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Strain Analysis of Crust at the Stabilization Stage Using and Applied Statistical Analysis

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A strainmeter goes through a period of instability immediately after installation. To determine the stability of strainmeters installed around the Andong fault zone, South Korea, an x-MR control chart analysis and a T^2 control chart analysis were conducted. The x-MR control chart analysis used an empirically determined 3σ control limit line to identify abnormal data in recently installed strain gauges. In the T^2 control chart analysis, the control limit line was set at a confidence of 95%. A comparison of the early stage of measurement with the terminal stage of measurement for three months after installation indicates that stabilization depends on the location and direction of each strain gauge in x-MR control chart analysis. In the T^2 control chart analysis, the number of values exceeding the control limit line decreased as the terminal stage was approached. Based on these results, it is suggested that the 3σ control limit line of an x-MR control chart can be used as a standard for single gauge stability, and that the 95% confidence limit of a T^2 control chart analysis could be used as the standard for the stability of multi-gauge strainmeters.

Key words: volcanic bomb, trachytic rock, rockfall magnitude, simulation, protection measure

Introduction

The frequency of damaging medium-to large-scale earthquakes has been steadily increasing in South Korea and abroad (KMA, 2015). Several recent studies have examined ways of reducing earthquake damage (Kanamori, 2005; Wu and Kanamori, 2005; Choi et al., 2011; Yun, 2012; Kim et al., 2013), including methodologies for earthquake prediction, analysis using displacement measurement methods, analysis of historic seismicity and earthquake monitoring data, and studies of related factors such as prior vibrations, uplift, and changes in ground water levels and seismic velocity (McCalpin, 1996; Maria and Carla, 1999; Burbank and Anderson, 2001; Keller and Pinter, 2001; Kim et al., 2004; Kyung and Lee, 2006; McCalpin, 2009; Waltham, 2009; Jeon et al., 2011; Kim et al., 2011; Lee et al., 2011; Choi et al., 2012).

Hart et al. (1996) studied tidal characteristics at installation sites to remove the effects of tides on borehole strainmeters, and Maria and Carla (1999) analyzed differences in tilt-strain gauge data patterns based on gauge installation location and orientation. Lee (2011) proposed six factors to consider for fault monitoring systems, including site characteristics, suitable equipment design for the intended purpose, data/electricity backup system, equipment quality and reliability, transparent data operation and open-to-the-public policy, and long-term operation in a stable environment. Hwang et al. (2012) corrected and

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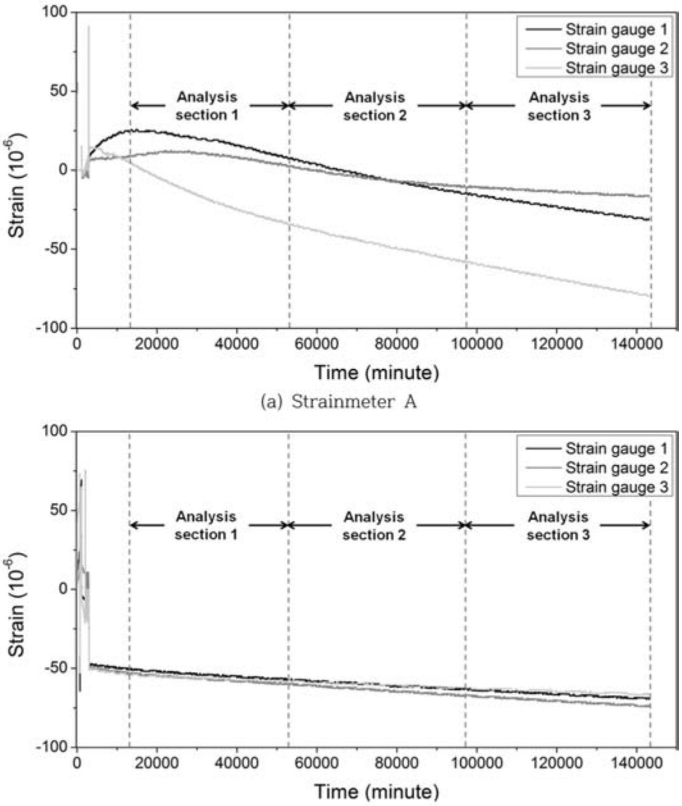
filtered data from strain gauges installed in the Eupcheon fault zone, South Korea, to conduct seismic observations for earthquake prediction and monitoring. Kim et al. (2013) analyzed the distribution characteristics of earthquake-inducing strain data using applied statistical methods to evaluate the possibility of earthquake prediction.

Because most fault monitoring hardware in South Korea relies on foreign technology, analyses are commissioned with payment for royalties. Therefore, the need for local instrument manufacturing and analysis technologies is gradually increasing (Sheen et al., 2012; Yun, 2012).

In this study, strain data were analyzed by applying univariate and multivariate statistical analyses to determine

(a) Strainmeter (b) Strain gauge

Fig. 1. Strainmeter installed around the Andong fault zone.



(a) Strainmeter A

(b) Strainmeter B

Fig. 2. Analyzed sections of the time series of strain measured by each gauge.

the initial stabilization of fault-behavior strainmeters developed in South Korea. Empirical criteria were developed to identify stabilization based on these techniques.

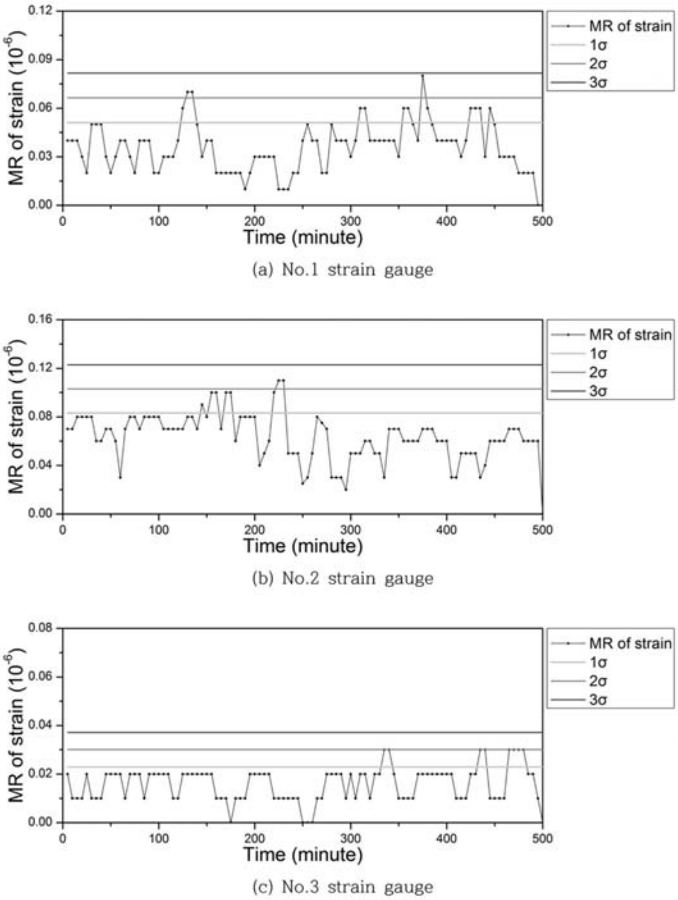
Study method

Collected data

Two multi-gauge fault-behavior strainmeters were installed around the Andong fault zone at different depths. The instruments were made by the Korea Institute of Geoscience and Mineral Resources (KIGAM) and configured to measure crustal strain in three directions, tilt in two directions, compass data in one direction, and temperature simultaneously (Fig. 1). Approximately 28,000 measurements of each data type were obtained from July 24, 2014 through October 20, 2014. The sampling interval was five minutes. Fig. 2 shows the sections of this time window used in the analysis. Unstable sections identified by eye were excluded. Each section contains approximately 30 days of data.

Analysis theory

The control chart method of Shewhart (1924) is commonly used to detect abnormalities in time series data. Recently, this method has been used in the areas of geology and geo-engineering to evaluate crustal strain, landslide prediction, prediction of tunnel collapse, anomalous behavior of soil structures, and ground water contamination(Yim et al., 2007; Yim et al., 2009; Kim et al., 2013; Kim et al., 2014; Yun et al., 2014). Of such analyses, those with one dependent variable in the control chart are called univariate statistics analysis, and those



(a) No.1 strain gauge

(b) No.2 strain gauge

(c) No.3 strain gauge

Fig. 3. x-MR control chart analysis for temporarily stabilized strain data from strainmeter A.

with two or more dependent variables are called multivariate statistics analysis. In the present study, to assess whether the strain gauges had stabilized, the x-MR control chart was used to analyze data from single strain gauges and the T^2 control chart was used to analyze data from multiple strain gauges.

The x-MR control chart method is mainly used to detect changes in the average from several data in samples for which individual (x) control charts and moving range (MR) control charts are simultaneously implemented (Yim et al., 2007; Yim et al., 2009). An analysis section (K) is set on the graph on which the measured values are plotted, and the difference between the highest and lowest value in the section is plotted. Values that plot outside the control limit lines are considered to indicate anomalous states. Control limit lines comprise an upper control limit (UCL) line and a lower control limit (LCL) line on the basis of the center line (CL) and are expressed by

$$UCL = \mu + z\sigma$$

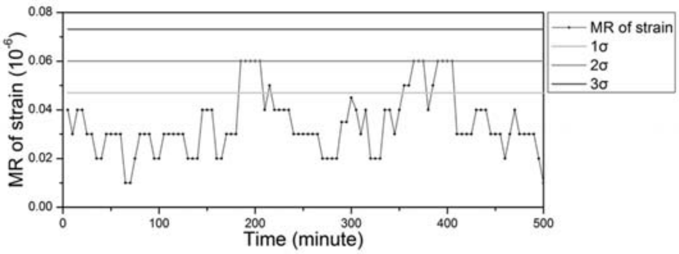
$$LCL = \mu - z\sigma \tag{1}$$

where μ is the mean value, σ is the standard deviation, and z is a scaling constant.

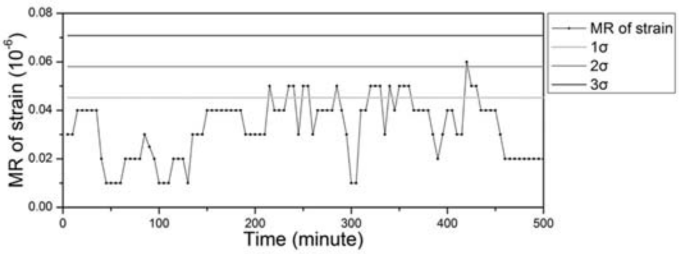
The T^2 control chart is a method of detecting changes in mean vectors during processing when the mean control value μ_0 and the control state covariance matrix Σ_0 are not known. The changes are calculated from

$$T_i^2 = n(\bar{X}_{i..} - \bar{X}_{...})'\bar{S}^{-1}(\bar{X}_{i..} - \bar{X}_{...}) \tag{2}$$

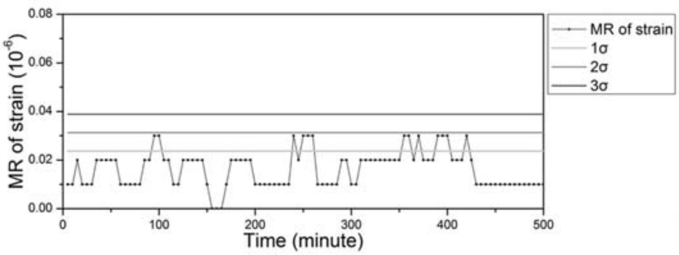
$$T_i^2 \sim \frac{p(g-1)(n-1)}{g(n-1)-(p-1)} F(p, g(n-1)-(p-1)) \tag{3}$$



(a) No.1 strain gauge



(b) No.2 strain gauge



(c) No.3 strain gauge

Fig. 4. x-MR control chart analysis for temporarily stabilized strain data from strainmeter B.

where the total mean is $\bar{X}_{...}$ and $\bar{S}$ represents the mean of the th sample variance covariance matrix S_i, n is the subgroup size, g is the number of subgroups, and p is the number of variables.

When Hotelling's T^2 statistics are used, the upper control limit (UCL) having probability α is given by

$$UCL = \frac{p(g-1)(n-1)}{g(n-1)-(p-1)} F(p, g(n-1)-(p-1), 1-\alpha)$$
$$LCL = 0$$

where $F(\nu_1, \nu_2, 1-\alpha)$ refers to the $(1-\alpha)$ denominator of the F distribution with degrees of freedom ν_1, ν_2. In this case, if α is set to 0.05, there is a 95% probability that a measured value judged as abnormal by the test is actually abnormal.

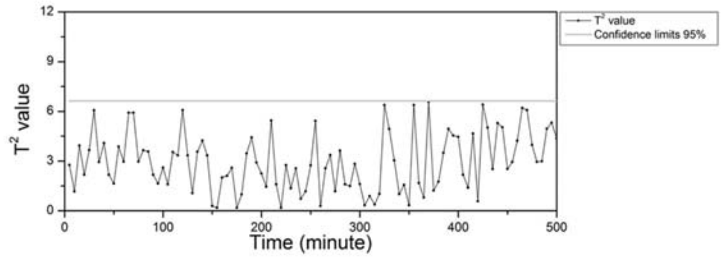
Data analysis

Criteria for stabilization

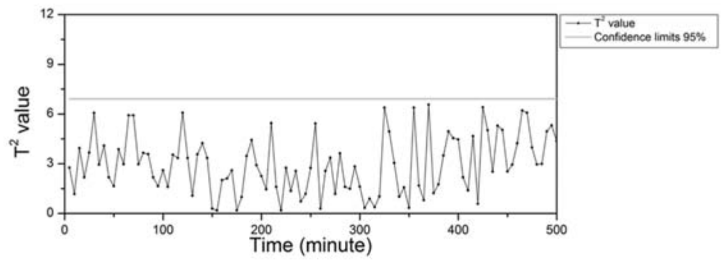
Although abnormal measurements are often detected after installation of new fault-behavior strainmeters, the measurements typically stabilize over time. Approximately one year is generally necessary for strainmeter stabilization (Gladwin et al., 1987), but strainmeters may be used before this time if stabilization can be demonstrated. Therefore, to quantitatively determine the stabilization time, x-MR control chart and T^2 control chart analyses were conducted for ~500 minutes of temporarily stabilized data to set empirical control limits. The stabilization of the strainmeters was then evaluated using the charts.

To set the criteria for stabilization, for use in x-MR control charts, we chose five plotted points for each analysis section (K) and tested control limit lines at 1σ, 2σ, and 3σ. Fig. 3 and 4 show the results of x-MR analysis of stabilized data from strainmeters A and B, respectively. All values for all gauges of strainmeter A fall within the 3σ limit. For strainmeter B, sample data from strain gauges 1 and 3 fall within the 2σ limit, and data from strain gauge 3 fall within the 3σ limit. Therefore, since all values fall within 3σ for all gauges, this value was adopted as our stabilization criterion for a single strain gauge.

Fig. 5 shows the results of T^2 control chart analysis of stabilized section data from fault-behavior strainmeters A and B. For a = 0.05, all data fall within the control limit lines with 95% probability. Therefore, this value was adopted as our stabilization criterion for multi-component strain gauges.



(a) Strainmeter A



(b) Strainmeter B

Fig. 5. T^2 control chart analysis for temporarily stabilized strain data.

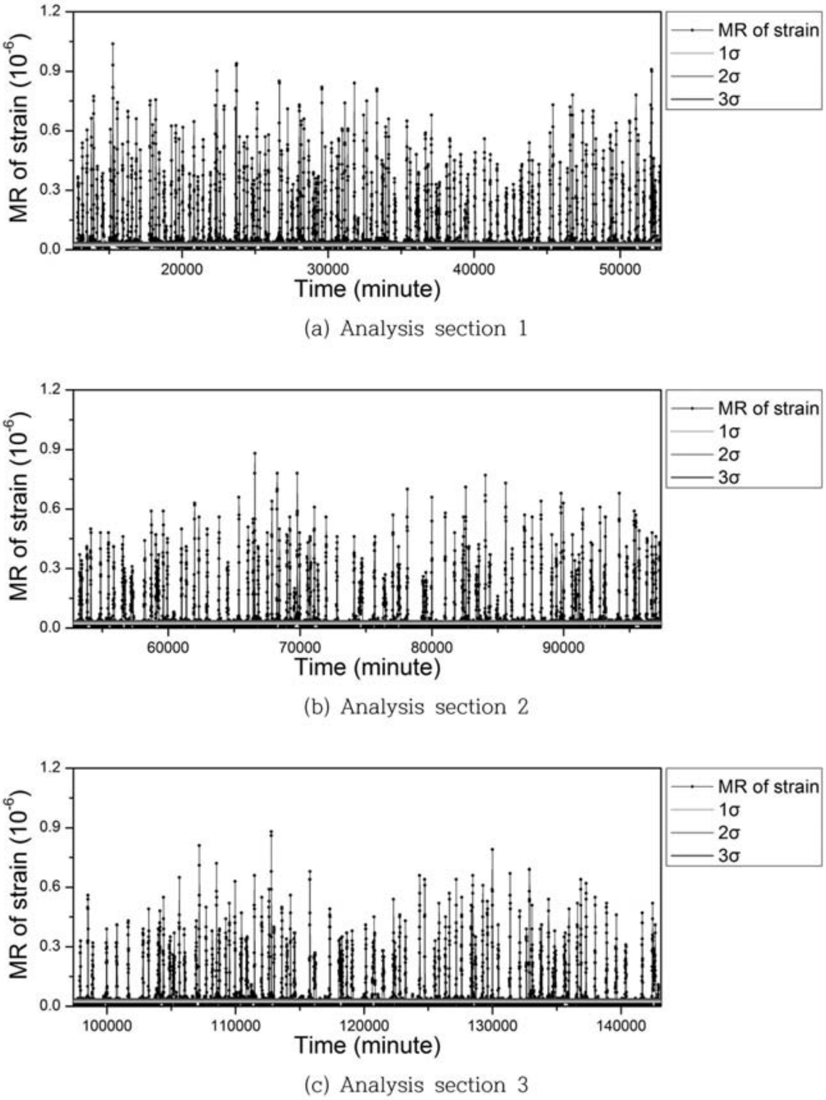
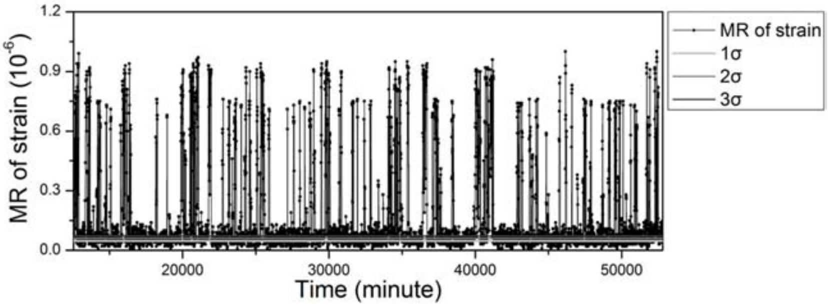


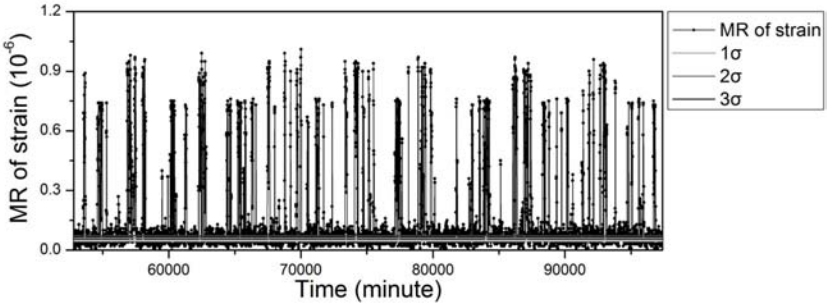
Fig. 6. Result of x-MR control chart analysis for the No. 3 strain gauge of strainmeter A.

x-MR control chart analysis of the stabilization stage

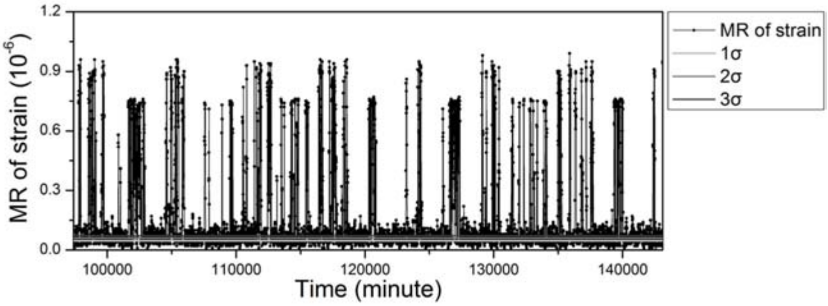
Univariate analysis was conducted using data obtained during the stabilization stage for approximately three months, with 60 points for each analysis section (K) and control limit lines at 1σ, 2σ and 3σ. Fig. 6 shows the results for strain gauge no. 3 from strainmeter A. The percentages of data exceeding the 3σ control limit line are 19.01% for strain gauge 1, 37.83% for strain gauge 2, and 39.29% for strain gauge 3. Strain gauge no. 3 showed a higher proportion of data exceeding the control limit line compared with other strain gauges. In section 2, 19.52% of measurements from strain gauge 1, 40.06% of measurements from strain gauge 2, and 25.76% of measurements from strain gauge 3 exceeded the 3σ control limit line. Strain gauge no. 2 showed a higher proportion of data exceeding the control limit line compared with other strain gauges. In section 3, 20.46% of data from strain gauge 1, 41.44% of data from strain gauge 2, and 24.90% of data from strain gauge 3 exceeded the 3σ limit. In the case of



(a) Analysis section 1



(b) Analysis section 2



(c) Analysis section 3

Fig. 7. Result of x-MR control chart analysis for the No. 1 strain gauge of strainmeter B.

section 3, as with section 2, strain gauge no. 2 showed a higher proportion of data exceeding the control limit line compared with other strain gauges.

Fig. 7 shows the results of analysis of strain gauge no. 1 of fault-behavior strainmeter B. In section 1, strain gauge no. 1 exceeded the 3σ control limit in 45.07% of all data, strain gauge 2 exceeded the limit in 62.46% of all data, and strain gauge 3 exceeded the limit in 16.82% of data. Strain gauge no. 2 had a relatively high proportion of data exceeding the control limit, compared with the other strain gauges. In the case of section 2, strain gauge no. 1 exceeded the control limit line 3σ in 42.77% of all data, strain gauge no. 2 exceeded the limit in 60.45% of all data, and strain gauge no. 3 exceeded the limit in 16.80% of all data. Strain gauge no. 2 still showed a higher proportion of data exceeding the control limit line compared with other strain gauges, although this decreased compared with section 1. In the case of section 3, strain gauge no. 1 exceeded the control limit line 3σ in 42.78% of all data, strain gauge no. 2 exceeded the limit in 60.57% of all data,

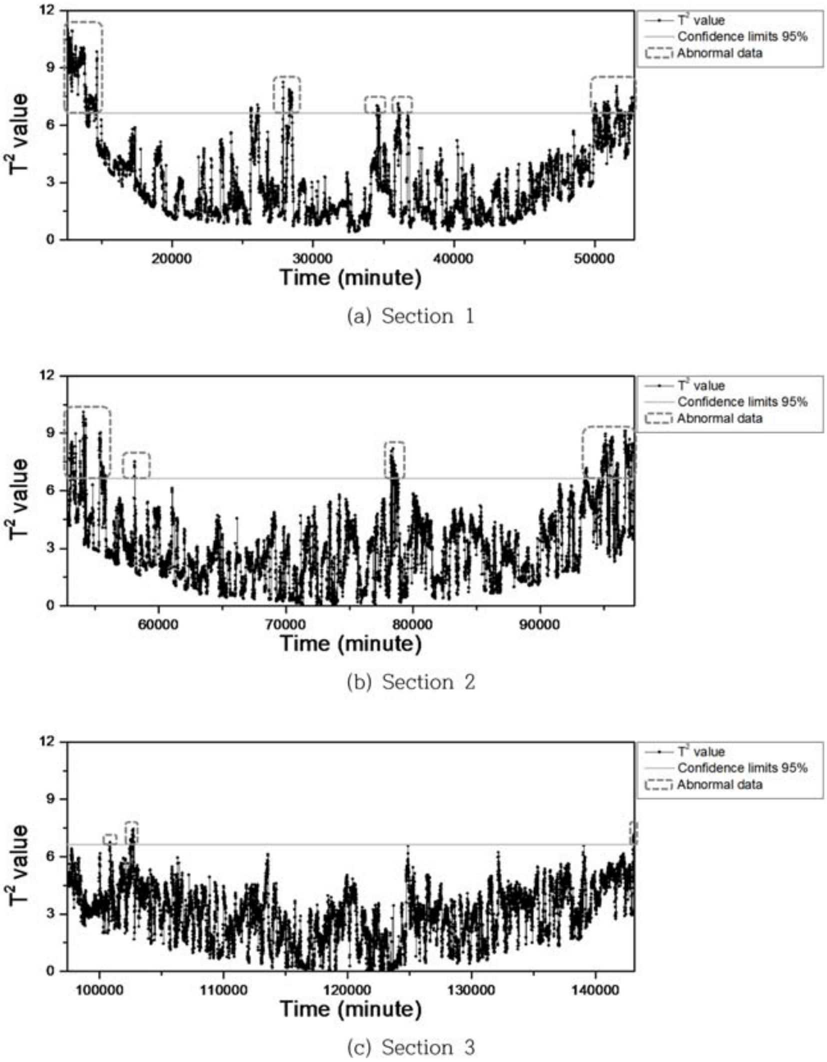


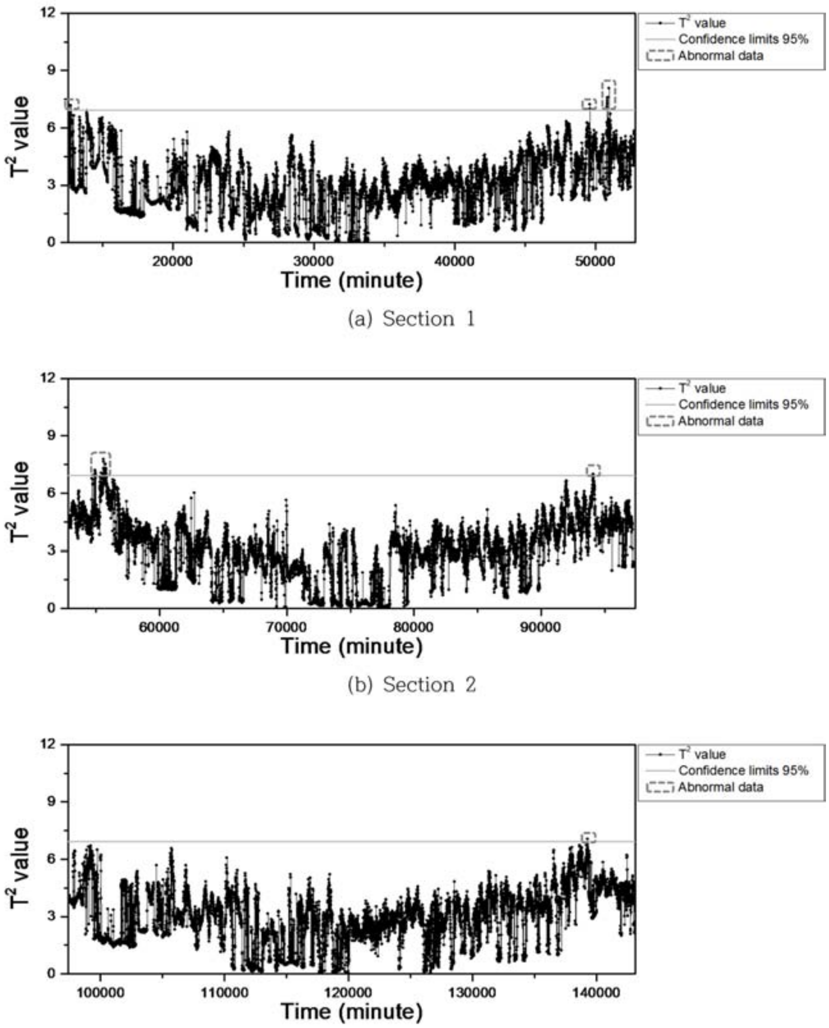
Fig. 8. Result of T^2 control chart analysis for strainmeter A.

and strain gauge no. 3 exceeded the limit in 20.44% of all data. Strain gauge no. 3 showed a higher proportion of data exceeding the control limit line compared with section 1, and strain gauge no. 2 showed a higher proportion of data exceeding the control limit line compared with other strain gauges.

T^2 control chart analysis of the stabilization stage

T^2 control chart analysis of the univariate data was conducted with control limit lines set at a confidence probability of 95%. Fig. 8 shows the results of T^2 control chart analysis of the strain gauge stabilization stage, for data obtained from fault-behavior strainmeter A. In the case of section 1, data exceeded the control limit lines at around 12,550~14,650, 25,650, 27,850, 34,550, 36,050 and 50,050~52,550 minutes. In the case of section 2, data exceeded the control limit lines at around 52,820~55,820, 57,820, 78,320 and 93,520~97,820 minutes. In the case of section 3, data exceeded the control limit lines at around 100,850, 102,690 and 143,070 minutes.

Fig. 9 shows the results of T^2 control chart analysis of data from the strain gauge stabilization stage of fault-



(a) Section 1

(b) Section 2

(c) Section 3

Fig. 9. Result of T^2 control chart analysis for strainmeter B.

behavior strainmeter B. In the case of section 1, data exceeded the control limit lines at around 12,730, 49,550 and 50,750 minutes. In the case of section 2, data exceeded the limit at around 54,920, 55,720 and 94,100 minutes. In the case of section 3, data exceeded the limit at around 139,190 minutes.

In all samples, there were a few cases where data exceeded the 95% reliability control limit lines. These results are less clear compared with the univariate assay values, which were up to 20 times larger than the control limit lines. This phenomenon can be attributed to the fact that in the case of T^2 analysis, strains measured in multiple directions have different values and affect each other, so that abnormal values might be underrepresented.

Analysis result

To estimate the stabilization time after strainmeter installation, x-MR and T^2 control analyses were conducted to calculate the proportions of measured values exceeding the control limit lines. These results are shown by section in Table 1. For strainmeter A, strain gauge no.3 can be

Table 1. Proportion of data exceeding the control limit line for each analysis section in the case of newly developed strainmeters.

Strainmeter A				
Analysis section	x-MR control chart analysis			T^2 control chart analysis
	No.1 Strain gauge	No.2 Strain gauge	No.3 Strain gauge	
1	19.01	37.83	39.29	7.36
2	19.52	40.06	25.76	5.14
3	20.46	41.44	24.90	0.38
Strainmeter B				
Analysis section	x-MR control chart analysis			T^2 control chart analysis
	No.1 Strain gauge	No.2 Strain gauge	No.3 Strain gauge	
1	45.07	62.46	16.82	0.17
2	42.77	60.45	16.80	0.34
3	42.78	60.57	20.44	0.01

considered stable by section 3, because the proportion of data exceeding the control limit line decreased from 39.29% in section 1 to 24.90% in section 3. Strain gauges 1 and 2 recorded more anomalous measurements in section 3 than in section 1, indicating they were not yet stabilized. However, the proportions of abnormal data were quite similar between sections 1 and 3. When all three strain gauges are evaluated simultaneously via T^2 control chart analysis, the percentage of abnormal measurements decreases from 7.36% in section 1 to 0.38% in section 3. This suggests the strain gauges can be considered stabilized.

For strainmeter B, strain gauge 1 can be considered stabilized because the proportion of data exceeding the control limit line decreased from 45.07% (section 1) to 42.78% (section 3), although the difference is insignificant. Strain gauge no. 2 also gradually stabilized, as the proportion of data exceeding the control limit line decreased from 62.46% to 60.57%. Strain gauge no. 3 cannot be considered stabilized because the proportion increased from section 1 to section 3. T^2 control chart analysis suggests that the system of strain gauges can be considered stabilized because the percentage of abnormal measurments decreased from 0.17% in section 1 to 0.01% in section 3.

The results of x-MR analysis indicate that three strain gauges installed in different directions and locations in the same fault system will stabilize differently from each other. Given that site stress acting on the crust has directivity, these results indicate that the strain gauges accommodate the directivity. Therefore, when determining whether strainmeters have become stabilized, the direction of site stress should be considered, and T^2 control chart analysis that can analyze multiple strain gauges simultaneously should be conducted while taking directivity into account.

Conclusion

With the aim of developing an empirical criterion for quantitatively determining strain gauge stabilization time, x-MR and T^2 control chart analyses were conducted using data obtained from strainmeters installed around the Andong fault zone. To detect anomalous strain measurements, 500 minutes of temporarily stabilized data was analyzed to determine an empirical 3σ control limit. Using the empirical criteria, we show that three of six strain gauges stabilized after only three months. Gauge stabilization depended on the location and direction of installation, even in the same strainmeter. We interpret this result to reflect the directivity and localization of crustal stress.

In T^2 control chart analysis, we established an empirical 95% confidence control limit to determine when two fault-behavior strainmeter systems had become stabilized. Our results suggest that an empirically determined 3σ control limit can be used in x-MR control chart analysis to identify the stabilization of single strain gauges after installation. Similarly, an empirically determined control limit can be used in T^2 control chart analysis to assess the stabilization of multi-component strainmeter systems.

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References

Burbank, D. W. and Anderson, R. S., 2001, Tectonic geomorphology, Wiley-Blackwell Science, 274p.

Choi, J. H., Ko, G. T., Kim, J. Y., and Kim, Y. S., 2012, A paleoseismological study based on the damage characteristics of speleothems in limestone cave: a case study from Seongryu Cave in Uljin, Korea, Journal of the Geological Society of Korea, 48(3), 225-240 (in Korean with English abstract).

Choi, S. H., Kim, H. S., Yoo, S. H., Chung, C. K., and Jang, I. S., 2011, A preliminary study of the seismic damage estimation for harbor sites, Earthquake Engineering Society of Korea, 15(3), 45-55 (in Korea with English abstract).

Gladwin, M. T., Gwyther, R. L., Hart, R. H. G., and Francis, M., 1987, Borehole tensor strain measurements in California, Journal of Geophysical Research, 92(B8), 7981-7988.

Hart, R. H. G., Gladwin, M. T., and Gwyther, R. L., 1996, Tidal calibration of borehole strain meters: Removing the effects of small-scale inhomogeneity, Journal of Geophysical Research, 101(B11), 25553-25571.

Hwang, J. S., Choi, J. W., Choi, W. H., Cho, S. I., and Chang, C. J., 2012, Analysis of the Great East Japan Earthquake observed by strainmeter of Eupcheon Fault Monitoring System, Journal of the Geological Society of Korea, 48(6), 491-501 (in Korean with English abstract).

Jeon, W. H., Kwon, K. S., and Lee, S. Y., 2011, Evaluation of groundwater level changes in Korea due to the earthquake in Japan, Journal of the Geological Society of Korea, 47(6), 695-706 (in Korean with English abstract).

Kanamori, H., 2005, Real-time seismology and earthquake damage mitigation, Annual Review of Earth and Planetary Sciences, 33(1), 195-214.

Keller, E. A. and Pinter, N., 2001, Active tectonics: Earthquakes, Uplift and Landscape, second ed., Pentice Hall, 362p.

Kim, B. R., Chae, B. G., Kim, Y. J., and Seo, Y. S., 2013, Application of statistical analysis to analyze the spatial distribution of earthquake-induced strain data, The Journal of Engineering Geology, 23(4), 353-361 (in Korean with English abstract).

Kim, S. B., Seo, Y. S., Kim, H. S., Chae, B. G., Choi, J. H., and Kim, J. S., 2014, Development of a method for detecting unstable behaviors in flume tests using a univariate statistical approach, The Journal of Engineering Geology, 24(2), 191-199.

Kim, Y. S., Jin, K., Choi, W. H., and Kee, W. S., 2011, Understanding of active faults: A review for recent researches, Journal of The Geological Society of Korea, 47(6), 723-752 (in Korean with English abstract).

Kim, Y. S., Park, J. Y., Kim, J. H., Shin, H. C., and Sanderson, D. J., 2004, Thrust geometries in unconsolidated quaternary sediments and evolution of the Eupchon fault, southeast Korea, The Island Arc, 13(3), 403-415.

Korea Meteorological Administraion (KMA), 2015, Earthquakes trends, Retrieved from http://www.kma.go.kr/weather/earthquake/domestictrend.jsp (in Korean).

Kyung, J. B. and Lee, K. H., 2006, Active fault study of the Yangsan fault system and Ulsan fault system, southeastern part of the Korean peninsula, Journal of the Korean Geophysical Society, 9(3), 219-230 (in Korean with English abstract).

Lee, H. A., Kim, H. M., Hong, T. K., and Woo, N. C., 2011, Earthquake observation through groundwater monitoring: A case of M4.9 Odaesan Earthquake, The Journal of Soil and Groundwater Environment, 16(3), 38-47 (in Korean with English abstract).

Lee, H. W., 2011, Technical trend analysis of a fault monitoring system, The Journal of Engineering Geology, 21(1), 87-95, (in Korean with English abstract).

Maria, Z. and Carla, B., 1999, Measurements and interpretations of tilt-strain gauges in seismically active areas, Earth-Science Reviews, 47(3), 151-187.

McCalpin, J. P., 1996, Paleoseismology, Academic press, 588p.

McCalpin, J. P., 2009, Paleoseismology (second ed.), Academic press, 613p.

Sheen, D. H., Lim, I. S., Park, J. H., and Chi, H. C., 2012, Earthquake magnitude determination using P phase for earthquake early warning, Journal of the Geological Society of Korea, 48(1), 101-111 (in Korean with English abstract).

Shewhart, W. A., 1924, Some applications of statistical methods to the analysis of physical and engineering data, Bell System Technical Journal, 3(1), 43-87.

Waltham T., 2009, Foundations of engineering geology, third edition, Taylor & Francis, 104p.

Wu, Y. M. and Kanamori, H., 2005, Experiment on an onsite early warning method for the Taiwan early warning system, Bulletin of the Seismological Society of America, 95(1), 347-353.

Yim, S. B., Jeong, H. G., and Seo, Y. S., 2009, Assessment of tunnel displacement with weak zone orientation using 3-D numerical analysis, The Journal of Engineering Geology, 19(1), 43-50 (in Korean with English abstract).

Yim, S. B., Kim, S. K., Seo, Y. S., and Park, S. H., 2007, A study on convergency of tunnel displacement using control chart method, The Journal of Engineering Geology, 17(2), 197-204 (in Korean with English abstract).

Yun, H. S., Song, G. J., Shin, Y. W., Kim, C. Y., Choo, S. Y., and Seo, Y. S., 2014, Application of x-MR control chart on monitoring displacement for prediction of abnormal ground behaviour in tunnelling, Journal of Korean Tunnelling and Underground Space Association, 16(5), 445-458 (in Korean with English abstract).

Yun, K. H., 2012, Study on the use of bracketed summations of the peak ground-motion acceleration per second for rapid earthquake alert notifications, Earthquake Engineering Society of Korea, 16(1), 37-45 (In Korean with English abstract).

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