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SUSTAINABLE DEVELOPMENT OF ENERGY, WATER AND ENVIRONMENT SYSTEMS

# Numerical simulation study of strip filling for water-preserved coal mining

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**Abstract**
The Jurassic coalfield in northern Shaanxi, China is one of the seven largest coalfields in the world. It is located in an arid region of northwestern China, with poor water resources and fragile ecological environment. Due to coal mining, the rock layers on the coal seam will be slumped and fractured to produce fissures. The penetrated fissures will cause a mine water burst disaster and cause damage to groundwater and surface water. The strip filling method can control the expansion of the diversion fissure zone and protect the groundwater and surface water from the underground mining of coal. In this paper, the effects of different strip filling conditions on the diversion fissure zone are studied by discrete element numerical experiments. The study indicates that the upward-fissure and the downward-fissure penetrations are the direct causes of the instability of the water-blocking rock group. After the upward fissure extends to a certain extent, there will be a downward fissure. Under the condition of controlling the width of the filling strip and the compressive strength, the strip filling method can effectively prevent the upward and downward fissures of the water-blocking rock group from penetrating and can ensure that the surface water system is not affected by the underground coal mining activities.

**Keywords** Water-preserved mining · Diversion fissure zone · Strip filling · Discrete element · Numerical simulation

## Introduction

The Jurassic coalfield in northern Shaanxi has the largest proven coal reserves in China, accounting for about 25% of the country's total. It is one of the seven largest coal fields in the world. The Jurassic coalfield is located in the inland arid region of northwest China, the border of the Muus Desert and the Loess Plateau in northern Shaanxi, with poor water resources and fragile ecological environment (Wang et al. 2010). During the coal seam mining process, under the action of mine pressure, the overlying strata layer of the working surface will produce severe movement, which will cause the overlying strata to fall and break to produce fissures (Xu et al. 2015; Wang et al. 2015). When the fissures are connected, a water diversion channel will be formed, that is, a diversion fissure zone (Zhang and Shen 2004; Miao et al. 2011). The diversion fissure zone develops into the aquifer, and the water in the aquifer will enter the stope, causing the mine to have a water burst disaster (Li et al. 2017). With the large-scale development of the mining area, it will also cause direct destruction of the water source and lead to the drying of wells, rivers, and reservoirs that were originally replenished by the aquifer (Qian et al. 2003). Therefore, how to protect water resources and protect the ecological environment to the maximum while mining coal resources is a major event for the sustainable economic development of the region (Li et al. 2000).

In order to protect groundwater resources and geological environment, Zhang et al. selected short-wall fully mechanized mining technology to achieve water-preserved coal mining under especially thick and hard rock formations (Zhang and Liqiang 2006). Fan et al. (2015) summarized the latest developments and existing scientific problems of the research on water-preserved coal mining in different stages of ecologically fragile mining areas in western China. In order to solve the contradiction between water preservation and coal mining,

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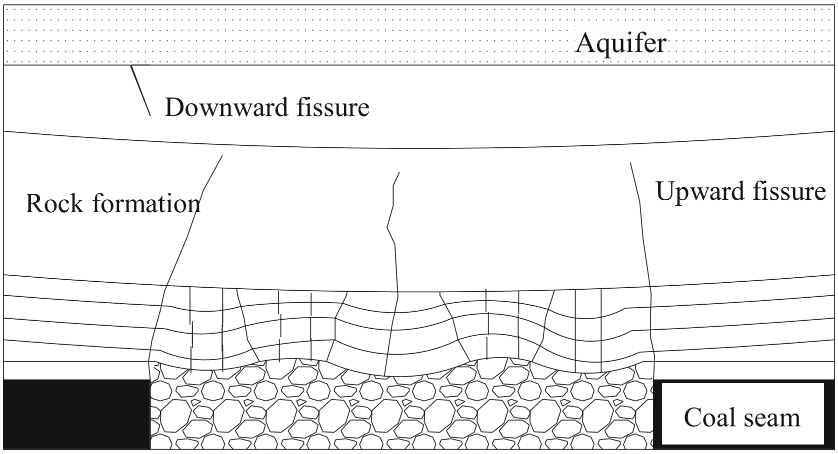

**Fig. 1** Schematic diagram of upward and downward fissures

Ma et al. proposed a longwall working face water-preserved mining technology with the rapid advancement of the working face as the core (Ma et al. 2014). Ning et al. (2015) established the evaluation model of water-preserved mining in roof coal seams of shallow-buried sandy mudstone, and obtained two basic conditions for water-preserved mining in shallow-buried coal seams, and proposed the evaluation method of water-preserved mining. Wang et al. (2012a, b) addressed the problem of abnormal development of diversion fissures in some mining areas and studied in depth the effects of structural stability of the main key layer on the evolution of the diversion fissures of the roof and the water level of the aquifer by simulation experiments and engineering exploration methods. Previous studies have shown that strip mining can control rock fissures and surface subsidence (Qian et al. 2008), but at the expense of coal resources loss, and there is a threat of extensive roof collapse. Strip filling of the goaf with eolian sand as the mainstay brings hope for water-preserved mining in northern Shaanxi (Fan et al. 2003). The successful practice of strip filling and mining of plaster material under buildings and water bodies (Song et al. 2010) illustrates its feasibility. The strip filling has a higher recovery rate of coal than strip mining, and the filling material has the characteristics of low strength and flexibility, which can eliminate the threat of large-scale roof collapse. The filling of the strip is smaller than the full filling, and the price of the sand-based paste material is low (Huang and Liang 2011). The purpose of protecting shallow phreatic water can be achieved by rationally designing the strip filling and mining parameters.

The coal-water geological characteristic of the coalfield in northern Shaanxi is “water above, coal below,” and the overburden rock is composed of bedrock and clay layer, which together constitute the water-blocking rock group (Fan and Zequan 2004). Mastering the development law of mining roof fissures and revealing the stability of the water-blocking rock group are the core of controlling the water-preserved mining of rock formations of shallow-buried coal seams (Huang 2017). Scholars at home and abroad have studied the development of diversion fissure zones in the caving method. Hu et al. (2012) proposed a hard rock lithology proportional coefficient and established a diversion height and multi-factor nonlinear model based on the multiple regression analysis. Wang et al. (2012a, b) established a theoretical computational mechanical model of the developmental height of diversion fissure zone based on the analysis of key bearing layer, rock stratum breaking, and free space. The development law of the diversion fissure zone of overburden rock in coal seam mining is obtained by the numerical simulation method. Based on a large number of field measurements, the prediction formula of diversion fissure zone is proposed, which provides a theoretical basis for water-preserved mining under aquifer (Abbas et al. 2012; Liu et al. 2015).

Considering the similarity of stress and strain in the clay aquiclude and the similarity of water-physical properties, it is shown by similar simulation experiments (Qing et al. 2007; Huang and Tengfei 2006) that the mining fissures of the overlying rock and soil are mainly composed of upward and downward fissures. The upward fissure is formed by the bottom-up slump and the subsurface subsidence of the top plate after the mining, and the fissure zone is a so-called diversion fissure zone. The downward fissure is a downward-developing tensile fracture formed by stratigraphic stretching on the surface of the formation (see Fig. 1). The conductivity of the upward and downward fissures in the aquiclude determines the stability of the water-blocking rock group, referred to as water-blocking property. If the upward fissure zone is in conduction with the downward fissure zone, the water-blocking property is unstable and the phreatic water will flow into the goaf. Otherwise, the water-blocking property is stable. By controlling the development height of the upward fissure zone or reducing the development depth of the downward fissure zone by a reasonable method, the water-blocking property of the aquiclude can be improved.

However, there is very limited research on discrete element numerical simulation of strip filling. In this paper, based on the on-site geological data, the numerical simulation experiment

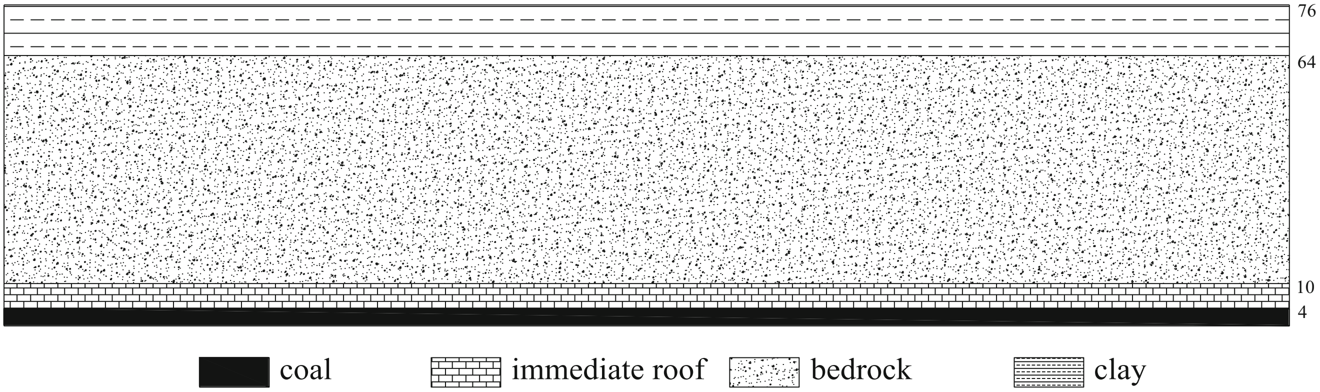

**Fig. 2** Geological features of the original rock in the numerical simulation experiment

was carried out to study the development law of mining "upward fissure" and "downward fissure" and the subsidence of water-blocking rock group. The purpose of this research is to determine reasonable filling parameters and lower filling cost, a breakthrough of the water-preserved mining method was formed to provide a scientific basis.

## Methods and materials

### Subjects

There are 12 layers of recoverable coal seam and partially recoverable coal seam in Yushenfu mining area. The main coal seam with the largest reserves in the whole area is 2–2 coal seam, which is located at the top of the coal system and the coal seam dip is nearly horizontal. According to the combined form, the coal-covered rock is divided into three categories: (1) sand layer–soil layer–weathered layer–base rock layer, accounting for 65% of the whole area; (2) sand layer–weathered layer–base rock layer, accounting for 20% of the whole area; and (3) soil layer–weathered layer–bedrock layer, accounting for 15% of the whole area. Among them, the sand layer contains eolian sand and Sarawusu group with a thickness of generally within 10 m, including phreatic water with a water depth of 0.90~9.27 m; the soil layer refers to the gravel loess and the hipparion red soil with a thickness of generally 20~80 m, which is a good aquiclude; the weathered layer refers to the top weathering zone of bedrock with a thickness of generally 20~25 m, which is a weak aquifer; the bedrock layer is mainly the unweathered bedrock on the main coal seam, mainly containing sandstone with a thickness of generally 30–380 m, which constitutes a water-blocking rock group together with the soil layer.

### Materials

The research object of the numerical simulation experiment is the shallow-buried coal bed bedrock clay-type overburden. In this case, there are both clay and bedrock layers in the overburden, which has the typical characteristic of the water-preserved mining area. Therefore, the bedrock clay-type water-blocking rock group with the clay layer accounting for 1/6 of the thickness of the water-blocking rock group is taken as the research object. According to the composition characteristics of the bedrock clay type, the thin soil layer is selected (12 m), the thickness of the coal seam is considered according to the most common average value of 4 m, the clay layer accounts for 1/6 of the thickness of the overburden, and the buried depth is 72 m. The filling method is a double strip filling mining mode along the long wall with equal spacing. According to the structural characteristics of bedrock clay-

**Table 1** Physical and mechanical parameters of numerical simulation

| No. | Name of rock layer | Thickness of rock layer/(cm) | Bulk weight /(t/m$^3$) | Compressive strength /(MPa) | Tensile strength /(MPa) | Bonding force c/MPa | Internal friction angle φ/(°) | Poisson's ratio |
|---|---|---|---|---|---|---|---|---|
| 1 | Coal | 4 | 0.87 | 0.087 | $6.33 \times 10^{-3}$ | $8 \times 10^{-3}$ | 38 | 0.20 |
| 2 | Immediate roof | 6 | 1.60 | 0.240 | 0.020 | 0.048 | 41 | 0.14 |
| 3 | Bedrock | 54 | 1.60 | 0.320 | 0.024 | 0.050 | 38 | 0.21 |
| 4 | Clay layer | 12 | 1.23 | 0.040 | $1.33 \times 10^{-3}$ | $6.67 \times 10^{-4}$ | 30 | 0.40 |
| 5 | Filling 1 | 4 | 0.87 | 0.012 | | | | |
| 6 | Filling 2 | 4 | 0.87 | 0.06 | | | | |

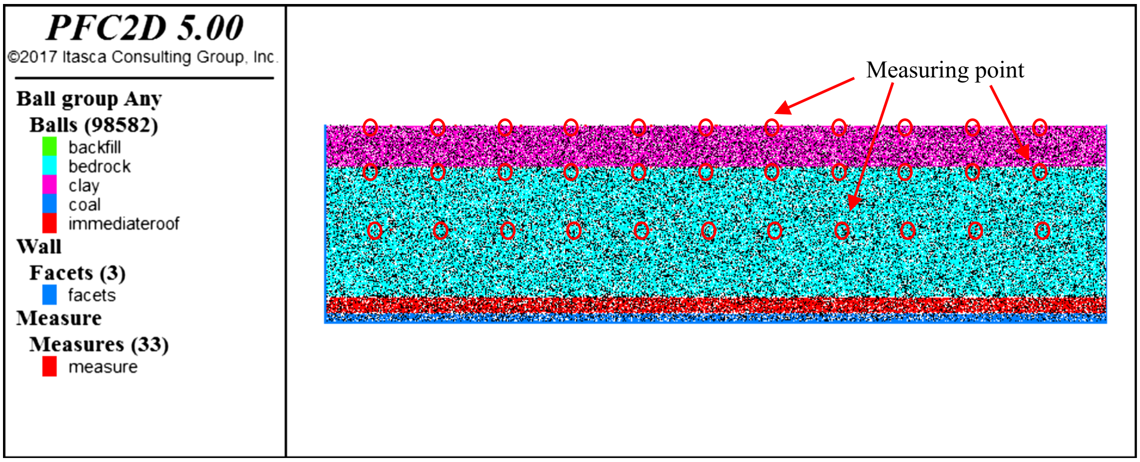

**Fig. 3** Numerical model

type overburden, the thickness of the water-blocking rock group is considered at 18 times of mining height, and the mining height is calculated according to 4 m. The thickness of the water-blocking rock group is 72 m and the working face is 250 m wide.

In order to facilitate the comparison with the similarity simulation experiment (Zhang 2015), the numerical model uses the geometric similarity condition of 1/100, gravity similarity condition of 2/3, gravity acceleration similarity condition of 1/1, displacement similarity condition of 1/100, strength, elastic modulus, cohesive force similarity conditions of 1/150, and internal friction angle similarity condition of 1/1. The geological features of the original rock in the numerical simulation experiment can be obtained as shown in Fig. 2.

Filling with two different filling materials, the compressive strength of the filling materials is 0.28 MPa and 1.5 MPa. According to similarity relationship, the physical and mechanical parameters of numerical simulation of each rock layer are shown in Table 1.

## Methods

The discrete element numerical model constructed based on the geological feature information and the numerical simulation physical and mechanical parameters of the original rock in the numerical simulation experiment are shown in Fig. 3.

Taking the center position of the bottom of the model as the coordinate origin, starting from − 1.25 to 1.25 m at the three elevations of the model of 0.76 m, 0.6 m, and 0.36 m, one measuring point is arranged at an interval of 0.25 m, and the displacement at the measuring point is recorded. The two sides of the model are symmetrically left with a boundary of 0.25 m. The working face has a length of 2.50 m. The filling mode of equal spacing is adopted. Mining is followed by filling two strips and using two filling materials. The mining to filling ratio is based on Table 2.

## Results

Numerical calculation is performed on the numerical model of different mining to filling ratio, and the calculated results are shown in Fig. 4.

It can be seen from Fig. 4 that for type 1 filling material, the strip-type filling mining with a width of 42.5 m and 50 m have similar control effects on the overlying strata of the coal seam, and the upward fissures are basically not developed, and no

**Table 2** The mining to filling ratio in the experiment

| No. | Mining(m) | Filling(m) | Mining to filling ratio | Aspect ratio of strip |
|---|---|---|---|---|
| 1 | 50 | 50 | 1.5 | 12.5 |
| 2 | 55 | 42.5 | 1.94 | 10.625 |
| 3 | 60 | 35 | 2.57 | 8.75 |
| 4 | 65 | 27.5 | 3.55 | 6.875 |
| 5 | 70 | 20 | 5.25 | 5 |
| 6 | 75 | 12.5 | 9 | 3.125 |
| 7 | 80 | 5 | 16 | 1.25 |

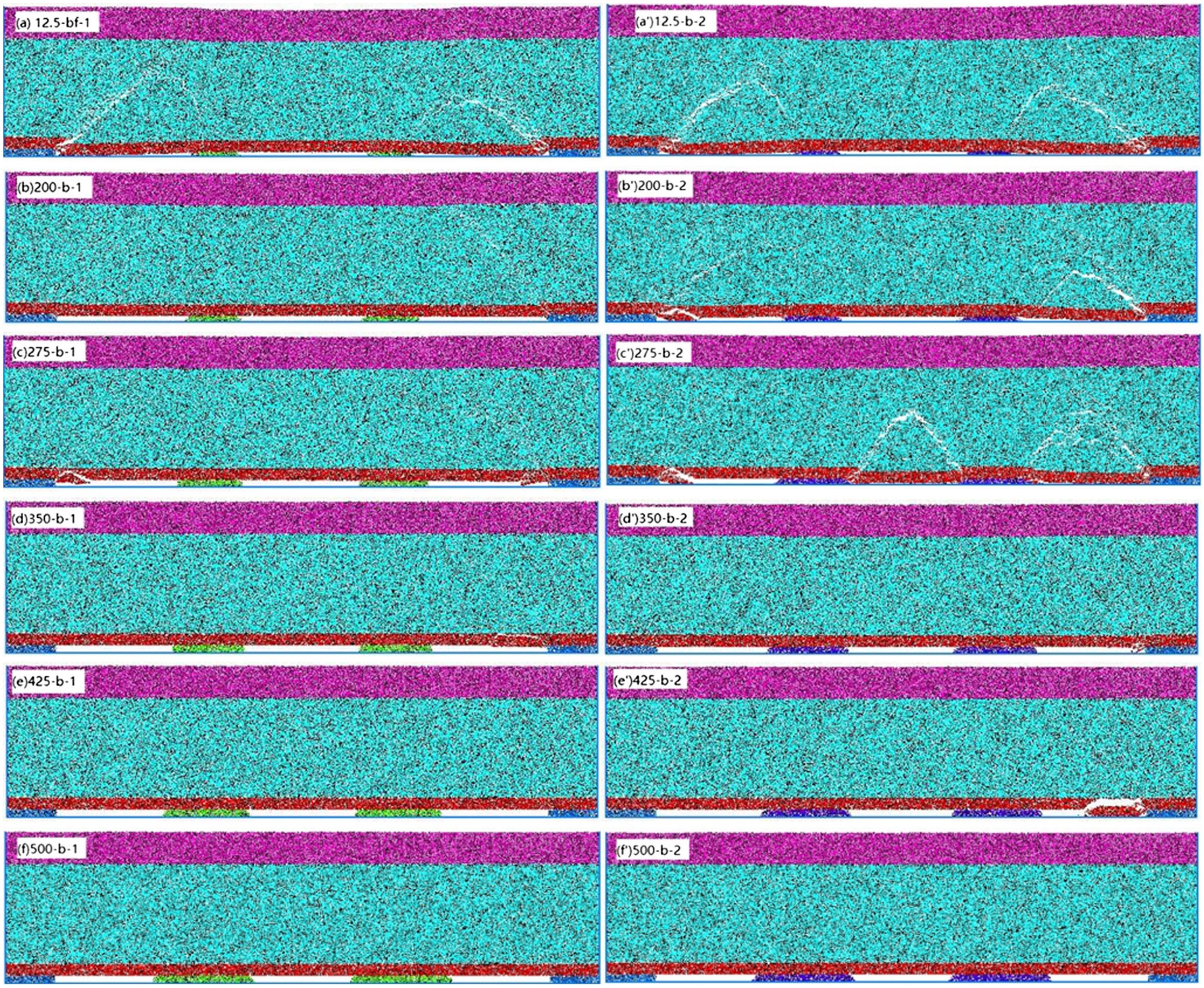

**Fig. 4** Numerical calculation results

downward fissures appear. It can be seen that the strip-type filling with a width of 42.5 m can effectively control the development of the diversion fissure zone of the overlying strata and protect the clay layer from damage. It can be seen from Fig. 4 that as the strip width decreases, the upward fissure expands and gradually affects the clay layer.

It can be seen from Fig. 5 that when the width of the filling strip is 42.5 m, the upward fissure does not extend to the clay layer, and the clay layer has no obvious displacement. When the filling strip width is 35 m, the upward fissure is close to the clay layer, and the clay layer begins to have a displacement. When the width of the filling strip is 27.5 m, the upward fissure extends to the clay layer, and the downward fissure appears above the clay layer, and the clay layer has an obvious displacement. No downward fissure appears until the upward fissure is fully expanded.

The data of each measuring point is plotted as a graph. The displacement law of the rock stratum at 36 m, 60 m, and 76 m of the roof under different filling strip widths is shown in Figs. 6, 7, and 8.

The amount of sinking at each measuring point is listed in Table 3. As can be seen from Figs. 6, 7, and 8 and Table 3, the first type of filling material, when the width of the filling strip is 12.5 m, the maximum displacement of the top plate at 36 m is 2.75 m, at 60 m is 2.07 m, and at 76 m is 1.94 m. The second type of filling material, when the width of the filling strip is 12.5 m, the maximum displacement of the top plate at 36 m is 3.10 m, at 60 m is 2.11 m, and at 76 m is 1.97 m. In the same position, using different strength filling materials, the amount of roof sinking is different, and the sinking amount of the weakly filling material is larger than the sinking amount of the high-strength filling material.

At the 36 m top plate, for the first filling material, when the width of filling strip is 12.5 m, the maximum sinking amount is 2.75 m, when the strip width is 27.5 m, the maximum sinking amount is reduced to 1.23 m, and

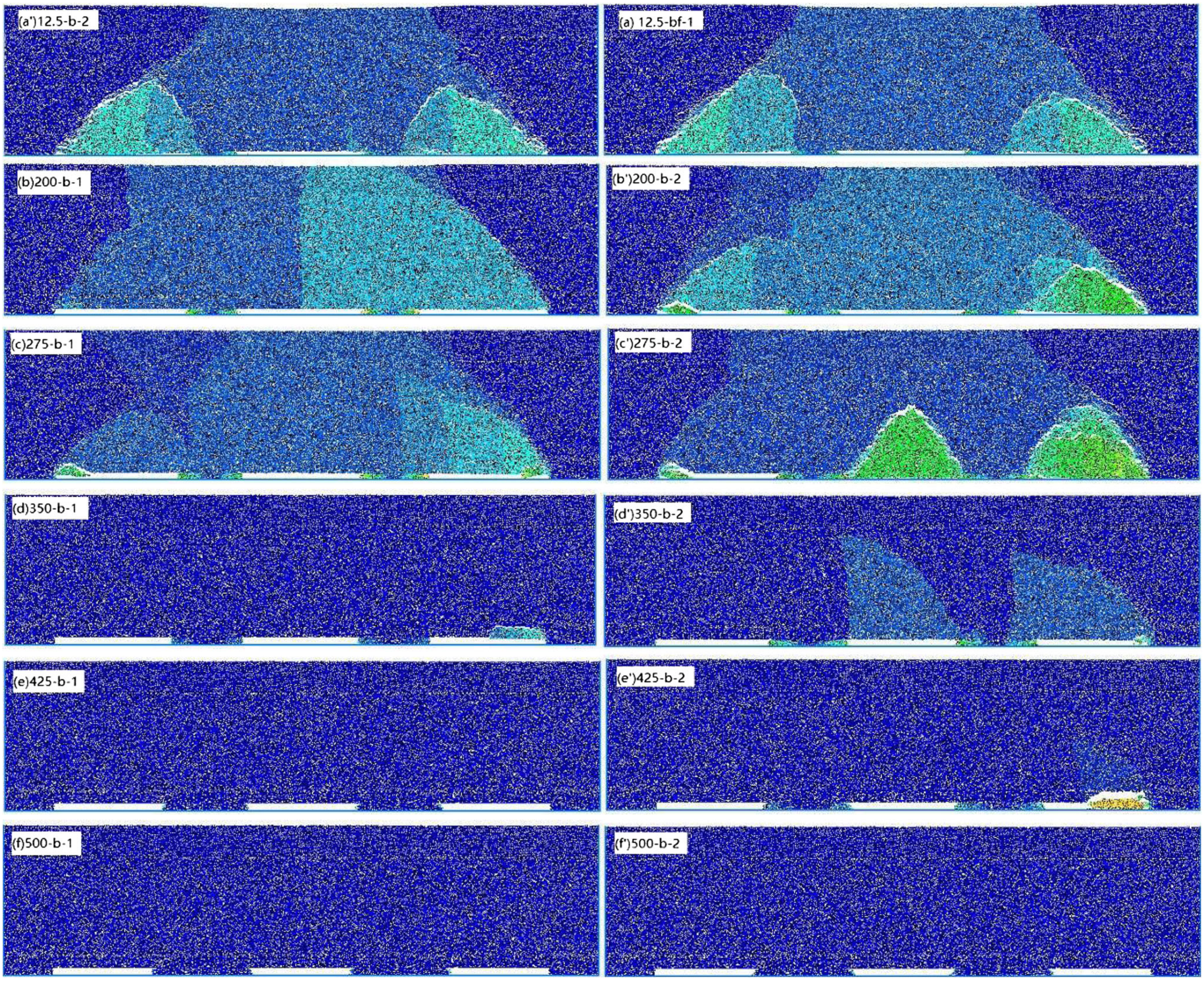

**Fig. 5** Displacement of strip filling rocks

when the strip width is 42.5 m, the maximum width is only 0.22 m. For the type 1 filling material, when the width of the filling strip exceeds 42.5 m, the amount of sinking of the top sheet does not decrease as the width of the filling strip increases. For the second filling material, when the width of filling strip is 12.5 m, the maximum sinking amount is 3.10 m, when the strip width is 27.5 m, the maximum sinking amount is reduced to 2.15 m, and when the strip width is 42.5 m, the maximum width is only 0.39 m. For the type 2 filling material, when the width of the filling strip exceeds 42.5 m, the amount of sinking of the top plate substantially decreases as the strip width increases. It can be seen that the amount of roof subsidence decreases with the increase of the width of the filling strip. When the strip width reaches a certain value, the sinking amount of the top plate no longer decreases with the increase of the width of the filling strip.

## Discussion

We mentioned the current state of research on strip filling. However, these studies mainly use physical experimental methods of similar materials and do not pay attention to the application of numerical simulation in this respect. In this study, we used discrete element numerical simulation to study strip filling by changing the strip filling parameters. We found that the experimental results of discrete element numerical simulations are very close to similar simulation experiments and field results. Strip filling material and strip width have an important influence on the movement of overlying strata. This finding extends the research method of strip filling and confirms the feasibility of discrete element numerical simulation for strip filling studies.

In addition, the improvements noted in our study were the penetration of the upward and downward fissures is

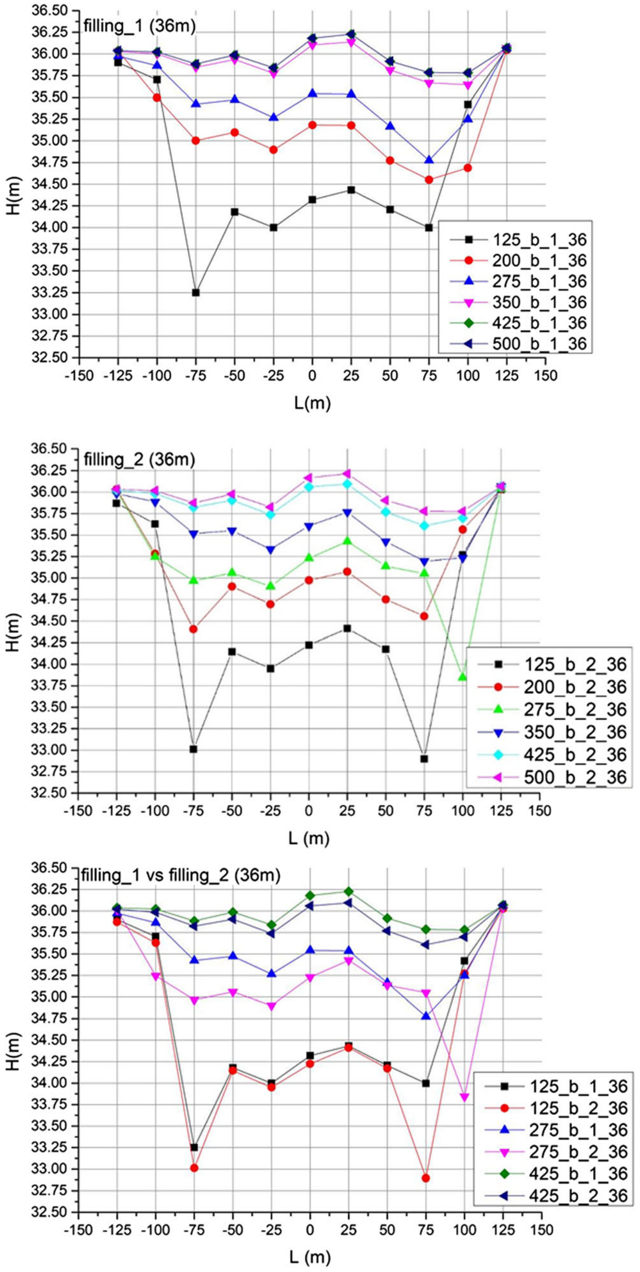

**Fig. 6** Displacement law of rock formation at 36 m

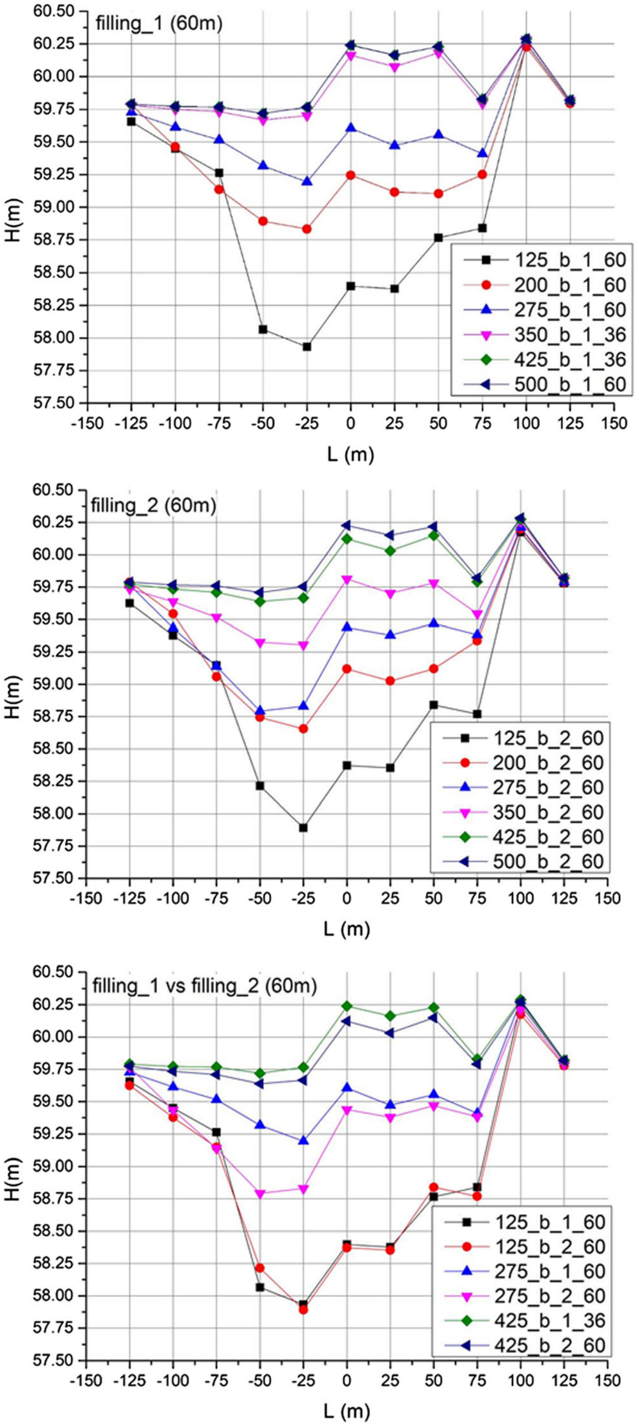

**Fig. 7** Displacement law of rock formation at 60 m

the direct cause of instability of the water-blocking rock group. When the width of the filling strip is greater than 42.5 m, the development height of the upward fissure zone of the intermediate filling strip is relatively small, the deformation of the rock layer is small, and there is no downward fissure in the upper part of the clay layer. There is no water guiding channel in the upper aquifer and goaf in the overburden. When the width of the filling strip is smaller than 35 m, the deformation of the rock layer suddenly increases, and a downward fissure appears in the clay layer. Therefore, when the aspect ratio of the filling strip is greater than 10.625, the filling strip can effectively control the development of the upward fissure and protect the aquifer from being damaged. The strength of the filling material also has a great influence on crack propagation. If the strength of the filling material is weak, the aspect ratio of the filling strip should be increased. At the same time, it can be seen that the position with the largest displacement in Figs. 6, 7, and 8 is concentrated in the middle. The possible reason is that the rock stratum

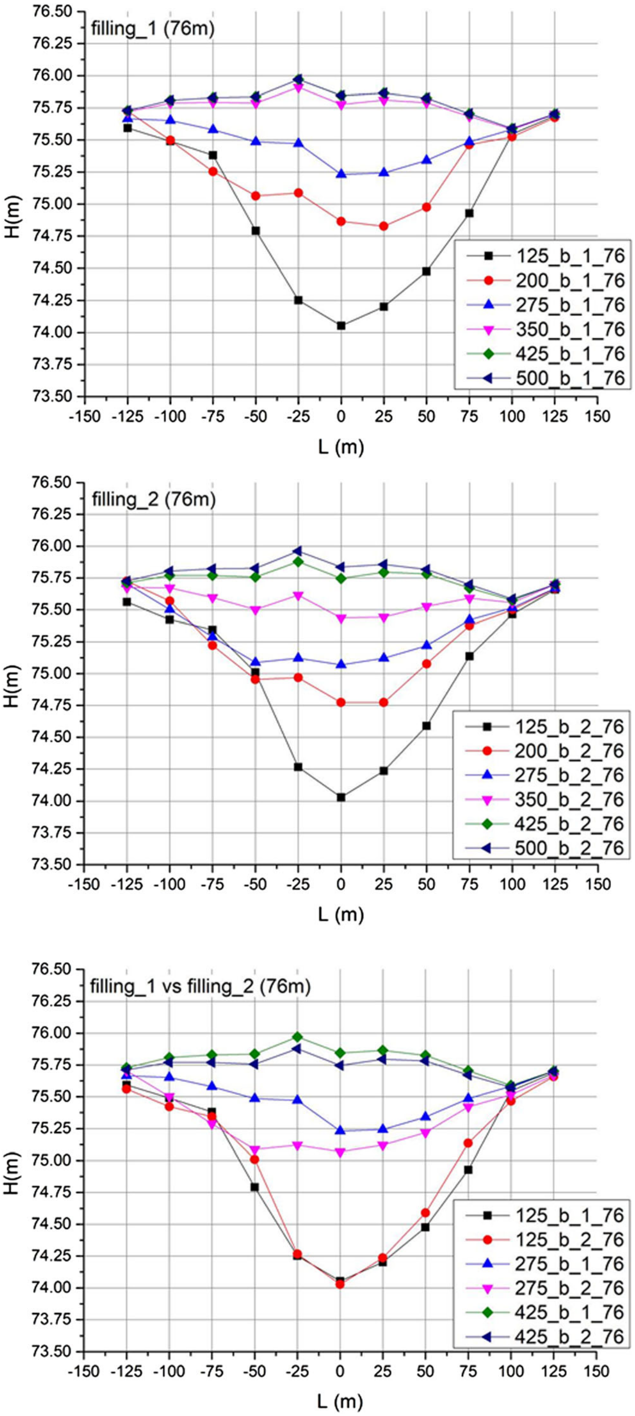

**Fig. 8** Displacement law of rock formation at 76 m

load exceeds the strength limit of the filling strip, and the filling strip is crushed, resulting in the loss of support of the rock stratum. Therefore, increasing the aspect ratio of the filling strip and the compressive strength of the filling strip are effective methods for controlling the development of the upward fissure.

**Table 3** Maximum sinking amount

| Backfill type | Width of filling strip (m) | Maximum sinking amount (m) | | |
|---|---|---|---|---|
| | | 36 m | 60 m | 76 m |
| 1 | 12.5 | 2.75 | 2.07 | 1.94 |
| | 20 | 1.45 | 1.17 | 1.17 |
| | 27.5 | 1.23 | 0.81 | 0.77 |
| | 35 | 0.35 | 0.33 | 0.42 |
| | 42.5 | 0.22 | 0.28 | 0.41 |
| | 50 | 0.22 | 0.28 | 0.41 |
| 2 | 12.5 | 3.1 | 2.11 | 1.97 |
| | 20 | 1.6 | 1.34 | 1.23 |
| | 27.5 | 2.15 | 1.17 | 0.93 |
| | 35 | 0.8 | 0.69 | 0.56 |
| | 42.5 | 0.39 | 0.36 | 0.43 |
| | 50 | 0.22 | 0.29 | 0.42 |

Most notably, this is the first study to our knowledge to investigate that discrete element numerical simulation can replace strip filling with similar simulated physics experiments. This can reduce the experiment time, increase the number of experiments and reliability, reduce the cost of the experiment, and can also be used for experimental research in other underground projects. However, some limitations are worth noting. Numerical simulations still use the principle of similarity without using actual dimensions and do not consider structures such as rock mass joints and fissures. At the same time, the current research has not considered the impact of biodegradation on filling materials, especially together with water. It should be considered that the possibility of the effect to be applied to the stone may have on the general biosusceptibility of the object (Warscheid and Braams 2000). Microbiota is indispensable and involved in the biodeterioration of stone (Liu et al. 2018), and various biocalcifying microorganisms have been used for protection of cementitious building materials (Shirakawa et al. 2015). An important question for future studies is the correlation between overburden load, fill strip bandwidth ratio, and filling material strength, and how to use the actual rock mass structure and size for discrete element numerical simulation. Simultaneously, it should be considered how to protect the filling materials from biodeterioration.

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