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Article

Three-Dimensional Physical Model Test Study on Mining-Induced Strata Movement of Open-Pit Final Slope

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Abstract: Strata and surface movement induced by mining under open-pit final slope is a huge threat to mine safety. Physical model test is an important method to study mining-induced strata and surface movement laws. Because of rock joints predominantly control rock mass deformation and failure, thus physical model test leaving out of consideration of rock joints is difficult to reflect the influence of rock joints on rock mass deformation. Therefore, this paper presents a three-dimensional physical model test considering simplified dominant rock joints. This test process includes the design of testing equipment, the construction of physical model with dominant rock joint sets, conduction of mining and deformation monitoring. And mining under eastern final slope of Yanqianshan iron mine was selected as a case to study the behavior of mining-induced strata and surface movement.

Keywords: physical model test; rock joint; strata and surface movement; final slope mining; surface settlement

1. Introduction

The serious strata and surface movement induced by mining in open-pit final slope would frequently trigger slope failure and surface subsidence, which would make the mining area into great threaten. Detailed research on mining-induced strata and surface movement are necessary to prevent and reduce disasters occurred in mining area. Whereas, there is a great lack of detailed and systematic studies on strata and surface movement induced by mining under open-pit slope. Methods to study underground mining-induced rock strata movement are mainly theoretical analysis method, numerical simulation method, and physical model testing method.

The theoretical method simplified the strata as a beam or slab model, and then the simplified model is analyzed by the mechanical analysis method. The widely used theoretical analysis model to study this problem are mainly the Pressure-arch Theory. For example, He and Zhang applied the Discontinuous Deformation Analysis(DDA) in investigating the formation of pressure arch[1]; Wang, Jing et al. conducted a systematic study on the pressure arch to predict collapse of deep-buried tunnel[2]. Chen et al. used the Cantilever Hypothesis to analysis the strata movement mechanism and surface deformation in an iron mine [3]. Tu et al. conducted a research on the gate road system failure based on the Cantilever Hypothesis [4]. Li et al. studied the static stress within fault-pillars using the Voussoir Beam Theory [5]; Ju and Xu found and defined three kinds of structural model affected by the key strata's position in super great mining height long wall face [6].

The mechanism of mining-induced strata movement can be well understood by the theoretical analysis method. However, significant inaccuracy is noticeable when simplifying the overlying strata as beam or slab under complicated geological conditions. With the development of numerical simulation method and computer technology, numerical simulation method shave been widely used to study underground mining-induced strata and surface movement. The most common numerical simulation methods include the Finite Element Method (FEM) and Finite Difference Method (FDM) based on the continuum mechanics, the Discrete Element Method (DEM) based on the non-

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continuum mechanics, and method by the combination of FEM and DEM (FEM-DEM) method. Unver and Yasitli conducted a research on the caving mechanism by FLAC3D [7]; Guo, et al. studied the strata behavior at long wall panel using COSFLOW software based on the FEM [8]; Wang et al. simulated the displacement variation, stress and strain of overlying strata and coal seams by ANSYS software based on the engineering background of working face in Zhao mine [9]; Wang, Kulatilake et al. simulated a tunnel mining under a high in situ stress condition by using the 3DEC software package [10]; Gao and Stead studied the mechanism of cutter roof failure by using DEM software PFC and 3DEC [11]. Xu et al. applied 3DEC to the research of strata and surface movement induced by mining under final slope [12]; Vyazmensky, Stead et al. analyzed the step-path failure development induced by block caving in a large open-pit slope by using the FEM/DEM method [13]. Based on numerical simulation the stress, strain and displacement of strata could be conveniently obtained and analyzed, but on account of the constitutive relation and mechanical parameters of rock mass are difficult to be defined accurately, hence, significantly different results very likely occur between the simulation results and actual conditions.

Physical model test is also usually adopted to study strata and surface movement caused by mining. Two-dimensional model with simplified geological condition is usually constructed in current physical model test, few researchers conduct three-dimensional model test for the difficulty in model construction, in current physical model test both the two-dimensional and three-dimensional model can only consider the major structural planes, such as the fault plane and bedding plane, and the widely-distributed joints in rock mass are always ignored or simplified. While, the physical model with no consideration of rock joints is difficult to reflect the influence of rock joints on strata and surface movement [14-18], however, rock joints and their distribution always dominantly control the rock deformation and strata movement caused by mining.

In order to reflect the influence of rock joints on strata movement, this paper presents a three-dimensional physical model test method which can consider the influence of rock joints on strata and surface movement induced by mining. The proposed method is mainly composed of: the design of the model box, the construction of physical model with the dominant joints, the mining method, and the monitoring of model deformation. The eastern final slope in Yanqianshan iron mine, Liaoning, China was taken as a case to study the strata and surface movement induced by mining. Then the model test result was analyzed and compared with field observation, and the result indicated that this method is not only very effective to study mining induced strata and surface movement but also can reveal the influence of the dominant rock joints on strata and surface movement.

2. Materials and Methods

In order to illustrate the testing procedure, the proposed method in this paper was introduced based on a case study-the underground mining of eastern final slope in Yanqianshan iron mine.

2.1. Model box

A model box is indispensable in physical model test and should be constructed according to the physical dimension of the model and the test requirements. For example, it should have enough strength and stiffness as well as be convenient for model construction and deformation monitoring during test. In the case study in this paper, a 4.3 m long, 2.3 m wide, and 3.6 m tall model box (Figure 1) was produced. Facet A of the model box is open to facilitate access by the staff, and facet B is closed. Facets C and D are made of high-strength plexiglass, through which the deformation of the model can be monitored.

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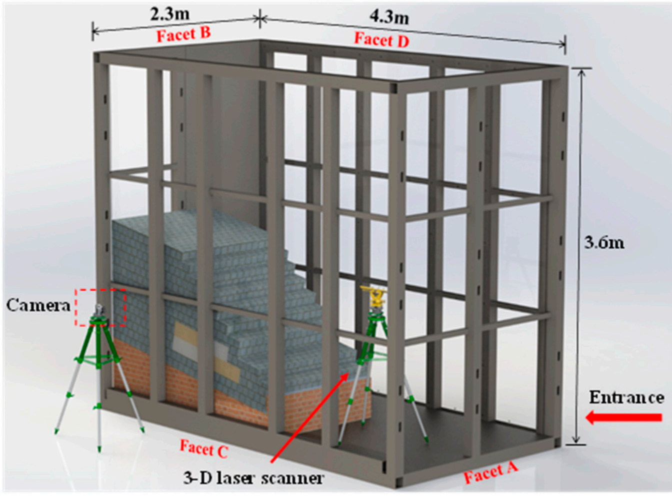

Figure 1. The model box and monitoring program

2.2 Model construction

Once the prototype was selected the size of test model could be determined based on the geometric similar ratio between the prototype and the test model. The similar ratio of the main parameters between the prototype and the test model should be determined first based on the similarity theory. In order to reflect the main engineering geology and structural characteristics of the rock mass, it is necessary to generalize the main distribution characteristics of the actual rock joints before construction of the model. To add the dominant joints to the test model, model blocks can be used for the model construction. The ore body can be simulated with several sandbags, and the step-by-step mining can be conducted by sequent taking the sand out of the sandbag.

2.2.1 Production of model blocks

The blocks required by a block construction model are made inside the mold. The design of the mold needs to be based on the geometry and size of the pre-designed model block, whereas the geometry and size of the model block need to be determined based on the distribution of the actual joints in the rock. For example, in the case study the distribution of joints in actual rock mass was simplified into three sets of equidistant orthorhombic joints, and thus the block required for the model construction was designed as a cube.

Before making the model blocks, it was necessary to select similar material to produce the model blocks. The physical-mechanical parameters of the similar material are defined as the physical-mechanical parameters of the actual rock mass divided by the corresponding similar ratios. The similar ratios of these parameters are derived based on the similarity theory [19]. In addition, materials selected to produce the model blocks should be economic, non-toxic, and easily available.

2.2.2Joint settings

In actual rock mass, a large number of joints with various occurrences and sizes frequently develop. In a physical model, it is often impossible to simulate a real complex joint system, and therefore necessary to simplify the real joint system. Hence, only the dominant joints affecting the rock mass structure and strength are taken into account when constructing a physical model. Before construction of the model, the dominant joints in actual rock mass are need to be classified into several sets according to their occurrences. Each group of joint surfaces is simulated using a number of parallel planes, whereas the block geometry for the model construction is determined according to the mutual intersection of the actual dominate joints. For example, in the case study, the dominant joints were simplified into three sets according the occurrence, and each one is orthogonal to the other two. Therefore, the model uses cubes for the block construction. The contact surface between the

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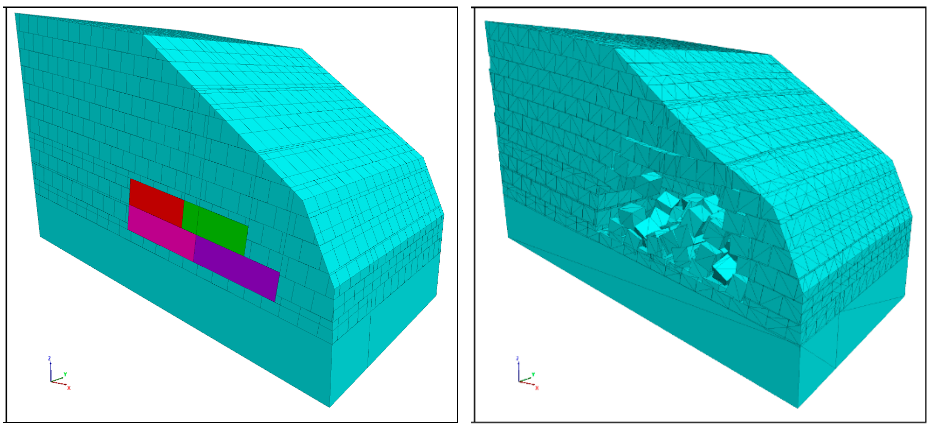
blocks is the joint surface, and the side length of the cube is the joint spacing. Before test, the joint spacing and joint strength should be properly designed.

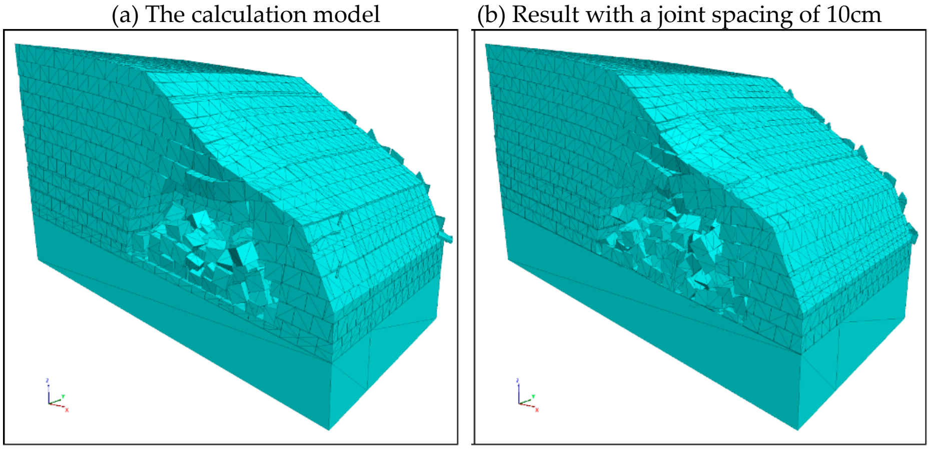
1. Determination of joint spacing.

According to the similarity theory, the joint spacing should be determined in accordance with the joint spacing in the actual rock mass divided by a geometric similarity ratio. However, a joint spacing calculated in this way is occasionally very small, which leads to a small size block required for the model construction. Small blocks are not only difficult to be made, but also would significantly increase the number of blocks needed for the model construction. For example, in the case of the Yanqianshan iron mine, the average joint spacing in real rock mass is about 30-40cm. According to the geometric similarity ratio of 100:1, the simulated joint spacing is only 3-4mm. When using cube blocks with a side length of 3-4mm to construct a cube model with a side length of 2m, approximately 290 million test cubes will be required, such a test model cannot be constructed under the existing test conditions.

Therefore, while ensuring that the deformation and destruction characteristics were similar to the actual situation, joints with as much spacing as possible were added to the model. In this paper, a Discrete Element Numerical Simulation method was used to determine the appropriate joint spacing. For example, in the case of open-pit final slope mining at the Yanqianshan iron mine, different numerical calculation models with different joint spacing were respectively constructed, and the deformation process of the strata and surface movement was simulated using 3DEC. The influence of joint spacing on the deformation and failure characteristics of the model was then analyzed. According to the calculation results, the critical value of joint spacing l_{cr} can be determined. When the joint strength spacing is less than l_{cr}, the influence of joint spacing on the deformation and failure characteristics of the model will no longer be obvious. Thus, l_{cr} can be used as the joint spacing in the model test. In Figure 2, the joint spacing values are from 10cmto 5 cm with a decrement of 0.5cm. Based on the calculation results, the final appropriate joint spacing can be determined as 7.5 cm.



(a) The calculation model (b) Result with a joint spacing of 10cm



(c)Result with a joint spacing of 9 cm (d) Result with a joint spacing of 8cm

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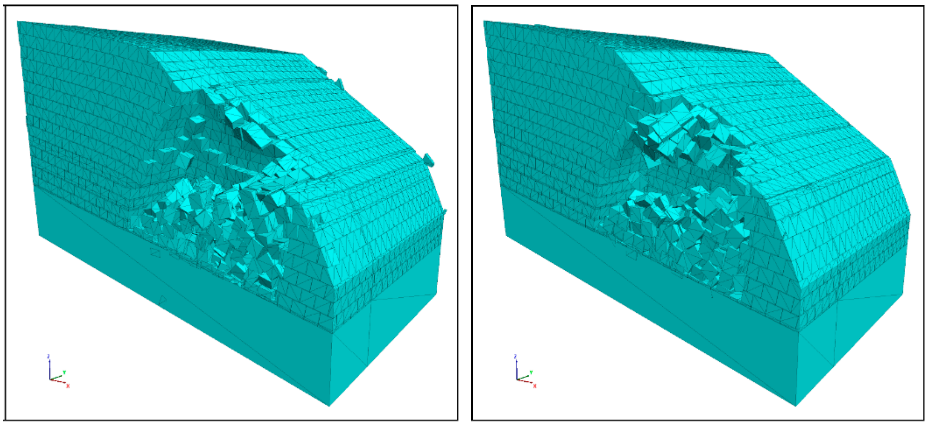
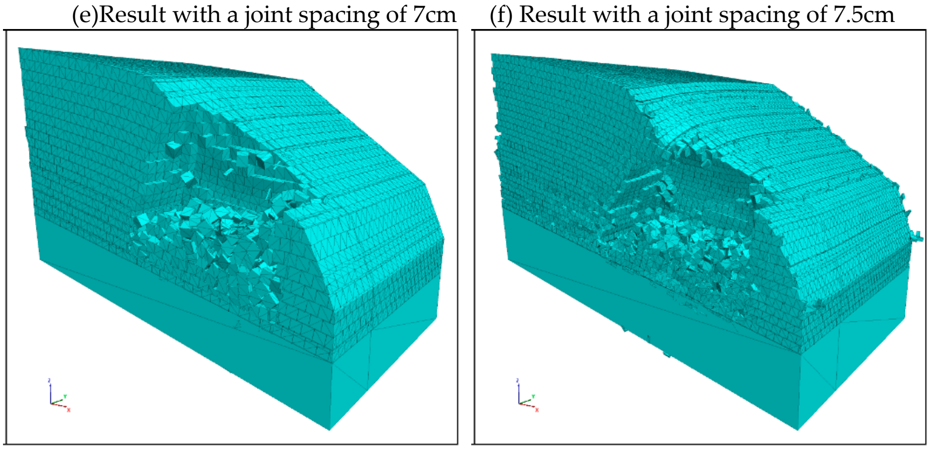


(e)Result with a joint spacing of 7cm (f) Result with a joint spacing of 7.5cm



(g)Result with a joint spacing of 7 cm (h) Result with a joint spacing of 7.5 cm

Figure 2. Calculation results with different joint spacing

2. Determination of joint strength

Joint strength is an important parameter to rock mass deformation and failure, thus in model test the joint strength should be determined according to the real joint strength. The Equivalent Discontinuous Modelling Method of jointed rock mass proposed by Xu and Bayisa is adopted to determine the joint strength, the relationship between joint spacing and joint mechanical parameters was built [20].

In this study the model blocks can be cemented by the adhesive, and the strength of the adhesive applied between the model blocks is the joint strength. The adhesive uses a combination of common building materials such as barite, quartz sand, gypsum, and white latex mixed to a certain proportion, the joint strength is varied while the proportion is different.

2.3 Mining design

The design of mining is an important part of a test, and the mining stage and mining way both have a certain impact on the test results. In a 2D model test, embedded test blocks or PVC pipes are often used to simulate an ore body, and in the test described here, the mining was simulated through the extraction of embedded blocks or PVC pipes [22-25]. In this paper, sandbags are used to simulate the ore body, and the sand is removed from the sandbag to model the mining process. This method is closer to an actual mining process. For example, a total of four sandbags were placed for the test described in the case study based on the actual ore body distribution characteristics and the actual mining process, as shown in Figure 3.

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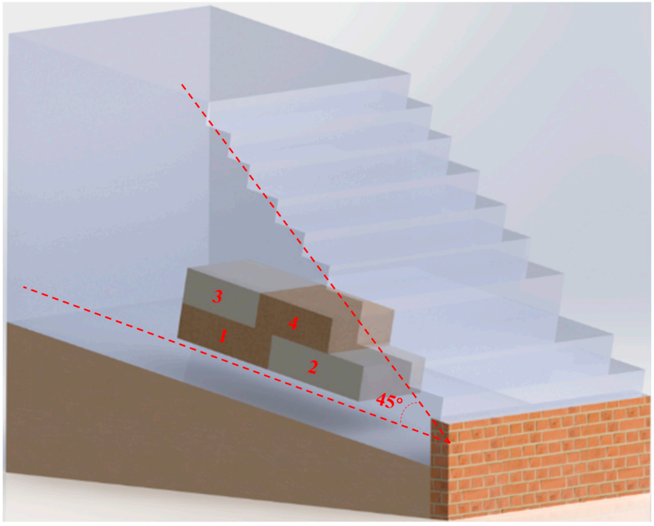


Figure 3. Simulation of ore body and mining process (sandbags #1 to #4 can be removed successively to simulate the mining process)

2.4 Monitoring

To avoid failure of the contact measurement method owing to a large local deformation of the model, non-contact measurement methods can be used to monitor the deformation and failure of the model, such as 3D laser scanning and digital photogrammetry [18, 22, 23]. The 3D laser scanner and photogrammeter were used to monitor the surface deformation of the model slope (Figure 1). The digital point cloud of the slope after each step of mining can be obtained by scanning the slope surface, and the displacement of the slope can be calculated. In the case study as shown in Figure 2, the C-facet of the model was in fact a vertical section along the center of the veins, and the strata and surface movement could be observed in this section. Therefore, for this study, we drew a series of identification points on a block near the glass side, and used a photogrammeter to obtain the initial state of the model and the location of each identification point during the mining process. Based on the results of each measurement, the displacement vector of the lateral block was calculated, and the behaviors of strata and surface movement were obtained.

3. Case study

3.1. Geological background

The Yanqianshan iron mine is located in Anshan City, Liaoning Province, China. The basic structural pattern of the mining area is a steep monoclinic structure trending toward a direction of 270°~300°, with a dip in direction toward the northeast or southeast, and a dip angle of 70°~88°; that is, the structure is partially upright. In the area of the eastern final slope, the iron ore body is located in the middle, strikes almost east-east, and dips to the northeast at approximately 70°. The ore body of the eastern final slope has a length of 300m~550m and an average thickness of 80m. The eastern final slope is located east of the XIV prospecting line until the open-air area, and has relatively developed fissures. Three sets of mutually intersecting dominant joints are developed in the rock, with one of the sets being a strata layer and other two sets intersecting this layer at a large angle while also intersecting each other. And to facilitate the modeling, in this study, the distribution of joints in the model is generalized into an orthogonal intersection, see in Figure4. The typical rock types and physical-mechanical parameters of rock mass in Yanqianshan iron mine are listed in Table 1.

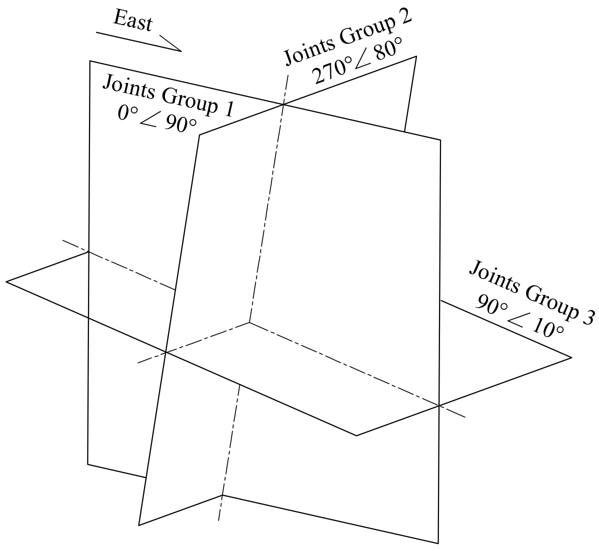


Figure 4. Thesimplified three dominant sets of joints in test model.

Table 1. Physical-mechanical parameters of rock masses in Yanqianshan iron mine

Rock mass	Compressive strength(MPa)	Deformation modulus(GPa)	Cohesion(MPa)	Internal friction angle(°)
Mixed rock	164.34	3~5	40~50	38~40
Diorite	181.47	2	55~60	40~42
Carbonaceous phyllite	44.52	1.5	35~38	35~38
Chlorite quartz schist	98.56	1.5~2	40~45	38~40

To visually observe the deformation of the surrounding rock in the mined-out area, we divided the eastern final slope into two parts along the axis of the iron vein, and selected one as the simulated model. The red shaded area in Figure 5was selected as the prototype.

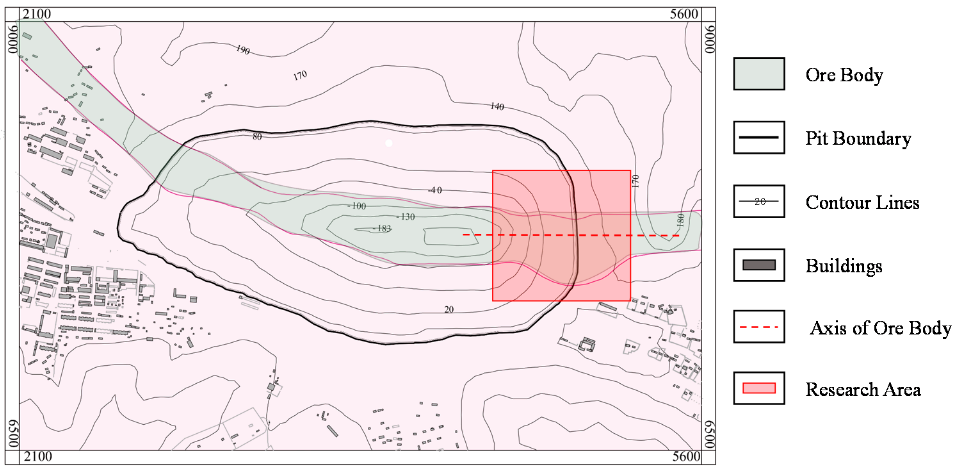


Figure 5. The eastern final slope to be studied is in red shade.

3.2. Model block production

For a physical model test, the geometric and material similarities of the model need to be controlled based on the similarity theory to reflect the deformation and failure of the rock mass under real conditions. The similarity ratio of controlling parameters are shown in Table 2. The joint spacing of the model was set to 7.5 cm, and three sets of mutually orthogonal joints were added in the model. Thus, cube blocks with a side length of 7.5 cm were produced using a similar material, and then used to construct the test model. For this study, a material similar to mixed rock found as the major rock type in the Yanqianshan iron mine was used to develop the blocks applied during the test. Based on the principles of economy, non-toxicity, and availability, the mixture of cement, quartz sand, barite, iron powder, gypsum, and water were selected to produce the blocks, the final mass proportion of the similar material used was determined through orthogonal tests and mathematical analysis. The final mass proportion and mechanical parameters of the similar material are shown in Tables 3 and 4. Between the blocks, an adhesive made of barite, quartz sand, gypsum, and white latex was applied to keep the blocks cemented. The adhesive between the blocks was made of a mixture of barite, quartz sand, gypsum, and white latex with a certain proportion. The proportions of these materials are shown in Table 5, and the strength of the adhesive is the joint strength, as shown in Table 6.

Table 2. Similarity ratios of the main controlling parameters

Parameters	Similarity Relationship	Similarity ratio
Geometry(C_L)	——	200
Bulk Density(C_r)	——	1
Stress(C_ε)	——	1
Poisson's Ratio(C_μ)	——	1
Friction Angle(C_φ)	——	1
Strain(C_σ)	$C_\sigma = C_\gamma \times C_L$	200
Elastic Modulus	$C_E = \frac{C_\sigma}{C_\varepsilon}$	200

Table 3. The mass proportion of similar material

Cement	Quartz sand	Barite	Iron powder	Gypsum	Water
1	28	28	6.67	3	7.07

Table 4. The properties of similar material used in this paper

Density（g/cm3）	Uniaxial compressive strength （MPa）	Deformation modulus（MPa）	Cohensive（MPa）	Friction angle (◦)
2.56	0.80	200.61	0.1735	38.94

The adhesive between the blocks was made of a mixture of barite, quartz sand, gypsum, and white latex. The mass proportions of these materials are shown in Table 5, and the strength of the joints in test model is shown in Table 6.

Table 5. The mass proportion of adhesive

Barite	Quartz sand	Gypsum	White latex
3.5	4.8	0.9	1

Table 6. The mechanical property of simulated joint

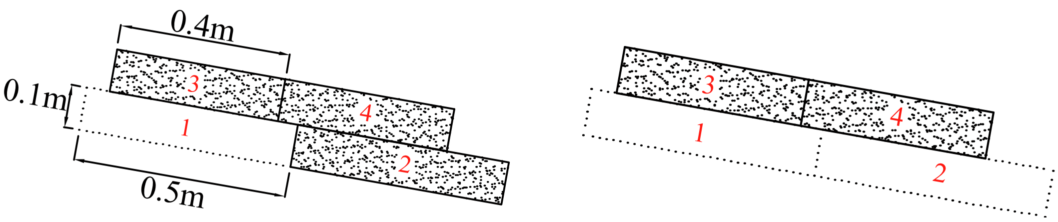
Cohesive (MPa)	Friction angle (°)	Tension strength (MPa)
0.164	20.45	0.00698

3.3. Model generalization

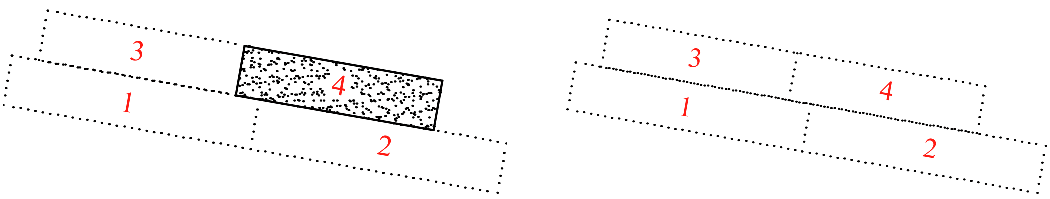
The generalization of the model was carried out according to the geological and geometric characteristics of the eastern final slope at the Yanqianshan iron mine. The study area was scaled down according to a geometric similarity ratio of 200:1. The resulting test model has a length of 2.3 m, width of 1.2 m and height of 2.0 m. The slope is inclined toward the eastern direction, and thus the three simplified sets of joints in the model are 90° ∠20° , 0° ∠90° , and 270° ∠70° (Figure 4), respectively. The ore body in test model is approximately 0.75 m from the top of the slope, with a length of approximately 1m, a width of approximately 0.4 m, and a thickness of approximately 0.2 m (Figure 6). The mining was designed to conduct at two levels, each of which having two steps. That is, during the test process, sandbags #1, #2, #3, and #4, shown in Figure 7 were "mined out" successively.

(a) The side view of (b) The front view

Figure 6. The side view and front view of the completed model



(**a**) mining of #1 ore body (**b**) mining of #1 ore body



(**c**) mining of #3 ore body (**d**) mining of #4 ore body

Figure 7. Illustration of the mining process

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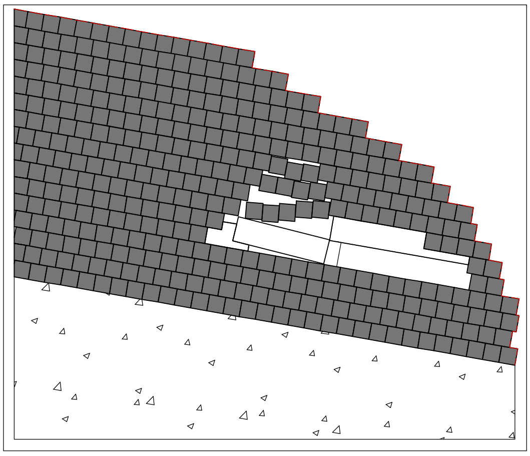
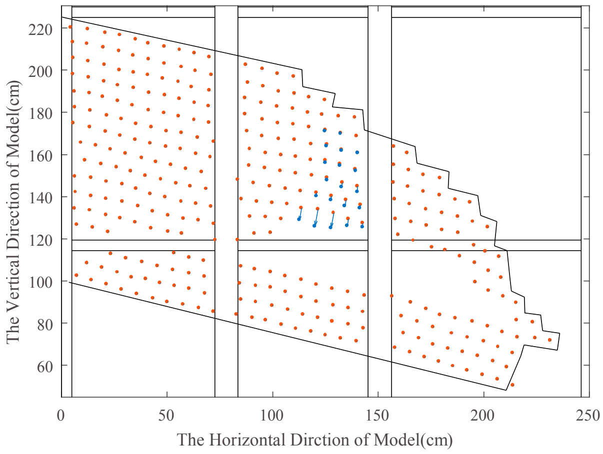
3.4. Testing process and results

3.4.1. Testing process

The test process involves the mining of ore bodies#1~#4. The model deformation after each step of mining is shown in figure 8~figure11.

Step1: Mining of ore body #1 (Figure 8(a)). After mining ore body #1, the model mainly had local deformations with clear vertical zoning characteristics. The first layer of blocks on the roof of the mined-out area collapsed and fell off, forming a local collapse zone. Then strata overlying this layer underwent a significant downward deflection, forming a deflection zone, which caused a certain degree of open deformation of the overlaying strata along the flat and steep joints, thereby forming a fractured zone (Figure 8(c)). From above the fractured zone to the slope surface, no significant deformation and failures occurred. And the displacement in figure 8(b) also indicated that the direction of strata movement was vertical downward to the mined-out area, and the maximum displacement appeared at the roof of the mined out area.



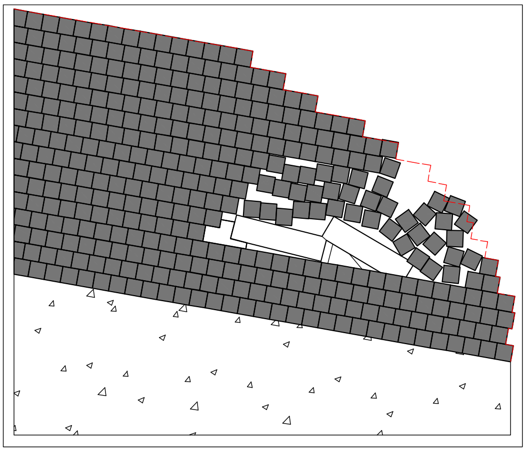


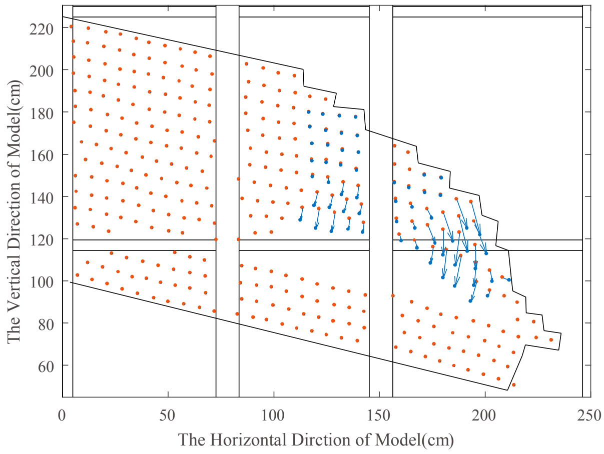
(**a**) Sketch of test model (**b**) Displacement vector

(**c**) Deformation of test model after mining #1 ore body

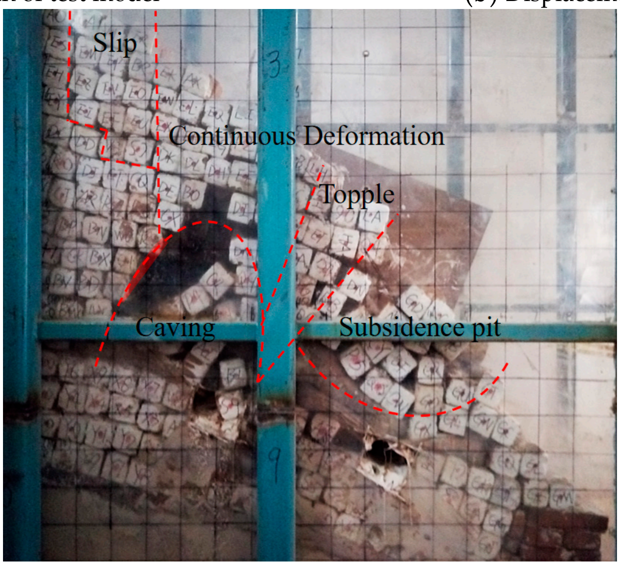
Figure 8. Defrmation occured after mining #1 ore body

Step 2: Mining of ore body #2 (Figure 9(a)). After mining ore body #2, the strata further deformed along the already opened joint surface, and significant dislocation of model blocks occurred along the steep joint surface (figure 9(a)). The range of mined-out area developed, and the strata above the mined-out area collapsed vertically. From above the collapse zone to the slope surface, as the downward deflection further developed, an obvious subsidence pit on the slope surface was appeared, as shown in Figure 9(c). The strata on the slope surface above the mined-out area underwent significant deflection, opening mainly along the steep joint surface, and the model blocks experienced an intensive disturbance, as shown in figure9(a). after mining of ore body #2, displacement of the test model was enlarged generally, the maximum displacement appeared above ore body #2, and the vector showed that surface blocks were mainly moved along the slope surface, blocks on the roof of the mined-out area were mainly moved vertical downward(9(b)).





(**a**) Sketch of test model (**b**) Displacement vector

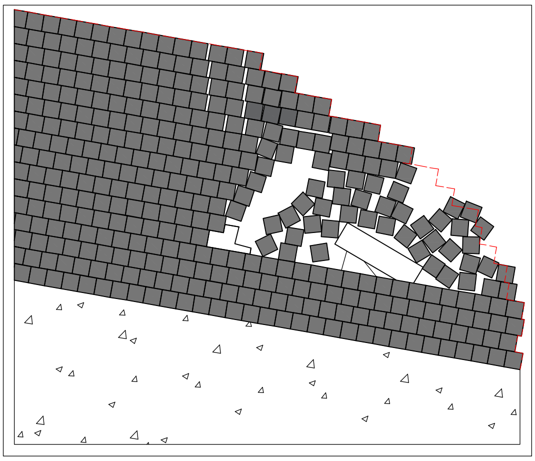


(**c**) Deformation of test model after mining #2 ore body

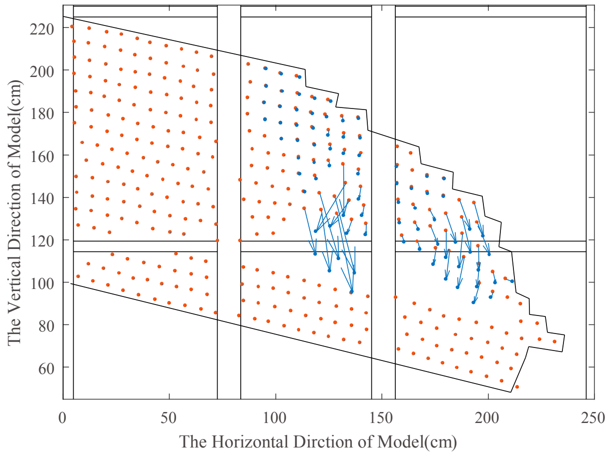
Figure 9. Defrmation occured after mining #2 ore body

Step3: Mining of ore body #3 (figure 10(a)). After mining ore body #3, all blocks in the fractured zone collapsed, forming a large caving zone, as shown in Figure 10(c). The surrounding rock in the mined-out area experienced a topple avalanche toward the surface, however, the strata on top of the mined-out area first underwent a vertical wide-range collapse. Obvious continuous deformation appeared. Displacement vector in figure 10(b) illustrated that while the mined-out are enlarged the surrounding rock mass were prone to the move toward the mined-out area. The range of slope surface subsidence further expanded. Toppling avalanche toward the mined-out area occurred in the surrounding rock mass, and as the rock mass deformation further developed, strata right above the

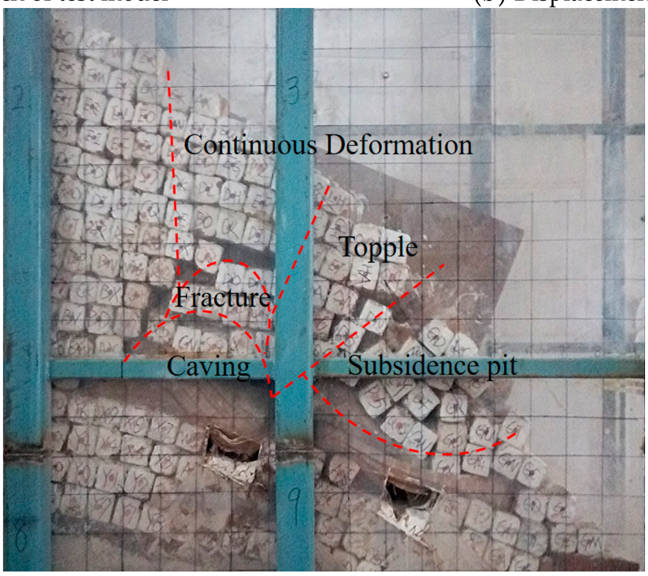
#3 ore body extensively fractured, and continuous deformation developed from the fractured zone to the slope surface. Traces of slide deformation were observed right above #2 ore body. Joint surfaces in fractured zone were further opened. The slope surface right above #2 ore body mainly experienced subsidence deformation, and significant slipping deformation occurred on the lower slope surface.



(**a**) Sketch of test model



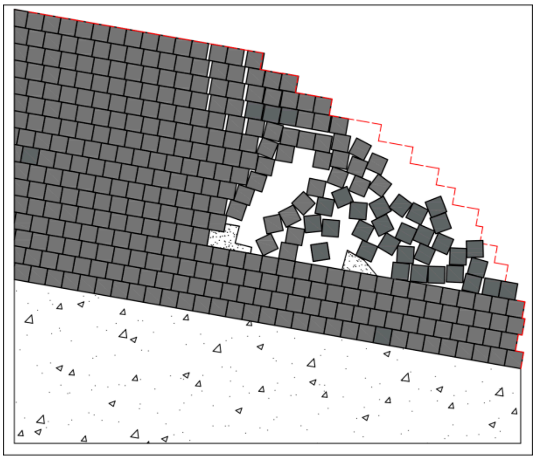
(**b**) Displacement vector

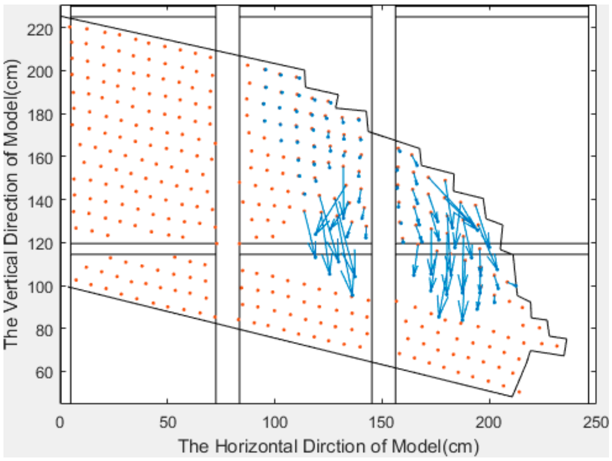


(**c**) Deformation of test model after mining #3 ore body

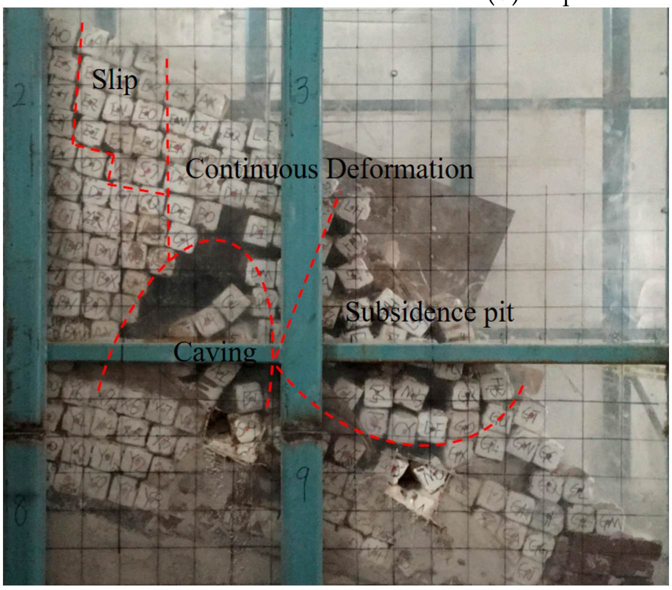
Figure 10. Defrmation occured after mining #3 ore body

Step4: Mining of ore body #4 (Figure 11(a)). The strata on roof of the mined-out area collapsed entirely. The surrounding rock of the mined-out area underwent a toppling avalanche toward the mined-out area, and eventually accumulated inside the mined-out area. The accumulated blocks resisted further toppling collapse of the surrounding rock. On the boundary of the mined-out area, significant shear dislocation deformation could be observed, as shown in the detailed view in Figure 11(c). The range of the subsidence pit on the slope surface continued to develop. Model blocks near the subsidence pit experienced intensive disturbance and started to slip along the bedding surface. The displacement vector in figure 11(b) showed that several blocks on slope surface avalanched, the surrounding blocks of the mined-out area mainly moved toward it, and the surface blocks mainly underwent subsidence and local sliding along the bedding surface.





(**a**) Sketch of test model (**b**) Displacement vector



(**c**) Deformation of test model after mining #4 ore body

Figure 11. Defrmation occured after mining #4 ore body

3.4.2 Characteristics of mining-induced strata and surface movement

The upper rock mass in the mined-out area is dominated by "well-shaped" collapse. Continuous deformation occurred on the overlaying slope surface of the ore body and formed a subsidence pit, the boundary of which is fundamentally a steep joint surface. Displacement vector map show that the collapse pit has steep and straight boundaries, yielding a clear well shape of the cross section. The above test phenomena and monitoring results show that subsidence occurred in rocks with steep and dense joints differs from the “trumpet-shaped” subsidence in a homogeneous rock mass.

At the beginning of mining, the deformation of the rock mass presented a typical vertical zoning characteristic. From the roof of the mined-out area to the slope surface, a collapse zone (complete collapse of blocks), fractured zone, and deflection zone occurred (figure 8). Meanwhile, the model blocks that had collapsed and accumulated in the mined-out area could prevent further deformation of the surrounding rock. As the mining progressed, the mined-out area expanded, and the strata deformation in the fracture zone further increased until a collapse occurred, and the fractured zone transforms into the collapse zone. Due to the influence of the blocks accumulated in the mined-out area, the overlying and sloping strata deformation in the mined-out area also exhibited significant zoning characteristics in the horizontal direction. From the back edge of the slope to the end of the slope, the following occurred: 1. at the top-left of the mined-out area, model blocks mainly slid along

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the strata layer, and the back edge of the slide area and the middle strata opened substantially along the steep joint surface. 2. In the area directly above the mined-out area, the model blocks mainly subsidized vertically along the steep joint surface toward the mined-out area, the steep joint surface on the boundary of the area was substantially opened, and the model blocks at the boundary underwent significant dislocation. 3. Finally, at the top-right of the mined-out area, model blocks in the front of the mined-out area, particularly those on the slope surface, experienced a sliding avalanche and eventually accumulated along the slope surface under the subsidence pit, forming an accumulation zone (figure 11).

4 Discussion

4.1 The cause of "well-shaped" collapse

Rock deformation and failure is predominantly controlled by the dominant joints, deformation always developed along dominate joint surfaces with relative weak strength [12, 25]. Whereas, it is one of the main challenges to reflect the joints' influence on strata deformation. Therefore, the 3D physical model test with consideration of dominant rock joints is presented. In this paper the test method was adopted to study the strata and surface movement induced by mining under the eastern final slope in Yanqianshan iron mine, and the test results revealed that the "well-shaped" collapse mainly occurred in rock mass with steep dominant joints, which is strikingly different with the "trumpet-shaped" collapse occurred in rock mass without dominant joints [22, 23, 26, 27]. During the mining, the surrounding rock mass subjected unloading resulted from mining resulted in rock mass deformation toward the mined-out area, thus rock mass on side wall of the mined-out area deformed to the mined-out, due to the existence of steep joint surface, toppling avalanche of blocks occurred along the joints surfaces. Whereas rock mass on the roof of mined-out area collapsed and the overlying rock mass underwent downward deflection due to the mining-induced unloading and the gravity of overlying strata. Thus the "well -shaped" collapse occurred, and the corresponding surface subsidence occurred at slope surface, the failure is identical with the field observation in Yanqianshan iron mine (figure 12). Whereas in homogeneous rock mass the "trumpet-shaped" or "funnel-shaped" collapse mainly occur, which means intensive subsidence just occurred in a shallow depth from the slope surface and strata movement is markedly mitigated from the surface to the mined-out area. whereas, in rock mass with steep dominant joints, almost strata from the surface to the mined-out area collapsed, thus the steep joints controls the depth and direction of strata and surface movement.

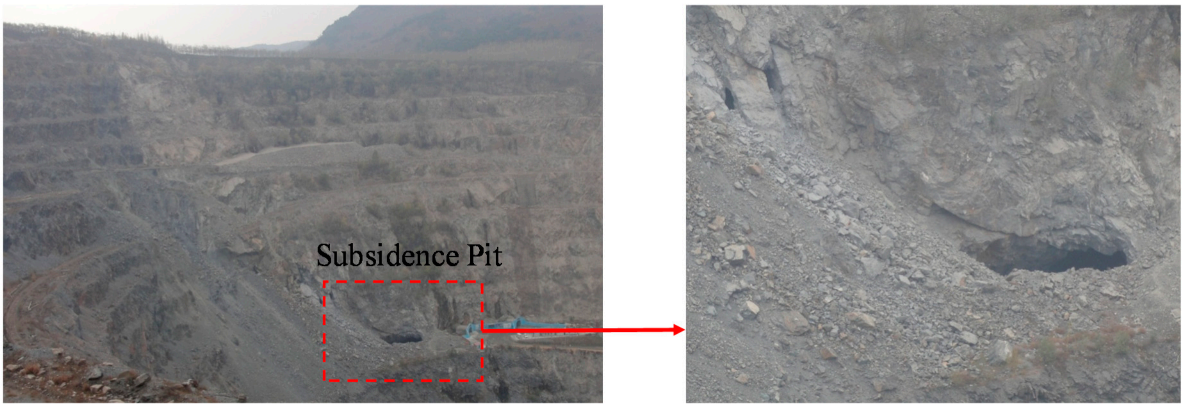

Figure 12. Subsidence pit observed at eastern final slope in Yanqianshan

The mined-out area-directional movement was the main deformation in the two sides of mined-out area. Following steep joints opened under unloading effect in the above mentioned process, the strata avalanched and toppled in the two sides of mined-out area. After mining ore body #4, the surrounding strata were seriously disturbed with some joint surfaces opened, and strata dislocation

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etc. Further deformation of surrounding rock mass was prevented by the blocks accumulated in the mined-out area.

4.2 Discussion on the experiment method

As an important research method, the physical model test has difficulties and limitations in quantitative research, however, this method can directly reflect the real process of strata movement in natural condition. The whole deformation process obtained from the test can provide an important reference to quantitative research. The 2-D physical model is mainly adopted with the simplified geological conditions, without considering the important influence of widely-spread joints in the real rock mass. The joints' absence in the physical model would lead to large differences between the experiment result and field observation, which is one of the challenges in physical model test method presently. In order to solve this problem, model blocks made of similarity materials were used to construct the test model, and the joints were simulated by the interfaces between the blocks. In order to satisfy the real joint strength, adhesive made by similar materials with certain proportion was filled in the interfaces, thus the joint strength in the test model could be determined. Both the production of the model blocks and the construction of the test model based on the similarity theory, all the materials used to produce the model blocks were inexpensive, nontoxic and available.

The phenomena of model test should well reflect the real deformation of geological body. The mechanism of strata and surface movement obtained is well agreement with the field observation and numerical simulation results. They are complement and support each other. The experiment results are verified by the field observation in the Yanqianshan iron mine, especially the mechanism of strata and surface movement was valuable to analyze the mining-induced failure at the eastern final slope in the Yanqianshan iron mine. For example, deformation and failure of rock mass at eastern final slope are: In 2014, the overlying strata has no large-scale deformation after mining; in 2015, the "well-shaped" subsidence pit has occurred, and the rock blocks at the back edge of the slope fell down into the pit. The transportation road was destroyed by the subsidence pit. Then the subsidence pit were further developed. At the beginning of mining, the strata presented a vertical-directional subsidence deformation, which caused by mining-induced unloading and the gravity of overlying strata. The "well-shaped" subsidence pit with the boundary along the steep joint surfaces reflects the influence of dominant joints on the strata movement. The experiment reproduced the real strata movement process, and revealed the controlling effect of dominant joints on strata movement. The 3D physical model test method proposed in this paper provides an effective method to study mining-induced strata and surface movement in jointed rock mass.

5 Conclusions

In this paper, a 3D physical model test method was proposed that incorporates simplified joints in the model. The method generalizes the dominant joints based on their real distribution in rock mass, and then builds the model through a block construction. The interfaces between the blocks act as the joint surface, the joint strength is determined based on the Equivalent Discontinuous Modeling Method of jointed rock mass. This testing method can theoretically be used to construct model with any joint distribution and strength. The test process mainly includes the model box design and production, generalization and construction of a 3D physical model with dominant joints, mining design, and monitoring. A numerical calculation method is adopted to calculate the effects of different joint spacing on the test results, and the appropriate joint spacing is determined based on the calculation results.

Mining under the eastern final slope at the Yanqianshan iron mine was taken as an case study in this paper and the test results indicate that the mining-induced "well-shaped" collapse would mainly occur in rock mass with steep dominant joints. At the early mining stage, the strata and surface movement has an obvious vertical zoning characteristic, whereas it exhibits an apparent horizontal zoning as the mining proceeds until the end.

The test phenomena described in this paper are consistent with the actual deformation and failure of the eastern final slope, and reflect the effects of the dominant joints on mining-induced strata and surface movement. Thus the test method proposed herein can intuitively reflect the entire process of mining-induced strata and surface movement at the microscopic scale.

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Supplementary Materials: The following are available online at www.mdpi.com/link, Figure S1: title, Table S1: title, Video S1: title.

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