Real-time Monitoring and Analysis of Particulate Pollutants in the Water-flooded Zone

Huiming Zhai, Chunjuan Shi, Xianjian Zou

Abstract—**The migration movement of particulate pollutants in groundwater is vital to protecting water resources and geological disasters. When faced with complex groundwater conditions, monitoring and analyzing particulate pollutants' movement between the water-flooded zone of soil and rock mass is impossible. A real-time monitoring method of visual diagnosis for water-flooded particulate pollutants is proposed by using a portable B-mode ultrasound diagnostic instrument. The testing analysis of the particulate pollutants in the water-flooded zone was carried out. Results show the ultrasound instrument has good real-time performance, strong penetration, and can realize the suit imaging and obtain high-quality ultrasonic images. It can realize the real-time monitoring and analysis of particulate pollutants in the water-flooded zone. It can analyze the regional size, migration path, and potential danger degree of particulate pollutants. The detection accuracy of underwater particulate pollutants is 0.1 mm, enough for the real-time monitoring of particulate pollutants and their migration in the groundwater. The measuring and tracking accuracy of particulate pollutants can reach 0.1 mm/s. It can provide a new technical means for preventing particulate pollution sources and some potential geological hazards.**

Index Terms—**Real-time monitoring, particulate pollutants, groundwater, imaging experiment**

I. Introduction

WATER is an indispensable environment for human beings and all living organisms. Groundwater is essential for urban, industrial, and agricultural water usage. In recent decades, various human activities have increased, and the diffusion of multiple pollutants. The laying of an impermeable or semi-impermeable road surface has also slowed the recharge rate of natural groundwater, increasing pollutants' concentration in groundwater, especially in certain areas [1]-[3]. With the development of industry and agriculture, the research of the groundwater environment has been the key issue, which is of great scientific significance to study further the relationship between groundwater and rock mass [4]. At present, the monitoring of the groundwater environment is mainly realized through physical and chemical analysis after pumping water sampling and through large-scale monitoring systems such as GIS with big data [5]-[7]. However, it is impossible to monitor and analyze the potential particulate pollutants in the groundwater or the field measuring data of the groundwater in the underground river in real-time for each monitoring point.

The interaction and gathering of human and secondary pollutants are deeply reflected in the large water-filled areas of underground karst caves or underground river caves [8]. In the less polluted underground water system, the water quality is up to standard, crystal clear, and even some cave organisms or plankton, such as white shrimp. However, many abnormal phenomena, such as corrosion and deformation, occur when water passes through regional rock and soil in areas where pollution exceeds the norm. No living bodies are in the water flow, or the water is entrained with corrosive particulate pollutants. Because the underground environment is pitch-black, the water flow in the underground river or cave is very calm or extremely rapid. The morphological structure of underwater rock and soil is complex and changeable. Therefore, it is not easy to detect and study the groundwater, water pollutants and underwater rock and soil using optical methods. In addition, the optical way could damage the dark environment originally attributed or some characteristics of water pollution. Therefore, for the detection of groundwater environment structure characteristics and the research on the laws of the water pollutant migration, urgent need for a new portable acoustic imaging detection method, which has high precision and is easy to adapt to the complex changeable groundwater environment.

With the further development and extended application of modern ultrasound imaging technology, ultrasound imaging instruments have been widely used in medicine and have gradually been applied to the model test of hydraulic engineering and geological engineering. Based on the high-frequency ultrasonic echo imaging principle, ultrasound instrument has better penetrability and higher resolution than traditional scanning imaging system. It can dynamically image and display the sediment topography in the flow in real-time. The image is real and intuitive, which brings great convenience to the scientific research of water flow and suspended particles [8]. Recently, the measurements of flow and particles by using a B-mode ultrasound instrument, such as low sediment concentration [9], incipient sediment velocity [10] and underwater model topographic line extraction [11], have shown the ability of real-time imaging recognition of aquatic particles and good topography. Image measurement can be carried out for imaging particles in water in terms of flow velocity and profile flow field. The dynamic measurement and 3D reconstruction of topography can be carried out for imaging underwater topography. They have

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realized real-time continuous non-contact real-time measurement and automatic analysis.

Portable ultrasonic diagnostic equipment has been developed. As a result, the real-time and intuitiveness of ultrasound imaging technology in the field visualization test has been greatly improved. The water-immersed ultrasonic synthetic aperture imaging probe has also been further applied in monitoring the water environment, geotechnical engineering, and flooded areas by imaging rock and soil mass profiles. Therefore, we take advanced medical ultrasonic diagnostic technology as an example. A new ultrasound with an improved instrument monitors the groundwater and particles' pollutant migration regularity. It reveals the interaction mechanism between the water-flooded zones. It can prevent further destruction of human activities on the groundwater and geotechnical structures. Those have important research significance and applications for geotechnical engineering, geological engineering, and environmental protection.

II. Contaminants in the Water-Flooded Zone

A. Groundwater Pollutant

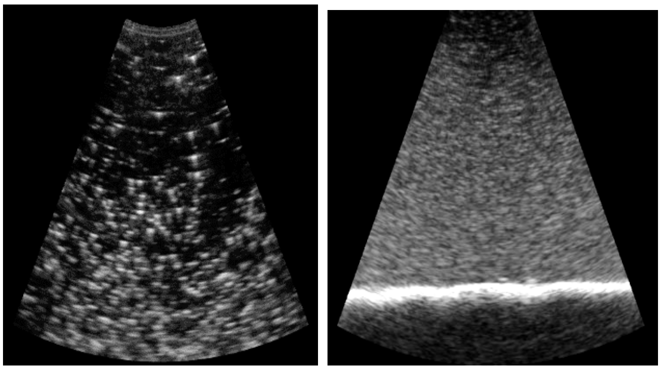
Pollutants in this paper refer to the tangible particulate or block-shaped pollution objects retained by groundwater pollutants after a long-time settlement in a water-flooded zone or chemical reaction. Under the action of long-term infiltration and corrosion of the water environment through physical and chemical reactions, groundwater pollutants will inevitably form a specific form of tangible structural characteristics in a certain water-flooded zone [12,13]. The features of particulate or block form and structures of pollutants are the key in the water-flooded zone. There is a great theoretical and practical significance to studying the parasitic environment and transport route of pollutants in the water.

According to the features of the underwater environment and the requirements of field geotechnical engineering tests, the medical B-mode ultrasound imaging technology is improved. It is applied to underwater geotechnical engineering for the geological survey. The improved ultrasound device can realize the real-time imaging detection and visualization analysis of groundwater in caves and pollutants underwater. By analyzing the ultrasound image data of groundwater, pollutants, underwater rock, and soil mass structures, we focused on the water-flooded zones. We solved the visualization of groundwater and the particle pollutants monitoring and real-time analysis problem to realize the research of migration regularity of particulate pollutants and their interaction mechanism in the water-flooded zone s.

B. Ultrasound Imaging Measurement Principle and Imaging Characteristics

B-mode ultrasonic instrument is mainly composed of a host and ultrasonic probe. The probe sends out the ultrasonic wave and receives the echoes in order. The ultrasonic waves can propagate directionally and can penetrate an object. The echoes produce when it encounters obstacles inside the thing or on the surfaces of two different things. Therefore, other characters and blocks will have other echoes. This echo is displayed on the ultrasound device's screen through inner signal processing technology. It can use to detect the internal structures of objects and their changes. Therefore, the basic principle of the B-mode ultrasound imaging device is as follows. Send an orderly series of ultrasonic waves into the interior of an object, scan in a certain order, and then continuously detect the delay time and intensity of the ultrasonic echoes. After the series of inner signal processing of electronic circuits and computers, we can get the B-mode ultrasonic image [14]. The image recorded the echoes and can judge the structure and change characteristics of the object structures.

The zones between water, soil, and rock in the model test are designed. The B-mode ultrasound instrument obtains images of water flow and particulate pollutants. They are some profiles, as shown in Figs. 1. In the figure, imaging spots are formed by the suspension movement of particulate pollutants (instead of sediment particles), and the sand wave terrain imaging bright bands formed by the strong reflection of the bottom bed surface. At the same time, the suspended particulate pollutants are moving, and the characteristics of the soil and rock terrain may be changed. Therefore, there may be many reflection images of the bed surface terrain. From Fig. 1, the background texture features and the imaging spot noise near the bed surface will be strong or weak according to water flow conditions.



(a) (b)

Fig. 1. Ultrasound image of particulate contaminants (sediment particles instead), (a) Particulate contaminants in streams, (b) Particulate contaminant parasitic boundaries.

III. Real-Time Imaging Monitoring Test of Pollutants

A. Ultrasonic Imaging Test System

The main equipment and instruments needed have two kinds of ultrasound instruments available during our imaging monitoring test of pollutants. They are a B-mode ultrasonic convex array instrument (TY-6858-I) and Apogee 1100 digital color Doppler ultrasound diagnostic system. We built an ultrasonic imaging test system for the real-time detection of pollutants in indoor water. The system comprises a flume control system, an ultrasound imaging acquisition system and a signal processing system at the main computer. They are shown in Fig. 2. The flume control system comprises a glass water tank, a water pump and a frequency converter. It is used to control the water flow speed and other main equipment. Another, the ultrasound imaging acquisition system is made up of a B-mode ultrasound instrument, a video image acquisition card, and the main computer. The signal processing system is primarily a computer and supporting signal processing software. It contains its own independently developed image signal processing software as the TY-6858-I ultrasound instrument is a traditional analogue portable B-mode ultrasound instrument. The output signal is a standard analogue video signal. Therefore, it is necessary to configure a video image acquisition card to realize the real-time transmission of image signals collected by the ultrasound instrument. The ultrasound instrument provides a video output port. The video image acquisition card is installed on the computer through the PCI port. The video output port of the B-mode ultrasonic instrument is connected through a data line to realize the connection between the B-mode ultrasonic video image and the computer. The ultrasound imaging test system is shown in Fig. 2.

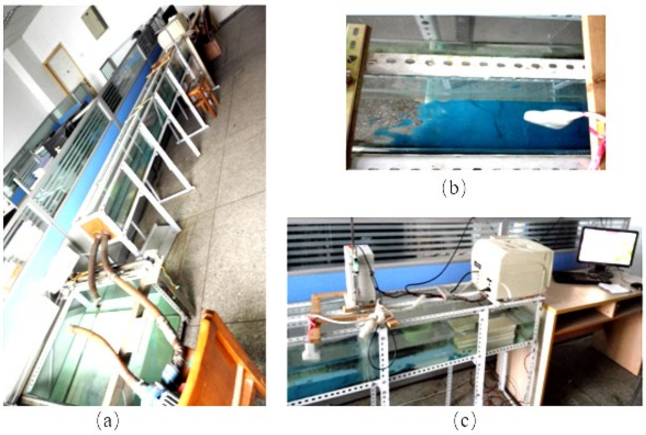


Fig. 2. Ultrasound imaging test system, (a) indoor glass water tank, (b) ultrasonic probe and model pollutants, (c) B-mode ultrasound instrument and computer.

In Fig. 2, the ultrasound instrument is mainly responsible for the ultrasonic imaging of water flow and pollutants in the region. It then transmits the B-mode ultrasonic imaging signals to the computer for processing through the acquisition card. The ultrasonic probe should be placed where the flow or area is relatively stable for a better pattern of ultrasonic images. In the test, we adjusted the relevant buttons in the control panel of the ultrasound instrument. We selected the appropriate parameters to obtain a better B-mode ultrasound image. During the model test process, the parameters related to the ultrasound instrument are generally set as follows. The frequency of an ultrasonic wave is set as 5 MHz. The type of focus is set as 2 and 3. The near-field gain is 0, and the long-range gain is 12. We can change these parameters according to the actual testing conditions.

B. Monitoring Experiments

The particulate pollutants are at the zone of soil and rock. Therefore, the probe of the portable ultrasound instrument was directly placed under the surface of the field water for observation and analysis. As a result, we can obtain video images of the imaging pollutants directly in the groundwater and the shallow surface. They are under the underwater soft rock mass as shown in Fig. 3. We analyzed and identified the morphological characteristics of imaging pollutants in water in video images, such as the bright imaging bands of soft rock surface at the bottom, the shape and the movement of abnormal spots or stripes from the imaging particulate pollutants. By analyzing and monitoring the changes of these spots or bright bands, we can realize the visualization analysis and detection of groundwater pollutants. In addition, we can observe the characteristics of the imaging structures and their changes in underwater particulate pollutants.

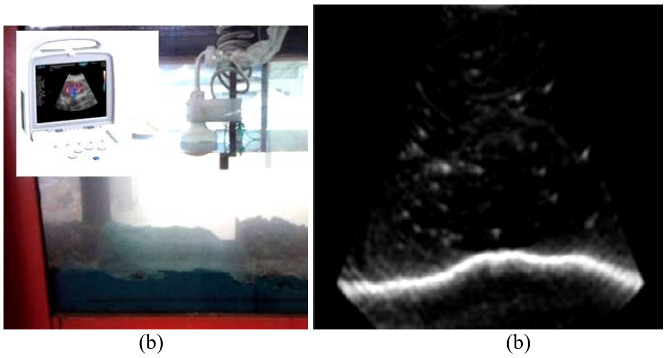


Fig. 3. The monitoring test of granular pollutants by using ultrasonic video, (a) Model test and the ultrasound instrument, (b) granular pollutants and their settling boundaries.

In pollutant transport, particulate pollutants will be transported by osmotic vehicle from top to bottom. The physical and chemical reactions and cross fusion are carried out with groundwater as the carrier. The continuous deposition occurs in the water-flooded zone, and then a particulate pollutant accumulation surface is formed. This accumulation surface will create a special particulate pollutant storage area over time. This experimental study is mainly based on the B-mode ultrasound imaging analysis of the imaging area as shown as Fig. 4. It can obtain the imaging features of the particulate pollutants in the area and the profile image characteristics of the regional organizational structures, which lays a foundation for the qualitative and quantitative analysis of pollutants.

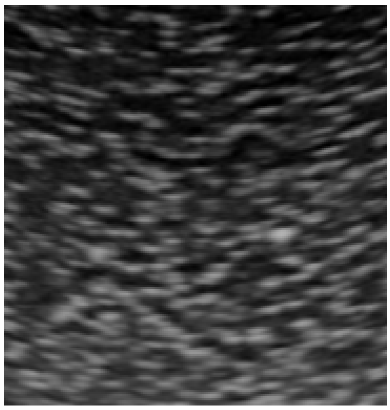


Fig. 4. The moving of particulate pollutants in the water-flooded zone

Therefore, the research and analysis of this experiment are mainly carried out in the following three parts:

Firstly, identify the morphological characteristics of pollutants underwater and track their migration changes.

Secondly, extract the bright imaging bands of particulate pollutants in the water-flooded zone and then realize the visualization and real-time monitoring.

Lastly, go on the qualitative and quantitative analysis of the internal organizational structures of the imaging area.

IV. Analysis and Discussion of Pollutant Form Characteristics

A. Morphological Characteristics Analysis of Pollutants

We analyzed the size and area of the imaging spots. In addition, we analyzed the brightness and width of the boundary structure's bright imaging band according to the particulate pollutants' features at the zones between the water, soil and rock. As a result, the grey concentration of imaging spots and bright bands and the relative change of the grey concentration can be calculated by the following formula:

$$C = \frac{\sum_{n=1}^{N_p} f(i,j)_n}{255 N_{\text{all}}} \times 100\% \tag{1}$$

$$\Delta R_C = \frac{\sum \left\| \Delta C_{n+1} - \Delta C_n \right\| / \sum \Delta C_0}{\sum \left\| \Delta S_{n+1} - \Delta S_n \right\| / \sum \Delta S_0} \tag{2}$$

where C is the gray concentration of imaging spots and bright bands, ΔR_C is the relative change of the gray concentration, $f(i,j)$ is the gray value of pixels in an image, ΔS_0 is the initial relative area and ΔC_0 is the initial value of relative gray concentration, N is the number of imaging spots.

The grey concentration and its relative change features are used to analyze the interaction between water and particulate pollutants. We analyzed the erosion damage variation law. The physical and chemical interaction between water-flooded zones and particulate pollutants was studied by analyzing their morphological characteristics. We can establish the characteristics of the internal relationship between their migration and evolution.

The main steps of the statistical analysis process for the morphological characteristics of pollutants are as follows:

Firstly, the size and area of the imaging spot are recognized, and the brightness and width of the bright imaging band at the junction are statistically analyzed.

Secondly, according to the characteristic quantity of statistical analysis, we evaluated the internal relationship and interaction mechanism between water-flooded zones and particulate pollutants.

Lastly, the influences of different contaminant materials are analyzed, and physical and chemical properties of rock and soil mass are estimated based on their parameters of ultrasound imaging characteristics in this area.

For the acquired B-mode ultrasound video images, the following steps are mainly used for later analysis and processing:

(1) The difference images of B-mode ultrasound images are calculated by difference operation between every two adjacent frames.

(2) The next image subtracts the difference between the two frames to obtain the target image, which improves the monitoring accuracy of pollutants in groundwater.

(3) The target image can be further processed by adaptive threshold segmentation and morphological filtering method to obtain the enhanced ultrasonic image of pollutants in the underwater and zones, further improving the monitoring accuracy of pollutants during the experimental test.

B. Results and Discussions

Digital acoustic beam synthesis technology is widely used in modern ultrasound diagnostic apparatus. This technique has improved the focusing characteristics of the acoustic beam and the image's resolution Moreover, a B-mode ultrasound instrument can obtain the light spot image of sediment particles with a diameter as small as 0.05 mm in water. In addition, the suspended sediment concentration and the underwater topography can be measured [29]. However, the existing technical solution cannot apply to good visual detection and real-time analysis of groundwater environmental problems. Therefore, we use the portable ultrasound imaging diagnostic instrument to achieve underwater detection and water-flooded zones' imaging analysis and obtain a series of ultrasonic images, including underwater pollutants, water-flooded zone, and some inner structures in ultrasonic images.

After many experimental tests, there is a one-to-one correspondence between each detail imaging feature and the actual water-flooded zone. These correspondence relations can reflect the physical or chemical evolution characteristics between pollutants and certain water-flooded zones. Results show that ultrasound imaging technology can realize the real-time observation of contaminants in the water environment and their bottom accumulation surface. Through the statistical analysis of the imaging spots' size and area and the imaging bright bands' brightness and width at the junction, the quantitative and qualitative analysis of the pollutants in the water and the bottom of the junction area are realized, including further study of their migration law. Therefore, the detection accuracy of underwater topography and particulate pollutants can be 0.1 mm. The detection and tracking accuracy can reach 0.1 mm/s after the experimental tests and qualitative analysis. The improved B-mode ultrasound instrument can monitor the particulate pollutants and their migration in the groundwater in real-time and with high accuracy.

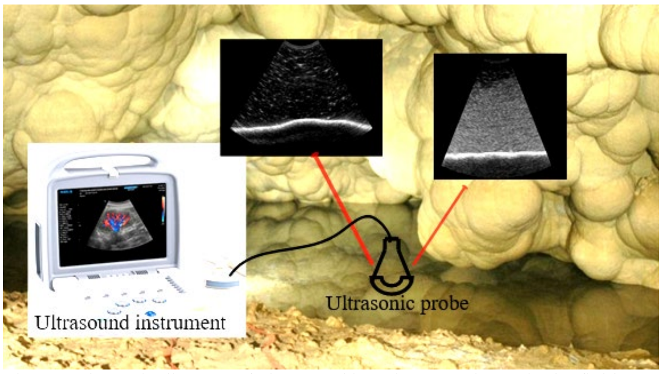


Fig. 5. Schematic diagram of ultrasound imaging experiment in the field cave.

On this basis, a portable ultrasound imaging monitoring system is developed. The system adopts full-digital Doppler ultrasound diagnostic apparatus and accordingly increases the frequency of ultrasonic waves. As a result, the imaging quality and accuracy of underwater pollutants and rock and soil at the bottom can greatly improve. Thus, the precise monitoring of pollutants in water can be realized. It is shown in Fig. 5. Through further research and analysis, this system is expected to realize the monitoring and analysis of particulate pollutants in the water environment. Furthermore, it can study the transport law of pollutants in the groundwater and research the interaction mechanism between zones in the water flow. This system will provide a new feasible way and a visualization real-time detection method for geotechnical geological engineering and mechanical engineering in water environments.

V. Conclusions

A novel portable ultrasound imaging diagnostic instrument is used. It can realize the imaging analysis of water pollutants in water-flooded zone and the particulate pollutants imaging detection of weak structural surface. After the quantitative and qualitative analysis of underwater ultrasonic image data, some conclusions can be obtained:

(1) Portable ultrasound imaging technology can realize the real-time imaging observation of particulate pollutants in the water-flooded and weak structural zone;

(2) A visual monitoring method for particulate pollutants in the water-flooded zone is proposed. A portable ultrasound imaging monitoring system is put up. The detecting accuracy of underwater moving particulate pollutants can be up to 0.1 mm;

(3) The quantitative and qualitative analysis of particulate pollutants in the water environment is possible. The research of migration rule of groundwater pollutants and interaction mechanism can be realized.

Acknowledgement

All images and data are from our actual drilling engineering and are permitted by the owners.

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