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# RATIONALIZATION OF GROUTING IN UNSATURATED SOFT ROCK FOUNDATION BASED ON RESULTS OF LONG-TERM PERMEABILITY TESTS

Yoshikazu YAMAGUCHI, Dr. Eng.
*Team Leader, Dam Structure Research Team, Hydraulic Engineering Research Group, Public Works Research Institute, Japan*

Hiroyuki SATOH
*Senior Researcher, Dam Structure Research Team, Hydraulic Engineering Research Group, Public Works Research Institute, Japan*

Kenji SHIMOYAMA
*Collaborating Researcher, Dam Structure Research Team, Hydraulic Engineering Research Group, Public Works Research Institute, Japan*

## 1. INTRODUCTION

In Japan, the permeability of dam foundations is generally evaluated by the Lugeon Water Test: a multi-stage constant pressure water injection test. The test is done by a unified method at dams throughout Japan, as stipulated by the “Guidelines for Lugeon Water Test” [1][2] in Japan. These technical guidelines were first enacted in June 1984 [1], then revised in July 2006 [2] in response to later technological progress. The revised guidelines are applicable to an extremely wide range of types of dam foundations, containing points concerning the execution of the test in soft rock foundations in addition to hard rock foundations as in the previous version.

In Japan, public works projects including dam construction projects now face a strong demand for project cost reduction and environmental conservation. It is, therefore, now necessary to construct dams on foundations which would formerly have been excavated, by first confirming the safety of each foundation based on the results of appropriate investigations and designs. Under such circumstances, at the higher elevation parts of the dam foundation where the load imposed by the dam body is relatively low, in many cases the foundation is either highly weathered soft rock or sedimentary soft rock. In such a foundation, it is generally difficult to improve the imperviousness by cement-based grouting. But on the other hand, in many cases, dominant water paths are not formed in soft rock foundations, and appropriate permeability tests generally reveal their low permeability [3][4]. And appropriate measures to be taken when performing a Lugeon Water Test in a low-strength soft rock foundation are presented in the revised version of the "Guidelines for Lugeon Water Test" [2] based on the results of previous studies. But, the guidelines do not refer to specific problems concerning unsteady seepage during the Lugeon Water Test and measures to appropriately evaluate the stable flow rate at each pressure stage in unsaturated soft rock foundation.

In this paper, problems evaluating the Lugeon value in the present Lugeon Water Test executed in an unsaturated soft rock foundation above the ground water surface as described above and measures which effectively resolve such problems have been clarified through long-term permeability tests at an actual dam site. At the same time, appropriate permeability evaluation methods have been discussed. In addition, the quantity of execution of dam foundation grouting has been lowered by appropriately evaluating permeability in soft rock foundations while considering the results of long-term permeability test results.

## 2. OUTLINE OF THE TEST SITE

### 2.1. OUTLINE OF THE TAIHO SUBDAM

The Taiho Dam is a multi-purpose dam constructed by the Okinawa General Bureau, the Cabinet Office, the Government of Japan, on the Taiho River on the Taiho River System in North-western Okinawa Prefecture. Because of topographical conditions at the site, the dam consists of two dams: a main dam with height of 77.5m constructed on the main channel of the Taiho River (concrete gravity dam) and a subdam with height of 66.0m which closes a low ridge upstream on the left bank side (rockfill dam). Table 1 shows the specifications of the main dam and the subdam.

A long-term permeability test was executed in curtain grouting holes (primary holes in BL2 and BL3) on the left bank rim of the Taiho Subdam.

## 2.2. GEOLOGICAL PROPERTIES AT THE TAIHO SUBDAM

The geology at the Taiho Subdam site is Nago Formation (Shimanto terrane), Neogene Tertiary System covered with Quaternary terrace deposits. The Nago Formation is, as shown in the geological section along the subdam axis in Fig. 1, mainly phyllite partially enclosing thin strata of tuff.

Table 1
Specifications of the Taiho Dam

| Dam specifications | Main dam | Subdam |
|---|---|---|
| Type | Concrete gravity | Rockfill |
| Height of dam | 77.5m | 66.0m |
| Dam crest length | 380m | 445m |
| Dam body volume | 500,000m$^3$ | 1,790,000m$^3$ |
| Normal water level (N.W.L.) | EL.68.0m | |
| Surcharge water level (S.W.L.) | EL.70.6m | |

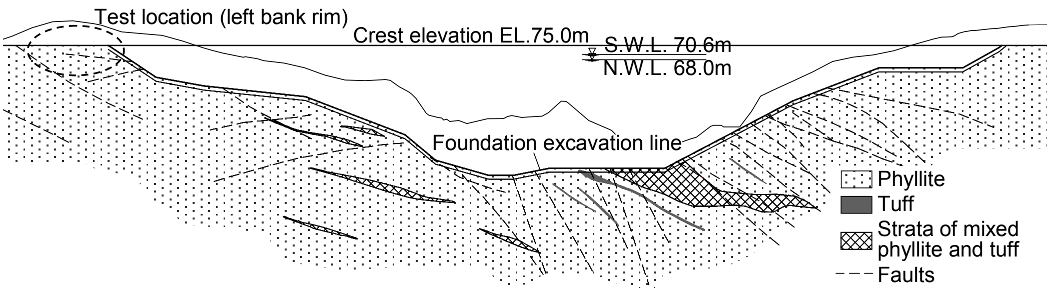


Fig. 1
Geological section along the Taiho Subdam axis

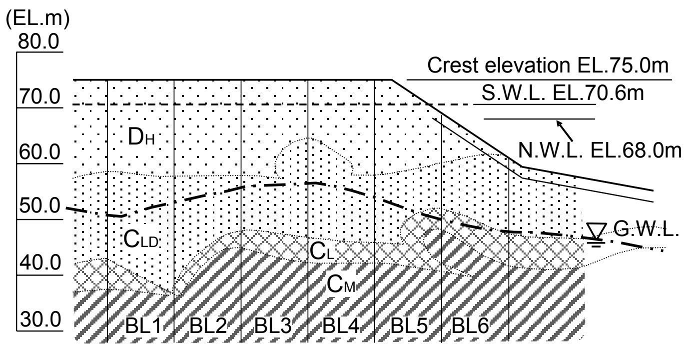


Fig. 2
Rock classification at the left bank rim of the Taiho Subdam

As shown in Fig. 2, on the left bank rim at the Taiho Subdam, $D_H$ class bedrock is distributed from EL. 75.0m (crest elevation) to near the EL. 58.0m (thickness of about 17m), and a long-term permeability test was conducted in this $D_H$ class bedrock. Deeper than this, $C_{LD}$, $C_L$, and $C_M$ class bedrocks are distributed.

Characteristics of the $D_H$ class bedrock are bedrock featuring overall advanced weathering, in homogeneous porous medium condition, and judged to have a Lugeon value of less than approximately 10Lu.

The ground water level at the left bank rim of the subdam is stable at around EL. 55.0m, so it is assumed that the $D_H$ class bedrock is a zone which is unsaturated overall, as shown in Fig. 2.

## 3. LONG-TERM PERMEABILITY TEST

### 3.1. PURPOSE OF PERFORMING THE LONG-TERM PERMEABILITY TEST

A Lugeon Water Test accompanied by a borehole hydrostatic permeability test (hereinafter referred to as "a Borehole Hydrostatic Permeability Test") was conducted in the unsaturated $D_H$ class bedrock distributed at the left bank rim of the Taiho Subdam. A borehole hydrostatic permeability test is a field permeability test performed by regulating the water level inside the injection pipe and controlling the pressure inside the test section by the water level differential. Therefore, this method permits the setting of the effective pressure at a low level by performing fine control of the height of the water column inside the injection pipe under low ground water level conditions, and is a test method suitable for soft rock foundations such as $D_H$ class bedrock where a low critical pressure is predicted.

In the test section where the Borehole Hydrostatic Permeability Test was conducted, six test boreholes (pilot holes of curtain grouting holes in BL1 to BL6) were formed as shown in Fig. 3, in the $D_H$ class bedrock below the surcharge water level (S.W.L. = EL. 70.60m), and a total of 26 stages were carried out.

The test section lengths (stage lengths) are usually 5.0m per stage, but in order to increase the precision of the permeability evaluation at this dam site, each stage was set at length of 2.5m: half of the normal length. A borehole water pressure sensor which measures the effective injection pressure was installed in the center of each stage, and the maximum values of the effective injection pressure were 0.3MPa at stage 1.1 and stage 1.2, 0.4MPa at stage 2.1 and stage 2.2, and 0.5MPa at stage 3.1. And considering that the test was in $D_H$ class bedrock, the pressure steps of the effective injection pressure were finely set at steps of 0.04MPa.

The drilling was done by the air bubble boring method so that fine particles of the $D_H$ class bedrock would not flow out. The injection pump was a low pulsation type pump.

According to the Borehole Hydrostatic Permeability Test, approximately 65% (17/26) of the relationship of the effective injection pressure P and the unit injection flow rate Q (P-Q curve) showed the "permeability decreasing type (hysteresis loop type)": as the pressure steps advances, the unit injection quantity per effective injection pressure falls and the injection flow rate differs at the pressure increasing step and pressure decreasing step. Fig. 4 shows a P-Q curve at stage 2.2 at BL3 as an example of a P-Q curve which displays this phenomenon. It confirmed that in the time history of the pressure increase process of the effective injection pressure and unit injection

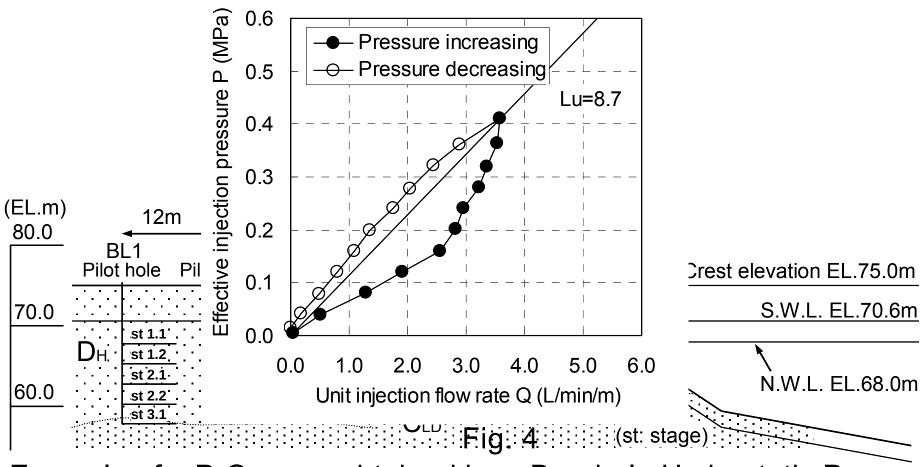


Fig. 4
Example of a P-Q curve obtained by a Borehole Hydrostatic Permeability Test (Stage 2.2 at BL3)

Fig. 3
Lugeon Water Test locations (Pilot holes, $D_H$ class bedrock)

flow rate in the same stage (P, Q-t figure), there is an unsteady seepage tendency: the quantity injected at each pressure step falls as shown in Fig. 5. The major cause is assumed to be the fact that at each pressure step during the increase of the pressure, a shift to the next pressure step occurred before the flow of water from the test section became steady.

The Lugeon values of $D_H$ class bedrock from BL1 to BL6 are, as shown in Fig. 6, distributed from 5 to 15Lu, and generally assessed as around 10Lu. But, because many data determined to be unsteady seepage were confirmed, a long-term permeability test in the $D_H$ class bedrock on the left bank rim of the subdam was carried out as a permeability test under steady seepage state.

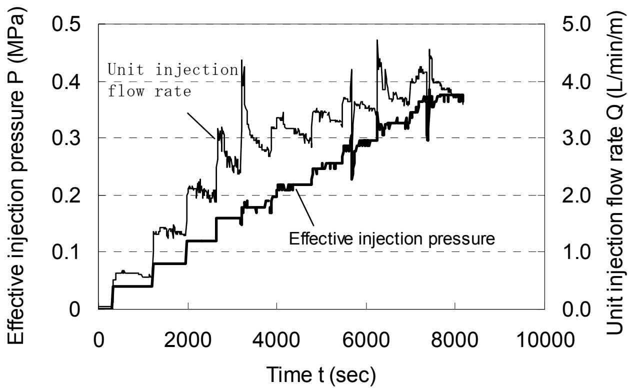


Fig. 5
Example of time history of the pressure increase process of the effective injection pressure and unit injection flow rate obtained by a Borehole Hydrostatic Permeability Test (Stage 2.2 at BL3)

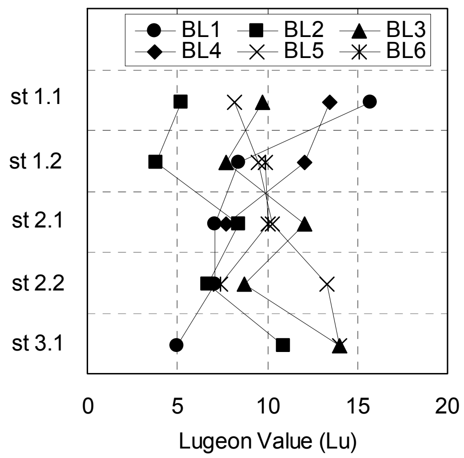


Fig. 6
Lugeon value distribution obtained by a Lugeon Water Test accompanied by a borehole hydrostatic permeability test ($D_H$ class bedrock)

### 3.2. LONG-TERM PERMEABILITY TEST METHOD

A long-term permeability test was carried out to clarify the precise permeability under steady seepage state in $D_H$ class bedrock in an unsaturated zone distributed at the left bank rim of the Taiho Subdam. Table 2 shows the specifications of the long-term permeability test. The test locations are shown in Fig. 7, and an outline of the long-term permeability test method is shown in Fig. 8.

In the test section where the long-term permeability test was conducted, two boreholes (primary holes of curtain grouting holes at BL2 and BL3) were drilled in the $D_H$ class bedrock below surcharge water level (S.W.L. = EL. 70.60m). The borehole diameter was set at 66mm, the test section length at 2.5m as it was in the Borehole Hydrostatic Permeability Test method executed at the pilot holes, and a total of 10 stages at both holes from stage 1.1 to stage 3.1 were prepared. The constant water head tank was installed near the

Table 2
Long-term permeability test specifications

| Item | Specification |
|---|---|
| Borehole diameter | φ66mm |
| Stage length | 2.5m |
| Constant water head *) | EL.78.20m |
| BL2 test hole **) | Stages 1.1 to 3.1 |
| BL3 test hole **) | Stages 1.1 to 3.1 |
| Injection flow rate measurement | 1 minute intervals |
| Measurement time | Min. 4 hours |

*) Constant water head tank is installed near the borehole to maintain a constant water level for injection.
**) Executed at the primary holes of the curtain grouting holes (total of 10 stages).

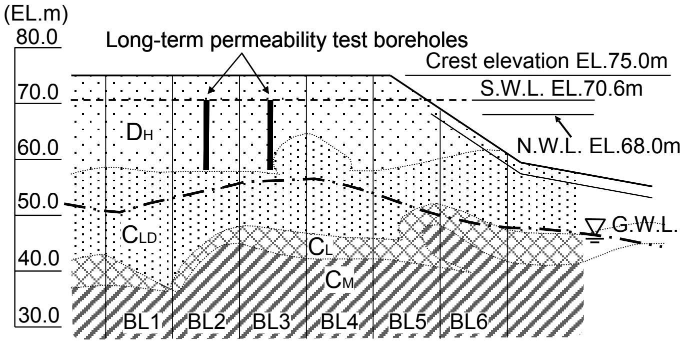


Fig. 7
Long-term permeability test locations

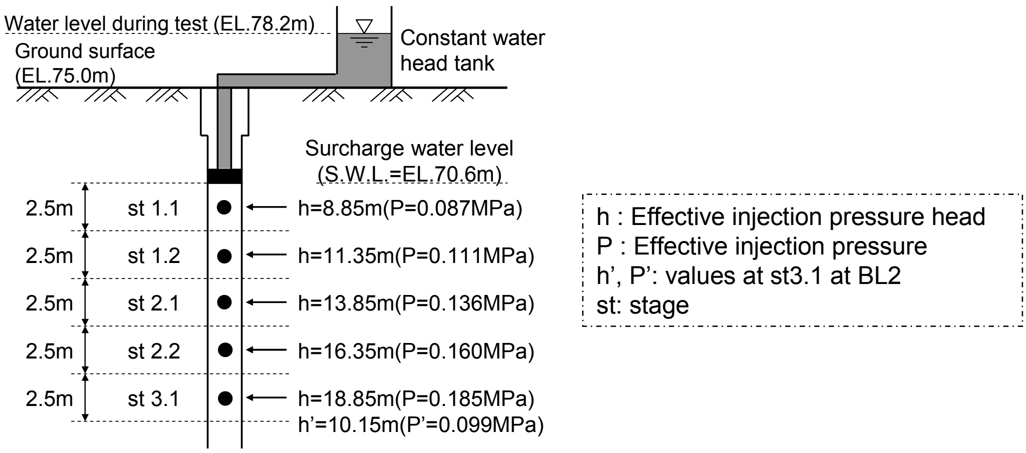


Fig. 8
Outline of the long-term permeability test method

boreholes, injecting water at a constant water head (EL. 78.20m). The injection flow rate was measured at 1 minute intervals for a minimum of 4 hours. The "Guidelines for Lugeon Water Test" [1][2] stipulates, "range of fluctuation of the 5-minute injection flow rate is an average ±10%" as the criteria for stable (steady) flow rate. But in this case, it was decided that the injection flow rate was stabilized by simultaneously satisfying the two standards shown below, in order to more reliably obtain a stable (steady) flow rate. The stable flow rate was assumed to be the average injection flow rate for an additional 5 minutes after a steady flow judgment.

(a) The 5 minute average injection flow rate is shifted each time by 1 minute which is the measurement interval, to calculate the 5-minute moving average injection flow rate Q, confirming that the difference between a certain 5-minute moving average injection flow rate $Q_1$ and the previous 5 minute moving average injection flow rate $Q_2$ is within ±10% of $Q_2$.

(b) It is confirmed that the range of fluctuation of the 5-minute injection flow rate is within an average of ±0.2L/min/st.

### 3.3. Test method of the water pressure test performed after the long-term permeability test

At the primary holes of BL2 and BL3 at the left bank rim of the Taiho Subdam where the long-term permeability test was carried out, the long-term permeability test execution was followed by a water pressure test, which is a simplified Lugeon Water Test [6], in order to perform a comparative verification at the same stage (total of 8 stages at both holes from stage 1.2 to stage 3.1). Table 3 summarizes the

Table 3
Water pressure test specifications

| Item | Specification |
|---|---|
| Borehole diameter | φ66mm |
| Stage length | 2.5m |
| BL2 test hole *) | Stages 1.2 to 3.1 |
| BL3 test hole *) | Stages 1.2 to 3.1 |
| Max. injection rate from stages 1.2 to 2.2 | 2L/min/m |
| Max. injection rate at stage 3.1 | 3L/min/m |
| Max. injection pressure at stage1.2** ) | 0.3MPa |
| Max. injection pressure at stages 2.1 and 2.2** ) | 0.4MPa |
| Max. injection pressure at stage 3.1** ) | 0.5MPa |
| Injection flow rate measurement | 10 second intervals |
| Pressure steps at stage 1.2 | 4 steps |
| Pressure steps from stages 2.1 to 3.1 | 3 steps |

*) Executed at the primary holes of the curtain grouting holes. (total of 8 stages)
**) Injection pressure measured at the gauge that is set up at the top of borehole.

specifications of the water pressure test.

Turning to the stable flow rate judgment for the water pressure test, assuming that the permeability of the foundation which was tested by the water pressure test is relatively low and the injection flow rate is small from the early stage, it would be highly possible that a long period of time would elapse until the flow rate was judged to be stable under the criterion, “range of fluctuation of the 5 minute injection flow rate is an average ±10%” stipulated in the “Guidelines for Lugeon Water Test” [1][2]. Therefore, as the stable flow rate judgment criterion at each pressure step, the criterion, “range of fluctuation of the 5 minute injection flow rate is within an average ±0.2L/min/st” was adopted, and the stable flow rate was assumed to be the average flow rate in the final minute of the five minute extended period after this criterion was satisfied.

The Lugeon value obtained by the water pressure test was calculated as the equivalent Lugeon value ($Lu_{WPT}$) as shown in Fig. 9.

# 4. PERMEABILITY EVALUATION BASED ON THE LONG-TERM PERMEABILITY TEST

## 4.1. DETAILED EVALUATION OF TEST RESULTS

### *4.1.1. Change over time of injection flow rate*

The change over time of the injection flow rate in the long-term permeability test was confirmed to be an unsteady seepage trend marked by a gradual decline of the injection flow rate over time at all stages. Fig. 10 shows change over time of the injection flow rate at stage 2.1 of BL2 as an example. The dashed lines in the figure

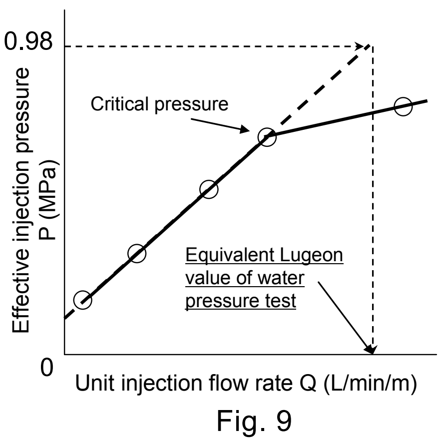


Fig. 9
Lugeon value conversion method in water pressure test

represent on-site measured data (injection flow rate at 1 minute intervals) and the solid lines represent 10 minute moving average data obtained by smoothing the scattering of on-site measured data to a certain degree. And in the on-site measurement (injection flow rate at 1 minute intervals) data for stage 2.1 at BL2, wide fluctuation of the injection flow rate at the initial step is seen, but this is assumed to be a result of adding the quantity injected at the initial part of the test to fill the borehole, so the first 5 minutes data were not considered in calculating the 10 minute moving average data.

### *4.1.2. Change over time of Lugeon value*

Because the long-term permeability test is a 1 pressure step Lugeon Water Test, the equivalent Lugeon value was calculated by solving Eq.[1] based on the average unit injection flow rate value Q for the final 5 minutes at which stability of the effective injection pressure P and injection flow rate at each stage were confirmed.

$$Lu_{\mathrm{LPT}}=(Q/P)\times 0.98 \qquad [1]$$

Where, $Lu_{\mathrm{LPT}}$ is equivalent Lugeon value based on long-term permeability test, $P$ is effective injection pressure (MPa), and $Q$ is unit injection flow rate (L/min/m).

Fig. 11 shows change over time of the equivalent Lugeon value calculated based on the 5-minute average injection flow rate at each stage. This figure shows the unsteady seepage trend - the injection flow rate falling over time beginning at the start of the test in all stages - but it is confirmed to be approximately the same as the stable flow rate after about 30 minutes have passed.

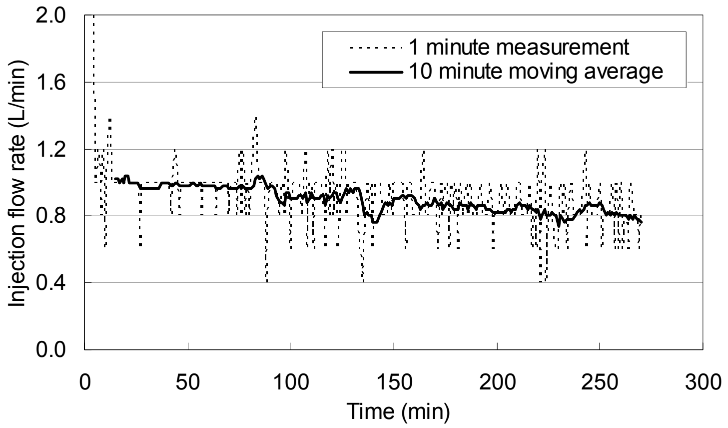


Fig. 10
Change over time of injection flow rate (Stage 2.1 at BL2)

4.2. COMPARATIVE VERIFICATION OF TEST RESULTS

Fig. 12 shows the relationship between the equivalent Lugeon value of the long-term permeability test ($Lu_{LPT}$) with the equivalent Lugeon value of the water pressure test ($Lu_{WPT}$). The equivalent Lugeon value of the long-term permeability test ($Lu_{LPT}$) was 5Lu or less at all stages. If the equivalent Lugeon value of the long-term permeability test ($Lu_{LPT}$) is evaluated at a lower value than the equivalent Lugeon value of the water pressure test ($Lu_{WPT}$), is generally in the range α (=$Lu_{LPT}$/$Lu_{WPT}$) = 0.1 to 0.5, and $Lu_{WPT}$ is lower than

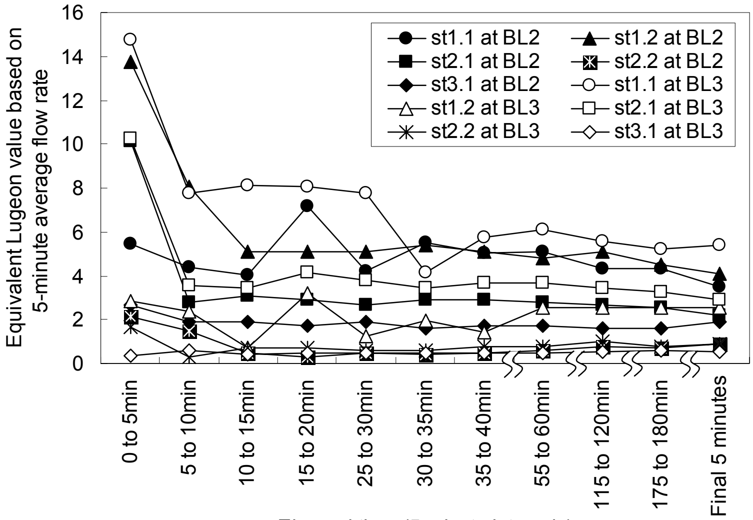


Fig. 11
Change over time of Lugeon value

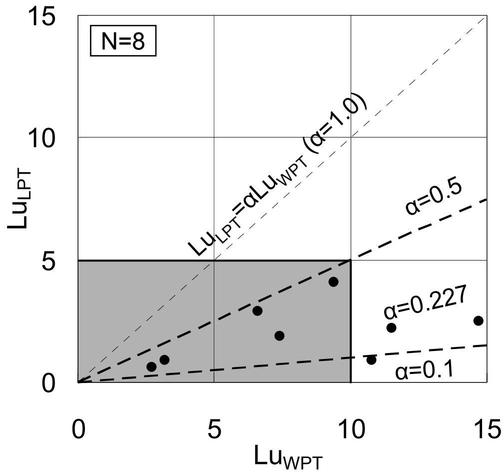


Fig. 12
Comparison of Lugeon values

approximately 10Lu, $Lu_{LPT}$ which is assumed to be a more appropriate permeability index can be assessed at 5Lu or less. Fig. 13 shows the P-Q curve figure and the equivalent Lugeon value of the water pressure test and the long-term permeability test at stage 1.2 of BL2 as an example.

This means that if a long-term permeability test is carried out in a foundation such as unsaturated weathered soft bedrock which is predicted to be severely affected by unsteady seepage and to have a low critical pressure, it will be possible to perform accurate permeability evaluations under steady seepage conditions, permitting the prevention of over-evaluations of Lugeon values. Consequently, performing a long-term permeability test can be counted on to reduce the range of foundation grouting and lower the number of grout injection holes.

But because the geological conditions and test specifications (injection time, judgments of stable flow rate time, etc.) vary between dam sites, the Lugeon value reduction rate based on a long-term permeability test must be verified for each site.

## 5. REFLECTION OF THE LONG-TERM PERMEABILITY TEST RESULTS IN THE DAM FOUNDATION GROUTING

Fig. 12 in the previous section shows that if the equivalent Lugeon value based on a water pressure test, $Lu_{WPT}$, is 10Lu or lower in $D_H$ class bedrock, $Lu_{LPT}$ which is assumed to be a more appropriate permeability index can be assessed as 5Lu or less. Taking advantage

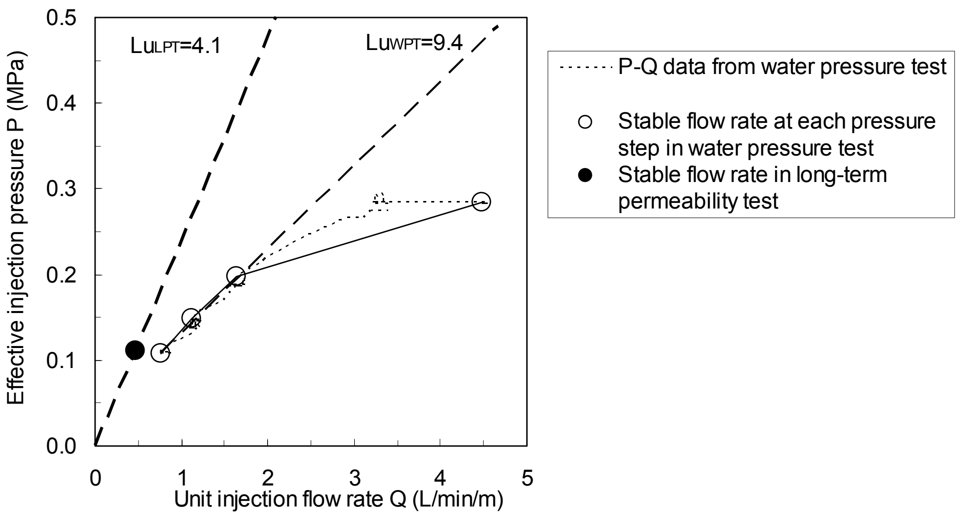


Fig. 13
Example of P-Q curve (Stage 1.2 at BL2)

of this fact to estimate the effectiveness of a long-term permeability test based on the results of a water pressure test in BL2 to BL6 on the left bank which includes $D_H$ class bedrock within the imperviousness improvement range appropriately evaluated the permeability of the $D_H$ class bedrock, reducing foundation grouting work. At this time, the improvement target value for the object foundation is 5Lu.

And from BL4 to BL6, the specifications of the water pressure test were changed from the specifications mentioned above, so the verification was performed accompanied by a separate long-term permeability test, and the appropriate permeability was evaluated based on the same method.

Fig. 14 shows the permeability evaluation results for the target stages. Of the 53 target stages, the value exceeded the target improvement value of 5Lu at 33 stages (62%), but at most of these, specifically at 29 stages, it was lower than 10Lu, so it was possible to evaluate the value as 5Lu or lower at 49 of the 53 stages. The results permitted the sharp reduction of the work of executing supplementary injection holes, and contributed to the cost reduction of foundation grouting at the Taiho Subdam. At stage 2 at BL6 where supplementary injection holes were drilled, long-term permeability tests in the supplementary injection holes confirmed that the target improvement values were satisfied.

## 6. CONCLUSIONS

To conduct this research, at the site of an actual dam (Taiho

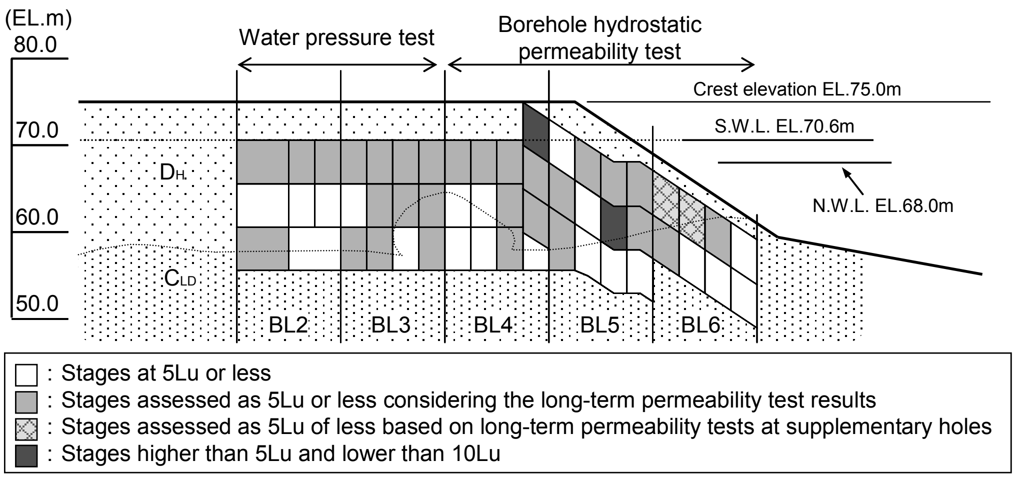


Fig. 14
Results of permeability evaluations at the stages investigated

Subdam), a long-term permeability test was carried out in an unsaturated soft rock foundation to estimate its permeability with improved accuracy. A normal water pressure test was also carried out after the long-term permeability test at the same location, to compare the permeability values (Lugeon values) obtained by the two tests. And permeability of $D_H$ class bedrock was appropriately evaluated based on the results obtained from the test, reducing the quantity of foundation grouting works.

The research has obtained the following conclusions.

(1) The equivalent Lugeon value of the long-term permeability test at the Taiho Subdam ($Lu_{LPT}$) was assessed as lower than the equivalent Lugeon value of the water pressure test ($Lu_{WPT}$), and the rate based on the equivalent Lugeon value was within a range of approximately α (=$Lu_{LPT}$ / $Lu_{WPT}$ ) = 0.1 to 0.5.

(2) If a long-term permeability test is carried out in dam foundation ground such as weathered soft bedrock in an unsaturated zone which is predicted to be severely impacted by unsteady seepage and to have a low critical pressure, it will be possible to perform accurate foundation permeability assessments under steady seepage conditions, preventing over-evaluations of Lugeon values.

(3) Appropriately assessing the permeability of $D_H$ class bedrock based on results obtained by a long-term permeability test can cut the number of grouting injection boreholes in this foundation.

A long-term permeability test is a permeability test which assesses permeability with the area around the borehole adequately saturated and stabilized (in steady seepage state), and the test itself is time-consuming, so it is time-consuming and uneconomical to perform it for many stages on-site. Besides, because geological conditions vary between sites, it is impossible to uniformly set the test time. In the future, we intend to continue the research encompassing these challenges, and conduct studies to propose a method of selecting the representative locations based on the geological state of each site, or a method of evaluating the steady flow rate based on unsteady seepage trends, and establish a rational method of evaluating the permeability of unsaturated soft bedrock.

## ACKNOWLEDGMENTS

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SUMMARY

Permeability of dam foundations is generally investigated by the Lugeon Water Test (LWT). The LWT is conducted according to the “Guidelines for Lugeon Water Tests” in Japan. But, these guidelines do not concretely describe the problems concerning unsteady seepage during the LWTs in unsaturated soft rock foundations for dams and an appropriate method of evaluating Lugeon values considering these problems.

In this study, long-term permeability tests were performed at a dam site composed of weathered soft rocks. In addition, we investigated an appropriate permeability evaluation method based on the above field test method. As a result, the Lugeon value evaluated by long-term permeability tests ($Lu_{LPT}$) is found to be smaller than that evaluated by general permeability tests ($Lu_{WPT}$). Furthermore, we can reduce the amount of dam foundation grouting by appropriately evaluating the permeability of dam foundations based on the results of the long-term permeability tests.

KEY WORDS

dam foundation
soft rock
Lugeon water test
long-term permeability test
unsteady seepage
grouting
cost reduction