Slope structural health monitoring method against rainfall-induced shallow landslide

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Abstract. The structural health monitoring of a slope against rainfall-induced shallow landslides has become an important issue in Japan with the recent instances of extreme weather. In particular, the early detection of a sudden rainfall-induced shallow landslide is well known to be relatively difficult compared with that of a slow-moving landslide. Thus, local governments or civil-structure management companies provide residents or users with early warning information of a disaster via rainfall-based data. However, rainfall information is not enough to predict the risk of individual slope disasters because it does not directly reflect the soil-moisture condition of a slope. To solve this problem, a soil moisture-based index (iQS) is proposed. The applicability of iQS in a real slope was evaluated using the result obtained by monitoring a real slope during heavy rainfall along an expressway. The monitoring results of the real slope were seen to agree well with the results of past laboratory experiments. This implies that slope deformation owing to the rise in water level does not occur unless the volumetric water content exceeds the iQS of the real slope. Based on this result, iQS can be used for predicting the risk of shallow landslides at an early stage.

1. Introduction
Rainfall-induced shallow landslides have become more frequent owing to recent occurrences of extreme weather in Japan. In particular, the early detection of a sudden rainfall-induced shallow landslide is known to be relatively difficult compared with the detection of typical landslide behaviour. In response to this problem, every local government provides residents with early warning information of rainfall-induced disaster through emails and a website based on the Japanese weather radar system and automated meteorological data-acquisition system. However, rainfall information is not enough to predict the risk of individual slope disasters occurring behind residential areas. In contrast, with regard to civil infrastructure, Japanese-expressway-operating companies have their own regulation standards...
to prevent rainfall-induced slope disasters based on historical rainfall data. However, sometimes the judgement of whether a shallow landslide will occur is not accurate because rainfall information does not directly reflect the soil-moisture condition of a slope.

Previous studies have proposed a prediction formula and graphical solution method for obtaining the failure time according to the relationship between the steady strain rate and creep rupture time [1, 2]. This relationship was evaluated and verified at several sites [1, 3, 4]. However, this method predicts landslide behaviour, such as failure within a few days, and is thus not suitable for detecting slope failure, which occurs within a short period owing to torrential rains. In contrast, Uchimura et al. [5] proposed a method for predicting slope failure during heavy rain by installing an inclinometer on the slope and measuring the change of the inclination angle. Moreover, both the local government and Japanese-expressway-operating companies need sufficient lead time to announce evacuations and road closures.

To solve the aforementioned problems, a soil moisture-based index (iQS) is proposed as the structural health-monitoring index of a slope against a rainfall-induced shallow landslide and is based on model slope experiments. In this study, the applicability of iQS in a real slope was evaluated using the result of real-slope monitoring during heavy rainfall along an expressway in Japan.

2. Basic concept for early prediction of shallow landslide
The authors clarified the relationship between volumetric water content at each depth and displacement (shear deformation) based on the past research findings obtained using model slope experiments, as shown in figure 1 [6, 7]. When rainwater infiltrates into the model slope, the volumetric water content at its shallow part (blue point) starts to increase first, and then the volumetric water content at the two points marked in red and black, immediately above the bottom part of the surface layer, starts to increase in order from the red to black points. These parts reach the quasi-saturated state; this is defined as the state in which the unsaturated hydraulic conductivity is theoretically balanced with the rainfall intensity unless the rainfall intensity exceeds the saturated hydraulic conductivity. This indicates that the entrapped-air still exists in the soil void. Subsequently, if the rainwater continuously infiltrates the slope, a water layer forms at the bottom of the surface layer, and the volumetric water contents start increasing again from the boundary part. This implies that the entrapped-air in the soil void replaces the pore water and the volumetric water contents increase again from the boundary part to the shallow part with increase in the water level. Then, a shallow landslide is caused by the decrease in effective stress owing to water pressure in the pores.

Koizumi et al. [6] defined the initial quasi-saturated volumetric water content (IQS) as the state at which infiltration and drainage in the vicinity of the sensor are balanced during the process of rainfall infiltration. As deformation does not occur unless IQS is exceeded, Koizumi et al. [6] indicated that the structural-health monitoring of a slope during rainfall is possible using the IQS as a regulation standard.

In the case of a real slope, the rainfall intensity is variable. Therefore, it is expected that the quasi-saturated volumetric water content also fluctuates according to the change in rainfall intensity. This relationship can be expressed by the relation between rainfall intensity and unsaturated hydraulic conductivity, as follows [8]:

\[ RI = k_{\text{IQS}} \]  

(1)
where $RI$ (mm/hour) is the rainfall intensity, and $k_{\text{IQS}}$ (mm/hour) is the unsaturated hydraulic conductivity when the volumetric water content reaches IQS and becomes constant. In other words, IQS shows the peak value of the volumetric water content under constant rainfall intensity in unsaturated condition, and it can be explained by the relationship between the unsaturated hydraulic conductivity and volumetric water content. Here, by considering the van Genuchten–Mualem (VG) model as an example, the relationship between $k_{\text{IQS}}$ and IQS is expressed as.

$$k_{\text{IQS}} = k_s \left\{ \left( \frac{\text{IQS} - \theta_r}{\theta_s - \theta_r} \right)^n \left[ 1 - \left( \frac{\text{IQS} - \theta_s}{\theta_s - \theta_r} \right)^{\frac{n}{m+1}} \right]^{\frac{1}{m+1}} \right\}^2$$

(2)

where $k_s$ (mm/hour) is the saturated hydraulic conductivity, $n$ is the parameter that gives the shape of the water characteristic curve, $\theta$ is observed volumetric water content, $\theta_r$ is the residual volumetric water content, and $\theta_s$ is the saturated volumetric water content. According to equation (1) and equation (2), the relationship between rainfall intensity and IQS can be expressed as follows:

$$RI = k_s \left\{ \left( \frac{\text{IQS} - \theta_r}{\theta_s - \theta_r} \right)^n \left[ 1 - \left( \frac{\text{IQS} - \theta_s}{\theta_s - \theta_r} \right)^{\frac{n}{m+1}} \right]^{\frac{1}{m+1}} \right\}^2$$

(3)

However, the maximum value of $k_{\text{IQS}}$ is $k_s$; the condition satisfied through equation (3) is $RI \leq k_s$. If $RI$ exceeds $k_s$, IQS theoretically becomes constant at the saturated volumetric water content. Although it is possible to estimate the relationship between rainfall intensity and IQS if each parameter in equation (3) is obtained, accuracy in the estimation of each parameter at the observation point is not guaranteed. To solve this problem, we propose a method to easily estimate the relationship between rainfall intensity and IQS based on the onsite monitoring data.

3. Monitoring of a real slope at the expressway

3.1. Outline of slope monitoring
The monitoring site is an embankment on an expressway in Japan. The material of the embankment is decomposed granite soil. Figure 2 shows the installation position of each sensor on the monitored slope.
To estimate the structural-health condition of the slope against rainfall infiltration, sensors were installed to measure soil moisture and slope tilt along with rain and water-level gauges. The soil-moisture sensor was installed at each depth based on the concept described in Section 2 and the result of the simple dynamic cone penetration test. The tilt sensor at each monitoring point was installed with the soil-moisture sensors to detect slope deformation. The gauge to measure water level was installed in a borehole and a rain gauge was installed on the cut slope in the westward direction 500 m away from the monitoring site. The monitoring was initiated in November 2017, and data were sent to the web server every 10 min via Internet-of-Things (IoT) using the wireless sensor network (WSN) technology, as shown in figure 3. The sensor nodes, which were operated using a solar power supply, can communicate with each other through the WSN in the intermittent mode. Here, we analysed the monitoring result of point A at the time of heavy rainfall in July 2018.

3.2. Results

Figure 4 shows the time-series variation of volumetric water contents and tilt angle, as well as the groundwater level and rainfall intensity at monitoring point A during heavy rainfall period of July 2018. As shown in figure 4(a) and figure 4(b), volumetric water contents increase in order from the shallow part, shown by the blue line, with rainfall infiltration. After the ratio of rise decreases and reaches the equilibrium state, the volumetric water contents re-increase in order from the deep part shown by the red line. Subsequently, the volumetric water content at the depth of 40 cm decrease and increase with
the rainfall intensity, and later each volumetric water content decreases in order from the shallow part. Moreover, fluctuations in the tilt angle and groundwater level were not confirmed.

![Diagram](image_url)

**Figure 4.** Time-series variation of monitoring data during heavy rainfall.

3.3. **Discussions**

The results provided in Section 3.2 are discussed in this section based on the concept presented in Section 2. In figure 4(a), although the volumetric water content at each depth increases with rainfall infiltration, the ratio of its raises temporarily decreases and reaches the equilibrium state. This changing point indicates the IQS for each sensor, as shown in figure 1, and it is understood that the volumetric water content at each depth reaches the quasi-saturated state. In other words, the monitoring results of the real slope were confirmed to agree well with those illustrated in figure 1. Subsequently, the volumetric water content increased again in order from 100-cm depth to 40-cm depth. This phenomenon indicates that a temporary water level different from that of the groundwater was generated at least up to the depth of 40 cm, indicating an increase in the risk of slope deformation owing to the reduction of effective stress. No change was observed in the tilt angle at point A because of a countermeasure work by using a precast framework. The constant groundwater level in figure 4(b) is attributed to the construction of underground drainage in the embankment.

**4. Estimation method of IQS by using onsite monitoring data**

Here, we consider a method to estimate IQS from onsite monitoring data. Figure 5 is a conceptual diagram showing the relationship between IQS estimated using onsite monitoring data and rainfall intensity. The relationship between the peak value of the volumetric water content and its related maximum rainfall intensity for each rainfall period, as shown in figure 6 is plotted in figure 5. The
relationship between IQS and rainfall intensity is represented by the solid line in figure 5. The solid line represents the theoretical relationship between RI and IQS based on the VG model. As the number of monitoring data increases along with the data of heavy rainfall, the relationship between IQS and rainfall intensity nears the solid line and can be accurately estimated as the blue dashed line.

![Figure 5](image)

**Figure 5.** Conceptual diagram of RI–IQS. VWC: volumetric water content.

![Figure 6](image)

**Figure 6.** Details of plot data in figure 5.

Figure 7 shows the relationship between the volumetric water content at the depth of 40cm and its related maximum rainfall intensity for each rainfall period from November 2017 to August 2018. The relationship between rainfall intensity and IQS at point A is approximately expressed by equation (4) by using the boundary line of this point group.

\[
IQS = 0.00015RI + 0.297
\]  

(4)
5. Proposal of regulation standard utilizing $iQS$

Here, we propose index $iQS$ for predicting the risk of shallow landslide at an early stage based on the aforementioned research outcome. The $iQS$ is a dimensionless value obtained by dividing the volumetric water content by the IQS corresponding to the rainfall intensity:

$$iQS = \frac{VWC}{IQS}, \quad (5)$$

where $iQS$ is the index of IQS and $VWC$ is the measurement value of volumetric water content. When $iQS = 1.0$, the volumetric water content reaches the quasi-saturated state. In addition, when $iQS > 1$, a water layer forms at the bottom of the surface layer and the volumetric water content starts increasing and reaches the saturated volumetric water content from deep to shallow. Figure 8 shows the time-series variations of volumetric water content at each depth and the $iQS$ at the depth of 40 cm. This graph shows that the time when $iQS$ reached 1.0 coincides with the time when the volumetric water content temporarily equilibrated. As shown in this graph, it is not easy to judge whether the water content has reached quasi-saturated state in real time only from the value of the volumetric water content. In contrast, the use of $iQS$ makes it possible to judge whether the quasi-saturated state is reached. In other words, by using $iQS$, it is possible to provide early-warning information about the occurrence of shallow landslide to local governments and infrastructure companies with sufficient lead time for evacuations and road closures.

6. Conclusions

Structural-health monitoring of slopes against rainfall-induced shallow landslide has become an important issue in Japan with the recent increase in extreme weather conditions. To solve this problem, this paper proposes $iQS$, a soil-moisture-based index, and its applicability to a real slope was evaluated through a real-slope-monitoring result during heavy rainfall along the expressway in Japan. The research findings are as follows.

A real-time monitoring system was developed utilizing IoT and WSN technology to function under the Expressway Real-time-Observation Network.

The monitoring results of the real slope were confirmed to agree well with the results of previous laboratory experiments. This implies that slope deformation owing to increase in the water level does not occur unless the volumetric water content exceeds IQS for the real slope.

We proposed a method to easily estimate the relationship between rainfall intensity and IQS based on onsite monitoring data.

In addition, we proposed $iQS$, an index for predicting the risk of a shallow landslide at an early stage.
Acknowledgments
The authors would like to thank T Yamamoto for technical assistance with the field work and experiments. This research was partly supported by Grant-in-Aid for Scientific Research (17K00615). We express our gratitude.

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