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Experimental investigation of solid-liquid two-phase flow in cemented rock-tailings backfill using Electrical Resistance Tomography

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HIGHLIGHTS

- ERT technology was used for visual detection of CRB in pipelines.
- FEM was established for ERT 'soft field' effect.
- The effects of CRB mixing parameters on the electrical conductivity were analyzed.
- Linear back projection algorithm was utilized to perform the inversion imaging.

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ABSTRACT

The cemented rock-tailings backfill (CRB) technique is a rapidly advancing technique for the mine backfill process. However, the inclusion of waste rocks in backfill materials increase the transportation burden on the backfill pipeline. In particular, it can accelerate pipeline wear and significantly increases the probability of the backfill pipeline being blocked by large waste rocks. To ensure safe transportation, we proposed a visual detection method for liquid-solid two-phase flow inside a backfill pipeline based on Electrical Resistance Tomography (ERT). In particular, we established a finite element model (FEM) for the 16-electrode ERT sensor to study in detail the detection sensitivity of the ERT 'soft field' effect. Using orthogonal experiments, we also analyzed the effects of the solid concentration, particle size, and waste rock-to-tailing ratio on the electrical conductivity of the backfill slurry. According to the experiment results, we simulated the positions of waste rocks in the pipeline. A linear back-projection algorithm was utilized to perform the inversion imaging of the 9 sets of flow patterns in the orthogonal experiments. The research results indicate that the most important factor affecting the conductivity of backfill slurry is the ratio of waste rock to tailings. The conductivity of the backfill slurry reached a maximum of 3.8 mS/cm for a solids concentration of 50 wt%, particle size of 25–50 mm, and waste rock-to-tailing ratio of 70/30. We found that waste rocks in the backfill pipelines could be accurately located using reconstructed images. Finally, we conclude that, with an imaging time of only 0.04 s, ERT analysis has the potential to fully meet the real-time requirement of online monitoring of the backfill slurry transportation.

1. Introduction

The use of cemented rock-tailings backfill (CRB) technology with long-distance pipeline transportation has numerous benefits. For example, it can lead to zero discharge of solid waste resources, eliminate environmental pollution, and solve problems of subsidence [1–3]. As a solid-liquid two-phase flow with complex components (tailings, waste rocks, binding materials and water, etc.), backfill slurry flows in a complex manner under the influence of multi-physical fields in the pipeline. Solid-liquid separation may increase the risk of pipeline blockage, which is the biggest enduring issue for the long-distance pipeline transportation of CRB. The reasons for pipeline blockage are complex and various, and involve transport parameters such as gradation, solid concentra-

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tion, critical slurry velocity, and the flocculation function of the slurry particles. Pipeline leakage is also a major cause of pipeline blockages. Pipeline leaks can result from damage to the pipeline by solid materials, acid and alkaline corrosion of the slurry from the pipeline system itself, and artificial factors such as external environment conditions and improper third-party construction. As shown in Fig. 1, blockages and leakages in slurry pipelines are common challenges faced the world over. Pipeline blockage accidents have occurred in American Black Mesa coal pipelines (because of unreasonable grain compositions) and Kunming salt mine pipelines (due to the gradual separation of crystals). Xu Zhenliang [4] analyzes the causes of slurry pipeline blockage accidents and proposes a variety of prevention measures.

With the aim of avoiding the blind excavation of the blocked pipelines and reducing the detection costs, the pipeline visual detection technology has developed as a topic of great interest [5–7]. The emerging Electrical Resistance Tomography (ERT) technique can provide information about phase distribution in a measured cross section. In particular, it can provide visually intuitive measurement results [8,9].

In recent years, many efforts have been made to develop new applications for ERT technology. Le et al. applied ERT to geo-environmental testing and conducted a two-dimensional imaging test on toxic pollutants in an industrial park in Da Nang, Vietnam [10]. Kazakis et al. used ERT technology to study the extent and geometric characteristics of seawater intrusion in the coastal aquifer of Thermaikos Gulf in eastern Greece [11]. Singh et al. used ERT technology to detect the porosity of gas-liquid two-phase flow in chemical reactors [12]. Vadlakonda et al. used ERT technology combined with pressure probes to study the fluid-dynamic characteristics of gas-liquid two-phase flow during flotation [13]. Zhou et al. explored the feasibility of using ERT technology to detect damage or cracks in engineered cementitious composites under monotonic uniaxial tension loading [14].

However, to date no research has reported on the use of ERT technology to detect liquid-solid two-phase flow of backfill slurry in a pipeline. The main difficulties are: (i) the "soft field" characteristics of ERT sensitivity fields, which seriously affect the quality of image reconstruction; (ii) a slurry made up of a liquid-solid two-phase fluid with complex components and varying concentrations has a complex and varied conductivity distribution, increasing the difficulty of ERT image reconstruction; and (iii) two-phase flow detection of backfill pipelines needs to meet the real-time needs of online detection, meaning that the image reconstruction algorithm must be fast.

In an effort to overcome these challenges, we present on the use of self-developed finite element method (FEM) to establish a 16-electrode ERT sensitive field. The "soft field" characteristics of the field were analyzed to obtain the sensitivity distribution at different locations in the ERT sensitivity field. Then, an orthogonal experiment was designed for CRB materials. We analyzed the effects of three main mixing parameters, i.e., solids concentration, particle size, and waste rock-to-tailing ratio, on the conductivity change of the backfill slurry. Finally, the current fastest imaging linear back-projection algorithm is used to reconstruct the image for the results of orthogonal experiments. Our results show that the reconstruction image can accurately reflect the position of waste rocks in a backfill slurry.

2. Materials and methodology

2.1. Materials used

2.1.1. Tailings

The copper-iron tailings used in this study were obtained from a dressing plant located in Anhui Province in China. Referring to the *Specification of Soil Test* (SL 237-1999) [15] and related literatures [16,17], the main physical properties of the tailings were tested and listed in Table 1. Particle size distribution (PSD) was displayed in Fig. 2, and median diameter (d_{50}) and weighted mean diameter (d_m) of the tailing particles are 97.00 μm and 127.17 μm, respectively. The chemical composition of the tailings is shown in Table 2, from which we can observe that the content of SiO_2 is 40.02 wt%. It is also clear that the proportions of metals and metal oxides are relatively high in the tailings. Furthermore, Sulphur (S) accounts for about 1.68 wt% of the contents. This high Sulphur content has damaging effects on the quality (e.g., strength deterioration) of cemented rock-tailings backfill (CRB) [18].

2.1.2. Waste rocks

The waste rocks used in the experiments, collected from the Anqing copper mine, were primarily made up of marble. The physical properties and chemical composition of the waste rocks are listed in Tables 3 and 4, respectively. During the experiment, a small jaw crusher was used to break the bigger rocks into smaller pieces, and the waste rocks were divided into three ranges by particle size (<10 mm, 10–25 mm, and 25–50 mm).

2.1.3. Binders

Portland cement (P.O.32.5) was used as the binder for the cemented rock-tailings backfill. The physical properties and chemical composition of Portland cement are shown in Table 5 and Table 6, respectively.

2.2. Methodology

2.2.1. Operational principle of ERT

ERT technology was first proposed in the nineteenth century on the mathematical basis of the Radon transform [19]. In response to the rapid development of computer and sensor technologies in the 1970s, researchers in the biomedical field proposed the Tomography Resistivity Technique (TRT) for circular electrode arrays and set out to find a fast, safe, and low-cost detection technique to replace X-ray based Computer Tomography (CT) techniques. In the 1980s, TRT was transplanted into the field of industrial inspection, where it developed into ERT technology.

The operating principle of ERT Technology is as follows: changes of the medium distribution in a pipeline cause changes in conductivity distribution in the sensitivity field in a consistent way for a given medium. By measuring changes in the conductivity/resistivity, the medium distribution in the pipeline can be reconstructed, allowing the parameters of the two-phase flow in the pipeline to be measured.

(a) pipeline blockage (b) pipeline burst

Fig. 1. Pipeline blockage and pipeline burst accidents of CRB in a metal mine in China.