



## **Overview of Inrush Patterns and Rheological Properties of Water-sand Mining under Pore Aquifer in China Coalmines**

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**Abstract:** Pore aquifer water is one of the major hazards in China's coalmines, causing severe pit flooding and human casualties. This article analyses the two types of water conduits, pre-existing and man-made, that are culpable to water-sand inrush when mining undertakes in pore aquifers. It also describes four patterns of inrush mechanisms: 1) water-sand inrush when mining-caused caving zone and water-conductive fissures channelling pore aquifer through pre-existing conduits, such as water-conductive faults; 2) water-sand inrush when mining-caused water-conductive fissures channelling pore aquifer; 3) water-sand inrush when mining-caused caving zone channelling pore aquifer; 4) when mining undertakes in steeply inclined coal seam, the water-resistant coal pillar caves and leads to water-sand inrush. This article has also studied the effect of the particles size distribution of pore aquifer on the rheological properties of water-sand by permeation tests. The purpose of this review is to concisely summarize and provide references for countries confronting similar problems and to facilitate international discussions on pore water control.

**Keywords:** pore aquifer, water-sand inrush conduits, water-sand inrush patterns, permeation failure, China

### **1. Introduction**

In China, coal is the major source of energy [1]. China also has the largest coal output in the world with a historical high of 4 billion tons in 2014. The 500,000 km<sup>2</sup> coal-bearing area is divided into six regions: North China Carboniferous-Permian, northeast and northwest Jurassic, South China late Permian, Tibet-West Yunnan Mesozoic, and Taiwan Paleogene [2,3]. As mining extends deeper, hydrogeological conditions are expected to become increasingly complicated, aggravating the threat of water hazards to mining and threatening safe production [4,5]. Complicated hydrogeological conditions at coal mines are associated with 30 common types of water hazards [6].

In China, most of the coal seams are covered by thick and giant thick Cenozoic Quaternary loose strata. The North China coal-bearing area, in particular, has overlying Cenozoic Quaternary loose strata as thick as 250m to 500m on top of the coal seam. Generally, loose strata breed multiple layers of pore aquifers, the bottom of which (known as the bottom aquifer) lays over the coal seam. The bottom aquifer acts as the direct water source and the main stratum of water-sand inrush. As an example, at midnight of Nov. 10, 2002, in Taoyuan coal mine, Huaibei of Anhui Province, a disastrous water burst caused by Quaternary pore water silted over 300m roadway and cost three lives [7]. In response to the government

requirement of "high yield, high efficiency, and safe production", the coal industry in China intensified the research into water-sand inrush mechanism for mining under water bodies [8-13].

### **2. Water-sand inrush conduits**

Water inrush was determined by water source, aquifuge and permeable channel [14,15]. There are two types of water-sand inrush conduits when mining under pore aquifers: pre-existing conduits and man-made conduits.

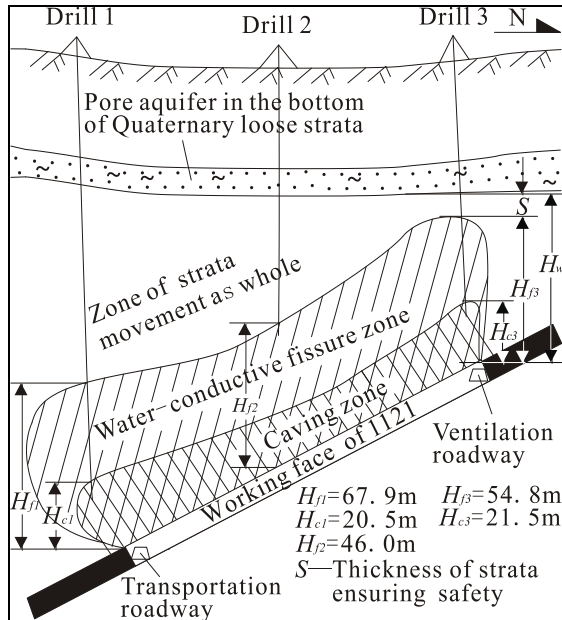
#### **2.1. Pre-existing conduits**

Natural conduits are present as water-conductive faults, karst (collapse column), pre-existing fissures and others. When the pre-existing conduits are exposed by mining activities and connect into the mining panels, water-sand inrush accidents can occur [16]. Almost 80 % of mining water inrush incidents in China (1995-2000) was associated with fractured fault zones with lagging water inrush [17].

#### **2.2. Man-made conduits**

Water inrush can also be affected by hydro-mechanical coupling interactions induced by human activities (e.g. mining methods) [17,18]. In the second half of the 1970s, vertical drilling into the overlying mining rock strata was widely adopted in China's coal mines. Mining-caused deformation in overlying rock strata and shifting patterns were inferred based on the

quantity of drilling washing fluid used. Stratification from the coal seam ceiling upward is respectively the caving zone, the water-conductive fissure zone, and the zone of strata movement as whole [19,20] (Fig. 1). The height of the caving zone ( $H_{c3}$ ) on the highest point and the height of the water-conductive fissure zone ( $H_{f3}$ ) are the primary factors for calculating the height of the safety coal (rock) pillars ( $H_w$ ) that should be retained under pore water bodies.



**Fig. 1** Measurements of the caving zone and water-conductive fissure zone in No. 1121 panel in Xieqiao coalmine, Huainan of Anhui Province

When mining causes water-conductive fissures or caving zones to channel the pore aquifer above, a man-made conduit for water-sand inrush is formed. In addition, mining may further stretch tectonic structures, such as faults, and other pre-existing fissures, which will then become more permeable to water [21,22]. Therefore, the ongoing development of pre-existing conduits in the overlying rock will aggravate the menace of water-sand inrush under pore aquifer.

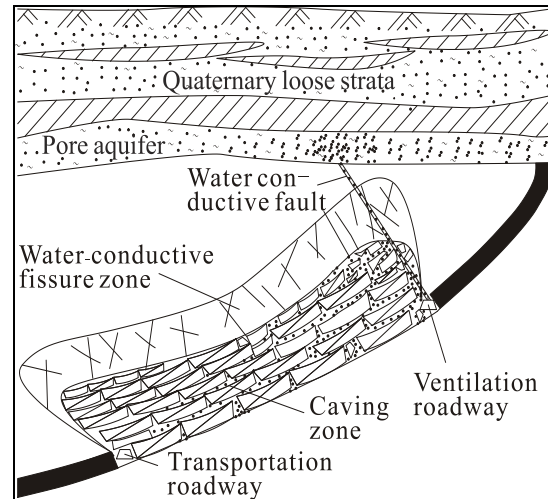
### 3. Patterns of water-sand inrush

In the existing research literature, some researchers proposed two or three patterns of water-sand inrush mining under pore aquifers [23]. Actually, from past water-sand inrush accidents in China coalmines, there are four major patterns of water-sand inrush according to the conduits of water-sand gushing into goaf area.

#### 3.1. Pattern I

After mining, the water-conductive fissure zone and the caving zone channel the pore water in the bottom aquifer of Quaternary loose strata (Fig. 2) through pre-existing conduits (e.g. water-conductive faults, pre-existing fissures, etc.). The quantity and speed of water-sand inrush are subject to the water (sand) conductivity of the pre-existing conduits. Case: in the

North China coal-bearing region, during mining on the No. 8109 panel in the Luling coalmine of Huaibei, Anhui, a normal fault with 7-meter height drop channelled the Quaternary bottom aquifer and fissures. On June 12, 2005, a water-sand inrush burst out a total of 80m<sup>3</sup> of sand and gravel. Production was suspended for a week.



**Fig. 2** Water-conductive fissure zone and caving zone channeling the pore aquifer via pre-existing conduits

#### 3.2. Pattern II

During mining, as water-conductive fissure zone implicate the pore aquifer in the bottom of Quaternary loose strata, the water and sand in it burst into mining panel. This pattern generates relatively smaller quantities of sand. Case: on May 31, 2001, in the Shendong coalmine in the northwest coal-bearing region, a water-sand inrush accident took place in the Quaternary pore aquifer, gushing out 4700m<sup>3</sup> of sand gravel and maximizing water inrush at 50~60m<sup>3</sup>/h. Over 400meters of the tunnel was silted and production was suspended for 20 days. Total economic loss struck at RMB1.4 million (approximately USD 210,000).

#### 3.3. Pattern III

The caving space caused by mining activities directly channels the bottom aquifer of Quaternary loose strata. As caving zone have bigger pores and stronger permeability, this pattern generates large quantities of water and sand in a rather forceful way. Case: on Feb. 9, 1967, in the Shulan Fengguang coalmine of Jilin, in the northeast coal-bearing region, a severe water-sand inrush from a Quaternary pore aquifer produced a gush of water at 1560m<sup>3</sup>/h and sand of 100,000 m<sup>3</sup>. Most tunnels were silted and the coalmining was halted.

#### 3.4. Pattern IV

Once a goaf space is created after mining a steeply-inclined seam ( $55^\circ < \alpha < 90^\circ$ ), the roof plate cannot cave as mining proceeds (Fig. 3a). As a result, the water-resistant coal column will cave and fill the goaf

space by force of gravity (Fig.3b). If such caving cannot be contained in time, water and sand in the overlying pore aquifer will enter into the working panel through the conduits caused by seam caving. A water-sand inrush accident is thus imminent and may cause ground collapse or other geological disasters [24]. Statistical analyses suggested that, although water inrush decreased from 2001 to 2012, the accidents triggered by gob area water still accounted for a higher proportion. Case: on July 31, 1965, in the Xinhe coal mine, Xuzhou of Jiangsu Province in the North China coal-bearing region, the water-resistant coal column caved during mining a steeply-inclined coal seam. Groundwater and water-sand from the Quaternary pore aquifer gushed into the pit, silting a 1200-meter tunnel with a total of 5788m<sup>3</sup> sand. The coal mine suspended production for 58 days and suffered a great loss.

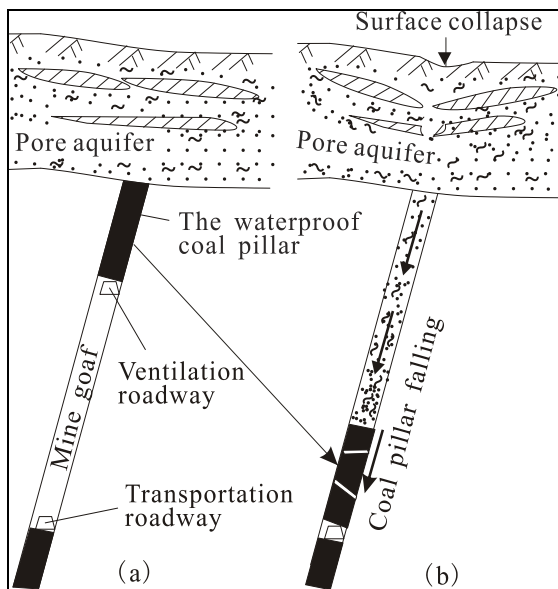


Fig. 3 Water-resistant coal column caving during mining steeply-inclined coal seam

When mining under pore aquifers, the direct cause of water-sand inrush is man-made conduits (water-conductive fissure strata, caving strata and the space left by coal pillars falling) channelling pre-existing conduits (water-conductive faults and pre-existing fissures, etc.). Both types of conduits are formed subject to the lithological characters and the hydrogeological properties of the bottom aquifer of Quaternary loose strata.

#### 4. Rheological properties of water-sand

By simulating mining conditions under a pore aquifer, permeation tests can be conducted to study rheological properties of water-sand [25]. Permeation tests revealed that water-sand inrush during mining under pore aquifers has demonstrated periodicity and intermittency (Fig.4). Each full cycle shows rhythmic changes in characteristics, including lithological composition of the pore aquifer, water head pressure, hydraulic gradient, and water-sand

volume, corresponding to the revolving energy concentration and release inside the pore aquifer [26]. There are two stages in a full cycle of water-sand inrush. On stage 1 (ab), aquifer releases energy. When highly pressurized pore aquifer is exposed, the water level declines sharply at around the sand outlets and hydraulic gradient increases rapidly. As hydraulic gradient reaches the extreme point, sand volume maximizes with major sand burst and minor quicksand. On stage 2 (bc), aquifer concentrates energy. Hydraulic gradient tapers down and water level resumes. Sand volume gradually decreases to quicksand with subsurface erosion by the end. When water level resumes to certain height, sand burst instantly for the next cycle.

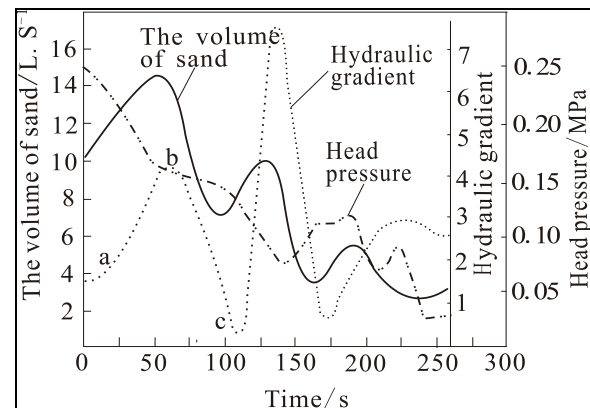
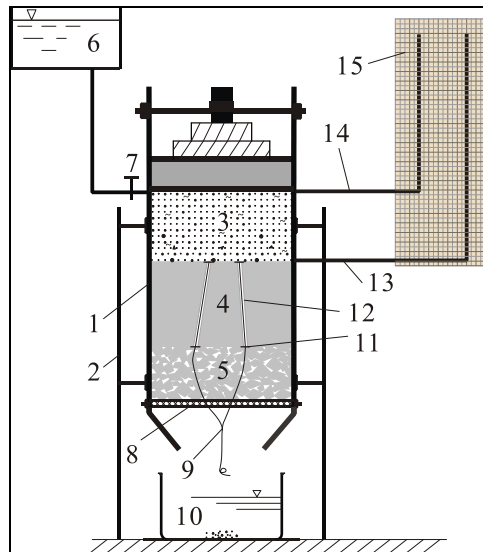


Fig. 4 Simulation test of water-sand inrush [26]

Many experiments have proved that the “critical hydraulic gradient” of water-sand inrush is closely correlated with fissure size in the overlying mining plate and the physico-mechanical properties of the soil mass in the pore aquifer [27,28]. When the fissure size goes up, the critical hydraulic gradient goes down. The critical hydraulic gradient causing destructive seepage in the pore aquifer will decrease exponentially with fissure width increases [29-31].

Previous research results mentioned above have provided a good foundation for us to study the rheological properties of water-sand mining under pore aquifer. However, in the Wanbei mining area of north China coal-bearing region, this is often the case that in a few of working faces which mining the same coal seam at the same upper limit by the same mining method under the same pore aquifer, some of them occur water-sand inrush disasters but others don't. The reason may be that there are regional differences in the particles size distribution of the pore aquifer by analysis and research. To further understand the composition of the particles group of pore aquifer impacting on the rheological properties of water-sand, the authors conducted penetration tests according to the water-sand inrush pattern II the engineering case of which is Taoyuan coalmine of Wanbei mining area in the North China coal-bearing region.

(1) Test apparatus. As shown in fig.5. We use the sand-gravel sample (3#) for simulating pore aquifer, the concrete block sample (4#) with two fractures (12#) for simulating water flowing fractured zone and the broken stone sample (5#) for simulating caving zone. In Taoyuan coalmine, the average thicknesses of pore aquifer, water-conductive fissure zone and caving zone are respectively 16m, 17.9m and 11.2m. So, the thicknesses of sand-gravel sample, concrete block sample and broken stone sample are respectively designed as 16cm, 17.9cm and 11.2cm according to the similarity ratio of 1:100. In addition, the inside diameter of metal cylinder for loading samples is 300mm.



1. metal cylinder ; 2. Fixed support ; 3. Sand-gravel sample ; 4. Concrete block sample with two fissures in a width of 2 mm ; 5. Broken stone sample with all the particles diameter bigger than 30 mm ; 6. water tank ; 7. Control valve of water tank ; 8. Steel plate of 50mm in thickness with hole of 30mm in diameter ; 9. Fine wire of 0.3~0.5mm in diameter ; 10. Plastic bucket ; 11. Thin plastic cushion ; 12. fissure ; 13. Pressure measuring tube 1 ; 14. Pressure measuring tube 2 ; 15. Coordinate paper with mm level

**Fig.5** Permeation test taking the water-sand inrush pattern II as the engineering case

(2) Test procedure. The test samples are installed as shown in fig.5. Need to emphasize is that: ①two fine wires(9#) need to be set before placing the broken stone sample(5#); ②the fissures(12#)in the concrete block sample(4#) are filled with salt and the thin plastic cushions (11#) sticking on the top surface and at the bottom surface of each fissure fixed on the fine wire(9#) are respectively used for separating water flowing from the sand-gravel sample (3#) and ensuring the stability of the salt in the fissures(12#) before beginning test; ③the gap between the concrete block sample (4#) and the inner wall of the metal cylinder (1#)needs to be sealed with melted wax; ④the water tank(6#)height needs to be adjusted so

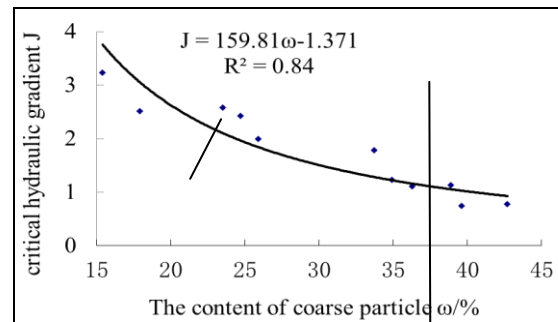
that the sand-gravel sample(3#)will maintain a certain degree of water pressure; ⑤the fine wires(9#)and the thin plastic cushions(11#) fixed on are pulled out to make the salt in the fissures(12#)fall into the pores of the broken stone sample(5#)and dissolving in the water flowing from the sand-gravel sample(3#), while recording the water pressure changes from the pressure measuring tube (13# and 14#)and the sand content changes from the plastic bucket(10#)in a certain period of time and then calculating the critical hydraulic gradients(J)of the sand-gravel sample deformation and failure. By the way, 11 sand-gravel samples are made up according to the particles analysis results (table 1) of the samples taken from the pore aquifer of 11 drill holes in Taoyuan coalmine. That is, this test should be repeated 11 times.

**Table 1.** Particles analysis results of the samples taken from the pore aquifer in Taoyuan coalmine (%)

Test sample No.	Drill hole No.	5~10 mm	>3.0 mm	>2.0 mm	>0.5 mm	<0.5 mm
SG-1	W08	6.1	17.5	24.7	91.2	8.8
SG-2	98G3	9.7	27.3	38.9	89.4	10.6
SG-3	00G1	5.8	16.8	23.5	90.3	9.7
SG-4	97G1	6.4	18.0	25.9	88.6	11.4
SG-5	95G1	4.4	12.4	17.9	89.0	11.0
SG-6	95G2	3.8	10.5	15.4	87.9	12.1
SG-7	94G1	9.1	25.6	36.3	91.8	7.2
SG-8	ASJ	8.6	24.2	34.9	90.9	9.1
SG-9	MSJ	8.4	23.5	33.7	88.9	11.1
SG-10	02-2	9.8	27.6	39.6	89.4	10.6
SG-11	02-1	10.5	30.2	42.7	90.1	9.9

(3) Results analysis. Test results have obtained the power correlation between the critical hydraulic gradient that causes destructive seepage in the aquifer (J) and the content ratio of coarse grit (diameter>2mm) in the aquifer ( $\omega$ ), which is  $J=159.81\omega^{-1.3712}$ , ( $R^2=0.8453$ ), see Fig. 6.

(1) When grit ratio  $\omega$  increases from 15% to 35%, the critical hydraulic gradient J linearly decreases. Seepage in pore aquifer intrudes in flowing soil or subsurface erosion mode.



**Fig. 6** Correlation between coarse grit content and critical hydraulic gradient in pore aquifer

(2) When grit ratio  $\omega$  grows to 35% and over, the critical hydraulic gradient J significantly decreases. Seepage in the pore aquifer intrudes in piping mode.

The underlying reason being: when the coarse grit ratio is over 35% fine grit, water cannot fill in the pores between coarse grit. The coarse and fine grit are not closely bound and the constraint force in-between is not strong enough, allowing fine grit to easily move between pores. As a result, the lower fine grit content creates a smaller constraint force between coarse grit, thus compromising the capability of soil mass in the pore aquifer in resisting seepage destruction. Fine grit will be easily driven out with seepage water flow in piping mode.

## 5. Conclusions

Based on the above analysis, conclusions can be drawn as follows:

(1) There are two types of conduits for water-sand inrush when mining under pore aquifer. First, natural conduits include water-conductive faults and pre-existing fissures. Second, man-made conduits include caving zones caused by mining activities, water-conductive fissures, and the goaf space caused by caving water-resistant coal column.

(2) Four water-sand inrush patterns occur when mining under pore aquifers: a) water-conductive fissure strata channelling the bottom aquifer of Quaternary loose strata through pre-existing conduits, b) water-conductive fissure strata implicating the bottom aquifer, c) caving strata implicating the bottom aquifer and d) the waterproof coal pillar falls when mining steeply-inclined seam. The intensity of the inrush is closely correlated with the lithology of the overlying rock strata and hydrogeological properties of the bottom aquifer.

(3) Laboratory simulation tests have revealed that the essence of water-sand inrush under pore aquifer mining is the energy concentration and release cycle inside the pore aquifer. The “critical hydraulic gradient” that causes water-sand inrush is correlated to the size of mining fissures in overlying plate and the physio-mechanical properties of soil mass in pore aquifer. The larger the water-conductive fissures, the smaller the critical hydraulic gradient; when coarse grit content in pore aquifer is over 35%, the critical hydraulic gradient will decrease significantly and seepage in pore aquifer inrushes in piping mode.

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