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OVERLYING SAND-INRUSHING MECHANISM AND ASSOCIATED CONTROL TECHNOLOGY FOR LONGWALL MINING IN SHALLOW BURIED COAL SEAMS WITH THE SOFT SURROUNDING ROCK

Taking the sand-inrushing accident of the Selian No. 1 coal mine in the Ordos of inner Mongolia as the research background, four main factors of sand-inrushing, including sand source, channel, sand-breaking power, and flowing space, were analysed. The disaster formation process (SCPS) illustrated that sand-inrushing disasters in shallowly buried coal seams with soft surrounding rock have the characteristics of being significantly influenced by mining, the development of vertical overburden channels, and sufficient space for water-sand mixed particles to flow. Universal Distinct Element Code (UDEC) software has been used to reveal that the vertical cracks in the overburden between the coal wall and support undergo a process of development and expansion along with the cumulative stress of mining. This showed that the vertical fissure through the overburden is the main pathway for the disaster. Combined with the site conditions, disaster occurrence mechanism, and numerical simulation results, a comprehensive prevention and control technology based on the working face and roadway grouting to block the channel was proposed. It contains reasonable mining height and optimisation of advancing speed, so that safe and efficient mining of coal seams in shallow-buried soft surrounding rocks could be achieved.

Keywords: Shallow-buried coal; Soft rock; Sand inrushing; Cracks; Safe and efficient; Mining

1. Introduction

A shallow coal seam is one with a shallow buried depth (usually less than 200 m), thin bedrock, and thick overburden of loose sand as the typical characteristics. In the longwall mining process, the main roof is generally broken, and it is difficult to form a stable structure. Fissures

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develop all the way to the surface, the surface has noticeable bench subsidence, and the rock pressure has an evident dynamic load phenomenon [1-4].

Consider Shen Dong Coalfield for instance. The coal seam in this region has the advantages of a thick coal seam, simple occurrence structure, single geological structure, etc., but at the same time, there are problems such as poor sand cementation and toughness of overlying strata, the roof of the stope is easy to cut down along the full thickness of the coal wall, and overburden rock fissures easily cause water flooding and sand-inrushing accidents [5-6]. Sand inrushing refers to the roof fall phenomenon caused by the overburden of water-sand mixed fluid or loose sand body inrush into the excavation space along the fissure during mining activities in stopes or roadways. This phenomenon easily halts production, causes equipment damage, or even causes casualties and seriously threatens the safety of mining operations [7]. According to incomplete statistics, typical sand-inrushing accidents have occurred, as shown in Fig. 1, in western mining areas of China since 2000. Sand-inrushing accidents have always been a serious issue in coal mines because of the characteristics of less foreboding, sudden occurrence, and strong energy storage. It is difficult to prevent and has a large scope of influence.

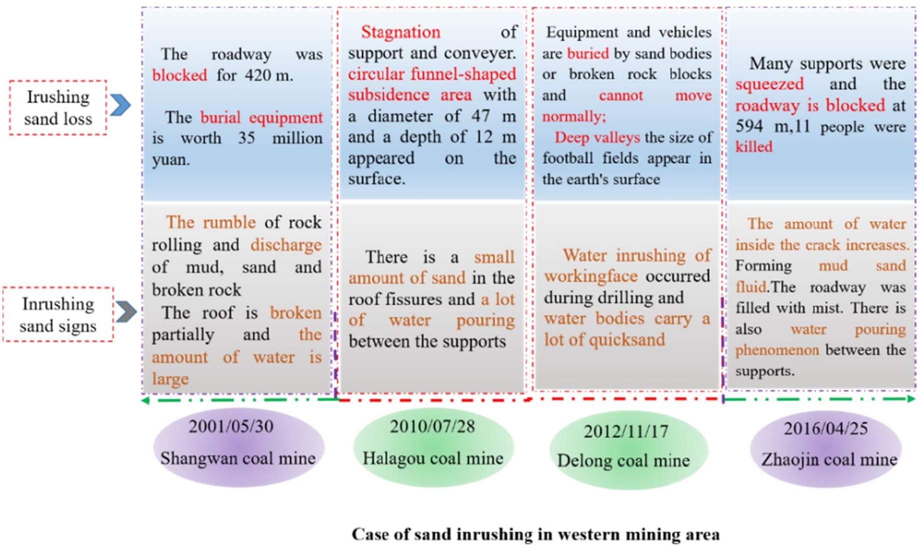


Fig. 1. Statistics of water-sand inrush disasters in western coal mines

World scholars have conducted a series of studies on the occurrence mechanism of and control technology for sand-inrushing accidents under various geological conditions in coal mining. The growth highness of the water-flow crack zone caused by undersea mining was delimited in the Xinli Zone of the Sanshandao Mine to guarantee mining safety, including theoretical analysis and numerical simulation [8]. Aiming to look into the safety risks related to mining under a loose aquifer and used factor analysis (FA) and Fisher discriminant methods to analyse and assess the risk of water-sand inrush under such conditions [9]. With the view of water erosion, seepage force, and soil cohesive force, a three-dimensional force analysis for soil particles on the side wall of the water inrush channel was conducted and established the critical condition of incipient particle motion [10]. Imitating the up-growth height of overlying rock water-conducting fractures at multiple mining heights revealed the evolution law of mining-induced overlying rock water-conducting fractures in shallow coal seams using the technology of transient electromagnetic detection [11-13]. The initiation, development, and occurrence of disasters were analysed, and a new sand-water transport testing system to study three phases of water-sand inrush was established [14]. Programming a test instrument that can simulate the immersion process of water and sand inrush and investigating the control factors of the disasters in the broken rock mass in the goaf [15]. Focusing on the thickness and thin rock intrinsic coal seam mining conditions and remedying by modifying the coal pillars to prevent sand flow instead of water seepage [16,17]. In view of the flowing evolution under seepage erosion, the seepage speed, fluid damage and permeability of the internal object were studied. The effects of the joint roughness coefficient (JRC) and homogeneity of the filling medium on the seepage evolution are discussed [18]. The breaking crack area is the main channel feeding in groundwater which caused small particle migration from fractured rocks of the faults, and to investigate particle migration with water flow, a 3D model was established for solid-water two-phase flow [19]. Comprehensive use of multiple analytical methods based on the principle of silo unloading and arching, combining them with actual inrush features to analyse the process of water and sand inrush accidents [20]. A callable model for inquiring about the mechanical intensity of the retaining wall was set up and improved safety management of water and sand flooding disasters on roadways [21]. The flow process in the saucer mixture in the rupture of the rock mass was studied, including the particle size distribution, void ratio, and initial mass of aeolian sand [22,23]. A mechanical model of water and sand inrush was studied, and the limit equilibrium conditions of water and sand inrush under different clay contents were established in the loose layer [24]. Given the particle loss, a series of seepage tests were performed correspondingly by a controlled seepage test device [25]. Looking into the mechanism of water feed and the sand movement induced by a borehole and developed measures for the prevention and remediation of such problems [26]. The influence of different mining heights on the control of water and sand in overlying consolidated Paleogene sandstone conglomerate aquifers provides theoretical support for similar mine mining to prevent water and sand disasters [27]. Under the influence of mining disturbance, the surrounding rock mass of mining space has its occurrence state of primary pore-fissure and damage state of new pore-fissure, which cut and divide the surrounding rock of the roof into multiple blocks of different sizes. When flowing or stored water passes through or is attached to the crack (pore) gap, a dual medium structure is naturally formed, which conducts water in the crack space and stores water in the pore rock mass. Based on the dual-medium structure, many scholars proposed three seepage models of rock mass fracture systems [28,29]. (1) The fractured coal and rock mass are abstracted as a dual water exchange model with a mixture of fractured and porous media. (2) The coal and rock mass is regarded as multiple rock blocks segmented by the orthogonal fracture system. Due to the anisotropy of the fracture inclination Angle, it is assumed that there is a fracture penetration principal axis at each position, and the fracture groups with the same occurrence are distributed vertically at equal intervals on both sides of the principal axis. (3) The fracture of coal and rock mass is abstracted as the infinite horizontal fracture is cut into multiple homogeneous rock blocks (the thickness of the rock block is much larger than the width of the fracture). The fracture water flow is horizontal while the rock block water flow is vertical. In addition, most scholars have adopted sophisticated real-time monitoring and analysis methods for the relationship between dynamic stress change course and development characteristics of fissured rock mass during coal mining [30-32]. The microseismic monitoring technology, 3D tomography method, two-dimensional complex structure cavity identification method and wave velocity imaging technology play an important role in the timely detection of water burst and sand burst abnormal areas (internal damage, fault) and guarantee the safety of mining, the former microseismic monitoring method is optimised, and the monitoring content is expanded [33].

The above research results provide a useful reference for analysis of the factors influencing overburden sand burst, the formulation of disaster prevention, and control technology. However, they fail to demonstrate that the shallow buried coal seam with soft surrounding sand inrushing rock fissure channel connects the overlying aquifer and cuts through the sand source layer and the formation process of sand inrushing disasters under the action of mining. Hazard control technology has not been proposed that can effectively solve security and production efficiency problems in the follow-up mining process in areas at risk of sand inrushing disasters. Therefore, combined with the background of field sand inrushing accidents, this paper explores the breeding characteristics and occurrence mechanism of mining-induced overburden sand collapse in the condition of shallow and soft surrounding rock seams. It proposes comprehensive disaster prevention and control technology based on the micro development characteristics and distribution range of simulated sand inrushing fractures to provide a scientific basis for the safe and efficient mining of shallow coal seams.

2. Engineering background

The Tongmei Selian No. 1 coal mine is located in the Gaotouyao mining area in northeastern Ordos, Inner Mongolia. The bedrock in this area is exposed in a large area and Quaternary loess. It is scattered on top of the hills, mainly in the semi desert area.

The average thickness is 4.0 m, the average burial depth is 170 m, the dip angle is 1~3°, and the strike length and a dip length of the working face are 1780 m and 280 m, respectively (there are 164 supports from the transport lane to the return air lane). During the continuous advancing process of the working face, an inrushing sand accident occurred between the coal wall and the supporting roof of hydraulic support #157~#164 in the mining space, resulting in the equipment of the working face being suspended and forced to stop production. The roof in this area had interlayer water pouring in the early stage, which caused serious silting of the sandy mudstone roof. The roof caving position was "cone"-shaped according to field observation, and the maximum height of the gangue scattered at the lower part of the caving roof was 2 m, on which there was a loose collapsed sand body, as shown in Fig. 2.

The immediate roof of the working face is mainly sandy mudstone, the main roof is siltstone, and the primary fractures are developed. The fracture roof is eroded by water for a long time, which reduces the compressive strength and intensifies the fracture propagation. The floor is sandy mudstone containing expandable clay minerals. The surrounding rock of the working face is soft and broken.

3. Mining-induced overlying rock and sand inrush process

During high-intensity mining of these shallow coal seams with soft surrounding rock, the mining-induced fractures in the overlying rock underwent a process of initiation, development, and expansion to the overlying aquifer and ultimately formed water-conducting fracture chan-

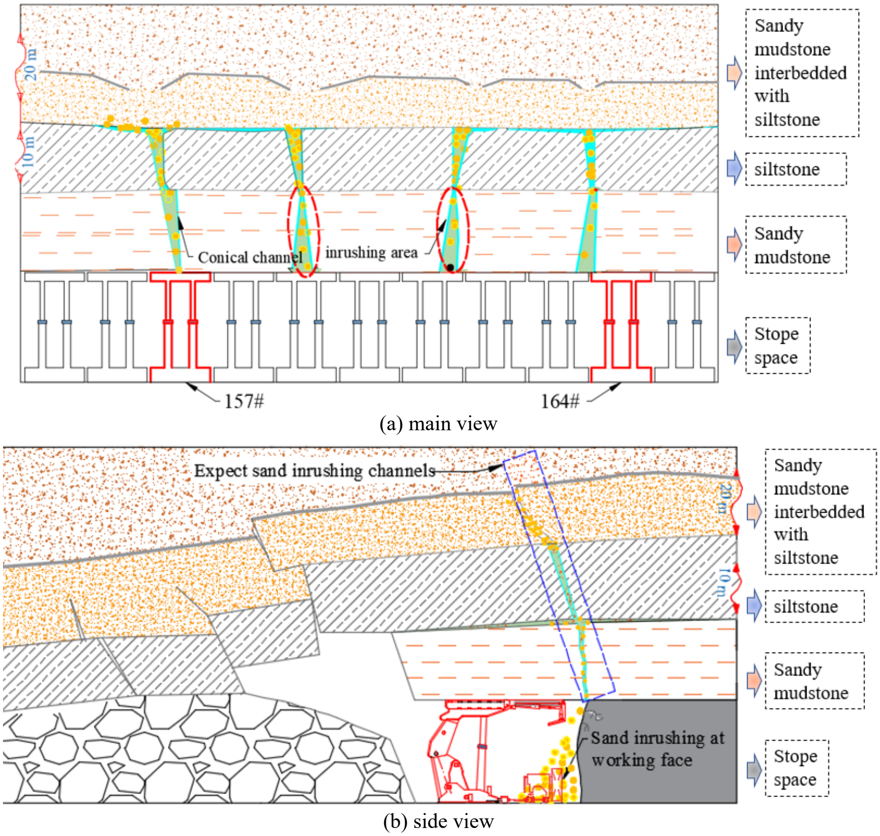
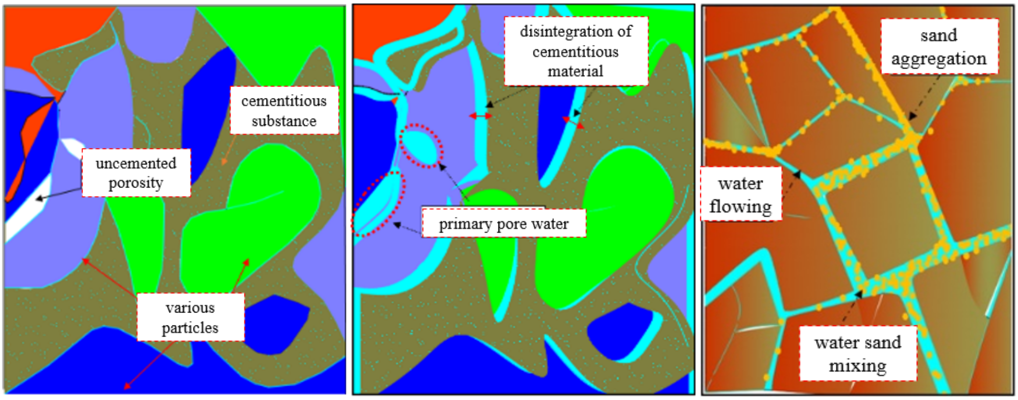


Fig. 2. Schematic of sand inrush disaster in LW8101

nels [34]. After the seepage and water loss of the overlying aquifer, the water flows from the fissure freely interacted with the mixed granular rock mass to form the water-sand mixture, which broke into the excavation space overlying fissure under the coupling action of seepage and stress. Therefore, combined with the overburden sand collapse accident of the 8101 working face, it is concluded that the occurrence of sand collapse is mainly affected by four factors, namely, the source of sand collapse, the channel of sand collapse, the dynamic force of sand collapse and the activity space of the loose sand body.

3.1. Sand source

The overburdened rock mass changes from the original stable state to the loose state due to the repeated mining actions of the 8101 working face and the surrounding working face and undergoes a dynamic process of "steady-unstable loose migration." The cemented blocks of sandy mudstone (Fig. 3a) were significantly affected by mining cracks, lost water, and disintegrated along the plane or joint plane to produce sand particles (Fig. 3b). With the increase in mining space, the overburden cracks expand to form a fracture network where primary and secondary fractures intersect each other (Fig.3c). When mining-induced fractures are connected to the sand source layer, sand body particles are affected by dead weight, intergranular extrusion pressure, and friction force, together with the horizontal or vertical flow of aquifer water. This results in large area migration of loose sand bodies [35,36], forming a water-sand mixture, providing the material source for the occurrence of a sand inrushing accident. The source of sand collapse particle flow is shown in Fig. 3.



(a) Multiple rock blocks are cemented to each other (b) Cemented rock disintegration (c) Water-sand mixture composition

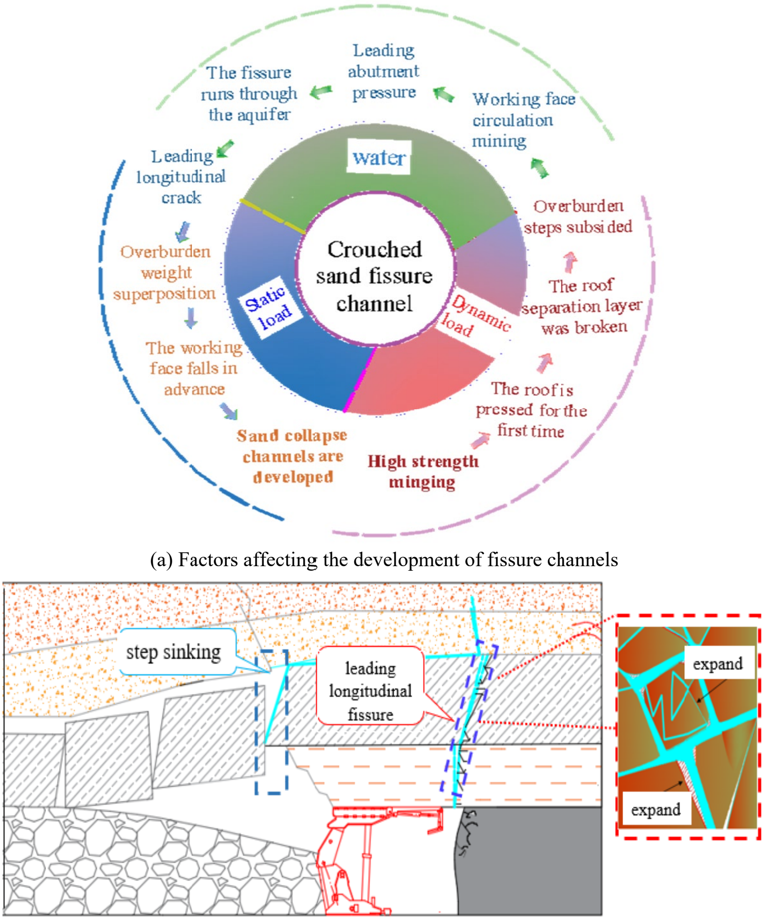
Fig. 3. Particle flow source of sand inrush

3.2. Sand channel

The 8101 working face of the Silian Coal Mine is located in the Shen Dong mining area. The rock surrounding the coal seam is mostly soft. According to the empirical formula for calculating the height of the water-conducting fracture zone in overburden rocks in this area [21]

$$H_{li} = \frac{100\sum M}{1.6\sum M + 2.2} \pm 5.6 \tag{1}$$

Where $\sum M$ is mining coal thickness. The theoretical water conduction height is 40.9±52.11 m, which exceeds the geological aquifer of the working face ① and endangers the aquifer ②. According to the calculation result of the empirical formula, the height of the mining-induced seepage fracture zone in the adjacent mine of the Shen Dong mining area is generally larger than that of the empirical formula, so the development height of mining-induced overburden fracture in the working face is larger than that of the empirical result. Combined with the development and expansion laws of longitudinal penetration cracks in the overburden of shallow and thin bedrock coal seams, the following can be seen: ① In front of the hydraulic support, the vertical stress of the soft surrounding rock under the overlying load increases significantly whilst working face mining. Due to the low strength of the direct roof, step subsidence is prone to occur under mining disturbance. ② The roof periodically sinks to form the working face pressure, which gradually penetrates the upward and downward fractures. The geometric characteristics (e.g., occurrence, morphology, opening) deteriorate with the multiple cumulative forces and the dynamic change of the dislocation between fractured rock masses. ③ As the working face continues to advance, the interforce of fractured rock blocks is continuously transmitted in multiple directions. After penetrating the water-conducting fracture zone, hydraulic erosion accelerates the process of activation of longitudinal fractures in the original overburden and expansion of new fractures. Finally, it penetrates the sand source layer, providing a flow channel for the sand body (as shown in Fig. 4).



（b） water immersion degradation of fissure channel

Fig. 4. Schematic diagram of crack development and water soaking in the process of sand inrush

3.3. Dominant power

Disturbed sand body particles in the process of flow along the fissure channel are driven by multiple forces (including sand weight force, the friction force between particles), water body carrying capacity (osmotic pressure and uplift force, drag force), and the factors induced by mining site disturbance. These factors lead to an increase in particle fluid velocity and increased kinetic energy due to agglomeration. After energy accumulates for a certain time, inrushing sand disasters occur.

The influencing factors of sand collapse dynamics are shown in Fig. 5. When water flows into the cavity of the sand collapse channel, due to the roughness of the surface of the sand particles, the water generates friction on the surface of the particles. When the Reynolds number is large (>10), the flow line at the top of the particle is separated [37], a vortex is generated on the backwater side of the particle, and a pressure difference is generated on the front and rear sides of the particle, forming resistance. The combined force of friction and resistance is the drag force, which is the main driving force of the sand collapse.

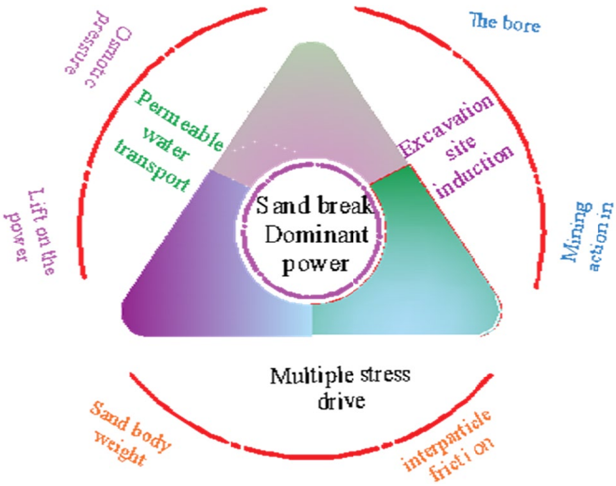


Fig. 5. Sand inrush dynamic impact factors

3.4. Scattering space

The main scattered space of the water-sand mixture caused by mining-induced overlying rock sand inrushing disaster is the excavation site. Therefore, the mining intensity, geological conditions, and construction procedures of the excavation site affect the occurrence probability of disasters. In the process of high-strength mining of shallowly buried coal seams, the coal-rock strata in front of the coal wall form an unstable structure under the action of mining stress, and roof water leakage often occurs at the 8101 working face, which results in a poor construction environment for the mining equipment and a decrease in the advancing speed of the working face. As a result, the excavation space is in danger of sand collapse, which contributes to the occurrence of on-site sand inrushing disasters. The space-time factors influencing sand source scattering on the working face are shown in Fig. 6.

The occurrence of overburden rock in shallow coal seams with soft surrounding rock and the condition of intensive coal mining lead to conditions prone to this kind of sand inrushing disaster due to the significant influence of mining activities, the development of longitudinal sand inrushing channels in overburden rock, and sufficient scattering space for water and sand mixed particles. Under the influence of high-intensity mining, the stable overburden produces

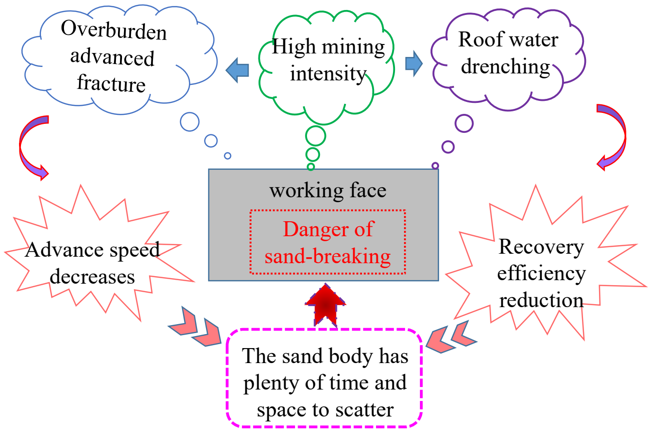


Fig. 6. Schematic diagram of the factors influencing scattering time and space

a crack channel in the cemented rock mass, which causes flowing water that carries loose sand bodies to run off and gradually forms the source of the sand body. In front of the working face, the primary fractures in the mining-induced overburden are activated, the secondary fractures are expanded, and multiple fractures are connected, constituting the longitudinal sand inrush channel. Driven by the internal stress of the sand body, carried by a water body that easily permeates the surrounding rock, and induced by engineering disturbance, the dominant force of sand collapse is formed. "Coal wall-supported" mining space provides scatter space for mobile sand bodies. In summary, the formation process of sand inrushing disasters generally has several stages, such as "stable overburden – the source of the sand body – sand collapse channel – dominant power – flow space – sand inrushing disaster," and a process diagram of sand inrush disaster formulation is shown in Fig. 7.

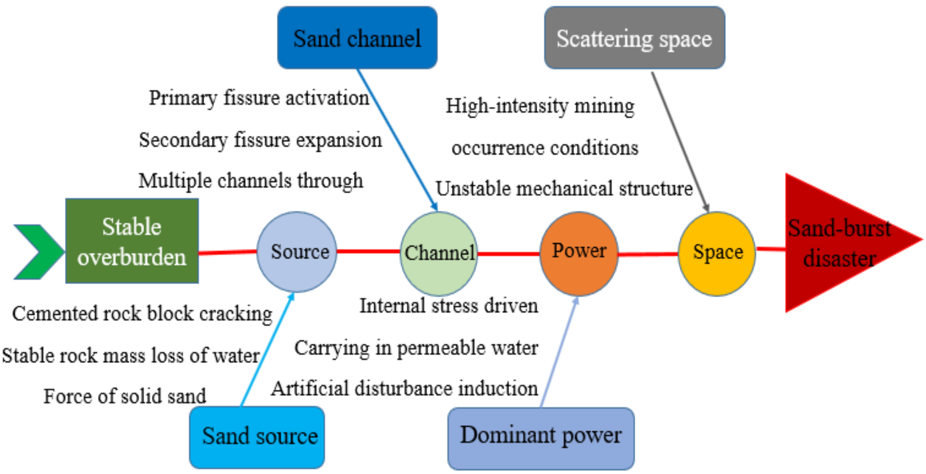


Fig. 7. Process diagram of sand inrush disaster formulation

4. Evolution characteristics of overburden rock burst sand channels induced by mining

In view of the geological conditions of the 8101 working face, a numerical model was established by using UDEC software to analyse the evolution characteristics of mining-induced overburden sand body fissures in shallow coal seams with the soft surrounding rock. The overall model adopts the typical Mohr-Coulomb yield criterion. The model is 240 m long and 175 m high and is divided into 14 layers. The left, right and lower boundaries of the model are fixed boundaries, and 4.5 MPa stress is applied to the upper free boundary, as shown in Fig. 8. According to the lab results of coal and rock mechanics testing, each stratum's physical and mechanical parameters are shown in Table 1. Based on the analysis results of influencing factors of mining-induced overburden sand outburst mentioned above in Section 3, the engineering model corresponding to actual mining size is adopted in this simulation. This is to explore the influence of factors such as the source of sand outburst, flow channel and scattering space on water and sand influx from the perspectives of fracture development height, angle and size. It should be noted that this paper mainly studies the evolution process of mining fractures, thus, it does not simulate the flow of aquifer water.

TABLE 1

Rock & coal characteristics and strength parameters

Lithology	Thickness /m	Density /kg·m^{-3}	Bulk modulus /GPa	Shear modulus /GPa	Cohesion /MPa	Internal friction angle /°	Tensile strength /MPa
Aeolian sand	8	2000	0.4	0.2	0.8	19	0.6
Sandy mudstone	22	2450	2.3	2.1	1.6	28	1.3
Coarse sandstone	8	2500	3.2	3.0	2.5	30	1.5
Conglomerate	10	2400	2.5	2.3	1.8	28	1.2
Siltstone	20	2500	3.4	3.1	2.4	30	1.1
Sandy mudstone	25	2550	2.3	2.1	1.6	28	0.7
Siltstone	20	2500	3.5	3.2	2.6	31	1.3
Coarse Sandstone	27	2550	3.2	3.0	2.5	30	1.1
Sandy mudstone	14.4	2600	5.5	5.0	3.5	32	1.8
Medium-fine-grained sandstone	3	2500	1.5	1.4	0.8	22	0.9
Mudstone	0.6	2000	1.0	1.0	0.5	15	0.5
2-2 coal seam	4	1400	2.5	2.3	2.5	28	1.5
Sandy mudstone	3	2400	2.2	2.0	1.5	28	1.3
Medium-grained sandstone	10	2550	2.6	2.4	2.0	30	1.5

Taking 30, 50, 70, and 100 m advancing distances in the working face as different mining degrees, the migration characteristics and fissure development laws of mining-induced overburden under various conditions are obtained, as shown in Fig. 9.

When the working face advances by 30 m, the direct roof breaks first, and tensile cracks occur in the central basic roof. An asymmetrical slip structure appears in the area where the

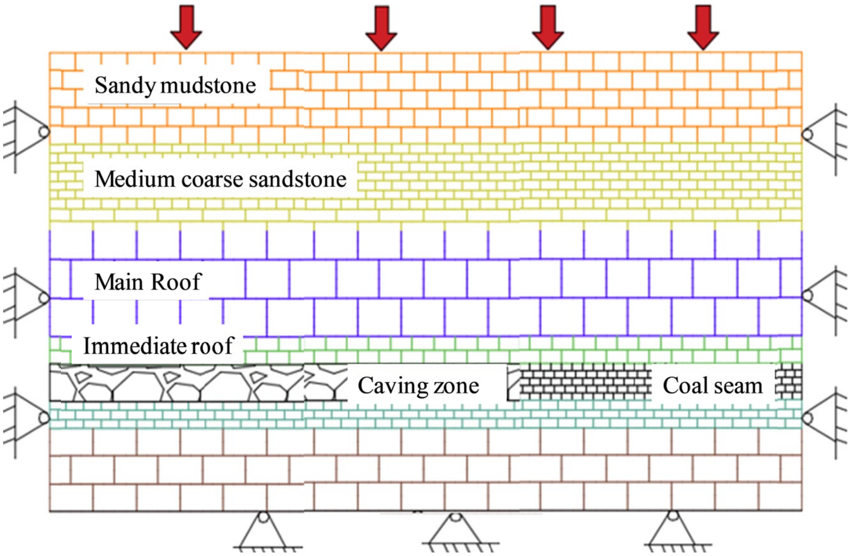
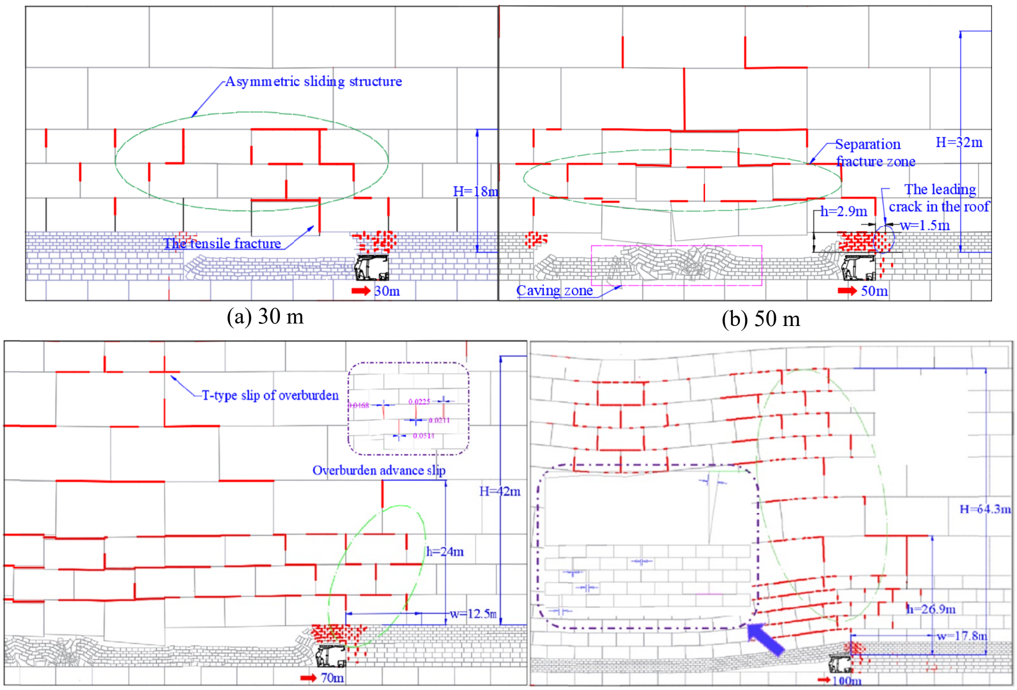


Fig. 8. Numerical model of fracture evolution in mining overburden



(a) 30 m (b) 50 m

(c) 70 m (d) 100 m

Fig. 9. Mining overburden migration and sand-inrushing channel evolution characteristics

overburden is 18 m away from the roof, which results in stress concentration in the rock strata above the working face support. In this process, overburden cracks develop in the overburden area above the goaf.

When the working face advances to 50 m, the direct roof continues to slip and break as the working face advances. The height of the overlying fracture zone extends to 32 m, and the bed-separated fracture zone appears on the basic roof. The soft surrounding rock above the support and in front of the coal wall forms an advanced crack zone in the roof; its height is 2.9 m, and its length is 1.5 m.

When the working face advances to 70 m, the overlying rock above the goaf exhibits a wide range of transverse separation fissures and T-slip phenomena, and the height of the water-conducting fracture zone grows to 42 m. The range of the advanced fracture slip zone in the overburden in front of the coal wall is 24 m high and 12.5 m long, and the crack opening start is approximately 0.05 m.

When the working face advances to 100 m, a large area of overburden subsidence occurs. The vertical height of the water-conducting fractured zone is 64.3 m, and the fissures in the lead section extend forward and upward to 26.9 m and 17.8 m, respectively. The start of the opening of the fractures is approximately 0.15 m. The bidirectional fissures gradually form a fracture network, which runs through the overlying aquifer and the sand source layer, forming the risk of sand inrushing disaster.

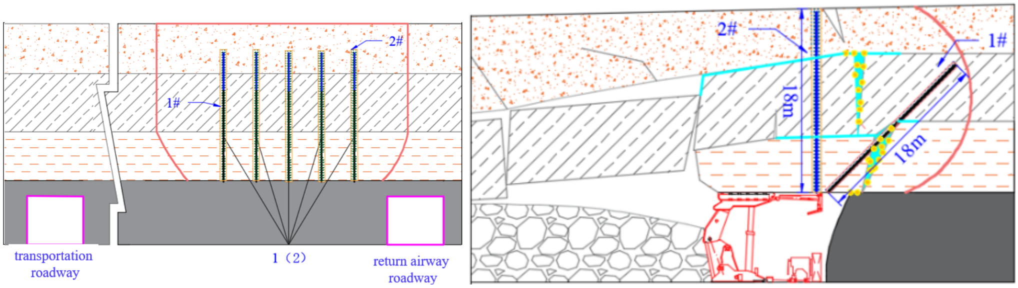
5. Field sand inrushing accident prevention and control technology

According to the occurrence history and numerical simulation of sand inrushing disasters, longitudinal cracks in the overburden between the coal wall and support are the main pathway of sand collapse. Sealing the longitudinal channel of sand collapse should be regarded as the key to effectively preventing and controlling sand collapse accidents. In addition, adjusting the scattering space of the water-sand mixture is an auxiliary prevention and control method. The construction technologies such as reasonable control of mining height and accelerating the advancing speed of the working face are proposed, which have achieved good results in field applications.

5.1. Blocking sand channels

(1) Working face vertical borehole grouting sealing

According to the numerical simulation, the overburden fissures are mainly concentrated in the coal-rock mass in front of the support-coal wall. The flow of a loose sand body in the fissure can easily cause the passage to expand, so the borehole grouting method can be used to block the broken sand passage. An advanced drilling hole (No. 1# in the figure) is arranged in the roof in front of the working face, with a hole depth of 18 m and an angle of 45° with the coal seam. A low viscosity, two-component synthetic polymer-polyamine gum lipid material (Marisan) is injected into the fractured surrounding rock mass. This can be expanded by water during high-pressure perfusion and extended along the cracks to achieve a filling effect, as shown in Fig. 10. Between the supports, vertical boreholes (#2) are arranged in the roof with a hole depth of 18 m to consolidate the loose rock mass of the roof. SJB60-8 mine explosion-proof grouting pump is used in this paper. The main parameters of the pump are shown in Table 2. To ensure that the grouting can fill the fractures tightly, in principle, it should be injected to a full capacity.



(a) main view (b) side view

Fig. 10. Injection into the working face

TABLE 2

Main parameters of the SJB60-8 mine explosion-proof grouting pump

Parameter	Rated flow	Rated pressure	Cylinder diameter	Inner diameter of suction pipe
	3.6 m^3/h	8 MPa	80 mm	51 mm
Parameter	Motor power	Sound pressure level	Input speed	Inner diameter of discharge pipe
	7.5 KW	110 dB(A)	1440 r/min	32 mm
Parameter	Plunger stroke	Water absorption height	Weight	Dimension (length × wide × High)
	73 mm	2 m	180 Kg	1600×600×80 mm

(2) Lateral hole grouting plugging of roadway

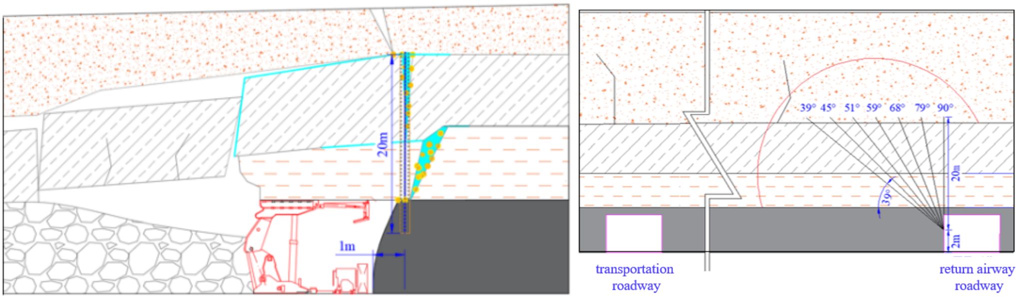
Lateral borehole grouting in roadways is a supplement to borehole grouting of the working face roof, which can be interwoven to improve the plugging effect of crack channels in the overburdened rock.

In the critical return air roadway in the sand collapse area of the working face, grouting holes were arranged from the side with solid coal to the potential sand collapse area. A total of seven holes were designed, with depths of 20, 22.5, 23, 24, 25, 26, and 27 m. The inclination angles in the horizontal direction were 90°, 79°, 68°, 59°, 51°, 45°, and 39°. The drilling and injection methods for the tunnel are shown in Fig. 11. The above two methods are difficult to be reflected in the numerical simulation due to the difficulty of simulating grouting, but the above methods have played a good control role in the field.

5.2. Improve the scattered space of the water-sand mixture

(1) Reasonable control of mining height

A large mining height leads to the development of overburden fractures, which easily cause leakage of soft roofs [11]. Therefore, appropriately lowering the mining height can reduce the space available for deformation of the overburden, which is conducive to the formation of a stable



(a) main view (b) side view

Fig. 11. Injection into the roadway

basic roof structure, thus reducing the failure range of the overburden and weakening the degree of fracture connectivity of the overburden. The strength of false mudstone roofs and medium and fine sandstone immediate roofs at the 8101 working face is low, while the relative strength and toughness of the coal seam are high. Therefore, industrial experience retention of 0.5~1.0 m of supporting coal is conducive to control of the stability of the roof.

(2) Optimise the advancing speed

By accelerating the advancing speed of the working face, the overburden subsidence is minimised, and the degree of development of the water-flowing fracture zone is controlled [38]. The longitudinal fractures in the overburden of the working face quickly enter the stage of "crack closure and recompaction", which is beneficial to redirect the water flow into the goaf. This reduces the degree of expansion of the water flowing in the overburden and controls the degree of connection of the longitudinal fractures to avoid the loose sand body entering the mining space via water flow through fissure passages. The field observations show that the range and amount of water on the working face increase greatly during the most frequent downtime periods in the production and overhaul. However, when the working face advances rapidly (the average coal cutting speed is 7.0 m/min), the water pouring onto the working face decreases obviously, which effectively prevents the overburdened rock from breaking down into the sand.

6. Conclusions

Based on the engineering analysis of overburden sand collapse accidents in shallow coal seam mining, four main controlling factors affecting the incidence of sand collapse disasters are proposed: the source of sand collapse, crack channel, dominant force, and scattered space. The occurrence history of mining-induced overburden sand collapse disasters (SCPSs) was constructed, and it was apparent that overburden sand collapse disasters were significantly affected by mining activities. Sand collapse via the longitudinal channels in the overburden occurred. The scattering space of water and sand mixed particles was sufficient.

UDEC simulation was used to analyse the migration and fracture distribution characteristics of the mining-induced overburden. The results showed that the earliest mining-induced fracture was located in the overburden above the goaf due to the tensile stress, and the development height was 18 m. The cumulative mining action in the overburden in front of the coal wall formed a leading crack zone (H 2.9 m, W 1.5 m) in the roof. As the working face continues to advance, the growth rates of H and W are 87.9% and 88%, respectively, and the water-conducting fracture zone in the overburden increases from 32 m to 42 m. Finally, the lateral and vertical cracks in front of the coal wall are connected and developed to 64.3 m (aquifer), and the opening of both initial cracks expands. The longitudinal fracture of the overburden formed between the coal wall and support is the main channel for the sand body to collapse into the mining space.

Considering the geological conditions conducive to the shallow coal seams with soft surroundings, a comprehensive prevention and control technology is proposed. This involves grouting to block the sand collapse channel and supplemented by reasonable control of mining height and appropriately accelerating the advancing speed of the working face to reduce the damage and expansion of the sand collapse channel and limit the scattering space of the sand-inrushing disaster.

Data availability statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declared that they have no conflicts of interest in this work.

References

[1] Q.X. Huang, Ground pressure behavior and definition of shallow seams. Chinese Journal of Rock Mechanics and Engineering **21** (8), 1174-1177 (2002). DOI: https://doi.org/10.3321/j.issn:1000-6915.2002.08.014.

[2] W.G. Du, J. Chai, D.D. Zhang, W.L. Lei, The study of water-resistant key strata stability detected by optic fiber sensing in shallow-buried coal seam. International Journal of Rock Mechanics and Mining Sciences **141** (6), 1-9 (2021). DOI: https://doi.org/10.1016/j.ijrmms.2020.104604.

[3] A. Kowalski, J. Białek, T. Rutkowski, Caulking of goafs formed by cave-in mining and its impact on surface subsidence in hard coal mines. Archives of Mining Sciences **66** (1), 85-100 (2021). DOI: https://doi.org/10.24425/ams.2021.136694

[4] Y. Jiang, R. Misa, K. Tajduś, A. Sroka, Y. Jiang, A new prediction model of surface subsidence with Cauchy distribution in the coal mine of thick topsoil condition. Archives of Mining Sciences **65** (1), 147-158 (2020). DOI: https://doi.org/10.24425/ams.2020.132712

[5] W.F. Yang, L. Jin, X.Q. Zang, Simulation test on mixed water and sand inrush disaster induced by mining under the thin bedrock. Journal of Loss Prevention in the Process Industries **57**, 1-6 (2018). DOI: https://doi.org/10.1016/j.jlp.2018.11.007

[6] W.H. Sui, G.T. Cai, Q.H. Dong, Experimental research on critical percolation gradient of quicksand across overburden fissures due to coal mining near unconsolidated soil layers. Chinese Journal of Rock Mechanics and Engineering **26** (10), 2084-2091 (2007). DOI: https://doi.org/10.3321/j.issn:1000-6915.2007.10.018

[7] Z.L. Yang, X.Y. Yu, H.M. Guo, Study on catastrophe mechanism for roof strata in shallow seam longwall mining. Chinese Journal of Geotechnical Engineering **29** (12), 1763-1766 (2007). DOI: https://doi.org/10.1016/S1872-2067(07)60020-5

[8] Y. Chen, G.Y. Zhao, S.F. Wang, A case study on the height of a water-flow fracture zone above undersea mining: sanshandao gold Mine, China. Environmental Erath Sciences **78** (4), 122-132 (2019). DOI: https://doi.org/10.1007/s12665-019-8121-7

[9] W.Q. Zhang, Z.Y. Wang, X.X. Zhu, A risk assessment of a water-sand inrush during coal mining under a loose aquifer based on a factor analysis and the fisher model. Journal of Hydrologic Engineering **25** (8), 1-12 (2021). DOI: https://doi.org/10.1061/(ASCE)HE.1943-5584.0001936

[10] J. Wu, C. Jia, L.W. Zhang, Expansion of water inrush channel by water erosion and seepage force. International Journal of Geomechanics **21** (7), 1-12 (2021). DOI: https://doi.org/10.1061/(ASCE)GM.1943-5622.0001985

[11] F.T. Wang, S.H. Tu, C. Zhang, Evolution mechanism of water-flowing zones and control technology for longwall mining in shallow coal seams beneath gully topography. Environmental Earth Sciences **75** (19), 1-16 (2016). DOI: https://doi.org/10.1007/s12665-016-6121-4

[12] X.G. Lian, H.F. Hu, T, Li, D.S. Hu. Main geological and mining factors affecting ground cracks induced by underground coal mining in Shanxi Province, China. Int. J. Coal Sci. Technol. **7** (2), 362-370 (2020). DOI: https://doi.org/10.1007/s40789-020-00308-1

[13] L. Li, F.M. Li, Y. Zhang, D.M. Yang, X. Liu. Formation mechanism and height calculation of the caved zone and water-conducting fracture zone in solid backfill mining. Int. J. Coal Sci. Technol. **7** (1), 208-215. (2020). DOI: https://doi.org/10.1007/s40789-020-00300-9

[14] X. Yang, Y.J. Liu, M. Xue, Experimental investigation of water-sand mixed fluid initiation and migration in porous skeleton during water and sand inrush. Geofluids **2020** (12), 1-18 (2020). DOI: https://doi.org/10.1155/2020/8679861

[15] J. Xu, H. Pu, J. Chen, Experimental study on sand inrush hazard of water-sand two-phase flow in broken rock mass. Geofluids **2021** (3), 1-9 (2021). DOI: https://doi.org/10.1155/2021/5542440

[16] Z. Yu, S. Zhu, Y. Guan, Feasibility of modifying coal pillars to prevent sand flow under a thick loose layer of sediment and thin bedrock. Mine Water and the Environment **38** (4), 817-826 (2019). DOI: https://doi.org/10.1007/s10230-019-00622-4

[17] C. Zhang, Y. Zhao, P. Han, Q. Bai. Coal pillar failure analysis and instability evaluation methods: A short review and prospect. Engineering Failure Analysis **138**, 106344 (2022). DOI: https://doi.org/10.1016/j.engfailanal 106344

[18] J.L. Shao, Q. Zhang, X.T. Wu, Investigation on the water flow evolution in a filled fracture under seepage-induced erosion. Water **12** (11), 1-18 (2020). DOI: https://doi.org/10.3390/w12113188

[19] Y.C. Wang, F. Geng, S.Q. Yang, Numerical simulation of particle migration from crushed sandstones during groundwater inrush. Journal of Hazardous Materials **362** (15), 327-335 (2019). DOI: https://doi.org/10.1016/j.jhazmat.2018.09.011

[20] G.B. Zhang, W.Q. Zhang, H.L. Wang, Research on arch model and numerical simulation of critical water and sand inrush in coal mine near unconsolidated layers. Geofluids **2020** (8), 1-12 (2020). DOI: https://doi.org/10.1155/2020/6644849

[21] X. He, Y.X. Zhao, C. Zhang, P.H. Han, A model to estimate the height of the water-conducting fracture zone for longwall panels in western China. Mine Water and the Environment **39** (4), 1-16 (2020). DOI: https://doi.org/10.1007/s10230-020-00726-2

[22] B.Y. Zhang, Q.Y. He, Z.B. Lin, Z.H. Li, Experimental study on the flow behaviour of water-sand mixtures in fractured rock specimens. International Journal of Mining Science and Technology **31** (3), 377-385 (2021). DOI: https://doi.org/10.1016/j.ijmst.2020.09.001

[23] C. Zhang, Y. Zhao, Q. Bai. 3D DEM method for compaction and breakage characteristics simulation of broken rock mass in goaf. Acta Geotechnica 1-17, (2022). DOI: https://doi.org/10.1007/s11440-021-01379-3

[24] B. Chen, S.C. Zhang, Y.Y. Li, J.P. Li, Experimental study on water and sand inrush of mining cracks in loose layers with different clay contents. Bulletin of Engineering Geology and the Environment **80** (1), 663-678 (2021). DOI: https://doi.org/10.1007/s10064-020-01941-5

[25] Q. Liu, B. Liu, Experiment study of the failure mechanism and evolution characteristics of water-sand inrush geo-hazard. Applied Sciences **10** (10), 1-18 (2020). DOI: https://doi.org/10.3390/app10103374

[26] G.M. Zhang, K. Zhang, L.J. Wang, Y. Wu, Mechanism of water inrush and quicksand movement induced by a borehole and measures for prevention and remediation. Bulletin of Engineering Geology and the Environment **74** (4), 1395-1405 (2015). DOI: https://doi.org/10.1007/s10064-014-0714-5

[27] L. Shi, Numerical simulation study on law of water and sand inrush in working face under condition of weakly cemented stratum. Coal Science and Technology **48** (07), 347-353 (2020). DOI: https://doi.org/10.13199/j.cnki.cst.2020.07.039

[28] Q.D. Zeng, J. Yao, J. Shao. Numerical study of hydraulic fracture propagation accounting for rock anisotropy. Journal of Petroleum Science & Engineering **160**, 422-432 (2018). DOI: https://doi.org/10.1016/j.petrol.2017.10.037

[29] D.P. Do, N.H. Tran, D. Hoxha, H.L. Dang, Assessment of the influence of hydraulic and mechanical anisotropy on the fracture initiation pressure in permeable rocks using a complex potential approach [J]. International Journal of Rock Mechanics & Mining Sciences **100**, 108-123 (2017). DOI: https://doi.org/10.1016/j.ijrmms.2017.10.020

[30] L.J. Dong, Q.C. Hu, X.J. Tong, Velocity-Free MS/AE Source Location Method for Three-Dimensional Hole-Containing Structures. Engineering **6** (7), 827-834 (2020). DOI: https://doi.org/10.1016/j.eng.2019.12.016

[31] Y.B. Zhang, X.L. Yao, P. Liang. Fracture evolution and localization effect of damage in rock based on wave velocity imaging technology. Journal of Central South University **28** (9), 2752-2769 (2021). DOI: https://doi.org/10.1007/s11771-021-4806-7

[32] L.J. Dong, Q.C. Hu, X.J. Tong, Empty region identification method and experimental verification for the two-dimensional complex structure. International Journal of Rock Mechanics and Mining Sciences **147**, 104885 (2021). DOI: https://doi.org/10.1016/j.ijrmms.2021.104885

[33] L.J. Dong, X.J. Tong, J. Ma, Quantitative investigation of tomographic effects in abnormal regions of complex structures. Engineering **7** (7), 1011-1022 (2021). DOI: https://doi.org/10.1016/j.eng.2020.06.021

[34] Y.F. Ren, Z.J. Li, Journal of China Coal Society, Experimental study on time series character of roof cutting in shallow working face **44** (S2), 399-409 (2019). DOI: https://doi.org/10.13225/j.cnki.jccs.2019.1125

[35] Y.P. Wu, M.S. Lu, Analysis on the occurrence condition of sand burst in shallow buried stope. Mining Pressure and Roof Management **20** (3), 57-58 (2004). DOI: https://doi.org/10.3969/j.issn.1673-3363.2004.03.021

[36] H.S. Jia, N.J. Ma, X.D. Zhao, "Open-close" law of longitudinal transfixion cracks in shallow buried coal face with thin bedrock. Journal of China Coal Society **40** (12), 2787-2793 (2015). DOI: https://doi.org/10.13225/j.cnki.jccs.2015.0065

[37] H.J.G. Diersch, O. Kolditz. Variable-density flow and transport in porous media: approaches and challenges. Adv. Water Resour. **25** (8), 899-944 (2002). DOI: 10.1016/S0309-1708(02)00063-5

[38] X. He, C. Zhang, P. Han. Overburden damage degree-based optimization of high-intensity mining parameters and engineering practices in China's western mining area. Geofluids 2020, 8889663 (2020).