The Effectiveness of a Wireless Sensor Network System for Landslide Monitoring

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ABSTRACT In this paper, the application of a WSN (Wireless Sensor Network) for landslide monitoring was studied. The WSN system consists of a sensor node for collecting and transmitting data using the IEEE 802.14e standard and a gateway for processing and transmitting the data to the final server. The topology of the sensor network adopts a highly flexible and reliable mesh type, and a test bed was built in three locations in Seoul. An instrumentation is done for each sensor node composing of two soil moisture sensors, one tensiometer, and one inclinometer and one rain gauge per test bed. For the estimation of optimal network topology among the sensor nodes, a susceptibility assessment of landslides, the density of trees and a viewshed analysis of the terrain were analyzed. As a result, the network connection worked quite well, and the response of the soil from rainfall was similar to the soil water characteristic curve obtained from laboratory tests. Therefore, a WSN system can be applied to landslide monitoring by collecting reliable data. In addition, the appropriate design method of WSN system for landslide monitoring was proposed.

INDEX TERMS Landslide, monitoring, network topology, wireless sensor network (WSN).

I. INTRODUCTION Recently, local heavy rains have been occurring frequently in South Korea due to climate change, leading to an increase in the number of landslides. Specifically, landslides have occurred in urban areas, causing damage to people and property. Additionally, the rainfall intensity, cycle and period have also been changing [1], [2]. The magnitude and occurrence of landslides due to rainfall have been increasing globally [1]–[5], and the amount of landslides due to local heavy rains have been increasing in Korea [6], [7]. Generally, rainfall in Korea occurs intensively during the summer seasons, such as June to September. Based off landslide history, landslides also occur during this period of heavy rainfall [8].

In Korea, the forecast and warning system for landslides is based on the amount of rainfall. However, 60% of landslides disasters occur in rainfall below the criteria for landslide warning by the Korea Forest Service [9]. For a steep slope, measuring instruments such as inclinometers, water level meters, and surface displacement measurements should be installed to observe the behavior of the slope. However, it is difficult to enter and install the equipment and to maintain the equipment due to the large area of the landslide. To overcome these shortcomings, several studies on landslide monitoring based on wireless sensor network (WSN) technology using information communication techniques have been recently studied [10]–[18]. The Korea Institute of Geoscience and Mineral Resources (KIGAM) and the National Institute of Forest Science have been conducting on-site testing in Korea to introduce WSNs into landslide monitoring [19], [20].

The measurement system based on a WSN can monitor a large area at a low cost. However, it has a disadvantage in that it may not be able to perform monitoring at a desired time due to rapid consumption of WSN power. Therefore, research on the development of sensor and routing protocol technology with a low power consumption and longer lifetime has been conducted [21].

Landslides are a complicated phenomenon and various factors like topography, soil characteristics, vegetation and rainfall influence this phenomenon. A generalized assessment or prediction involving this unpredictable and huge data...
is quite a challenge. There is need for regional landslide monitoring techniques considering the various local live data. Traditionally, landslide monitoring has been performed in two dimensions by selecting representative area. This method is still used as an important method for identifying the causes and mechanisms of slope disaster when vulnerable slopes and management targets are clear. However, when large topographical area is involved watershed scale monitoring techniques are needed.

To date, regional scale landslides prediction methods have been used depending on topographic, geologic, hydrologic variables and changes in land use [22], [23]. Landslide susceptibility assessment on regional scale is useful for avoiding landslide losses [24]. Implementing data for landslide factor, such as weather conditions, topography and vegetation, in Geographic Information System (GIS) might be a start for a regional landslide susceptibility assessment [25]. Due to the ability to process spatial data, Geographic information systems (GISs) are broadly used for landslide analyses [10]. In particular, physical based models combine a geotechnical model and a hydrological model for analysis of rainfall induced landslides. They can be used for determining locations and the timing of the occurrence of a rainfall-induced landslide on a regional scale using GIS. Consequently, susceptibility assessments of landslides on regional scale are needed to avoid or reduce landslide losses, and combining the hydrologic models with geotechnical models. Due to the large and remote areas involved, it is necessary to apply low-cost, low-power-based wireless sensor network (WSN) technology. This can facilitate and ease power supply, manifold input, and measurement data collection. In particular, Ramesh [10] constructed WSN system for mountain slopes near a residential area in India. Ramesh [26] collected real-time data using tiltmeter, geophone, rain gauge, and pore pressure meter to measure the influencing factors of slopes. The data collection rate and collected data are both reliable. This ensures the applicability of WSN for landslide monitoring.

In this paper, the applicability of WSN technology for landslide monitoring is studied, and the design and application method of a WSN measurement system for landslide monitoring based on measurements in a test bed are proposed. And it is focused on the applicability of WSN for landslide monitoring and data acquisition rather than occurrence of landslide.

II. LANDSLIDE MONITORING BASED ON A WIRELESS SENSOR NETWORK (WSN)

A. WSN SYSTEM

A wireless sensor network (WSN) is defined as a self-organizing and multihop networks of wireless sensor nodes used to monitor and control physical phenomena [27]. The WSN typically includes sensor nodes, gateways (or base stations) and clients. The structure of the system is shown in Fig. 1.
protocol (TSMP) from Dust Networks, Inc. are applied to construct a multihop network with a low power consumption.

E. ADVANTAGES FOR LANDSLIDE MONITORING

In the case of landslides, its occurrence and damage range are wider than other disasters. Therefore, the method of monitoring the stability of facilities through representative sections such as single point measurement or two-dimensional section measurement, which was performed in the existing infrastructure, is not valid. In addition, in case of steep slopes, it is not easy for manpower to access, and when using wired-based equipment, there is a concern about equipment loss such as disconnection by exposing natural phenomena. In addition, when monitoring the wide area using the existing wire-based measurement system, the cost of construction is enormous. Accordingly, low-cost, low-power wireless measurement systems are required to reliably measure wide ranges.

F. SUSCEPTIBILITY ASSESSMENT OF LANDSLIDES

To make a reasonable network topology among the sensor nodes, a landslide susceptibility analysis was performed using a GIS-based YS-slope model [28], which can take both rainfall infiltration and groundwater flow into account. This model is a landslide analysis model using physical methods such as computer programs (e.g., SINMAP, SHALSTAB, TRIGRS models), and an improved hydrological model and geotechnical model were adopted. In addition, the model was developed to analyze the slope failure of unsaturated soil due to rainfall, which is a typical type of slope failure in Korea. As shown in Fig. 3, the geotechnical characteristics, hydraulic characteristics, vegetation, and geometric characteristics are constructed as spatial data, and the landslide analysis is made possible by using raster data from the GIS, which is a matrix data structure.

For the YS-slope model, the infinite slope model was used as a physically based model for landslide analysis. This model assumes that the infinite slope is much shallower than its length, and the most critical failure surface is a straight line parallel to the slope. The failure surface and boundary conditions are different in the case of a rise in the groundwater level and in the case of a drop in the wetting front, respectively. The Mohr-Coulomb criterion for the stability analysis was improved by considering the pore-water pressure and pore-air pressure [29]. In addition, the infinite slope model was improved by considering the uniform load from the vegetation and the additional shear strength cause by the reinforcing effect of the roots, which were proposed by Hammond et al. [30]. Therefore, this model considers the spatial and temporal variations of groundwater. If the critical failure surface is parallel to the infinite slope as shown in Fig. 3, the factor of safety (FS) for the infinite slope can be calculated as follows:

$$FS = \frac{(c_s' + c_r') + \gamma_t \cdot D_s + q_0 + (\gamma_{sat} - \gamma_w) \cdot D_w \cos^2 \beta \cdot \tan \varphi'}{(\gamma_t \cdot D_s + \gamma_{sat} \cdot D_w + q_0) \sin \beta \cos \beta}$$  (1)

where $c_s'$ is the cohesion of the soil, $c_r'$ is the constant number of additional shear strengths from the roots, $q_0$ is the uniform load from trees, $D_w$ is the depth of the wetting band ($=D_{wm} + D_{wn}$), $D_s$ is the depth of the unsaturated soil ($=D_{um}$), $\gamma_t$ is the total unit weight of the soil, $\gamma_{sat}$ is the saturated unit weight of soil, $\gamma_w$ is the unit weight of water, and $\beta$ is the angle of slope.

The assumption proposed by Green and Ampt [31] that the volumetric water content and deficit in the water content remain constant above the wetting front is essentially adopted in this model. However, the Green-Ampt model has the drawback that it cannot clearly distinguish the relationship between the permeability and rainfall intensity. To overcome this, the method of estimating the cumulative infiltration by rainfall was applied by comparing the rainfall intensity with the permeability [1], [32].

In addition, the ponding time was applied to consider the relationship between the rainfall infiltration and runoff [32]. The rainfall infiltration ($I_R$) can be obtained by using the trial and error method with a variable cumulative infiltration. The depth of the wetting front temporarily formed in the vadose zone ($D_{wn}$), taking the soil properties into account, is defined as the ratio between the rainfall infiltration $I_R$ and the deficit in the water content $\Delta \theta$ as follows:

$$D_{wn} = \frac{I_R}{\Delta \theta} = \frac{I \cdot t_p + f_p K_s (1 + \frac{\psi_f - \Delta \theta}{F})}{\Delta \theta}$$  (2)

where $I$ is the rainfall intensity, $t_p$ is the time for ponding, $I_R$ is the rainfall infiltration, $t_w$ is the rainfall duration, $K_s$ is the saturated permeability, $\psi_f$ is the head of the metric suction, $F$ is the infiltration, and $\Delta \theta$ is the deficit in the water content.

For groundwater flow in the YS-slope model, the raster model of GIS and Darcy’s law were combined to consider the groundwater flow. However, only the landslide susceptibility induced by the rainfall intensity duration at a 100-year return period was analyzed as shown in Fig. 4, so the groundwater flow model was not considered in this study.

III. STUDY AREA

A. TEST BED

To monitor landslides in urban areas, three areas located in Seoul, Korea were planned as test beds and installed WSN system for each test beds. The data for slopes in Seoul [33]
FIGURE 3. Flow chart of GIS-based YS-slope model [28].

were referred and reviewed for the selection of a reliable test bed. The histories of landslide and debris flow, topographical characteristics (soil depth >0.5 m, and a 20 ~ 40° slope angle), areas where the geological boundary or fault has changed, areas where the factor of safety for landslide and debris flow was relatively low, and the species of bedrock (e.g., granite and gneiss) were comprehensively collected and analyzed in 110 areas. Based on the results of the analysis, three representative watersheds, which have high possibility of landslide occurrence among 110 areas in Seoul, were selected as the test beds as shown in Fig. 5: the Guryong mountain (TB-1), Gwanak mountain (TB-2), and An mountain (TB-3).

**B. GEOLOGICAL, TOPOGRAPHICAL AND GEOTECHNICAL CHARACTERISTICS**

Comprehensive field and laboratory studies were conducted to determine the geological, topographical and geotechnical characteristics of the three test beds. Areas TB-1, TB-2, and TB-3 are underlain by banded gneiss mixed with fine-grained gneiss, granite, and biotite banded gneiss, respectively. The characteristics of weathered soil vary depending on each type of bedrock. The weathered soil of TB-1 is a distributed mixture of coarse and fine-grained textures. In general, the strength of weathered soil is considered low. Because the weathered soil of TB-2 is composed of coarse-grained texture, its strength is considerably lowered. The weathered soil of TB-3 is composed of medium-grained texture, and the RQD of the soft rocks is poor due to the effect of a small amount of limestone. In the case of the foundation rock which composed of limestone, the RQD is relatively low, about 40 ~ 60 [34].

For TB-1, the geology of the slopes consists of an approximately 2.0-m-thick layer on average and the slopes become steep closer to the top, and there are many steep slopes that are over 40°. For TB-2, the soil depths are 0.5 m to 1.5 m, and
the slope is 27° on average. The geology of TB-3 consists of a 0.5-m-thick layer, which is a relatively shallow depth, and the slope is approximately 21°. The topographical characteristics of TB-1, TB-2, and TB-3 are summarized in Table 1. For each test bed, the soil depth was estimated by analyzing the results of the borehole survey, test pit, refraction seismic survey, and multichannel analysis of the surface waves (MASW) using kriging.

To investigate the geotechnical characteristics of the test beds, a field investigation and laboratory test were comprehensively conducted. The field investigation included (1) surface geological survey, (2) borehole survey, (3) test pit, (4) standard penetration test (SPT), (5) field density test, (6) field permeability test, (7) surface permeability test, (8) cone penetration test (CPT), (9) refraction seismic survey, and (10) multichannel analysis of surface waves (MASW). In addition, laboratory tests for determining the soil properties included (1) soil classification, (2) water content, (3) Atterberg limits, (4) grain size distribution, (5) soil-water characteristic curves (SWCC), and (6) the shear strength parameter via the direct shear test. Specifically, the pressure plate extractor [35] was used to obtain the soil-water characteristic curves for test beds. Fig. 6 shows the soil-water characteristic curves for three test beds. The prediction model proposed by van Genuchten [36] is used to fit the soil-water characteristic curve to the test data.

The geotechnical properties and parameters for the unsaturated soil-water characteristic obtained from field and laboratory tests are summarized in Table 2. As a result of the investigation of the vegetation distribution in this area, the representative species of trees were Quercus mogolica (known as Mongolian Oak), Pinus rigida (known as pitch pine), and Pinus koraiensis. The tree density was approximately 250 ~ 830 trees/ha. A biomass estimation equation and existing values from previous studies were used to apply the vegetation load of 0.22 kPa and an additional shear strength of the roots of 1.0 kPa [37].
TABLE 1. Topographical characteristics of test bed.

| Contents | TB-1 | TB-2 | TB-3 |
|----------|------|------|------|
| Angle(°) | Area (m²) | Analysis area (m²) | Area (m²) | Analysis area (m²) | Area (m²) | Analysis area (m²) |
| 0–5      | 494,244 | 977,757 | 65,148 | 19,986,911 | 2,419,198 |
| 5–10     | 1,130,434 | 2,035,046 | 174,166 | 24,3 |
| 10–15    | 1,852,980 | 2,945,376 | 354,274 | 14,6 |
| 15–20    | 2,327,418 | 3,939,824 | 552,900 | 22,9 |
| 20–25    | 1,580,789 | 3,850,654 | 587,294 | 24,3 |
| 25–30    | 744,426 | 2,952,042 | 381,422 | 15,8 |
| 30–35    | 272,993 | 1,929,908 | 190,488 | 7,9 |
| 35~      | 112,589 | 1,356,304 | 113,506 | 4,7 |

Slope

Flat | 543,465 | 1,083,121 | 53,347 | 2,2 |
N | 967,443 | 2,378,144 | 172,921 | 7,1 |
NE | 943,391 | 2,659,990 | 257,754 | 10,6 |
E | 576,656 | 2,334,735 | 319,710 | 13,2 |

Aspect

SE | 1,291,263 | 1,726,687 | 199,894,51 | 256,239 | 10,6 |
S | 1,501,787 | 920,548 | 249,568 | 10,3 |
SW | 911,613 | 1,773,499 | 392,596 | 16,2 |
W | 667,388 | 3,134,662 | 459,951 | 19,0 |
NW | 1,114,768 | 3,978,265 | 258,365 | 10,7 |

FIGURE 6. Soil-water characteristic curves for three test beds: (a) TB-1, (b) TB-2, and (c) TB-3.
TABLE 2. Geotechnical properties and parameters for unsaturated soil-water characteristics.

| Contents                        | TB-1                          | TB-2                          | TB-3                          | Description                        |
|---------------------------------|--------------------------------|--------------------------------|--------------------------------|-------------------------------------|
| Permeability (cm/sec)           | $2.87 \times 10^{-5}$–$3.32 \times 10^{-4}$ | $5.73 \times 10^{-5}$–$6.78 \times 10^{-4}$ | $2.51 \times 10^{-4}$–$3.94 \times 10^{-4}$ | Field permeability test              |
| Cohesion (kPa)                  | 7.6                            | 6.0                            | 4.3                            | Direct shear test, borehole shear test |
| Internal friction angle ($)      | 33.9                           | 32.5                           | 35.2                           | Direct shear test, borehole shear test |
| Unit weight (kN/m$^3$)          | 16.2                           | 18.0                           | 17.4                           | Laboratory test of density          |
| $\alpha$                        | 0.02308                        | 0.28                           | 0.3495                         | SWCC test                           |
| van Genuchten parameters        | $n$ = 0.93325                  | 3                              | 2.0715                         | SWCC test                           |
|                                 | $m$ = 5.4085                   | 0.224667                       | 0.2145                         | SWCC test                           |
|                                 | Air entry value                | 4.3675                         | 2.723333                       | SWCC test                           |
| Saturated volumetric water content ($\theta_s$) | 0.5025                        | 0.39                           | 0.51                           | SWCC test                           |
| Residual volumetric water content ($\theta_r$) | 0.0475                        | 0.04                           | 0.06                           | SWCC test                           |

C. PROPOSED DESIGN METHOD OF WSN SYSTEM FOR LANDSLIDE MONITORING

We proposed the appropriate design method of WSN system for landslide monitoring. Fig. 7 shows the flow chart of construction of WSN for landslide monitoring.

**Step 1.** Selection of site and properties for landslide monitoring

**Step 1-1.** Select the measurement site through data collection and geotechnical investigation (laboratory, site).

**Step 1-2.** Select the key properties for landslide monitoring, such as water content, matric suction, inclination and rainfall.

**Step 2.** Design of wireless sensor network system

**Step 2-1.** Select the sensor type according to the soil properties, and check the power used by each sensor and design the whole network.

**Step 2-2.** Select the landslide hazard area based on landslide susceptibility assessment and analyze the line of sight communication for the selected area.

**Step 2-3.** Determine the number of multihop, sensor and network device (base and node).

**Step 3.** Construction of web server

**Step 3-1.** Register the network devices for web server and check the transmission and reception status of web server.

D. LANDSLIDE MONITORING

To monitor the landslide, a wireless sensor network (WSN) system was installed on three test beds (TB-1: Guryong mountain, TB-2: Gwanak mountain, and TB-3: An mountain). Rainfall-induced landslides commonly occur when the temporal saturated wetting bands are generated or the groundwater level rises due to rainfall infiltration. In other words, rainfall-induced landslides are closely related to rainfall duration, antecedent rainfall, and cumulative rainfall [7], [38]–[40]. Therefore, it is important to know the change in water content, matric suction, and surface displacement in order to predict rainfall-induced landslides. In this study, a rain gauge, tensiometer, soil moisture sensor, and inclinometer (displacement measurement) were selected as the measurement parameters, as shown in Table 3.

FIGURE 7. Flow chart of construction of wireless sensor network for landslide monitoring.

One base station was installed in each test bed, and ten sensor nodes were connected to the base station. For each sensor node, one tensiometer, two soil moisture sensors, and
one inclinometer were installed, and one rain gauge was installed on each test bed. The configuration of the sensor node is shown in Fig. 8.

**IV. RESULTS AND DISCUSSION**

**A. RESULT OF LANDSLIDE SUSCEPTIBILITY ASSESSMENT**

For the deployment of the sensor nodes, a susceptibility assessment of the landslides was preliminarily performed for each test bed and then the landslide hazard area was selected as the measurement location based on the results. In addition, areas where the rocky outcrops were exposed or the soil depth was very shallow were excluded from the monitoring. The susceptibility assessment of landslides took the soil depth and topography of the test beds into account, and the input properties were applied based on the results obtained from field and laboratory tests. The rainfall condition was applied at 15.9 mm/h [41] of the rainfall intensity for a 24 hours duration at a 100-year return period in the Seoul area.

Fig. 9 shows the results of the landslide susceptibility assessment. As a result of the analysis, the landslide hazard for TB-1 was high in the steep slope upstream and the valley of the middle-low stream. In the case of TB-2, it was determined to be dangerous at the steep slopes of the upstream and middle stream (refer to the lower right area in Fig. 9(b)). However, field surveys revealed that rocky outcrops were exposed in this area, therefore the area in the middle stream, which has a low safety factor, was selected as the dangerous area. TB-3 is a terrain where valleys are not clearly formed, and the safety factor was low at the steep slopes upstream. In TB-1, TB-2, and TB-3, the areas with a safety factor of less than 1.0 were calculated as 3125, 3550, and 7175 m$^2$, respectively. Based on the results of the landslide susceptibility assessment, the locations of sensor nodes were selected as the first sites for safety factors less than 1.0, and the second sites for those less than 1.2.

**B. ANALYSIS OF WIRELESS COMMUNICATION RANGE**

Generally, the wireless communication environment in the mountains is not good, and it is known that is the main reason for this is due to topology. In this study, we investigated the factors affecting the wireless communication range in the test beds for the deployment of WSN sensor nodes. The effects of diffraction and diffusion attenuation were analyzed in addition to the generally known topographic reflection attenuation. To this end, the characteristics of the vegetation community and radio wave were compared.

Wireless Fidelity (Wi-Fi) was adopted for the wireless communication among the sensor nodes of the WSN. The 2400 $\sim$ 2483.5 MHz band is typically used in Korea, and 2.4 GHz of communication frequency is applied in this study.

| Sensor type       | Model                                      | Range      | Acc.   |
|-------------------|--------------------------------------------|------------|--------|
| Tensiometer       | Jet fill tensiometer (Soil moisture        | 0 $\sim$ 100 kPa | ±1.0%  |
|                   | Equipment Corp.)                           |            |        |
| Soil moisture     | EC-5 (Decagon Devices, Inc.)               | 0 $\sim$ 100% | ±3.0%  |
| sensor            | KWRG-105 (Wellbian System)                |            |        |
| Rain gauge        | SCA121T-D07 (Murata Electronics)          | ±30$^\circ$ | ±1.5%  |
| Inclinometer      |                                            |            |        |

**TABLE 3. Specification of the sensors.**
This is a microwave frequency and shows a short wavelength range of 12.5 cm (Eq. (3)). Specifically, it has the following characteristics: 1) a strong directivity due to high frequency, 2) reflection due to complex terrain, 3) diffraction due to trees, and 4) attenuation of transmission distance due to diffusion.

\[ \lambda = \frac{c}{f} \]  

where \( \lambda \) is the wavelength, \( c \) is the wave velocity (=3 \times 10^8 \text{ m/sec}), and \( f \) is the frequency (=2.4 \times 10^9 \text{ cycles/sec}).

To investigate the species distribution and the structural diversity of the vegetation communities, a survey was conducted in a circular quadrat with a radius of 11.3 m and an area of 0.04 ha. All living trees with a diameter at breast height (DBH) of 6 cm or more were counted. As a result of the survey on 9 circular quadrats, the tree densities were determined to be 380 \( \sim \) 830 trees/ha for TB-1, 50 \( \sim \) 700 trees/ha for TB-2, and 300 \( \sim \) 750 trees/ha for TB-3. In addition, the distributed species of trees were dominated by Quercus mogolica (known as Mongolian Oak), which is a broad-leaved tree, and Pinus rigida (known as pitch pine) and Pinus koraiensis, which is a coniferous tree. The average diameters at breast height (DBH) were 23.1 cm for Mongolian oak, 15.7 cm for pitch pine, and 10.8 cm Pinus koraiensis. It was assumed that Mongolian oak, pitch pine, and Pinus Koraiensis were distributed as a proportion of 7:1.5:1.5, and then the calculated average DBH based on this proportion was 20.1 cm. The tree densities and DBH for the test beds are summarized in Table 4.

In particular, this can lead to the occurrence of a large attenuation due to diffusion because the DBH of pitch pine and Pinus koraiensis are similar to the 2.4 GHz wavelength. In addition, attenuation due to diffraction may also be large, since the DBH of Mongolian Oak is larger than the wavelength. To analyze the path loss due to the influence of the trees and terrain, the communication range test was performed under a terrain condition that is similar to the mountain. As a result, a range that can be communicated in the absence of obstacle was 90 \( \sim \) 250 m, however it was actually measured as 60 \( \sim \) 100 m in test beds.

The landslide monitoring requires consideration of mountain slope topography, such as valleys and ridges, because...
it is essential to construct a wireless sensor network system for a wide range. Therefore, viewshed analysis should be conducted to consider topography for each point based on the intersection points derived from mesh generation, and determine the area that is able to communicate in the line of sight for the final deployment of the sensor nodes. The viewshed analysis is a method to select visible area from the fixed point. In other words, a viewshed analysis can determine a range in which a specific combination of a transmitter, an antenna, and a terrain allows signal reception. The viewshed analysis was performed at each test bed using ArcMap program. Based on the results from ArcMap program, a concentric circle was drawn reflecting the maximum communication range, and then the visibility and distance to the point located inside the concentric circles can be checked. The viewshed analysis is essentially calculated as follows [42]:

$$
F(P) = \begin{cases} 
F(P) + 1, & P \in V \\
F(P), & \text{Otherwise}
\end{cases}
$$

$$
G(P) = \begin{cases} 
\text{visible}, & F(P) = 0 \\
\text{invisible}, & F(P) > 0
\end{cases}
$$

where $P$ is any point on the surface, $V$ is the occlusive volumes according to view point, $F$ is the function of the stencil value, and $G$ is the function of distinguishing the visible point and invisible point.

The line of sight communication was analyzed with a maximum distance of 100 m, which was measured in the test beds, and the area marked in red was the area where the line of sight of the sensor node (i.e., viewer, green point in Fig. 10) was secured, as shown in Fig. 10. In the range marked in red, the point with a safety factor of 1.0 or less can be selected as the location of the sensor in the vicinity of the viewer.

As a result, the visibility of the view point (i.e., the range able to communicate in the line of sight) for selecting the position of neighboring sensor node is $43 \sim 62\%$ (average 58%) within the radius of communication. Finally, we selected 11 locations of gateways and sensor nodes using the viewshed analyses in each test bed.

**C. DEPLOYMENT OF THE SENSOR NODE**

Based on the result of the landslide susceptibility assessment, the area with a safety factor of 1.0 or less was selected as the area of sensor node installation. The wireless communication range considering the characteristics of the used frequency and the density of trees was analyzed, and the base stations and sensor nodes were arranged at 11 positions based on the results. Finally, the sensor nodes were placed by testing the communication conditions in the field, as shown in Fig. 11.

A topology analysis was performed on the test beds. In the case of the star network topology, two base stations are required for each test bed. However, in the case of the mesh network topology, communication is possible with only one base station. Fig. 12 shows a comparison of the network topologies applying 1) star network topology and 2) mesh network topology in TB-2. To apply the star network topology in the test bed, it is confirmed that this type is inefficient because an additionally base station should be installed. On the other hand, in the case of the mesh network topology, the communication range can be secured using multihopping, and the reception rate and communication delay can also be reduced. Therefore, it is determined that the application of the mesh network topology is superior to the star network topology in landslide monitoring.

**D. MEASUREMENT RESULT USING WSN**

In this study, the test beds were selected for each watershed with relatively high landslide hazard in the Guryong mountain (TB-1), Gwanak mountain (TB-2), and An mountain (TB-3) [43]. The bedrocks are banded gneiss, granite, and biotite banded gneiss for TB-1, TB-2, and TB-3, respectively, and the geotechnical characteristics of their upper soils are all different. In addition, the slope of each watershed is gentle and wide in the order of TB-1, TB-2, and TB-3, and the

![Figure 10. Results of analyzing the line of sight of the sensor node: (a) point 1, and (b) point 2.](image)
soil depth in each test bed was not significantly different (0.5 ~ 2.0 m). Specifically, the groundwater level for TB-1 was located at 1.7 ~ 2.0 m during the dry season.

Measurement using the WSN were performed from the beginning of the rainy season to the end of the rainy season, and it was confirmed that the water content changed suddenly as rainfall started and penetrated into the ground, as shown in Fig. 13.

Additionally, the permeability in the field can be measured using the WSN. The permeability of the soil was estimated to be $6.7 \times 10^{-3}$ cm/sec from the difference of the electric signals obtained from the sensor nodes at different depths, which is similar to the permeability of $1.2 \times 10^{-3}$ cm/sec obtained from the laboratory test. The measured permeability in the field using the WSN can be calculated as follows:

$$k_m = \frac{d \theta}{dt} = \frac{d}{dt} \left( \frac{V_{out} - V_0}{\text{sensitivity}(V)} \right)$$  

where $k_m$ is the measured permeability in the field, $\theta$ is the matric suction, $t$ is the time, $V_{out}$ is the output voltage, $V_0$ is the voltage when $\theta$ is zero, and $V$ is the voltage.

Fig. 14 shows the maximum and minimum matric suction and volumetric water content of each test bed measured during the dry season and rainy season. In addition, the results of matric suction and volumetric water content measured
The measurement results (i.e., matric suction and volumetric water content) obtained from the tensiometers and soil moisture sensors in the WSN system were compared with the soil-water characteristics curve (SWCC) obtained from the laboratory test, as shown in Fig. 15. The results measured from the WSN are similar to the SWCC from laboratory tests. However, it shows a somewhat lower volumetric water content than that from laboratory tests at 10 kPa or more. This is because the results in the field are measured during the saturation of the soil with time, which is different from the laboratory test conditions. The occurrence of landslides due to the saturation of soil during rainfall is closer to the wetting path than the drying path in the SWCC. In addition, since the soil is repeated in the drying and wetting paths, the test in both paths is important. However, only the drying path was performed in this study. Generally, the soil-water characteristics curve obtained from the test in the drying path is slightly lower than the SWCC, as shown by the dotted line in Fig. 15 [44]. In addition, the water contents obtained from WSN during rainfall were 26%, 36%, and 40%, and those obtained from laboratory test were 26.6%, 27.7%, and 35.6%, for TB-1, TB-2, and TB-3, respectively. Therefore, it is confirmed that the measurement results using the WSN well reflect the response of the soil by rainfall. In conclusion, we have confirmed that the fundamental electrical and communication errors of the WSN system were sufficiently negligible and it is possible to apply the WSN system for landslide monitoring in the field.
V. SUMMARY AND CONCLUSION

In this paper, a test beds-based study was conducted to demonstrate the feasibility of data acquisition using WSN system for landslide monitoring. The WSN system was constructed to enable the detection of mountainous terrain characteristics and landslides, and a method to optimize the deployment of sensor nodes was proposed. The applicability of the system was verified by analyzing the results obtained from tensiometers and soil moisture sensors installed at each sensor node. The following conclusions were drawn from the present study:

1) To overcome the communication environment of the mountainous area, a self-organizing mesh network topology and a time synchronized mesh protocol (TSPM) of Dust Networks, Inc. were applied to the WSN system for landslide monitoring. As a result, the mesh network topology was more reliable and flexible than the star network topology, and a good network connection can be secured.

2) To construct the WSN system in the mountain area, factors influencing the communication range in the mountain were analyzed. The average diameter at breast height (DBH) in the test beds was 20.1 cm, which was similar to the wavelength of 12.5 cm caused by the communication frequency (≈2.4 GHz) of sensor nodes. Additionally, the density of trees was up to 830 trees/ha, which is a high value and it leads to the attenuation of transmission distance due to diffraction and diffusion.

3) The methodology for the deployment of an optimal network topology based on the test beds was proposed. The optimal network topology of sensor nodes is as follows: (1) Based on the results of the landslide susceptibility assessment, the areas classified as hazardous areas are selected as the candidate areas for installing sensor nodes. (2) Sensor nodes are deployed by analyzing the communication range according to the density of the trees, and the viewshed analysis by the terrain. (3) After confirming the communication status through field tests, sensor nodes can be finally deployed.

4) Based on the monitoring data in TB-1, TB-2, and TB-3, it was confirmed that the network connection was quite well, and the response of the soil by rainfall was similar to the soil water characteristic curve obtained from the laboratory test. In addition, since the soil-water characteristics curves respond to rainfall, they change according to the dry season and rainy season. It was determined that the volumetric water content increased from 0~0.15 to 0.2~0.45, and the matric suction decreased from 30~50 to 0.2~7 kPa.

5) As a result of the landslide monitoring using the WSN system, it is confirmed that the measurement results using WSN well reflect the response of the soil by rainfall. In conclusion, it is confirmed that the fundamental electrical and communication errors of the WSN system were sufficiently negligible and it is possible to apply a WSN system for landslide monitoring in the field. In addition, the appropriate design method of WSN system for landslide monitoring was proposed.

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REFERENCES

[1] J. Kim, S. Jeong, and R. A. Regueiro, “Instability of partially saturated soil slopes due to alteration of rainfall pattern,” Eng. Geol., vols. 147–148, pp. 28–36, Oct. 2012.
[2] S. Jeong, Y. Kim, J. K. Lee, and J. Kim, “The 27 Jul. 2011 debris flows at Umyeomnyeon, Seoul, South Korea,” Landslides, vol. 12, no. 4, pp. 799–813, 2015.
[3] M. Borga, G. Dalla Fontana, and F. Cazorzi, “Analysis of topographic and climatic control on rainfall-triggered shallow landsliding using a quasi-dynamic wetness index,” J. Hydrol., vol. 268, nos. 1–4, pp. 56–71, 2002.
[4] C. J. Lee and N. J. Yoo, “A study on debris flow landslide disasters and restoration at Inje of Kangwon province, South Korea,” Korean Soc. Hazard Mitig., vol. 9, no. 1, pp. 99–105, 2009.
[5] Z. Liao, Y. Hong, D. Kirschbaum, R. F. Adler, J. J. Gourley, and R. Wooten, “Evaluation of TRIGRS (transient rainfall infiltration and grid-based regional slope-stability analysis)’s predictive skill for hurricane-triggered landslides: A case study in Macon County, North Carolina,” Nat. Hazards, vol. 58, no. 1, pp. 325–339, 2011.
[6] Y. S. Song, “Stability analysis of the unsaturated infinite slope considering suction stress under steady infiltration condition,” J. Korean Geotech. Soc., vol. 29, no. 7, pp. 5–15, 2013.
[7] J. Kim, Y. Kim, S. Jeong, and M. Hong, “Rainfall-induced landslides by deficit field matric suction in unsaturated soil slopes,” Environ. Earth Sci., vol. 76, no. 23, p. 808, 2017.
[8] C. Y. Yune, K. J. Jun, K. S. Kim, G. H. Kim, and S. W. Lee, “Analysis of slope hazard-triggering rainfall characteristics in Gangwon province by database construction,” J. Korean Geotech. Soc., vol. 26, no. 10, pp. 27–38, 2010.
[9] J. H. Kim, S. S. Jeong, Y. M. Kim, and K. W. Lee, “Proposal of design method for landslide considering antecedent rainfall and in-situ matric suction,” J. Korean Geotech. Soc., vol. 29, no. 12, pp. 11–24, 2013.
[10] M. V. Ramesh, “Design, development, and deployment of a wireless sensor network for detection of landslides,” Ad Hoc Netw., vol. 13, pp. 2–18, Feb. 2014.
[11] Z. Zhang, S. D. Glaser, R. C. Bales, M. Conklin, R. Rice, and D. G. Maks, “Technical report: The design and evaluation of a basin-scale wireless sensor network for mountain hydrology,” Water Resour. Res., vol. 53, no. 5, pp. 4487–4498, 2017.
[12] A. Giorgetti, M. Lucchi, E. Tavelli, M. Barla, G. Gigli, N. Casagli, M. Chian, and D. Dardari, “A robust wireless sensor network for landslide risk analysis: System design, deployment, and field testing,” IEEE Sensors J., vol. 16, no. 16, pp. 6374–6386, Aug. 2016.
[13] T. Gracchi, A. Lotti, G. Saccorotti, L. Lombardi, M. Nocentini, F. Mugnai, G. Gigli, M. Barla, A. Giorgetti, A. D’Antolini, A. Fiaschi, L. Matassoni, and N. Casagli, “A method for locating rockfall impacts using signals recorded by a microseismic network,” Geoenviron. Disasters, vol. 4, 2017, Art. no. 26.
[14] A. D’Antolini, M. Barla, G. Gigli, and A. Giorgetti, “Combined Finite-Discrete numerical modelling of runout of the Torgiovanetto di Assisi rockslide in central Italy,” ASCLE Int. J. Geomech., vol. 16, no. 6, 2016, Art no. 00416019.
[15] G. S. Bhadravaj, M. Metha, M. Y. Ahmed, and M. A. I. Chowdhury, “Landslide monitoring by using sensor and wireless technique: A review,” Int. J. Geomatics Geosci., vol. 5, no. 1, pp. 1–8, 2014.
[16] M. Castillo-Effer, D. H. Quintela, W. Moreno, R. Jordan, and W. Westhoff, “Wireless sensor networks for flash-flood alerting,” in Proc. 5th IEEE Int. Caracas Conaf. Devices, Circuits Syst., Puntu Cana, Dominican Republic, Nov. 2014, pp. 142–146.
[17] L. Mucchi, S. Jayouzi, A. Martinelli, S. Caputo, E. Intrieri, G. Gigli, T. Gracchi, F. Mugnai, M. Favalli, A. Fornaciai, and L. Nannipieri, “A flexible wireless sensor network based on ultra-wide band technology for ground instability monitoring,” Sensors, vol. 18, no. 9, pp. 2948, 2018.
[18] A. Rosi, M. Berti, N. Bicocchi, G. Castelli, A. Corsini, M. Mamei, and F. Zambonelli, “Landslide monitoring with sensor networks: Experiences and lessons learnt from a real-world deployment,” Int. J. Sensor Netw., vol. 10, no. 5, pp. 111–122, 2011.
[19] Y. S. Song, Y. C. Cho, and S. Hong, “Analyses on variations in the unsaturated characteristics of a mine waste-dump slope during rainfall,” Environ. Earth Sci., vol. 75, no. 14, p. 1106, 2016.

[20] B. G. Chae, H. J. Park, F. Catani, A. Simon, and M. Berti, “Landslide prediction, monitoring and early warning: A concise review of state-of-the-art,” Geosci. J., vol. 21, no. 6, pp. 1033–1070, 2017.

[21] M. Nasser, J. Kim, R. Green, and M. Alam, “Identification of the optimum relocalization time in the mobile wireless sensor network using time-bounded relocalization methodology,” IEEE Trans. Veh. Technol., vol. 66, no. 1, pp. 344–357, Jan. 2017.

[22] F. Cotecchia, F. Santaloia, P. Lollino, C. Vitone, and G. Mitanotta, “Deterministic landslide hazard assessment at regional scale, in: Proceedings of GeoFlorida,” in Proc. Adv. Anal., Modeling Design, West Palm Beach, FL, USA, Feb. 2010, pp. 20–24.

[23] S. D. Pardeshi, S. E. Autade, and S. S. Pardeshi, “Landslide hazard assessment: Recent trends and techniques,” SpringPlus, vol. 2, no. 2, p. 523, 2013.

[24] E. E. Brabb, “Proposal for world-wide landslide hazard maps,” in Proc. 7th Int. Conf. Field Workshop Landslides, S. Novosad and P. Wagner, Eds. Rotterdam, The Netherlands: Balkema, 1993, pp. 15–27.

[25] P. A. Burrough, R. A. McDonnell, and C. D. Lloyd, Principles of Geographical Information Systems. Oxford, U.K.: OUP Oxford, 2015.

[26] M. V. Ramesh, “Real-time wireless sensor network for landslide detection,” in Proc. 3rd Int. Conf. Sensor Technol. Appl., 2014, pp. 405–409.

[27] Internet of Things: Wireless Sensor Networks, Int. Electrotechn. Commiss., Geneva, Switzerland, 2014.

[28] J. Kim, “GIS-based Susceptibility assessment of landslides using geotechnical and hydrological model,” Ph.D. dissertation, Dep. Civil Environ. Eng., Yonsei Univ., Seoul, South Korea, 2015.

[29] D. Pradel and G. Raad, “Effect of permeability on surficial stability of homogeneous slopes,” J. Geotech. Eng., vol. 119, no. 2, pp. 315–332, 1993.

[30] C. Hammond, D. Hall, S. Miller, and P. Swetik, “Level I stability analysis (LSA) documentation for version 2.0,” U.S. Dept Agric, Ogden, UT, USA, Gen., Tech. Rep. INT-285, 1992.

[31] W. H. Green and G. A. Ampt, “Studies on soil physics, 1. The flow of air and water through soils,” J. Agric. Sci., vol. 4, no. 1, pp. 1–24, 1911.

[32] R. G. Mein and C. L. Larson, “Modeling infiltration during a steady rain,” Water Resour. Res., vol. 9, no. 2, pp. 384–394, 1973.

[33] Investigation of slopes and construction to prevent the landslide damage (Phase 1), The Seoul Inst., Seoul, South Korea, 2012.

[34] L. Zhang, “Determination and applications of rock quality designation (RQD),” J. Rock Mech. Geotech. Eng., vol. 8, no. 3, pp. 389–397, 2016.

[35] D. G. Fredlund, and H. Rahardjo, Soil Mechanics for Unsaturated Soils, Hoboken, NJ, USA: Wiley, 1993.

[36] M. T. van Genuchten, “A closed form equation for predicting the hydraulic conductivity of unsaturated soils,” Soil Sci. Soc. Amer. J., vol. 44, no. 5, pp. 892–898, 1980.

[37] S. S. Jeong, M. H. Hong, and J. H. Kim, “A wireless sensor network technique and its application in regional landslide monitoring,” J. Korean Geotech. Soc., vol. 34, no. 9, pp. 19–32, 2018.

[38] R. H. Campbell, Soil Slopes, Debris Flows, and Rainstorms in the Santa Monica Mountains and vicinity, Southern California, CA, USA: USGS, 1975, pp. 1–51.

[39] F. Guzzetti, S. Peruccacci, M. Rossi, and C. P. Stark, “Rainfall thresholds for the initiation of landslides in central and southern Europe,” Meteorog. Atmos. Phys., vol. 98, no. 3, pp. 259–267, 2007.

[40] S. S. Jeong, J. H. Kim, Y. M. Kim, and D. H. Bae, “Susceptibility assessment of landslides under extreme-rainfall events using hydrogeotechnical model: A case study of Unmyeonsan (Mt.), South Korea,” Nat. Hazards Earth Syst. Sci. Discuss., vol. 2, pp. 5575–5601, 2014.

[41] Improvement and Complementary Study of Probability Rainfall, Ministry of Land, Infrastructure, and Transport, Sejong, Seoul, South Korea, 2015.

[42] W. Feng, W. Gang, P. Deji, L. Yuan, Y. Liu, and W. Hongbo, “A parallel algorithm for viewshed analysis in three-dimensional Digital Earth,” Comput. Geosci., vol. 75, pp. 57–65, 2015.

[43] Investigation of Mountain Areas and Construction Damage Reduction System, Final Report of Research Project for Landslide Monitoring, Seoul Metropolitan City, Seoul, South Korea, 2017.

[44] N. Lu, and W. J. Likos, Unsaturated Soil Mechanics. Hoboken, NJ, USA: Wiley, 2004.

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