

ISSN 0386-5878
Technical Memorandum
of PWRI No. 3022

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PERMEABILITY AND LUGEON VALUES OF DAM FOUNDATIONS

August, 1991

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PERMEABILITY AND LUGEON VALUES OF DAM FOUNDATIONS

by

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Abstract :

In surveying the permeability of dam foundations, a Lugeon water test is usually adopted and the permeability is evaluated by the Lugeon value (Lu). The curve between pressure and the rate of water injection (p-q curve) is drawn by using the test results and the Lugeon value is obtained from the slope of the straight line part of the p-q curve. However, quite a few p-q curves which have various shapes other than a straight line are obtained when Lugeon water tests are performed in the field. Therefore, in order to interpret the results of Lugeon water tests accurately the authors perform the following things : (1) p-q curves obtained from Lugeon water tests are classified into several categories, (2) causes of several p-q curves classified in (1) are summarized and (3) the methods to determine the accurate Lugeon value from each p-q curve are illustrated.

Keywords : Lugeon water test, p-q curve, Lugeon value, seepage analysis.

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1. INTRODUCTION

In designing dams, it is very important to grasp the permeability of foundations. The most popular field permeability test for dam foundations is the Lugeon water test (LWT) using boreholes. Permeability is evaluated with a Lugeon value (or unit) which is expressed by the liters of water injected per 1 meter of length of test section for 1 minute at a pressure of 10 kgf/cm², after a p-q curve is drawn by using the observed data of effective pressure p (kgf/cm²) and rate of water injection q (ℓ/min/m).

In Japan, a standard testing method for LWT has been established as a technical guide by the Ministry of Construction¹⁾ in order to perform the tests in a unified manner. To accumulate many results obtained with a standardized testing method is very useful for the investigation of permeability for dam foundations. We often have trouble in analyzing the Lugeon value in case the dam foundation is not composed of hard rock with little discontinuity but of hard rock with many joints and fissures, soft rock or sand and gravel deposit having large deformability. For instance, p is not proportional to q, the configuration of the p-q curve of the ascending stages of pressure is different from that of the descending stages and so on. Since M. Lugeon²⁾ advocated this testing method in 1933, the Lugeon value has not been regarded as a quantitative index for permeability. However, because p-q curves obtained from LWT reflect the hydraulic characteristics of the foundation, it is possible to get a lot of information with proper analyses. In this technical report we analyze the causes of many shapes of p-q curves and propose a method of determining Lugeon values which indicate the permeability governing seepage in the dam foundation. Lugeon values obtained from this procedure are no longer qualitative indexes but quantitative ones concerning permeability.

2. ANALYSIS OF RESULTS OF LUGEON WATER TESTS

(1) Effective pressure

Effective pressure is calculated by correcting the gauge pressure by hydrostatic pressure, groundwater pressure and head loss due to resistance in the injection pipe (see Fig. 1). In calculations the following formulae are used according to the location of the groundwater level.^{3), 4)}

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 of the elevation between the pressure gauge and the center of the test section (m),

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

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

γ_w = unit weight of water (1 tf/m³ = 0.1 kgf/cm²/m).

Head loss h_3 can be obtained 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 test the section. Constant α should be determined by the test. When this is not performed, α is regarded to be 7×10^{-5} (min²/ℓ) approximately.

② Above groundwater table

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

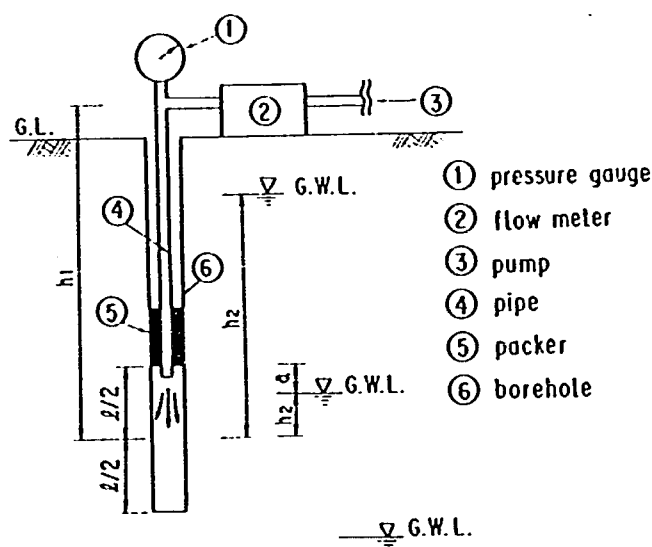


Fig. 1 Schematic view of Lugeon water test.

③ Other conditions

$$\left. \begin{aligned} p &= p_0 + \gamma_w \left\{ (h_1 - h_2 - \frac{a^2}{2l}) - h_3 \right\} \quad (\text{kgf/cm}^2) \\ a &= \frac{l}{2} - h_2 \quad (0 \leq a \leq l) \end{aligned} \right\} \quad (4)$$

(2) Determination of Lugeon value

By using the results of LWT, namely the relationship between effective pressure p (kgf/cm²) and the 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 we have confirmed the proportional relationship between p and q , we determine the Lugeon value (Lu) as the rate of water injection at a pressure of 10 kgf/cm². However, if the rate of water injection suddenly increases at a pressure (critical pressure p_{cr}) below 10 kgf/cm² as illustrated in Fig. 3, then the Lugeon value corresponding to 10 kgf/cm² is to be analyzed from the linear trend of the relation between the rate of water injection and pressure below the critical pressure. We call this value the equivalent Lugeon value (Lu').

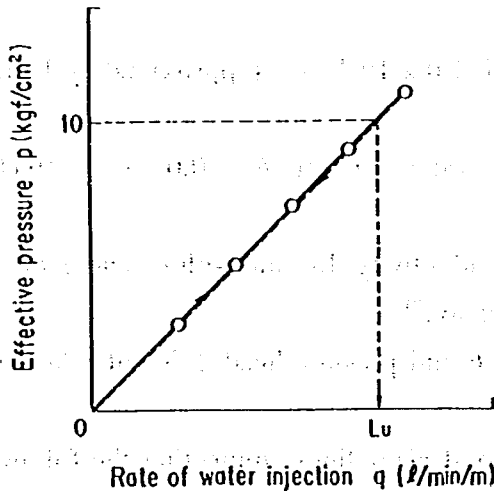


Fig. 2 p - q curve.

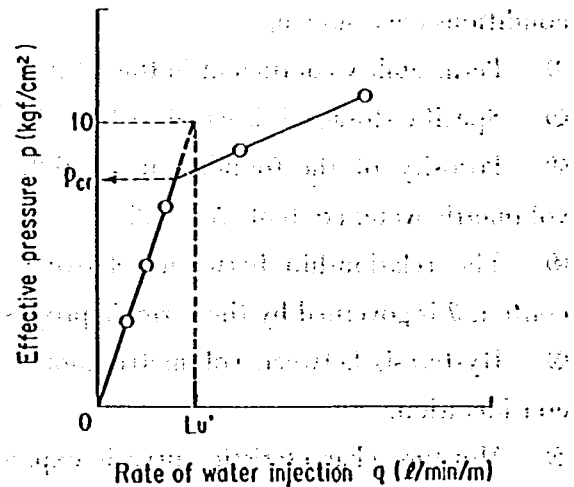


Fig. 3 p - q curve with critical pressure.

3. OUTLINE OF SEEPAGE ANALYSIS

Because we often utilize saturated-unsaturated seepage analysis in this technical paper, we explain the outline of it in this chapter. The fundamental equation is expressed as follows.⁵⁾

$$\left. \begin{aligned} \operatorname{div} k(\theta) \vec{\nabla}(\psi + z) &= (C(\theta) + \epsilon S_s) \frac{\partial \psi}{\partial t} \\ \epsilon &= \begin{cases} 0 & \text{in an unsaturated zone} \\ 1 & \text{in a saturated zone} \end{cases} \end{aligned} \right\} \quad (5)$$

where, $k(\theta)$ = permeability tensor,

ψ = water pressure head,

θ = volumetric water content,

$C(\theta)$ = specific water capacity = $\partial \theta / \partial \psi$,

S_s = specific storage,

z = vertical coordinate (positive upwards),

t = time.

A schematic view of the model for seepage analysis is an axisymmetric one as shown in Fig. 4. This has almost infinite scale concerning water injection from the test hole.⁶⁾

In case we don't refer to the input properties of seepage analysis hereafter, the following conditions are assumed.

- ① Permeability coefficient in the saturated zone k_0 is 1.0×10^{-4} cm/s (approximately 10 Lu).
- ② Specific storage S_s is equal to 1.0×10^{-7} cm⁻¹.
- ③ Porosity of the foundation $n = 0.2$, minimum water content $\theta_r = 0.0$ and effective volumetric water content $\theta_e = 0.2$.
- ④ The relationship between relative hydraulic conductivity K_r and volumetric moisture content θ is governed by the formula proposed by S. Irmay.⁷⁾
- ⑤ Hysteresis between volumetric moisture content θ and pressure head ψ is not taken into consideration.
- ⑥ Moisture characteristic curve is expressed as two straight lines connecting the following three points, that is, $(\theta = 0.2, \psi = -0.0 \text{ m})$, $(\theta = 1.0 \times 10^{-6}, \psi = \psi_0 = -1 \text{ m})$ and $(\theta = 0.0, \psi = -17.5 \text{ m})$.

Unsaturated characteristic curve is illustrated in Fig. 5.

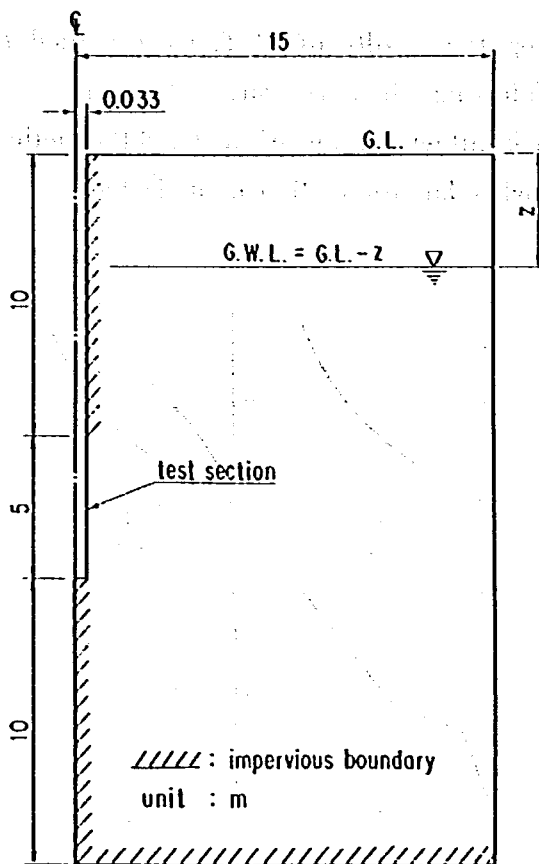


Fig. 4 Analytical model.

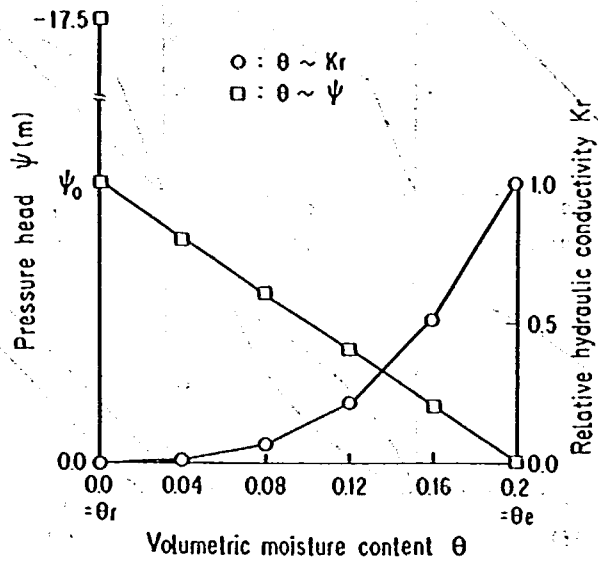


Fig. 5 Unsaturated properties.

4. CLASSIFICATION OF p-q CURVES

Before summarizing the method of analyzing the results of LWT, we classified the shapes of p-q curves as shown in Fig. 6. In the following chapters, causes of occurrence of the above-mentioned p-q curves are summarized, their influence is investigated and the methods of calculating Lugeon values governing seepage through a dam foundation are indicated.

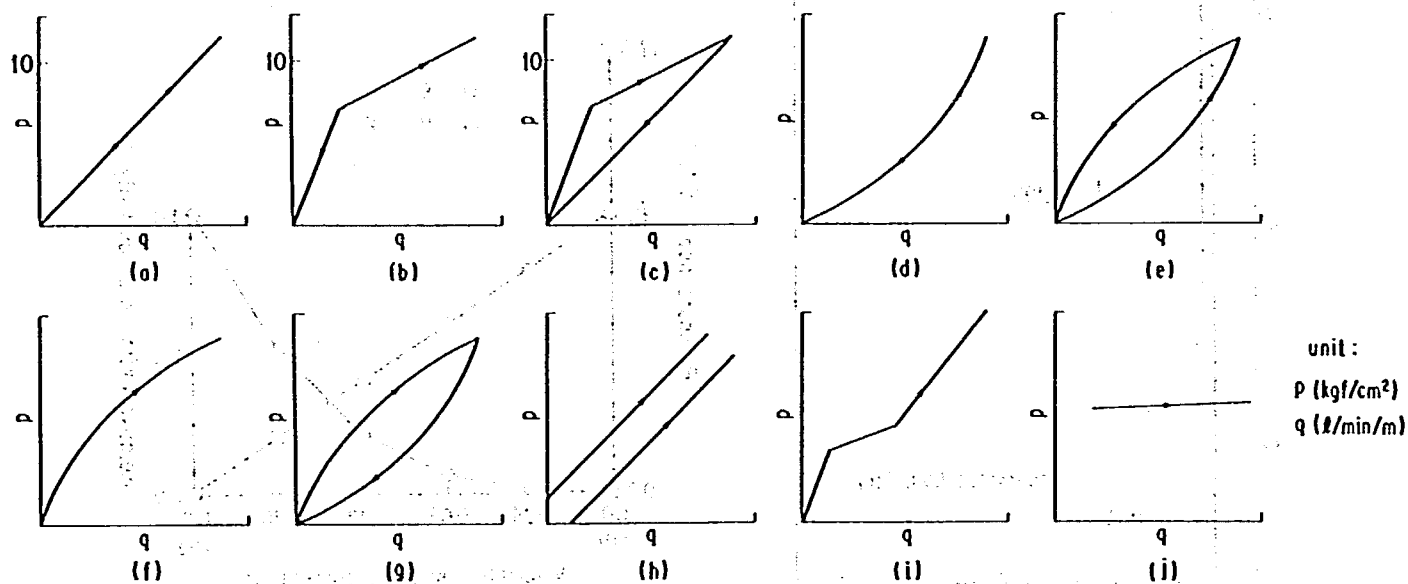


Fig. 6 Patterns of p-q curves.

5. STRAIGHT LINE TYPE p-q CURVE

(1) Curve with p_{cr}

This type of p-q curve is a straight line through the origin, and lines of both ascending and descending steps in pressure are regarded to be almost the same, as shown in Fig. 6 (a). Furthermore, critical pressure p_{cr} is not recognized at an effective pressure of less than 10 kgf/cm². This p-q curve can be obtained in case flow of water injected from the testing hole is laminar and the surrounding foundation hardly deforms during water injection. It is very easy to calculate the Lugeon unit from this straight line type p-q curve. This is because the hydraulic gradient of seepage through the dam foundation during impounding of the reservoir is very small and water flow is considered to be almost laminar. This has been made clear by Sueyoshi et al.⁸⁾ with a jointed rock foundation model and by Matsumoto et al.⁹⁾ with a porous media model.

(2) Curve without p_{cr}

This is a p-q curve in which critical pressure p_{cr} is recognized at an effective pressure of less than 10 kgf/cm², as shown in Fig. 6 (b) and (c). In this case we have to extrapolate the equivalent Lugeon value Lu' from the linear part of the p-q curve at the lower pressure. If we calculate Lu' from the part of the curve at the higher pressure, the permeability of the dam foundation is overestimated. Though we have to evaluate whether the dam foundation is broken due to the filling of the reservoir separately, it is not too much to say that the former Lu' indicates the real permeability unless p_{cr} is too small. We can decide p_{cr} with an abrupt increase of discharge. This phenomenon depends upon temporary or permanent opening of fissures, formation of new joints, wash-out of joint filling materials and so on. This type of curve can be divided into two patterns. One is the one curve type (see Fig. 6 (b)), in which the results at pressures in increasing and decreasing steps trace one curve, and the other is the hysteresis loop type (see Fig. 6 (c)), in which the results at both steps form a hysteresis loop. When a p-q curve is drawn as in the former pattern, fissures of foundation around the injection hole can be assumed not to deform permanently. However, critical pressure is obtained as the pressure at which the rate of water injection from the test section increases suddenly according to the technical guide. Moreover, before tests, we have to confirm whether the packer for sealing is effective or not, in order to measure accurate results.

6. PERMEABILITY DECREASING TYPE p-q CURVE

(1) Causes of occurrence

At the pressure ascending stage, this type of p-q curve indicates a decrease of permeability due to the increment of pressure, as illustrated in Fig. 6 (d) and (e). This type of curve consists of two patterns, namely the one curve type (see Fig. 6(d)) and the hysteresis loop type (see Fig. 6(e)). In case of the hysteresis loop type, discharge of the pressure ascending stage is usually larger than that of the pressure descending stage. Causes of the occurrence of these types of curve are summarized as follows :

(One curve type)

- ① Flow of water injected from the testing hole is turbulent.
- ② Effective pressure is not corrected regarding head loss due to resistance in pipe h_3 or h_3 is underestimated.
- ③ In case of tests carried out below the groundwater level, there is a possibility that the shape of the p-q curve would not be a straight line through the origin because of the rise of groundwater level due to water injection. It is difficult to judge whether the shape of the p-q curve is of a permeability decreasing type or a permeability increasing type (see Chapter 7). We investigate the above-mentioned point in the following section.
- ④ Above the groundwater table, water flow from the injection hole is influenced by gravity and the unsaturated characteristics of the foundation. This might result in the occurrence of this type of p-q curve.

(Hysteresis loop type)

- ① Slime due to unsatisfactory washing of the testing borehole, suspended solids or air in the water gradually fills voids in the foundation.
- ② Before water flow becomes steady at some pressure, the value of the pressure is changed.

(2) Detailed investigations on the one curve type

a) Turbulent flow

Since water flow of LWT is radial, a large hydraulic gradient takes place near the injection hole. Therefore, if the tests are conducted in jointed rock foundations or coarse gravel deposits, flow can not be laminar but turbulent. Because flow resistance is larger in turbulent flow conditions than in laminar ones, the increment ratio of discharge becomes smaller with the increase of pressure. However, observed data of p and q of both ascending and descending pressure stages are distributed near the one curve. Many scholars and engineers, for instance Kutzner¹⁰⁾, Ewert¹¹⁾, Howlsby¹²⁾ and Lancaster-Jones¹³⁾, have also pointed out the influence of turbulent flow on the results of LWT.

On the other hand, seepage through the dam foundation is almost laminar as mentioned above. In performing the tests we should use highly viscous fluids instead of water or adopt very low pressure so as to determine the Lugeon unit under laminar flow condition.

Furthermore it is very important to observe geological conditions well and to presume seepage conditions through the dam foundation.

LWT with highly viscous fluids is more effective than that with low injection pressure as countermeasures against turbulent flow^{(14), (15)}.

b) Head loss due to resistance in pipe

Many dam engineers^{(10), (16)} have indicated that the correction regarding head loss due to resistance in pipe h_3 has a large influence on the accuracy of calculations of effective pressure. The necessity of this correction is also described in technical guides. Because h_3 is proportional to discharge squared, a permeability decreasing type p-q curve can easily appear without correcting the effect of h_3 . We try to calculate the degree of influence on the accuracy of the Lugeon unit by ignoring h_3 . The condition that an error in the Lugeon value by ignoring h_3 is smaller than β , can be solved by use of equations (1) to (4), as follows. The Lugeon value obtained without correction is apparently smaller than the real one.

$$Lu^2 \cdot L \leq 5.7 \times 10^4 \times \beta \dots \dots \dots (6)$$

where, Lu is the Lugeon unit with the correction of effective pressure by h_3 .

We substitute 0.03, 0.05 and 0.1 for β in equation (6) and illustrate these three equations in Fig. 7.

For the purpose of estimating head loss, we should make the corrective equation for h_3 by experiment with an injection pipe or install a pore pressure gauge in the test section.^{(10), (16)} Particularly, the latter method is very effective and has become a general technique recently.

Furthermore we have to pay attention to the removal of air from water in the injection pipe. Air in the pipe causes the scatter of observed data, such as pressure and discharge.⁽¹⁷⁾ To replace a short part of the steel pipe with an acrylic one is a useful method for observing the existence of air in the pipe.

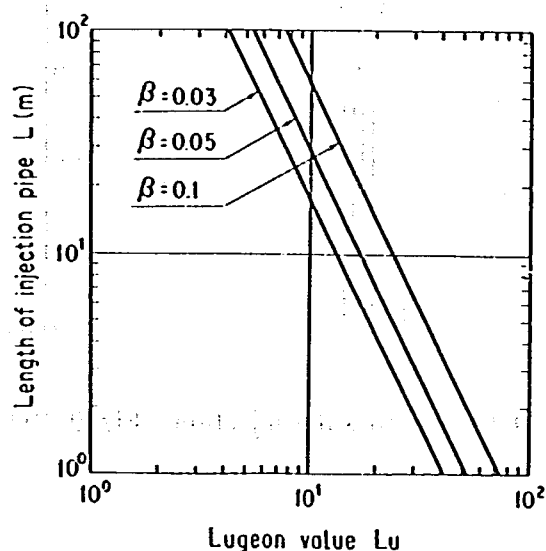


Fig. 7 Effect of head loss h_3 .

c) Rise of groundwater level due to water injection

Harita & Toyoda¹⁶⁾ have reported that groundwater level rose because of water injection of LWT performed at a dam site composed of sedimentary rocks of the Neogene period (see Fig. 8). We investigate the influence of rise of groundwater level due to water injection on the results of LWT with seepage analysis.

Discharges analyzed in both fixed and variable groundwater level conditions are shown in Fig. 9. Effective pressure p is 0.4 kgf/cm^2 for all cases. Discharges under fixed groundwater level conditions are larger than those under variable ones, but even the maximum difference between the two conditions is only seven percent at $z = 7.5$ meters. The smaller z is, the smaller the difference is.

Consequently the closer the groundwater level is to the testing section, the larger is the effect on the decrease of effective pressure due to water injection. But the degree of decrease of discharge is not so large. We illustrated a p - q curve obtained from seepage analysis at $z = 7.5$ meters in Fig. 10. We found that we could obtain a p - q curve whose shape was the straight line through the origin even at $z = 7.5$ meters. Therefore there is no problem in calculating Lugeon values. The target of the above-mentioned analysis is soft rock or sand and gravel foundations whose permeability is governed by Darcy's law. On the other hand, since seepage through hard rock foundations mainly depends upon direction and distribution of discontinuities, such as fissures, joints and so on, it is very difficult to evaluate the rise of groundwater level around the test section quantitatively. However, the degree of influence on jointed rock foundations is not much different from that on porous media.

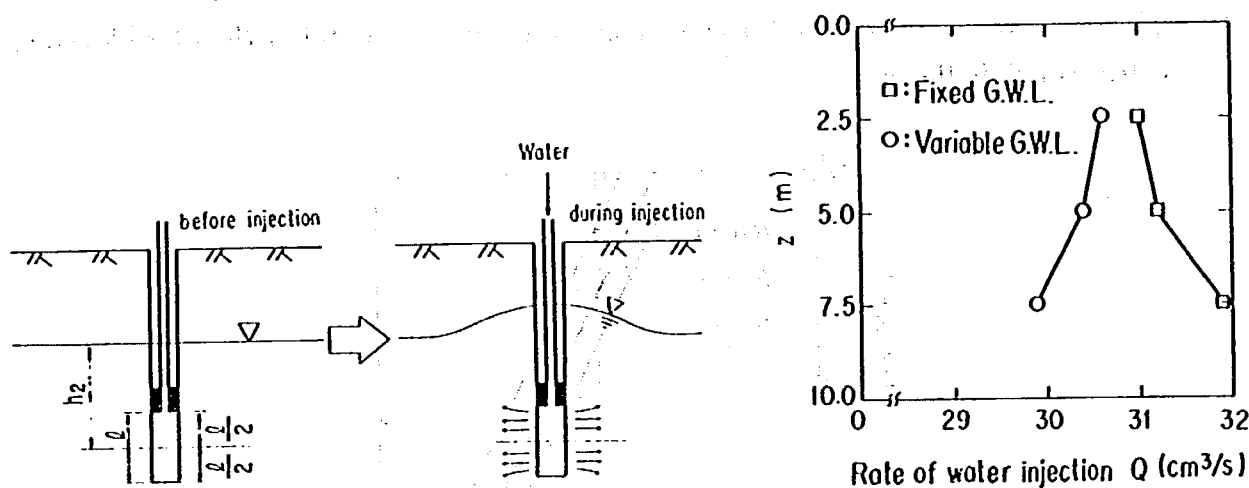


Fig. 8 Rise of ground water table due to water injection. Fig. 9 Relationship between z and Q .

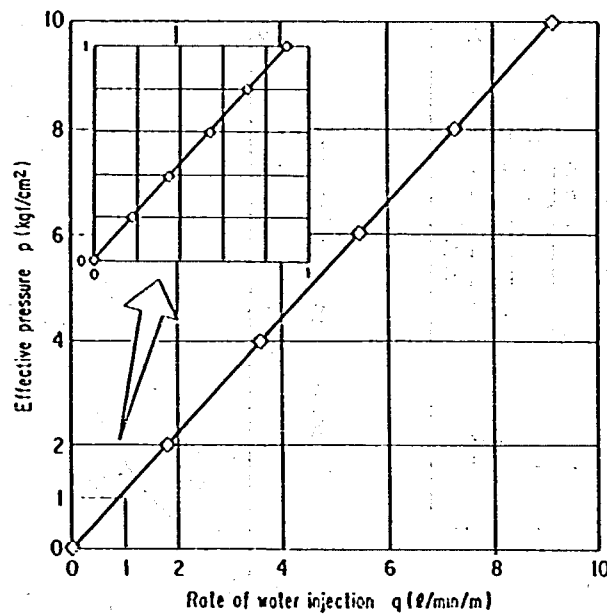


Fig. 10 p - q curve at $z = 7.5$ m.

d) Gravity and capillarity

We have estimated the influence of gravity and capillarity on the shape of the p - q curve in the case of LWT performed above the groundwater table, with seepage analysis.

Discharges (here, the equivalent Lugeon unit Lu') obtained from seepage analysis carried out under the various conditions in the location of groundwater level, p and ψ_0 , are illustrated in Figs. 11 and 12. At the same injection pressure, discharges of tests conducted above the groundwater table are larger than those of tests below the groundwater table because of the existence of gravity and capillary flows. This difference increases as ψ_0 becomes larger, p becomes smaller and the groundwater level is closer to the test section. Some investigators, Stephen & Neuman¹⁸⁾, Philip¹⁹⁾, have represented similar results. Although the shape of p - q curves obtained from tests below the groundwater level is a straight line through the origin, that above the groundwater level belongs to the permeability decreasing type because of gravity and capillary flows. Lugeon values obtained from the latter tests are larger than those from the former tests which are supposed to govern the seepage through dam foundations in filling of reservoirs. That is because seepage flow through dam foundations is potential flow. Because the difference between the two values depends upon the unsaturated characteristics of the foundations, the injection pressure and the location of groundwater level, it is very difficult to evaluate the difference quantitatively considering these three parameters. We should use comparatively large pressure (see Fig. 12) and pay much attention to the unsaturated characteristics at each dam site hereafter to obtain real Lugeon units.

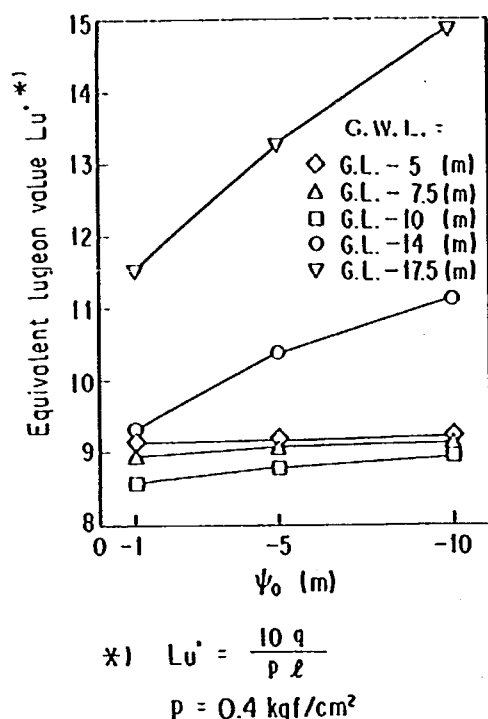


Fig. 11 Relationship between ψ_0 and Lu' .

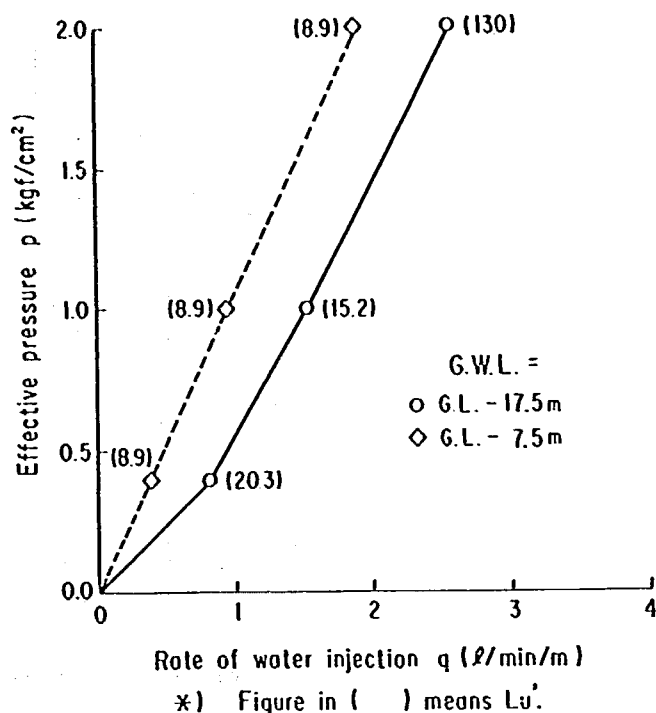


Fig. 12 p-q curves under two ground water level conditions.

(3) Detailed investigations on the hysteresis loop type

a) Void filling

Since insufficient washing of slime or suspended solids and air in testing water cause void filling of foundations, apparent permeability decreases with the passage of time. Therefore we obtain permeability decreasing and hysteresis loop type p-q curves.^{10), 11)} We have to wash the testing holes before tests and use clean water. However, long-term washing of holes would lead to loss of time and erosion of foundations, if foundations are composed of soft rocks or sand and gravel deposits. At the early stage of the survey of dam foundations we should investigate the proper length of consecutive time for water injection.²⁰⁾

When we meet the p-q curve effected by void filling in spite of several countermeasures mentioned above, we have to calculate the Lugeon value on the basis of the tangent slope of the curve at the lower pressure part of the pressure ascending course.

b) Unsteady flow

If we conduct LWT on foundations having low permeability and large deformability according to technical guides, it would be possible to obtain the p-q curve illustrated in Fig. 13 due to unsteady flow. Long-term water injection is a good countermeasure against the effect of unsteady flow.^{21), 22)} At the early stage of the survey, we should confirm how long the proper length of successive time for water injection is, and how large the difference between real Lugeon units and calculated ones is. In case we obtain the p-q curve influenced by an

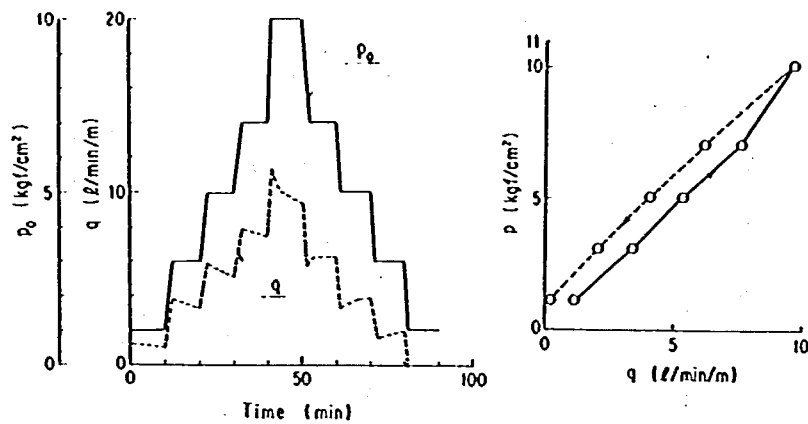


Fig. 13 p_0 and q with time and p - q curve.

unsteady flow (see Fig. 13) in spite of long-term water injection, we should calculate Lugeon units on the basis of the straight line connecting the origin and the maximum pressure point. For the purpose of investigating the required time up to the steady flow condition t , we have carried out unsteady seepage analysis under various conditions in the location of the groundwater level, S_s and ψ_0 . The results of the analyses are shown in Figs. 14 ~ 16.

In the case of tests conducted below the groundwater table, the larger S_s is, the longer t is. However t does not depend upon $C(\theta)$ ($= \partial \theta / \partial \psi$). On the other hand, in the case of the tests above groundwater level, the larger $C(\theta)$ is, the longer t is. But t does not depend upon S_s . Furthermore it is easy to presume that t gets longer as k becomes smaller, according to the fundamental equation.

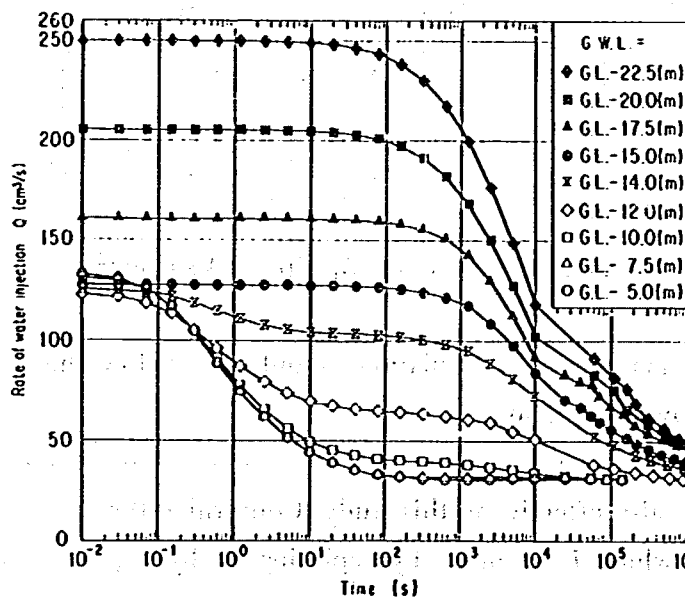


Fig. 14 Effect of ground water level ($p = 0.4 \text{ kgf/cm}^2$).

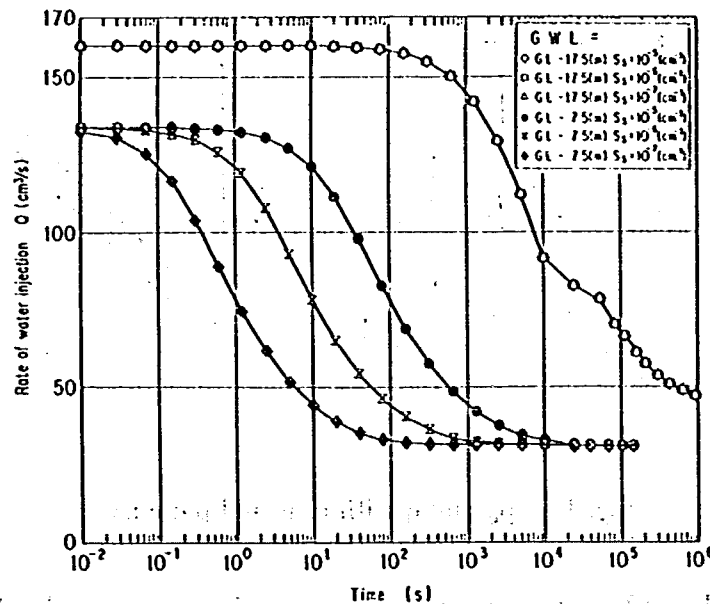


Fig. 15 Effect of S_s ($p = 0.4 \text{ kgf/cm}^2$).

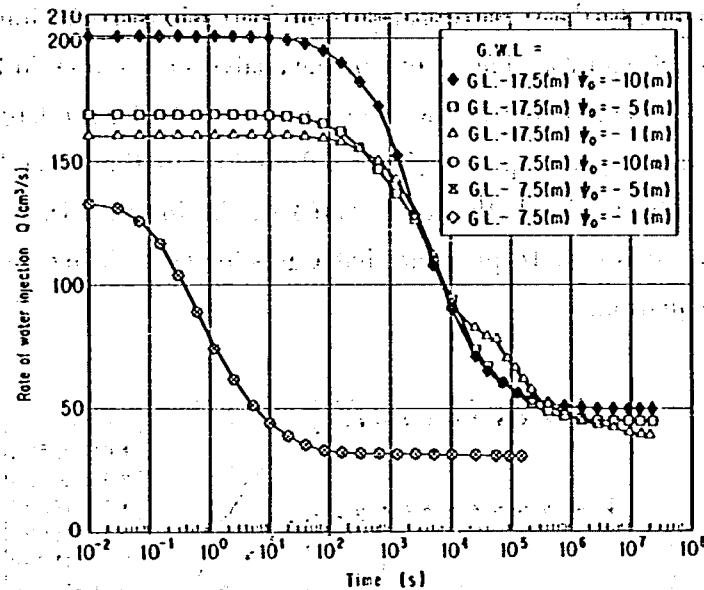


Fig. 16 Effect of ψ_0 ($p = 0.4 \text{ kgf/cm}^2$).

Nishigaki²³⁾ has made similar simulations about tests below the groundwater level, and has proposed the following equation.

$$t = 60,000 (S_s/k) \text{ (s)} \dots \dots \dots (7)$$

This equation is also effective in this study. Concerning the tests above the groundwater table, the equation which is arranged by replacing S_s by $C(\theta)$ is effective. Though it is difficult to evaluate the hydraulic characteristics of the foundation, such as k , S_s and so on, before LWT, elaborate observation of geological conditions to calculate t roughly with some results of previous research about unsaturated characteristics^{24), 25)} is very important.

7. PERMEABILITY INCREASING TYPE p-q CURVE

(1) Causes of occurrence

At the pressure ascending stage, this type of p-q curve indicates that permeability increases due to the increment of pressure, as shown in Fig. 6 (f) and (g). This type of curve is composed of the one curve type (see Fig. 6 (f)) and the hysteresis loop type (see Fig. 6 (g)), similar to the permeability decreasing type p-q curve. Discharge at the pressure ascending stage of the hysteresis loop type p-q curve is usually smaller than that of the pressure descending stage. The reasons why these types of p-q curve would be obtained are listed as follows :

(One curve type)

- ① Overestimation of head loss due to resistance in pipe h_3 .
- ② Though fissures and cracks are enlarged by injection pressure, this deformation is not permanent and the foundation returns to its former state due to decrease of pressure.

(Hysteresis loop type)

- ① Enlargement of fissures and cracks due to injection pressure is permanent and foundation does not return to its former state.
- ② Fillings in fissures and cracks of jointed rock foundations and/or soil particles composing soil foundations are washed out.

(2) Detailed investigations on the one curve type

a) Head loss

If we overestimate head loss h_3 in analyzing the Lugeon units, we obtain permeability increasing and one curve type p-q curves. Countermeasures against it are the same as those described in 6. (2) a).

b) Temporary deformation

If fissures and cracks of jointed rock foundations or voids of soft rock foundations and/or sand and gravel deposits are enlarged by water injection, the apparent permeability gets larger due to the increment of pressure, and this results in obtaining permeability increasing type p-q curves. However, if the deformation of the foundation is not permanent but temporary, p-q curves become the one curve type.

When we dam engineers obtain this type of curve, we usually calculate the Lugeon unit Lu_2 (see Fig. 17) by using a straight line connecting the origin and the maximum pressure point from a safe viewpoint. Though locally concentrated water pressure is applied to dam foundations at LWT, it is not during the filling of reservoirs. Furthermore, dam bodies work as overburden loading or counterweight to control upheaving or lateral flow of dam foundation. Therefore, it is possible to calculate the Lugeon value by extrapolating the line connecting the origin and the minimum pressure point, on condition that overburden loading is evaluated quantitatively.

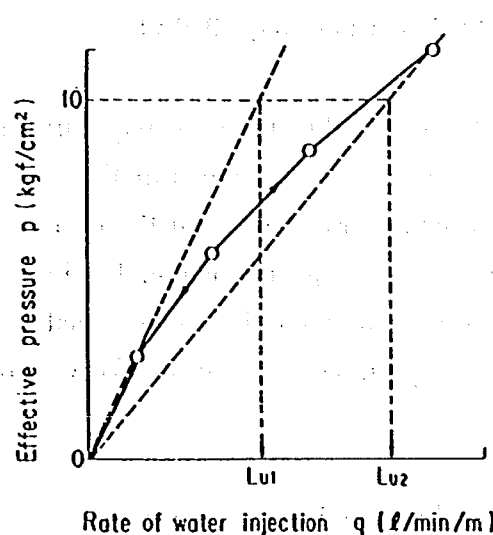


Fig. 17 Determination of Lugeon value.

(3) Detailed investigations on the hysteresis loop type

In case fissures and cracks of jointed rock foundations deform permanently or filling of fissures and cracks and soil particles composing soil foundations are washed out, permeability increasing and hysteresis loop type p - q curves are obtained. There are three methods of determining Lugeon values from the above-mentioned p - q curves.

- ① The method of calculating Lugeon value Lu_1 (see Fig. 18) using a straight line connecting the origin and the minimum pressure point at the pressure ascending stage.
- ② The method of calculating Lugeon value Lu_2 (see Fig. 18) using a straight line connecting the origin and the maximum pressure point.
- ③ The method of calculating Lugeon value Lu_3 (see Fig. 18) using a straight line connecting the origin and the minimum pressure point at the pressure descending stage.

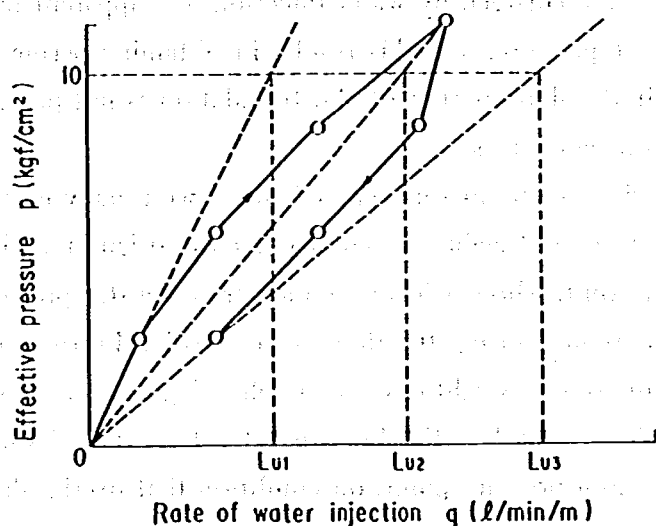


Fig. 18 Determination of Lugeon value.

There is much difference between flow conditions in foundations during LWT (radial flow condition) and those during the filling of a reservoir (one-dimensional flow condition). That is the reason why it is very difficult to investigate the permanent deformation or wash-out of soil particles during impounding of a dam reservoir with the results of LWT. Therefore, we hesitate to propose that Lu_1 has to be adopted as the Lugeon value. From a safe viewpoint, it is acceptable that Lu_2 or Lu_3 might be adopted as the Lugeon value.

8. OTHER TYPES OF p-q CURVES

(1) Straight line type p-q curve without passing through the origin

We sometimes meet p-q curves which have a linear relationship between p and q, but do not pass through the origin, as shown in Fig. 6 (h). Occurrence of this type of p-q curve is mainly supposed to depend upon the measuring accuracy of groundwater pressure before LWT. Because distribution of groundwater pressure is very complicated in rock foundations and does not always indicate static water pressure distribution, we have to pay attention to the existence of perched groundwater or confined groundwater. The best countermeasure against it is to install a pore pressure gauge in the test section and to observe the groundwater pressure around the test section before the test.

Since it is possible to mistake this type of p-q curve for a permeability decreasing type p-q curve, we have to make careful treatment in analyzing the results of LWT.

(2) Multi-slope type p-q curve

The multi-slope type p-q curve illustrated in Fig. 6 (i) would be obtained because of insufficient washing of the testing hole or abrupt opening of fissures and cracks. In the former case, the Lugeon value has to be decided from the line before bending. On the other hand in the latter case, it has to be calculated from the line after bending. Therefore we have to calculate the Lugeon value by analyzing the washing condition of the borehole and geological conditions as a whole.

(3) Gentle slope type p-q curve

In this report we define gentle slope type p-q curves as p-q curves obtained from the following reasons.

① When LWT is conducted at a jointed rock foundation having high permeability, the capacity of the injective pump cannot be sufficient. This results in the occurrence of this type of p-q curve.

② If we perform LWT for weak rock foundations or sand and gravel deposits with high pressure the same as for hard rock foundations, foundations would be broken even at the lowest pressure of the test and the permeability would be overestimated.^{1), 3), 26), 27)}

In the case of ① mentioned above, a short-length test section, a low pressure test and a highly viscous fluid test are good countermeasures in order to get the precise Lugeon value. But an increment of the capacity of the pump without changing the length of the test section and injective pressure is not effective.

In the case of ② mentioned above, injection pressure has to be controlled accurately at a low range of pressure using a pump with a low pulsatory motion and installing a large capacity chamber to the pump. Furthermore we should perform other in-situ permeability tests to check the accuracy of LWT.^{3), 26), 27)}

9. CONCLUSIONS

The summary of this paper is shown below.

- ① The p-q curves obtained from LWT have been classified into several categories on the basis of their shapes, as illustrated in Fig. 6.
- ② We have arranged the causes of occurrence of each type of p-q curve.
- ③ Investigations on the influence of each cause on shape of curve have been performed.
- ④ We have proposed a method of calculating Lugeon values which govern seepage through the dam foundation during the filling of a reservoir. Concretely speaking, we have to measure effective pressures precisely by measuring groundwater pressure around the test section and correcting head loss in the pipe accurately. Much attention has to be paid to unsteady flow, filling in foundations and deformation and breakage of foundations. Finally we have to analyze whether the test section is located below or above the groundwater table and whether flow condition is turbulent or laminar.

10. ACKNOWLEDGEMENTS

We wish to express our gratitude to Mr. Fuminori Hirose, Hazama-Gumi Ltd., and Mr. Hideo Shibuichi, Nittoc Construction Co. Ltd., who gave us great assistance and help with this study.

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**PERMEABILITY AND LUGEON
VALUES OF DAM
FOUNDATIONS**

ISSN 0386-5878

土木研究所資料第3022号

平成3年8月(1991)

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Abstract :

In surveying the permeability of dam foundations, a Lugeon water test is usually adopted and the permeability is evaluated by the Lugeon value (Lu). The curve between pressure and the rate of water injection (p-q curve) is drawn by using the test results and the Lugeon value is obtained from the slope of the straight line part of the p-q curve. However, quite a few p-q curves which have various shapes other than a straight line are obtained when Lugeon water tests are performed in the field. Therefore, in order to interpret the results of Lugeon water tests accurately the authors perform the following things : (1) p-q curves obtained from Lugeon water tests are classified into several categories. (2) causes of several p-q curves classified in (1) are summarized and (3) the methods to determine the accurate Lugeon value from each p-q curve are illustrated.

Keywords : Lugeon water test, p-q curve, Lugeon value, seepage analysis.

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