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Study on the Calculation of Attenuation Quality Factor *Q*-Value in Microseismic Monitoring: Results from Two Rock Engineering Cases

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Abstract. The quality factor *Q*-value is one of the important parameters for calculating microseismic source parameters, and it is also an important reference for reflecting geological information. However, there are few studies on the *Q*-value of rock engineering at present, and its understanding needs to be further improved. For the above reasons, we adopted the widely used Atkinson method to calculate *Q* in two rock engineering. The results show that the *Q* in the microseismic monitoring is mainly on the order of 10^1~10^2, which is generally smaller than the *Q* in earthquake seismology. When the frequency is less than 500Hz, the *Q* is a constant, and when the frequency is greater than 500 Hz, it increases with the frequency. The research results also show that the *Q* in the engineering with high in-situ stress and complete rock mass structure is larger than that in the low in-situ stress and broken rock mass is relatively broken, indicating that the *Q*-value can reflect the geological information to a certain extent.

Keywords. Microseismic monitoring, rock engineering, attenuation, quality factor, *Q*-value

1. Introduction

With the increasing construction of deep rock engineering, there are more and more dynamic disasters, such as rockburst, mine earthquake, etc. As a three-dimensional, real-time, and effective safety monitoring method, microseismic monitoring technology is applied more and more in engineering [1]. For example, Chen *et al*. used microseismic monitoring for rock burst warning of deep-buried tunnels, which accurately warned rockburst and improved the efficiency of tunnel construction [2]. Xu

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et al. applied microseismic monitoring to the safety monitoring of rock mass stability of underground powerhouse of hydropower station, and gave an accurate early warning to the unstable parts of rock mass, thus reducing the harm caused by engineering accidents [3]. These monitoring and early warning are based on statistics and analysis of microseismic source parameters. For the research on the calculation of source parameters, seismology has developed relatively perfect theories and methods, and most of them can be directly transplanted to the calculation of microseismic source parameters. However, sometimes, due to differences in scale and other aspects, the values of the parameters will also be different, so it is necessary to carry out adaptive research.

In the field of microseismic monitoring, there have been abundant research and many achievements on the arrival picking, location, and focal mechanism, and good results have been achieved in engineering applications [4]. However, there is A small amount of research on source parameters such as source spectrum and radiation energy, and the calculation of source parameters mainly depends on the calculation of source spectrum. The attenuation correction is an extremely important step in the calculation of the source spectrum [5, 6].

The microseismic wave attenuation is caused by the inelasticity and inhomogeneity of medium. The quality factor *Q*-value can be used not only for spectrum correction in the process of source spectrum calculation but also for reflecting many information changes such as geology and stress, which has important significance and wide application. However, microseismic monitoring in rock engineering is different from those of natural earthquakes in terms of media properties and scales, so it is still necessary to study the calculation of microseismic attenuation parameters.

The *Q* is a quantitative representation of attenuation and is different under different conditions. It is generally considered that *Q* is a frequency-dependent parameter, but some studies have shown that *Q* is independent of frequency. More researchers believe that *Q* is a constant at low frequency and related to frequency at high frequency, but there is no conclusion yet [7]. At present, research on *Q* in microseismic monitoring field of rock engineering is still scarce, and there are few references for the *Q*, so more research is still needed.

Based on the above reasons, Atkinson Method, a widely used method for calculating the *Q*, is adopted in this paper to calculate the *Q* in rock engineering, which is expected to provide an effective reference for using attenuation information to study regional geological conditions and spectrum attenuation correction.

2. Method

There are many methods to calculate *Q*-value, such as the spectral ratio method, Atkinson method, and coda method. The spectral ratio method is a direct method to calculate *Q*, requiring fewer a priori assumptions. However, it has strict site requirements, and it is difficult to get effective results by directly using microseismic data in engineering [8]. The *Q* calculation method proposed by Atkinson in 1992 is one widely used method in seismology [9]. The method is to use multi-source and multi-sensor data to fit the theoretical source spectrum. Because this method does not require the orientation of sensors and seismic sources, and the interception of waveforms only depends on the arrival of S-waves, this method is widely used due to its few restrictions and simple calculation. Atkinson method is used to calculate Q, which is mainly divided into two steps: displacement spectrum calculation and Q-value calculation.

2.1. Displacement Spectrum Calculation

Data processing steps [10]:

(1) Intercept "S window". The window begins with the S-phase arrival and continues 90% of the total energy of S-wave. And the "S window" length is an integer power of 2.

(2) The lag-window spectral technique is adopted to obtain a stable Fourier spectrum. The Fourier spectrum of the acquired S-wave window data is calculated by sliding with 64 samples as a segment and 50% overlap between segments. When performing the fast Fourier transform, add 5% cosine-taper to each segment.

(3) Compute the estimated velocity spectrum:

$$\bar{u}(f)=\left[\sum_{i=1}^{m}u_i^2(f)\frac{T}{mt}\right]^{\frac{1}{2}} \tag{1}$$

where T is the “S window” duration, t is the duration of each segment, and m is the number of segments.

(4) Calculate the noise spectrum. Take a segment of signal (64 sampling points) before P-phase arrival to calculate the noise spectrum $N(f)$.

(5) Deduct the noise, and then obtain the corrected velocity spectrum:

$$u(f)=\left[\bar{u}^2(f)-N^2(f)\right]^{\frac{1}{2}} \tag{2}$$

(6) Compute the displacement spectrum:

$$d(f)=u(f)/(2\pi f) \tag{3}$$

2.2. Q-value Calculation

According to seismological knowledge, the displacement spectrum recorded by the sensor can be expressed as:

$$S(f)=O(f)\bullet G(R)\bullet A(f,r) \tag{4}$$

where $O(f)$ is the observed source spectrum, $G(R)$ is the geometric spreading with $G(R)=1/R$, and $A(f, r)$ is the attenuation with $A(f,r)=e^{-\frac{\pi fR}{v_c Q(f)}}$.

Number the parameters in (4):

$$S_{ij}(f)=O_i(f)\bullet G(R_{ij})\bullet e^{-\frac{\pi fR_{ij}}{v_c Q(f)}} \tag{5}$$

where i is the source order number and j is the sensor order number. $O_i(f)$ represents the i-th source spectrum, $S_{ij}(f)$ represents the observed displacement spectrum of the i-th microseism received by the j-th sensor, and R_{ij} represents the distance from the j-th sensor to the i-th source.

Logarithm of both sides, we get

$$\lg S_{ij}(f) = \lg O_i(f) + \lg G(R_{ij}) - c(f)R_{ij} \tag{6}$$

where $c(f) = \dfrac{(\lg e)\pi f}{v_c Q(f)}$, and the quality factor $Q(f) = \dfrac{(\lg e)\pi f}{v_c c(f)}$ can be obtained。

(6) can be changed to

$$\lg O_i(f) = \lg S_{ij}(f) - \lg G(R_{ij}) + c(f)R_{ij} \tag{7}$$

Define residuals

$$\varepsilon = \sum_{i=1}^{M}\sum_{j=1}^{N}\left|D_{ij}(f)\right| \tag{8}$$

where

$$D_{ij}(f) = \left[\lg O_i(f)\right]_j - \frac{\sum_{j=1}^{N}\left[\lg O_i(f)\right]_j}{N} \tag{9}$$

We can obtain $c(f)$ when using the genetic algorithm by minimizing the defined residual ε. Then the quality factor can be obtained $Q(f)$.

3. Engineering Applications

3.1. Engineering Introduction

To ensure the reliability and comparability of the calculation results, two typical rock projects are selected to analyze the attenuation calculation results.

3.1.1. Project 1: Hangjiang-to-Weihe Project in Qinling

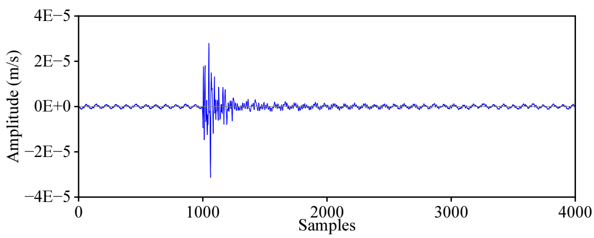
The Hanjiang-to-Weihe Project, the South-to-North Water Diversion Project in Shaanxi China, aims at solving the water-shortage problem of the cities located on the Weihe river coast in the central Shaanxi area. The Qinling water conveyance tunnel is one of the key projects in the whole project whose construction is difficult. The Qinling Tunnel is 81.779 km long, and the maximum buried depth of the tunnel is about 2012 m, which makes it have serious problems such as high in-situ stress, high-temperature construction, and super-long distance exhaust air supply. For the above reasons, long-term microseismic monitoring was carried out on-site. Hard and brittle rocks, mainly quartzite and granite, are found in this area. The rock mass was relatively complete and the faults were undeveloped [11]. Under the condition of high stress and high brittleness rock, rock burst frequently occurs in the construction project, which seriously affects the construction safety and progress of the project. This time, a section of microseismic data during drilling and blasting construction is selected. During construction, rockburst occurred frequently, and the drilling and blasting construction produced less noise than TBM construction, which made the signal-to-noise ratio of the recorded microseismic signals high, so we can get more high-quality data for the calculation of the *Q*-value.

3.1.2. Project 2: Yebatan Hydropower Station Underground Powerhouse

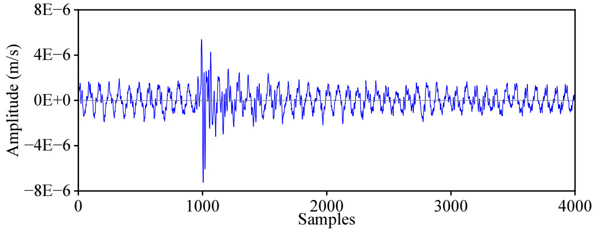
The Yebatan Hydropower Station is located on the mainstream of the Jinsha River in Baiyu County, Sichuan Province, and Gongjue County, Tibet Province. The water diversion and power generation buildings are arranged on the right bank of the dam site. The underground powerhouse mainly includes the main powerhouse, main transformer room, and tailrace surge tank. The vertical buried depth of the underground powerhouse area is 252~420m. According to the PD08 exploration flat tunnel, the lithology is mainly quartz diorite and granodiorite, and the structure of the rockmass is broken. The structural planes are developed, mainly including faults, dense cracks, and joints. Physical and geological phenomena in the area are mainly manifested as weak weathering of superficial rocks, strong unloading, and random collapse. To monitor the instability of rock mass structures such as spalling and collapse in the construction of the underground powerhouse, a microseismic monitoring system is introduced for continuous monitoring, and a large number of low-energy microseismic events are observed during construction, which also provides rich and high-quality data for this *Q*-value calculation.

3.2. Data Selection

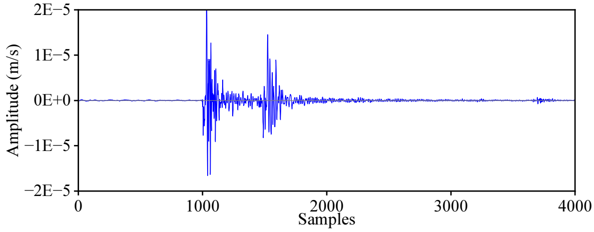
It is necessary to select microseismic signals with high quality because of the requirements in the calculation of the *Q*-value. Firstly, the events with poor overall signal quality are removed, and secondly, the waveforms with low signal-to-noise ratio are removed. To improve the accuracy of “S window” and noise spectrum calculation, it is necessary to ensure that a microseismic signal record contains only one event, some cases are shown in figure 1. We selected 166 microseismic events from Hangjiang-to-Weihe Project and 143 events from Yebatan Project finally.



(a) Typical microseismic signal (accepted)



(b) Microseismic signals with excessive noise (rejected)

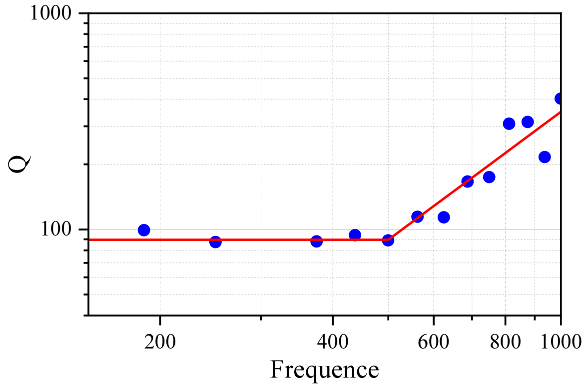


(c) microseismic signals containing several events (rejected)

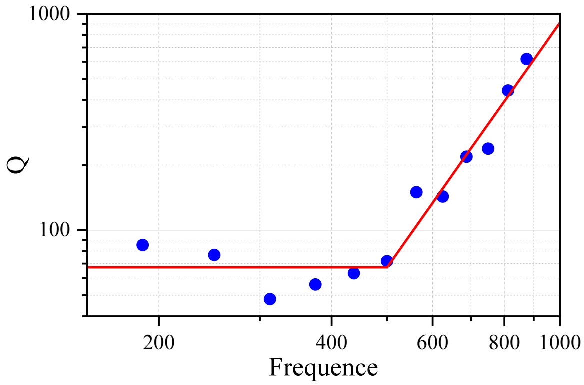
Figure 1. Typical accepted and rejected microseismic signals

3.3. Calculation Results and Analysis

According to experience and other references, the lower limit of Q interval is 10, and the upper limit is 1000 [8]. For each frequency point, the genetic algorithm is used to get the optimal value. The data whose calculation results fall outside the set interval and have large dispersion are eliminated to get the final calculation result, as shown in figure 2.



(a) Q in Hangjiang-to-Weihe Project



(b) Q in Yebatan Project

Figure 2. Calculation results and fitting of Q for different projects.

The blue dot represents the calculation result of Q, and the red curve represents the fitting result.

It can be seen from figure 2 that when the frequency is below 500Hz, the Q is a constant. When the frequency is greater than 500, the Q increases with the increase of frequency. This rule is consistent with the change of Q in seismology, but the difference is that in seismology, it is considered that when the frequency $f < 1$ Hz Q is a constant, but it increases when $f > 1$ Hz. There is the following relationship when $f > 1$ Hz [12]:

$$Q(f) = Q_0 f^{\alpha} \tag{10}$$

Therefore, the following functional form is used during fitting Q:

$$Q(f) = \begin{cases} Q_0, & f \le 500 \\ Q_1 f^{\alpha}, & f > 500 \end{cases} \tag{11}$$

and $Q(f)$ satisfied $Q_0 = Q_1 \cdot 500^{\alpha}$. The final fitting result is shown in figure 2.

The Q expression in Hangjiang-to-Weihe Project is:

$$Q(f) = \begin{cases} 89.59, & f \le 500 \\ 4.4494e^{-4} \cdot f^{1.9652}, & f > 500 \end{cases} \tag{12}$$

The Q expression in Yebatan Project is:

$$Q(f) = \begin{cases} 67.36, & f \le 500 \\ 4.8123e^{-9} \cdot f^{3.7592}, & f > 500 \end{cases} \tag{13}$$

By comparing the Q in earthquake seismology, we can know that the frequency ranges concerned by microseisms and earthquakes are different. The frequency ranges concerned by seismology are mainly in the order of 10^{-1}~10^{0}, while microseisms are mainly in the order of 10e1~10e2. In their respective effective frequency ranges, the *Q* in microseisms and earthquakes is different, and the *Q* in seismology is mainly distributed in the order of 10^{2}~10^{3} [13], while the microseismic centers are usually distributed in 10^{1}~10^{2}. The *Q* of engineering microseismic monitoring is generally lower than that of earthquakes.

The relationship between *Q* and frequency is consistent with that in seismology. However, it is obvious that this demarcation point is quite different, and many seismological studies think that this demarcation point is 1 Hz. This study preliminarily estimates that the demarcation point in microseismic monitoring of two rock projects is 500Hz, and a more accurate demarcation point still needs further study. In addition, in the two rock projects, in the low-frequency band (the main distribution frequency band of the microseismic signal), the *Q* of the Hangjiang-to-Weihe Project is higher than that of the Yebatan Project, which indicates that the microseismic wave propagation attenuation in the Hangjiang-to-Weihe Project is less. This is related to the high in-situ stress and the completeness of the rock mass in the Hangjiang-to-Weihe Project, while a relatively low in-situ stress and broken rock mass in the Yebatan Project, which indicates that the *Q*-value can reflect the geological information to some extent.

4. Conclusion

In this paper, the *Q*-value of two rock engineering is calculated by Atkinson method, and the main conclusions are as follows:

(1) The frequency range of interest in rock engineering microseismic signals is quite different from that of earthquakes. The *Q* in each frequency range of interest is also different. The *Q* of microseismic engineering is lower than the *Q* in seismology usually.

(2) The *Q* is independent of frequency at low frequencies and increases at high frequencies with increasing frequency. The demarcation point between the two modes is approximately 500 Hz.

(3) In the main frequency band of interest (low-frequency band), the *Q* of the project with high in-situ stress and good rock mass integrity is higher than that of the project with low in-situ stress and broken rock mass. The *Q*-value can reflect the geological information to a certain extent.

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