DEVELOPMENT OF A SLOPE DISASTER MONITORING SYSTEM FOR EXPRESSWAY OPERATION AND MAINTENANCE CONTROL

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ABSTRACT

This paper reports on the development of an advanced slope disaster monitoring system for practical use on expressways in Japan. Owing to a rise in unexpected heavy rainfall events, the incidence of rain-induced slope failure is increasing in Japan. To address this problem, the West Nippon Expressway Company Ltd. (W-NEXCO), in addition to its responsibility for monitoring the health of aging civil structures, is tasked with the real-time monitoring of rain-induced slope failure, has developed, in cooperation with Osaka University, a user-friendly slope disaster monitoring system based on an ad hoc, multi-hop sensing technology. This monitoring system, called a mesh network, comprises monitoring stations using the W-NEXCO private network and multiple sensor nodes. The monitoring stations are powered by rechargeable batteries with solar panels, while the sensor nodes are primarily battery-driven. Correspondingly, AC power supply is not necessary at the monitoring sites. The sensor nodes enable multi-sensing functionality for monitoring anchor axial force, ground surface displacement, water level, pore water pressure, rain intensity, volumetric water content, and feature contact output channels for activating warning signal lamps. In this manner, the sensor nodes are useful not only for monitoring slope failure but also for signaling the need for slope maintenance via a ground anchor and embankment drainage evaluation. W-NEXCO is placing wireless local area network (WLAN) access points along expressways to allow for the rapid and stable importing of monitoring data collected from each slope structure into the W-NEXCO private server. In this study, we confirmed the applicability of this system and its WLAN network based on the results of communication tests performed on actual expressway slopes.

Key words: Slope disaster, expressway operation, monitoring system, wireless sensor network.

1. INTRODUCTION

In Japan, there has been a trend toward concentrated heavy rainfall events occurring within short timeframes, as shown in Fig. 1. Because sediment disasters caused by flash flooding are difficult to predict, it is important to strengthen slope monitoring systems and implement countermeasures based on a determination of preliminary signs of disaster. Earthen structures account for approximately 70% of the extensions on expressways managed by the West Nippon Expressway Company Ltd. (W-NEXCO); this makes the prediction of and countermeasures for sediment disaster owing to rainfall important. In addition, as aging infrastructure greater than 30 years old accounts for 40% of all the expressways managed by W-NEXCO, it is necessary to monitor the structural health of slopes that employ ground anchors.

Constructing long-term real-time monitoring systems to address the problem of slope failure requires the placement of several types of sensors, data collecting devices, and data transmission devices at each monitoring site. In conjunction with this, real-time monitoring systems are necessary in each management office. Several efforts to solve problems by implementing this monitoring infrastructure have been reported, including systems based on wireless technology (Maneesha et al. 2009; Intrieri et al. 2012; Koizumi et al. 2012; Smarsly et al. 2012; Choi et al. 2013; Koizumi et al. 2013a; Koizumi et al. 2013b; Smarsly et al. 2014; Giorgetti et al. 2016; Takemoto et al. 2016). However, in most such studies the monitoring targets have been limited to, “landslide monitoring” (Maneesha et al. 2009) or “ground anchor tension monitoring” (Choi et al. 2013).

W-NEXCO has also made a number of efforts to solve this problem. Figure 2 shows an overview of the W-NEXCO slope monitoring system, in which all data collected from the sensor nodes at each expressway monitoring site are sent to a management office via a private local area network. In this paper, we give an overview of this system and provide examples of its application.
2. CURRENT STATUS AND SLOPE MONITORING SYSTEMS

2.1 Typical Slope Monitoring Method

Figure 3 illustrates a typical slope disaster monitoring system in Japan. In this system, measurement data from devices such as extensometers are sent to a data logger via cable and then transmitted wirelessly to a data server. For monitoring purposes, road managers access the data server via the Internet. To construct such a system, it is necessary to establish wiring between a measurement device and a data logger, data server, and Internet connection.

2.2 Issues in Monitoring

The general monitoring method discussed above has several problems. Such systems can fail because of damage to cables caused by wildlife or lightning. The labor and cost associated with laying cables is also significant. In addition, most systems are constructed independent of location and can use different monitoring systems at each monitoring site, making it difficult for administrators to manage all the sites at once. Furthermore, the use of general Internet lines results in low robustness in emergency situations. For the above reasons, there is a clear need for innovative slope monitoring systems.

3. PROPOSED SLOPE MANAGEMENT SYSTEM FOR EXPRESSWAY OPERATION AND MAINTENANCE CONTROL

3.1 System Overview

To solve the above problems, a candidate monitoring system must have three attributes: a robust, user-friendly sensing system; the ability to perform multiple sensing; and the ability to simultaneously monitor multiple slopes using a system such as the W-NEXCO private wireless local area network. Figure 4 shows a system developed in accordance with these requirements, and the features of which are described below.

3.2 Wireless Sensor Network

The system adopts a mesh networking topology based on wireless sensor network technology. The mesh network is a multi-hop, ad hoc network comprising a monitoring station and multiple sensor nodes with sensing functions. In a wireless communication system such as this, both the data collection rate and communication distance are important. The performance of the system was evaluated on six expressway slopes. The evaluation results in Fig. 5 show the wireless communication performance for each communication distance, revealing a maximum communication distance in the test of 420 m and a data collection rate close to 100%.

3.3 Sensor Node

Figure 6 provides details on the sensor node, the specifications of which are given in Table 1. The palm-sized case of the node contains a mounted circuit board with multiple sensing functions, a built-in tilt sensor, a wireless module, and battery space. This wireless compact sensor node reduces the cost and labor time of on-site operation. In existing systems, the battery life has been continuously monitored for one year with approximately hourly communication. Depending on environmental
factors at the worksite, expected equipment failure can be mitigated through the use of IP65-compliant cases. The sensor node features strain gauge-type channels (such as a water level sensor, load cell, extensometer, crack opening displacement sensor, and temperature sensor), voltage and current-type channels (such as a soil moisture sensor), a contact input channel for the rain gauge, and a contact output channel for the warning signal lamp. Data measured by the sensors are sent to the wireless module either as analog or digital data, converted to digital signals by an A/D converter within the sensor node, and then periodically transmitted to the monitoring station under the control of the microprocessor unit (MPU). Correspondingly, the sensor node is useful not only for monitoring slope failure but also for slope maintenance via the ground anchor method and embankment drainage evaluation.

Table 1 Specifications of sensor node

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit current</td>
<td>120 mA @ 3.3 VDC</td>
</tr>
<tr>
<td>Receive current</td>
<td>31 mA @ 3.3 VDC</td>
</tr>
<tr>
<td>Power-down current</td>
<td>&lt;1 μA @ 25º C</td>
</tr>
<tr>
<td>Protocol</td>
<td>XBee 802.15.4 (Proprietary 802.15.4)</td>
</tr>
<tr>
<td>RF data rate</td>
<td>250 Kbps</td>
</tr>
<tr>
<td>Battery capacity &amp; spec</td>
<td>8Ah ~ 3.6V</td>
</tr>
<tr>
<td>Additional A/D converter</td>
<td>16bit resolution × 1</td>
</tr>
<tr>
<td>Transmit current</td>
<td>120 mA @ 3.3 VDC</td>
</tr>
</tbody>
</table>

3.4 Monitoring Station

Each monitoring station manages data monitoring at one site. The monitoring station aggregates data arriving from sensor nodes at the site and periodically transfers it to servers in the W-NEXCO data center. In addition, the monitoring station also has the function of sending an e-mail to a registered destination when a value exceeding the preset threshold value is observed. Each monitoring station is equipped with a solar panel and a rechargeable battery, with no AC power supply required on-site. An overview of a monitoring station is shown in Fig. 7, with specifications provided in Table 2. The solar panel is 535 mm in length × 666 mm in width and generates 39 W of power. The battery has a capacity is 24 Ah and is designed so that the base station can operate even if there is no sunshine for five days. The variation in the remaining battery charge at a site is shown Fig. 8, from which it is seen that the battery retained a sufficient level of charge even during the winter season, when there were low amounts of sunshine.
### Table 2  Specification of low-power MPU

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>ARM926EJ-S (400 MHz)</td>
</tr>
<tr>
<td>RAM</td>
<td>128 MB (LPDDR-266)</td>
</tr>
<tr>
<td>ROM</td>
<td>32 MB NOR Flash Memory</td>
</tr>
<tr>
<td>3G Module</td>
<td>SierraWireless HL8548</td>
</tr>
<tr>
<td>Power consumption</td>
<td>2 W Maximum</td>
</tr>
</tbody>
</table>

#### 3.5 Monitoring System

Measurement data collected using the system can be remotely monitored in real time via the Internet. A system screen is shown in Fig. 9; Fig. 9(a) shows a plot of measured points on a map, with changes in color and icon face marks based on preset thresholds to clearly indicate abnormal measurements. Detailed measurement data can be graphed for selected measurement points, as shown in Fig. 9(b). Data can be downloaded from the web server at any time. When a new monitoring site is established, its readings are automatically registered on the web server, which relays fundamental information on the added sensing items and their location to the monitoring system. This system provides road managers with a practical method for monitoring the conditions on multiple slopes over the Internet.

#### 3.6 W-NEXCO Private WLAN

Currently, road management systems employ communication cables to control and communicate with equipment used for road management such as information boards and emergency telephones. W-NEXCO aims to construct an advanced expressway management environment in which installed radio antennas are incorporated into the communication cabling and to promote the development of a WLAN environment for management of the overall expressway space. Improving this WLAN environment will allow data collected from the monitoring system to be stably incorporated into company servers without resorting to outside broadband services and will further reduce the cost of equipment installation and improve the availability and reliability of monitoring data.

#### 3.7 Summary of the Developed System

The developed system utilizes wireless sensor network technology integrated into a W-NEXCO private WLAN. The multiple-sensing-device sensor nodes all wirelessly communicate with each other. Data are collected at the monitoring station and sent to the W-NEXCO data server via a private WLAN. Depending on the scale of the network, this system can reduce the overall cost of monitoring.

### 4. APPLICATION EXAMPLE

#### 4.1 Rainfall-Induced Slope Failure Monitoring

In this section, we demonstrate the results of using the W-NEXCO monitoring system, focusing first on the slope failure results.

Figure 10 shows a plan view of a monitoring site, in which eight sensor nodes—shown in detail in Fig. 11—are installed and the volumetric water content is measured at two depths at each sensor location. Tilt data are also monitored by each of the sensor nodes, and a rain gauge is connected to one sensor node to measure the amount of rainfall. Figure 12 shows the monitoring results produced by one of the sensors one week before and after a heavy rainfall. A total of 236 mm of precipitation was measured, with a maximum rain intensity for 10 min of 10.5 mm. The site is formed of weathered granite, and it is seen from the figure that, although the volumetric water content increases at the time of rainfall, it decreases quickly thereafter. No change is observed in the inclinometer readings, confirming that no surface displacement has occurred.

The measurement results for the same period from another site about 100 km away are shown in Figure 13. The total amount of precipitation was 141 mm, with a 10-min maximum rain intensity of 9.75 mm. The decrease in the rate of the volumetric water content following rainfall at this site, which is formed of...
weathered mudstone, is slower than at the previous, weathered granite site, even though the total amount of precipitation is smaller than at the previous site (Fig. 12). The tilt angle increased from zero to 0.8 degrees after an increase in the volumetric water content in the shallow part of the site on July 3, from which it is deduced that the risk of failure is relatively higher in the latter site. This indicates that water infiltration behavior, including drainage behavior, is affected by the geological condition and therefore that rainfall information alone is insufficient to evaluate slope stability during heavy rains.

There are no places in either site in which slope failure has occurred during the monitoring to date, but monitoring of slope failure remains possible using this method.

4.2 Anchored Rock Slope Stability Monitoring

We next show the results of ground anchor monitoring. Figure 14 shows a plan view of the monitoring site, in which two groundwater level gauges, three anchor load cells, and one rain gauge are monitored (ID 7 has been installed for relaying). The load cell of the anchor is connected to the sensor node, as shown in Fig. 15. The monitoring results for a period of approximately one month are shown in Fig. 16, from which it is confirmed that the groundwater level rises following rainfall. However, although the anchor load fluctuates following a one-day cycle as a result of temperature change, no increase is observed in the load cell following rainfall; thus, the monitoring system can successfully diagnose the soundness of the ground anchor.
4.3 Trial Communication Using W-NEXCO WLAN

To improve the robustness of the system, we conducted a communication test in which general outside broadband service was replaced by the W-NEXCO private WLAN discussed in the previous chapter.

Prior to establishing a full-fledged WLAN, a trial environment was established along part of an existing expressway and a communication test of the system was carried out. Figure 17 shows the status of the test site, while Table 3 shows the test results. The testing confirmed that the data measured by wireless sensors could be captured via the W-NEXCO WLAN.

4.4 Future Vision

Utilizing the developed system and WLAN environment, monitored data can be collected more easily than was previously possible. W-NEXCO is developing technology for collecting and analyzing collected data with the goal of building a more advanced road management system. Our plan is to use the initial data analyses from this technical development process to capture otherwise unobserved events that contain information useful for road management. Currently, we are installing monitoring equipment on an under-construction highway about 40 km in length for the purpose of technology development. A schematic of this process is shown in Fig. 18.

![Test site status](image)

**Table 3  Installation Monitoring Equipment and Communication Results**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Number of point</th>
<th>Range</th>
<th>Data volume</th>
<th>Communication frequency</th>
<th>Collection rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt sensor</td>
<td>6 places</td>
<td>350 m</td>
<td>0.2 MB/day</td>
<td>1 time / 10 min</td>
<td>96.9 %</td>
</tr>
<tr>
<td>Soil water sensor</td>
<td>12 places</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range gauge</td>
<td>1 places</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5. CONCLUSIONS

A slope monitoring system using a wireless sensor network was developed to solve the problems faced by existing slope monitoring systems. The use of a battery and a wireless communication method makes cables redundant and allows the system to be installed easily. We confirmed the usefulness of the system in field tests. In addition, W-NEXCO is developing a WLAN for road management, and to test it we successfully constructed a real-time monitoring system utilizing wireless sensor network technology and the W-NEXCO private WLAN without the need for an outside broadband service.

REFERENCES


