Experimental investigation on stability and early warning of waste dump using guided wave monitoring

Wen He1,2, Chansong Zheng1, Fengfan Lin1, Hao Chen1 and Quankun Xie1

1 School of Resources and Environmental Engineering, Jiangxi University of Science and Technology, Ganzhou, Jiangxi 341000, China
2 Engineering Research Center of High-efficiency Development and Application Technology of Tungsten Resources (Jiangxi University of Science and Technology), Ministry of Education, Ganzhou, Jiangxi 341000, China

corresponding author: Wen He; e-mail: hewen@jxust.edu.cn

Abstract: Waste dump landslides caused by the excavation of the base of the waste dump slope were simulated, and the guided wave technique was applied for waste dump stability monitoring. The influence of inner diameter and wall thickness of waveguides on guided wave attenuation is analyzed. The variation characteristics of the ring down count (RDC) rate and the trend of b value during landslide are discussed, which provides a theoretical basis for the guided wave monitoring and early warning for the stability of waste dumps. The results show that: (1) The guided wave signal attenuation is related to the frequency and the wall thickness, while the inner diameter has little effect. In the range of 0–170 kHz, the signal attenuation increases with the frequency. In the range of 170–512 kHz, the higher the frequency and the thicker the wall, the greater the signal attenuation is. (2) Guided wave RDC rate and video monitoring can reflect the whole process of landslide. The RDC rate curves have three prominent data peaks, which implies three landslide accidents. The video monitoring can respond to the whole process of changes in the scene in real-time. The change of parameter curve is more intuitive than the field picture. (3) The b value fluctuates significantly during the instability of the waste dump. At the early stage of the waste dump landslide, low-amplitude guided wave events are the majority, and the b value is at a high level. When a landslide occurs, the high amplitude events caused by friction and collision between gravel and waveguide increase rapidly, and the b value drops to the minimum value rapidly. When the waste dump is readjusted to the equilibrium state, the b value shows an upward trend. There is an obvious turning point in the b value curve before waste dump failure, which can be used as the precursor of landslide.

Keywords: waste dump; guided wave monitoring; attenuation; b value

1. Introduction

The waste dump is an unconsolidated medium accumulation body formed by the gradual accumulation of the discarded waste rock stripped from open-pit mines [1-2]. The stability of waste dump is affected by many factors such as design and site selection, water, foundation rock mass properties, blasting vibration et al. [3]. The instability of waste dumps is widespread in tropical countries with the regular rainy season and earthquake-prone areas, often causing major safety accidents and economic losses. Therefore, scientifically monitoring and forecasting the stability of waste dump has always been the goal of many scholars.
The stability of soil and rock slopes has been monitored using acoustic emission (AE) techniques for decades by international researchers. Slope deformation is regularly accompanied by the generation of AE [4]. In order to reduce the AE energy dissipation in the propagation process, metal tubes are used to provide a low-attenuation propagation path for AE signals [5]. The mechanisms of deformation behavior and AE generation are different for soil and rock slopes. Thus, the corresponding types of AE monitoring devices are also different. In soil applications, gravel material is generally used to backfill the gap between waveguide and borehole because of the high attenuation of low AE levels [6]. The interaction between gravel and waveguide mainly generates AE. Since the rock slope deformation produces more energy than soil, a waveguide is typically used to detect the AE [7]. Field monitoring verifies the response-ability of AE to slope deformation [8-9], and previous experimental investigation further evidence shows that AE identifies the changing velocity and quantifies the displacement rate [10-11]. Therefore, the AE rate trigger values can be set based on the standard landslide velocity scale to provide early warning [12]. What is more, Lizheng Deng et al. (2019) made an in-depth study to verify the potential of acceleration as an indicator for landslides [13]. The evidence obtained in the previous paper shows that the guided wave monitoring system is mainly applied to the fine-grained soil slope and cutting slope, and the study of the guided wave signal is mainly focused on the discrimination of slope deformation stage and the quantification of slope slip rate. Nevertheless, the application of guided waves in waste dump stability monitoring is rare. By increasing a funnel opening area at the bottom of a model slope toe, the landslide event caused by the excavation of a waste dump toe was simulated. The waveguide size is optimized by analyzing the influence of inner waveguide diameters and wall thicknesses on guided wave attenuation, and studying the variation characteristics of guided waves, and discussing the variation trend of b value during landslide provide a theoretical basis for guided wave monitoring of waste dumps.

2. Experimental system and test procedure

Many researchers conducted indoor slope instability tests by rainfall, prefabricating sliding surface, changing slope angle, and other methods [14-15]. The previous model was used as a reference, and an adjustable opening was set to remove particles and lead to landslide events in this study. The waste dump landslide experiment system comprises a test box, a traction device, a high definition camera, and monitoring devices, as shown in figure 1.

![Figure 1. The waste dump landslide experiment system](image)

2.1. Landslide model design

In the physical model test, the geometry and mechanical properties of the waste dump are abstracted and simplified. The complexity of the prototype geological conditions is removed, and the essential characteristics of the prototype are retained. The similar indicators such as model slope angle, internal friction angle, capacitance, cohesion and heaviness are made consistent with the field by adjusting the similar material ratios to satisfy the similarity theory.
Figure 2 shows the model design and size, and different colors represent different parts. A wooden plate was placed at the bottom of a model box with a 20 cm pad to reserve a storage space for falling waste rock. An opening of 0.15 × 0.1 m was cut, then a chute, a slide block, a spring, and a steel wire rope were installed at the bottom of the opening. A spring is connected both to a slider and to the board. The traction device comprises a universal electronic testing machine, a pulley, and a wire rope. One end of the wire rope was connected to the slider, and the other end through the pulley is connected to the testing machine. When the pressure head in the testing machine rises, it pulls the slider to make the opening closed; When the pressure head drops, the slider slides down under the spring’s action.

The gravel was collected from a nearby metal mine waste dump. According to the lumpiness distribution measurement results of three sampling points on-site, the field's particle size distribution was simplified to four kinds of particle size, as listed in table 1. Gravel with corresponding quality was weighed in proportion and mixed to stack on the wooden substrate, making the adjustable opening wholly covered with the particles.

Table 1. Particle size and content of waste dump model

| particle size | 1~5 mm | 5~10 mm | 10~15 mm | 15~20 mm |
|---------------|--------|---------|----------|----------|
| particle content | 10% | 10% | 30% | 50% |

2.2. Monitoring devices

The whole waste dump landslide process was recorded by a high-definition (HD) camera (30 frames per second, 12 million pixels). Furthermore, the PCI-2 AE equipment from PAC Acoustics Company was adopted to collect waveforms and parameters in real-time. Figure 3 shows the major measurement components, including two UT-1000 sensors, two 40 dB amplifiers, an acquisition board, and a signal analyzer. The representative landslide pictures were extracted for mutual verification and comparison with guided wave parameters.

Figure 3. Major components of AE monitoring device

As an essential part of the guided wave monitoring system, many scholars have studied the influence of waveguides on the signal. Dixon et al. [5] concluded that the main factors affecting the propagation of the guided wave signal are the design criteria of the waveguide, such as: diameter, solid or hollow, wall thickness, and method of joining. LiZheng Deng et al. [13] conducted comparative tests to analyze the effects of different waveguide materials. In this experiment, the influence of waveguide size on guided wave attenuation was analyzed. A 1 m waveguide was used, and the inner diameter and wall thickness are shown in Table 2.
Table 2. The inner diameter and wall thickness of the waveguide

| waveguide | inner diameter /mm | wall thickness /mm |
|-----------|--------------------|-------------------|
| 1"        | 30                 | 2                 |
| 2"        | 30                 | 4                 |
| 3"        | 32                 | 4                 |
| 4"        | 30                 | 6                 |
| 5"        | 34                 | 4                 |

2.3. Landslide test procedure

If the signal acquisition threshold is set too high or too low, information will be lost, or environmental noise will be collected. According to the pre-test results, the threshold was set as 33 dB, the maximum sampling rate was 1 MHz, and the sampling length was 1k. The testing machine descent speed was set as 20 mm/min. With the gradual increase of the opening area, many gravel falls, and it leads to landslides.

3. Results and analysis

3.1. The influence of waveguide inner diameter and wall thickness

A three-dimensional air-tube-air model is established in cylindrical coordinates based on the theory of elastodynamics. Assuming that the guided wave propagates in simple harmonics, the dispersion equation of the guided wave is established by using the global matrix method according to the continuity conditions of displacement and stress. Then the dispersion equation of the guided wave is solved numerically by extrapolation prediction and two-scale iterative approximation algorithm, and the attenuation dispersion curves are obtained.

Figure 4 shows the attenuation curves of guide waves in waveguides of different sizes. In the range of 0–170 kHz, the signal frequency plays a significant role in guide wave attenuation, and the attenuation value increases with the increase of frequency, except for a sudden change at 50 kHz. However, in this frequency range, the attenuation curves for each size have similar variation trends, with little difference and influence on attenuation values. In the range of 170–512 kHz, the attenuation is influenced by both frequency and wall thickness. The higher the frequency and the thicker the wall, the greater the attenuation value is. The influence of the inner diameter on attenuation is weak; as a result, the minimum wall thickness waveguide of 2 mm is selected as the optimal size for guide wave monitoring.

![Figure 4](image_url)

Figure 4. The attenuation curves with different waveguide inner diameters and wall thicknesses

3.2. Landslide test results of camera pictures and guided wave characteristic parameters
Figure 5 shows the waste dump landslide movement recorded by a high-definition camera. The numbers at the bottom left of each picture are the occurrence time of the corresponding phenomenon, the yellow dotted line is the landslide boundary. The landslide was observed for the first time in the slope foot at 54.107 s. The debris at the foot of the slope took the lead in sliding, causing the overlying bulk to lose support, and gradually expand to the upper part of the slope. At 57.039 s, the bulk destabilization extended to the top of the slope, eventually forming a larger scale slide and lasting until 58.108 s. At 59 ~61 s, the slide extent rapidly decreased, and the slope gradually regained equilibrium from instability.

In Figure 5, two acoustic sensors were attached to two waveguides separately and were connected to the acquisition board. With the continuous increase of the opening area, the waste dump gravel rolled down. Friction and collision were happening between the gravel and waveguides, which generated guided wave signals in the waveguides. The variation characteristics of guided wave parameters can represent the evolution process of landslides. Figure 6 shows the variation of guided wave ring down count (RDC) rate and peak frequency against time during the landslide process. As can be seen from Figure 6, there are three noticeable abrupt changes in the RDC rate, indicating that three landslide events occurred during the test. When the RDC rate is low, the slope body is in a stable state, and when the RDC rate changes rapidly, it is a process of model instability. What is more, the RDC rate reached the maximum value in a short time and then returned to the low level, indicating that the landslide movement had strong suddenness, rapid evolution, and a short duration of about 10s. In order to study the characteristics of guided waves' peak frequencies during the landslide, the collected waveform signals were processed by FFT. The peak frequencies are mainly concentrated in 10-40 kHz and 280-300 kHz.

![Figure 5](image1.png)

**Figure 5.** The landslide process of the waste dump

![Figure 6](image2.png)

**Figure 6.** Variation in guided wave RDC rate and peak frequency against time for one test
3.3. Variation characteristics of $b$ value during the landslide of waste dump

Guided wave parameters and video monitoring can reflect the landslide process. However, the visual inspection, camera, and guided wave parameters could hardly capture the obvious landslide symptoms before the failure of the waste dump. In order to provide a theoretical basis for guided wave early warning of waste dump stability, the variation trend of $b$ value during the waste dump landslide is discussed.

The study of $b$ value originated in seismology, and Gutenberg et al. [16] first discussed the relationship between earthquake frequency and magnitude. The $b$ value as essential precursor information of earthquakes has been further studied and introduced to the field of rock AE by geotechnical scholars. An increase in the $b$ value of AE means that small-scale crack damage is predominant within the material, a slight fluctuation in the $b$ value indicates a more uniform distribution of cracks at different scales within the material, and a rapid decrease in the $b$ value implies a larger-scale expansion and penetration of cracks within the material [17]. AE’s $b$ value can reflect the variation of microcracking scale within the rock, and sudden changes in $b$ value can also be used as precursors of rock damage [18]. The $b$ value is a statistical value related to the total amount of data, data distribution, number of samples, and sliding sampling length. For different tests, the number of acoustic emission data collected is different, so that the sample number and step size should be selected flexibly [19-20]. The guided wave data of the waste dump model is mainly generated from the interaction between gravel slide and waveguide. The sample data length and step length should try to separate the data during the landslide from the data before the landslide to avoid too little data within a specific magnitude range, which will cause a significant error impact on the calculation of the $b$ value.

The amplitude of AE is divided by 20 to correspond to the earthquake magnitude so that the amplitude distribution is roughly similar to the earthquake magnitude distribution [21]. Generally, the least square method is used to calculate $b$ value, and the formula is:

$$\log[N(A/20)] = a - b \times (A/20)$$

(1)

Where $A$ is the amplitude of the AE event, $N(A/20)$ is the cumulative frequency of the AE event with amplitude no less than $A/20$, $a$ is an empirical constant, and $b$ is the $b$ value.

Figure 7 shows the guided wave event rate and $b$ value curves obtained from the three experiments during the waste dump landslide. To obtain accurate $b$ values, 200 samples and 100 steps of signals were used in channel 1, and 600 samples and 300 steps were used in channel 2. As channel 2 connected waveguide is closer to the center of the sliding body than channel 1, there is a difference between channel 1 and 2. When the event rate remains low, the $b$ value is high, indicating that low-energy and low-amplitude events account for the majority and no apparent slide occurs in the waste dump. When the event rate increases sharply, the $b$ value shows a rapid decrease; that is, the first landslide event occurs, and the high amplitude and high energy events, caused by the mutual friction and collision between gravel and waveguide increase rapidly. Then the event rate recovers to a lower level, and the $b$ value increases over time and reaches the maximum, indicating that low-energy and low-amplitude events increase. The slope body adjusts to the equilibrium state under the action of gravity for a while, then the other two landslides' $b$ values repeat the previous variation characteristics. The above results show that when the waste dump does not slip or recoils to the equilibrium state, the collected guided wave events with low amplitude and small energy account for a large proportion, and the $b$ value is at a significant value or presents an apparent upward trend. When a landslide occurs, the $b$ value decreases rapidly to the minimum. There is an obvious turning point in the $b$ value before sliding, which can be used as the precursor of a waste dump landslide.
4. Conclusions

This study investigated the variation process of waste dump landslides through a waveguide, AE technology, and camera monitoring. The following conclusions can be obtained:

The attenuation of the guided wave signals is related to the frequency and the waveguide wall thickness, while the inner diameter had little effect on the attenuation. In the range of 0~170 kHz, the signal frequency plays a significant role in attenuation, and the signal attenuation increases with the increase of frequency. In the range of 170~512 kHz, the higher the frequency and the thicker the wall, the greater the signal attenuation is. The peak frequency of the waste dump model landslide is mainly concentrated in 10~40 kHz and 280~300 kHz, so the waveguide with an inner diameter of 30 mm and a wall thickness of 2 mm is selected.

The waste dump instability caused by excavation experiences a short time from the beginning of deformation to the final landslide failure and has a solid sudden and short duration. Guided wave parameters and video monitoring can reflect the whole process of landslide. The guided wave parameters with three prominent data peaks imply three landslide accidents. The result of the $b$ values can reflect the change process of landslides and provides help for early warning of waste dump slide. When the waste dump does not slide, the $b$ value is at a higher level. When a landslide occurs, the $b$ value drops to the minimum value rapidly. There is an obvious turning point in the $b$ value before sliding, which can be used as the precursor of a waste dump landslide.

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Acknowledgments
This research was supported by the National Natural Science Foundation of China (No.51604127 and No.51874268), the China Postdoctoral Science Foundation (No.2019M650156), and the Jiangxi Province Postdoctoral Fund (No.2018KY41). The authors would like to express their gratitude to all the research support, and to thank the reviewers and the handing editor for their valuable comments and suggestions.