Development of technology for determining the face shotcrete thickness by logistic regression

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Abstract. The authors have been studying to evaluate the risk of rock falling from the face in consideration of the geological condition of the face and the face shotcrete thickness using logistic regression in order to prevent the face falling accident in tunnel excavation. This technique estimates the risk of rock falling by a logistic function obtained from computer jumbo drilling data, quantitative evaluation of weathering and cracks by image analysis of the face, and face shotcrete thickness as parameters. In this paper, the authors report the results of collecting data at a tunnel site of slate and sandstone and examining the method of determining the face shotcrete thickness according to the ground conditions using the logistic function. The logistic function that calculates the face falling probability obtained by logistic regression is transformed into a function that calculates the face shotcrete thickness by inputting the geological quantitative evaluation parameters and assuming the presence of rock falling at the probability of 50%. By using this function, it is possible to output the face shotcrete thickness to prevent rock falling by inputting the quantitative geological evaluation values of the face. As a result of examining slate and sandstone tunnel, the accuracy of determining the occurrence of rock falling was 69%.

1. Introduction
The authors have developed a technology to quantitatively evaluate the degree of weathering and cracks by image analysis of tunnel face photographs, and established a system that presents face shotcrete thickness using the technology. This development targets rock falls up to 1 m in size that can be prevented by shotcrete. The system is applied at the tunnel site, with the aim of preventing rock fall accidents on the face during tunnel excavation. However, rock fall and peeling of the face are related not only to weathering and cracks, but also to other parameters such as strength, spring water, and face shotcrete thickness. Therefore, in order to improve the evaluation accuracy of the risk of peeling, and to obtain the optimum face shotcrete thickness, the data of ground conditions, such as strength and weathering, as well as the face shotcrete thickness, are accumulated. The data are fed to machine learning to determine the face shotcrete thickness that is needed to prevent rock fall accidents from the face. In this paper, the authors examined the applicability of the system using logistic regression with a case study of tunnel that is mainly composed of slate and sandstone.

2. Collection of face quantitative evaluation data
The system developed by the authors was used to collect the quantitative evaluation data of the face. Specifically, it is composed of a weathering / crack evaluation system based on image analysis of face...
photographs, a strength distribution evaluation system using drilling data of computer jumbo, and a face shotcrete thickness management system. The details of each system are described below.

2.1. Evaluation system for weathering area ratio and crack intersection density by image analysis of face photographs
This system quantitatively evaluates weathering and crack crossing density by image analysis of face photographs.

The degree of weathering is evaluated from the color tone values of pixels of face photographs based on the fact that the color tone of the rock changes when the rock is weathered, due to the formation of clay minerals, the leaching of metal ions, and the formation of oxides.

For the crack crossing density, the first step is the extraction of the crack from the change in brightness on the image. Then, two components of the main dominant direction are detected for each mesh in which the photograph is divided into 20 cm × 20 cm. Then, as a result of comparing the predominant directions of adjacent meshes and connecting cracks with similar directions, the degree of intersection of cracks and branches is determined for the range of 5 × 5 mesh centered on the target mesh. It is evaluated by a new index called crack crossing density.

2.2. Face strength distribution evaluation system using computer jumbo drilling data
This system evaluates the strength of the face as a distribution of drilling energy coefficient by kriging from the drilling data of blasting holes and rock bolt holes collected by computer jumbo.

2.3. Face shotcrete thickness measurement system
This system uses 10 laser rangefinders mounted on the shotcrete spraying machine to measure the face shotcrete thickness during face shotcrete in real time and accumulate data.

2.4. Collection of face peeling information
Large-scale rockfalls that lead to disasters occur very infrequently, and it is difficult to collect the data necessary for verification. Therefore, it was assumed that the face with small-scale peeling that occurs when the blasting hole is drilled, has a high possibility of leading to a rock fall disaster.

3. Outline of the optimum face shotcrete thickness determination technology

3.1. Use of logistic regression
Various machine learning can be used to evaluate the risk of face peeling from multiple parameters such as rock weathering and strength. In this study, logistic function that can quantitatively evaluate the influence of main parameters was adopted. Logistic regression was used because the formula for calculating the face shotcrete thickness according to the situation can be easily derived.

3.2. Evaluation method of peeling risk by logistic regression
Logistic regression was used to evaluate the risk of peeling from the quantitative evaluation results of the geological condition of the face. In logistic regression, the probability P that the target event occurs under a certain condition Z is defined by equation (1) and (2). Since the target event here is "peeling", P is the probability that peeling will occur. In addition, Z shown in equation (2) is a condition that affects peeling, which is obtained from the quantitative evaluation results of the geological condition and the face shotcrete thickness. In logistic regression, the discrimination coefficient (βw, β0) that defines equation is determined from the data. In the practical stage, if P that is calculated from the geological condition obtained by the face and the face shotcrete thickness is 50% or more, it is judged that there is peeling, and if it is less than 50%, it is judged that there is no peeling.

3.3. Method of determining face shotcrete thickness by logistic regression
In the logistic function, the presence or absence of peeling occurrence is judged at the peeling probability \( P \) of 50%. Therefore, if \( P \) is 0.5 (50%) here, the face shotcrete thickness from equations (1) and (2) can be transformed into equation (3) for obtaining face shotcrete thickness “\( S_i \)” according to the ground conditions. When performing actual excavation, the drilling energy coefficient \( (p) \), weathering area ratio \( (w_i) \), and crack intersection density \( (c_i) \) can be obtained at the time of blasting hole drilling. Since these parameters can be obtained before the face shotcrete is sprayed, the face shotcrete thickness can be determined according to the ground conditions. Note that \( p_i, w_i, c_i \), and \( S_i \) indicate the normalized values of the measured values.

\[
P = \frac{1}{1 + \exp(-Z)} \quad (1)
\]

\[
Z = \beta_w w_i + \beta_c c_i + \beta_p p_i + \beta_s s_i + \beta_0 \quad (2)
\]

\[
S_i = -1 \times \frac{\beta_w w_i + \beta_c c_i + \beta_p p_i + \beta_0}{\beta_c} \quad (3)
\]

\( P \): Probability of peeling  
\( Z \): Condition determined by the quantitative evaluation results of the ground condition and the face shotcrete thickness  
\( \beta_w, \beta_c, \beta_p, \beta_s, \beta_0 \): Discrimination coefficient  
\( w_i \): Weathering area ratio  
\( c_i \): Crack intersection density  
\( p_i \): Drilling energy  
\( s_i \): Face shotcrete thickness  

\* \( w_i, c_i, p_i, s_i \): Normalized value

4. Application example in tunnel

4.1. Geological outline of the tunnel

The tunnel is located in the Shimanto belt, and slate and sandstone mainly appeared in the face. The sandstone was strong and the face was stable, the slate had cracks, and the face was very fragile.

4.2. Quantitative evaluation results and peeling status of the face

Figure 1 shows an example of the quantitative evaluation results of the face, and table 1 shows the quantitative evaluation results and the peeling status of each face. The number of target faces was 16, and 8 of them were confirmed to be peeled.

In table 1, the faces that were confirmed to be peeled off are shown in cells with red hatches. The weathering, cracks, and fracture energy coefficient show the average value of one face, and the face shotcrete thickness in the table shows the maximum and minimum values of the face shotcrete thickness measured with the face. In logistic regression, these were averaged and treated as 1 face and 1 data.

4.3. Evaluation of peeling risk by logistic regression

Table 2 shows the discrimination coefficient and the odds ratio for each evaluation item obtained by logistic regression from the 16 face data. The odds ratio indicates the degree of influence of parameters on the probability of occurrence of peeling.

Here, the sign of the discrimination coefficient for each item is considered and the influence of the ground evaluation items and the face shotcrete thickness on the probability of occurrence of peeling is
examined. The $P$ (probability of peeling) shown in equation (1) increases as $Z$ increases. Since ground evaluation items for calculating $Z$ and the face shotcrete thickness are all observed values with positive sign, if the discrimination coefficients are positive, the probability of peeling increases as the items become larger.

![Face Photo](image1.png)

**Figure 1.** Example of face quantitative evaluation (TD.644m)

| Tabel 1. Geological quantitative evaluation results and peeling status |
|---------------------------------------------------------------|
| **TD.(m)** | **Weathered area ratio(%)** | **Crack intersection density(%)** | **Drilling energy(J/cm³)** | **Face shotcrete thickness(mm)** | **Max** | **Min** |
| 644 | 0 | 34 | 292 | 30 | 180 |
| 648 | 0 | 14 | 225 | 29 | 63 |
| 652 | 0 | 38 | 192 | 96 | 121 |
| 659 | 0 | 36 | 232 | 25 | 100 |
| 664 | 0 | 26 | 267 | 62 | 67 |
| 692 | 0 | 16 | 63 | 32 | 135 |
| 763 | 16.8 | 36 | 164 | 58 | 66 |
| 767 | 0 | 42 | 159 | 43 | 66 |
| 834 | 0 | 47 | 254 | 91 | 91 |
| 836 | 2 | 26 | 261 | 40 | 40 |
| 841 | 0 | 8 | 206 | 70 | 85 |
| 855 | 0 | 8 | 286 | 71 | 98 |
| 862 | 0 | 7 | 124 | 77 | 77 |
| 896 | 0 | 7 | 245 | 51 | 88 |
| 900 | 0 | 6 | 235 | 79 | 187 |
| 914 | 1.3 | 36 | 213 | 36 | 81 |

| Peeling face |
Table 2. Discrimination coefficient and odds ratio for each evaluation item

| Evaluation items          | Weathered area ratio | Crack intersection density | Drilling energy | Face shotcrete thickness | Constant |
|---------------------------|----------------------|-----------------------------|-----------------|--------------------------|-----------|
| Discrimination coefficient| $\beta_w$            | $\beta_c$                   | $\beta_p$       | $\beta_s$                | $\beta_0$ |
|                           | 1.45                 | -0.66                       | -0.61           | -1.08                    | 0.11      |
| Odds ratio                | 4.25                 | 0.52                        | 0.54            | 0.34                     |           |

For example, the discrimination coefficient for weathering area ratio is 1.45, which is a positive value, indicating that the probability of peeling increases as the degree of weathering area ratio increases. In addition, the drilling energy coefficient is a negative value of -0.61, indicating that the probability of peeling decreases as the drilling energy coefficient increases. These tendencies are consistent with the general idea of face stability assessment.

On the other hand, the crack crossing density shows a negative value of -0.66, indicating that the probability of peeling decreases as the crack crossing density increases, and the higher the crack density, the more stable the face. The result is opposite to the general idea. When checking the actual tunnel condition, the development of cracks is remarkable to the extent that it cannot be confirmed in the photograph. In this case, the ground is weak and peeling occurs as shown in figure 2 (TD.862m). On the other hand, for TD.834m images, the ground condition is good and the cracks can be clearly confirmed. In this case, the crack intersection density is high, but peeling does not occur. This tendency can be confirmed even in soft rock tunnels, and it is considered that the same tendency was observed in this study. From these results, it is important to consider various parameters such as strength in addition to weathering and cracks in order to evaluate the probability of peeling.

Figure 3 shows the relation between the condition Z using the logistic function that can be defined by the discrimination coefficient, and the probability peeling P. In this plot, the points represent 16 faces, the orange point is the face with peeling, and the blue point is the face with no peeling. As described above, since P determines the presence or absence of peeling with 0.5 as the boundary, the evaluation is correct if the orange point is in the range larger than 0.5 and the blue point is in the range smaller than 0.5. Table 3 shows the overall evaluation accuracy, which was 69%.

In this study, since the size of data used for the analysis was as small as 16 faces, and the geological conditions and the thickness of the shotcrete were evaluated as the average value of one face, it was difficult to reflect the local geological conditions of the area. This is considered to be the reason why the evaluation accuracy is resulted in 69%.
Figure 2. Crack intersection density and drilling energy (TD.862m, TD.834m)

Figure 3. Evaluation of the probability of peeling by a logistic function
Table 3. Evaluation accuracy of logistic regression

| Prediction | Actual | Correct answer rate |
|------------|--------|---------------------|
|            | Stable | Peeling             |
| Stable     | 4      | 3                   | 57% |
| Peeling    | 2      | 7                   | 78% |
| Correct answer rate | 67% | 70% | 69% |

4.4. Face shotcrete thickness determined by logistic regression

The face shotcrete thickness according to the face condition can be calculated by the quantitative evaluation result formula (3) of the face. Here, assuming the ground conditions shown in table 4, the method of determining the face shotcrete thickness was examined. The ground condition is shown in the face of TD.692m in table 1. The face shotcrete thickness that actually applied was 32mm, and peeling has occurred. In this case, equation (1) shows that the probability of peeling of 87%, and equation (3) requires a face shotcrete thickness of 72 mm. This can be confirmed from the relation between the face shotcrete thickness and the peeling probability that is shown in figure 4.

Next, figure 5 shows the required face shotcrete thickness calculated by equation (3) when only the drilling energy coefficient changes among the conditions in table 4. As shown in the previous section, it can be seen that the required face shotcrete thickness decreases as the drilling energy coefficient increases, that is, as the face strength increases. Similarly, figure 6 shows the face shotcrete thickness required when only the degree of weathering changes among the conditions shown in table 4. It can be seen that the face shotcrete thickness increases as the degree of weathering increases, but it is shown that an unrealistic thickness exceeding 100 mm is required. This is because, as shown in table 1, the values of weathering are close to 0 except for TD.763m, and most of the range of the graph shown in figure 6 is not in the training data, so it exceeds the predictable range. From this, it can be seen that learning with a large number of diverse data is required to present an appropriate face shotcrete thickness.

Table 4. Example of ground conditions

|               | Weathered area ratio | Crack intersection density | Drilling energy |
|---------------|----------------------|----------------------------|-----------------|
| Measured value| 0                    | 16                         | 249             |
| Normalized value| -0.35              | -1.36                      | 0.55            |
Figure 4. Relation between face shotcrete thickness and probability of peeling

Figure 5. Relation between drilling energy and face shotcrete thickness

Figure 6. Relation between Weathering area ratio and face shotcrete thickness
5. Conclusion

Based on the results of quantitative evaluation of the face, the technique for determining the face shotcrete thickness using logistic regression was examined, and following sentences summarize the results.

- By logistic regression, we were able to quantitatively present the probability of rock fall and the face shotcrete thickness required to prevent peeling.
- The discrimination coefficient and odds ratio can be used to evaluate how each of the face evaluation items affect the probability of peeling.
- It is important to consider various parameters in the face evaluation items, such as strength in addition to weathering and cracks.
- It may not be possible to properly evaluate the face of conditions that exceed the range of training data.

Based on the above, the authors intend to proceed with the following efforts and put them into practical use.

- Continue to accumulate data to improve evaluation accuracy and expand the scope of application.
- Accumulate various geological data in multiple tunnels to expand the scope of application.
- Evaluate the face after dividing into smaller sections so that the local peeling phenomenon can be evaluated.

References

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