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A New Method for Rapid Quantitative Measurement of the Strikes and Dips of Cracks on the Tunnel Face

H.Tobe
Kajima Corporation, Tokyo, Japan
tobeh@kajima.com *(email of corresponding author)*

Abstract

Safe and rational tunnelling construction requires accurate and rapid evaluation of the rock conditions at the tunnel face and the selection of appropriate support structures patterns based on that evaluation. Rock mass conditions observed at the face include rock strength, weathering grade, spacing of cracks, and strike and dip of cracks. Of these items, quantitative evaluation of rock strength, weathering grade, and spacing of cracks has been developed recently. On the other hand, although quantitative analysis methods exist for the strike and dip of cracks using laser surveying and photogrammetry, the analysis takes a lot of time, making it difficult to apply. Therefore, the author has developed a method for the rapid quantitative evaluation of the strike and dip of cracks by optimizing the colour tone and arrangement of lighting. Specifically, red, blue, and green lights, which correspond to the three primary colours of light, are placed on three sides of the face. Then, the author analysed the colour tones of the reflected light from the face because there is a relationship between the strike/dip of cracks and the colour tone of the reflected light on the face. This method yields results in under 10 seconds, achieving an accuracy comparable to that of photogrammetry.

Keywords

Image analysis, Crack, Strike and dip, Tunnel face

1 Introduction

The construction of mountain tunnels and rock cutting operations requires a focus on safety and rationality. Therefore, it is necessary to accurately evaluate the geological conditions of the rock at the working face and select appropriate support patterns and slope countermeasures based on that evaluation. The geological conditions evaluated at the face include rock strength, degree of weathering and alteration, spacing of cracks, and strike and dip of cracks. Of these items, quantitative evaluations of rock strength, degree of weathering and alteration, and spacing of cracks have been realized (Tobe et al,2019; Tobe et al, 2021).

On the other hand, although there are quantitative evaluation methods using laser surveying and photogrammetry for the strike and dip of cracks, the analysis requires a lot of time. Therefore, it was difficult to apply these to construction such as mountain tunnels, where the time until the construction cycle (spraying) at the excavation is short. Consequently, a method capable of quantitatively evaluating the strike and dip of cracks through measurement and analysis within a few minutes was needed.

Authors have developed a method to quickly measure the strike and dip of cracks by taking a single photo of the face by devising the arrangement and colour of the lighting (Tobe et al.,2023). With this method, the time required from taking the image to analysing it is about 5 seconds, allowing for rapid evaluation. In this paper, author explain the theory behind this measurement method and provide an overview of our field trial of this method.

2 Method

2.1 Principles of appearance and measurement of cracks in the face

Since there are latent cracks in rock mass before excavation, when excavation exposes rock mass that was previously covered by others, stress release causes the cracks that were previously in contact to open, causing the separated rock pieces to fall. For this reason, the unevenness of the rock mass that appears at the face often reflects the latent cracks in the rock mass before the face appeared. Therefore, by quantitatively measuring the direction of the unevenness that appears on the face surface, the direction (strike and dip) of the principal cracks in the rock mass distributed at the face and its surroundings can be evaluated. This is also true for laser surveying and photogrammetry.

When lighting with different colours is applied from multiple directions to an uneven face like this, the brightness of the colour components contained in the reflected light depends on the direction of the unevenness of the excavation surface, provided that the conditions such as the distance from the light, the type of rock, and the degree of weathering are the same. In other words, when lights with different colour components such as red, green, and blue are applied to the face from different directions, namely the right, top, and left, respectively, the reflected light from the cracks facing to the right shows a colour tone that contains a stronger red component than the cracks facing in other directions (Fig. 1). Similarly, a crack facing upwards will reflect light with a strong green component, while a crack facing to the left will reflect light with a strong blue component. Therefore, by photographing the face using multiple lights with different colour components and directions and analysing the colour tones of the pixels in the photograph, the directions of the cracks in the tunnel face can be quickly measured (Fig. 1).

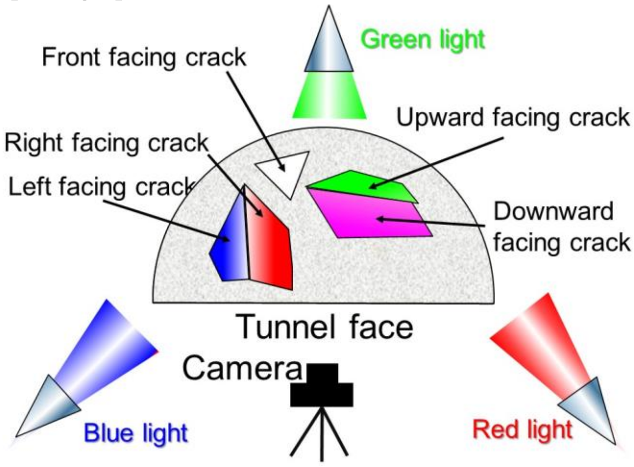


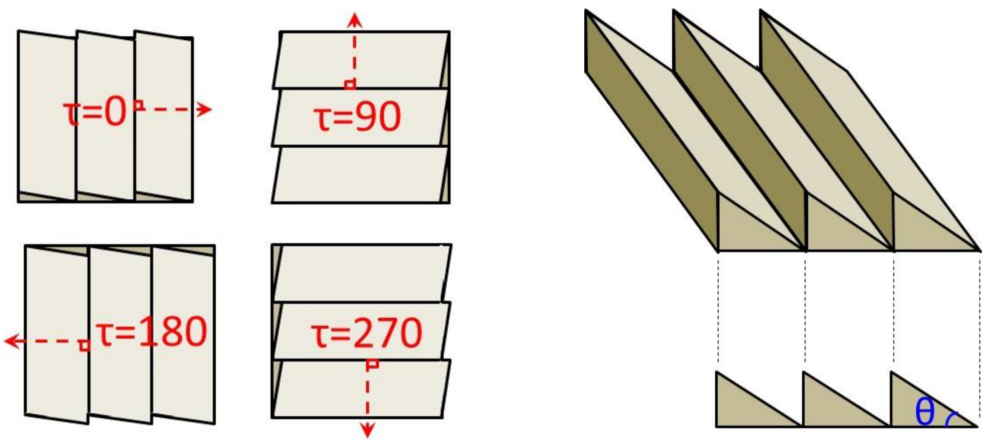
Fig.1 Outline of the method

2.2 Definition of crack direction (rotation angle τ, protrusion angle θ)

The crack direction measured with this method is the relative angle from the tunnel face, assuming the face to be a vertical plane, rather than the absolute strike and dip that is typically used. This relative angle is defined in two ways: the relative rotation angle with respect to the assumed face, and the angle protruding from the assumed face.

The first angle defined is the angle between the vector projected from the normal vector of the crack onto the face and the horizontal vector pointing to the true right. In other words, the horizontal right direction of the face surface is τ = 0°, and the angle that increases with left rotation is defined as the rotation angle τ. Therefore, the minimum value of τ is 0°, and the maximum value is 360° (however, the direction is the same as 0°). This is shown diagrammatically in Fig.2a. As shown in the figure, if the normal line of the crack facing upward, the rotation angle τ at this time is the angle rotated from true right to left by τ (τ =90°) (Fig. 2(a)).

The second angle defined is the degree to which it protrudes forward from the vertical face, and is defined as the protrusion angle θ. If it is parallel to the vertical face, the protrusion angle θ will be at its minimum value of 0°, and the more it protrudes from the face, the greater the angle will be, reaching a maximum of 90°. In the example in Fig.2(b), the protrusion angle θ is approximately 30°.



(a) Rotation angle τ **(b) Protrusion angle θ**

Fig.2 Defined angles of the method

2.3 Relationships among rotation angle τ, protrusion angle θ, and RGB value

In measuring reflected light using this method, it is theoretically thought that cracks in the same direction as the light source will reflect the most reflected light of that light source component. on the other hand, a crack that is at an angle of 180° with the light source is thought to show the least reflected light of the light source. Furthermore, in angles with 90° and 270°, they are thought to show an intermediate value between the maximum and minimum values. In other words, the reflected light intensity Rfi of a certain colour component i is defined by equation (1) using the angle β of the lighting position, the rotation angle τ of the crack, and the maximum brightness m of the reflected light. RGB stands for the three primary colours of light: red, green, and blue.

$$Rfi = m/2 * cos\,\alpha + m/2 \qquad (1)$$

Where *Rfi* Reflected light intensity (*i* is one of RGB; e.g., that of red colour component is Rf_R)
m Maximum brightness of reflected light
β Angle at which the light is located
τ Rotation angle τ
α Angle between τ and β, τ-β

Therefore, if the R light is installed in a direction of 0°, the G light is at 90°, and the B light is at 180°, the relationship between the rotation angle τ and the reflected light intensity Rfi is as shown in Fig.3.

In this case, the ratio of the difference between the three values of the reflected light Rf_R, the reflected light Rf_G, and the reflected light Rf_B of B is uniquely determined for the rotation angle τ. In other words, the ratio of Rf_R-Rf_G : Rf_G-Rf_B : Rf_B-Rf_R will be the same ratio (including sign) for the same rotation angle τ. Because of this, the rotation angle τ can be calculated by shining light of different colours on the face from different directions and comparing the difference in the intensity of the reflected light at the face. For example, if Rf_R-Rf_G : Rf_G-Rf_B : Rf_B-Rf_R = 1:1:-2, then the rotation angle τ can be determined to be 0. Using this, the rotation angle τ of the unevenness of the entire face can be calculated simply by calculating the ratio of the RGB values of the pixels at the face photographs.

On the other hand, the protrusion angle θ can be calculated not by the ratio of the difference in the RGB values of the reflected light Rf when the rotation angle τ was determined, but by its magnitude. In other words, when the rotation angle τ=0, the ratio of the difference in RGB values, that is, the ratio Rf_R-Rf_G : Rf_G-Rf_B : Rf_B-Rf_R, remains constant regardless of the value of the protrusion angle θ, but the magnitude of the RGB difference is very small, almost 0, when the protrusion angle θ≒0, and increases as the protrusion angle increases, reaching a maximum when the protrusion angle θ≒90°(However, this is only the case when the light source is very close to the face.). The relation is given by equation (2).

$$sin\theta = \frac{Dxy}{Dmax} \tag{2}$$

Where *Dxy* *Rfi-Rfj* measured at any position (x, y)
i,j Any of RGB
Dmax Maximum value of Rfi-Rfj theoretically calculated at rotation angle τ
θ Protrusion angle

Therefore, by using equations (1) and (2), the rotation angle τ and protrusion angle θ of the unevenness of the entire face can be calculated.

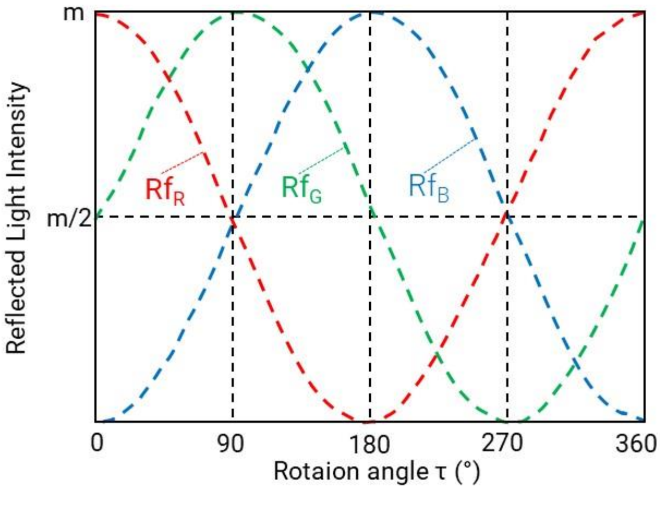


Fig.3 Relationship between Reflected light intensity and rotation angle τ

3 Verification by model experiment

To verify the method, a mountain tunnel model was created, and an experiment was conducted. The model was made of cardboard and had a semicircular shape with a diameter of 15 cm. In other words, it was about 1/100 the size of a typical mountain tunnel (Fig4.).

In the model experiment, four types of simulated tunnel faces made of cardboard with protrusion angles θ = 15°, 30°, 45°, and 60° were used (Fig.5), and the RGB values were measured with a digital camera while rotating the simulated tunnel face from rotation angle τ = 0 to 315° in 45° increments (Fig.6). The position for measuring the RGB values was the centre of the bottom end of the tunnel face, which is equidistant from all LEDs. The measured RGB values were normalized with the maximum value set to 1 and the minimum value set to 0 and were calculated as Rfi.

The lighting for illuminating the tunnel face (excavation surface) was done using LEDs of the three primary colours of light: red, green, and blue. The red LED was installed at 0° on the right end, the green LED at 90° on the top end (top), and the blue LED at 180° on the left end, at a distance of 30 cm from the face (Fig. 5).

The result of the experiment shows in Fig 6. The legend in Fig.6 refers to the colour components of the protrusion angle θ. In other words, "15R" in Figure 5 refers to the brightness of red (R) measured using a simulated face with protrusion angle θ = 15° . According to the results, R was maximum when τ = 0°, G was maximum when τ = 90°, and B was maximum when τ = 180°, and at τ = 270°, R and B were close to each other, and G showed a low value. It was also confirmed that these features showed intermediate results at intermediate angles. In addition, it was found that the larger the protrusion angle θ, the more prominent the above features become, so it was possible to detect θ. These results were consistent with the theory presented in Chapter 2.

Furthermore, author confirmed cases where the magnitude of the RGB values reversed when the protrusion angle θ was small. This is thought to be due to the influence of reflection from the wall of the model.

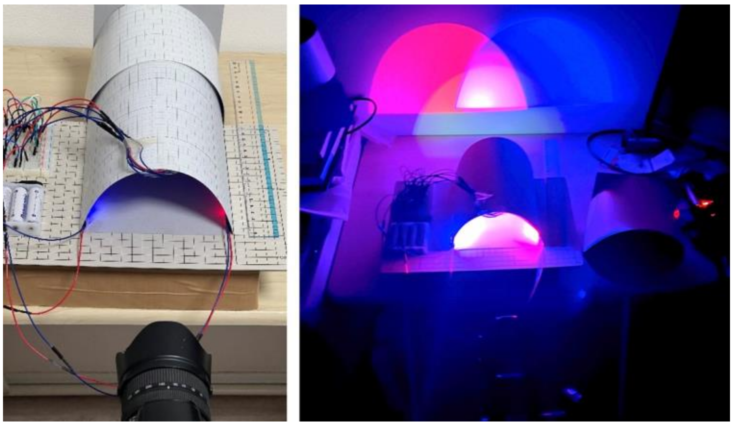


Fig.4 Model experiment

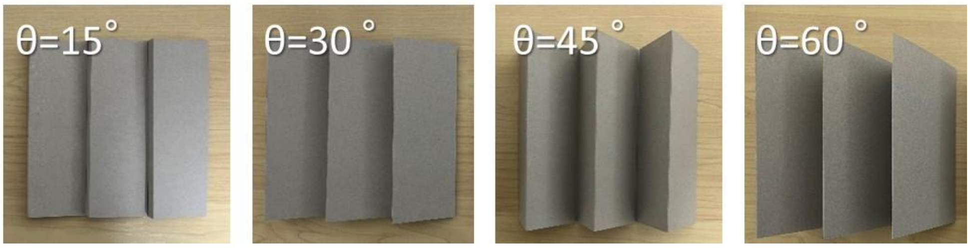


Fig.5 Simulated faces with protrusion angles θ = 15°, 30°, 45°, and 60°

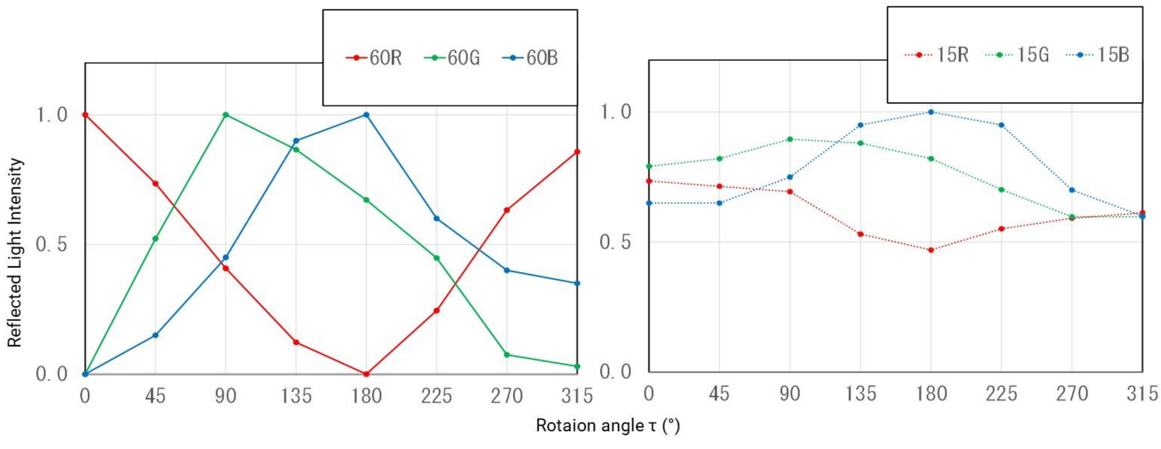


Fig.6 Result of the model experiment

4 Comparison of field trials with visual observations

This method was tested at the actual face, with a camera set up 10m away from the tunnel face, a blue light 5m to the left of the camera, a red light 5m to the right of the camera, and a green light 5m above the camera. Figure 7 shows the tunnel face photographed at this time. All lights except the three-colour light source were turned off.

For the three main cracks in Fig.7, a clinometer was used to measure the rotation angle τ and protrusion angle θ relative to the expected tunnel face, and the results were compared with the measurement results obtained by this method (Table 1). Table 1 shows that there is a difference of 1 to 11° for the rotation angle τ and about 2° for the protrusion angle θ between the measurements obtained by this method and those obtained by the clinometer, but the difference is not large.

The reason for the difference is thought to be that the reflected light from the surrounding bedrock and the original colour of the rock surface mix with the lighting, affecting the reflected light from the face.

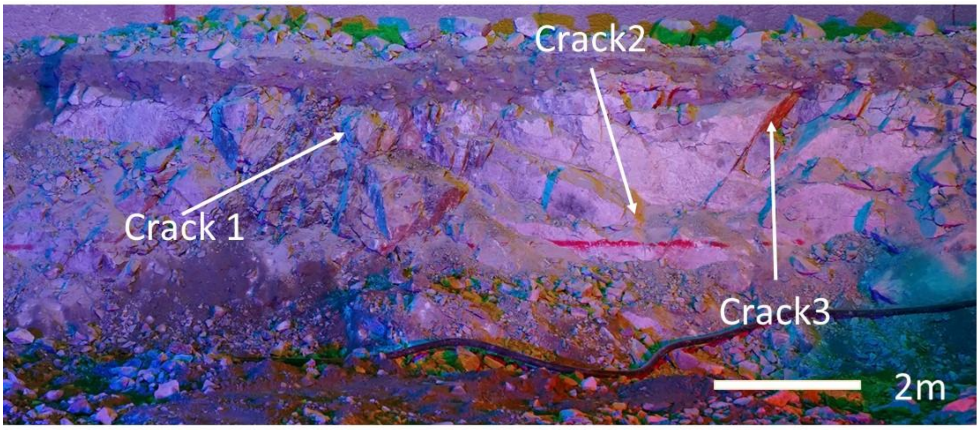


Fig.7 Field trial of the method

Table 1 Comparison of the analysis results using this method with those measured using a clinometer

	This method		Using clinometer	
	τ(°)	θ(°)	τ(°)	θ(°)
Crack1	201	39	212	41
Crack2	20	64	19	62
Crack3	290	38	298	40

5 Conclusions

This study presents a method for the rapid measurement of the strike and dip of cracks in the tunnel face by utilizing lighting of different colours with a single photograph. The method was successfully tested in both model experiments and at an actual site.

In the field test, the results were roughly consistent with the theory, but there was a discrepancy of about 5 to 10 degrees. This discrepancy is believed to be caused by the influence of reflected light and the natural colour of the rock. To address this, measures such as attaching a hood to the light source to reduce reflections from the surroundings are necessary and incorporating a program to photograph the rock before shining the light on it to obtain the original colour of the rock and then reduce the effects of this.

In the future, the authors plan to test this method at a tunnel construction site to further develop its practical application for measuring the strike and dip of cracks.

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