Research Article

Experimental Investigation of the Influence for Stopping Sequence and Granular Grading on Lateral Pressure during the Nonpillar Sublevel Caving Mining

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In this study, a self-designed scaled physical model was conducted to investigate the variation laws of lateral pressure under different stopping sequences and granular gradings, and drawing ore in the experiments was used to simulate the mining process. Under the limiting equilibrium state, the values of lateral pressure increased exponentially with the increasing depth of granular media, and the growth rate of lateral pressure gradually decreased as the depth of granular media increased. Then, the laboratory results indicated that the distribution laws of lateral pressure were divided into three parts, namely, the drawing influencing region, the upper descending zone, and the central growth area. As the height of the isolated extraction zone (IEZ) increased, the scope of the drawing influencing region and the upper descending zone increased, while the range of central growth area decreased. In the case of an invariable height of IEZ, more reduction ratio and the scope for drawing influencing region could be appeared in the lower wall. Increasing the space between the drawpoints and granular grading were an effective way to control the reduction rate of lateral pressure in the drawing influencing region, while the scope of the above parts kept stable. Moreover, the average values of lateral pressure showed an increasing trend as the granular grading decreased at the same number of drawing ore.

1. Introduction

The nonpillar sublevel caving mining was usually adopted to extract the underground metal mine, which has a high mining intensity, consumes little mining costs, and uses simple stopping technology [1–3]. However, the surface subsidence was inevitably generated in the vicinity of the mining operations based on the main characteristic of this mining method. The inaccurate range of the surface subsidence could significantly deteriorate recovery ratio, the loss of natural resources, and operational safety. Meanwhile, the distribution laws of lateral pressure were the essential factor to predict the range of surface subsidence induced by the nonpillar sublevel caving mining [4–7]. Hence, it was quite essential to investigate the distribution laws to control and

avoid the loss of natural resources and jeopardizes surface subsidence.

Recently, many great efforts had made to study the distribution laws of lateral pressure using physical models, theoretical analyses, and numerical analyses. Meanwhile, the conventional laws of lateral pressure are based on the theory of Janssen, Coulomb, Reimbert, Wilfred Airy, and Rankine and then the widespread computational formulas of lateral pressure as shown in Table 1 [8–19]. The theory of Janssen had been widely used, but the different coefficient of lateral pressure was applied in the different specifications. Reimbert [14] studied the equation based on laboratory tests, where the coefficient of lateral pressure was variable. Then, Chen [17] reported a formula of lateral pressure with an inclined angle according to the assumption of the Janssen equation,

TABLE 1: The conventional computational formulas of the lateral pressure.

The conventional laws	Proposer
$p = \gamma S / f C [1 - e^{-(fKC/S)z}]$; $K = 1 - \sin \theta / 1 + \sin \theta$ $p = \gamma D / \tan \phi [1 - (1 + (z/c))^{-2}]$; $c = R/4K \cdot \tan \phi - h_s/3$; $K = 1 - \sin \theta / 1 + \sin \theta$ $p_a = (1/2)\gamma z^2 K_a$; $K_a = \cos^2(\theta - \varepsilon) / \cos^2(\varepsilon) \times \cos(\phi + \varepsilon) [1$ $+ \sqrt{\sin(\phi + \theta) \times \sin(\theta - \beta) / \cos(\phi + \varepsilon) \times \cos(\varepsilon - \beta)}]^2$; $p_b = (1/2)\gamma z^2 K_b$; $K_b = \cos^2(\varphi + \varepsilon) / \cos^2(\varepsilon) \times \cos^2(\varepsilon - \delta)$ $[1 - \sqrt{\sin(\delta + \varphi) \times \sin(\varphi + \beta) / \cos(\varepsilon - \delta) \times \cos(\varepsilon - \beta)}]^2$ $H/D < 1.5$, $p = (1/2)\gamma z^2 (1/\sqrt{\tan \theta [\tan \theta + \tan \phi]} + \sqrt{1 + (\tan \phi)^2})^2$; $H/D > 1.5$, $p = \gamma D / \tan \phi + \tan \theta (1 -$ $\sqrt{1 + (\tan \theta)^2 / (2z/D)})(\tan \phi + \tan \theta) + 1 - \tan \phi \times \tan \theta)$	Janssen [13] Reimbert [14] Coulomb [15]
$p = (\gamma S / f C) \sin \alpha (1 - (f / \tan \alpha)) [1 - e^{-(fKC/S \sin \alpha)z}]$; $K = 1 - \sin \theta / 1 + \sin \theta$ $p_a = \gamma z K_a$, $K_a = 1 - \sin \theta / 1 + \sin \theta$; $p_b = \gamma z K_b$, $K_b = 1 + \sin \theta / 1 - \sin \theta$	Wilfred Airy [16] Chen [17] Rankine [18]

Note: p was the lateral pressure; p_a was the active lateral pressure; p_b was the passive lateral pressure; K was the coefficient of the lateral pressure; K_a was the coefficient of the active lateral pressure; K_b was the coefficient of the passive lateral pressure; γ was the unit weight of granular media; S was the horizontal projected area of the class silo; C was the perimeter of horizontal projection for the class silo; f was friction coefficient between granular media and class silo; $f = \tan \phi$, ϕ was the friction angle between granular media and class silo; z was the height of granular media; ε was the angle between class silo and vertical line; θ was the internal friction angle of granular media; α was the dip of the soil surface; D was the inner diameter of the class silo; ζ was the angle of repose for granular media.

which had been used in thin orebody. Otherwise, the scaled physical experiments had been widely utilized in the laboratory, with low cost, simpler operation, and low time consumption. Brown et al. researched the patterns of pressures in storage and discharge state with two different free-flowing solids [20]. Meanwhile, Ren et al. designed the setup to study the variation laws of lateral pressure during the process of drawing ore [21]. With the development of numerical simulation technique, a mass of number codes, including ANSYS [22, 23], DEM [24, 25], and PFC [26], were developed and applied in the models of lateral pressure for granular media. The PFC3D software was employed to simulate the distribution laws for internal pressure of the material during the coal discharging process [27], and the ADINA software was performed to predict the value of lateral pressure in the silo [28]. These studies had provided a critical understanding, including the distribution laws of lateral pressure under the limiting equilibrium state, the influence on the lateral pressure among materials, the influencing factors of the geometry for bin shape, and the coefficient characteristic for the lateral pressure and its changing trend.

In nonpillar sublevel caving mining, the movement and nonuniform granular conditions of granular media for the caved rock zone were very common [29, 30]. Thus, the distribution laws of lateral pressure were influenced by mining. However, most of these studies had focused on the distribution laws for lateral pressure at the limiting equilibrium and uniform granular conditions. Few investigations were reported for the distribution laws under the drawing ore and nonuniform grading conditions. Although some important factors such as the size of drawpoint, the properties of the material, and the dip and width of orebody could affect the lateral pressure, the stopping sequence and granular grading were also vital to analyze the stress states of side wall for surface subsidence. Considering the influence of the stopping sequence and granular grading on the distribution laws of lateral pressure, scaled physical experiments were carried out, and the variation laws of lateral pressure during drawing ore were found in this study. This work could not only help researchers to understand the mechanism of gravity flow for granular media, but also provided a theoretical tool for predicting the scope of the surface subsidence induced by the nonpillar sublevel caving mining.

2. Materials and Model

Castro et al. [31] reported that the shape of the isolated extraction zone (IEZ) was not significantly affected by the geometrical scale using a large 3D physical model. To reduce the effect on the operation or flow capability, the setup should be rational and feasible. Thus, some hypotheses of scaling were applied as follows: (1) the geometrical scale of 1 : 100 was used to simulate for the whole block geometry, including block dimensions (height and area of draw), the dimensions of drawpoint, and the particle size; (2) the bulk density and the residual friction angle in the model were the same as those in the field; (3) the wall friction angle was

similar to the internal friction angle; and (4) the scale of times was related to the scale of the length by $\lambda_t = 100^{1/2} = 10$.

The equipment was composed of a drawing-ore device, a data collection system, and a supporting bar for adjusting the orebody dip, as shown in Figure 1. As shown in Figure 2, the drawing-ore device was made up of upper and lower walls, front and back walls, drawpoints, and test channels, with the size of 50 cm × 25 cm × 160 cm (width × length × height). The granular media in the drawing-ore device was required to measurably stable during the experimental process. Hence, the walls of lower and upper were made from steel. Then, four drawpoints (the length and width of them were both 3 cm) were set in the bottom of the lower wall, and the interval was 7.6 cm. Also, the drawpoints were used to simulate the different stopping sequences. To precisely obtain the values of lateral pressure, the upper and lower walls were made up of 16 panels, respectively, and the corresponding size was 50 × 10 cm (width × length). Then, 1#–8# test channels were placed in the lower wall and 9#–16# test channels were installed in the upper wall, and the interval was 20 cm in the respective wall. 1# and 9# test channels were 15 cm away from the bottom of the device, and 8# and 16# test channels were 5 cm away from the top of the device. The test channels collected information regarding the lateral pressure with different measured heights, and the measured height of each test channel is shown in Table 2. Then, the values of lateral pressure with different heights were transferred from the test channels to the data collection system during the drawing process. In the study, the stopping sequence and granular grading were investigated as influencing factors to possess the distribution laws of lateral pressure during drawing ore. Dolomite was used as the experimental material in the test and was regarded as cohesionless.

3. Experimental Process

The basic operation and theoretical foundation of the isolated drawing experiments were provided by Zhang et al. [32]. A total of 9 physical simulation tests were designed to study the influence of the stopping sequence and granular grading on the distribution laws of lateral pressure. As shown in Tables 3–5, three different stopping sequences and three granular gradings were taken into account in this study. According to the geometrical scale and nonpillar sublevel caving mining [1, 33], the height of orebody (30 cm) and the drawing mode of nondilution were employed. To keep the ore flow capabilities consistent with the test materials, the ores were obtained directly from the test materials, and their size was in accordance with the test material. Then, the ores were red painted to distinguish them from the test materials. To make the flow velocity of granular media keep constant and full similitude of mine conditions, the single mass of the ores drawn from the drawpoints was about 200 g per time and the independent advance of ore breaking was approximately 1.5 cm. Moreover, each experiment was repeated 3 times to decrease the influence of random movements of experimental materials based on the flow behaviors during the drawing process. To avoid the influence

FIGURE 1: The schematic diagram of the physical model.

FIGURE 2: The schematic diagram of the drawing-ore device. Note: 1#, 2#, . . . , 16# represent the test channels, and I, II, III, and V represent the drawpoints.

TABLE 2: The measured height of each test channel.

Test channels	The lower wall								The upper wall							
	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#	11#	12#	13#	14#	15#	16#
Measured height (m)	1.45	1.25	1.05	0.85	0.65	0.45	0.25	0.05	1.45	1.25	1.05	0.85	0.65	0.45	0.25	0.05

on the testing data, the drawing-ore device was remained horizontal on the ground and the adjusting bar was fixed on the experimental model.

After completing the above steps, the drawpoints were blocked with the elastic materials so as to simulate the real state without blasting. Then, the incompact ores were

TABLE 3: Summary of laboratory schemes.

Granular grading	Stoping sequence		
	Interval faces	From center to end	From end to center
Group 1	Scheme 1	Scheme 4	Scheme 7
Group 2	Scheme 2	Scheme 5	Scheme 8
Group 3	Scheme 3	Scheme 6	Scheme 9

TABLE 4: Summary of stoping sequence.

Stoping sequence	Summary
Interval face	(1) Unfold the drawpoints of II and V; (2) recorded the values of lateral pressure during the drawing process; (3) blocked the corresponding drawpoint once the waste rocks were drawn from the drawpoint; (4) let the drawing-ore device sit for 20 minutes; (5) unfold the drawpoints of I and III; (6) repeated the step of (2) and (3).
From center to end	(1) Unfold the drawpoints of II and III; (2) recorded the values of lateral pressure during the drawing process; (3) blocked the corresponding drawpoint once the waste rocks were drawn from the drawpoint; (4) let the drawing-ore device sit for 20 minutes; (5) unfold the drawpoints of I and V; (6) repeated the step of (2) and (3).
From end to center	(1) Unfold the drawpoints of I and V; (2) recorded the values of lateral pressure during the drawing process; (3) blocked the corresponding drawpoint once the waste rocks were drawn from the drawpoint; (4) let the drawing-ore device sit for 20 minutes; (5) unfold the drawpoints of II and III; (6) repeated the step of (2) and (3).

TABLE 5: Summary of granular grading.

Granular grading	Group 1			Group 2			Group 3		
The mass percent (%)	24.6	38.6	36.8	24.6	38.6	36.8	24.6	38.6	36.8
The granular size (mm)	<2	2~4	4~6	<3	3~6	6~9	<4	4~8	8~12

dropped into the setup with 30 cm, and a smooth surface of the ores would be obtained. Next, the surface of the ores was surrounded by a little waste rock, such that each ore granular was stabilized. Otherwise, the ore granular in the surface would move randomly in the ore loading process, thereby affecting the experimental results. Also, the other incompact waste rocks were dropped into the setup, so no more materials could be dropped into the experimental model. Finally, the total internal space of setup was filled with the experimental materials. Additionally, the internal friction angle and friction angle between granular media and the drawing-ore device were analyzed. Meanwhile, the total mass and density of granular media were calculated once the ore loading process was terminated. Since the internal model was filled with the experimental materials, the elastic material blocking the drawpoints was taken off, and the materials were then drawn from the drawpoints. According to the above scheme, the corresponding drawpoints were unfolded. During the drawing process, the flow speed of granular media should remain as constant as possible rather than fast. Hence, the single mass of the ore drawn from the drawpoints was about 200 g each time, and the values of lateral pressures and the number of drawing ore were recorded. Then, the corresponding drawpoint was terminated once the waste rocks were drawn. The interval time of 20 minutes was employed to simulate the mining conditions. Then, the next corresponding drawpoints were unfolded and the previous steps were repeated. Consequently, the variation laws of lateral pressure could be received once the waste rock reached the last drawpoint.

4. Experimental Results

4.1. The Relationship between Lateral Pressure and Depth of Granular Media. Figure 3 presents the relationship between the lateral pressure and depth of granular media under the limiting equilibrium state. The values of lateral pressure increased exponentially with the increasing depth of granular media, and the growth rate of lateral pressure gradually decreased as the depth of granular media increased. Then, the porosity of granular media increased when the granular grading increased. However, the unit weight decreased accordingly. Hence, the values of lateral pressure showed an increasing trend as the granular grading decreased for the same depth of granular media. Meanwhile, the porosity of granular media decreased as the depth of granular media increased, and the value of lateral pressure among granular grading increased with the increasing depth of granular media.

4.2. Characteristic of Variation Laws for Lateral Pressure. The relationship between the number of drawing ore and the values of lateral pressure with different schemes are shown in Figures 4–12, respectively. Due to the 20-minute interval time, the process of drawing ore could be divided into two stages, and IEZ induced by two drawing stage was independent [34]. It was suggested that the measured values from 1# and 9# test channels decreased exponentially with an increasing number of drawing ore in each drawing stage. Then, the lateral pressure of 2#, 3#, and 10# test channels was firstly enhanced and then diminished as the number of

FIGURE 3: The relationship between the lateral pressure and depth of granular media under the limiting equilibrium state.

FIGURE 4: The relationship between the number of drawing ore and the values of lateral pressure with scheme 1.

FIGURE 5: The relationship between the number of drawing ore and the values of lateral pressure with scheme 2.

drawing ore increased in the two drawing stages. Meanwhile, the lateral pressure of 8# and 16# test channels had a negative relationship with the number of drawing ore. The values of other test channels showed an increasing trend as the number of drawing ore rose.

In the drawing process, the scope of IEZ and isolated movement zone (IMZ) increased with an increase in number for drawing ore. Then, the granular media in the IMZ could be loosened, and that above the IMZ slowly collimated and the internal friction angle gradually increased. Hence, the lateral pressures were projected to continue decreasing while the test channels located in the scope of IME. Meanwhile, because of the relatively small scale of IMZ and increasing internal friction angle in the initial drawing phase, the measured values were augmented while the test channels above the scope of IMZ and then the lateral pressure descended as the IMZ reached the testing range of test channel. Due to the descending surface of granular media, the value of 8# and 16# test channels tended to gradual

decline. As the nondilution ore drawing was used, the height of the IEZ and IMZ was about 30 cm and 73.8 cm, respectively. Hence, the other values were expected to rise as the test channels were higher than 73.8 cm.

The variation rates of lateral pressure under different stoping sequences and granular gradings are exhibited in Table 6. A new standpoint was proposed that the distribution laws could be divided into three parts. One part was drawing influencing region, which is located in the IMZ and had a positive relationship with the number of drawing ore. The other part was the upper descending zone, which is located in the surface of granular media and the volume was equal to the IEZ. The last part was central growth area, which was between the previous two parts. Then, the lateral pressure had a positive relationship with the number of drawing ore in the central growth area. As the number of drawing ore increased, the scope of drawing influencing region and upper descending zone increased, while the range of central growth area decreased. Moreover, the reduction rate of

FIGURE 6: The relationship between the number of drawing ore and the values of lateral pressure with scheme 3.

FIGURE 7: Continued.

FIGURE 7: The relationship between the number of drawing ore and the values of lateral pressure with scheme 4.

FIGURE 8: The relationship between the number of drawing ore and the values of lateral pressure with scheme 5.

FIGURE 9: The relationship between the number of drawing ore and the values of lateral pressure with scheme 6.

FIGURE 10: Continued.

FIGURE 10: The relationship between the number of drawing ore and the values of lateral pressure with scheme 7.

FIGURE 11: The relationship between the number of drawing ore and the values of lateral pressure with scheme 8.

FIGURE 12: The relationship between the number of drawing ore and the values of lateral pressure with scheme 9.

lateral pressure showed a declining tendency as the height of granular media grew in the drawing influence region.

In the case of an invariable mining scheme and the same number of drawing ore, more reduction ratios and the scope for drawing influencing region could be appeared in the lower wall. Once the height and mass of the IEZ were identified, the scope of the drawing influencing region and the upper descending zone could be obtained and used to predict the range for the surface subsidence. Additionally, it was found that the stoping sequence and the granular grading both had a primary influence on the value of lateral pressure.

4.3. The Relationship between Lateral Pressure and Stopping Sequence. To convenient obtain the influencing effect of stopping sequences, the schemes were divided into three groups (group 1: scheme 1, scheme 2, and scheme 3; group 2: scheme 4, scheme 5, and scheme 6; and group 3: scheme 7, scheme 8, and scheme 9). The different stopping sequences would cause the changing of the granular grading after the first stage of drawing ore. Hence, the first stage of drawing

ore in the same group was selected for studying the variation laws of lateral pressure influenced by stopping sequence so as to reduce the impact of granular grading, and the reduction rates of lateral pressure in the first stage for drawing ore are shown in Table 7. It could be noted that the scope of the three parts was unaffected by the stopping sequence, whereas the stopping sequence had an impact on the drawn mass at the same height of IEZ.

Meanwhile, the stoping sequence had a remarkable influence on the reduction rates of lateral pressure in the drawing influencing region. For the same granular grading and height of IEZ, more reduction rates of lateral pressure were observed with a decrease in the space between the drawpoints. For these three different stopping sequences (scheme 1, scheme 4, and scheme 7) with the same granular grading and height of IEZ (30 cm), the reductive rates of 1# and 9# test channels were 4.77% and 3.56%, 6.75% and 5.10%, and 2.89% and 2.59%, respectively, whereas the scope of drawing influencing region kept stable.

TABLE 6: The variation rates of lateral pressure under different stoping sequences and granular gradings.

Test channel	Variation rates of lateral pressure (%)								
	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6	Scheme 7	Scheme 8	Scheme 9
1# $h = 1.45$ m	-9.89	-8.46	-6.70	-10.87	-9.39	-7.70	-9.26	-7.69	-6.60
2# $h = 1.25$ m	-7.07	-5.57	-4.71	-7.83	-6.50	-5.40	-6.19	-5.20	-4.40
3# $h = 1.05$ m	-2.94	-1.75	-1.63	-3.43	-2.83	-1.62	-2.77	-1.91	-1.60
4# $h = 0.85$ m	3.20	2.85	2.17	1.76	2.13	4.28	2.94	2.54	3.32
5# $h = 0.65$ m	2.75	2.19	2.01	3.17	1.57	1.96	2.69	2.23	2.14
6# $h = 0.45$ m	2.12	2.27	2.04	3.15	1.77	1.06	2.51	2.43	2.18
7# $h = 0.25$ m	3.22	2.43	2.31	3.83	3.65	1.45	2.73	2.54	2.49
8# $h = 0.05$ m	-6.39	-4.34	-5.61	-5.77	-4.41	-4.28	-5.93	-6.24	-5.05
9# $h = 1.45$ m	-7.64	-6.18	-5.03	-8.65	-7.00	-5.64	-6.75	-5.49	-5.00
10# $h = 1.25$ m	-5.31	-4.26	-3.80	-6.74	-5.11	-4.17	-4.95	-4.09	-3.58
11# $h = 1.05$ m	1.49	2.10	0.85	1.73	1.39	1.17	1.78	1.53	1.30
12# $h = 0.85$ m	2.41	2.01	1.05	2.01	1.62	1.29	2.34	1.56	2.09
13# $h = 0.65$ m	1.76	1.49	1.29	1.33	1.26	1.26	1.79	1.58	1.49
14# $h = 0.45$ m	3.62	3.28	3.07	3.95	3.47	3.48	3.63	3.49	2.88
15# $h = 0.25$ m	2.08	2.01	2.29	3.10	2.88	2.41	2.66	2.49	2.03
16# $h = 0.05$ m	-3.49	-2.47	-3.9	-4.0	-3.97	-3.16	-6.20	-6.78	-6.40

TABLE 7: The reduction rates of lateral pressure in the first stage for drawing ore.

Group	Scheme	The variation rates of lateral pressure (%)				
		1# $h = 1.45$ m	2# $h = 1.25$ m	3# $h = 1.05$ m	9# $h = 1.45$ m	10# $h = 1.25$ m
1	1	-4.77	-3.94	-1.32	-3.56	-3.12
	4	-6.75	-4.72	-2.37	-5.10	-3.81
	7	-2.89	-2.15	-0.84	-2.59	-1.82
2	2	-3.89	-3.14	-1.03	-3.21	-2.52
	5	-6.12	-4.04	-2.16	-4.16	-3.55
	8	-2.82	-2.10	-0.80	-2.34	-1.42
3	3	-2.95	-2.55	-0.86	-2.61	-2.02
	6	-4.58	-3.18	-1.08	-3.12	-2.57
	9	-2.67	-1.59	-0.74	-2.30	-1.44

4.4. The Relationship between Lateral Pressure and Granular Grading. To obtain the effect of granular grading, the different mining schemes were divided into three groups (group 1: scheme 1, scheme 4, and scheme 7; group 2: scheme 2, scheme 5, and scheme 8; group 3: scheme 3, scheme 6, and scheme 9), and the relationships between the granular grading and lateral pressure of reduction rates and average values are shown in Table 8. With an increase in the granular grading, the scope of the drawing influencing region had no significant decrease, whereas the mass drawn from the drawpoints decreased. Additionally, it was found that the granular grading had a primary influence on the variation rate of lateral pressure, in which the reduction rate and reductive ratio in the drawing influencing region were inconsistent with each other in same stoping sequence, and the reduction rate had a negative relationship with the granular grading. With the same stoping sequence and height of IEZ, the average values of lateral pressure increased as the granular grading decreased at the same height of granular media. Because of the more mobility and unit weight of granular media, which were generated from the more uniform and smaller size of the granular, the more reductive rate and average values of lateral pressure were obtained. For three granular gradings (scheme 4, scheme 5,

and scheme 6) with the height of IEZ of 30 cm and the same stoping sequence, the reduction rates of 1# and 9# test channels were 10.87% and 8.65%, 9.39% and 7.00%, and 7.70% and 5.64%, respectively, and the average values of the lower wall and upper wall were 1696 Pa and 1720 Pa, 1428 Pa and 1452 Pa, and 1336 Pa and 1348 Pa, respectively.

5. Discussion

In this study, the stoping sequence and granular grading were chosen as the main influencing factors on the distribution laws of lateral pressure induced by nonpillar sublevel caving mining. For calculating the lateral pressure, its success mainly depended on the stoping sequence, granular grading, the properties of granular media, and structural parameters. For instance, in terms of the layout of the sublevel parameters used in this test, the bigger the height of sublevel was, the bigger the shape of IEZ at the same stoping sequence and granular grading, and therefore bigger range of drawing influencing region and reductive rate of lateral pressure that would correspondingly be appeared.

Research on the variation laws of lateral pressure played an important role in predicting the scope of surface subsidence for theoretical and practical guidance in mine

TABLE 8: The relationship between the granular grading and lateral pressure of reduction rates and average values.

Group	Scheme	The variation rates of lateral pressure (%)					The average values of lateral pressure (Pa)	
		1# $h = 1.45$ m	2# $h = 1.25$ m	3# $h = 1.05$ m	9# $h = 1.45$ m	10# $h = 1.25$ m	The lower wall	The upper wall
1	1	-9.89	-7.07	-2.94	-7.64	-5.31	1638	1662
	2	-8.46	-5.57	-1.75	-6.18	-4.26	1482	1500
	3	-6.70	-4.71	-1.63	-5.03	-3.80	1360	1368
	4	-10.87	-7.83	-3.43	-8.65	-6.74	1696	1720
2	5	-9.39	-6.50	-2.83	-7.00	-5.11	1428	1452
	6	-7.70	-5.40	-1.62	-5.64	-4.17	1336	1348
	7	-9.26	-6.19	-2.77	-6.75	-4.95	1682	1962
3	8	-7.69	-5.20	-1.91	-5.49	-4.09	1542	1558
	9	-6.60	-4.40	-1.60	-5.00	-3.58	1330	1338

production. The main characteristics of the reductive rate and the variation laws for lateral pressure could be referenced to propose a method for predicting the failure condition of rock mass, as well as deeply analyzing the mechanisms of rock movement and determining the stoping parameters. For instance, Li et al. tried to predict the range of surface subsidence induced by the nonpillar sublevel caving mining [5]. The distribution laws of lateral pressure were the foundation of constructing a correct predicting calculation since the laws intensively reflected the stress characteristics of rock mass in the caved rock zone.

In this study, a new standpoint was proposed that the distribution laws could be divided into three parts, and then the lateral pressure increased exponentially with increasing depth of granular media. Ren et al. [35] and He et al. [36] reported the distribution laws of lateral pressure from different orebody dip conditions, which seemed consistent with the scope of drawing influencing region, but to a certain extent had its variation on the upper descending zone and the central growth area. These abovementioned results are under the invariable width of orebody, and the vibration of blasting is not considered; further studies are essential to improve this simple description to the more comprehensive results of complex gravity flow encountered in actual mines. In addition, certain parameters, such as the width and dip of orebody, the size of drawpoint, the properties of granular media and the shape of wall side, could be considered and studied using a 3D physical model or in situ experiments.

6. Conclusions

In this study, a laboratory-scaled physical model was designed to investigate the influence of stoping sequence and granular grading on the lateral pressure during the drawing process. Under the limiting equilibrium state, the values of lateral pressure increased exponentially with the increasing depth of granular media, and the growth rate of lateral pressure gradually decreased as the depth of granular media increased. Meanwhile, the experimental results showed that the distribution laws of lateral pressure were divided into three parts including the drawing influencing region, the upper descending zone, and the central growth area. The shape of three parts was virtually identified under different stoping sequences and granular gradings. In addition, the

mass drawn or the height of the IEZ could increase the scope of drawing influencing region and upper descending zone and could reduce the range of the central growth area. For the same height of IEZ, more reduction ratio and the scope for drawing influencing region could be appeared in the lower wall. Then, the influencing laws of granular grading and stoping sequence on the reduction rates of drawing influencing region complemented each other. The reduction rates in the drawing influencing region showed an increasing trend as the interval of drawpoint and granular grading decreased, and the scope of these parts was negligibly affected by the stoping sequence and granular grading. Moreover, the average values of lateral pressure increased with a decrease in the size of granular media as the height of the IEZ and stoping sequence remain constant.

The experimental results could help to understand the distribution laws of lateral pressure under stoping sequence and granular grading and provided an experimental tool to predict the range of surface subsidence.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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