Modeling and simulation of the effect of rock grain sizes on vibration characteristics when rock drilling

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(Section 3 of this paper has been published in Shock and Vibration, Volume 2020, Article ID 9036371)

Abstract. A numerical simulation method and an experimental method were employed to investigate the relationships between the mineral particle sizes and spectral characteristics of the sound or vibration signals generated during rock drilling processes. Several rock models with different aggregates were generated by means of determining the locations of aggregates randomly. The modal analysis of the rock models was conducted to reveal their vibration characteristics. Simulation results indicated that the smaller the aggregate size, the larger the high-frequency composition of sound and vibration. Several drilling experiments were performed on the rock specimens of different aggregate sizes. By using an indoor signal acquisition and analysis system, data from the sound waves and vibrations were collected, and characteristic signals were extracted. Moreover, the spectral characteristics of the sounds and vibrations of different aggregate sizes were identified. The experiment results are consistent with the conclusion of the simulation. The study provides a possibility for developing a method to evaluate the rock structure information collected from drilling vibration or sound signals for a fine exploration of geological surveys.

1. Introduction

In the field of geology and engineering drilling, traditional methods are employed to judge the geological condition, including the lithology, rock joints, nature of abnormal bodies, and depth and scale of the development of abnormal bodies. The judgment is mainly based on the properties of rock cores, such as abnormal bodies and changes in the color and composition of rock dusts and washing fluids. However, applying these methods to some types of rocks (i.e., weathering, gravel, and soft rock formations) is difficult because the rock samples taken out by drilling cannot keep the integrity of the original rock well [1]. In the past several decades, a measurement while drilling (MWD) technology has been developed. MWD is a type of well logging that incorporates the measurement tools into the...
drill string and provides real-time information (i.e., drilling speed, thrust, energy, and rotational speed) [2-9]. The drilling mechanical parameters have good continuity and strong recognition ability for soft rock formations; however, this type of mechanical parameters is not sensitive enough to lithology, and the recognition accuracy still needs to be improved [3, 8, 9].

The rock drilling process is essentially a complex rock crushing process in which a drill bit impacts, crushes, grinds, and cuts the rock. In this process, the physical and mechanical properties of rock (cement, particle size, porosity, strength, hardness, and rock anisotropy), physical and mechanical properties of rock mass (integrity of rock mass, influence of water), and other characteristics can affect the vibration characteristics of the drill string [2]. Therefore, the drill string vibration signals contain valuable information of rock formation. These vibration signals are unaffected by electrical signals generated during drilling operations and sensitive to formation interfaces. Such signals can also provide real-time information. Some progress has been made in the research related to the vibration and sound wave characteristics in the rock drilling process.

Al-Shuker et al. used drill string vibration signals to infer formation changes [10]. Esmaeili et al. studied the effect of rock compression strength from drill string vibration in oil well drilling [11]. Shreedharan et al. researched lithology identification on the basis of acoustic characteristics [12]. Fleigner et al. noticed the influence of vibration characteristics on lithology in investigating drill pipe vibration-based drilling quality evaluation [13]. Vardhan et al. and Kumar et al. found that the intensity of drilling noise is an effective index for evaluating lithology [14-17]. In the study of the frequency spectrum characteristics of drill string vibration, Gao et al. divided the vibration into three frequency segments of low, medium, and high; they pointed out that the main index for the identification of formation changes is the high-frequency segment [18-20]. Liu et al. pointed out that during continuous crushing, the mechanical properties of a rock determine the frequency characteristics of the vibration wave of the drill string [21]; Li carried out experimental research on the seismic while rock drilling and identified different lithologies by means of short-time Fourier transform and related analysis. The cross-correlation algorithm was used to remove the interference noise from the frequency-domain signal and extract the effective components for determining the frequency range of the drilling rig and lithology in the frequency spectrum [22]. Han conducted variance analysis, energy analysis, time-consuming analysis, drilling speed analysis, and spectrum analysis in processing the drilling vibration measurement while drilling data; the hardness changes in rock formation were successfully identified, proving the effectiveness of the MWD method in advanced drilling lithology and the accurate calibration of the drilling depth [23]. Li et al. applied the MWD technology to the identification of weathered crusts and achieved good results [24].

In Li et al.’s study, an indoor drilling vibration acoustic wave signal acquisition system was constructed; typical geotechnical materials, such as limestone, white marble, granite, and aerated concrete, were also selected for drilling experiments; moreover, drilling acoustic waves and rock vibration signals were collected. The results showed that the data can reflect rock properties and revealed the vibration spectrum characteristics of the drill string of the abovementioned typical geotechnical materials. Li et al. investigated the relationships between particle sizes and spectral characteristics of the sound or vibration signals generated during rock drilling processes; they also found that the larger the amplitudes of sound and vibration, the larger the grain size [25].

However, only few studies on the mechanism of vibro-acoustic response in rock drilling were reported. In this research, a numerical simulation method was employed to reveal the mechanisms of spectral characteristics of the sound or vibration signals generated during rock drilling processes; laboratory experiments were also conducted to verify the numerical analytical results.

2. Numerical simulations of grain size effect on the vibro-acoustic characteristics of rock drilling

The numerical models for grain size effect were set up using random aggregate model (RAM). Then, numerical modal analysis was performed using a finite element method.

2.1. Numerical rock models
To create concrete models, a 2D numerical method was used to simulate the random aggregate structure [26]. In this method, the area of a 2D aggregate is used as a main parameter to give the corresponding aggregate invasion judgment criteria, and random bones are established according to the polygonal random growth method. Meanwhile, the bones conflicted or overlapped during the packing process were removed with conflict and overlap criteria on the basis of an area index. Four models with different sizes were generated, as illustrated in Figure 1. The aggregate sizes of these four models were 6, 9, 12, and 15 mm, respectively. The properties of the bones and cement in these models are presented in Table 1. The density of the bones is approximately 1.15 times of the cement density.

Figure 1. RAM. (a) aggregate size 6 mm; (b) aggregate size 9 mm; (c) aggregate size 12 mm; (d) aggregate size 15 mm.

Table 1. Basic properties of rock models

| Property | Elastic modulus /GPa | Poisson’s ratio | Density /kg/m^3 | Tensile strength/MPa |
|----------|----------------------|-----------------|-----------------|----------------------|
| Aggregate | 55.5 | 0.16 | 2300 | 6 |
| cement | 26 | 0.22 | 2000 | 2.5 |

2.2. Modal analysis
The rock model is a cuboid of 150 mm × 150 mm × 50 mm. The bottom surface is fixed, and the surrounding four sides have lateral constraints. Finite element (FE) modal analysis was conducted (Figure 2), and the result is shown in Table 2. As the particle size increased, the frequencies decreased.
Figure 2. FE model in the modal analysis

Table 2. Natural frequencies of models with different aggregate sizes

| Order | Aggregate size(mm) | 6       | 9       | 12      | 15       |
|-------|--------------------|---------|---------|---------|----------|
| 1     |                    | 2203.4  | 1782.6  | 1345.7  | 915.14   |
| 2     |                    | 2211.9  | 1863.1  | 1502.3  | 1228.6   |
| 3     |                    | 2216.2  | 1914.3  | 1522.5  | 1300.4   |
| 4     |                    | 2240.8  | 2015.5  | 1570.6  | 1395.6   |
| 5     |                    | 2255.2  | 2036.9  | 1747    | 1427.8   |
| 6     |                    | 2266.7  | 2044.3  | 1794.8  | 1476.6   |
| 7     |                    | 2273.4  | 2054.3  | 1868    | 1541.6   |
| 8     |                    | 2335.8  | 2063.9  | 1876.7  | 1638.6   |
| 9     |                    | 2346.5  | 2074    | 1912.6  | 1689.3   |
| 10    |                    | 2364.2  | 2098.2  | 1925.8  | 1702.2   |

3. Experimental verification

The above modal analysis revealed the dynamic characteristics of concrete models. The corresponding modal testing was not conducted to verify its results. In our preliminary research, several drilling experiments were performed to investigate the relationship between grain sizes and vibration characteristics of concrete drilling. The experiment result can verify the above modal analysis indirectly. This section has been published in Shock and Vibration, Volume 2020, Article ID 9036371 [25].

3.1. Specimen preparation

The drilling experiments were conducted using the concretes of different aggregate sizes to simulate the effect of rock grain sizes on the vibration properties. Ordinary Portland cement 425# was used.
The same batch of stones was sieved to five grades through a set of crushed stone sieves. No admixtures or additives were added. To eliminate the effect of specimen sizes and forms, all the specimens were made into cylinders (diameter = 110 mm, length = 200 mm). The precision conformed to the national standard (GB/T 50081-2002). The aggregate sizes of the specimens showed no correlation with the total weight; hence, the effect of specimen weight on the vibration spectrum could be excluded. The properties of the concrete specimens are shown in Table 3, and the appearance of the concrete specimens is illustrated in Figure 3.

Table 3. Properties of rock samples

| Sample no. | Aggregate size range (mm) | Average aggregate size (mm) | Mass (g) | UCS (MPa) | TS (MPa) | P-wave velocity (m/s) |
|------------|---------------------------|-----------------------------|----------|-----------|----------|---------------------|
| 1          | <0.5                      | 0.25                        | 3014.7   | 23        | 1.8      | 3871                |
| 2          | 0.5–1.7                   | 1.1                         | 3027.8   | 20        | 2.1      | 3700                |
| 3          | 1.7–7.1                   | 4.4                         | 2697.9   | 21        | 2.0      | 3999                |
| 4          | 7.1–22                    | 14.55                       | 2746.4   | 25        | 2.2      | 3780                |
| 5          | 22–32                     | 27                          | 2450.8   | 22        | 1.9      | 4211                |

Figure 3. Appearance of concrete specimens used for rock drilling experiments

The experiments in this study used ZB4132GP, which is a numerical-controlled vertical driller that can feed automatically compared with portable drills; moreover, its drilling feed rate can be precisely controlled. Therefore, the effect of the penetration rate on the vibration and sound characteristics can be excluded. The data acquisition system consists of a computer, sound pressure transducer (INV9206), two accelerometers (YD-9), and data acquisition card hardware along with analysis software (BK 3053-B-120 from Brüel & Kjær). These sensors are connected to the BK 3053-B-120 data acquisition hardware with data cables, which are connected to a personal computer with a Windows operating system (64-bit).

3.2. Methodology
The experiments were performed inside a closed laboratory without external noise perceivable by human ears. In this case, the results were accurate. During these experiments, impregnated diamond
core bits with an inner diameter of 20 mm were used. The bits were always maintained sharp and were replaced by new ones in a timely manner before they became blunt. A vise was fastened firmly to the drill machine. A small water pump was also used for circulating the cooling water. The flow remained steady while drilling.

The drilling experiments were conducted for each concrete specimen. Through each experiment, the specimen maintained a clamped state with a bench vise. The rotary speed was set at 280 rpm. At least four clips of sound waves and vibration signals were acquired using the BK PULSE Smart Signal Acquisition. The sampling frequency was 32768 Hz. Each clip lasted more than 10 s. The drilling machine was set at an automatic feed mode. Considering that these experiments were performed indoor, the noise in the surrounding environment was weak, and the drilling conditions remained unchanged. Therefore, no additional preprocessing was required after excluding abnormal data. The amplitudes of the vibration signals acquired were the acceleration values, which, after two-stage time-integrations, were taken as vibration amplitudes. For the sake of convenience, this study used acceleration values as indexes.

3.3 Frequency-domain analysis of the grain size effect on the drilling sound and vibrations

FFT was adopted to observe the spectral characteristics of the sound waves while drilling specimens. A frequency segmentation method was also used to process the data of the drilling sound and vibration signals of the specimens of five aggregate sizes. This method involves segmenting frequency ranges and performing integration to sound pressure or vibration amplitude to compare their frequency characteristics [25].

Two frequency bands were selected from the high- and low-frequency domains, and the ratio of their integral values was calculated. For low frequency, the frequency band selected was 4000–6000 Hz; for high frequency, the frequency band chosen was 14000–15000 Hz.

Table 4 shows the results. As the aggregate size increased, the high-frequency composition tended to decrease. That is, as the aggregate size increased, the integral values of the amplitudes in the low-frequency band increased gradually; however, in the high-frequency band, they decreased gradually. This experimental result is consistent with the modal analysis qualitatively.

| Feed rate (mm/min) | 33.1 | 47.4 | 71.6 | 87.7 |
|-------------------|------|------|------|------|
| Average aggregate size (mm) | 0.25 | | | |
| 4000–6000 Hz | 0.11843036 | 0.127980472 | 0.122082455 | 0.126124159 |
| 14000–15000 Hz | 0.13187579 | 0.147968224 | 0.156227476 | 0.14774893 |
| Average aggregate size (mm) | 1.1 | | | |
| 4000–6000 Hz | 0.113067482 | 0.128451176 | 0.129916535 | 0.129387436 |
| 14000–15000 Hz | 0.108604888 | 0.125634557 | 0.130128317 | 0.122180644 |
| Average aggregate size (mm) | 4.4 | | | |
| 4000–6000 Hz | 0.152988891 | 0.163404004 | 0.146624211 | 0.141636967 |
| 14000–15000 Hz | 0.124767589 | 0.114370381 | 0.115314122 | 0.114600094 |
| Average aggregate size (mm) | 14.55 | | | |
| 4000–6000 Hz | 0.17636855 | 0.218840959 | 0.19055561 | 0.178583591 |
| 14000–15000 Hz | 0.112965259 | 0.123606084 | 0.097188293 | 0.097987889 |
| Average aggregate size (mm) | 27 | | | |
| 4000–6000 Hz | 0.418510364 | 0.175652912 | 0.153415494 | 0.205641333 |
4. Conclusion
The modal analysis showed that rocks with fine particles have high natural frequencies, whereas rocks
with coarse particles have low frequencies. The results of the laboratory experiments verified this
trend. The study indicated that rock grain sizes have a certain effect on the vibro-acoustic
characteristics in rock drilling. On the basis of these results, frequency characteristics can be adopted
to estimate rock grain sizes.
However, this research only focused on modal analysis. Additional theoretical research and
simulation experiments must be conducted for further advances in rock structure detection.

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