Development of a Method for Detecting Unstable Behaviors in Flume Tests using a Univariate Statistical Approach

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We describe a method for detecting slope instability in flume tests using pore pressure and water content data in conjunction with a statistical control chart analysis. Specifically, we conducted univariate statistical analysis on x-MR control chart data (pore pressure and water content) collected at several points along the flume slope, which we separated into three parts: upper, middle, and lower. To assess our results in the context of landslide forecasting and warning systems, we applied control limit lines at 1σ , 2σ , and 3σ levels of uncertainty. In doing so, we observed that dispersion time varies depending on the control limit line used. Moreover, the detection of instabilities is highly dependent on the position and type of sensor. Our findings indicate that different characteristics of the data on various factors predict slope failure differently and these characteristics can be identified by univariate statistical analysis. Therefore, we suggest that a univariate statistical approach is an effective method for the early detection of slope instability.

Key words : flume test, pore pressure, water content, x-MR control chart, univariate statistics

Introduction

Landslides are typically triggered following a decline in the shear strength of soil or rock slopes, with shear failure related to various factors such as the characteristics of ground surface layers and the slip surface (Seo et al., 2008). Specifically, landslides caused by rainfall result from increases in pore pressure, volumetric water content, and unit weight, as well as decreases in shear strength (Brand, 1981; Brenner et al., 1985; Yoshida et al., 1991; Lee and Park, 2004; Meilani et al., 2005; Kim and Jeong, 2008).

Existing studies of the relationships between rainfall and landslides include predictions of landslide events, intensity

and duration of rainfall, establishment of critical values through cumulative rainfall analysis, and rainfall-based GIS predictions (Caine, 1980; Crozier, 1995, 1999; Aleotti, 2004; Chae and Seo, 2010; Jang et al., 2010). Additionally, to compensate for insufficient observational data in landslide-prone areas (of Korea and elsewhere), laboratory flume tests have been conducted since the late 1970s. Previous flume tests in Korea have focused on patterns of landslide occurrence and dispersal of debris, characteristics of landslide triggers, and classification of landslide behavior. Elsewhere, flume test studies have been used to investigate relationships between landslide distance and changes in pore pressure, and the results have been used to classify the stages at which pore pressure changes result in

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Fig. 1. Geologic map of the Sangju area, showing sampling sites of weathered granitic soils (modified from Kim and Lee, 1986).

slope failure (Wang and Sassa, 2001; Okura et al., 2002; Chae et al., 2006; Sagong et al., 2006; Jeong et al., 2011).

In the present study, we used a univariate statistical analysis to develop a landslide forecasting and warning method, which includes the detection of abnormalities in slope behavior, controlled in real time. We conducted laboratory flume tests on weathered granitic and gneissic soils, analyzing the resulting pore pressure and water content data using x-MR control chart statistics.

Study area and geologic setting

Sangju area

We collected samples of weathered soil from Sangyong-ri, Whasuh-myon, Sangju-si, and Gyeongbuk-do, all of which are underlain by a white-green-colored porphyritic granite. This Permian lithology contains abundant feldspar megacrysts (Kim and Lee, 1986) and is associated with an elongate batholith underlying Yeongdong, Okcheon, and Boeun and centered on Jijun-ri.

Jangsu area

The Jangsu area is underlain primarily by banded, leucocratic-granitic gneiss of Precambrian age, although mixtures of other lithologies outcrop locally (Lee and Nam, 1969). We collected samples of weathered gneissic soils from Gongjeong-ri, Anseong-myon, Muju-si, and Joellabuk-do (Fig. 2).

Design and methodology of the model testing device

Flume test equipment

The flume apparatus used in our experiments measures 2.0 m in length, 0.3 m in width, and 1.4 m in height, with a slope angle of 35°. The upper, tilted, and lower soil tanks measure 0.3 m, 1.5 m, and 0.5 m in length, respectively (Fig. 3). To facilitate observation of soil behavior and displacement, one of the flume walls was constructed of glass, and colored sand was inserted at intervals of 0.1 m. The lower end of the flume was kept open to maintain drainage conditions as similar to a natural state as possible. We divided the bottom of the tilted soil tank into upper (HS), middle (MS), and lower parts (LS), and installed pore pressure meters at 0.1 m, 0.3 m, and 1.3 m distance from the base. Additionally, ADR (water content) sensors were positioned at 0.25 m, 0.7 m, and 1.15 m from the base (Kim et al., 2008).

Test conditions and test samples

We subjected samples of weathered granitic (GR) and gneissic (GN) soils to a specific set of conditions, where rainfall intensity was 200 mm/hr and initial water content was fixed within a 7%-22% range. We used a slope angle of 25°-35° as this value is typical of naturally occurring low-angle slope failure (Table 1; Kim et al., 2008). To compare landslide characteristics between rock types, we

Fig. 2. Geologic map of the Jangsu area, showing sampling sites of weathered gneissic soil (modified from Lee and Nam, 1969).

Fig. 3. Side-on schematic diagram illustrating the configuration of the flume test apparatus.

performed repeated analyses of both lithologies under the same set of conditions. All samples were classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS), with GR soils exhibiting a more even distribution (Table 2). Grain-size distribution curves for each lithology are shown in Fig. 4.

Analytical theory

As a univariate analysis, tool, an x-MR control chart is a statistical approach to detecting abnormalities in data collected in real time. Specifically, an analysis section (K) is established on a graph of observed values, and

Table 1. Flume test conditions for weathered granitic and gneissic soils.

Test No.	Rainfall intensity (mm/hr)	Slope angle (°)	Initial water content (%)
GR-1	200	30	9
GR-2	200	30	19
GR-3	200	25	7
GR-4	200	25	8
GR-5	200	30	11
GR-6	200	25	16
GR-7	200	25	9
GR-8	200	35	15
GN-1	200	30	15
GN-2	200	25	12
GN-3	200	25	21
GN-4	200	35	20
GN-5	200	30	22
GN-6	200	25	20

differences between maximum ($x_{\max}$) and minimum ($x_{\min}$) values are depicted on the x-MR control chart (Lim et al., 2007; Lim and Seo, 2009). To identify abnormalities on the x-MR control chart, a control limit line is established using the central line (CL) as the basis. This control limit line is based on the average and standard deviation, via

Table 2. Physical properties of weathered granitic and gneissic soils.

Specimen	Grain size	Pebble (%)	Sand (%)	Silt and clay (%)	Coefficient of Uniformity (Cu)	Coefficient of Curvature (Cg)
Granitic weathered soil		0.00	99.99	0.01	2.47	1.15
Gneissic weathered soil		0.00	99.99	0.01	3.20	1.13

(a) Granitic weathered soil

(b) Gneissic weathered soil

Fig. 4. Particle size distribution curves for each lithology, based on sieve analysis.

equations (1) and (2), respectively.

$$\mu = \sum \mu_i / n \quad (1)$$

$$\sigma = \sqrt{\frac{n \sum \mu_i^2 - (\sum \mu_i)^2}{n(n-1)}} \quad (2)$$

Control limit lines incorporating the upper control limit (UCL) and lower control limit (LCL) as references are expressed in equations (3) and (4), respectively, where μ represents the average, σ is standard deviation, and z is a coefficient. The control limit line can then be established by adjusting z . Although the control limit line is determined using a 3σ control limit line (Shewhart, 1924), the detection capability of these analyses can be enhanced by employing a 2σ control limit line (Yeom and Jeong, 2008).

$$UCL = \mu + z\sigma \quad (3)$$

$$LCL = \mu - z\sigma \quad (4)$$

In this study, we employ a three-step control boundary line using equations (5)–(7). Where data exhibit a normal distribution, we calculated reliability of the control limit line at 68.27% (1σ), 95.45% (2σ), and 99.73% (3σ), where reliability represents the probability of an ideal dispersion (Fig. 5).

Fig. 5. Graphical depiction of control limits for an x-MR control chart (modified from Shewhart, 1924).

$$1\sigma \text{ control limit} = \mu + \sigma \quad (5)$$

$$2\sigma \text{ control limit} = \mu + 2\sigma \quad (6)$$

$$3\sigma \text{ control limit} = \mu + 3\sigma \quad (7)$$

Results and discussion

With the analysis section (K) set at 50 seconds, we performed univariate statistical analysis for each point along the tilted flume at which sensors are located and soil characteristics observed. We then calculated the average and standard deviation of each data series in order to set stepwise control limit lines. In addition, we analyzed both the failure time and the time taken for dispersion to occur, with the three control limit lines corresponding to 1σ , 2σ ,

Table 3. Control chart depicting time differences between slope failure and landslide dispersion. (unit:sec)

Test No.	Water content									Pore pressure								
	1 σ			2 σ			3 σ			1 σ			2 σ			3 σ		
	LS	MS	HS	LS	MS	HS	LS	MS	HS	LS	MS	HS	LS	MS	HS	LS	MS	HS
GR-1	715	640	210	685	570	-	160	-	-	30	510	90	-	-	-	-	-	-
GR-2	20	-	350	10	-	200	-	-	180	160	-	30	110	-	20	90	-	-
GR-3	500	410	110	480	380	-	-	-	-	-	20	160	-	-	150	-	-	-
GR-4	1300	1310	500	1280	667	450	-	-	422	500	700	1040	490	570	1030	480	-	1010
GR-5	210	180	90	190	120	80	170	-	70	260	150	180	240	130	140	100	110	130
GR-6	530	730	510	430	-	-	-	-	-	-	-	170	-	-	-	-	-	-
GR-7	1190	1300	1110	1150	1290	1110	1120	1270	1080	230	740	430	210	30	10	120	10	10
GR-8	40	30	40	40	30	40	30	-	30	40	50	120	40	50	50	40	40	50
GN-1	160	50	80	60	50	70	50	50	-	60	70	60	50	50	40	40	50	40
GN-2	280	70	30	210	60	-	50	50	-	50	80	90	40	70	80	30	60	70
GN-3	140	280	680	90	250	650	-	-	640	290	340	520	220	270	510	-	260	500
GN-4	100	90	110	90	80	100	80	70	-	100	210	140	-	190	120	-	110	100
GN-5	670	680	970	590	500	930	210	490	900	830	120	-	-	-	-	-	-	-
GN-6	2210	2130	2000	2200	-	1960	2190	-	1870	120	710	690	0	-	680	-	-	0

Fig. 6. Results of x-MR control chart analysis for GR-4.

and 3 σ . Failure time was marked with a dotted line and the predicted time with an $\times$, and differences between the two are given in Table 3.

Several runs produced relatively good predictions in both granitic and gneissic lithologies. In the case of granitic sample GR-4, dispersion was detected 450-1310

seconds prior to failure in each of the sensors, within 1 σ and 2 σ . Within 3 σ , dispersion was detected 400-1000 seconds prior to failure at water content HS and pore pressure LS and HS (Fig. 6). Within 1 σ , dispersion was detected approximately 20-640 seconds earlier than at 2 σ , and 40 seconds earlier at 2 σ than at 3 σ . Similarly, in the

Fig. 7. Results of x-MR control chart analysis for GR-5. **Fig. 8.** Results of x-MR control chart analysis for GN-3.

GR-5 model dispersion was detected 70-170 seconds before failure at all positions, except water content MS, within 2σ , making it an early detection. Indeed, we detected dispersion 80-240 seconds and 90-260 seconds prior to failure within 2σ and 1σ , respectively, for all x-MR analysis data pertaining to this run (Fig. 7). Within 1σ , dispersion was apparent 10-60 seconds earlier than at 2σ , and 10-20 seconds earlier at 2σ than at 3σ .

For gneissic sample GN-3, we detected dispersion at each sensor 90-680 seconds before slope failure within 3σ . However, early detection was only possible on water content HS and pore pressures HS and MS (Fig. 8). Moreover, for this model, we forecast failure 10-70 seconds earlier within 1σ than at 2σ , and 10-20 seconds earlier at 2σ than 3σ . In the GN-4 model run, we were able to detect failure at 3σ 70-110 seconds prior to the

Fig. 9. Results of x-MR control chart analysis for GN-4.

event at all positions except water content HS and pore pressure LS (Fig. 9). In this run, within 1σ , we detected failure on all positions 1080 seconds earlier than at 2σ , and 10-80 seconds earlier at 2σ than 3σ .

The results of our 14 model experiments show that significant variability exists in prediction of failure time. We suggest that this is most likely due to differences in physical soil characteristics (e.g., compaction, initial water content) among the samples.

Conclusion

We analyzed modeled pore pressure and water content data to evaluate the efficacy of statistical analysis for assessing trends in the factors causing rainfall-triggered landslides. Moreover, we used the results of our experiments to establish management criteria and examine the validity of landslide forecasting and warning systems. Our laboratory-based flume tests incorporated a rainfall intensity of 200 mm/hr and slope inclination of 25° - 35° . We divided the model slope into three vertical sections and installed water content and pore pressure sensors at each position. Finally, we conducted univariate statistical analysis on individual data series to detect slope instabilities.

Using our modeled data, we analyzed the x-MR control

chart and established a three-step control limit line, in which reliability is defined within 1σ , 2σ , and 3σ . We used this control limit line to test a stepwise landslide forecasting and warning system. Modeled slope instabilities were detected from seconds to minutes prior to the actual failure, and at a relatively low reliability relatively high probability was identified and the unstable behavior was detected from tens of seconds to thousands of seconds more quickly.

Univariate statistical analysis can be applied to observational data to help estimate dispersion times and detect slope instability. However, our study shows that prediction times can vary depending on the position and type of sensor used, and highlights the need for analyses that take into account correlations between numerous data sources.

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