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Development of face safety monitoring system (FSMS) using x-MR control chart

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ABSTRACT

The inability of current displacement-monitoring systems to analyze the behavior of the rock mass at a tunnel face during excavation represents a safety hazard. This study tests a face safety monitoring system (FSMS) to help improve safety. It can identify abnormal displacement and trigger an alarm by calculating in real time relevant safe control limits. It does this by applying mathematical and statistical algorithms and control charts. The applicability of the system was verified in a tunnel where a small collapse occurred. The measured displacement exceeded the control limit approximately 20 s before the collapse. If the displacement of tunnel faces is measured in real time using this system, workers can evacuate immediately upon an alarm being triggered in response to abnormal behavior of the rock mass.

1. INTRODUCTION

Analyzing displacement in tunnels is a useful method for ensuring their stability during excavation. In particular, the behavior of rock masses in weak zones such as faults, folds, and weathering zones can be predicted by analyzing trends in the displacement caused by excavation (Schubert and Vavrovsky, 1994; Schubert and Steindorfer, 1996; Steindorfer, 1998; Schubert et al., 2002). However, the behavior of a rock mass cannot be easily predicted when the displacement is minute or gradual. In addition, the level of tolerable displacement may vary even in a single tunnel, depending on the geological conditions and support types; consequently, workers cannot easily quantitatively judge any abnormal behavior of the ground. In particular,

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excavation by the new Austrian tunneling method (NATM) involves installing a displacement-monitoring system at points a set distance from the tunnel face, thereby precluding measurements of displacement at the face. To address this problem, Yun et al. (2015) developed a face safety monitoring system (FSMS) that can quantitatively determine any abnormal behavior of the ground by measuring displacement at the tunnel face. The present study describes the FSMS and verifies its applicability in tests in a tunnel under construction.

2. Face safety monitoring system (FSMS)

The FSMS is a displacement monitoring system that can measure displacement at a tunnel face using wireless laser distance meters. The system comprises units for measurement and data processing, and an alarm (Fig. 1). The measuring unit emits a laser toward the tunnel face and measures the displacement using the reflected signals (Fig. 1a). It can simultaneously monitor displacements at many points on the tunnel face through the use of multiple laser distance meters. The data processing unit uses software developed to monitor the measured displacements in real time, and can simultaneously manage data from up to eight laser distance meters (Fig. 1b). The software displays a time series graph of the displacement as soon as signals are received, allowing immediate analysis of any changes in the displacement. The software employs a statistical algorithm using control charts, thus enabling control limits to be set by calculating the means and standard deviations of the received data in real time. Therefore, if the displacement exceeds this control limit, the alarm unit can be promptly activated (Fig. 1c) and workers can evacuate quickly. The system is simple to install and operate because it does not require any separate target. In addition, it enables direct measurement of tunnel face displacement during excavation, because it does not interfere with the excavation work.

3. x-MR control charts

The displacement (x) and moving range (MR) control charts used here are an application of the basic concept of the control chart created by Shewhart (1924). They set control limit values (both upper and lower) using the mean ($\bar{x}$) of x measured on the tunnel face, the mean ($\overline{MR}$) of the MR, and coefficients for control limits (d_2, d_3). The MR is the difference between the maximum and minimum values within a moving range of k most recent values (Fig. 2). of the displacement data (Equation 1). That is, the x control chart plots the displacement data measured at the tunnel face and uses the control limits to determine whether the data are abnormal (Fig. 3a), while the MR control chart calculates the MR value for the set of k data points and plots the control limits for the values to determine whether the data are abnormal (Fig. 3b). The control limits in the x and MR control charts are calculated by Equations (2) and (3), respectively. The value of k required to calculate the control limits was set here to 3, and the coefficients for the control limits d_2 and d_3 were set to 1.693 and 0.888, respectively.

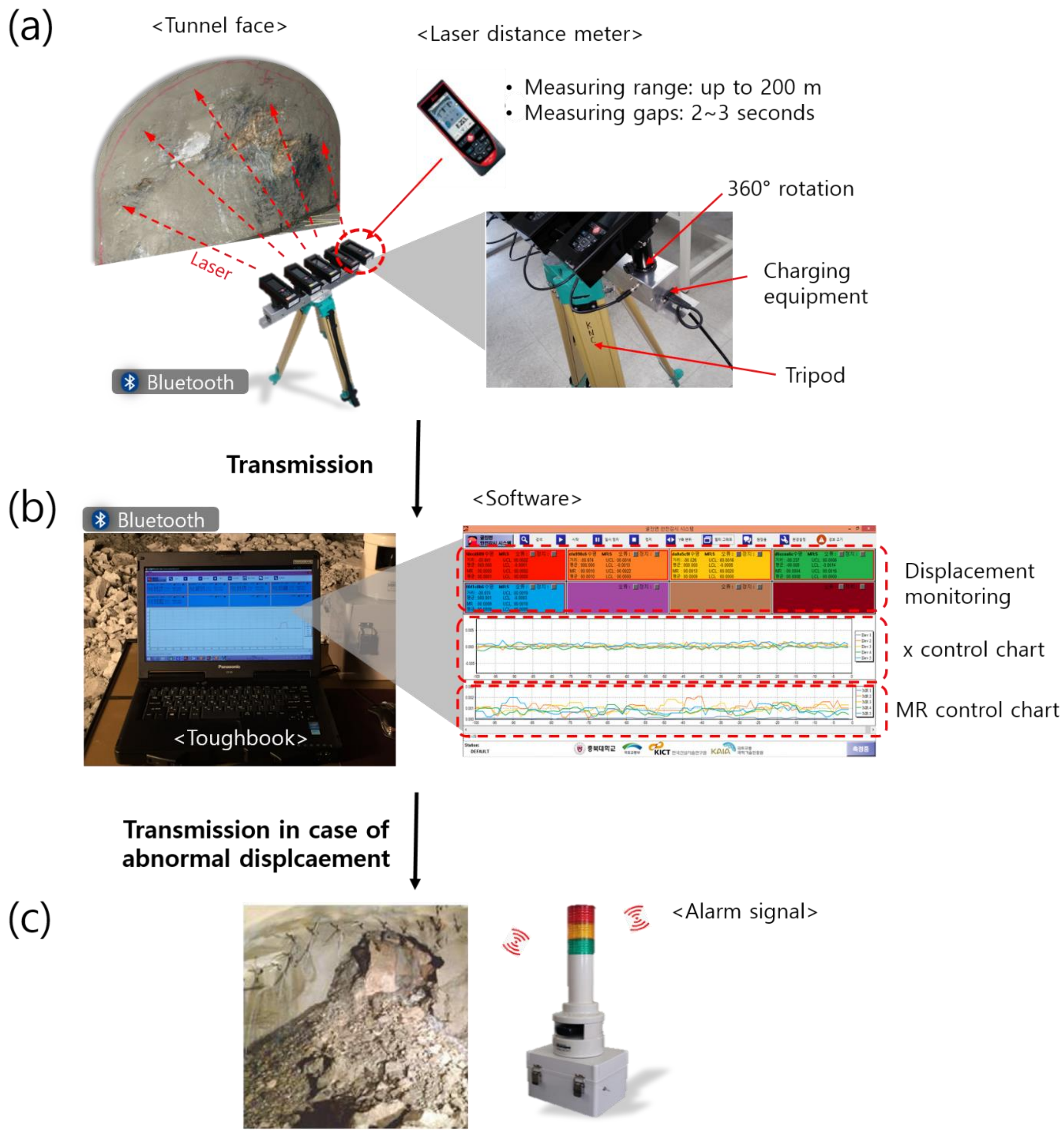

Fig. 1 Schematics of the (a) measuring unit, (b) data processing unit, and (c) alarm unit of the face safety monitoring system (modified from Yun et al., 2015)

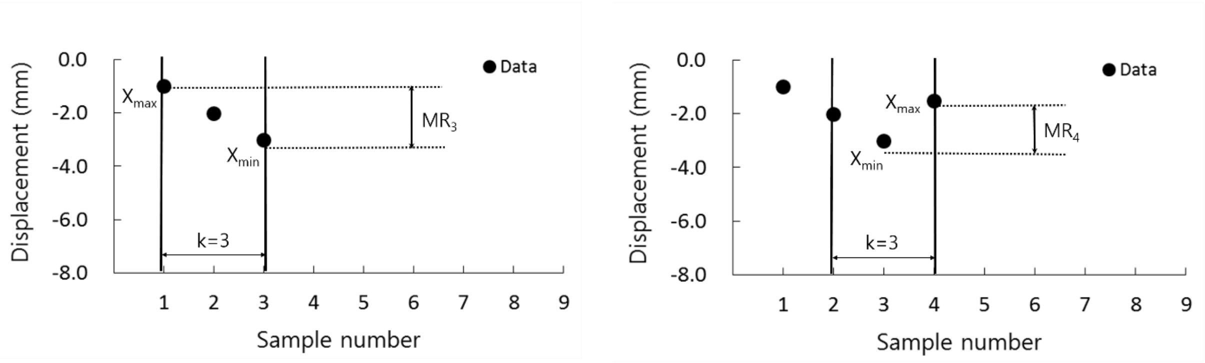

Fig. 2 The calculation method of a MR value in the x-MR control chart method (after Yun et al., 2014)

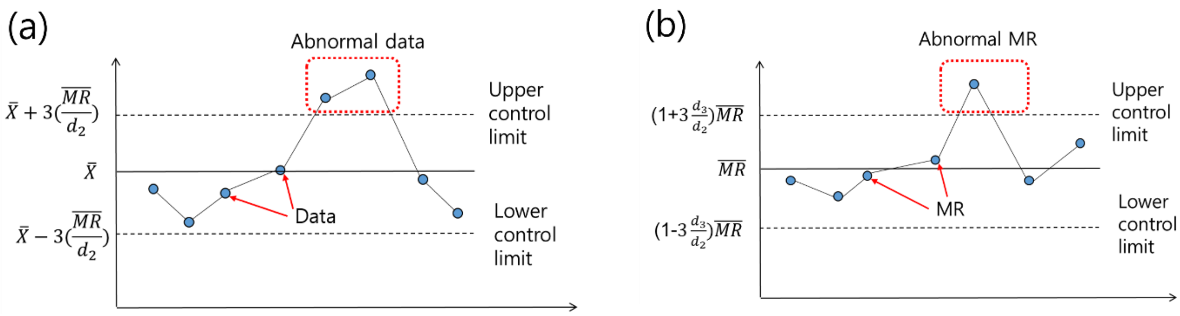

Fig. 3 Representative sample of (a) x and (b) MR control charts (after Yun et al., 2015)

$$MR_i = x_{max} - x_{min}(i = k, k+1, k+2, \cdots, n) \qquad (1)$$

$$x\ control\ chart: \bar{x} \pm 3\left(\frac{\overline{MR}}{d_2}\right) \qquad (2)$$

$$MR\ control\ chart: \left(1 \pm 3\frac{d_3}{d_2}\right)\overline{MR} \qquad (3)$$

4. Applicability analysis of FSMS in a tunnel

To verify the applicability of the FSMS, a test was conducted in a tunnel under construction (Fig. 4). The subject was a road tunnel that was the site of a small rockfall during drilling at the tunnel face. Figure 5 shows approximately 100 data points measured using the FSMS at the tunnel face before and after the rockfall. The upper graph is the x control chart, and the lower is the MR control chart. The x control chart shows that the measured displacement initially remained around the mean line, but then exceeded the lower control limit approximately 20 s before collapse. The MR control chart shows that the MR value exceeded the upper control limit before the collapse, indicating that the collapse could have been predicted.

Fig. 4 Tunnel face monitored by FSMS in a tunnel

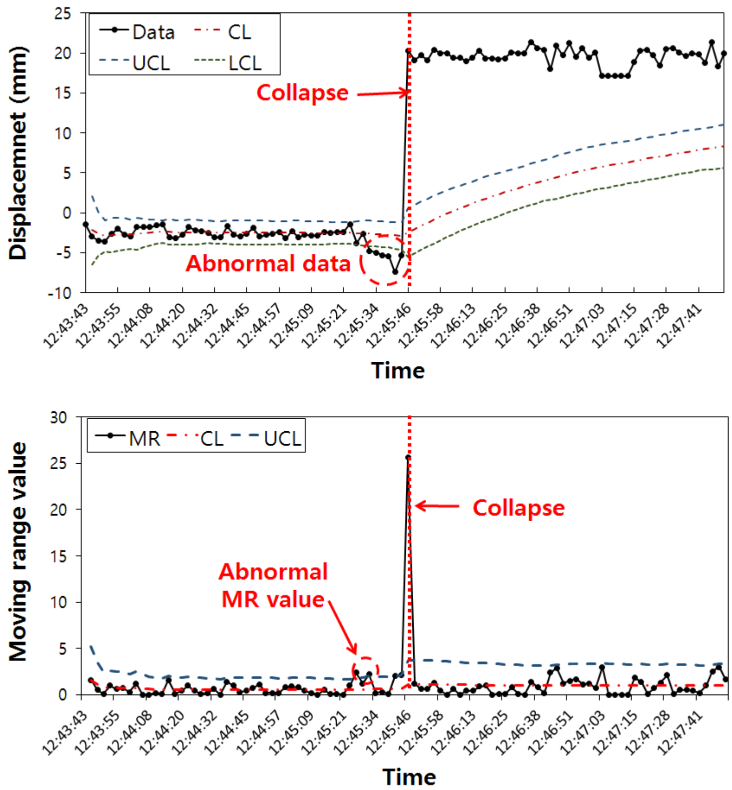

Fig. 5 x-MR control charts of longitudinal displacements monitored by FSMS in a tunnel with a small rockfall

5. CONCLUSIONS

This study describes the FSMS and verifies its applicability in a tunnel where a small collapse occurred. The results show that the collapse could have been predicted, suggesting the system could improve workers' safety. Various tests to establish the applicability of this system are ongoing in tunnels under construction. Given that the system can measure displacement at tunnel faces in real time, workers can quickly evacuate once the alarm is sounded in response to abnormal behavior of the rock mass.

Acknowledgments

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