11TH INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

Reproduction of groundwater behaviour in road embankment with Digital Twin of field measurement of volumetric water contents

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Abstract

The real-time monitoring system for soil moisture state have been developed to prevent slope disasters in Japan. There are still many unsolved issues that prevent the adoption of the real-time monitoring systems. In this study, the availability of the digital twin of infiltration of rainwater into the soil was discussed to make effective use of measurement data and to help solve the issues. In general, the physical space provided through field measurements and the cyber space in which measured phenomena are modelled and numerically simulated are highly integrated in the digital twin. The data assimilation analysis, specifically the merging particle filter, was applied to perform the digital twin. The field measurement of the volumetric water contents in the embankment in Japan was chosen as the target of this research. A unsaturated-saturated seepage analysis based on the finite element method (FEM) was adopted as a simulation model for the cyber space. First, the reproducibility of measured volumetric water contents by the assimilated simulation model was confirmed. The behaviour of estimated groundwater, which was unmeasured, by the data assimilation analysis was presented. The infiltration mechanism of rainwater into the soil was elucidated based on the relationship between measured volumetric water contents and the estimated groundwater level. Consequently, it was confirmed that the digital twin, in which the data assimilation analysis is applied, could be available in the rainwater infiltration into the soil.

Keywords: Slope Stability, Field measurement, Numerical analysis, Data assimilation, Digital twin

1. Introduction

In Japan, slope failures caused by heavy rain have occurred frequently during the rainy seasons. Slope failures are caused by the excessive infiltration of rainwater into the soil. It is important to estimate the moisture condition in the soil to assess the risk of slope failure. A field monitoring system, by which the moisture condition in the soil can be observed in real time, has been developed. Currently, the field monitoring systems have been applied in many slopes in Japan (Sakuradani 2018).

In the field monitoring, it is desirable to measure as many kinds of physical items as possible. On the other hand, the number of physical items is limited by the problems of power supply required for measurements and wireless transmission cost of measurement data. In addition, some physical items are very difficult to measure. Therefore, it is desired to estimate unmeasured physical items from limited number of measurements. It is a good example to estimate the groundwater level from the measured volumetric water contents.

"Digital Twin" is a trendy keyword in the information technology. The digital twin develops the digital replica of physical phenomena in the cyber space. The digital replica must be up-dated in real time with the field measurement data on physical phenomena. The application of the digital replica will be able to solve the various problem in the physical space. In other words, TYPE-B prediction (Lambe 1973) is performed in real time. If the digital twin of infiltration of rainwater into the soil can be performed, the moisture condition in the soil can be elucidated accurately and higher estimation of the risk of slope failure will be enabled.

In this study, the availability of the digital twin of infiltration of rainwater into the soil was discussed. The field measurement of the volumetric water contents in the embankment in Japan was chosen as the target of this research. An unsaturated infiltration analysis based on the finite element method (FEM) was adopted as a simulation model for the digital replica. The data assimilation, in which the simulation model (specifically analytical parameters, boundary condition and so on) was up-dated through the comparison between the measured and the analytical volumetric water contents, was applied in the digital twin. The availability of the digital twin in the rainwater infiltration into the soil was discussed through the reproducibility of the volume water contents, consideration of moisture condition in the soil based on the unmeasured ground water which was estimated with the data assimilation analysis.

2. Data assimilation

Data assimilation is the most important technology in the digital twin. It is a technique used to identify the simulation model using the field measurements. Figure 1 shows the role of data assimilation in the rainwater infiltration into the soil. In the field measurement, the soil moisture state can only be obtained at the measurement position. Therefore, the spatial variation in soil moisture state cannot be elucidated. Furthermore, the change of the soil moisture state cannot be predicted. On the other hand, the spatial variation of the soil moisture state can be obtained by a numerical simulation, such as unsaturated or saturated seepage analyses. It is also possible to predict the progress of soil water state using numerical simulations.

However, the numerical simulation results are not completely reliable, because the simulation model has many uncertainties. The data assimilation analysis can highly integrate field measurement and numerical simulation. The defects in field measurements and numerical simulations are cancelled by both advantages, respectively. That is, the simulation model must be updated to assimilate the field measurement results in the data assimilation analysis, whenever field measurement is carried out. Therefore, the reliability of numerical simulations is verified. On the other hand, the assimilated numerical simulation can supplement the field measurement to reveal the spatial variations in soil moisture state including the unmeasured physical items. Moreover, a reliable prediction of soil moisture state can be provided.

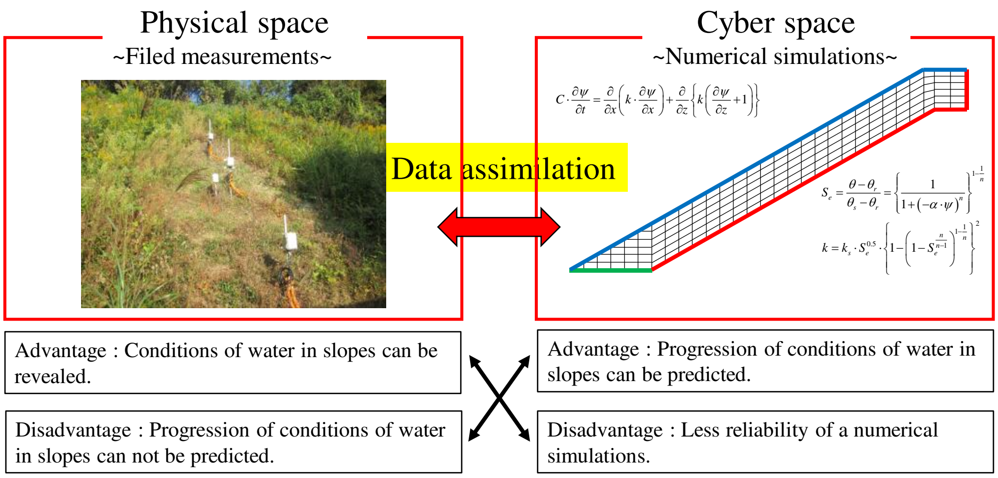

Figure 1: Role of data assimilation in the rainwater infiltration into the soil.

In this study, the merging particle filter (Nakano et al 2007), a kind of particle filter (Kitagawa 1996), was applied as the data assimilation technique. The merging particle filter is one of the most sophisticated sequential data assimilation methods. In this method, the probability distribution of a physical quantity and its realizations are approximated. Each realization is called a particle, and each set is called an ensemble. Each particle has a simulation model and information on the physical quantity at each time, providing a simulation result. The particle filter method evaluates the number of particles at a discrete time using Bayes' theorem. Figure 2 shows the computational procedure for the merging particle. In the merging particle filter, data assimilation is carried out by repeating four calculation steps: (a) first stage prediction, (b) filtering, (c) resampling, and (d) merging. For example, seven particles are prepared in Figure 2. For (a), the first-stage prediction, numerical simulations are carried from *t-1* to *t*. When the field measurements are performed and measurement results given to the numerical simulations, (b) filtering is performed. In this process, the weight of each particle is calculated by Bayes' theorem based on the degree of fitness of the numerical simulation results to the field measurement results. In Figure 2, the weight is expressed by the size of the circles. That is, the red and orange circles are large because the numerical simulation results for both particles are similar to the field measurement results. Conversely, the yellow and black circles are small, which differ from the field measurement results. In (c) resampling occurs; the particles are extracted and restored according to the weight assigned by (b) during filtering. In Figure 2, the particles are restored according to the weight, so that the total number of particles is

21. Therefore, the number of red circles is 5, and the number of orange circles is 4. Conversely, the number of both yellow and black circles, is 1. Finally, in (d) merging occurs; 21 circles are grouped into three sets and weighted sums performed for each set. Thus, the seven particles were regenerated. The regenerated particles have a higher probability of containing information from the red and orange circles, which will provide more similar numerical simulation results to the field measurement results. Conversely, the regenerated particles have a lower probability of containing information on both the yellow and black circles. As a result, the particle probability of producing the field measurement results increases. By repeating the above calculation step, the particles are automatically updated in the simulation model with a high fitness for the field measurement results.

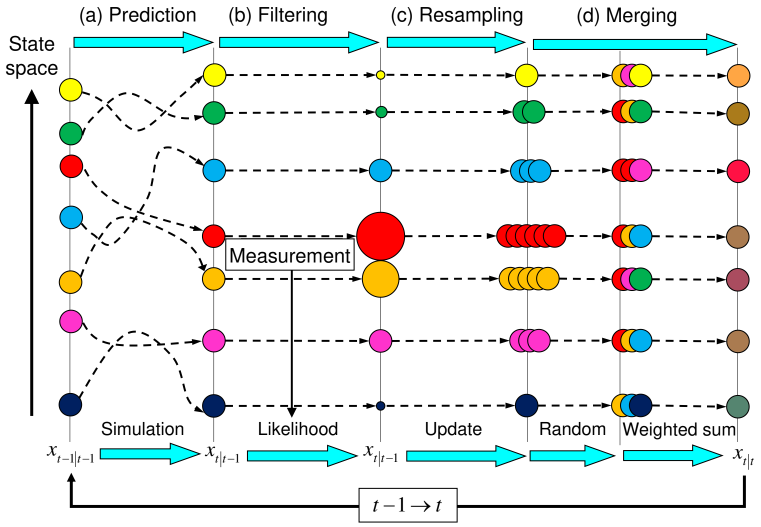

Figure 2: Computational procedure for the merging particle.

3. Field measurement

The photo-1 shows the embankment where the field measurements have been carried out (Oda et al 2021). The embankment was constructed in the north part of Osaka prefecture in Japan for an expressway. The embankment was made of weathered granite soils. Three soil moisture sensors for measuring the volumetric water content of soils were installed at the position marked with a yellow circle in the photo. Soil moisture sensors were installed at depths of 40 cm, 80 cm, and 100 cm from the ground surface, respectively. Moreover, a rain gauge was installed in the vicinity. Measurements by both soil moisture sensors and rain gauge have been taken at 10-minute intervals.

Photo 1: Embankment for field measurement.

4. Simulation model

4.1 Modelling of field measurement site

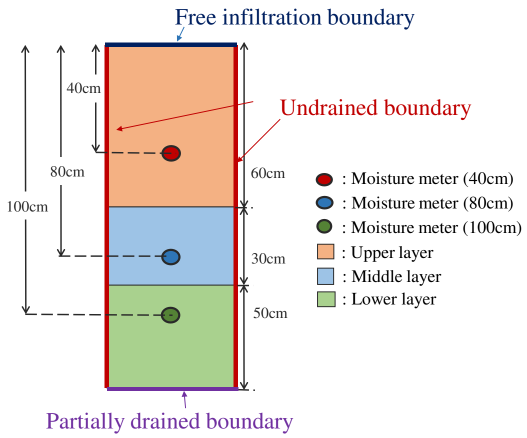

Figure 3: Analytical model

Figure 3 shows the analytical model. The Rainwater into soils from the ground surface infiltrates only in the direction of gravity. Therefore, the modelling for considering rainwater infiltration only in the vertical direction in this paper. The applicability of modelling based on such an idea has already been already confirmed through many cases (Oda et al 2019). In addition, three kinds of soil moisture parameters corresponding to the soil moisture sensor position are applied to the model. The boundary condition of the bottom of the analytical model is modelled as a partial drainage condition (Ito et al, 2020). In this boundary condition, the viewpoint of the tank model is applied, so that the drainage quantity from the bottom can be controlled. If the infiltrated water from the upward of the model is larger than the drainage from the bottom of the model, the part of infiltrated water will stay in the model. As a result, the degree of saturation increases, and groundwater is generated. On the contrary, if the infiltrated water from the upward is less than the drainage, the groundwater level lowers.

4.2 governing equations

In this study, an unsaturated-saturated seepage finite element analysis was applied as the simulation model. The following equation (Akai et al 1977) was applied in the numerical simulations.

$$C \cdot \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left\{k(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right\} \quad (2)$$

where $C(=\partial\theta/\partial x)$ is the hydraulic capacity function, Ψ is the matric potential, and k is the unsaturated hydraulic conductivity. The Van Genuchten model (Van Genuchten 1978), given in Equation (2), was adopted to express the soil water retention behavior. The Mualem model (Mualem 1976), given by Equation (3), was adopted to estimate the unsaturated hydraulic conductivity, *k*.

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r} = \left\{\frac{1}{1+(-\alpha\cdot\psi)^n}\right\}^{1-\frac{1}{n}} \quad (3)$$

$$k = k_s \cdot S_e^{0.5} \cdot \left\{1-\left(1-S_e^{\frac{n}{n-1}}\right)^{1-\frac{1}{n}}\right\}^2 \quad (4)$$

Here, S_e is the effective soil water saturation, θ is the volumetric water content, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, α and n are material parameters, and k_s is the saturated hydraulic conductivity. In this study, θ_s, θ_r, α, n, and k_s are unknown soil moisture parameters corresponding to unsaturated soil hydraulic properties.

5. Availability of data assimilation analysis

Figure 4 shows the variation of volumetric water contents with time. The heavy rainfall started just after the data changed on 7/5. In the stage (I), the volumetric water contents increased rapidly. The shallower the sensor location is, the earlier it increases. Although continuous heavy rains occurred, the volumetric water content did not significantly change in the stage (II). In the stage (II), the quasi-saturated state, in which the amount of water that infiltrates upward is balanced by the amount of water that drains downward, is kept. (Koizumi et al, 2018) The volumetric water contents re-increased rapidly in the stage (III). They were kept to almost constant at the stage (IV). Finally, they decreased slowly in the stage (V). The shallower the sensor, the earlier the volumetric water content decreases. The data assimilation analysis can almost follow the behaviour of these volumetric water contents.

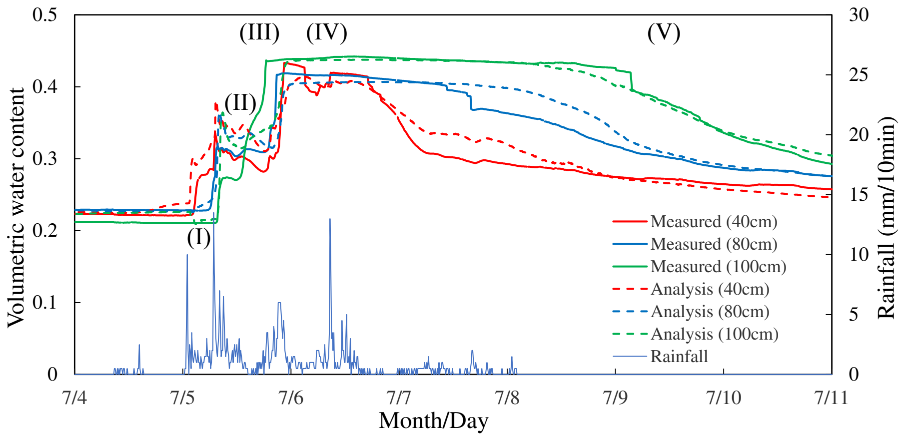

Figure 4: Variation of volumetric water contents with time

6. Estimated groundwater

Figure 5 shows the variation of groundwater level which was estimated from the data assimilation analysis with time. The groundwater level is generated in the midnight of 7/5, and it rapidly increases afterwards. It reaches the depth of about 40 cm of the peak value in the early morning of 7/6. After that, the groundwater level is maintained until the evening of 7/6, and then monotonically decreased with time. The generation of groundwater is not caused by intense rainfall, such as morning of 7/5 and morning of 7/6, but by relatively weak rainfall. That is to say, the quasi-saturated state is formed by the rainfall in the first half, and the groundwater was formed by the rainfall afterwards. It is also very steep from the generation of groundwater level to its peak despite weak rainfall intensity. The groundwater of this embankment was about 18 m deep and hardly fluctuated during the rainfall period. Therefore, as already pointed out, the groundwater that is assumed to occur this time is temporary.

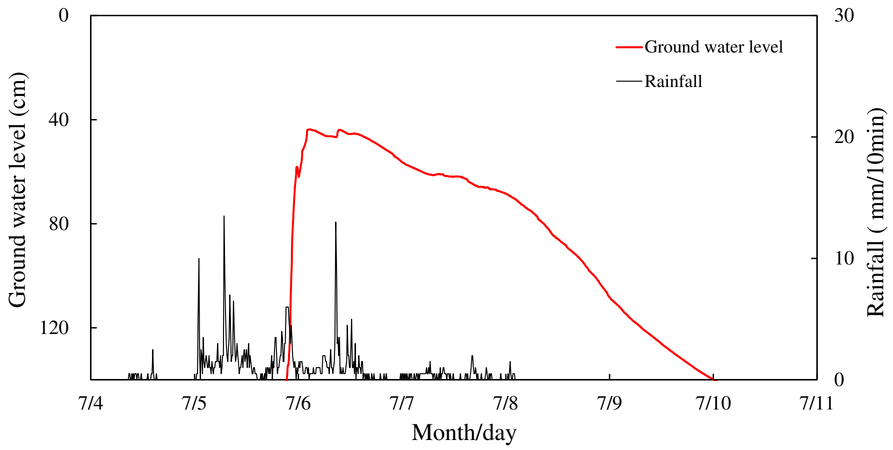

Figure 5: Variation of groundwater level with time

7. Infiltration mechanism of rainwater into soil

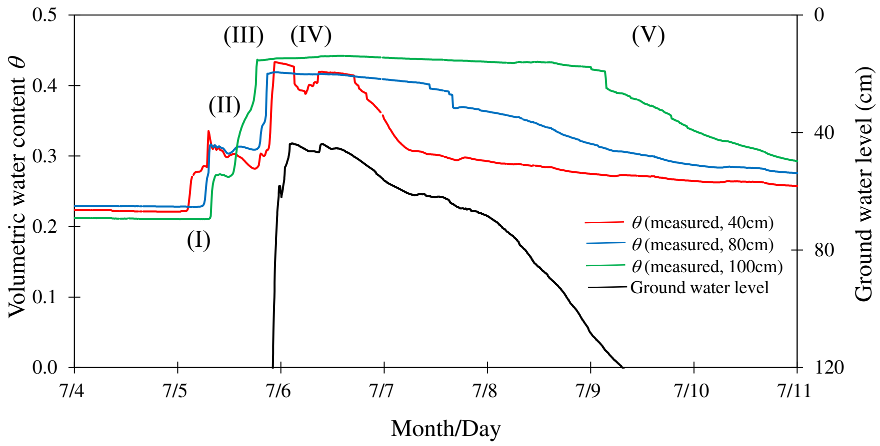

Figure 6: Variation of measured volumetric water contents and analysed groundwater level with time

Figure 6 shows the variation of volumetric water contents and groundwater level with time. The volumetric water contents are measured, while the groundwater level was based on the data assimilation analysis. In the stage (I), the volumetric water contents increase because of infiltration of rainwater from ground surface, judging from absence of groundwater. Then, the volume water content increases earlier as the sensor position is shallower. In the stage (II), the quasi-saturated state, in which the amount of water that infiltrates upward is balanced by the amount of water that drains downward, is kept. In both stages (I) and (II), soils are under unsaturated. In the stage (III), the groundwater is generated, and the groundwater level raises rapidly to the depth of about 40 cm. The volumetric water contents re-increase because soils below the groundwater level, depth of about 40cm, is saturated. Therefore, the volume water content re-increases earlier as the sensor position is deeper. At stage (IV), the groundwater level is kept at a depth of about 40 cm. As long as the groundwater level is higher than each sensor position, the soils below its depth are saturated. Therefore, the volumetric water content reaches the saturated volumetric water content and does not increase further. When the rainfall becomes weak and stops at the stage (V), the groundwater level gradually falls. As the soil above the groundwater level becomes unsaturated, the volumetric water content decreases. Therefore, the volume water content decreases earlier as the sensor position is shallower.

The behavior of the analyzed groundwater can reasonably explain the field measurement results of volumetric water contents. That is, the analyzed groundwater level can be judged to be highly reliable. It is suggested that unmeasured physical quantities are estimated by data assimilation analysis. And, the data assimilation analysis can be carried out every time the measurement result is obtained, so it is sufficiently correspondent to the real-time monitoring.

8. Conclusions

Data assimilation analysis in which the particle filter method is applied can reproduce the field measurements of volumetric water content.

The groundwater behaviour estimated by the data assimilation analysis can adequately explain the behavior of measured volumetric water contents.

The data assimilation analysis is available in the rainwater infiltration into the ground, because unmeasured physical quantities (i.e., groundwater level) can be estimated.

References

Akai, K., Ohnishi, Y., & Nishigaki, M. (1977). Finite element analysis of saturated-unsaturated seepage in soil, *Journal of JSCE*, 264, 87–95. (in Japanese)

Ito, S., Oda, K., Koizumi, K., Nishimura, M., Danjo, T., & Sako, K. (2020). Proposal of the method estimating seepage analysis model including a boundary condition using merging particle filter, *Journal of JSCE*, C-76(1), 52–66. (in Japanese)

Kitagawa, G. (1996). Monte carlo filter and smoother for non-gaussian nonlinear state space models, *Journal of Computational and Graphical Statistics*, 5(1), 1-25.

Koizumi, K., Sakuradani, K., Oda, K., Komats, M. & Ito, S. (2018). Relationship between initial quasi-saturated volumetric water content and rainfall-induced slope deformation based on a model slope experiment, J*ournal of GeoEngineering*, 13(4), 179-187

Lambe T. W. (1973). Predictions in soil engineering, *Geotechnique*, 23(2), 149–202.

Mualem, Y. (1976). A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media, *Water Resources Research*, 12, 513–522.

Nakano, S., Ueno, G. & Higuchi, T. (2007). Merging particle filter for sequential data assimilation, *Nonlin. Processes Geophys*, 14, 395–408.

Oda K., Ito, S. & Koizumi, K. (2019). Method on Identification of Infiltration Characteristics of Unsaturated Decomposed Granite Soils, *Proceedings of the 7th international Symposium on Geotechnical Safety and Risk*, 655–660.

Oda K., Koizumi K., Ito S. and Tsutsumi H. (2021). Relationship between soil water index and water conditions in a slope at heavy rainfall simulated by data assimilation, *Proceedings of the Kansai Geo-Symposium 2021*. 9, 58–63. (in Japanese)

Sakuradani, K., Koizumi, K., Oda, K. & Tayama, S. (2018). Development of a slope disaster monitoring system for expressway operation and maintenance control, *Journal of GeoEngineering* 13(4) 189-195.

Van Genuchten, M. (1978). Calculating the unsaturated hydraulic conductivity with a new closed-form analytical model, *Research Report*, No.78-WR-08, Princeton Univ.