale (mm/pixel)		3.3 ~ 5.1	3.7 ~ 7.6
profiles (mm)		430 ~ 1,050	480 ~ 710
Point intervals (mm)		2.0	2.0

With visual comparisons of the 3D images of 2012 and 2014, it was found that there were roughness alterations especially on the periphery of exposed joints in both rock zones. The images show a large alteration of colours on the surfaces accompanied by the exfoliation of thin rock flakes in the shale sections. In sandstone sections, however, dominant changes occurred around the edges of joints as shown in Figure 8 (b). Two sections which showed noticeable changes on the exposed rock surfaces between 2012 and 2014 surveys were selected in both rock types. In the 3D images of the selected sections, JRC values were estimated for the profiles in four radial directions (steepest, 45˚, 90˚, 135˚) as shown in Figure 9. The changes of JRC values are different over time according to the rock types. For the given two years, the JRC values for the shale sections increased due to the exfoliation with flakes. In the sandstone regions, the JRC values diminished slightly according to its rounded edges. Also, the positions of loss of roughness due to weathering were detected by comparing of the extracted profiles between the two years.

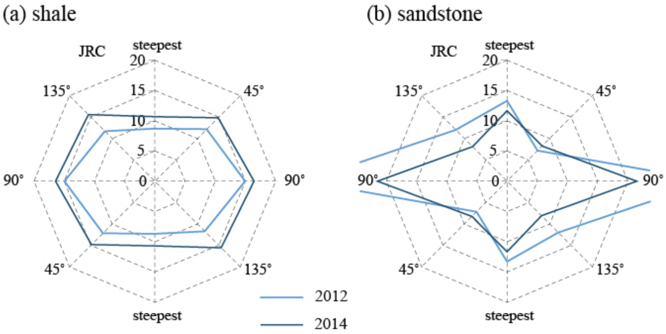

Figure 9 Alteration of photogrammetric JRC values in radial directions over the two year interval in the shale section (a), and the sandstone section (b)

The colour data of the pixels of the 3D images was converted to greyscale with 8 bit pixel depth. Along the locations of the profiles which were employed to estimate JRC values, the brightness integer (I) values were extracted and the changes of (I) values were compared with the changes of asperity heights of the profiles. The variance of brightness integers increases with the increase of roughness and that sandstone samples showed large values of bright integers compared to shale due to its bright geological colour base. The greyscale images of the shale sections show more inconsistent variations of brightness than those of sandstone sections caused by discoloration of weathered products. Because of the changeable colours, it was difficult to define the correlation between the changes of roughness and the changes of (I) values.

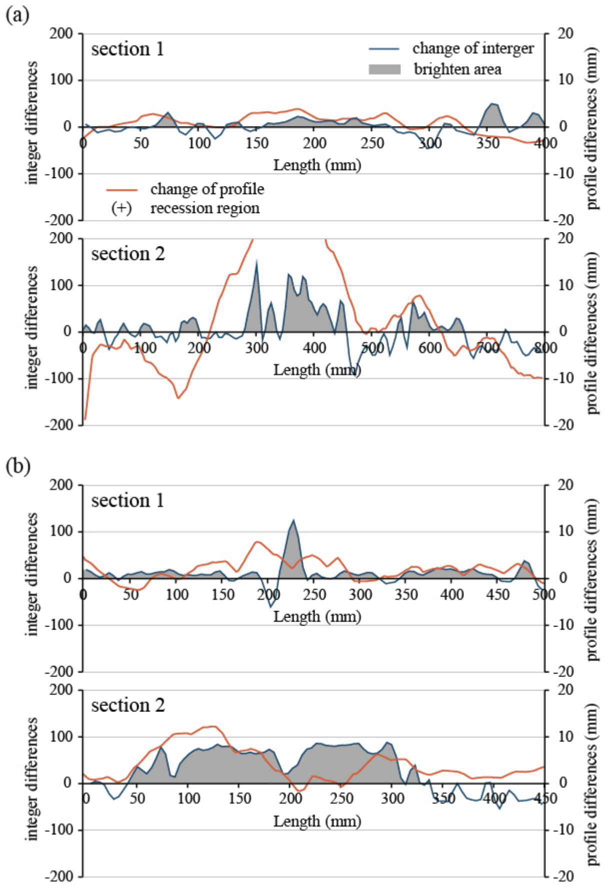

Figure 10 Changes of brightness integers (I) and the loss of roughness of profiles in vertical directions; shale (a), sandstone (b)

However, it can be said that overall trend of the variation of (I) values responds to the roughness profile differences. The sandstone sections showed more noticeable relationship between the recession regions and the change of (I) values than the shale sections because of the simplicity of its texture. Also, the change of (I) value of sandstone was strongly influenced by differences of luminance between the photographing in 2012 and 2014. The difference of brightness in surveys led to an extraneous increment of (I) values as shown in Figure 10. Using the correlations between (I) values and profile differences, the guide range of brightness integer can be obtained from the same positions which indicate marked differences of roughness along the profile. This procedure is well demonstrated in the previous study (Kim et al., 2016b).

Using an image threshold technique of MATLAB, the pixel data of the greyscale images were filtered within the obtained guide ranges of (I) values. The obtained threshold images are presented in Figure 11. The percentage of the filtered area to the total area is used to quantify the products of weathering. In the case of sandstone, because the range of brightness is relatively simple, the filtered areas can be used as an indicator of the products of weathering. The recession area in the sandstone sections was considerably increased (8.6% to 25.4 %). By contrast, the recession areas are inconsistently distributed on the surfaces of the shale sections. This is a limitation of this technique which is related to the differences of luminance. This result can be explained by the responses of chemical weathering due to the lamination characteristics of shale. However, the image analysis technique shows that the brightness data in the pixels of 3D images can be used to study the progress of weathering of rocks considering their geological conditions.

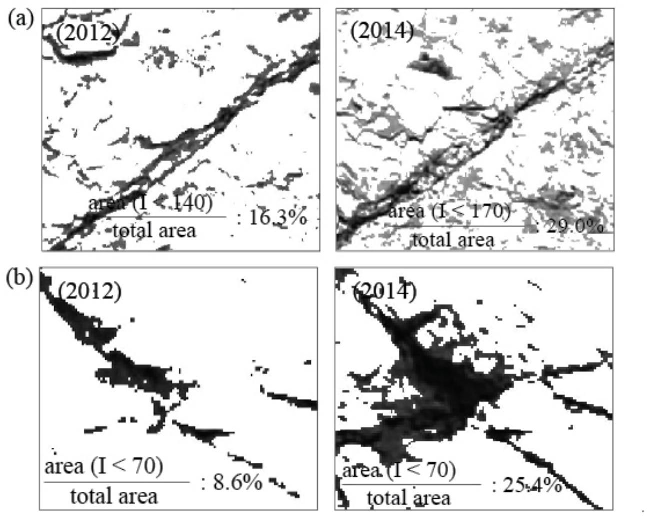

Figure 11 Comparisons of filtered areas by MATLAB threshold technique over the two year interval; shale section 2 (a), sandstone section 2 (b)

4. DISCUSSION

Photogrammetry has proven to be inexpensive and efficient in creating geospatial data of large scale rock slopes. This technology has successfully employed to create 3D models for numerical analysis. With regard to roughness investigation, photogrammetry is questionable due to various influencing factors. When dealing with the factors, uncertainties in one may be associated with uncertainties in another. That can be one of the reasons why photogrammetry for roughness investigations has been insufficiently studied and used to data. However, many examples of successful roughness simulations using close range photogrammetry have been found in various areas such as geology, archaeology and medical science. It can be said that close range photogrammetry is a useful technique of providing deterministic design values in the field of rock slope engineering under the condition when the obtained data lie within reasonable ranges. In this respect, it is important to mention that the feasibility of photogrammetry depends on the required accuracy of the produced models.

From an engineering point of view, the influence of the accuracy of 3D models on the corresponding roughness coefficients should be evaluated when considering the influence of the values on the mechanical behaviour. This study demonstrates that the point interval is an important factor and determines the level of accuracy of photogrammetric roughness data. It is obvious that accurate data can be obtained when the images are taken at close distances with long focal lengths and thus the point intervals are short. As mentioned in Section 2.2.2, for the same measurement interval with manual measurement (e.g. less than 1.0 mm), field photogrammetric roughness data could be interpreted using the developed error models by the authors with close correlations (Kim et al., 2015b). It is worth mentioning that this model is valid as an ideal standard for the estimation of the amount of errors beyond the predicted error ranges. Also, the orientations of measurement surfaces in relation to the line of sight for cameras have considerable influence on the accuracy of roughness data. Field data proposed a high-angle oblique range to provide a good match between the error models and photogrammetric JRC data distributions.

The study presented in this paper also emphasizes the benefits of the use of digital images, which possess colour data in the pixels of the images for the analysis of the variation of roughness. The use of greyscale images is adequate to simplify the analysis when the geological features of rocks are uncomplicated. The simplified greyscale images of 3D models are used to study the quantification for rock weathering combined with the photogrammetric roughness data. As presented in Section 3.3, the case study shows close correlations between the change of image brightness and the change of surface roughness. In order to analyse the brightness values in pixels of images, a threshold technique of MATLAB® image analysis tool provides to apply for filtering for the areas of interest. The filtered area can be used to indicate the vulnerability of weathering. However, the intensity of brightness should be carefully interpreted by considering both luminance conditions for photographing and the geological characteristics of rocks. Lighting, camera angles, lens aperture values and the conditions of the surfaces of interest at the moment of photographing can influence on the brightness integers of images. The limitations of this technique are also related to the level of accuracy of photogrammetry models.

5. CONCLUSION

This study discusses the feasibility of close range photogrammetry from various points of view for any investigations into rock slopes focussing on the uses of rock surface roughness. As the most influential factor for the accuracy of 3D images, photogrammetry setups and the corresponding point intervals were widely discussed through literature review and collected data from experiments and field surveys. In order to study roughness characteristics from rock surfaces, CLP requires quite close camera-to-object distances. The allowable distances can be established by considering camera setup to obtain the point intervals less than 1 mm.

Field photogrammetry surveys produce scattered data and plotted mainly overestimated JRC values. In order to interpret the level of accuracy of photogrammetric JRC values this study introduced an error model based on laboratory tests and field data. The error model which increases existing knowledge of photogrammetric errors is helpful as a guideline which can compare with the obtained roughness data in specific photograph setups to estimate the accuracy of photogrammetric roughness data.

This study also discussed the use of image analysis using 3D photogrammetry models combined with roughness data for rock weathering investigation. Photogrammetric 3D models provide two dimensional roughness profiles and the 3D RGB images can be converted to greyscale images and used as a source of the threshold image analysis tool of MATLAB. The combined image analysis with photogrammetric roughness data could compensate the limitations of both the use of 2D roughness data and the use of the integer values of 2D images. It can be concluded that the image analysis using the brightness data in the pixels of 3D images can be used to investigate the progress of weathering combined with the changes of roughness data on rock surfaces.

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