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A method based on musical-staff-inspired signal processing model for measuring rock moisture content

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ABSTRACT

Mechanical properties of rocks change under hydrous condition, which easily causes instability and failure of rock, and triggers a disaster. Measuring the effect of moisture on the acoustic emission characteristics of rocks, and establishing an automatic identification model are the outstanding issues at present. In this study, a large number of acoustic emission data were collected during the rupture of rocks with different moisture contents, and the data were transformed by the musical-staff-inspired model. Several parameters, including contour, amplitude, and slope of signal, are quantitatively expressed in musical space. A curves similarity determination method was incorporated for data training. Results indicate success of measurement of rock moisture.

1. Introduction

Measurement of the rock moisture content is important in hydrological, ecological, and geotechnical engineering. Some petrologic properties of rocks, such as shear strength, tensile strength, and deformation behavior, decrease with increasing moisture. Furthermore, swelling deformation and expansive pressure occur in certain hydrophilic rocks after encountering water [1,2]. Rock damage caused by hydration weakening, which is the primary cause of engineering rock failure, is more serious than those generated by external mechanical factors [3]. Thus, research on measuring the rock moisture content has important implications for engineering practice, such as in providing reference and theoretical guidance for monitoring mine pillars, underground working, concrete construction, and other geotechnical engineering structures [4]. The rock moisture content measurement methods varied, with unique functions for each method. For example, the argillaceous rock shrinkage and swelling properties at various constant uniaxial stresses and the material linear mechanical behavior at different moisture levels were experimentally studied using a system that combines hydromechanical loadings with optical observations, with the digital image correlation by Yang et al. [5]. Matsukura et al. [6] conducted a non-destructive rock moisture measurement using an infrared optical moisture meter, and the laboratory test indicated a linear relationship between infrared ray absorbance intensity and the rock moisture content, which can be applied to further elucidate the weathering processes in sandstone. Seven different rock types were used in the comparison experiment conducted by Sakaki et al. [7], and the improved scheme for gap effects were demonstrated. Moreover, two designs for surface probes were proposed, which had great advantages in measuring accuracy and installation.

Among the numerous measuring methods, the technique based on acoustic emission (AE) is an effective non-destructive method that has dynamic monitoring coverage, high sensitivity, and other superiorities [8,9]. Its waveform signal parameters often provide the precursor of rock failure, which reflects the evolution laws about the initiation, propagation, and fracture of internal material damage during the destructive process of rock. According to this capacity, AE has been applied to mining, slope engineering, concrete construction, and other engineering applications [10–13]. Many beneficial research achievements have been published since Kaiser found the relationship between AE event and the stress applied to the material; this phenomenon was called Kaiser Effect by later scholars. For example, Ishida and Moradian et al. utilized AE to observe the fracture situation during the direct sheer process; the results validated the use of high-precision AE to monitor the damage evolution and crack growth in rock failure [14,15]. The characteristics of AE prior to uniaxial compressive rock failure are described by Rudajev et al. [16]. Verstrynge et al. combine AE-controlled creep tests with a dedicated multi-scale methodology to analyse the influence of moisture on the mechanical behavior of sandstone [17]. Based on electromagnetism and AE technology, Jing and Zhang et al. revealed the features of the fracturing process of rocks with different moisture contents [18].

Although AE technology is widely utilized, a distinguishing method for rock moisture content that can tightly combine moisture content

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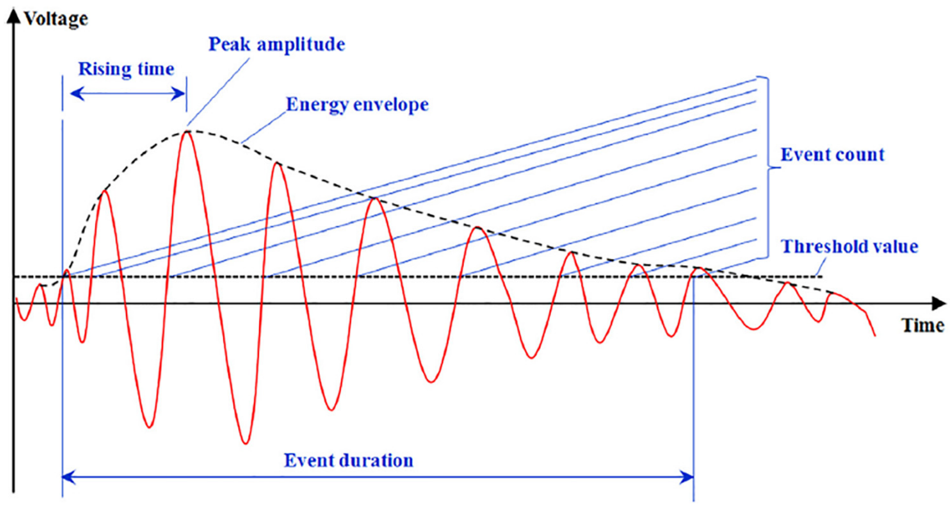

Fig. 1. Definition of the AE characteristic parameters in a simplified waveform.

and AE characteristics has not been established. Considering the difficulty of establishing an automatic analysis model in terms of large amount of data and many characteristic parameters of AE signals, the present study utilizes the musical-staff signal processing model to dispose AE signal processing method. The developed model and AE technology were then used to evaluate rock moisture content.

2. Musical-staff-inspired model for AE signal processing

The common geotechnical characteristics of AE signal, including amplitude, event duration, rising time, AE event count, threshold value, and energy envelope [19–21], are shown in Fig. 1.

In a common method to analyze the characteristics of AE signal, rising time reflects the AE signal changing rate, and energy consumption reflects the energy level of AE signal. These parameters describe a certain feature of AE signal within a short time and are incapable of reflecting the global integrated characteristics, such as signal contour and changing trends within a wide time domain. However, the aforementioned parameters lack the standard expressions of discrete signals. Thus, a musical-staff-inspired signal processing method is applied in this study.

A musical staff is a set of five horizontal lines and four spaces that represent different musical pitches [22–24], as shown in Fig. 2.

Guided by the demarcation and labeling in the spaces of musical staff, this model quantifies the pitch and meter, and designs the nine grid lines in the time domain of the AE signal wave, which is also defined as sampling line. The intersection between a grid line and signal wave is defined as a musical note.

2.1. Envelope acquisition of original signal

Given that $X(t)$ is the equation of a continuous analog signal in time domain, and assuming that the envelop equation is $f(t)$, then,

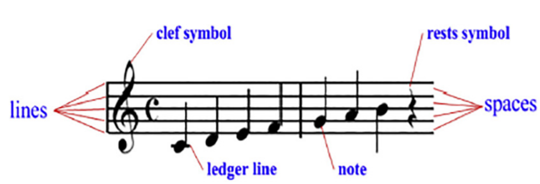

Fig. 2. Musical staff.

$$f(t)=\begin{cases} f_0(t) & t\in[t_0,t_1] \\ f_1(t) & t\in[t_1,t_2] \\ \vdots & \vdots \\ f_{n-1}(t) & t\in[t_{n-1},t_n] \end{cases} \tag{1}$$

where $t_0,t_1,...,t_n$ are the times corresponding to peaks of $X(t)$.

$f(t)$ reaches its maximum and minimum values ($f(t)|_{t=tp} = f\max$ and $f(t)|_{t=tq} = f\min$) when $t = t_p$ and $t = t_q$, where t_p and t_q are located in the section $[t_0,t_n]$.To acquire the envelope quantitatively, the sample lines are designed on the envelope wave. $S_n(t)(n = 0,1,2...8)$ are used to express the equation of a sampling line. S_0 (t), S_1 (t), S_2 (t)⋯S_8 (t) signify $SL1,SL2,SL3,...,SL9$. Thus, the musical notations on sampling lines ($SL1-SL9$) correspond to $1,2,3,4,5,6,7,\dot{1},\dot{2}$. To decrease data loss, the wave of $f(t)$ is divided equally into M sections. The sampling line is designed by considering the maximum and minimum values of the divided sections, and the value of M can be determined based on the application fields. Then, the equally divided section is defined as $k(0 < k < M)$, which exists in $[T_{k-1},T_k]$. Therefore, the function of the sampling line is expressed as (2).

$$S_n(t)|_k = q + n\times\Delta_k,\ (\ n= 0,1,2\cdots8;\ T_{k-1}\leqslant t< T_k) \tag{2}$$

where $\Delta_k = (1/8)\cdot|p-q|$ is the voltage difference between adjacent sampling lines in part k, p and q are the maximum and minimum values in the time section of section k, respectively. Assuming the signal k section was processed in the musical-staff-inspired model, the basic principle is shown in Fig. 3.

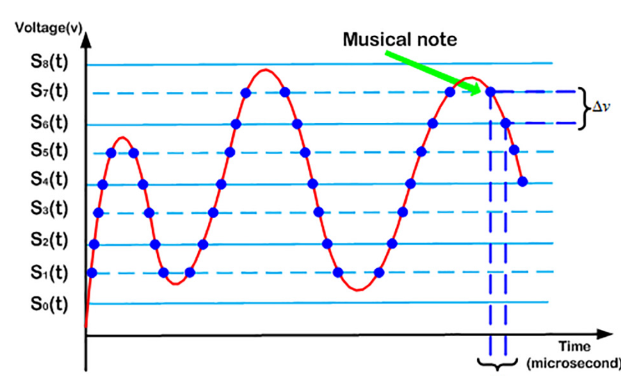

Fig. 3. Basic principle of musical-staff-inspired model.