INFLUENCE OF FLOW DIMENSION ON PREDICTION OF SPRING WATER FOR MOUNTAIN TUNNEL EXCAVATION

*Moritada Mori[1],Yasuyuki Kubota[2], Toru Yasuda[3] and Satoshi Nishiyama[4]

[1]Takenaka Civil Engineering & Construction, Japan; [2]Environmental Science and Technology, Okayama University, Japan; [3] Pacific Consultants Co., LTD, Japan; [4]Graduate School of Environmental and Life Science, Okayama University, Japan

ABSTRACT: Mountain tunnel excavations using the New Australian Tunneling Method should be assessed in light of the method's impact on spring water in the excavation and the surrounding water environment. Water flow across a tunnel (excluding watertight tunnels) has long been modeled as a well spring, which can be predicted by employing Kogiso's Sequential Data Assimilation - System on Water Information of Ground (SDA-SWING) method, a spring prediction method using Bear's formula. However, Bear's formula is a well formula based on Dupuit's quasi-uniform flow that, when applied to tunnel excavation, always yields an error in the results due to the flow dimension. SDA-SWING method solves this error by applying an ensemble Kalman filter to correct the hydraulic conductivity so that the calculation result matches the actual measurement. Nevertheless, such an error positions a great influence on the future prediction accuracy. Thus, in this study, we have improved the SDA-SWING method to consider three-dimensional flow. We used the method in simulating 3D seepage flow analysis for a simple tunnel excavation model and verified its ability to reproduce 3D flow and improve the future prediction accuracy.

1. INTRODUCTION

Certain problems on groundwater exist during excavation of mountain tunnels. These include sudden spring water, tunnel drainage treatment, and the surrounding water environment. On a positive sense, these issues can be addressed with a groundwater prediction model ascertaining its quick and smooth flow. Generally, the New Australian Tunneling Method (NATM) is a technique where all drainage flows on the back of the lining of a tunnel are collected in the shoulder drainage, to always flow out of the tunnel (Ex: RDA/JICA [1]). With this method, groundwater flow at a point several weeks to several months after excavation reaches a steady flow. Additionally, immediately after excavation, the groundwater level starts to drop, allowing for formation of an unsaturated area just above the tunnel (Takahashi et al [2]). This is the primary reason why water flow across tunnels (excluding watertight tunnels) in hydraulics has long been modeled as an open well spring. And this method is a very simple modeling technique compared with other methods such as 3D seepage flow analysis and thus involves modeling-associated errors. To account for the disadvantages just mentioned, Takahashi et al [3]. developed the System on Water Information of Ground (SWING) method to predict spring water during tunnel excavation, prioritizing on its applicability at the construction site and adopting a simple well formula in which obtained measurements can be

used for immediate back analysis. In their study, they observed the inflow of groundwater on the tunnel excavation as the amount of muddy water treatment and mainly used the observation data to identify unknown parameters. Nevertheless, the method demonstrated three issues:
(1) SWING method is a spring prediction method using Bear's formula (Bear et al [4]). Apparently, this is a well formula based on Dupuit's quasi-uniform flow that when applied to tunnel excavation would produce an error in the result due to the flow dimension.
(2) It was generally difficult to control groundwater inflow during the tunnel excavation, given its dependence on the heterogeneity of the geological structure.
(3) Parameter optimization was a trial-and-error process, which required a highly skilled personnel.

Among the three issues, the second one proved difficult to solve even when the analysis method was improved. On the contrary, the other issues were solved. Kogiso et al [5]. developed the Sequential Data Assimilation – SWING (SDA-SWING) method, modified using an ensemble Kalman filter (EnKF) to automatically find the optimal hydraulic parameters under various error considerations. However, as EnKF is a data assimilation method proposed by Evensen et al [6], it was only able to completely solve the third issue above, whereas it had difficulty dealing with the other two. In this study, we aim to elucidate the error caused by the difference in the flow dimension

of the SDA-SWING method and to improve it so that a 3D flow can be considered. Moreover, we will use this method to simulate a 3D seepage flow analysis for a simple tunnel excavation model. Essentially, we will compare both results to confirm the effectiveness of the improvement.

2. SWING METHOD PRINCIPLE

SWING method uses slice volumes, reflects observation data at the site, and enables the inverse analysis using the simplified model. Consequently, this analysis potentially improves the prediction accuracy. For development of the SWING method, this analysis should be satisfied with the strength and weakness of conventional prediction methods of tunnel groundwater inflow.

2.1 Slice volumes during tunnel excavation

A slice volume refers to the tunnel excavation area divided at equal intervals (see Fig. 1). We conducted groundwater flow analysis for each slice of the volume, assuming Dupuit quasi-uniform flow (see Fig. 2), as in the following procedure. First, slice 1 groundwater level was lowered after the tunnel excavation; it was lowered only until the end of its excavation. Next, a new slice volume (slice 2) was added when it reached the analysis range. We performed the analysis as we accumulated the slice volumes sequentially with the excavation progress.

2.2 Calculation of groundwater inflow and range of dropped groundwater level

Certain assumptions were considered when working with the SWING method (see Fig. 3) for our tunnel excavation. First, the tunnel was excavated in the aquifer above the impermeable layer. Second, the size of the excavated tunnel should be relatively small compared with the analytical domain. Third, the initial groundwater table above the tunnel should be in a horizontal position. (The initial groundwater table was located at position H_o from the upper boundary of the impermeable layer.) Fourth, the rainwater infiltration rate ε was considered in the model. The SWING method employed equations for a Dupuit quasi-uniform flow.

According to these equations, the groundwater inflow to the tunnel per unit length $q(t)$ and groundwater level $h(x,t)$ can be calculated using Bear's formula:

$$\begin{cases} \frac{h(x,t)^2 - h_O^2}{H_O^2 - h_O^2} = \frac{x}{R(t)} \\ q(t) = k\frac{H_O^2 - h_O^2}{2R(t)} \end{cases} \qquad (1)$$
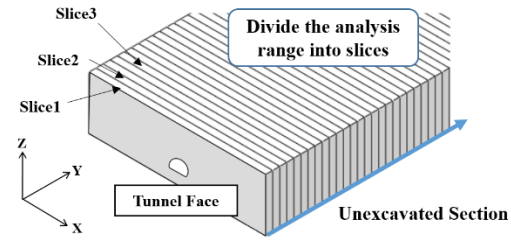

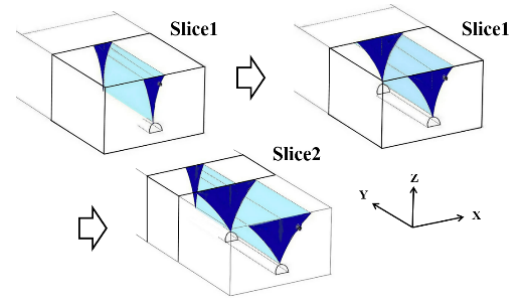Fig. 1 Slice volume during the tunnel excavation

Fig. 2 Summation of slice volumes during the tunnel excavation process

Where ε is the rainfall infiltration rate, k is the stratum hydraulic conductivity, $h(x,t)$ is the groundwater level at position x as a function of time t, H_o is the initial groundwater level, h_o is the location of the tunnel from the impermeable layer, $q(t)$ is the amount groundwater inflow to the tunnel for each slice volume, and $R(t)$ is the range of influence (where the groundwater level is lowered as a result of tunnel excavation) in each slice volume.

The first relation in Eq. (1) can be restructured to obtain an expression for the groundwater level function at any position x and time evolution t during the excavation process:

$$h(x,t) = \sqrt{\frac{x}{R(t)}(H_O^2 - h_O^2) + h_O^2} \qquad (2)$$

Considering the water balance, the amount of groundwater inflow to the tunnel should be equal to the sum of the groundwater lost in the aquifer and rainwater infiltration (see Fig. 3). This relationship is expressed by the Bernoulli equation,

$$qdt = k\frac{H_O^2 - h_O^2}{2R(t)}dt = \lambda_e \frac{H_o - h_o}{3}dL + \varepsilon Rdt \qquad (3)$$

Where λ_e and ε indicate the porosity and rainfall infiltration rates, respectively.

In terms of t with initial condition $R(t) = 0, t = 0$, Eq. (3) can be integrated between limits to yield

$$R(t) = \left[\frac{k(H_O^2 - h_O^2)}{2\varepsilon}\left\{1 - e^{-\frac{6\varepsilon t}{\lambda_e(H_o - h_o)}}\right\}\right]^{\frac{1}{2}} \qquad (4)$$

Accordingly, the range of influence at $t = \infty$ can be calculated using

$$R(\infty) = \left[\frac{k\left(H_o^2 - h_o^2\right)}{2\varepsilon}\right]^{\frac{1}{2}} \qquad (5)$$

Where as the instantaneous groundwater inflow (per unit length) for each slice volume can be obtained using

$$q(t) = \frac{k\left(H_o^2 - h_o^2\right)}{2R(t)} \qquad (6)$$

We used these equations to calculate the amount of groundwater inflow to the tunnel and the range of influence of the groundwater table for each tunnel excavation stage (every slice volume), as shown in Fig. 2. We summed the obtained groundwater inflow values in each slice volume for the total slice volumes and then compared the total amount (of groundwater inflow) with the observation data. Subsequently, we back-calculated the hydraulic conductivity for each slice volume based on the observation data and repeated the process for each excavation stage, updating the hydraulic conductivity field afterward. In turn, we could use the updated hydraulic conductivity field to predict the groundwater inflow to the tunnel. In the SWING method, rainwater infiltration is normally considered using the rainfall infiltration rate ε, which can be determined using a multi-tank model proposed by Takahashi et al [7].

2.3 Incorporation of EnKF in the SDA-SWING method

Moreover, in the SWING method, it is necessary to optimize the hydraulic conductivity based on observation values, such as the groundwater inflow level and the surrounding well water level. Regardless of such optimization, because this method follows Dupuit's quasi-uniform flow, it is bound to produce errors that do not consider 3D flow and non-uniformity of the geological structure, in addition to errors associated with obtaining observations and errors caused by variations in hydraulic conductivity. Thus, to obtain optimal solutions based on the observed values in the presence of the various errors, we applied a type of sequential data assimilation method known as EnKF, by observing these procedures:

For data assimilation, we considered a simultaneous, system model and observation model, collectively known as "state space model," and defined separately by these expressions:

System model:
$$x_t = f_t(x_{t-1}) + v_t, \quad v_t \sim N(0, Q) \qquad (7)$$
Observation model:
$$y_t = h_t(x_t) + w_t, \quad w_t \sim N(0, R) \qquad (8)$$

Where vectors x_t and y_t indicate the state of a system and the observed data at a discrete time, and vectors v_k and w_k denote system noise and observation noise, respectively; the operator f_t represents the temporal evolution of a state from time t_{k-1} to t_k according to the system model based on the simulation; and h_k projects the state vector x_k to the observation space. When we performed optimization with an observation data, we sought for the combination of state models that can reproduce these data assuming that noise (v_t, w_t) is included in the state of a system vector and observed data vector. The resulting system model is represented by Eq. (9), where the existence of a state transition matrix and the inclusion of system noise were part of the assumptions.
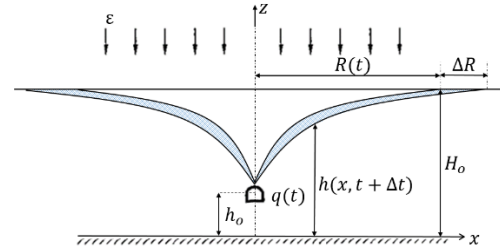

Fig. 3 Schematic figure for the groundwater level variation caused by tunnel excavation
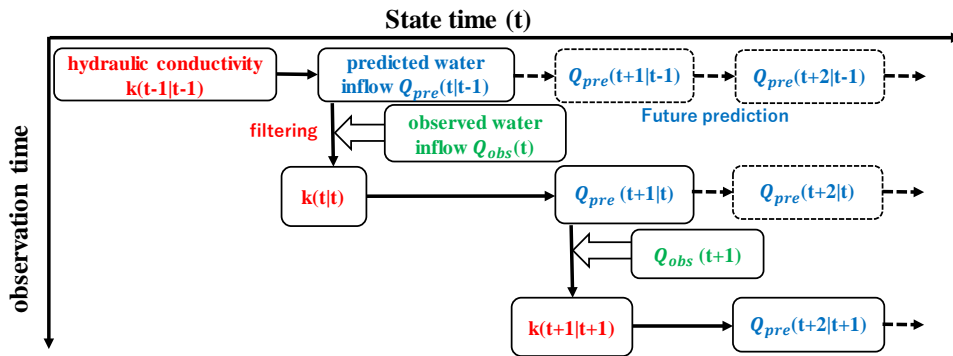

Fig. 4 The SDA-SWING method incorporating the EnKF

System model:
$$x_t = x_{t-1} + v_t \quad , \quad v_t \sim N(0, Q) \qquad (9)$$

The state variable vector in the SDA-SWING method was hydraulic conductivity k and void rate λ, whereas the observation variable vector was groundwater flow. However, v_t was applied only to k, which greatly affected the analysis results for the state of a system. Here, Q was the total value $\Sigma q(t)$ of spring water $q(t)$ per slice.

With EnKF, we found that it yields better accuracy when the probability distribution of the state of a system is closer to a Gaussian distribution. Moreover, we assigned the system noise to the logarithmic value of the hydraulic conductivity, which likewise followed a Gaussian distribution (Saito et al [8]). If presumably, the time required to excavate a unit slice volume is given by $m(d)$ and the total amount of spring water from the unit slice volume in the existing section at time t is $Q'(t)$, then the state space model for excavating a unit slice volume slice (j) can be expressed as follows:

$$x_t^j = \begin{Bmatrix} K_{t-1}^j \\ \lambda_{e(t-1)} \end{Bmatrix} + \begin{Bmatrix} v_t^{K_t} \\ 0 \end{Bmatrix} \quad \text{※} K_t^j = ln(k_t^j) \qquad (10)$$

$$y_t - Q'^{(t)} = h_{t-m(j-1)}(x_t^j) + w_t \qquad (11)$$

We updated the state space model at the stage where groundwater inflow was given as the top observation. Then, after construction of each slice, we determined the state quantity (k and λ) that most reproduces the observation value of the groundwater inflow obtained at the construction of the unit slice volume.

For this reason, the state quantity of the existing unit slice volume was a constant value when the unit slice volume to be excavated has shifted. From this, the total value $Q'(t)$ of spring water per unit slice volume in the existing construction section at time t can be expressed by

$$Q'^{(t)} = \sum h_{t-m(n-1)}(x_t^n) \qquad (12)$$

Furthermore, the initial hydraulic conductivity of the unit slice volume newly accumulated in the analysis range produced an average value of the hydraulic conductivity identified in the existing unit slice volume.

3. APPLICATION EXAMPLE OF SDA-SWING METHOD AND SUBJECT

Reference [9] shows an application example of the SDA-SWING method in actual tunnel construction. An outline of the tunnel construction is shown in Table 1, and a geological section is shown in Fig. 5.

Most of the basement rock in this tunnel plan area was composed of Jurassic accretionary deposits (Mino belt). Additionally, it was divided into two units based on constituent rock type, geological structure, and age: a "Samondake unit" consisting of orderly layered components of sandstone, mudstone, and chert and a "Funabuseyama unit" mainly composed of mixed rock facies such as sandstone, greenstone, limestone, chert, and mudstone.

The two unit boundaries were located 1,200 to 1,400 m from the tunnel entrance.

Preliminary geological surveys in this tunnel addressed fracture zone sections at two points of the muddy mixed rock—greenstone change points located 350 m from the unit boundary and the face. However, the above-ground part of the construction section excluding the tunnel entrance was a mountainous area where humans would find difficulty entering in and where measurement works such as observation wells could be insufficient but can be resolved by the SDA-SWING with computerized construction.

In the actual measurement during construction, sudden spring water was confirmed at a position other than the assumed fracture zone. However, almost no spring water was observed after that.

Figure 6 shows the analysis results of groundwater inflow rate prediction by SDA-SWING, based on observation values of the groundwater inflow rate from an excavation date down to 1178 m. Despite filtering conducted in the section (900–1,178 m), where there was almost no increase in groundwater inflow due to the excavation progress, we have expected the prospective process to increase the groundwater inflow with tunnel excavation, thereby delivering a trend. In addition, in the prediction, the shape of the groundwater inflow increased and decreased repeatedly with excavation progresses.

Nevertheless, in the actual construction, such an increase in groundwater inflow and short-time but large fluctuations were not confirmed, which produced discrepancies in the predicted value and the observed value of the groundwater inflow.

To predict the cause, we assumed two points:
(1) In the SWING method, we based our calculation of the amount of spring water in Bear's formula.

Table 1   Tunnel construction overview

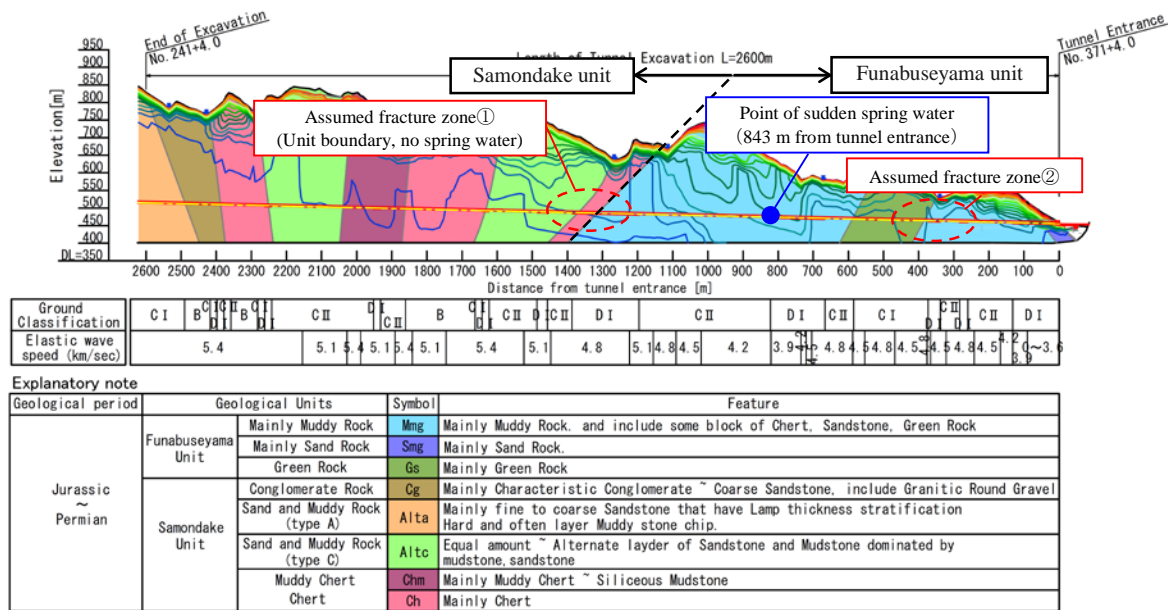| overview data	Value
Cross-sectional area of tunnel	48 m^2
Earth covering length	334 m
Excavating method	NATM
Rock type	sandstone, greenstone, limestone, chert, mudstone

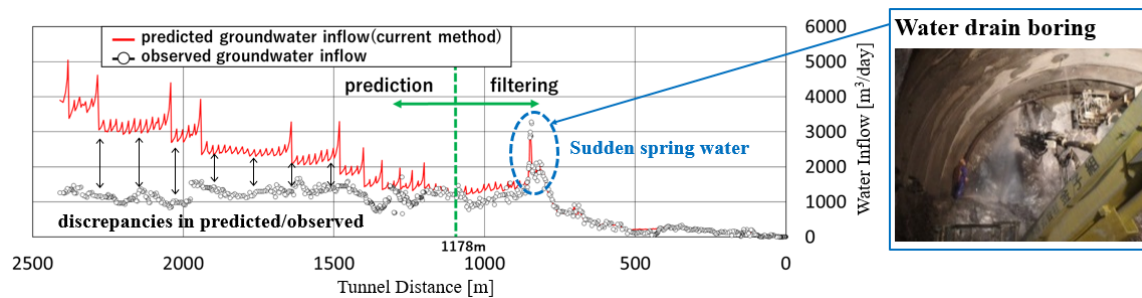Fig. 5 Geological profile of the tunnel construction site

Fig. 6 Result of groundwater inflow prediction with the SDA-SWING method

Thus, if the earth covering length would increase with the excavation progress, then water collection range would increase, along with an inevitable increase in the amount of spring water.

As a countermeasure, we set the initial hydraulic conductivity of the unit slice volume newly accumulated in the analysis range so that it would yield the average of the hydraulic conductivity identified in the existing construction. However, such action was not enough to reflect the fluctuation of geological information in the unexcavated section.

(2) Bear's formula was independently applied into each slice in the SDA-SWING method. This did not produce any decrease in groundwater level in the unexcavated section in front of the tunnel face, as shown in Fig. 7.

Moreover, when each slice enters the analysis range as the excavation progress, the water level would have also decreased from the elapsed time 0 (day) and would have created a large fluctuation of spring water. In the actual construction though, the groundwater level dropped in advance in front of
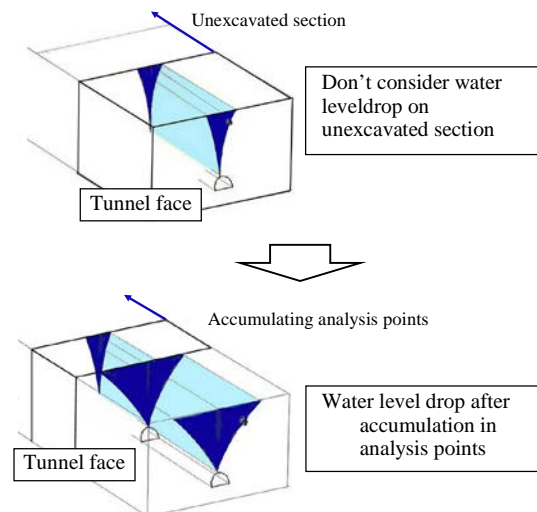

Fig. 7 Groundwater level at SDA-SWING method

the tunnel face, with an expectation that no significant fluctuation of spring water would occur during excavation.

Alternatively, this suggests that it is necessary to consider not only the one-dimensional (face plane direction) flow but also the effect of the water level drop ahead of the face rather than the depth direction flow. Even in the horizontal direction of a tunnel, this method complies with Dupuit's quasi-uniform flow and does not consider vertical water flow.

Moreover with the SDA-SWING method, the initial hydraulic conductivity given to each slice does not reflect the change in the geological information of the unexcavated work area; instead, the average value of the hydraulic conductivity identified by the unit slice volume in the existing construction section is given.

Thus, the amount of spring water would inevitably increase depending on the earth covering length.

Additionally, we could only expect difficulty in achieving improvement if the geological information cannot be understood accurately.

Thus, in this study our focus was fixed on determining the effect of water level drop in front of the face, and to verify such an effect, we conducted various numerical experiments on virtual tunnels with constant physical properties.

4. VERIFICATION BY NUMERICAL EXPERIENCE

We carried out the verification through numerical experiments on a simple simulated tunnel model. The properties of the tunnel are shown in Table 2. The tunnel was assumed to have a horizontal surface and constant physical properties, where the groundwater level was the same as the ground surface.

We analyzed the simulated tunnel using three methods, namely,
(1) 3D seepage flow analysis (FEM),
(2) SWING method, and
(3) SDA-SWING method.

For (1), the analytical result could be regarded as a theoretical solution. Here, the analysis model of 3D seepage flow is as shown in Fig. 8. On the basis of the assumption of the SWING method, the tunnel excavation was modeled as a well excavation in slice units, and the well flow rate was taken as the amount of spring water during tunnel excavation.

Accordingly, Figs. 9 and 10 respectively show the range of the groundwater level lowered when slice 10 was excavated and when the groundwater level of the unexcavated section was lowered with focus on slices 1 and 2. From the result, a groundwater level lower of the unexcavated section in front of the tunnel face occurred on 3D seepage flow analysis. In (2), the result was a value that does not perform a back analysis of the hydraulic conductivity.

Thus, we directly compared the error for this method with that in (1) due to the flow dimension of the SWING method.

We used the result in (1) in the result of (3) as an observed value. Thus, we confirmed that EnKF works normally when the error existing between (1) and (2) is corrected using EnKF; thus, we confirmed the accuracy of the future prediction model. Table 3 shows the setting values of the state space model in EnKF.

In setting the system noise, we assumed that the hydraulic conductivity varied by one order of magnitude. In addition, the value of observation noise was reduced as much as possible. With this, we intended the EnKF behavior to prioritize the observation values.

Table 2   Tunnel construction overview

Input data	Value
Slice pitch (m)	20
k: Hydraulic conductivity (m/s)	5×10^{-7}
λ_e: Porosity	0.1
ε: Rainfall infiltration rate	5×10^{-8}
Model height (m)	150
Distance from the bottom of model to tunnel (m)	10
Excavation speed (m/day)	2

Table 3   Values of the state space model

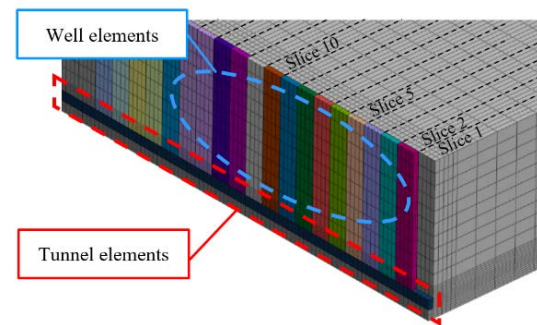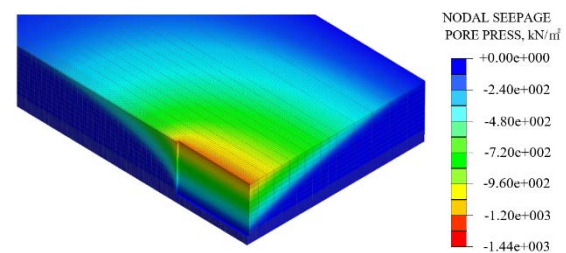| Input data	Value
Variance value of system noise	1.0
Variance value of observation noise	1.0×10^{-3}
Number of ensemble member	2,500
Initial of hydraulic conductivity (m/s)	5×10^{-7}

Fig. 8 FEM analysis model (slice 1 excavating)

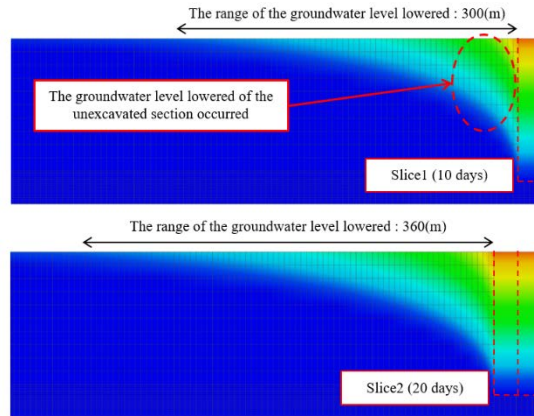Fig. 9. The range of the groundwater level lowered in Case 5 (slice 10)

Fig. 10 Range of the groundwater level lowered focusing on slices 1 and 2

Fig. 11 Groundwater inflow in FEM and SWING, SDA-SWING method

Fig. 12 Transition of hydraulic conductivity on SDA-SWING method

Figure 11 shows the time transition of groundwater inflow from the excavation start date to the 100th day, through the application of the two methods for FEM observations, namely, SWING and SDA-SWING. Apparently, there was a huge difference in the flow rate increase immediately after each excavating slice move next. This value was large with the SWING method that did not consider the drop in the water level of the front slice. On the contrary, this value was small when considered in the FEM.

In the first slice, the water level did not decrease even in FEM and showcased the same tendency of water level drop as in SWING. In the SDA-SWING method, we adjusted the water permeability to the FEM result by varying the hydraulic conductivity.

Figure 12 shows the transition of hydraulic conductivity of each slice, which thereby showed that the filtering process in EnKF functions normally.

Figure 13 shows the results of future prediction after data assimilation for up to four slices. In future prediction, we simply calculated the groundwater inflow with the SWING method using the hydraulic conductivity that has been assimilated up to slice 4.

As can be observed in Fig. 13, there was a noticeable difference between the results of SWING and FEM, and the hydraulic conductivity was forcibly manipulated to eliminate this. However, as shown in Fig. 12, there was a difference in the analysis results due to the flow dimension between SWING and FEM, which appeared as an error in the future prediction phase.

5. SWING METHOD IMPROVEMENT

To improve the future prediction accuracy of the SWING method, we carried out the following actions. Because conventionally, only one-dimensional flow is considered in SWING, we applied improvements in the method to allow 3D
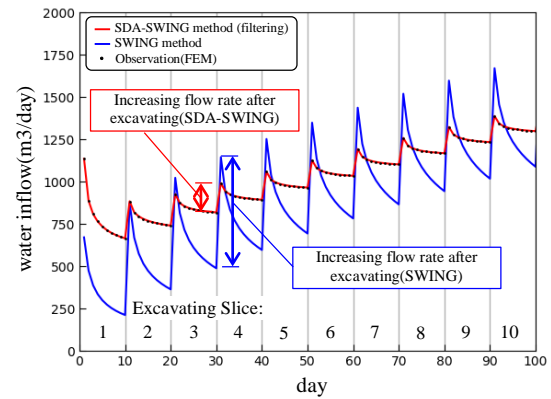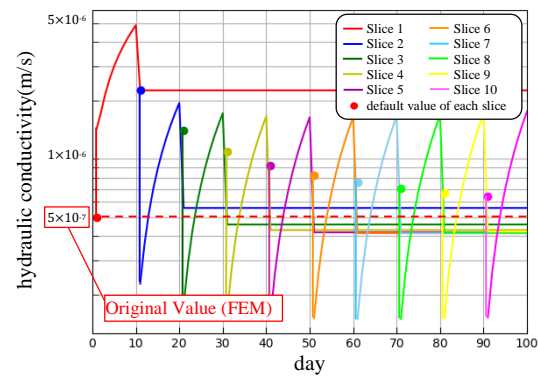

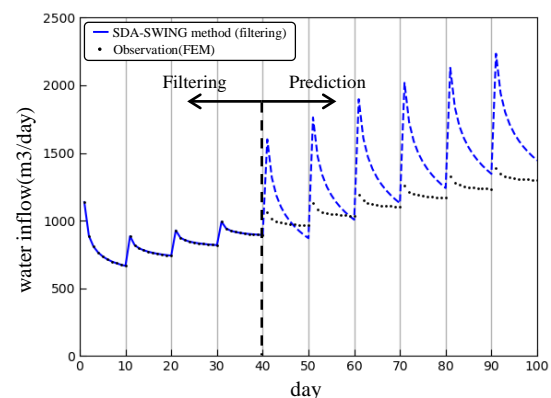Fig. 13 Future prediction accuracy after slice 5 on SDA-SWING method

flows with the simplest possible means, without using methods quasi-three-dimensional analysis proposed by Ohnishi et al [19].

5.1 Consideration of two-dimensional flow

To consider vertical two-dimensional (2D) flow, it is necessary to consider a 2D seepage flow

analysis. To take into account 2D flows (horizontal and vertical), Nishigaki proposed a formula corrected on the basis of Bear's, which originated from a parametric study using 2D FEM analysis.

We incorporated this formula (say, Nishigaki's formula) represented by Eqs. (13) and (14) into the SWING method, to solve the error due to 2D flow. Note that it observes the same format as Bear's formula in Eqs. (4) and (6):

$$R(t) = 1.22 \left[\left(\frac{k}{\varepsilon}\right)^{\frac{1}{2}} - 1\right] H_o \left[1 - \left(\frac{h_o}{H_o}\right)^2\right] \qquad (13)$$

$$q(t) = \frac{0.72 H_o^{-1} k (H_o^2 - h_o^2)\left(\frac{k}{\varepsilon}\right)^{-0.35}}{\left[1 - e^{-\frac{6\varepsilon t}{\lambda_e (H_o - h_o)}}\right]^{\frac{1}{2}}} \qquad (14)$$

5.2 Consideration of three-dimensional flow

To emphasize, the SWING method considers horizontal flow, whereas the Nishigaki's formula considers both horizontal and vertical flows in two dimensions. For 3D flow, it is necessary to consider the groundwater level lowering in the forward of the tunnel face.

Such a concept is illustrated in Fig. 14. Here, the $R(t)$ covered each slice in front of the face, making it necessary to add the amount of groundwater in this range with the assumption that the water level reduction range in front of the face was equivalent to that in the horizontal direction.

Meanwhile, Fig. 15 shows the concept of prior groundwater level drop occurring in the slice to be excavated. Note that the shapes of the water flow curve at the time of reaching the excavation and the water level drop in advance were different; however, the total amount of spring water in the target slice up to the time of calculation was preserved. Furthermore, it could be inferred that the elapsed time equivalent to the flow rate has passed with the progress of excavation.

5.3 Improvement results

Figure 16 shows the improvement results for Fig. 13. From Sections 5.1 and 5.2, as a result of considering the 3D flow by the SDA-SWING method, the prediction accuracy has greatly improved.

Figure 17 shows the transition of hydraulic conductivity of each slice in the SDA-SWING method after improvement. Because of improvement in the analysis accuracy of the SWING method itself, the fluctuation range of the hydraulic conductivity has also been reduced.

However, as the excavation progressed, the initial hydraulic conductivity could be seen to have converged to a slightly smaller value, as compared
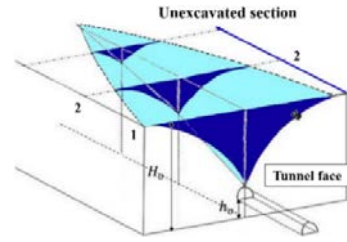

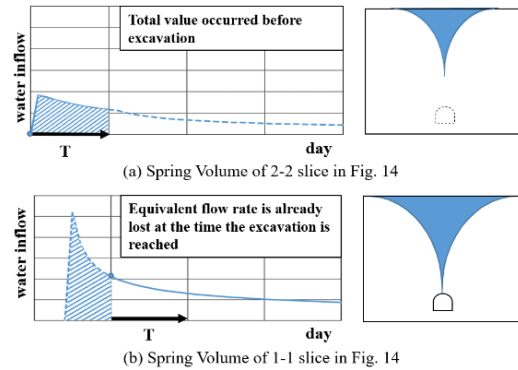Fig. 14 Groundwater level lowering in the forward of the tunnel face

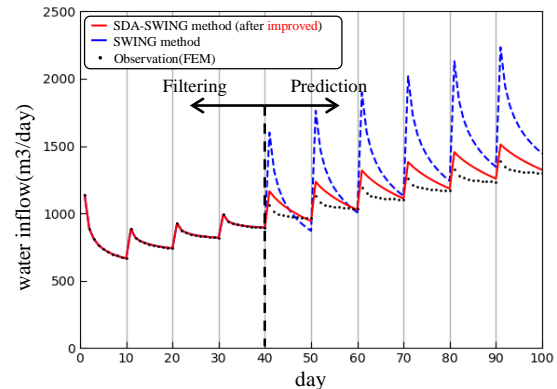Fig. 15 Concept of prior groundwater level drop

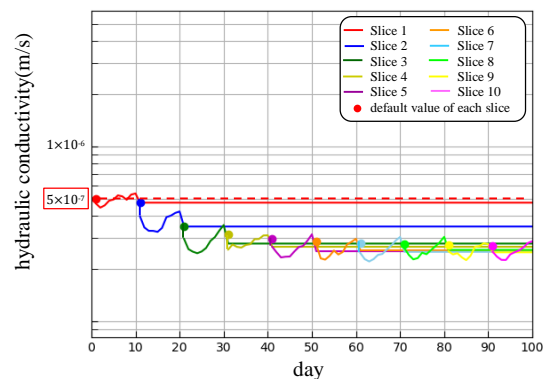Fig. 16 Groundwater inflow in FEM and SDA-SWING method (after improvement)

Fig. 17 Transition of hydraulic conductivity on SDA-SWING method (after improvement)

with the simulated tunnel model.

This seems to represent an error related to the 3D flow that has not been solved by this improvement method.

From the aforementioned results, we could say that the improved SDA-SWING method is equivalent to the FEM analysis under various preconditions.

6. CONCLUSIONS

In this study, we focused on errors caused by differences in flow dimensions among the various errors of the SDA-SWING method. To solve this problem, we improved the SDA-SWING method using two ways, namely, (1) introduction of the Nishigaki's formula and (2) calculation of the water level drop ahead on the slice volume of the tunnel face.

Consequently, under the condition of NATM tunnel excavation, the analysis accuracy of the SWING method can be brought close to that of the 3D seepage flow analysis. Furthermore, the future prediction accuracy of the SDA-SWING method has improved.

Some issues that were not solved in this study are as follows:

(1) This method was only an ex-post evaluation method. For example, as discussed in Section 3, prediction of sudden spring water in advance is a very difficult task.

(2) In relation to (1), there is a need to establish a method in SDA-SWING that reflects physical exploration methods such as advanced boring and electromagnetic exploration.

(3) Only the evaluation of the wellhead spring water volume was performed herein. Nevertheless, it is possible to add the observation well value and river/swamp flow rate as observation values. In addition to hydraulic conductivity, the porosity of the ground can be regarded as a variable. However, various noises in that case have not been evaluated.

(4) Despite the study being a numerical experiment, it is necessary to confirm the accuracy presented here by applying the method to actual tunnel construction.

On this note, we plan to resolve these issues as a future direction for our research.

7. REFERENCES

[1] Road Development Authority (RDA) / Japan International Cooperation Agency (JICA), Guideline for design of road tunnel - technical assistance for improvement of capacity for planning of road tunnels Japan / Sri Lanka, 2018, pp.48-49

[2] Takahashi, H., Applied geological considerations on tunnel springs, Journal of railway technical research report, No.279, 1962, pp.1-103

[3] Takahashi, K., Ohnishi, Y., Yasuda, T., Xiong, J., Simplified seepage analysis system applied to tunnel excavation for assessment of water inflow. Proceedings of the Symposium on Underground Space, Vol. 13, 2008, pp.147-150.

[4] Bear, J., Dynamics of Fluid in Porous Media, Dover Publications, 1998, pp.420-422.

[5] Kogiso, J., Koyama T., Takahashi, K., Yasuda, T., Ohnishi, Y., Development of SWING method with sequential data assimilation, Proceeding of the Japan Society of Civil Engineers F1 (Tunnel Engineering) , Vol. 66, No. 1, 2012, pp.9-15.

[6] Evensen, G., The Ensemble Kalman Filter: theoretical formulation and practical implementation, Ocean Dynamics, Vol.53, 2003, pp.343–367.

[7] Takahashi, K., Ohnish, Y., XIONG, J., Koyama, T., "Tank Model and its Application to Groundwater Table Prediction of Slope", Chinese Journal of Rock Mechanics and Engineering, Vol.27(12), 2008, pp.2501-2508.

[8] Saito, M., Kawatani, T., Theoretical study on spatial distribution of hydraulic conductivity, Proceeding of the Japan Society of Civil Engineering, No.645, 2000, pp.103-114.

[9] Mori, M., Sawa, T., Ichikawa A., Mori K., Sawazaki K., Nishimura, N., Yasuda T., Ohnishi, Y., Prediction of spring water during mountain tunnel construction by SDA-SWING method, Summary Collection of Annual Meeting of Japan Society of Civil Engineers , Vol. 77, 2017, pp735-736.

[10] Nishigaki, M., Komatsu, M., Irie, Akira., Yano, K., Ota, T., Simple Method for Predicting Changes of Groundwater Caused by a Construction of a Mountain Tunnel Digging and its Applicability, Proceeding of the Japan Society of Civil Engineers, No.778, 2004, pp.125-137.

[11] Awaji, T., Kamachi, M., Ikeda, M., Ishikawa, Y., Data Assimilation, Kyoto University, 2009, pp.63-92.

[12] Higuchi, T., Ueno, G., Nakano, S., Nakamura, K., Yoshida, J., Introduction to Data Assimilation-Simulation Technology for the Next Generation, Asakura Shoten, 2011, pp1-240.

[13] Umeda, K., Yanagisawa, K., Yoneda, S., Creation of hydraulic conductivity database for Japanese ground, Journal of Japan Society of Engineering Geology, No.37, 1995, pp.69-77.

[14] Koyama, K., Kogiso, J., Takahashi, K., Yasuda, T., Ohnishi, Y., Development of swing method with sequential data assimilation (SDA-

SWING) and its application to groundwater problems in real tunnel construction, Tunneling and Underground Space Technology, No.28, 2012, pp.229-237

[15] Kishinaka, K., Koyama, T., Kogiso, J., Takahashi, K., Yasuda, T., Onishi, Y., Improvement of SWING method and its application to groundwater inflow during real tunnel construction, Lecture of Applied mechanics, Japan Society of Civil Engineers, Vol62, OS14, 2013, pp28-29.

[16] Oshima, H., Hydrogeological study on spring water accompanying tunnel excavation and associated water balance change, Journal of railway technical research report, No.1228, 1983, pp.1-58

[17] Sato, K., Groundwater modeling of mountain tunnel and application of simulation techniques, Engineering geology Journal of the Japan Society of Engineering Geology, Vol.23, 2003,

pp.178-184.

[18] Akai, K., Ohnishi, Y., Nishigaki, M., Finite element analysis of saturated - unsaturated seepage in soil, Proceeding of the Japan Society of Civil Engineering, No.264, 1977, pp.87-96.

[19] Ohnishi, Y., Nishigaki, M., Nishino, K., Fundamental study of a new quasi-three dimensional numerical analysis for hydrogeological problems, Proceeding of the Japan Society of Civil Engineering, No.424, 1990, pp.85-94.

[20] Japan Tunnelling Association., Research report on tunnel spring investigation method (II), 1980, pp.128.