Calculation of Filling Ratio of Fissures for Curtain Grouting by Acoustic Velocity of Rock Masses

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Abstract. In the construction of hydropower projects, the detection method for curtain grouting has not been recognized for the filling the fissures at present. This paper calculates the filling ratio of fissures in rock masses using acoustic velocity data before and after grouting. According to a simplified two-phase model of rock mass, a calculation formula of filling ratio for rock mass fissures is derived from acoustic velocity. The rock mass velocity ratio curve before grouting is fitted according to Poisson distribution formula to obtain the rock mass velocity, and then the filling ratio for rock mass fissure grouting is calculated by combining water, cement, rock mass velocity before and after grouting. The filling ratio of fissures in the rock mass after curtain grouting by using the acoustic velocity of the rock mass in a hydropower project can be mutually verified by the results of the borehole TV and water pressure test.

1. Introduction
Curtain grouting in a hydropower project is to inject slurry into fissures and voids of rock and soil masses under a certain pressure to form a continuous water-blocking curtain, which is the main means to reduce seepage flow and seepage pressure and plays an important role in ensuring the safety of hydraulic structures.

The commonly used detection methods for curtain grouting in the hydropower project are water pressure test, geophysical detection, core drilling method, etc\textsuperscript{[1-4]}. The water pressure test is used to identify the grouting effect by detecting the permeable rate of the grouted rock mass. The permeable rate from the water pressure test reflects the relative permeability of the grouted rock mass under a certain pressure, which is the recommended practice. The advantage of the water pressure test is that it is carried out under a given pressure and has the advantage of reflecting the water blocking capability of the curtain rock mass under water pressure. However, it also has the disadvantages of high cost, extended time, complicated equipment, etc. In order to make up for the shortage of the pressure water test, a geophysical survey method is usually used to assist in detecting the curtain grouting effect.

Geophysical detection usually adopts such methods as rock mass velocity detection and borehole TV observation, which can indirectly reflect grouting quality and is an auxiliary method for the recommended practice. Geophysical survey has many detection methods, which are favorable for comprehensive analysis and have the advantages of rapidness, cost-effectiveness and convenience for large-area testing, etc.
Detecting grouting quality by the acoustic velocity of a rock mass is an indirect method to reflect the grouting quality by testing the propagation velocity of acoustics in the rock mass before and after grouting and comparing the increase of the rock mass velocity before and after grouting.

At present, there is no sophisticated detection method for filling fissures in rock masses by the curtain grouting. In the grouting process, the amount of grout injected does not actually reflect the filling of fissures. In this paper, the filling ratio of grouting slurry in the rock mass fissures is derived by testing the propagation velocity of acoustics in a rock mass before and after grouting.

2. Calculation method

In borehole acoustic testing, the rock masses around the borehole wall can be regarded as a combination of the rock mass, structural plane and fissure that is filled with water. Referring to the three-phase diagram of soil in soil mechanics[5], the underground rock mass is regarded as two phases of rock mass and water, and the two-phase diagram is shown in Figure 1(a).

According to the relation between distance and velocity, i.e. Formula (1), the fissure ratio in a rock mass can be derived, see Formula (2).

\[
\frac{L_r}{V_r} + \frac{L_w}{V_w} = \frac{L}{V_q} \tag{1}
\]

\[
\frac{L_w}{L} = \frac{V_w(V_q - V_r)}{V_q(V_q - V_w)} \tag{2}
\]

After grouting, the rock mass fissures are partially filled with slurry, as shown in Figure 1(b). According to the relation between distance and velocity, i.e. Formula (3) and joint Formula (2), the filling ratio of fissures is derived, as shown in Formula (4).

\[
\frac{L_r}{V_r} + \frac{L_c}{V_c} + \frac{L_w - L_c}{V_w} = \frac{L}{V_h} \tag{3}
\]

\[
\frac{L_c}{L_w} = \frac{V_c(V_r - V_w)(V_h - V_q)}{V_h(V_c - V_w)(V_r - V_q)} \tag{4}
\]

Where: \(V_r\)—rock mass velocity; \(V_w\)—water velocity; \(V_c\)—cement velocity; \(V_q\)—rock mass velocity before grouting; \(V_h\)—rock mass velocity after grouting; \(L\)—rock mass length; \(L_w\)—fissure width; \(L_r\)—rock mass width; \(L_c\)—width of cement-filling fissure; \(L_w/L\)—rock mass fissure ratio; \(L_c/L_w\)—fissure-filling ratio after grouting.

3. Project cases

A large hydropower station in northeast China was classified as a large-type(1) project. The rock mass in the dam site area was metamorphic conglomerate, which was hard and intact. The curtain grouting was divided into III sequences of construction, with the grouting hole spacing of 2m and grouting...
pressure of 3MPa. The curtain grouting test adopted the comprehensive methods of water pressure test, single-hole acoustic test and borehole TV observation.

A grouting pilot hole for the single-hole acoustic velocity test was used for pre-grouting detection, and the post-grouting detection hole was located between the two adjacent grouting holes.

For the single-hole acoustic test before grouting, a total of 25 holes and 7,370 test points were tested with an average velocity of 5,267 m/s; after grouting, 24 holes and 7,129 test points were tested, with an average velocity of 5,430 m/s. Statistics of acoustic velocities before and after grouting were shown in Figure 2 and Table 1.

In Formula (4) for calculating the filling ratio of fissures, the rock mass velocity ($V_r$) is unknown. In order to determine the rock mass velocity in the works, such methods are usually used as the maximum measured velocity in borehole, empirical value and others with an intact rock mass adopted for the velocity test. Each of the above methods has its advantages and disadvantages.
Table 1 Statistical sheet of rock mass velocities before and after grouting

| Velocity (m/s) | No. (ea) | Ratio (%) | Velocity (m/s) | No. (ea) | Ratio (%) |
|----------------|----------|-----------|----------------|----------|-----------|
| 6061           | ---      | ---       | 6061           | 10       | 0.14      |
| 5882           | 4        | 0.05      | 5882           | 360      | 5.05      |
| 5714           | 90       | 1.22      | 5714           | 877      | 12.30     |
| 5556           | 1181     | 16.02     | 5556           | 2083     | 29.22     |
| 5405           | 1886     | 25.59     | 5405           | 2062     | 28.92     |
| 5263           | 1820     | 24.69     | 5263           | 779      | 10.93     |
| 5128           | 1267     | 17.19     | 5128           | 373      | 5.23      |
| 5000           | 586      | 7.95      | 5000           | 220      | 3.09      |
| 4878           | 235      | 3.19      | 4878           | 138      | 1.94      |
| 4762           | 101      | 1.37      | 4762           | 59       | 0.83      |
| 4651           | 67       | 0.91      | 4651           | 45       | 0.63      |
| 4545           | 42       | 0.57      | 4545           | 25       | 0.35      |
| 4444           | 22       | 0.30      | 4444           | 14       | 0.20      |
| 4348           | 26       | 0.35      | 4348           | 20       | 0.28      |
| 4255           | 16       | 0.22      | 4255           | 13       | 0.18      |
| 4167           | 8        | 0.11      | 4167           | 18       | 0.25      |
| 4082           | 5        | 0.07      | 4082           | 8        | 0.11      |
| 4040           | 1        | 0.01      | 4000           | 8        | 0.11      |
| 4000           | 4        | 0.05      | 3922           | 11       | 0.15      |
| 3922           | 5        | 0.07      | 3846           | 3        | 0.04      |
| 3846           | 2        | 0.03      | 3774           | 1        | 0.01      |
| 3774           | 1        | 0.01      | 3704           | 1        | 0.01      |
| 3571           | 1        | 0.01      | 3571           | ---      | ---       |
| 3509           | ---      | ---       | 3509           | 1        | 0.01      |

It tends to cause lower velocity measurements by taking the intact rock mass for the velocity test. As the velocity of a rock mass is influenced by surrounding rock pressure, temperature, humidity, etc. [6], the measured velocity value is higher. After the rock mass is made into a test block, the test conditions have changed and the measured velocity value is lower. Meanwhile, the selection of test blocks should be representative. When the number of test blocks is small, the discreteness of test data tends to be large, resulting in significant deviation in values. By taking the maximum measured velocity in borehole, it tends to cause the larger velocities of rock masses, while the selection of empirical value is easy to be influenced by personal subjective factors. As personal engineering experiences are different, the velocity values for the same type of rock mass are also quite different.

Poisson distribution is a common discrete probability distribution in statistics and probability. It was published by French mathematician Poisson in 1838. The Poisson distribution is often used to describe the probability distribution of the number of random events in unit time and space. Poisson distribution is closely related to binomial distribution and normal distribution.

The probability mass function of Poisson distribution[7] is:

$$P(X = k) = \frac{e^{-\lambda} \lambda^k}{k!}, k = 0,1,\ldots$$  \hspace{1cm} (5)

Where: $\lambda$ is the average number of random events in unit time (or unit area).

The lithology in the curtain grouting area of the dam site is metamorphic conglomerate with single lithology. The grouting holes in depth are regularly deep and shallow, and the measuring points are
evenly distributed in space. See Figure 3(a) for the probability curve of measured acoustic velocity before grouting and Figure 3(b) for the shape of common Poisson distribution curve. Based on the observation, there is approximately a mirror-image relationship between the probability curve of measured rock mass velocity before grouting and the common Poisson distribution curve ($\lambda=4$), so Poisson distribution can be used to fit the probability curve of rock mass velocity before grouting in the work area.

In Figure 2, it is shown that the probability curve of rock mass velocity after grouting is shifted to the trend of velocity increase due to the influence of grouting compared with the probability curve of rock mass velocity before grouting, and its shape is quite different from the Poisson distribution curve.

According to the normal distribution formula, the Poisson distribution fitting formula of rock mass velocity is established.

\[
k = \frac{-(V - V_r)}{\sigma}
\]

\[
P(X = k) = \frac{e^{-\lambda} \lambda^{-(V - V_r)/\sigma}}{[-(V - V_r)/\sigma]!}
\]

Where: \(V_r\)—rock mass velocity; \(\sigma\)—velocity classification value; \(V\)—velocity.

The acoustic velocity of a rock mass before grouting is fitted according to Formula (7). When \(\lambda=2.3\), \(V_r=5590\text{m/s}\) and \(\sigma=130\text{m/s}\), the error is the minimum. See Table 2 for fitted velocity values and Figure 4 for fitted velocity probability curves.

The 2.15% rock mass fissure ratio and the 63.1% fissure cement filling ratio after grouting are derived by substituting into Formulas (2) and (4) the water velocity \(V_w=1450\text{m/s}\), the cement velocity \(V_c=3720\text{m/s}\) (field cement block test), the average velocity of rock mass before grouting \(V_q=5267\text{m/s}\), the average velocity of rock mass after grouting \(V_h=5430\text{m/s}\) and the fitting rock mass velocity \(V_r=5590\text{m/s}\).

24 holes were tested after grouting with the borehole TV, identifying 313 fissures, 128 of which were well filled with cement, accounting for 40.9%, 21 of which were partially filled, accounting for 6.7% and 164 of which were unfilled, accounting for 52.3%.

The data show that the fissure-filling ratio observed by the borehole TV is quite different from the fissure-filling ratio calculated by the acoustic velocity, for the fissure-filling ratio calculated by the acoustic velocity is calculated by volume with the borehole TV observation.
Figure 4. Poisson fitting velocity before grouting

| Fitting rock mass velocity (m/s) | k | Ratio (%) |
|-------------------------------|---|-----------|
| 5720                          | -1| ---       |
| 5590                          | 0 | 10.03     |
| 5460                          | 1 | 23.06     |
| 5330                          | 2 | 26.52     |
| 5200                          | 3 | 20.33     |
| 5070                          | 4 | 11.69     |
| 4940                          | 5 | 5.38      |
| 4810                          | 6 | 2.06      |
| 4680                          | 7 | 0.68      |
| 4550                          | 8 | 0.19      |
| 4420                          | 9 | 0.05      |
| 4290                          | 10| 0.01      |
| 4160                          | 11| 0.00      |
| 4030                          | 12| 0.00      |
| 3900                          | 13| 0.00      |
| 3770                          | 14| 0.00      |
| 3640                          | 15| 0.00      |
| 3510                          | 16| 0.00      |

The filling ratio of fissures is calculated by strips. It is found through observation that the filling ratio of wide fissures is higher than that of narrow fissures, and the statistics by strips are greatly influenced by human experiences. The results of volume calculation have a good correlation with those of water pressure test, which makes it accurately expressed. Overall, the fissure-filling ratios obtained by the two methods can be mutually verified.

4. Conclusions

(1) In this paper, the filling ratio of fissures in the grouted rock mass is calculated by the acoustic velocity of the rock mass before and after grouting, and the results are generally consistent with the observations of the borehole TV, which shows that the method of calculating the filling ratio of fissures in the grouted rock mass by using the acoustic velocity of the rock mass is feasible with the accurate results.

(2) The determination of rock velocities should be based on field test data statistics. For the measuring points with single lithology and uniform spatial distribution, the acoustic velocity data of a rock mass conforms to Poisson distribution, and Poisson distribution fitting is suitable to determine the acoustic velocity of the rock mass.
(3) At present, the direct evaluation index of curtain grouting quality is the permeable rate from the water pressure test with single parameter. The testing and calculation results of rock mass fissure-filling ratio can be used to evaluate the curtain grouting quality together with the permeable rate.

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