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Rapid Saturated Permeability Evaluation Method of Unsaturated Dam Foundations

Yoshikazu Yamaguchi, Hiroyuki Satoh, Hiroki Sakamoto, Satoshi Yoshida
Public Works Research Institute (PWRI), Japan
yamaguti@pwri.go.jp

Kenji Shimoyama
NEWJEC Inc., Japan

ABSTRACT:
In many of Japan's more recent dams, the lower section is built on a foundation of weathered soft rock or unconsolidated sedimentary soft rock. To properly evaluate the permeability of this type of foundation, long-term testing should be carried out. However, this is not always practical due to time and cost restraints. This study clarifies the effect of the analysis conditions used for saturated-unsaturated seepage analysis, which simulates field permeability tests, on the unsteadiness of the injection flow rate and the stable flow rate. From the results, we propose a method for estimating the stable flow rate based on long-term permeability tests, using the test results during a appropriate testing time from practical viewpoint. Reproducibility of this method is verified through comparison with actual long-term test results.

Keywords: Dam foundation, Soft rock, Long-term permeability test, Saturated-unsaturated seepage analysis, Unsteady seepage

1. INTRODUCTION

In many of Japan's more recent dams, the lower section is built on a foundation of weathered soft rock or unconsolidated sedimentary soft rock. In this type of foundation, if the groundwater level is low and the foundation is unsaturated, the water flow during a permeability test becomes unsteady. In such cases, in the limited injection time, a steady flow rate may not be achieved at each injection pressure step, resulting in an overestimation of permeability. A possible solution is long-term permeability testing (Yamaguchi, Shimoyama et al., 2010). In this test, a steady flow rate is obtained by prolonging the injection time. However, this test method is not always practical in terms of time and cost. If the saturated permeability could be evaluated based on injection flow rate data within a appropriate testing time from a practical viewpoint, the amount of foundation grouting could be reduced and the construction period shortened, resulting in lower costs.

In this study, we conducted saturated-unsaturated unsteady seepage analysis to simulate long-term permeability testing, while progressively varying the effective injection pressure, saturated hydraulic conductivity, and groundwater level to evaluate the effect of these conditions on the analysis results: unsteady seepage properties and stable flow rate. On the basis of the analysis results, we propose a method for estimating the stable flow rate, which is necessary for evaluating the saturated hydraulic conductivity from the results of a field permeability test within a appropriate testing time. In addition, to evaluate its applicability, we applied this method to the results of an actual long-term permeability test carried out in an unsaturated soft rock foundation. We then verified the reproducibility of the method by comparing the estimated stable flow rate with the measured rate.

2. ANALYSIS CONDITIONS AND RESULTS

2.1. Analysis Model and Physical Properties

Since this research considers a soft rock foundation with few predominant cracks, we conducted seepage analysis using a porous-medium model. Fig. 1 outlines the analysis model and Table 1 summarizes the specifications. This is an axisymmetrical model with a radius of 30 m and height of 25 m. The test hole has a radius of 0.033 m and the test section was a 5 m area from 10 m to 15 m below the ground surface. Boundary conditions were set as follows: the outside boundary of the model, which is below the groundwater level, was defined as the constant head boundary; the outside boundary above the groundwater level was defined as the seepage boundary; and the other boundaries were defined as impermeable boundaries.

Table 1. Model specifications

Item	Value
Model radius *R* (m)	30
Model height *H* (m)	25
Borehole diameter ϕ (mm)	66
Test section upper end depth from ground surface (m)	10
Test section length *L* (m)	5

Table 2. Physical properties analysis

Item	Value
Saturated hydraulic conductivity k_s (cm/s)	1.3×10^{-4}
Specific storage S_s (cm^{-1})	1.0×10^{-7}
Porosity *n*	0.2
Unsaturated seepage characteristics	Figure 2

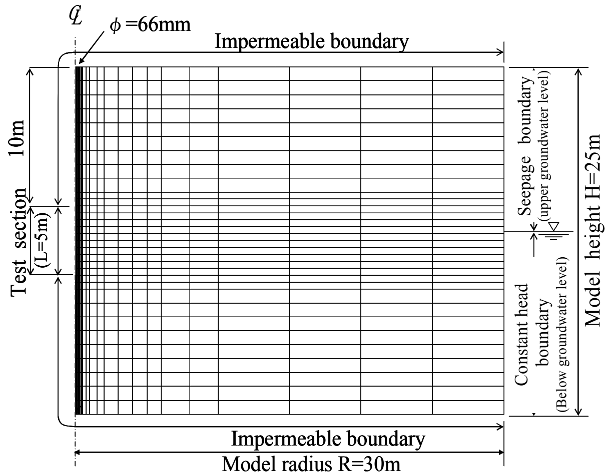


Figure 1. Outline of the analysis model

Table 2 lists the physical properties used for the analysis while Fig. 2 shows the unsaturated seepage characteristics. The physical properties were set with reference to previous research (Matsumoto et al., 1987), assuming that the foundation is a porous medium with isotropic permeability of about 10 Lu. The physical properties shown in Table 2 and Fig. 2 were designated as the "basic model properties" and were also used in our previous research (Yamaguchi and Ikezawa, 2008). The injection time for the analysis was 1×10^9 sec (about 31 years), which is considered to be sufficiently long for the flow rate to have reached a steady state.

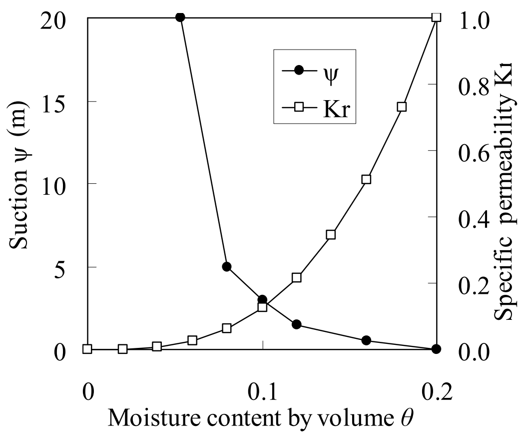


Figure 2. Unsaturated seepage characteristics

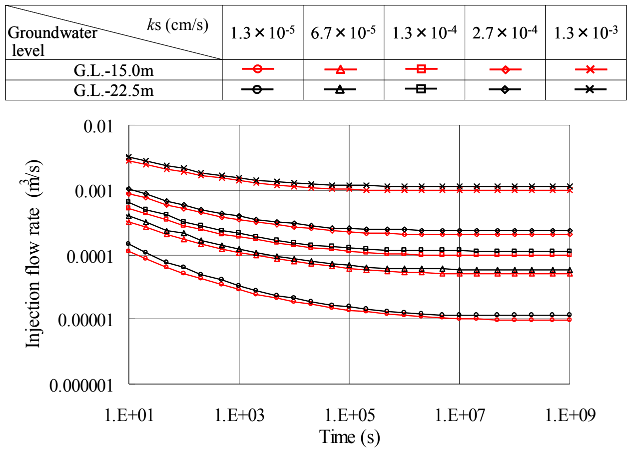
2.2. Study Cases

Table 3 summarizes the study cases. We varied the groundwater level and/or effective injection pressure to study the effect on the unsteadiness of the injection flow rate and stable flow rate.

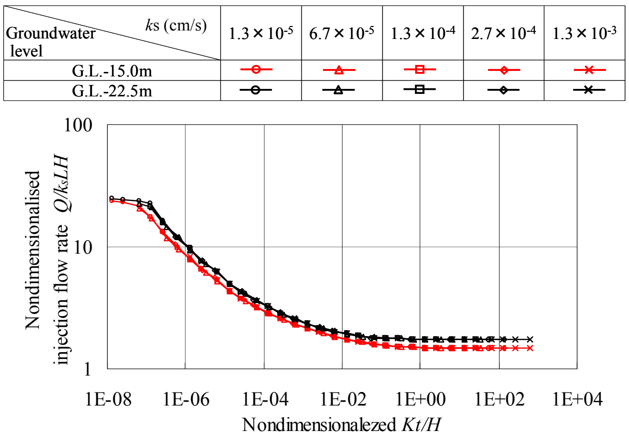
In principle, the saturated hydraulic conductivity was set at $k_s = 1.3\times10^{-4}$ cm/s, which corresponds to about 10 Lu. Four additional values, ranging from $k_s = 1.3\times10^{-5}$ cm/s (1 Lu) to $k_s = 1.3\times10^{-3}$ cm/s (100 Lu), were set in order to investigate the effect of the saturated hydraulic conductivity on the groundwater level (G.L. −0 m, −15 m and −22.5 m) and effective injection pressure (0.098, 0.49 MPa).

Table 3. Study cases

Saturated hydraulic conductivity k_s (cm/s)	Effective injection pressure (MPa) / Groundwater level (m)	0.049	0.098	0.196	0.294	0.49	0.98	Remarks
1.3×10^{-4}	−0 −5	●	●	●	●	●	●	Groundwater level is located above test section
	−10	●	●	●	●	●	●	Groundwater level is located at upper end of test section
	−11.25 −12.5 −13.75	●	●	●	●	●	●	Ground water level is located within test section
	−15	●	●	●	●	●	●	Groundwater level is located at lower end of test section
	−20 −22.5	●	●	●	●	●	●	Groundwater level is located below test section
1.3×10^{-5} 6.7×10^{-5} 2.7×10^{-4} 1.3×10^{-3}	−0 −15 −22.5	-	●	-	-	●	-	Effect of saturated hydraulic conductivity



(a) Time history of flow rate using analysis results



(b) Time history of flow rate using nondimensionalized data

Figure 3. Comparison of time history of injection flow rate (Effective injection pressure of 0.098 MPa)

2.3. Study Results

2.3.1 Effect of the saturated hydraulic conductivity of the foundation

Fig. 3(a) shows the time history of the injection flow rate. The higher the saturated hydraulic conductivity, the higher the injection flow rate; and the larger the saturated hydraulic conductivity, the shorter the time until the injection flow rate becomes steady. To examine this in more detail, we nondimensionalized the flow rate and the time, and then investigated the conformity of their distribution. The injection flow rate and the time were nondimensionalized as described below.

a) The injection flow rate was nondimensionalized by solving Q/k_sLH, with saturated hydraulic conductivity k_s, pressure head equivalent to the effective injection pressure H, and test section length L.

b) The time was nondimensionalized by solving $t\ k_s/H$, with the reciprocal of saturated hydraulic conductivity $1/k_s$ and pressure head equivalent to the effective injection pressure H. Fig. 3(b) shows the time history of the nondimensionalized injection flow rate and nondimensionalized time. If the groundwater level and effective injection pressure are equal, the nondimensionalized injection flow rates are almost in conformity and form a single curve.

3. STABLE FLOW RATE ESTIMATION METHOD AND ITS APPLICATION

3.1. Estimation Method of Measured Injection Flow Rate Based on Seepage Analysis

From the results in the previous section, we clarified the characteristics of the time history of the injection flow rate based on the seepage analysis described below. When test conditions such as effective injection pressure and groundwater level are identical, if the injection flow rate and time are nondimensionalized by the saturated hydraulic conductivity, the time history of the injection flow rate becomes a single curve.

Focusing on this fact, we propose a fitting method which reproduces the measured injection flow rate using a correction coefficient based on the flow rate obtained from the seepage analysis.

(1) Seepage analysis

An analysis model that reproduces the test conditions such as effective injection pressure, groundwater level, and test hole size, is prepared and seepage analysis is conducted by setting the saturated hydraulic conductivity k_1.

The time history of the injection flow rate obtained in this way is defined as $q_B(t)$.

(2) Preparing the approximation formula of $q_B(t)$

As described below, when the output time of $q_B(t)$ is multiplied by the correction coefficient α, the fitted output time varies according to the value of α. So, the flow rate value at the same time as the data before correction cannot always be obtained. Therefore, the analysis flow rate $Q_B(t)$, which is the approximation equation of $q_B(t)$, is used for the fitting. The form of the approximation equation is expressed as Eq. (1) based on the form of the time history of the injection flow rate.

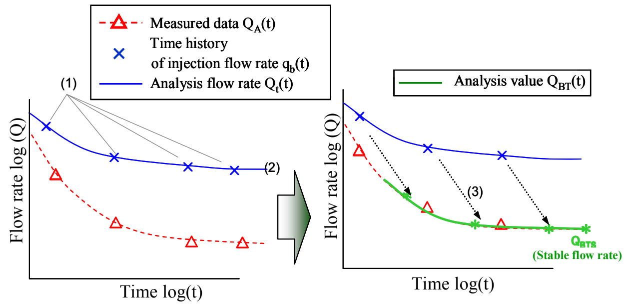
$$Q_B(t) = a \cdot t^b + c \qquad (1)$$

where a, b, and c are constants that are set based on the method of least squares, etc.

(3) Conducting the fitting

Eq. (2) is used to conduct the fitting so that the flow rate in the analysis results $Q_B(t)$ conforms to the measured flow rate data $Q_A(t)$.

$$Q_{BT}(t) = \alpha Q_B(\alpha\, t) \qquad (2)$$



(1) To obtain the time history of the injection flow rate $q_B(t)$ from the seepage analysis
(2) To set a and b conforming to $q_B(t)$ as $Q_B(t) = a \cdot t^b + c$
(3) Q_{BT} is set by obtaining α such that $Q_{BT}(t) = \alpha Q_B(\alpha t) \fallingdotseq Q_A(t)$ by using the method of least squares, etc.

Figure 4. Fitting procedure

where α is the correction coefficient and is set using the method of least squares, etc. The stable flow rate of $Q_{BT}(t)$ obtained by the fitting is Q_{BTS}.

Fig. 4 is a schematic diagram of the fitting procedure from steps (1) to (3).

3.2. Application to Results of Long-term Permeability Tests at the Taiho Saddle Dam

We applied this fitting method to the results of long-term permeability tests conducted at the left bank of the Taiho Saddle Dam (Yamaguchi , Shimoyama et al., 2010) to verify the reproduction precision of the stable flow rate.

3.2.1 Outline of the long-term permeability test and the test data

Table 4 summarizes the specifications of the long-term permeability test conducted at the Taiho Saddle Dam, and Fig. 5 shows a schematic drawing of the long-term permeability test. Fig. 6 shows the rock classifications at the left bank and the locations of the test holes. The D_H class phyllite bedrock, which was the target of the long-term permeability test, is overall strongly weathered and is in a homogenous, porous state. There are also several schistosity planes or cracks. However, their continuity is sufficiently low to assume no dominant water channels. Details on the test and geological conditions are provided in Yamaguchi, Shimoyama et al. (2010).

Fig. 7 shows the time history of the injection flow rate at Block 2 where the unsteadiness of the injection flow rate is relatively strong. The figure also shows the data measured at 1-min intervals and the data for 10-min moving averages calculated to ensure smooth scattering of the measured data.

3.2.2 Reproduction analysis of long-term permeability test results at the Taiho Saddle Dam

We conducted reproduction analysis based on the saturated-unsaturated unsteady seepage analysis for long-term permeability test data which indicated unsteady flow tendencies. Then, we applied the analysis results to the fitting of the measured data. We analyzed the data at five stages, as shown in Fig. 6.

Table 4. Specifications of long-term permeability test

Item	Specification
Borehole diameter φ	66 mm
Stage length	2.5 m
Constant water head*	EL. 78.2 m
Injection flow rate measurement	1-min intervals
Measurement time	Min 4 h

*A constant water head tank is installed near the borehole to maintain a constant water level for injection.

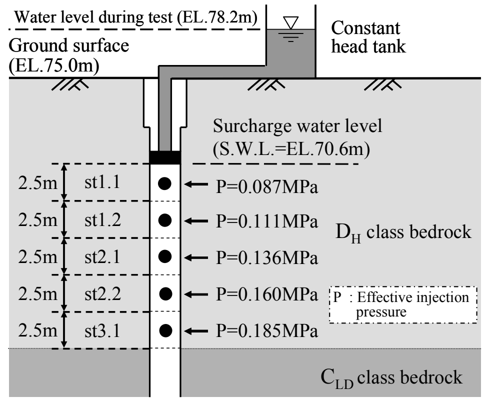


Figure 5. Outline of the long-term permeability test

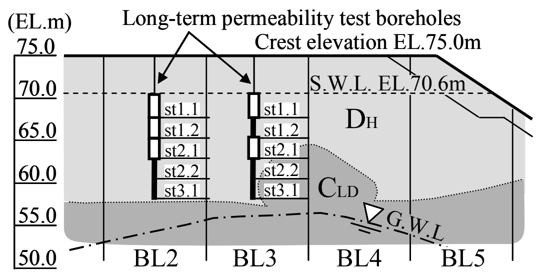


Figure 6. Locations of long-term permeability test boreholes
(□ : Selected stages for reproduction analysis)

Due to the large scattering of the measured data to be compared with the analysis results, we used the injection flow rates based on a 10-min moving average.

(1) Unsaturated seepage characteristics

1) Outline of specimens and unsaturated seepage characteristics test

To obtain the unsaturated seepage characteristics needed for the saturated-unsaturated seepage analysis, we carried out laboratory tests on specimens obtained at the dam site. The unsaturated seepage characteristics test was conducted using the test method proposed by Nishigaki et al (2010). Due to space limitations, the details of sampling and testing methods are not described here, but can be viewed in Yamaguchi, Sakamoto et al. (2010). Fig. 8 shows the unsaturated seepage characteristics of phyllite, which was used in this study. The characteristics were approximated from test results using the van

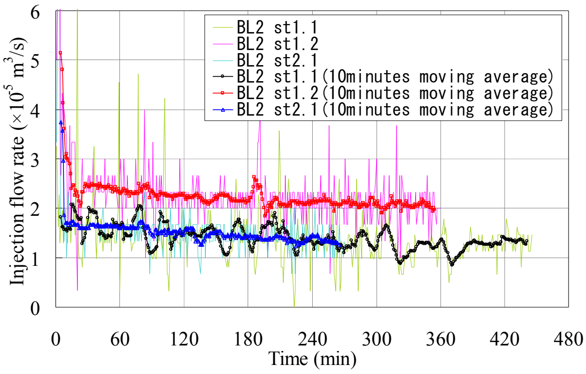


Figure 7. Injection flow rate (Block 2)

Genuchten model (van Genuchten, 1980).

(2) Analysis model and analytical physical properties

Fig. 9 shows an example of the analysis model, which was axisymmetrical, with a radius of 30 m and height of 25 m. The boundary conditions were set the same as in Fig. 1. The test section length was 2.5 m, and the test hole diameter was 0.033 m. The test holes were installed so that the depth of the test section was almost identical to the actual depth in order to reproduce the conditions of the long-term permeability test as accurately as possible at each stage.

Table 5 shows the analytic material properties. In this study, we used the in situ test reproduction model properties and the basic model properties shown in Table 2 and Fig. 2 to investigate the effect of the unsaturated seepage characteristics. Among the physical properties of the reproduction model, the saturated hydraulic conductivity k_s and the specific storage S_S were considered to be the same values as in the basic model, hypothesizing soft rocks as a porous medium of about 10 Lu. Porosity and unsaturated seepage characteristics of the reproduction model were set according to the results of the laboratory test. The porosity was set at 0.48, and the unsaturated seepage characteristics were set using Fig. 8.

(3) Fitting and verification of reproducibility

In order to verify the reproducibility of the measured data by this fitting method, we conducted fitting between the results of the seepage analysis and the measured data from the long-term permeability test at the Taiho Saddle Dam. Given the scattering of the measured data, we used the average data of the last hour of the test for calculating the stable flow rate. In this study, Q_{AS} means the stable flow rate calculated by long-term permeability tests, Q_{BTS} means the stable flow rate calculated by the fitting method. Q_{AS} was used for evaluating the degree of reproducibility of Q_{BTS}. Since the injection flow rate during the first hour of the test is disturbed, the time used for the fitting was set from 60 to 120 min at the start of the test.

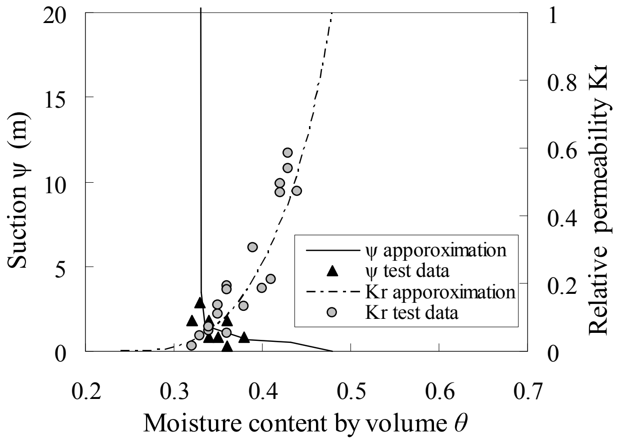


Figure 8. Unsaturated seepage characteristics

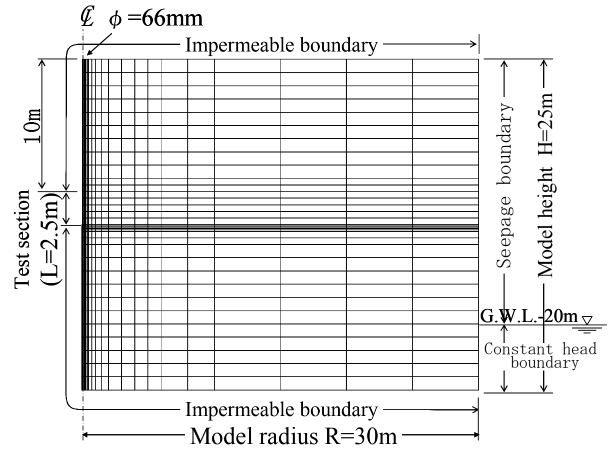


Figure 9. Example of analysis model (Stage 2.1)

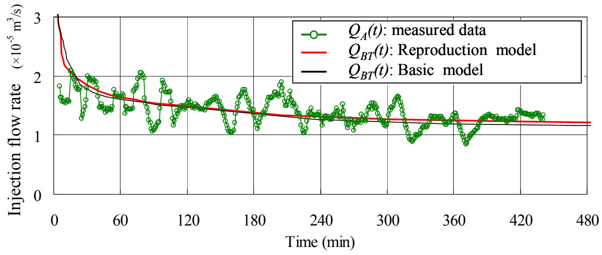
Table 5. Analysis physical properties

Item	Reproduction model	Basic model
Saturated hydraulic conductivity k_s (cm/s)	1.3×10^{-4}	1.3×10^{-4}
Specific storage S_s (cm^{-1})	1.0×10^{-7}	1.0×10^{-7}
Porosity n	0.48	0.20

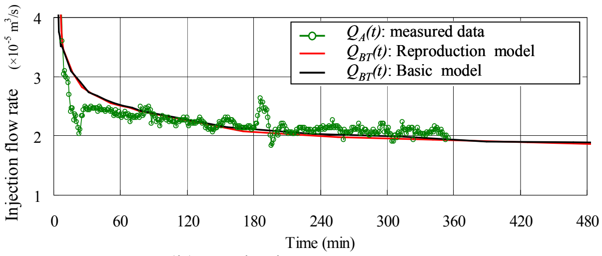
(4) Verification results

Fig. 10 shows the time history of the measured data $Q_A(t)$ and the fitting results $Q_{BT}(t)$ at each stage. It reveals that regardless of the unsaturated seepage characteristics, $Q_A(t)$ and $Q_{BT}(t)$ conform closely, and that the measured injection flow rate data can be reproduced relatively accurately.

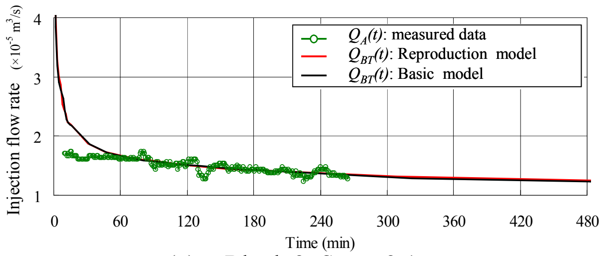
Table 6 summarizes the precision of the reproduction of the stable flow rate Q_{AS} based on the stable flow rate Q_{BTS}. When the reproduction model was used as the unsaturated seepage characteristics, the Q_{AS} reproduction precision ranged from 0.94 to 1.04, revealing that measured data can be reproduced with high precision. Even when the basic model was used as the unsaturated seepage characteristics, the reproduction precision of Q_{AS} was high at 0.92 to 1.04. Thus, this verification did not



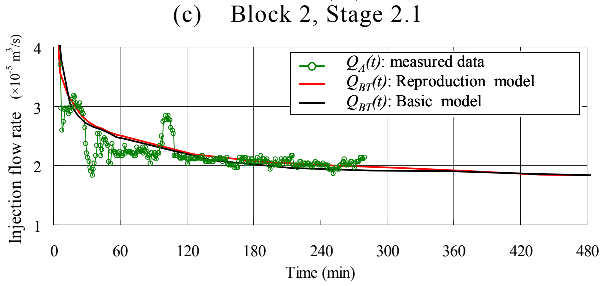
(a) Block 2, Stage 1.1



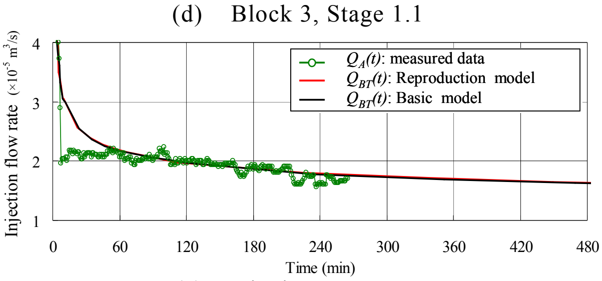
(b) Block 2, Stage 1.2



(c) Block 2, Stage 2.1



(d) Block 3, Stage 1.1



(e) Block 3, stage 2.1

Figure 10. Time history of injection flow rate

find any significant differences in reproducibility precision caused by differences in unsaturated seepage characteristics.

4. CONCLUSIONS

The following are the conclusions of this research.

(1) We investigated the effects of the analysis conditions in saturated-unsaturated seepage analysis that reproduced the long-term permeability test by changing the saturated hydraulic conductivity, effective injection pressure, and groundwater level.

(2) Based on the results, an estimation method for the measured stable flow rate was proposed. In this method, we use saturated-unsaturated seepage analysis and the measured data within a appropriate injection time.

(3) The proposed method was applied to long-term permeability test conducted at the left bank of the Taiho Saddle Dam. As a result, the reproduction precision of the stable flow rate was high, ranging from 0.92 to 1.04.

Table 6. Reproducibility precision of stable flow rate

Block		2	2	2	3	3
Stage		1.1	1.2	2.1	1.1	2.1
Reproduction model	Q_{AS}(m^3/s)	1.31×10^{-5}	2.06×10^{-5}	1.36×10^{-5}	1.70×10^{-5}	2.02×10^{-5}
	Q_{BTS}(m^3/s)	1.22×10^{-5}	1.97×10^{-5}	1.35×10^{-5}	1.78×10^{-5}	2.00×10^{-5}
	Q_{BTS}/Q_{AS}	0.94	0.96	0.99	1.04	0.99
Basic model	Q_{AS}(m^3/s)	1.31×10^{-5}	2.06×10^{-5}	1.36×10^{-5}	1.70×10^{-5}	2.02×10^{-5}
	Q_{BTS}(m^3/s)	1.20×10^{-5}	1.94×10^{-5}	1.35×10^{-5}	1.78×10^{-5}	1.97×10^{-5}
	Q_{BTS}/Q_{AS}	0.92	0.94	0.99	1.04	0.98

Q_{AS}: Measured stable flow rate
Q_{BTS}: Analysis stable flow rate

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