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# Failure pattern of large-scale goaf collapse and a controlled roof caving method used in gypsum mine

Lu Chen[1,2], Zilong Zhou[2], Chuanwei Zang[*3,4], Ling Zeng[**1] and Yuan Zhao[2]

[1]*School of Civil Engineering, Changsha University of Science and Technology, Changsha, Hunan, 410083, China*
[2]*School of Resources and Safety Engineering, Central South University, Changsha, Hunan, 410082, China*
[3]*School of Mining and Safety Engineering, Shandong University of Science and Technology, Qingdao 266590, China*
[4]*Key Laboratory of Mining Disaster Prevention and Control, Qingdao 266590, China*

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**Abstract.** Physical model tests were first performed to investigate the failure pattern of multiple pillar-roof support system. It was observed in the physical model tests, pillars were design with the same mechanical parameters in model #1, cracking occurred simultaneously in panel pillars and the roof above barrier pillars. When pillars 2 to 5 lost bearing capacity, collapse of the roof supported by those pillars occurred. Physical model #2 was design with a relatively weaker pillar (pillar 3) among six pillars. It was found that the whole pillar-roof system was divided into two independent systems by a roof crack, and two pillars collapse and roof subsidence events occurred during the loading process, the first failure event was induced by the pillars failure, and the second was caused by the roof crack. Then, for a multiple pillar-roof support system, three types of failure patterns were analysed based on the condition of pillar and roof. It can be concluded that any failure of a bearing component would cause a subsidence event. However, the barrier pillar could bear the transferred load during the stress redistribution process, mitigating the propagation of collapse or cutting the roof to insulate the collapse area. Importantly, some effective methods were suggested to decrease the risk of catastrophic collapse, and the deep-hole-blasting was employed to improve the stability of the pillar and roof support system in a room and pillar mine.

**Keywords:** physical model test; pillar collapse mode; pillars-roof support system; deep hole blasting; Gypsum mining

## 1. Introduction

In underground mine, pillars are left to support the overburden, creating a safe environment for workers and equipment. Therefore, many empirical formulas for pillar strength have been established to design the size of pillar, and the factor of safety (pillar strength/average pillar stress) is routinely used to assess the stability of pillar (Hustrulid 1976, Esterhuizen *et al*. 2011). Although significant researches have been done to understand the bearing capacity and failure characteristics of single pillar (Jaiswal and Shrivastva 2009, Zhou *et al*. 2018b, c), it still is difficult to assess the stability of pillars, as it is influenced by many factors including ore pillar load, uniaxial compressive strength, underground water, etc. (Yang *et al*. 2017, Ning *et al.* 2017, Nikadat and Marji 2017, Li *et al*. 2018a,b Wu *et al*. 2019a,b ). Catastrophic pillars collapse remains a challenging engineering problem in underground mine and many other underground engineering project (Cording *et al*. 2015, Liu *et al*. 2018, Yang *et al*. 2016 a, b Zhang *et al*. 2016).

It seems that research focusing on the mechanical behavior of single pillar may not meet the requirement of underground engineering to assess the stability of pillar and roof support system, as stress redistribution across multiple pillars has been shown to be a crucial factor in large-scales collapses (Poulsen 2010, Zhao *et al*. 2018a, b). When an individual pillar fails, its load or a percentage of load will be transferred to neighboring pillars and may cause those pillars to successively overload (Hauquin *et al*. 2016). A cascading pillar collapse should be considered a system effect rather than the result of mechanical response of individual pillars. Hence, Wang *et al*. (2011) provided a numerical double-pillar model to analyse the roles of factors including stiffness, uniaxial compressive strength and homogeneity index in cascading pillar collapse process and associated acoustic emission behavior. Ma *et al*. (2012) established a dynamic analysis method to investigate cascading pillar collapse phenomenon with the help of Voronoi graph method. Zhou *et al*. (2017, 2018a) carried out multiple pillars and roof system compression tests to investigate the stress redistribution failure mechanism. These past researches have greatly increased our understanding of the components, or risk factors, which can contribute the collapsed disaster of pillar-roof support system. But the failure pattern is complex and its corresponding mechanism is still not fully understood.

In recent years, with the development of similar materials and measurement technology, laboratory model test has become a useful and important method to investigate displacement characteristics of wall rock around

∗Corresponding author, Associate Professor
E-mail: chuanweizang@163.com
**Corresponding author, Associate Professor
E-mail: zl001@csust.edu.cn



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a mine, failure mechanisms of cavern construction engineering and foundation superstructure system, etc. (Liu *et al*. 2013, Zhang *et al*. 2017, Zhang *et al*. 2019). e.g., Ren *et al*. (2010) conducted a physical simulation test to investigate deformation and subsidence characteristics of ground with the help of digital close-range photogrammetry technology, which is a non-contact optical technique and has been successfully used for measuring evaluation of rock crack (Lin and Labuz 2013, Li *et al*. 2016). Zhu *et al*. (2011) presented an experimental setup using a stiff modular loading frame, hydraulically applied simulated loads and in vivo excavation to explore the influence of material nonlinearities and spalling failure in underground space under high in-situ stresses. Li *et al*. (2013) developed a large-scale geomechanical model test system to study the surrounding rock stress evolution process of deep roadway. Lin *et al*. (2015) conducted a geomechanical physical model test to study the cracking, failure and stability of the "large, long, deep and in-group" tunnels constructed in a hydropower station of China.

These pioneer works have showed the advantage of physical model test to investigate cracking and overall progressive failure process of the underground geotechnical engineering structure. In this paper, the failure characteristic of multiple pillars-roof support system was studied by two physical model tests according to a mine engineering prototype in Hunan province, China, and the failure patterns were discussed. Then some effective methods were suggested to decrease the risk of catastrophic collapse of pillar-roof support system. And the deep-hole-blasting was employed to break and cut the roof to improve the stability of the pillar and roof support system in a gypsum mine.

## 2. Description of the physical model test

### 2.1 Experimental system

The experimental system is shown in Fig. 1. The maximum size of model is 1600 × 800 × 200 mm. Vertical load is applied by two hydraulic jacks which are controlled by a hydraulic pump, and two load sensors are attached on the jacks. The maximum load offered by hydraulic jacks is 300 kN.

A non-contact optical measure technique namely digital speckle correlation method (DSCM) was used to record and analyse the displacement characteristics of pillars-roof system. This method is implemented through calculating the surface displacement based on series of digital images from a reference un-deformed and subsequent deformed states. As illustrated in Fig. 2, a subset R centre at the point P in the reference un-deformed image is chosen, and image intensity information of subset R is used to match and track its corresponding location (point P') in the subsequent target deformed image. Then the displacement fields of zone of interest are determined by repeating the same procedure. It is necessary to emphasize that the spackle pattern on surface should be created as well-distributed and highly contrast in order to successfully extract the displacement and deformation (Zhou *et al*. 2018a). In this study, the data analysing system is accomplished in Matlab (MathWorks®) environment to estimate surface deformation information. A charge-coupled device camera

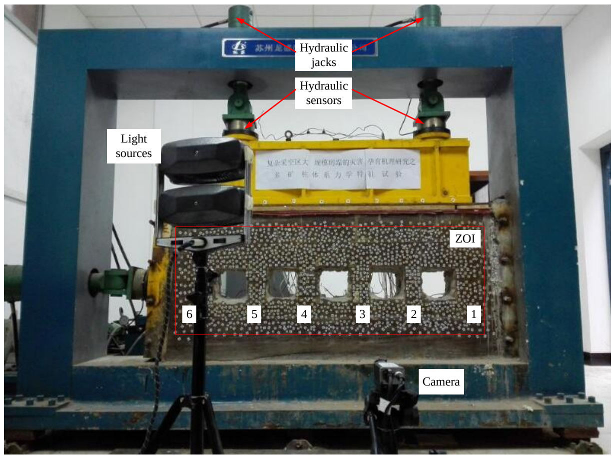



Fig. 1 Similarity mechanics model test system of complex rock mass. ZOI – Zone of interest

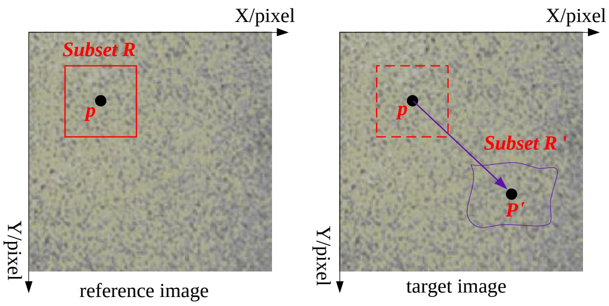



Fig. 2 Digital speckle correlation match method

(CCD Basler PiA 2400-17gm), light sources and image acquisition device were utilized to record digital images, the maximum resolution of CCD is 2456 × 2058 pixels and maximum speed of image collection data is 75 M/s. Furthermore, it is easy to regulate the resolution and frame rate according to the size of objects required. The size of the zone of interest (ZOI) of 1400×600 mm$^2$ was selected for analysing by DSCM in this study as shown in Fig. 1.

### 2.2 Physical model setup

Physical model test is usually used for rupture analysis of geotechnical engineering. To get a reliable result, the physical model must satisfy a series of similarity criteria in terms of geometry, stress and mechanical parameters (Liu *et al*. 2013, Zhu *et al*. 2018). The ratios of prototype parameters to physical model were expressed as

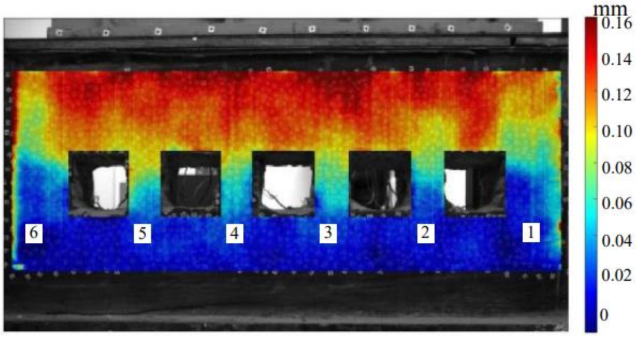
$$\frac{C_E}{C_\gamma C_L} = 1 \tag{1}$$

$$\frac{C_\sigma}{C_\gamma C_L} = 1 \tag{2}$$

$$C_\mu = C_\varepsilon = 1 \tag{3}$$

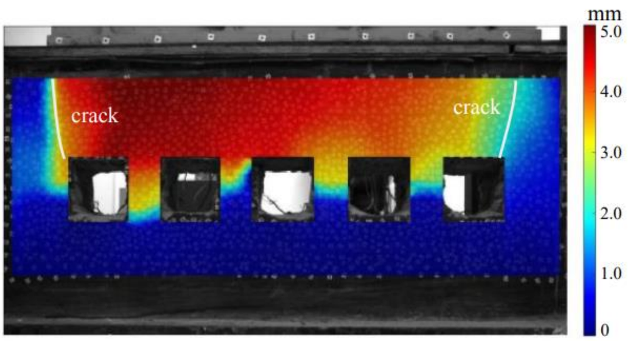
$$C_\sigma = C_\tau = C_\delta = C_E \tag{4}$$

where $C_E$, $C_\gamma$, $C_L$, $C_\mu$, $C_\varepsilon$, $C_\sigma$, $C_\tau$ and $C_\delta$ represent the similarity constants for Young's modulus, unit weight,




(a) Elastic deformation


(b) Crack initiation




(c) Panel pillars collapsed and roof subsided

Fig. 3 Contour maps of displacement and the failure process of model #1

geometry size, Poisson's ratio, strain, stress, shear strength and displacement, respectively.

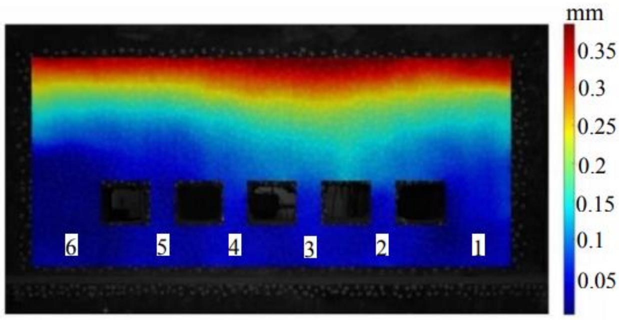
In this study, physical models were carried out based on a working mine located in Hunan province, China. The geometric proportion was set as $C_L$=50, according the similarity criteria. Thus the heights and widths of the pillars and the room widths used in the physical model were set to be 100, 100 and 120 mm, respectively. The details of the mining layout and physical model parameters can be found in previous paper (Zhou *et al*. 2018a). As shown in Fig. 1, the model was set with six pillars, pillar 1 and pillar 6 were set as barrier pillar, pillar 2 to pillar 5 was panel pillars. In this study, two physical model tests were carried out. In the physical model #1, all pillars had the same mechanical parameters. For model #2, the panel pillar 3 was designed with relatively weaker bearing capacity than other panel pillars. Both physical model were loaded to almost lose its bearing capacity, and the displacement was monitored during the load process.

## 3. Results and discussions of the experimental

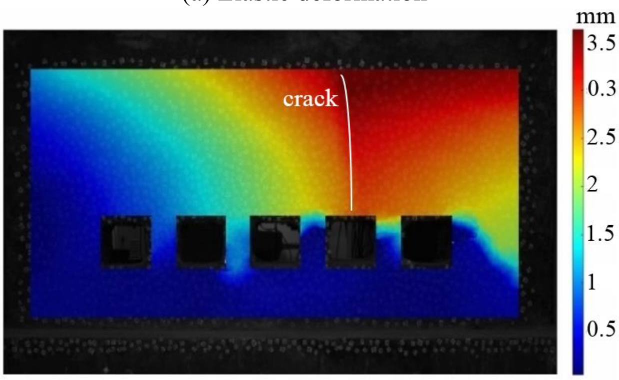
The primary function of pillar is to support roof, offering a safe circumstances for workers and machinery. However, it is easily damaged by external load induced by mining activity. Hence both physical models were compressed by a uniformly distributed load according to the layout shown in Fig. 1. In this section, the displacement and failure pattern in the physical model tests are presented.

### *3.1 Displacement and crack evolution in physical model #1*

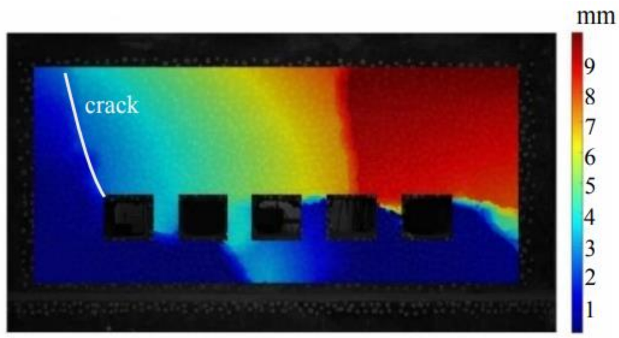
Pillar is always loaded by roof, so the compression process of pillar is the result of a convergence process of roof and floor. Thus the displacement of pillar and roof was monitored. During loading process, the whole deformation and collapse process could be divided into three typical stages as shown in Fig. 3. It is found that the displacement




(a) Elastic deformation




(b) Crack initiation and evolution




(c) Roof cut

Fig. 4 Contour maps of displacement and the failure process of model text #2

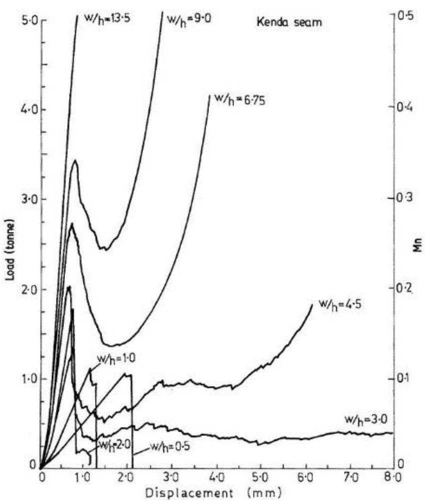



Fig. 5 Load versus displacement curves from laboratory testing of 54 mm diameter cylindrical coal samples (Das 1986)

of pillars and roof were almost uniform at the start stage of loading. This stage can be described as elastic deformation stage. Then, the discontinuous displacement could be found in the pillar 2 to the pillar 5 and the roof in the positions above left side of pillar 1 and right side of pillar 6. Those observations indicated that the model reach crack initiation stage, and when crack occurred in panel pillars, the roof was also fractured at the edge of the barrier pillar. Consequently, the load can't transfer from deteriorative panel pillars to barrier pillars. The third phase was collapse stage, the pillars 2 to 5 lost its bearing capacity, inducing the subsidence of the roof supported by those pillars as show in Fig. 3(c). However, the barrier pillars were still stable in this time.

### *3.2 Displacement and crack evolution in physical model #2*

The physical model #2 was also performed according to the layout shown in Fig. 1. According to the result, the whole deformation and collapse process could be also divided into three typical stages as shown in the Fig. 4, which depicts the corresponding vertical displacement contour maps. The first phase was elastic deformation stage, the vertical displacement was also almost uniform at this plastic stage, especially in the top of model. The second phase was crack initiation and evolution stage. In this phase, discontinuous displacement can be clearly observed in the roof and pillars 1, 2 and 3, indicating crack damage had initiated at those positions. Then, macro crack occurred in the roof between pillar 2 and 3, and the pillars 1 to 3 lost its bear capacity. The third phase was stress redistribution and roof cut stage. In the beginning of this stage, the barrier pillar 6 was strong enough, hence the stress could transfer to pillar 6. Those pillars could temporarily support roof, Moreover, the function of pillar 6 and roof above pillars 3 to 6 could be considered as a cantilever beam, so the roof above pillar 6 was suffered shear stress and bending moment simultaneous, the shear crack occurred eventually in the roof above right side of pillar 6 as shown in Fig. 4(c).

## 4. Failure type of multiple pillar-roof system

In underground pillars support system, the bearing characteristics of single pillar is usually influenced by the width/height(W/H) ratio as shown in Fig. 5, and a barrier pillar with W/H > 10 is considered as indestructible (Das M.N. 1986). Thus, when a pillar-roof support system formed in a mined panel, the barrier pillar is not easy to crush and lose its bearing capacity. However, the panel pillar with a low W/H ratio is easily damaged and cause collapsed disaster. Furthermore, the bearing characteristics of roof depends on the thickness, mechanical property, jointing of rock mining layout and so on. Consequently, for a multiple pillar and roof support system, any excessive deformation or failure of pillar or roof may cause subsidence that can occur as sinkholes or troughs as shown in Fig. 6 (Bruhn *et al.* 1978). In this study, three types of failure modes were analysed according to the condition of pillar and roof as followed:

### *4.1 Roof caving result in sinkhole or caving arch*

As shown in the right of Fig. 6, some sinkholes subsidence was presented. Generally, the main causes of sinkhole subsidence were a shallow depth of cover, weak enough overburden, geological discontinuities and dissolution of rocks. In the condition of weak overburden, the roof may easily fail between pillars. After the initial tensile or shear failure of the roof, if the pillars were strong enough, the roof caving will continue to propagate upward the ground surface, resulting in a sinkhole (Sahu and Lokhande 2005). However, if the pillars collapse and the roof caving occurred in the same time as shown in Fig. 7, the caving arch would form (Ma *et al*. 2012). It necessary to emphasize that the caving arch will continue to propagate unless it is arrested by barrier pillars or panel boundary.

### *4.2 Multiple collapse events occur*

In general, uneven subsidence can be caused by pillar failure or stress concentration under the influence of geological conditions, mining method, barrier pillars, etc. The discontinuous deformation of roof would eventually induce a crack. Once cracks formed in the roof, the whole multiple pillar-roof support system would be separated into two or multiple independent local pillar-roof support systems. As shown in Fig. 8, during the deformation and failure process of model #2, the crack occurred in some panel pillars and the roof between pillar 2 and pillar 3, forming two independent pillar-roof support systems. The one consisting of pillars 1, 2 and the roof above those pillars, which could be defined as the right bearing system (RBS). The other system consisted of pillars 3 to 6 and the roof above those pillars, and can be defined as the left bearing system (LBS). The RBS moved downward firstly, resulting in the first collapse in the physical model. This collapse mechanism can be described that pillars reach critical stable state simultaneously, the independent system

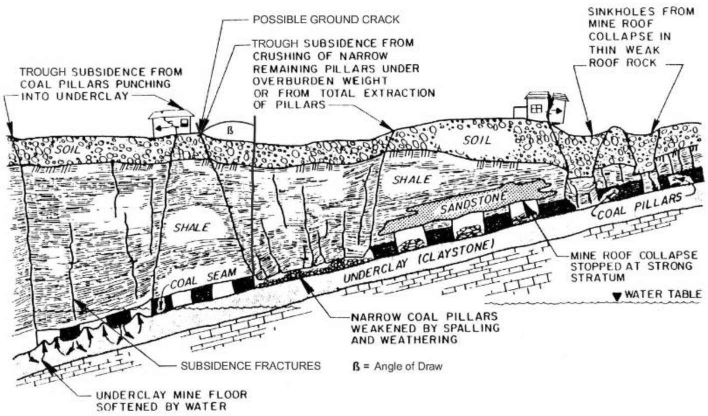



Fig. 6 Type of subsidence (Bruhn *et al.* 1978)

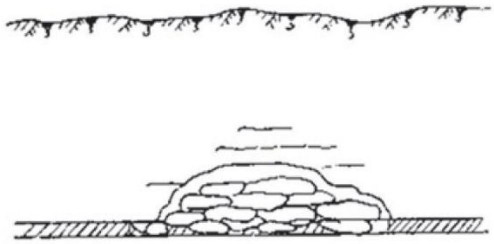
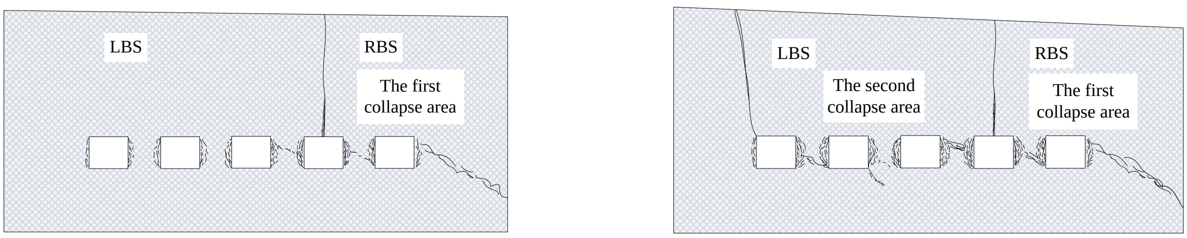


Fig. 7 Caving arch (Ma *et al.* 2012)




(a) Cracking evolution and some pillars collapse

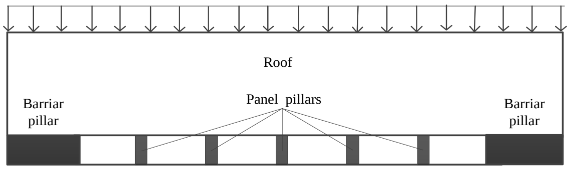
(b) The roof broken again

Fig. 8 Cracking evolution and collapses process

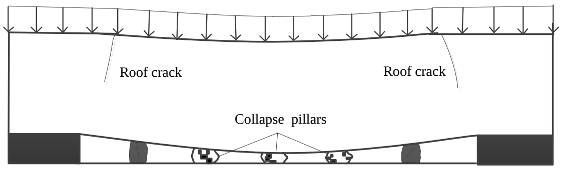
will then collapse suddenly. For the LBS, the fracture zone only occurred in pillars 3 and 4, and the pillars 5 and 6 were strong enough, particularly pillar 6. Therefore, the stress in pillar 6 continued to increase after the first collapse and carried the most of external load, so the LBS was still stable. Those indicated that failed pillars can transfer load to stronger pillars through the roof in an independent multiple pillar-roof support system, thus a barrier pillar is effective to prevent the occurrence of sudden collapses caused by failed pillars. After that, a discontinuous deformation occurred in the roof in the position above the right side of pillar 6 and it caused a roof crack. The roof then lost its load transfer function, that induced the second collapse as shown in Fig. 8(b). However, pillar 6 did not lose its bearing capacity, which continued to support the roof. At this moment, the whole multiple pillar-roof support system had been separated into three pillar-roof structures, the first was comprised of roof and pillars 1 and 2, which was an unstable structure. The second was roof and pillars 3 to 5, that was also an unstable structure. The third was roof and pillar 6, that was a stable structure. This collapse process and failure behaviour is shown in Fig. 8. It can be concluded that adequate barrier pillars played an important role to break the roof, restricting the spread of failure surrounding them and limiting the potential failure area. Hence the stability of remaining pillar-roof system was improved.

### *4.3 Cascading pillar collapse and abrupt roof subsidence*

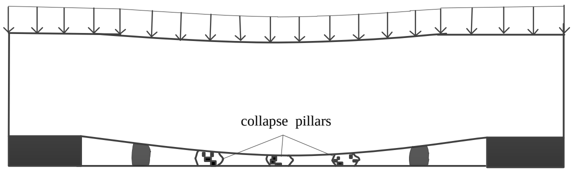
Pillars usually suffer a non-uniform stress and deformation due to different external stress environment and inherent mechanical properties, thus pillars usually do not reach post-failure stage and lose bearing capacity simultaneously. For a multiple pillar-roof support system with hard roof, when shear fracture zones occurred in part of panel pillars, the load borne by the failed pillar transfers rapidly to its neighboring pillars, which usually causes them to fail. If the roof was fractured above barrier pillar as shown in Fig. 9(b). The similarly deformation and failure process can be found in physical model #1, the fracture zone occurred in the panel pillars and the roof above barrier



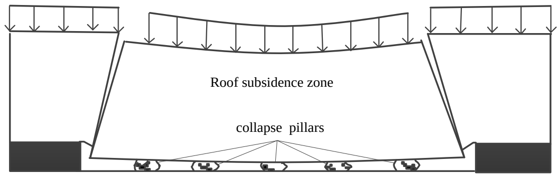

(a) Pillars-roof support system formed in a mined panel




(b) Damaging occurred simultaneously in panel pillars and roof

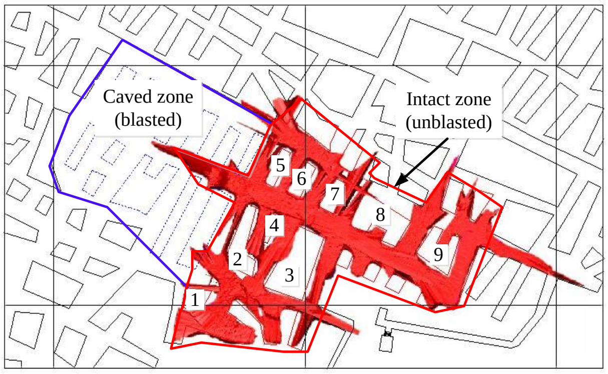



(c) Panel pillars was failing, but no crack occurred in roof

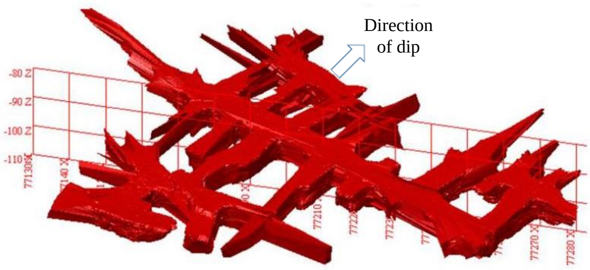



(d) Pillars collapse and roof subsidence

Fig. 9 Large-scale failure process and collapse models




(a) The caved and intact zone




(b) The three-dimensional model of gob

Fig. 10 The layout of room and pillar system

pillars simultaneously. Once all panel pillars lost their bearing capacity in stress redistribution process, load could not be transferred to barrier pillars which were still strong enough. Consequently, the panel pillars collapsed and abrupt roof subsidence event occurred. It should be noted that, in this collapse process, the barriers pillar failed to share the load of failure pillars to prevent collapse, however it is usually considered as important and useful structure to restrict failure of one panel to spread to adjacent panel (Zipf and Mark 1997). The collapse process and mechanisms could be presented by Fig. 9 (a), 9(b) and 9(d).

Sometimes, when part of the panel pillars approach the post-failure stage or lose bearing capacity, macro-crack can not be found in the roof. The external load will then be transferred from collapsed pillars to barrier pillars and a goaf could been formed as shown in Fig. 9(c). However, once a shear crack occurs on the roof above barrier pillar, the roof will lose its function to distribute load, causing a cascading pillar collapse and roof subsidence. The collapse process and mechanisms are presented in Fig. 9(a), 9(c) and 9(d). (Ma *et al*. 2012). In this collapsing process, the barrier pillar shares the load of failed pillars and forms a large-scale goaf. Sometimes, only a few tens of pillars fail; in extreme cases, hundreds, depending on the size of independent pillar-roof panel systems. This action was considered as the primary reason for the large-scale ground collapse that occurred in Xingtai gypsum mines in China(Wang *et al.* 2008).

## 5. Some suggestions and field applications

### *5.1 Suggestions for improving stability of pillar-roof system*

Based on above discussion, it is indicated that multiple pillar-roof support system collapses are usually caused by a failed pillar or fractured roof, but the initial failure only occurs in an independent and small pillar-roof system that is separated by roof crack, and adequate barrier pillars could limit potential failure to just one system. Thus, roof cracks induced by discontinuous deformation, barrier pillar and geological structure can be utilized to divide one pillar-roof support system into several smaller independent systems. Consequently, the roof span will be effectively reduced, resulting in a small tributary area. Moreover, if a local pillar-roof system located in a stress concentration zone is destroyed by roof crack, fault, controlled roof caving, etc., the tributary area of neighbour pillars will be reduced. The vertical stress of those pillars will be released, which is favourable for improving the stability of pillar-roof system and decreasing the risk of roof subsidence.

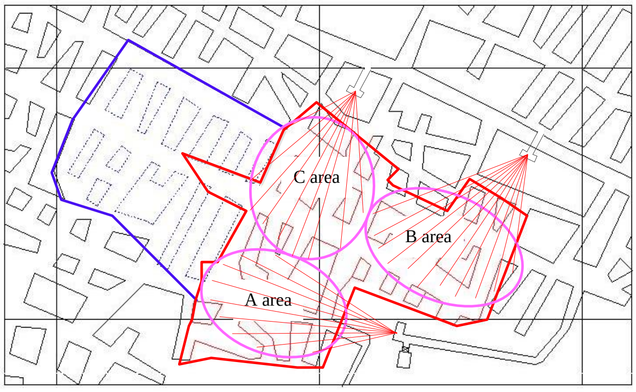
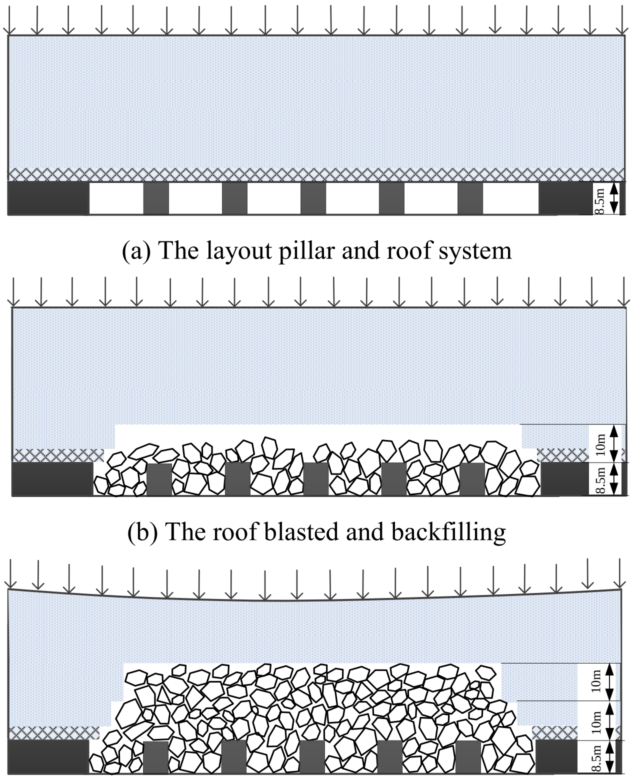



Fig. 11 The layout of blasting deep holes




(a) The layout pillar and roof system

(b) The roof blasted and backfilling

(c) The exposed roof caved

Fig. 12 The controlled roof caving process and backfilling

### *5.2 Controlled roof caving using deep-hole blasting*

An underground gypsum mine at shandong Province, China, had a weak surrounding rock. The room and pillar method was used to extract a gypsum seam at a depth of about 250 m. The thickness of seam changed from 1.56 m to 21.76 m, and the seam had a dipped at an angle of approximately 6° toward North. The roof of the mining seam consisted of mudstone, marlstone and siltstone. This combined roof had a total thickness of approximately 30 m. And the stability of roof was generally poor, with a uniaxial compressive strength of 5-7 MPa. Thus, the roof was difficult to control.

Pillar collapse or roof caving often happens even without any warning information. According to field investigation, the collapse process and mechanisms are similar to the failure pattern as discussed in section 4.3. Such failure characteristics pose a great threat to the safety and efficiency of mining. Now, the panel covered 9 pillars within the area of 8000 $m^2$, forming a gob with volume of approximately 20000 $m^3$ as shown in Fig. 10. if pillars fail and roof damage occur, catastrophe collapse may be caused. Consequently, the effective method should be performed to reduce the risk of unexpected roof and pillar collapse. As discussed, when the roof cut, the stress of neighbour pillars would decrease, hence the deep-hole blasting method was utilized to cut the roof and backfilled the gob to increase the stability.

According to field investigation, the average height of room was 8.5 m, the coefficient of volumetric expansion of roof was about 1.4. It was necessary to blast and break roof about 20 m to completely backfill the gob. However, when the intact zone was blasted, the predicted exposed area maybe reach 6000 $m^2$, the roof would cave induced by gravity due to weak bearing capacity. Therefore, only three rows in vertical direction were designed to cut roof with height of about 10 m, the drilling rig of SKZ-120A was employed to drill the deep-holes with diameter of φ 100 mm. It was hard to drill and blast the roof with high of 10 m among potential blasting area simultaneously, so three small blasting areas were designed as shown in Fig. 11. And all row of deep holes were expected to break and cut the roof about 3.3 m. Firstly, the bottom holes were drilled and charged, three potential blasting area were blasted. Then the second and third rows were done sequentially. The blasting parameter can be optimized to meet requirement in blasting process. Fortunately, approximately 10 m of roof with volume of about 50000 $m^3$ were directly broken, backfilling in gob. Then the exposed roof caved, resulted from gravity and completely backfilled gob as shown in Fig. 12. Consequently, the vertical stress born by neighboring pillars of caved zone was released, and the stability of the pillar and roof support system in the surrounding mining areas was improved.

## 6. Conclusions

In this study, the failure characteristics of multiple pillars-roof system were investigated by physical model tests, the failure modes were analysed. Then some effective methods were suggested and deep-hole-blasting was employed to decrease the risk of catastrophic collapse in a gypsum mine. The following conclusions can be drawn:

• During the loading process of physical model #1, cracking occurred simultaneously in panel pillars and the roof above barrier pillars, because the pillars were set with the same mechanical parameters. Then the panel pillars 2 to 5 lost its bearing capacity, resulting in the subsidence of the roof supported by those pillars.

• For physical model #2, the pillar 3 was set as a weaker pillar, which induced the non-uniform displacement of roof during loading process, the whole pillar-roof system was divided into two independent pillar-roof support systems by roof crack between pillar 2 and 3, and two pillars collapse and roof subsidence events occurred. The first was induced by the pillars failure, and the second was caused by the roof cut.

• When a pillar-roof support system formed in a mined panel. Any failure of bearing component would induce a subsidence event. Three types of failure pattern may occur due to the different condition of pillar and roof, the first is that roof caving resulted in caving arch or sinkhole; the second is that bearing structures failed in different time, pillars collapse and roof subsidence event occurred many times; the third is that part of panel pillars failed firstly, then stress redistribution induced cascading pillar collapse and abrupt roof subsidence, but the barrier pillar can limit the potential failure area to just to one panel.

• In a pillar and room mine, if the layout of panel and barrier pillars, controlled blast method and geological structure can be considered adequately to separate the large gob into smaller and independent support systems, and some pillars and roof could be broken purposely to release stress, the risk of roof catastrophic pillars collapse can be decreased.

• The deep hole blasting method was employed to break and cut the roof in an underground working gypsum mine at shandong Province, China. According the characteristic of room and pillar system, three blasting area were designed, approximately 10 m of roof with volume of about 50000 $m^3$ were directly broken, backfilling in gob. Then the exposed roof caved resulting from gravity and completely backfilled gob.

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