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Laboratory study of the influence of dip and ore width on gravity flow during longitudinal sublevel caving

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ABSTRACT

A self-designed scaled physical draw model was used to mimic the extraction of a moderately stable and inclined medium-thick ore body. In terms of the ore dip and width, the gravity flow of the blasted ore and waste rock was investigated using tracing with labeled markers. The laboratory results indicate that the ore dip and its width have an impact on the flow axis and shape of the draw body. The flow axis was divided into two parts with lower and upper flow axes, respectively. The upper flow axis was parallel to the upper inclined wall, and the lower flow axis coincided with the axis of the draw point. The length of the upper flow axis and the area of draw body, influenced by the upper inclined wall, increased as the ore width or its dip decreased. The shape of the draw body in the lower part had longitudinal asymmetry and was similar to an inverted water drop; however, the shape of the draw body, which was influenced by the upper inclined wall, produced a variation and rotation to a certain extent, and no longer had the revolution symmetry about the central axis of the draw point. To this end, the gravity flow presented can provide a theoretical basis for ore recovery optimization.

1. Introduction

An inclined medium-thick ore body refers to a type of ore body with an ore width ranging from 4 to 15 m, where its dip ranges from 30° to 55°.[1] Such deposits account for approximately 23% of non-ferrous metal ores in underground mines in China.[2] With the increase in mining depth, the ground pressure correspondingly increases, as do the numbers of low-grade, inclined medium-thick ore bodies in general. The exploitation of such deposits is considered by the mining industry to be one of the difficult problems of deep mining. The adoption of a filling method is not suitable for low-grade ore. Using an open-stope method, although lower ore loss and dilution rates can be obtained, the cost of maintaining the stope stability is high and mining safety is difficult to guarantee.[3] A sublevel caving method is usually chosen to extract these deposits owing to a low mining cost, safe operation, and flexibility in dealing with the ground pressure.[4] However, its main characteristic is that caved ore surrounded by overlying waste rock are drawn from draw points. Owing to the application of inappropriate draw management practices or an unreasonable structural parameter design, ore recovery indices, such as the loss and dilution rates, significantly deteriorate. The loss rate is as high as 40% in some mines when using a caving method. Thus, mobile space conditions of an inclined medium-thick ore body usually lack flexibility, and residual ore can not be recovered in the next sublevel.[5–7] Therefore, research on gravity flow has a significant value in controlling and avoiding the entry of dilution into the ore during rock extraction.

To date, studies on the gravity flow of caved rock in caving mines have been conducted using physical models, theoretical and numerical analyses, and full-scale trials.[8–12] Although, in situ trials can better reflect the full similitude of real in situ draw conditions, the present investigation into the mechanics of broken rock during isolated drawing have been achieved through model draw experiments owing to the high cost, time consumption, and practical difficulties in directly managing and observing the blasted ore and waste rock flow in situ. Scaled physical models have thus been more widely used in laboratory settings, and such experiments have been critical to research on draw problems. For instance, the flow behaviors and mechanics of broken rock were studied through model draw experiments conducted by a large number of researchers using gravel, sand, or rocks as the medium.[13–16] These studies, which have provided a critical understanding, have included the movement of material in an isolated draw point, the influence on the drawing among the multiple draw points, the main influencing factors of the geometry of the extraction and movement zones, the flow mechanisms under confined conditions, and the characteristics of the ore body and its changing trend.

The original locus of the material extracted from an isolated draw point in underground mining, which depends mainly on the volume of the extracted material, is referred to as the draw body or isolated

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extraction zone (IEZ).[17] The flow characteristics of blasted ore and caved waste, namely, the IEZ shape and ore recovery indices, are closely related to the stope boundary conditions, which is also a topic of considerable research interest in the field of draw theory.[18] In cave mining, inclined wall boundary conditions, which are more common in actual mines, refer to the flow of blasted ore and caved waste rock, which can be influenced by the inclined wall when the dip of the ore body is less than 90° and greater than the natural repose angle of the material.[19] However, most researches have been mainly aimed at simulating material flow under infinite and semi-infinite boundary conditions. Fewer researches into material flow under inclined boundary conditions have been conducted thus far, however. Although some important factors such as the size of the draw point, the particle size, and the properties of the material have an impact on the flow of broken rock, the ore width and its dip are also critical factors to the successful extraction of inclined medium thick ore bodies.[20] Considered the influence of the dip and width of the ore body on the gravity flow of blasted ore and cave waste, scaled physical model draw experiments were carried out, and the characteristics of the flow axis and draw body are presented in this paper. This will help understand the mechanism of ore loss and dilution, and then provide a theoretical basis for reducing the ore dilution while improving ore recovery in the field.

2. Model and media

Magnetite was used as the extracted material in the tests, the largest block size of which was 500 mm, and was taken directly from the Qidong iron mine in Hunan province in China. The ore width mimicked ranged from 4 to 10 m, and the scale of the draw model should be rational and feasible because too large or too small of a model would have a certain effect on the operation or flow capability. In addition, Castro reported that the geometrical scale has no significant influence on the shape of the IEZ when using a large 3D physical model.[21] Therefore, based on the similitude principle, a scaled physical draw model with a geometrical scale of 1:25 was designed to run flow simulations for longitudinal sublevel caving during isolated drawing tests under inclined wall conditions.

The size of the model was $1.8 \times 0.1 \times 1.6\,m^3$ (length × width × height), as shown in Fig. 1. The isolated draw model consisted of a stainless steel frame, upper and lower inclined walls, front and back walls, small holes for adjusting the dip and width of the ore body, and a draw drift. The isolated draw point (the height and width of which were both 0.1 m), which was close to the lower inclined wall, was located at the bottom of the setup. The front wall of the model was acrylic glass to allow direct observations of the flow trend of the material. The other walls were made of board because the ore body and surrounding rock mimicked in this test were moderately stable. To conveniently load the material and place labeled markers, it is essential to mention that the back wall of the model was piled with 24 separate battens, the widths of which were all 50 mm.

In addition, the experimental material was further processed indoors and broken into particles whose size was less than 20 mm based on the geometrical scale. The particle size distribution is shown in Fig. 2. The bulk density of magnetite ore was 1841 kg/m^3 and its natural repose angle was 33.4°. During these isolated drawing tests, when the particles flowed to the draw point, rock breakage occurred owing to abrasions, although the effect was negligible. The influencing factors mainly considered were the width of the ore body and its dip (namely, the inclined wall angle in the tests).

3. Experimental processes

3.1. Physical simulation schemes of isolated drawing tests

A total of 12 physical simulation experiments were designed to investigate the effects of the dip and the width of the ore body on the characteristics of the flow axis and the shape of the draw body. As shown in Table 1, three different dips of the ore body (angles of 45°, 50°, and 55°, respectively) and four different widths (4, 6, 8, and 10 m, respectively) were taken into account in this study. According to the geometrical scale, the widths of the ore body in the tests were 16, 24, 32, and 40 cm, respectively. To reduce the impact of random movements of particles based on the flow behaviors of the ore draw, each physical simulation scheme was repeated three times.

3.2. Placement of labeled markers

To make the flow characteristics of the labeled markers in accordance with those of the experimental material, the markers were selected directly from the extracted material, and their size ranged from 8 to 12 mm. As shown in Fig. 1, each labeled marker, which was sprayed with white paint to distinguish it from the others, was pasted with a white label with a symbol in red font. Symbols such as '1–1′ and '1–2′ indicate the respective coordinate point in the model. Taking '1–2′ as an example, the Fig. '1' in front of the hyphen (-) represents the layer number, i.e., the first layer or H = 50 mm in this example, and the following Fig. 2 represents the second particle placed away from the lower inclined wall. Fig. 1 indicates that the marked particles were distributed every 50 mm in the height direction, and a row of labeled markers with a spacing of 15 mm was placed at the centre of each horizontal level.

3.3. Ore loading and drawing processes

To make certain that *the inclined wall angle and width of the ore body* can be easily changed to satisfy the requirements of physical simulation schemes, the adjusting holes mentioned above were made using a portable electrical drilling machine. The entire model should keep horizontal on the ground to avoid negatively influencing the experimental data.

The particular ore loading process is as follows. First, the top of the draw point was sealed using an iron plate that aimed to mimic the original condition without blasting, and the batten of the first layer was inserted into the framework for preparation. After finishing the above preparations, the incompact particles were filled into the model until the loading surface of the granular particles was flush with the upper edge of the batten, and the labeled markers of the first layer were then located using the positioning board to ensure the accuracy of the coordinate points. Next, the second batten was inserted into the model. Thus, the labeled markers of the first layer were surrounded by a few particles subsequently, such that each marked particle was stabilized. Otherwise, the labeled markers would move randomly during the ore loading process, thereby affecting the experimental results. When the labeled markers were covered and completely immobilized by the particles, the second layer of the model was filled sequentially under the same conditions as the first layer. Finally, according to the procedure above, the entire inner space of the model was filled with particles. Additionally, during the ore loading process, the mass of the particles for each layer was accurately weighed. The volume and total mass of the filling particles were also statistically analyzed, and the bulk density of the ore was then calculated once the ore loading process was terminated.

Because the entire model was filled with particles, the iron plate sealing the draw point was taken out, and particles were then drawn from the draw point. During the process of ore draw, the flow speed of the particles should not be fast, and should remain as constant as possible. Meanwhile, the single mass of the ore drawn from the draw point with a small bucket was about 0.1 kg each time, and the numbers of labeled markers drawn and their corresponding amount were recorded. To draw ore under stable pressure and maintain a flat surface medium, the incompact granules should be duly added on top of the model once the ore draw begins at the bottom. The single masses drawn