

WATER PROBLEMS IN SOFT ROCK FOUNDATIONS FOR DAMS

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by

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Abstract:

We summarize problems of soft rock foundations, give results of permeability tests, seepage failure tests and measurements of groundwater pressure distribution, and show countermeasures against them. We also propose a rational method of seepage control for soft rock foundations, considering interaction between stress and permeability.

Keywords: soft rocks, dam, permeability, seepage failure, groundwater pressure, seepage control.

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1. INTRODUCTION

Most good damsites in Japan have already been developed. Many remaining damsites have soft rock foundations, such as sedimentary rock of the Neogene period, volcanic deposit of the Quaternary period and weathered granite. The number of dams constructed on soft rock foundations is likely to increase; compared to hard rocks of previous damsites, soft rocks have low strength and large deformability. Furthermore, the large seepage force applied to dam foundation from the reservoir, causes many water problems for soft rock foundations. We describe in this technical paper the following:

- ① Appropriate testing method for permeability of soft rock foundations with low strength, and interpretation of the results.
- ② Seepage failure potential and testing method of soft rock foundations.
- ③ Rational method of measuring complicated groundwater pressure distributions and examples of observed data.
- ④ Seepage control methods for soft rock foundations.

2. INVESTIGATION OF PERMEABILITY

2.1 Overview

There are two in-situ permeability tests for foundations: the "Bore Hole Permeability Test (BHP Test)" to survey local permeability with one borehole, and the "Pumping Test (P Test)" to measure the average permeability of a relatively large region with plural boreholes and/or wells. Even if the average permeability of an area is not high to control seepage, it is necessary to treat the foundations properly where local permeability is high. The permeability in the depths of the foundation must also be surveyed. BHP tests are therefore mainly used to investigate permeability of dam foundations. The most popular of the many BHP tests for dam foundations is the Lugeon water test (LW Test), developed by M. Lugeon in 1933¹⁾. In this chapter, we show the LW test method and a few examples of LW tests performed in soft rock foundations.

2.2 Lugeon water tests

(1) Testing procedure

After digging a borehole in the foundation, we expand the packer to form a test section for the LW test and inject water at several constant pressures (see Fig. 1). We calculate Lugeon value using the observed effective pressure p (kgf/cm²) and rate of water injection q (ℓ/min/m).

(2) Analyses of Lugeon water tests

(a) Effective pressure

Effective pressure, as shown in the Japanese technical guide for LW test²⁾, is calculated by correcting the gauge pressure for hydrostatic pressure, groundwater pressure and head loss due to resistance in the injection pipe (see Fig. 1). The following formulae are used according to the location of the groundwater level^{3)~5)}.

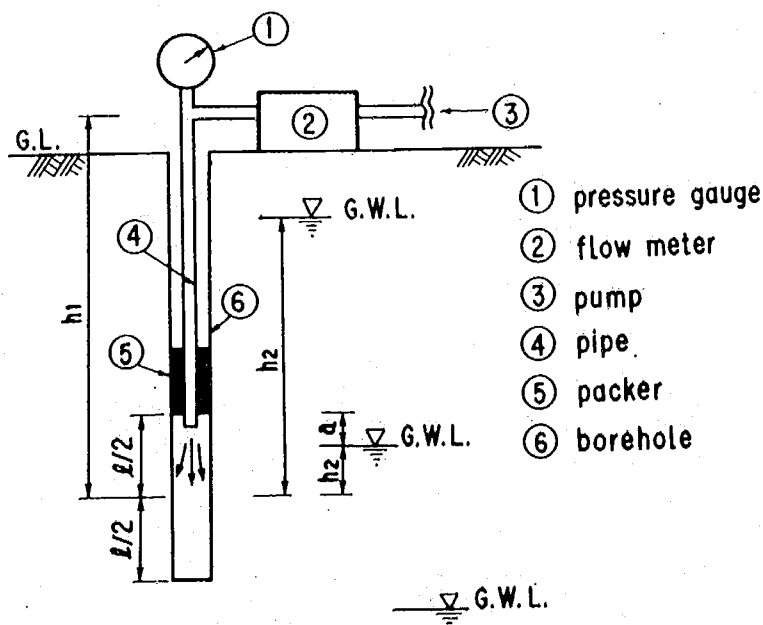


Fig. 1 Schematic view of Lugeon water test.

① Below groundwater table

$$p = p_0 + \gamma_w(h_1 - h_2 - h_3) \text{ (kgf/cm}^2\text{)} \dots\dots\dots (1)$$

where, p = effective pressure (kgf/cm²),

p_0 = gauge pressure (kgf/cm²),

h_1 = difference in elevation between pressure gauge and center of test section (m),

h_2 = groundwater head at center of test section (m),

h_3 = head loss due to resistance in pipe (m),

γ_w = unit weight of water (lbf/m³ = 0.1 kgf/cm²/m).

Head loss h_3 is derived from the following equation:

$$h_3 = \alpha Q^2 L \dots\dots\dots (2)$$

where, Q is the rate of water injection (ℓ/min) and L is the length from the pressure gauge installed on the ground surface to the test section. The constant α should be determined by the test. If this is not done, α is assumed to be 7×10^{-5} (min²/ℓ) approximately²⁾.

② Above groundwater table

$$p = p_0 + \gamma_w(h_1 - h_3) \text{ (kgf/cm}^2\text{)} \dots\dots\dots (3)$$

③ Other conditions

$$p = p_0 + \gamma \left\{ (h_1 - h_2 - \frac{a^2}{2\ell}) - h_3 \right\} \text{ (kgf/cm}^2\text{)} \dots\dots\dots (4)$$

$$a = \frac{\ell}{2} - h_2 \quad (0 \leq a \leq \ell)$$

(b) Determining the Lugeon value

Using the results of LW tests for the relationship between effective pressure p (kgf/cm²) and rate of water injection for 1 meter of test section for 1 minute q (ℓ/min/m), a p - q curve is drawn as shown in Fig. 2. After confirming the proportional relation between p and q , we determine the Lugeon value (L_u) as the rate of water injection at a pressure of 10 kgf/cm². However, if the rate of water injection suddenly increases at a critical pressure per below 10 kgf/cm² as illustrated in Fig. 3, then the Lugeon value corresponding to 10 kgf/cm² is derived from the linear relation between the rate of water injection and pressure below the critical pressure. This value is the equivalent Lugeon value (L_u').

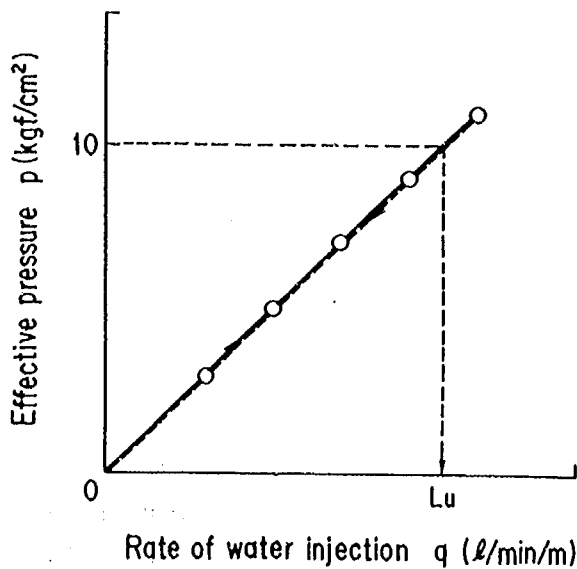


Fig. 2 p-q curve.

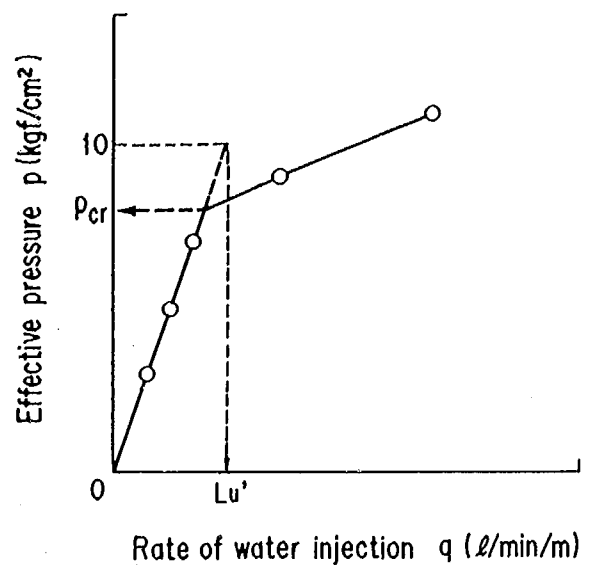


Fig. 3 p-q curve with critical pressure.

2.3 Examples of Lugeon water tests in soft rock foundations

Since the LW test was originally developed as an in-situ permeability test for hard rock foundations for dams, a high injection pressure was used. If we conduct LW tests in soft rock foundations with the same method, many problems arise. We describe the problems and give examples of LW tests performed in soft rock foundations.

(1) Tests in shallow soft rock foundations

Since soft rocks have low strength and the shallow part of soft rock foundations has a small overburden loading, the LW tests conducted at high water pressures would break the foundations even at the lowest test pressure, and permeability would be overestimated. We have seen many such cases. One example follows.

Two kinds of LW test were performed in alternating beds of sandstone and mudstone of the Miocene, at K Dam site. One LW test used a pump with a high pulsatory motion (referred to as the conventional method), the other LW test used a pump with a large capacity air chamber to control pulsatory motion and low injection pressures accurately (referred to as the accurate method). Test results under similar conditions are illustrated in Fig. 4^{2),3)}. In the p-q curve with the conventional method, there is no abrupt point of discharge increase; the calculated Lugeon value Lu' is approximately 30. However, in the p-q curve with the accurate method, the point p_{cr} is very clear and the Lugeon value calculated from the linear part of p-q curve below p_{cr} is 1.4. Other in-situ permeability test with a pit were made under the same geological conditions in the exploratory adit and the calculated coefficient of permeability was 3.2×10^{-5} cm/s ($1.0Lu = 1.0 \times 10^{-5}$ cm/s). This result approximately coincides with the accurate result.

In soft rock foundations, therefore, LW tests should be performed by controlling the injection pressure accurately, typically installing a large capacity air chamber to injection pump,

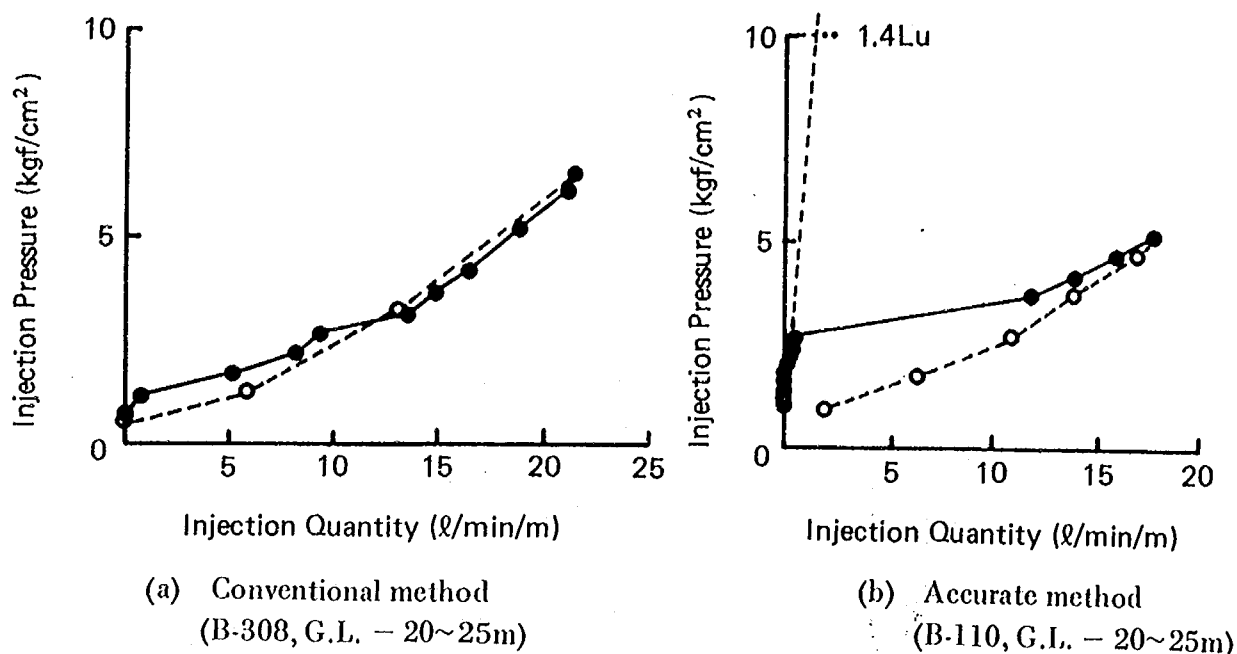


Fig. 4 Results of Lugeon water tests at K DAM.

and applying pressure utilizing the hydrostatic pressure. Other in-situ permeability tests based on Darcy's law should also be conducted to verify the accuracy of the LW tests^{6),7)}.

(2) Tests in deep soft rock foundations

Even when LW tests are conducted in a deep part of soft rock foundations, when the groundwater level is very deep, the water pressure applied to the soft rock foundation around the test section will be high, just by filling the injection pipe with water. This may break the foundation and permeability might be overestimated. The left bank of O Dam mainly comprises mudstone, tuff breccia and tuff, the Miocene of the Neogene period. Two adjacent boreholes, B-22 and B-62-24, were dug at this site for LW tests. In borehole B-22, we performed LW tests while controlling the injection pressure at the ground surface. In borehole B-62-24, we conducted LW tests while adjusting the water level in the hole to be at the lower range of the effective water pressure (see Fig. 5)⁸⁾. Test results are given in Fig. 6. These figures lead to the following:

- ① Water levels in boreholes tend to become deeper as boreholes become longer. Finally stable water levels, which are assumed to be groundwater levels, exist in deep boreholes.
- ② Lugeon values in B-22 are very large except for the deeper part, at 60 to 70 m below ground surface. Critical pressure could not be clearly determined.
- ③ Lugeon values in B-62-24 are relatively small except for one stage. Since we could perform LW tests at low effective pressures, we could recognize the critical pressure for all testing sections. The result was that LW tests should be performed by arranging the water level in testing holes when groundwater level in soft rock foundations is very deep. It is necessary to survey the causes of low groundwater level.

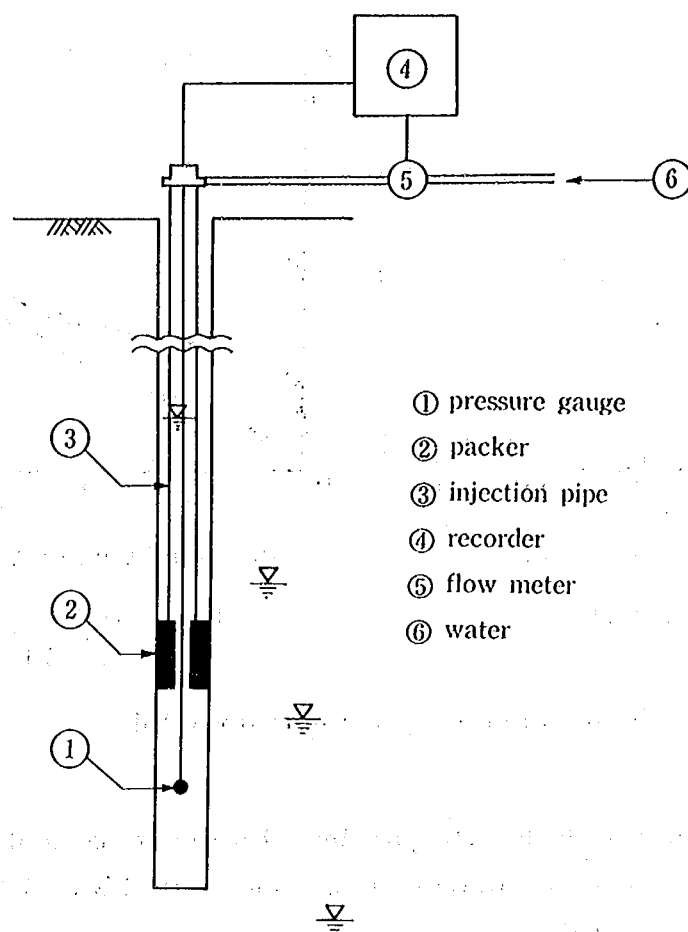


Fig. 5 Schematic view of hydrostatic permeability test.

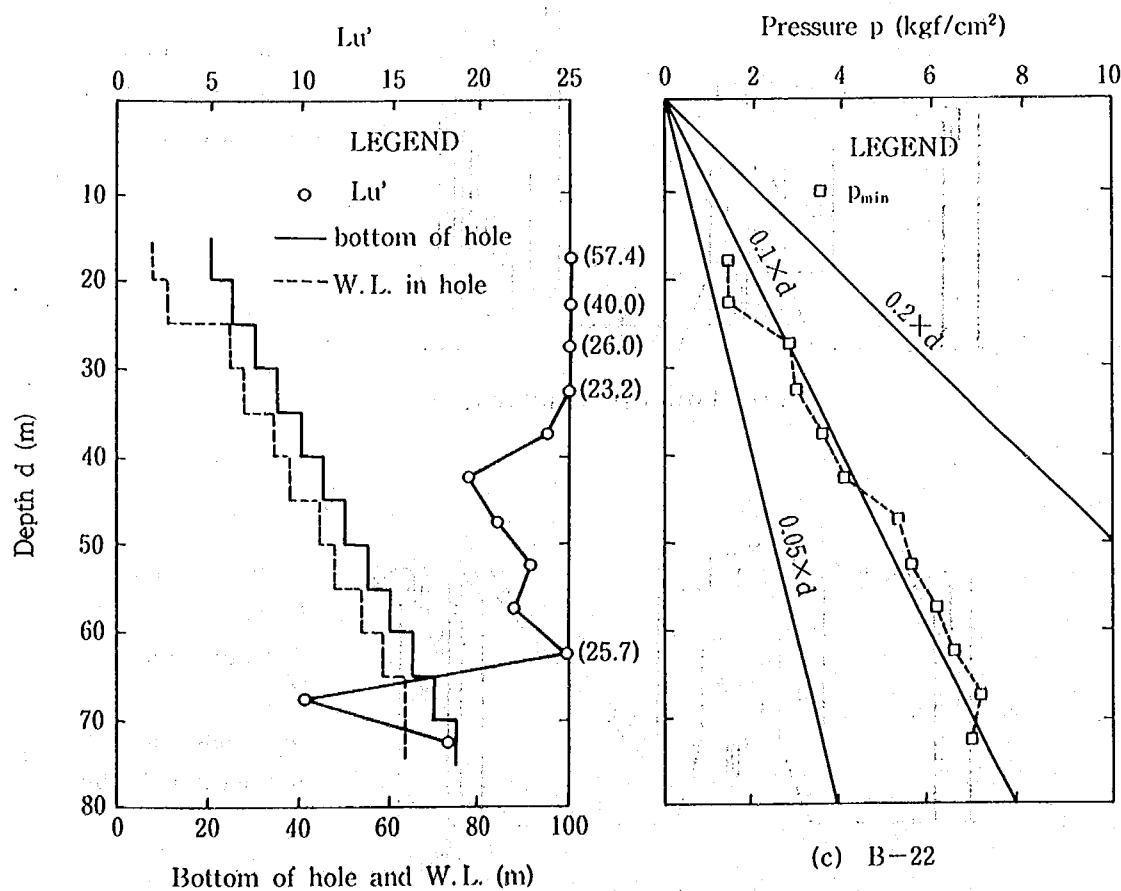
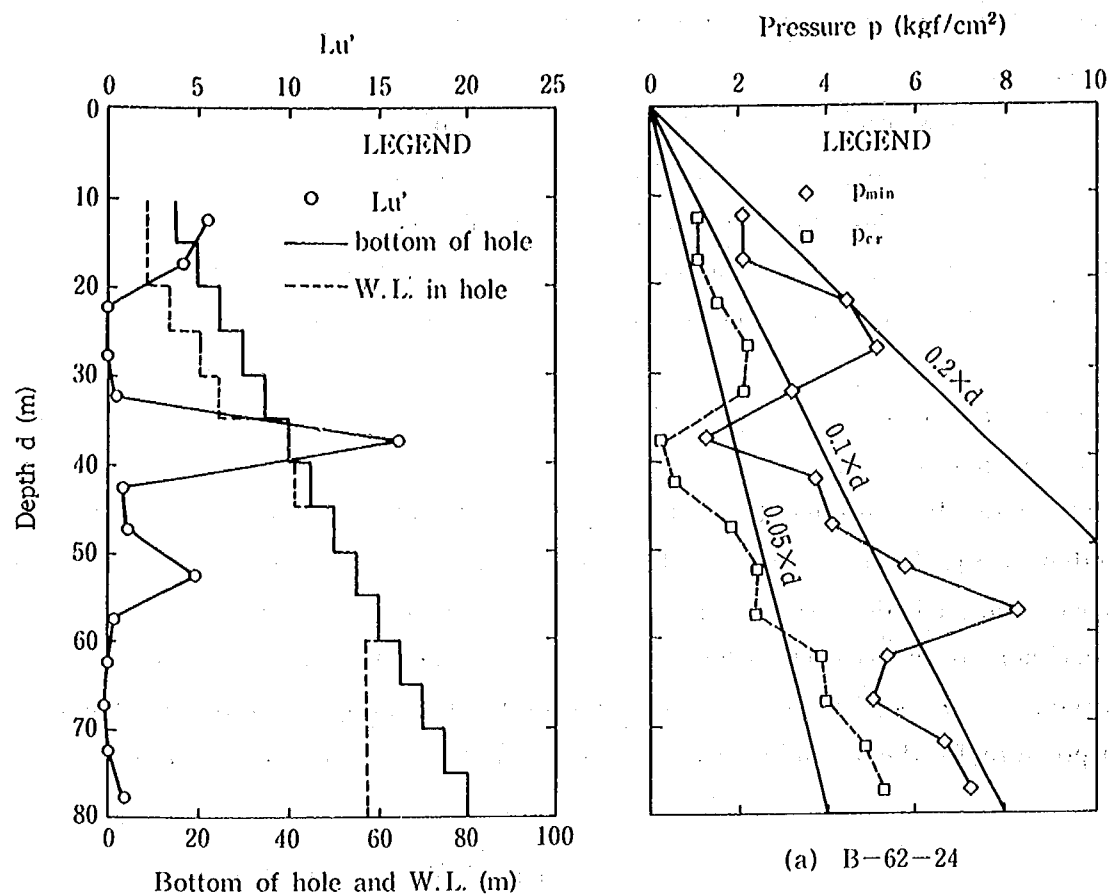


Fig. 6 Results of Lugeon water tests at O Dam.

3. INVESTIGATION OF SEEPAGE FAILURE POTENTIAL

3.1 Overview

The many I/W tests shown in Chapter 2 reveal that most soft rock foundations for dams have comparatively low permeability. However, since soft rock foundations generally have low strength, seepage failures of foundations due to the large seepage force from the reservoir should be investigated. In this chapter, we select piping failure as one type of seepage failure and show the results of studies on laboratory and in-situ piping tests.

3.2 Laboratory tests⁹⁾

(1) Testing methods

We do not have testing standards for piping tests yet. However, the testing equipments illustrated in Fig. 7 were generally used for previous works. We injected water from the bottom of a specimen, gradually increasing pressure, and measured the hydraulic gradient at failure of the specimen as the critical hydraulic gradient i_{cr} . For the low water pressure range test (approximately 0.2 kgf/cm^2 or less) the water level in a standpipe is controlled by applying low water pressure; for the test in high water pressure range test, an air compressor is used.

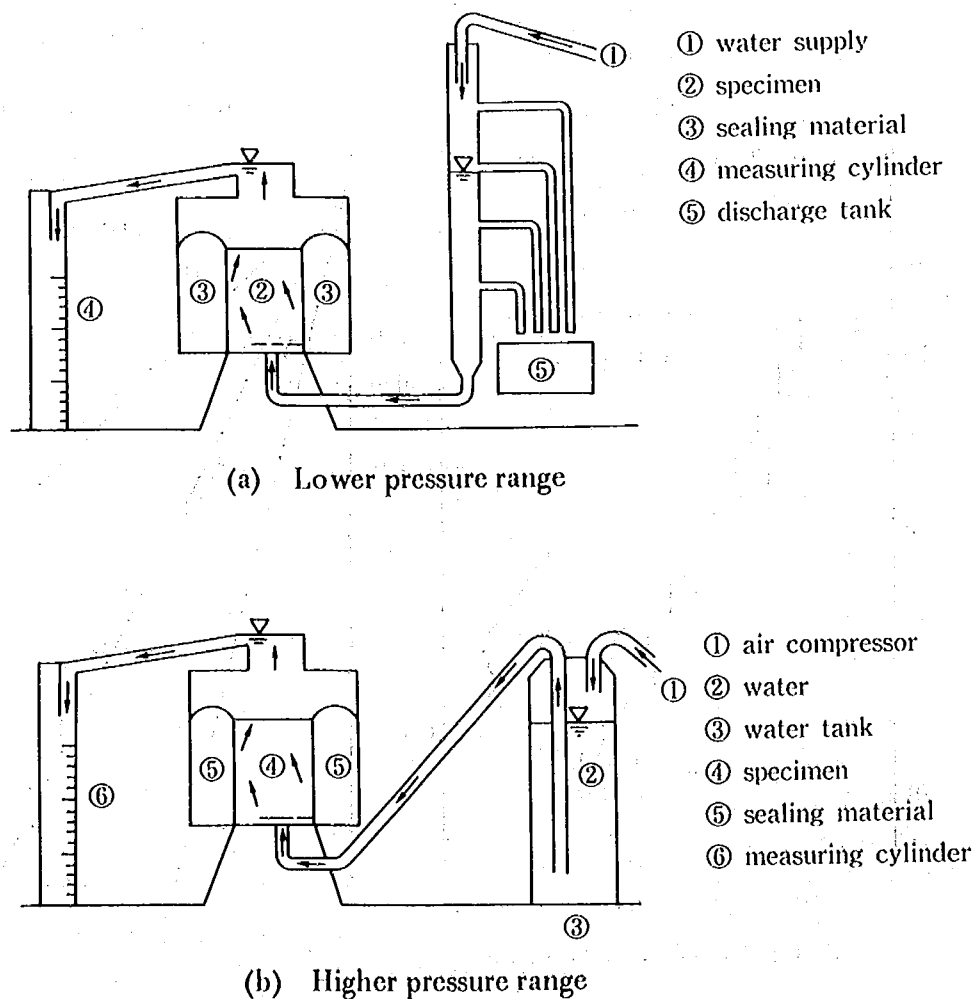
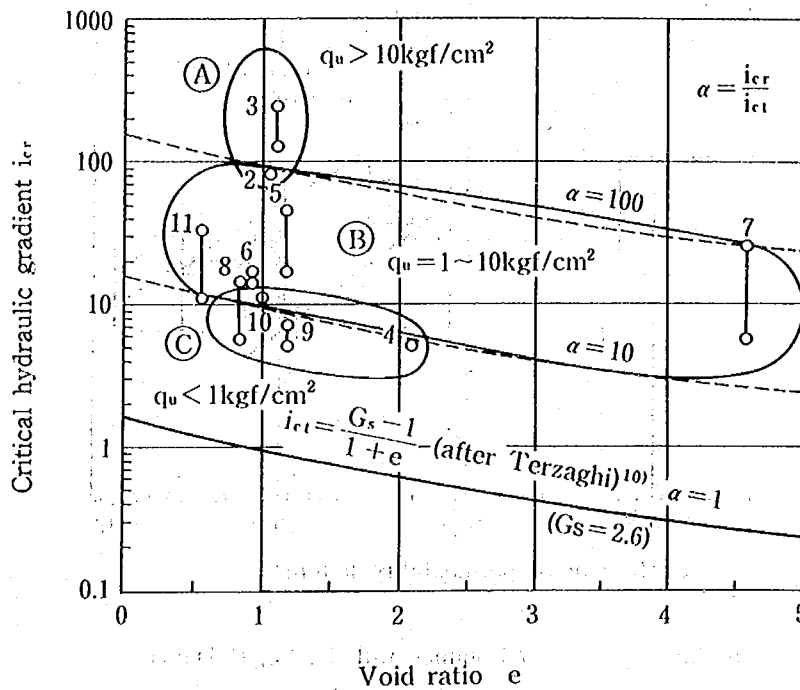


Fig. 7 Laboratory piping tests.

(2) Relationship between critical hydraulic gradient and physical properties

(a) Void ratio

We conducted many laboratory piping tests for undisturbed specimens of soft rocks. The relationship between critical hydraulic gradient i_{cr} and void ratio e of undisturbed specimens is shown in Fig. 8. Although most void ratios are almost a unit, critical hydraulic gradients scatter from 10 or less to 100 or more. This is why i_{cr} is greatly influenced by the strength of specimens, namely the degree of consolidation of soil particles. The theoretical critical hydraulic gradient i_{ct} ($= (G_s - 1)/(1 + e)$, where, G_s = specific gravity of soil particles) is also shown in Fig. 8. Friction between soil particles, cohesion, grain size, gradation and so on are neglected when calculating i_{ct} . The ratio $\alpha = i_{cr}/i_{ct}$ therefore expresses the degree of consolidation.

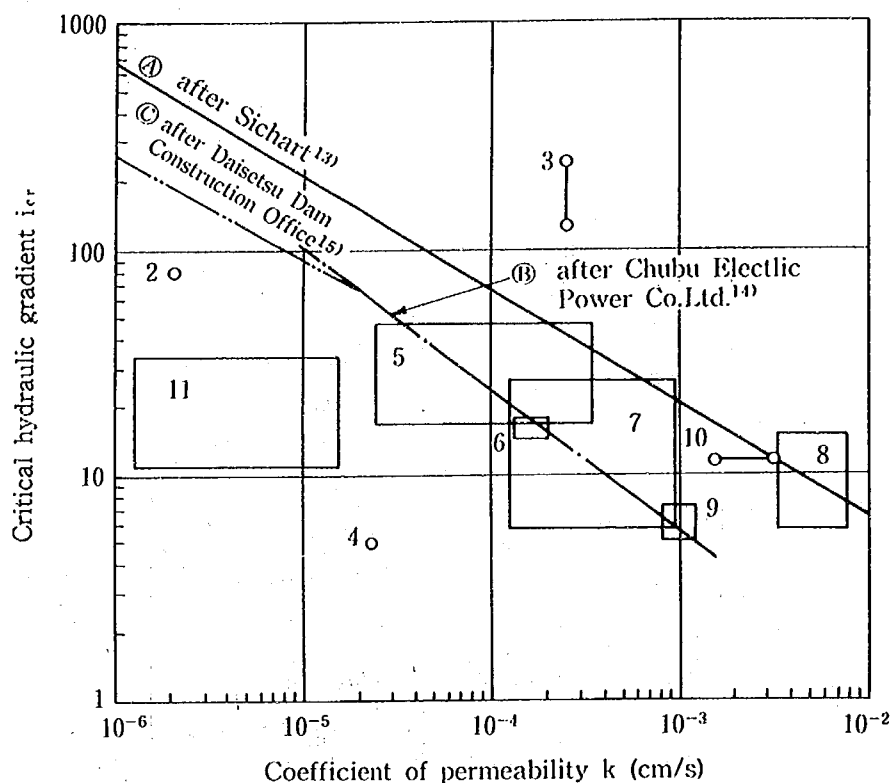


- | | |
|--|---|
| 1 : sandstone (S Dam) | 7 : pumice fall deposit (I Dam) |
| 2 : mudstone (S Dam) | 8 : sand (Kongoh formation) (Nagara Dam) ¹²⁾ |
| 3 : pumice tuff (Izarigawa Dam) ¹¹⁾ | 9 : sand (Narita formation) (Nagara Dam) ¹²⁾ |
| 4 : white volcanic ash (R Dam) | 10 : sandstone (P Dam) |
| 5 : sirasu (I Dam) | 11 : tuff (K Dam) |
| 6 : non-welded tuff (I Dam) | |

Fig. 8 Relationship between i_{cr} and e .

(b) Coefficient of permeability

Fig. 9. illustrates the relationship between i_{cr} and the coefficient of permeability k . The three lines in Fig. 9 indicate the relationships between k and i_{cr} proposed by Sichart¹³⁾, Chubu Electric Power Co. Ltd¹⁴⁾, and Daisetsu Dam Construction Office¹⁵⁾ respectively. The general trend shows that i_{cr} becomes smaller as k increases, but test results are comparatively scatter. This scatter depends upon the degree of consolidation of soft rocks and the accuracy of laboratory tests.



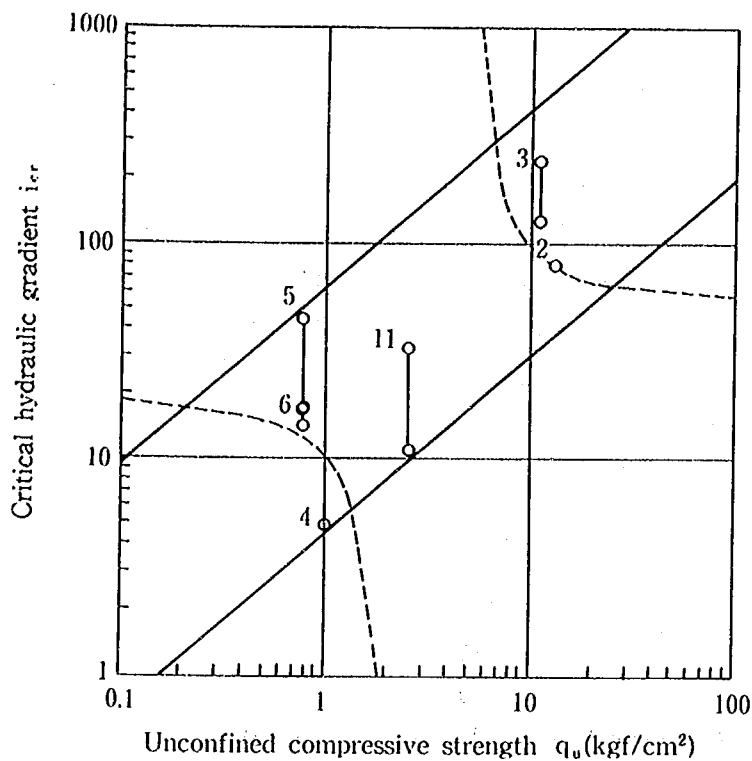
- | | |
|--|---|
| 1 : sandstone (S Dam) | 7 : pumice fall deposit (I Dam) |
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| 5 : sirasu (I Dam) | 11 : tuff (K Dam) |
| 6 : non-welded tuff (I Dam) | |

Fig. 9 Relationship between i_{cr} and k .

(c) Unconfined compressive strength

Fig. 10 shows the relationship between i_{cr} and unconfined compressive strength q_u . This figure shows that i_{cr} becomes larger as q_u increases.

We propose that selection between laboratory and in-situ tests should be made on the basis of the relationship between q_u and i_{cr} in Table 1. The primary testing method is the laboratory



- | | | | |
|------------------------|--------------------------------|-----------------------------|-----------------------------|
| 1 : sandstone | (S Dam) | 7 : pumice fall deposit | (I Dam) |
| 2 : mudstone | (S Dam) | 8 : sand (Kongoh formation) | (Nagara Dam) ¹²⁾ |
| 3 : pumice tuff | (Izarigawa Dam) ¹¹⁾ | 9 : sand (Narita formation) | (Nagara Dam) ¹²⁾ |
| 4 : white volcanic ash | (R Dam) | 10 : sandstone | (P Dam) |
| 5 : sirasu | (I Dam) | 11 : tuff | (K Dam) |
| 6 : non-welded tuff | (I Dam) | | |

Fig. 10 Relationship between i_{cr} and q_u .

Table 1 Evaluating proper piping test.

Testing methods	In-situ	Laboratory and In-situ	No need
Unconfined compressive strength q_u (kgf/cm ²)	$q_u \leq 1$	1 ~ 10	$10 \leq q_u$
Critical hydraulic gradient i_{cr}	$i_{cr} \leq 10$	10 ~ 100	$100 \leq i_{cr}$

test since it is very economical and simple. If the collection of undisturbed specimens is very difficult because of extremely low strength soft rocks or if verification of the accuracy of laboratory test results is needed, in-situ piping tests should be performed. Generally, if q_u of soft rock is less than 1 kgf/cm², it is very difficult to gather undisturbed specimens. For dam foundations, the foundations are safe during impounding of reservoirs, if i_{cr} is larger than 100.

3.3 In-situ tests

Although in-situ piping tests are more expensive than laboratory ones, there are many benefits of in-situ tests, as follows:

- ① We can consider heterogeneity of real foundations with in-situ tests.
- ② When soft rock foundations are too weak, it might be impossible to get undisturbed samples. However, we can still perform in-situ piping tests at such sites.

We performed three types of in-situ piping tests for soft rock foundations: ① Single-hole injection method¹⁶⁾, ② Multi-hole injection method^{17),18)} and ③ Single-hole pumping method (see Fig. 11). The features of these three test type are summarized in Table 2.

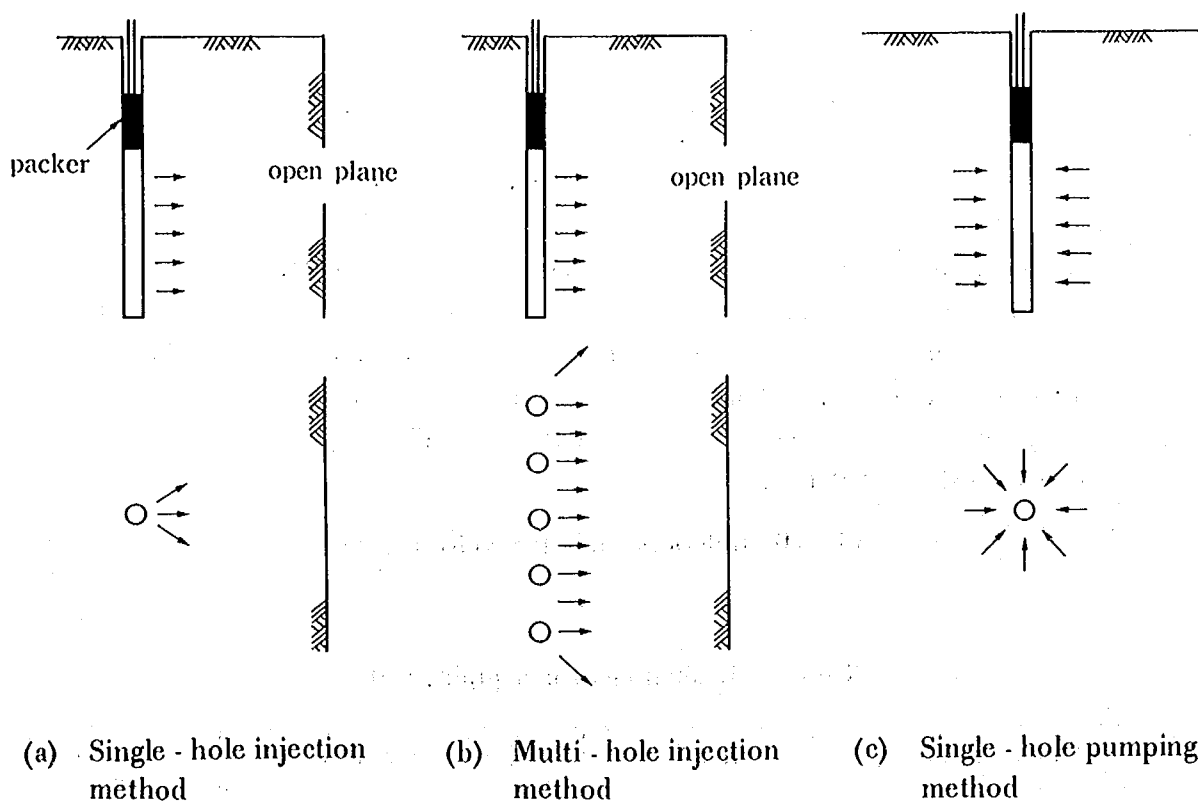


Fig. 11 In-situ piping tests.

Table 2 Characteristics of three types of in-situ piping tests.

Testing methods	Single - hole injection method	Multi-hole injection method	Single - hole pumping method
Advantages	① Very simple and economical ② Since assumed fracturing area is open plane, observation of fracturing is very easy.	① Approximately one - dimensional flow ② Since assumed fracturing area is open plane, observation of fracturing is very easy.	① Simple and economical ② Although we cannot produce one - dimensional flow condition in this test, maximum hydraulic gradient takes place at borehole wall which is also open plane. Therefore, failure usually starts from downstream.
Disadvantages	① Distribution of hydraulic gradient changes abruptly (not constant) ② Fracturing usually takes place around the injection hole. This failure is not piping but hydraulic fracture. ③ The vicinity of open plane could be loose. We might underestimate piping potential.	① Because water is injected not from trench, but from boreholes, it is very difficult to solve the problems (①, ②) perfectly in single - hole injection type test. ② The vicinity of open plane could be loose. We might underestimate piping potential.	① It is difficult to observe failure in a hole.

3.4 Scouring tests¹⁹⁾

It is desirable to obtain i_{cr} of soft rock foundations more easily. At present, we are studying the relationship between i_{cr} and the results of scouring tests (see Fig. 12), these tests are very simple and easy to handle¹⁹⁾. The results of laboratory piping tests and scouring tests for compacted weathered granites, namely i_{cr} and scour resistance value (s_r), are plotted in Fig. 13. The relationship between i_{cr} and s_r is apparent, and we are planning to perform many scouring tests both at laboratories and in the field to investigate this method.

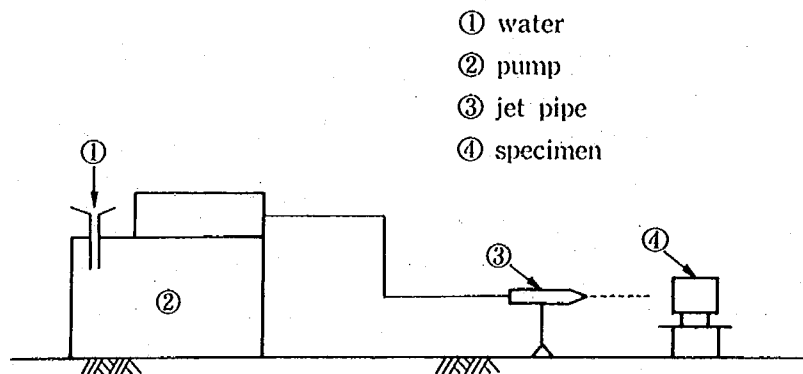


Fig. 12 Scouring test (for laboratory test).

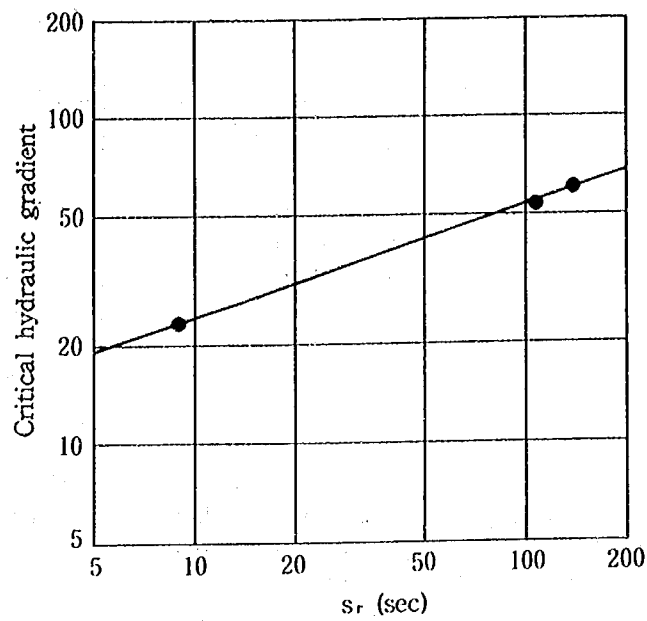


Fig. 13 Results of scouring tests for weathered granites.

4. MEASUREMENTS OF GROUNDWATER PRESSURE DISTRIBUTIONS^{20)~23)}

4.1 Overview

The distributions of groundwater pressure in rock foundations are very complicated due to joints, fissures, beddings and so on. However, the conventional method of measuring groundwater pressure at dam sites is performed by observing water levels in boreholes. It is almost impossible to measure the complicated distributions of groundwater pressure in rock foundations precisely by this method. Furthermore, it is not economical to obtain data only at one point of one borehole. We have thus studied and developed a rational method of measuring groundwater pressures at plural points of one borehole.

4.2 Measuring system

The Multiple Groundwater Level Measuring System (MGL System) is installed in the foundation as shown in Fig. 14. After drilling a $\phi 66$ mm hole for geological investigation, this hole is enlarged to $\phi 116$ mm. Several pore pressure gauges are installed in the pipe (referred to as MGL pipe) and this pipe is inserted in the $\phi 116$ mm hole. Filter zones are formed in holes near the pore pressure gauges and filling grouts are injected in other zones.

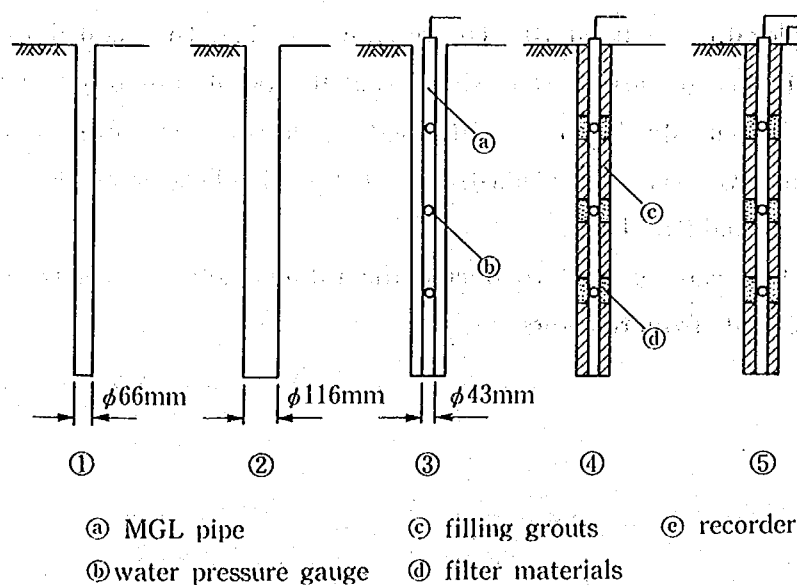


Fig. 14 MGL system.

4.3 Practical examples

The geological map along the dam axis of the left bank of M Dam is illustrated in Fig. 15. This dam site is mainly composed of soft rocks of the Miocene of the Neogene period. MGL systems were installed in boreholes BL - 8.9 and 10.

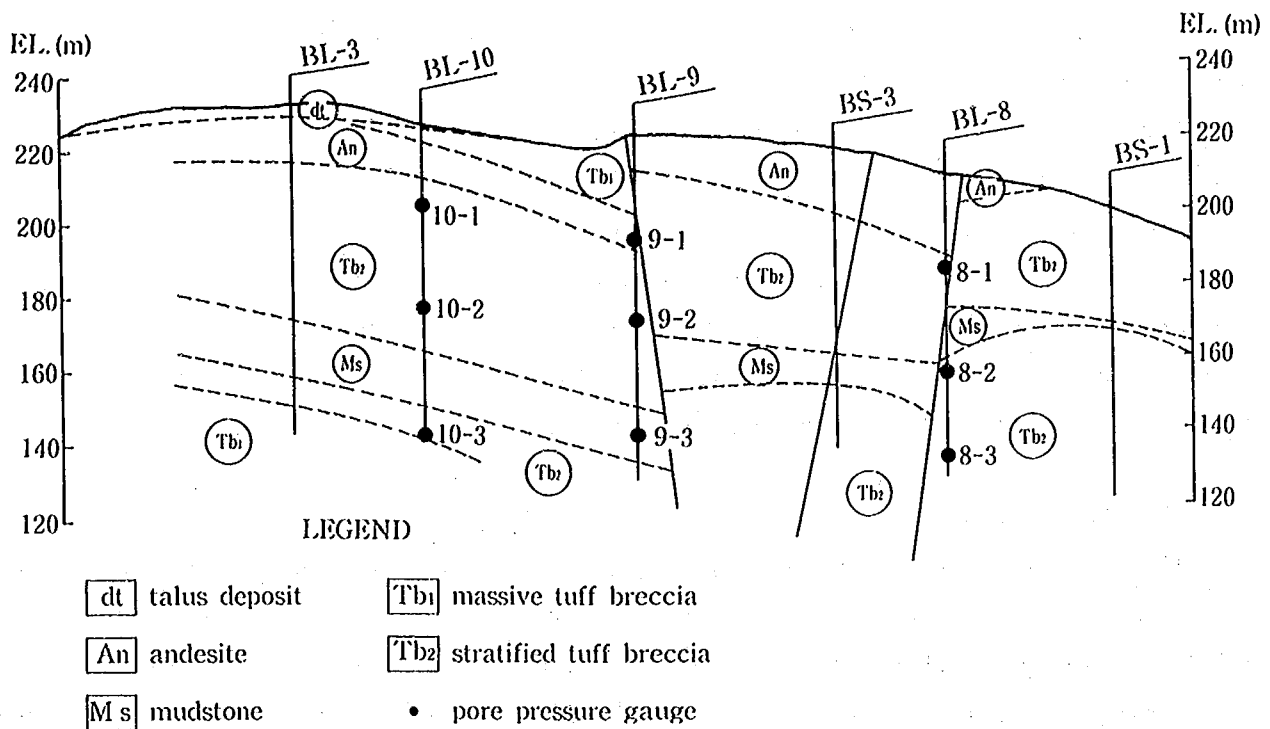


Fig. 15 Geological map of left bank of M Dam.

Results of exploratory drills at BL-10 are shown in Fig. 16. As drilling advanced, the water level in BL-10 became lower. This shows that the distribution of groundwater pressure is very complex at M Dam site. The results of long term measurements of groundwater pressure at BL-10 using the MGL system are illustrated in Fig. 17. This figure shows that there are two stable aquifers around BL-10.

The MGL system can be used to decide the rational area of seepage control, and to monitor the leakage route from reservoirs.

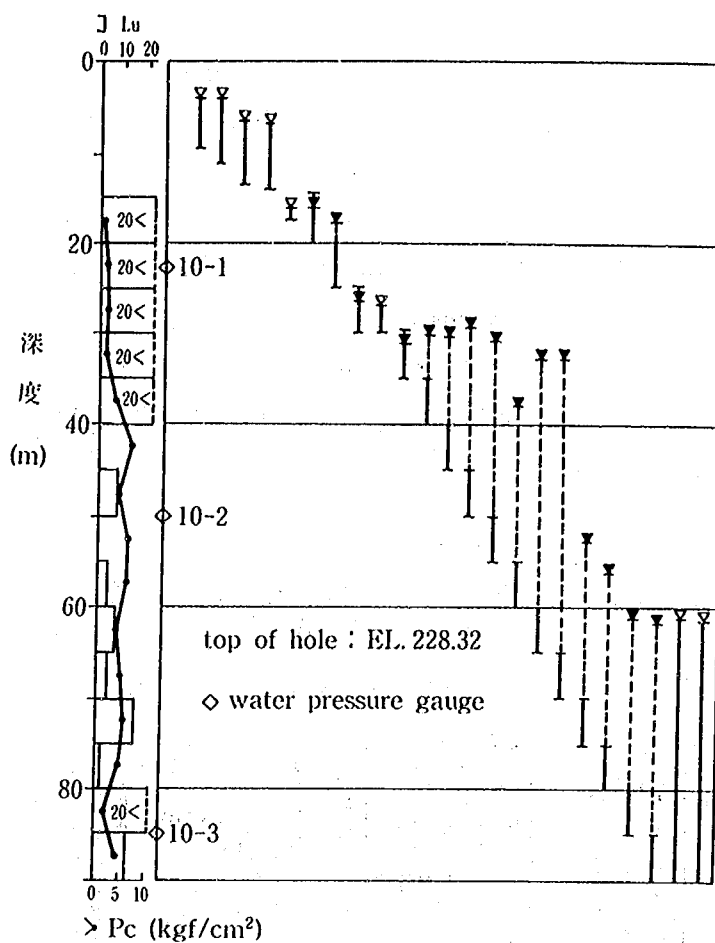


Fig. 16 Results of exploratory drills.

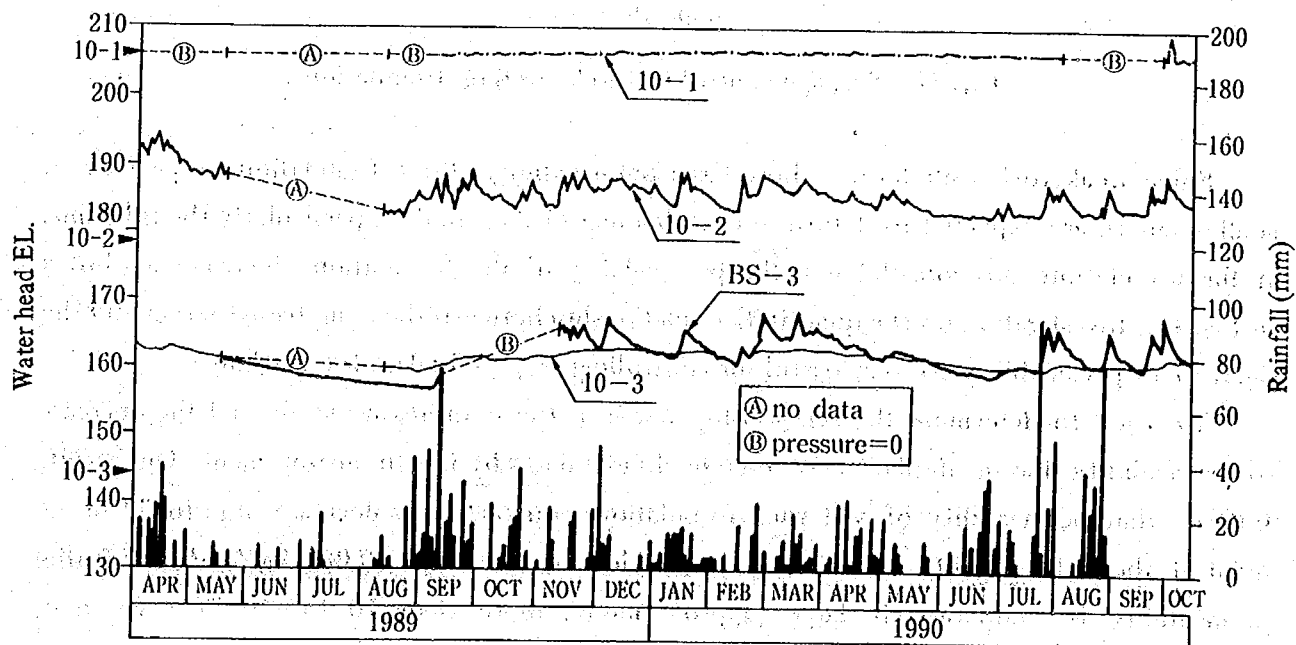


Fig. 17 Change with time of groundwater pressures around BL - 10.

5. SEEPAGE CONTROL

After determining permeability, seepage failure potential and the distribution of ground-water pressure of soft rock foundations precisely during investigation and design phases, appropriate seepage control for foundations should be planned. Cement grouting is the most popular seepage control method for dam foundations. However, since higher grouting pressures cause fracturing or lifting of the surface of foundations, the allowable pressures should be kept low in soft rocks. This sometimes creates serious difficulties particularly in improving the permeability for shallow foundations. Therefore, for seepage control for soft rock foundations, we should consider diaphragm walls, earth blankets, relief wells and drain holes in addition to cement groutings (see Fig. 18). The combination of plural methods is also worth examining.

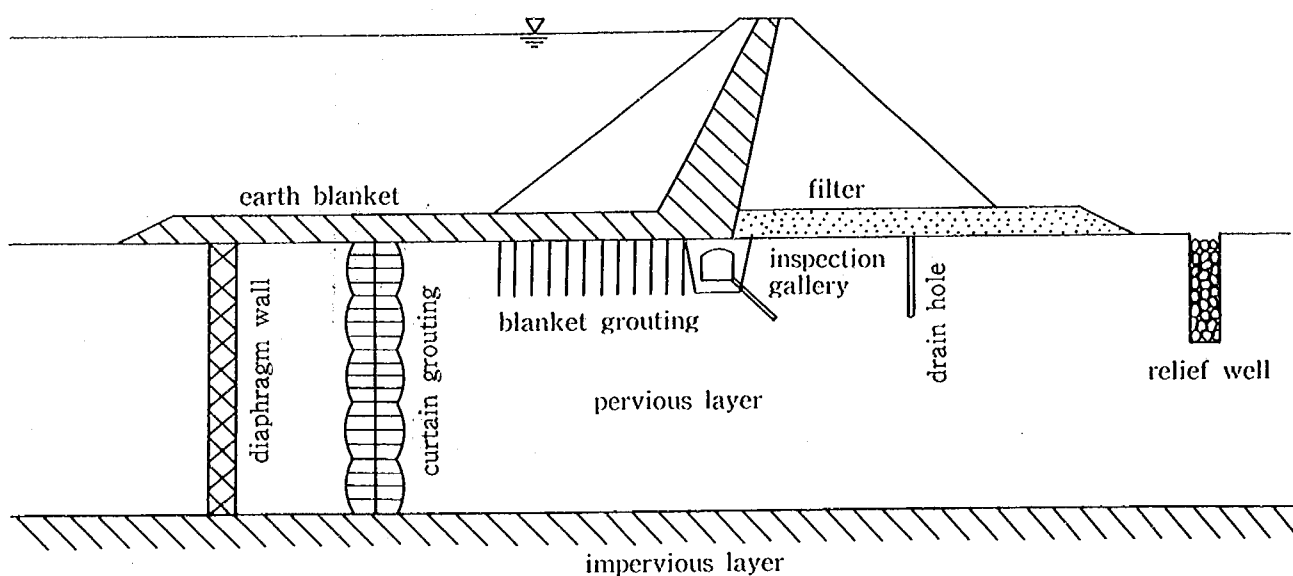


Fig. 18 Seepage control methods for dam foundations.

Since weak rock foundations show large deformability, these foundations, especially in shallow areas, are expected to deform due to loading of dam bodies, particularly the fill dams. If the foundations are consolidated, the permeability of the foundations decreases as shown in Fig. 19. Investigation on the quantitative relationship between the compressive strain and the decrease of permeability are very useful for controlling seepage in dam foundations.

We tried to determine the relationship between the compressive strain and the decrease of permeability due to fill placement in embankment dams by in-situ measurement. Our results indicate that permeability of soft rock foundations comparatively decreases due to fill placement if the deformability modulus of foundations is less than $10,000 \text{ kgf/cm}^2$ and initial permeability is comparatively large (approximately, more than 10 Lu)^{24)~30)}. We have proposed theoretical models to explain this and presented a rational seepage control method for soft rock foundations by considering the interaction between stress and permeability.^{31).32)} Refer to our previous reports for further details.

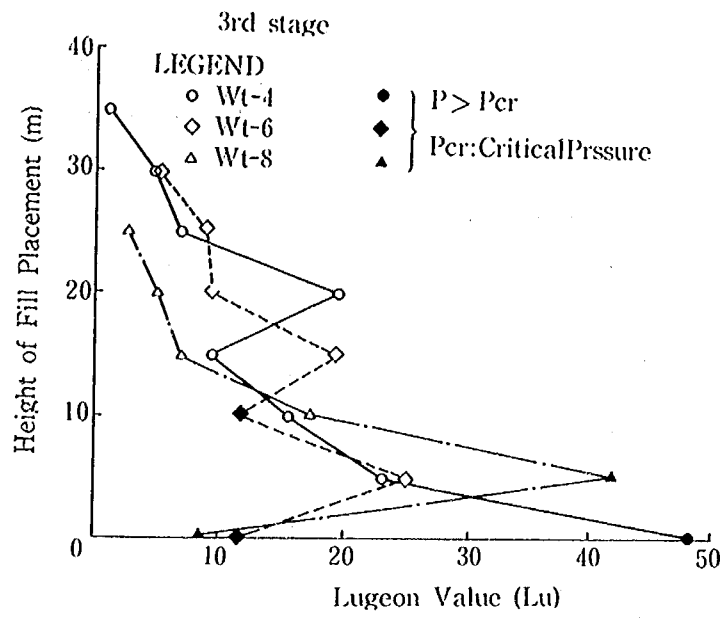


Fig.19 Change of Lugeon values due to fill placement (N Dam).

6. CONCLUDING REMARKS

When designing foundation treatments for soft rock foundations for dams, it is very important to understand the characteristics of foundations accurately. We emphasized the importance of problems concerning water particularly for soft rock foundations. We have discussed permeability, seepage failure potential and distribution of groundwater pressure and proposed a rational seepage control method for soft rock foundations.

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**WATER PROBLEMS
IN SOFT ROCK FOUNDATIONS
FOR DAMS**

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Abstract:

We summarize problems of soft rock foundations, give results of permeability tests, seepage failure tests and measurements of groundwater pressure distribution, and show countermeasures against them. We also propose a rational method of seepage control for soft rock foundations, considering interaction between stress and permeability.

Keywords: soft rocks, dam, permeability, seepage failure, groundwater pressure, seepage control.

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