Improvement of a slope disaster warning system for practical use

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ABSTRACT

This paper reports on the development of an advanced slope disaster monitoring system for practical use. In 2010, we developed a distributed wireless sensor network and installed it on a slope along an expressway to detect and monitor water behavior and deformations in the slope due to heavy rainfalls at an early stage. In this previous research, three major issues remained unresolved: poor wireless communication data collection rate, sensing performance, and monitoring system. To resolve these issues, in 2013, improved monitoring systems with wireless mesh network functions were set up on slopes along six expressways managed by the West Nippon Expressway Company in Japan. Consequently, we confirmed that data were constantly being sent to the data server every ten minutes, even at single-hop wireless communication distances up to 400 m. Improvements in the sensor nodes by adding strain gauge sensors and contact input and output devices made them useful not only for monitoring slope failure but also for maintenance of the slope by the ground anchor method and evaluation of the drainage effect of the embankment. (However, improvements in the electric field strength and addition of a retry function resulted in a decline in battery life.) The improved monitoring system allows road managers to view the data at each site at any time. Further, the data can also be downloaded from the webserver on the Internet.

Keywords: warning system, wireless sensor network, real-time monitoring, structure health monitoring, disaster prevention

1. INTRODUCTION

This paper reports on the development of an advanced slope disaster monitoring system. In 2010, we developed a distributed wireless sensor network and installed it on the slopes along expressways to detect and monitor water behavior and deformations in the slope due to heavy rainfalls at an early stage. Each sensor node consisted of a wireless communication device employing an intermittent mode that significantly reduces the energy consumed, an acceleration sensor that is used as an inclination meter, and two compact soil-water sensors. In our previous research, three major issues remained in the construction of a robust and practical monitoring system. The first issue is the fact that the data collection rate via wireless communication is insufficient for practical use. The amount of data collected was sometimes less than 80% depending on the wireless communication conditions. A more robust and high performance wireless module was therefore needed to solve this problem. The second issue was that the durability of the sensors and the sensing performance needed to be improved. In 2010, the first priority was development of the system at a low cost via wireless sensor network technology. Consequently, the sensing performance was not considered high priority at that time. To improve the sensing performance, more robust, durable, and easily installable sensors were needed. In addition, the sensors added should not only be able to monitor sediment disaster in critical conditions caused by heavy rains but also slope structure health over the long term. The third issue was that the monitoring system needed to be expanded from a single-user remote monitoring system to a multi-user remote monitoring system on the web. To resolve these issues, in 2013, improved monitoring systems with wireless mesh network functions were set up on the slopes along six expressways managed by the West Nippon Expressway Company in Japan.

2 WIRELESS SENSOR NETWORK

The slope disaster early warning system developed in 2010 was a wireless sensor mesh network system (Koizumi et al. 2013a). A mesh network is a multi-hop ad hoc network formed by a monitoring station and multiple sensor nodes with sensing functions, as
depicted in Fig. 1. The sensor nodes communicate with each other without routers operated by an AC power supply. Even if the monitoring station is far from the sensor nodes, the communication pathway can be assured by inserting sensor nodes between them. In addition, even if some sensor nodes can no longer operate, the rest of the nodes can still communicate with each other by automatically changing the communication pathway. Moreover, new sensor nodes can be set up on the slope after the mesh network is constructed. These sensor nodes automatically connect to the network, and the mesh network is expanded. By constructing this mesh network system operating in intermittent mode, long-term monitoring is achieved using a compact battery pack. However, the issue of stability of data collection in the system developed in 2010 (hereafter called Ver. 2010) still remained. To resolve this issue, the wireless module was changed into a high-power type with retry function in the 2013 version of the system (hereafter called Ver. 2013), as shown in Table 1. In this section, the practical effects of the improvements from Ver. 2010 to Ver. 2013 are evaluated.

Because the wireless communication environment differs according to setting, topology, and wireless communication distance, it is difficult to evaluate it in a single uniform standard. To evaluate the relationship between wireless communication distances and data collection rates in the six test sites with different site conditions, two types of evaluation items were prepared. One was the condition that a line of sight exists between a sensor node and the base station, and the sensor node is the closest to the base station. The other condition is that there is no line of sight between the sensor node and the base station, and the sensor node is the farthest from the base station. Table 2 shows the relation between the wireless communication distances and the data collection rates under the line of sight communication environment in the six test sites operating Ver. 2013 and the one test site operating Ver. 2010. The data collection rates by Ver. 2013 range from 96.6% to 100%, whereas the data collection rate by Ver. 2010 is 91%. The maximum communication distance by single-hop communication in this field test to satisfy this data collection rate is 420 m at Slope-I.

Table 2. Data collection rates for line of sight communication environment.

| Range(m) | Collection Rate(%) |
|----------|--------------------|
| Slope-M(2010) | 87 | 91.0 |
| Slope-K(2013) | 49 | 99.9 |
| Slope-Y(2013) | 5 | 99.9 |
| Slope-O(2013) | 127 | 99.1 |
| Slope-H(2013) | 130 | 98.2 |
| Slope-A(2013) | 177 | 96.6 |
| Slope-I(2013) | 420 | 100 |

Table 3 shows the relations between the wireless communication distances and the data collection rates under the non-line of sight communication environment in the six test sites operating Ver. 2013 and one test site operating Ver. 2010. The data collection rates by Ver. 2013 range from 94.5% to 100%, whereas the data collection rate by Ver. 2010 is 74.2%. The maximum communication distance by multi-hop communication in this field test to satisfy this data collection rate is 560 m at Slope-I.

These results show that the data collection rate in Ver. 2013 improved regardless of whether a line of sight existed. It indicates that the data loss rate due to lack of a line of sight is low and wireless network stability is established. On the other hand, there was a reduction in battery life compared with Ver. 2010 owing to the improvements in the electric field strength and addition

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Table 1. Specifications for the wireless modules

| Frequency Band | 2010 | 2013 |
|----------------|------|------|
| Transmit Power | 1mW  | 63mW |
| Range          | 100m | *Observed value 420m |
| Retry Count    | -    | 10   |

Table 2. Data collection rates for non-line of sight communication environment.

| Range(m) | Collection Rate(%) |
|----------|--------------------|
| Slope-M(2010) | 119 | 74.2 |
| Slope-K(2013) | 100 | 99.8 |
| Slope-Y(2013) | 34 | 99.5 |
| Slope-O(2013) | 150 | 99.2 |
| Slope-H(2013) | 205 | 97.0 |
| Slope-A(2013) | 280 | 94.5 |
| Slope-I(2013) | 560 | 96.8 |
of the retry function.

3 SENSING EQUIPMENT

3.1 Improvement of present sensing equipment

The process of generation of a shallow landslide is hypothesized in Fig. 2 from previous studies (Koizumi et al. 2013b). The fundamental concept of this hypothesis is that a slope failure warning sign can be detected by monitoring the water infiltration behavior before deformation appears on the slope. The focus of attention is on the soil-water behavior in the field saturated condition, which is not the fully saturated but the saturated status with entrapped air in situ.

![Fig. 2. Expected process until shallow landslide.](image)

The field saturated condition is defined as the equilibrium status between inflow and outflow of soil moisture in the slope. Further, volumetric water content exceeding the status of the field saturated condition was defined as the warning sign of the start of small deformation. To develop a warning system based on this concept in Fig. 2, we developed a distributed wireless sensor network in 2010 and installed it on a slope along an expressway to detect and monitor water behavior and deformations in the slope due to heavy rainfalls at an early stage (Koizumi, 2012). Each sensor node comprised a wireless communication device that employed an intermittent mode (which significantly reduces energy consumption), an acceleration sensor that is used as an inclination meter, and two compact soil-water sensors. In our previous research, the practical issues of durability and sensing performance of the sensor remained. To improve the durability and the performance, a soil-water sensor mounted in a case protected by IP68 was chosen, as shown in Table 4. Further, a needle type probe that can be inserted into compacted soil layer without any difficulty was selected. The acceleration sensor was converted into a tilt sensor, which has high detection accuracy, and the resolution of the ADC was modified from 12 bit to 16 bit. Consequently, the detection accuracy was improved for practical use from 1.0 degree to 0.1 degree. In addition, to understand the relationship between rainfall and volumetric water content, a channel for measuring rainfall was mounted on the sensor node.

![Table 4. Specification of sensors in Ver. 2010 and Ver. 2013.](image)

Figs. 3 and 4 show the monitoring results for volumetric water content and tilt for two slopes with different soil properties. The data indicate variations during heavy rainfall in July 2014. The total amount of precipitation is 141 mm and the maximum rain intensity for 10 mins is 9.75 mm in Fig. 3. By contrast, the total amount of precipitation is 236 mm and the maximum rain intensity for 10 mins is 10.5 mm in Fig. 4. The data sampling interval was every 10 mins. Two soil-water sensors were mounted in one sensor node. One of the soil-water sensors was installed on the upper part of the slip surface and the other was installed at the middle point between the slip surface and the surface of the slope. The slip surface is defined as the depth beyond 10 Nd. The tilt sensor was mounted on the sensor node. The plus side of the tilt sensor (X axis) indicated the tilt of the lower part of the slope.

![Fig. 3. Relation among rainfall, VWC, and tilt angle on Slope-O.](image)

![Fig. 4. Relation among rainfall, VWC, and tilt angle on Slope-Y.](image)

In Fig. 3, the decrease in the rate of the volumetric water content after the rainfall stops on Slope-O (formed by weathered mudstone) is relatively slow.
compared with that on Slope-Y (formed by weathered granite) in Fig. 4, even with total amount of precipitation smaller than that of Slope-Y. This indicates that water infiltration behavior, including drainage behavior, is affected by the geological condition and so rainfall information alone is insufficient to evaluate the slope stability during heavy rains. The tilt angle on Slope-O increased from zero to 0.8 degree after the volumetric water content in the shallow part increased on July 3. This result reflects the improvement in detection accuracy in Ver. 2013.

### 3.2 Enhancement of sensing function

When the slope warning system in Ver. 2010 was modified not only for monitoring of slope failure but also for maintenance of deteriorated slope structure, a sensing item was added to enhance the sensing function. Figs. 5 and 6 show the respective sensing function in Ver. 2010 and Ver. 2013.

![Fig. 5. Specification for a sensor node in Ver. 2010.](image)

In Ver. 2013, the channels of the strain gauge type, such as water level sensor, load cell, extensometer, crack opening displacement sensor, and temperature sensor, are mounted on the sensor node. In addition, a contact input channel for the rain gauge and a contact output channel for a warning signal lamp are present. Further, a separate battery pack is integrated into the sensor housing to simplify installation. As a result, the improved sensor node is useful not only for monitoring of slope failure but also for maintenance of the slope by the ground anchor method and evaluation of the effect of drainage on the embankment by adding strain gauge sensors and contact input and output devices. Fig. 7 shows the installation points for the ground anchor, groundwater monitoring well, and precipitation sensor used to evaluate deformation against estimated slip lines on Slope-A. Fig. 8 shows the monitoring result for the anchor load cells, water levels, and hourly rainfall intensity in Fig. 7. Although groundwater levels change according to rainfall intensity, there is no variation in the anchor load cell during the heavy rains on June 25. This indicates that the ground anchor is functioning normally.

![Fig. 7. Cross section of anchor block slope on Slope-A.](image)

![Fig. 8. Relation among rainfall, groundwater levels, and anchor load cell on Slope-A.](image)

### 4 MONITORING SYSTEM

A single-user real-time monitoring system was developed in Ver. 2010. In this system, a single user was able to access the base station on a timely basis to observe the stability of the slope during the rainy season. In contrast, Fig. 9 shows a multi-user real-time monitoring system. In Ver. 2013, the monitoring data from slopes under the control of an expressway company are sent to a web server through each base station and road managers can monitor the condition of each slope practically over the Internet. This monitoring system also incorporates WEB-GIS, allowing the user to easily understand each monitoring location. Data can also be downloaded from the webserver at any time and a warning signal established beforehand can be sent by e-mail. When a new
monitoring site is established, the sensing contents are automatically registered on the webserver by setting fundamental information about the sensing items and location information.

Fig. 10. A multi-user real-time monitoring system.

5 CONCLUSIONS

Ver. 2010 of the slope disaster warning system developed was improved as follows in Ver. 2013:
1) Data are constantly sent to the data server every ten minutes even at single-hop wireless communication distances up to approximately 400 m.
2) Improving the sensor node by adding strain gauge sensors and contact input and output devices makes it useful not only for monitoring slope failure but also for maintenance of the slope by the ground anchor method and evaluation of the drainage effect of the embankment. (However, improvements in the electric field strength and addition of a retry function resulted in a decline in battery life.)
3) The improved monitoring system enables road managers to monitor the stability of any slope structures under the control of an expressway company over time.

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