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ORIGINAL PAPER

Mechanism of water inrush and quicksand movement induced by a borehole and measures for prevention and remediation

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Abstract In coal mining, a poorly sealed borehole is one of the channels that can lead to an inrush of water and quicksand movement, seriously compromising the safety of the coal mine. In this paper, we used the water inrush and quicksand incident at Longde Coal Mine as an example in order to investigate the mechanism of water inrush and quicksand movement induced by a borehole, as well as to develop measures for the prevention and remediation of such problems. Two sand funnel models and a water inrush outlet model are introduced from which to calculate the flow of the water and quicksand; a comparison of the two shows that the flow predicted by the water inrush outlet model is more consistent with observations from the accident than the sand funnel models. Based on the water inrush outlet model, the aquifer thickness and borehole diameter are the two key factors affecting the flow. The aquifer channel is inferred as tubular, with its diameter gradually decreasing from ground surface to underground, and a time-dependent surface subsidence model is constructed. Finally, we develop a prevention method, "Prior to mining development, borehole should be investigated and plugged for prevention," and propose a remediation method, "Changing the pipeline flow into fracture flow, followed by changing the fracture flow into pore flow, and finally grouting and plugging."

Keywords Borehole · Water inrush and quicksand movement · Prevention or remediation · Sand funnel · Water inrush outlet

Introduction

On November 17, 2012, a disaster involving an inrush of water and quicksand occurred at Longde Coal Mine during the drilling of a borehole towards the mine. The water and quicksand movement resulted in the collapse of a large area above the mine, burying much of the underground equipment and many vehicles. Fortunately, there were no casualties, but the economic loss was huge. The location of the accident was 100 m from the air shaft. At the time, a borehole 18 cm in diameter was being drilled from the ground surface underground for the supply of power. During the drilling, no protective casing was used. Because the predicted depth did not match the actual drilling depth, which was not as deep as estimated, the mine roof was inadvertently penetrated. The incident happened at about 170 m below the surface. Given the presence of a thick aquifer, the flow of water and sand into the working face increased gradually, and after approximately five hours, had formed a valley about the size of a football field, as shown in Fig. 1. The deepest section of the newly formed valley was approximately 25 m below the original surface.

Assuming that the surface subsidence trough is like an inverted cone, with a depth of 25 m and a 45° slope angle, the total subsidence volume is approximately 16,350 m^3, and the average flow is 3,270 m^3/h. With a borehole only 18 cm in diameter, it is not conceivable that such a huge

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Fig. 1 Water and quicksand inrush disaster at Longde Coal Mine of China Huadian Corporation (Ifeng.net 2012)

flow could happen. Although there are some reports on water inrush and quicksand flows caused by poorly sealed boreholes (Pan and Ding 1999; Ge 2007; Xu 2012), studies on the mechanism and prevention measures of such failures are inadequate, as it is still not possible to accurately predict the type and scale of such disasters or to provide fast and effective remedial measures.

Accidents during coal mining involving an inrush of water and quicksand under an unconsolidated alluvium aquifer, which is caused by fracture channels in the roof, are a severe hazard, causing significant damage, large financial loss, and a large number of casualties each year (Bai and Elsworth 1990; Booth et al. 1998; Booth and Bertsch 1999; Zhang and Peng 2005; Huang et al. 2012; Yang et al. 2014; Chen et al. 2014). However, the conditions or mechanism of such a phenomenon are complex, and are thought to relate to factors including the scale and properties of the overlying aquifer, the mining method, thickness and strength of the overlying strata, and structural characteristics of the overlying strata (Miao et al. 2009, 2010; Bai and Miao 2009; Ding et al. 2014).

Because the underground mining of coal is hidden from view, field observations of factors influencing the water inrush and movement of quicksand are difficult and potentially unsafe. Therefore, scholars often utilize physical model testing in order to study the mechanism involved in the inrush of water and quicksand. For example, Tang et al. (1999) researched the mechanism of sandy silt seepage deformation in mines under conditions of forced vibration. In their paper, the authors discussed the factors relevant to seepage and evaluated the qualitative and quantitative relationships between these factors and seepage characteristics. Zhang et al. (2002) discovered that water inrush and quicksand movement in the weakly cemented fine quicksand layer deposited during the Tertiary and Jurassic Periods had characteristics of periodicity. Through various experiments on the ability of the rock contact surface to filter sand, Zhang et al. (2006a) concluded that sand inrush would not occur with a minimum rock contact surface height of 5.0 m. Sui and Dong (2008) deduced that pore water pressure could be an important precursor for monitoring and forecasting quicksand hazards in mines. Sui et al. (2007) concluded that the initial water level and width of fissures were key factors controlling the levels of quicksand movement into the working face of a mine. Yang et al. (2012) studied the movement of mixed water and sand flows across overburden fissures induced by mining in thin bedrock. Chen et al. (2014) assessed the influence of the fractures and excess pore water pressure in overlying strata on water and quicksand inrush at the Luling coal mine.

In addition to the above-referenced studies using model tests, several researchers have analyzed the mechanical characteristics of water and quicksand movement. For instance, based on the theory of ground dynamics, Zhang et al. (2006b) investigated critical hydraulic conditions related to seepage failure and estimated a formula for preventing an inrush of sand. Sui et al. (2008) analyzed stress conditions of sand particles during the process of water inrush and quicksand movement, and established a discrimination method for evaluating critical hydraulic gradients. Wu and Lu (2004) developed a mechanical model of sand pseudo-structure based on the laws of incipient sediment motion in order to study the forces acting on sand granules prior to an inrush, and proposed a theoretical formula of sand inrush generation conditions based on water height.

Despite the continuous efforts of many scientists, understanding the mechanism governing the inrush of water and quicksand that is characteristic in coal mining disasters remains a challenge for engineers. Thus far, they have been unable to accurately predict the type and scale of disaster or provide fast and effective remedial measures. In this paper, we use the incident at Longde Coal Mine as an example in order to investigate the mechanism involved in the inrush caused by a borehole, as well as steps for the prevention and remediation of such a phenomenon. We introduce two sand funnel models and a water inrush outlet model to study the flow characteristic, and we provide a discussion of the aquifer channel shape and surface time-dependent subsidence. Lastly, we propose corresponding prevention and remediation measures. This research will provide a significant theoretical and technological contribution with regard to safety and environmental protection in the area of coal mining.

Geological setting

Longde Coal Mine, with an annual output of 5 million tons, is owned by the Huadian Coal Industry Group Co., Ltd. The mine is located in the Maowusu Desert in Dabaodang Township of Shenmu County, China, between 38°43′57″N and 38°47′39″N latitude and between 109° 58′07″E and 110°03′05″E longitude. To the east of the Longde mine is the Heilonggou coal mine, to the south is the Dabaodang shaft area, to the west is the Xiaobaodang shaft area, and to the north is an area where no mining is planned. The total area of the Longde mine is 20.5 km^2, with a length of approximately 6.3–8.4 km and a width of approximately 2.4–3.1 km.

According to the geological report by Duan (2012), the total thickness of the overlying loose layer near the air shaft is about 67 m, including the Quaternary Holocene aeolian sand and the Late Pleistocene Salawusu formation sand and mudstone interbed. The strata below the overlying loose layer are, successively, the Middle Pleistocene Lishi Formation sandy mudstone, the Jurassic Zhiluo Formation strongly weathered rock, the Jurassic Zhiluo Formation weakly weathered rock, and the Jurassic Yan'an Formation unweathered bedrock, immediate roof, and coal. A stratum diagram of the Longde mine is shown in Fig. 2.

Hydrogeologic conditions of the main strata in the Longde mine are shown in Table 1. The underground water level is −21.6 m. The aquifer below the hydrostatic level includes, successively, the Holocene aeolian sand, 9.0 m; the Late Pleistocene Sarawusu Formation sand and mudstone interbed, 36.4 m; the Middle Pleistocene Lishi Formation sandy mudstone, 6.9 m; the Jurassic Zhiluo Formation strongly weathered rock, 16.5 m; and the Jurassic Zhiluo Formation weakly weathered rock, 20.2 m. The total thickness of the aquifer is about 88 m, and the deepest location extends to −110.6 m.

Flow calculation model for water inrush and quicksand

Analysis using the sand funnel model

Granular matter is one of the most common materials found on the earth. A system consisting of a large number of grains behaves quite differently from the well-investigated states of matter such as solids, fluids, and gases (Lu and Liu 2004). Granular matter refers to solid particles between 1 μm and 10^4 m in size, such as natural sand, soil, coal, ore, ice, and snow (Bao and Zhang 2003). Aeolian sands are one type of granular matter, and if we do not consider the influence of groundwater, the flow of the aeolian sands near the ground surface through the borehole into the working face is similar to the sands flowing through a three-dimensional funnel under gravity, as shown in Fig. 3.

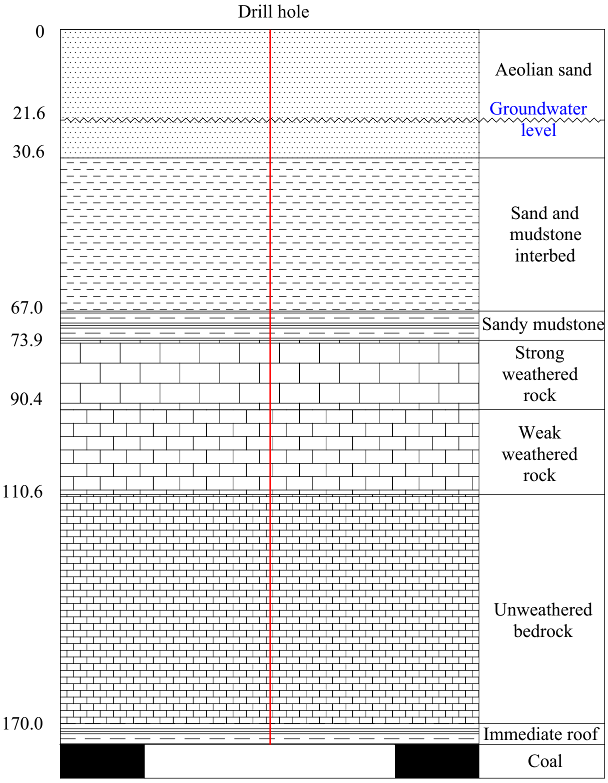


Fig. 2 Stratum diagram of Longde Coal Mine

Beverloo model

The empirical formula proposed by Beverloo et al. (1961) is the most widely used for the flow of a powder through a funnel. In this model, the flow W is dependent upon the diameter of the funnel orifice to the power of 2.5. The specific calculation formula is shown in Eq. (1). Le Pennec et al. (1995) later studied the effect of gravity on the flow of granular material in an hourglass, and their results showed that the Beverloo model was strictly effective at least for 13g, where g is the natural acceleration of gravity.

$$W = C\rho_{\mathrm{b}}\sqrt{g}(D - kd)^{2.5} \tag{1}$$

Table 1 Hydrogeologic conditions of the main strata in the Longde mine

Geologic time scale				Code	Strata	Water occurrence state	Permeability (m/d)
Erathem	System	Series	Formation				
Cenozoic	Quaternary	Holocene		Q_{4eol}	Aeolian sand	Pore phreatic water, laminar	18.3–860
		Late Pleistocene	Salawusu	Q_{3s}	Sand and mudstone interbed	Pore phreatic water, laminar	8.1–17.6
		Middle Pleistocene	Lishi	Q_{2l}	Sandy mudstone	Pore phreatic water, laminar	0.03–3.6
Mesozoic	Jurassic	Middle Jurassic	Zhiluo	J_{2z}	Strong weathered rock and Weak weathered rock	Fissure phreatic water, laminar and turbulent coexist	0.16–5.3
			Yan'an	J_{2y}	Unweathered bedrock, Immediate roof and Coal	Fissure water, laminar and turbulent coexist	0.032–0.1

Fig. 3 Flow of sand flow through a three-dimensional funnel

where W represents the average mass flow through the orifice, kg/s; C is an empirical constant associated with the geometry of the hopper or silo, which depends on the friction coefficient and can be set equal to 0.55; k is an empirical constant independently associated with particle shape—generally, k is approximately 1.5 for spherical particles but will be larger for particles with edges and corners; ρ_b is the apparent density, kg/m^3; g is the acceleration of gravity, m/s^2; D is the diameter of the orifice, m; and d is the average diameter of the powder particles, m.

Equation (1) can be obtained using dimensional analysis and can be physically explained if it is assumed that the granular flow is driven by the behavior of grains or particles near the orifice (Mankoc et al. 2007). Following this line of reasoning, the belief is that just above the orifice, there is a free-fall zone limited by an arch. Above the arch, the grains are well-packed, and their velocities are negligible, whereas below the arch the particles accelerate freely under the influence of gravity. If the characteristic size of this arch is somehow proportional to the radius of the orifice, the velocity of the grains through the orifice corresponds to a particle falling without initial velocity from a distance proportional to the radius of the orifice. A primary consequence of this assumption drawn by Mankoc et al. (2007) is that (1) the particle's velocity is proportional to 1.5 times the diameter of the orifice, and (2) the flow W depends on the orifice diameter to the power of 2.5. Cheng (2012) concluded that the physical essence of flow following the Beverloo model was that the pressure in the particle arch remained constant.

We can deduce From Eq. (1) that the volume flow formula can be obtained as Eq. (2)

$$q = C\sqrt{g}(D - kd)^{2.5} \tag{2}$$

where q represents the average volume flow through the orifice, m^3/s.

According to the conditions mentioned above, the parameters $C = 0.55$, $k = 2$, $d = 0.2$ mm, and $D = 180$ mm are substituted in Eq. (2), and we then obtain the maximum volume flow $q = 0.024$ m^3/s $= 86.4$ m^3/h. Unfortunately, the flow calculated with the Beverloo model is far lower than the value inferred from the accident, and thus the Beverloo model cannot accurately explain the water and quicksand inrush at Longde Coal Mine.

Tsubanov model

Tsubanov and Antonishin (1968) developed a flow formula for the powder passing through a flat funnel. They verified that the influence of the repose angle was not as important on the flow of the powder through a funnel with a flat bottom: the flow does not depend on the angle of repose. The mass flow is simplified as

$$G = \frac{2.15}{1 + 11.8\frac{d}{D}} g\rho_b D^{2.5} \tag{3}$$

where G is the mass flow of the granular material through the funnel orifice in unit time, kg/s; D is the diameter of the orifice, m; d is the diameter of the powder particles, m; g is the acceleration of gravity, m/s^2; and ρ_b is the apparent density, kg/m^3.

We can deduce from Eq. (3) that the volume flow rate formula can be obtained as Eq. (4)

$$q = \frac{2.15}{1 + 11.8\frac{d}{D}} g D^{2.5} \tag{4}$$

The application scope of the Tsubanov model is as follows: $7 < D/d < 300$; the powder diameter $d > 0.15$ mm; the funnel angle $\alpha < 60$ %; $D_c/D > 3$, where D_c is the diameter of the funnel passageway.

The parameters $d = 0.2$ mm and $D = 180$ mm are substituted in Eq. (4), and the maximum volume flow is obtained as $q = 0.29$ m^3/s $= 1{,}044$ m^3/h. However, the flow q is still smaller than that observed for the accident.

Based on the above analysis, neither the Beverloo model nor the Tsubanov model can accurately explain the huge flow of water and quicksand that occurred during the Longde mine accident. The reason may be that neither model considered the effect of the groundwater. If there is no action of groundwater, the remaining sand particles will still coalesce or adhere to each other, and will form a stable structure, according to Protodyakonov's arch effect theory, although some of the sand particles may fall successively, as shown in Fig. 4. If groundwater action is present, the water flows from the vertical and horizontal directions will break the equilibrium of Protodyakonov's arch, as shown in Fig. 5. This means that the flow of the water inrush and quicksand movement certainly will be higher than that of the sand through the funnel under the influence of the groundwater. Therefore, both the Beveloo and Tsubanov models fail to explain the huge flow of water and sand-bursting.

Fig. 4 Protodyakonov's arch phenomenon (Lu 2004) in sand without water

Analysis using the water inrush outlet model

The water inrush outlet model

When the ideal barotropic fluid flows steadily under the action of low potential volume force, the line integral of the motion equation along a streamline is the fluid mechanical energy conservation equation, which is well known as the Bernoulli equation (Chanson 2004; Mulley 2004; Oertel et al. 2010). For the uncompressed homogeneous fluid under gravity, the Bernoulli equation is as expressed as Eq. (5)

$$p + \frac{1}{2}\rho v^2 + \rho g h = c \tag{5}$$

where v is the fluid flow velocity at a point on a streamline, m/s; g is the acceleration due to gravity, m/s^2; h is the elevation of the point above a reference plane, with the positive z-direction pointing upward—so in a direction opposite the gravitational acceleration—n this case, h is the vertical height of the water (the aquifer thickness), m; p is the pressure at the chosen point, MPa; g is the acceleration of gravity, m/s^2; and c is constant.

Using the Bernoulli equation, a water inrush outlet model is proposed as shown in Fig. 6. The flow of the water through a circular hole can be obtained as Eq. (6)

$$q = A \cdot v = \frac{\pi D^2}{4} \cdot v = \pi r^2 \cdot v \tag{6}$$

where q is the flow, m^3/s; A is the cross-sectional area, m^2; and D and r are the diameter and radius of the outlet, respectively, m.

For the water and quicksand accident, the velocity of the fluid can be calculated as Eq. (7) under the assumption that (1) the crack (borehole) is at least linked to the underground water level, (2) the water does not have initial velocity, and (3) the influence of atmospheric pressure is not considered, namely $c = p + \frac{1}{2}\rho v^2 + \rho g h = 0$.

$$v = \sqrt{2gh} \tag{7}$$

If we substitute Eq. (7) into Eq. (6), then

$$q = \frac{\pi D^2}{4}\sqrt{2gh} \tag{8}$$

In Eq. (8), the flow q is directly proportional to the square root of the aquifer thickness h and the square of the borehole diameter D. It is thus clear that aquifer thickness h and borehole diameter D are the two primary factors influencing the flow of the water and quicksand inrush. Thus, three corresponding effective treatments for the quicksand and water inrush are (1) to reduce the aquifer thickness h, (2) to install a casing in the borehole, and (3) to grout and plug the borehole.

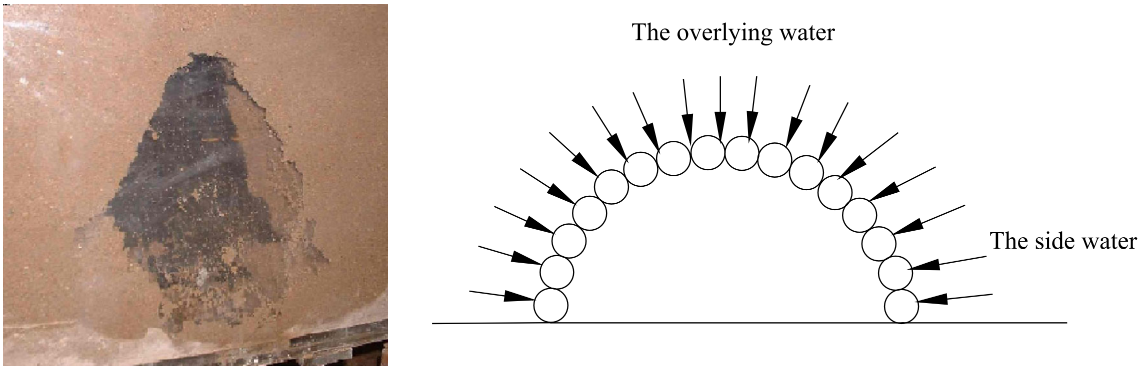


Fig. 5 Destruction of Protodyakonov's arch by water

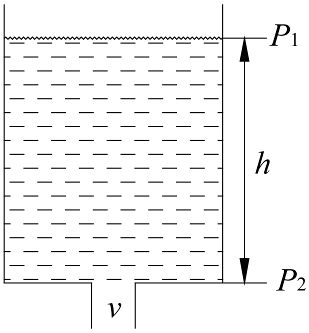


Fig. 6 Water inrush model

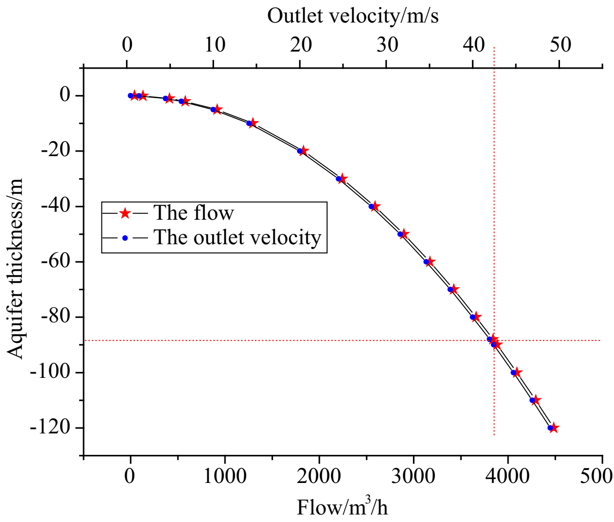


Fig. 7 Relationship between the flow of water and quicksand inrush and the outlet velocity and thickness of the aquifer

By substituting the diameter $D = 0.18$ m into Eq. (8), the flow of the water inrush and quicksand movement can be calculated as follows: if the aquifer thickness h is 110 m, the flow q will be 4,294 $\mathrm{m^3/h}$; if the aquifer thickness h is 88 m, the flow q will be 3,841 $\mathrm{m^3/h}$. Although the calculated value is larger than the inferred value of 3,270 $\mathrm{m^3/h}$, the value calculated by the water inrush outlet model is closer to the inferred value than that of the sand funnel model, especially when the aquifer thickness h is 88 m. This suggests that the water inrush outlet model can better explain the water inrush and quicksand accident at Longde Coal Mine.

The relationship between the flow of water and quicksand inrush and the outlet velocity and thickness of the aquifer is shown in Fig. 7. From this figure, the outlet velocity is 41.95 m/s when the aquifer thickness is 88 m, while the outlet velocity is 46.9 m/s with an aquifer thickness of 110 m. Therefore, a small hole can result in a large-scale accident and enhanced outlet velocity.

Generally, the flow of groundwater in the aquifer is governed by the seepage mechanics, and the flow and velocity are related to the permeability coefficient of the aquifer. However, the proposed water inrush outlet model is not based on seepage mechanics, but assumes that the particular mixture of water and sand is different from the liquid and particle fluid, and should be related to the liquefaction phenomenon of the aeolian sand.

Aeolian sand liquefaction

Traditionally, sandy soil liquefaction refers to the phenomenon whereby sandy soil below the water level exhibits characteristics of a liquid when it is subjected to a strong earthquake. Whether sandy soil is liquefied is related to its type and state. Liu et al. (1979) have provided a limit value of the characteristics index of sandy soil by combining domestic and international data:

1. The average particle size of the liquefiable sandy soil is in the range of 0.02–1 mm.
2. The uniformity coefficient of the sandy soil is not greater than 10.
3. The relative density of the sandy soil is not greater than 75 %.

4. The soil plasticity index of the sandy soil is less than 10.

The overburden layer of the Longde Coal Mine is thick aeolian sand (Duan 2012). Aeolian sand is the accumulation of sand blown by the wind (Li et al. 2006):

1. The main particle size is between 0.074 and 0.250 mm, which accounts for more than 90 % of the components.
2. Particles larger than 0.25 mm in size are rare and account for only 0.1 %, while the particles less than 0.074 mm account for less than 9 %.
3. The uniformity coefficient is approximately 1.35;
4. Because the aeolian sand consists primarily of medium- and fine-grained sand, and contains almost no clay or silt, it is loose (the relative density of the sandy soil is far lower than 75 %), and it is not plastic under natural conditions. In most cases, the plasticity index value of the aeolian sand is close to zero.

Based on the above analysis, aeolian sand meets all four necessary conditions of sand liquefaction. At the same time, coal mining may lead to a vibration failure in a mining area [referred to as a rockburst (Li et al. 2012)], which is similar to an earthquake and can result in sand liquefaction (Wang 2009). This demonstrates that the water inrush outlet model is rational and reasonable.

Despite the fact that the water inrush outlet model can satisfactorily explain the huge flow of water inrush and quicksand movement that occurred at Longde Coal Mine, the movement of the overlying strata and ground surface is still unclear, and this will be explained in the following section.

Analysis of channel shape and surface time-dependent subsidence

The channel of the water and quicksand inrush in the overlying strata is subdivided into three parts, including the sand basin, the channel with variable diameters D_{m}, and the intact borehole in the unweathered bedrock with constant diameter D. The locations of the three parts are shown in Fig. 8. In the figure, O indicates the origin of the ground surface above the borehole, A is the deepest location of the sand basin, B indicates the location at the interface between the unweathered bedrock and the weakly weathered bedrock, and F identifies the outlet of the borehole in the working face. Therefore, the sand basin is depicted from O to A, the channel with variable diameters D_{m} is depicted from A to B, and the intact borehole in the unweathered bedrock with constant diameter D is depicted from B to F. Because the unweathered bedrock is generally of high strength, we assume that the diameter of the borehole in the unweathered bedrock remains constant, and the following text then focuses on the channel in the aquifer and the sand basin on the ground surface.

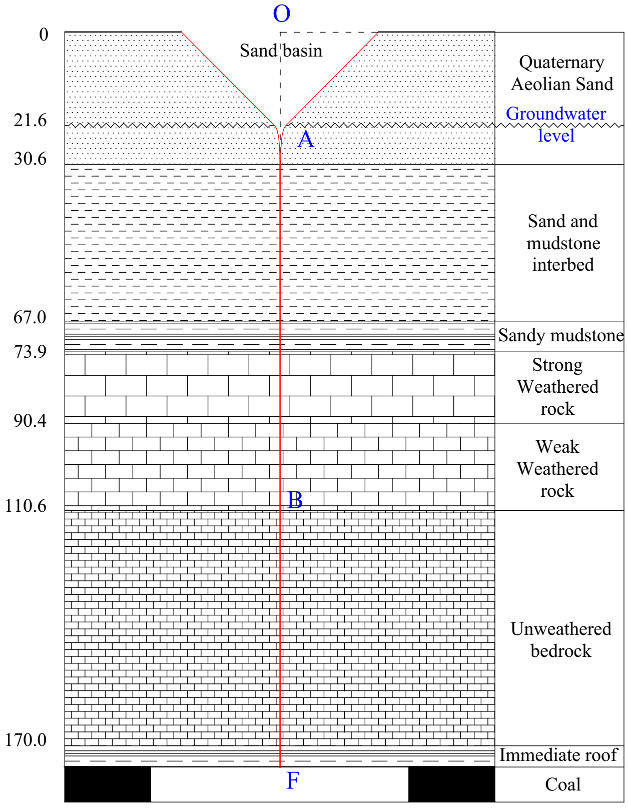


Fig. 8 Flow channel through the entire overlying strata

The flow channel in the aquifer

Assuming that the flow of water inrush and quicksand movement from A to B is like water being dropped from top to bottom, the flow will be constant at different cross-sectional levels. The deeper the location, the larger the velocity of the mixed flow will be, and the smaller the cross-sectional area of the mixed flow will be. We can conclude that the greater the distance of the mixed flow from location B in the bedrock, the larger its diameter will be. It can be inferred that the channel of the water and quicksand inrush in the aquifer is tubular, with its diameter gradually decreasing from the surface to the underground.

By transforming Eq. (8), the channel diameter D_{m} of the water inrush and quicksand movement can be obtained as Eq. (9):

$$D_{\mathrm{m}} = 2\sqrt{\frac{q}{\pi\sqrt{2gh}}} \tag{9}$$

Based on the inferred flow $q = 3{,}271\ \mathrm{m^3/h} = 0.9086\ \mathrm{m/s}$ in the Longde accident, the channel diameter and radius of the water and quicksand inrush, which changes with depth *h*, is shown in Table 2, and the channel shape with the depth is as shown in Fig. 9. The change in the radius with depth is very gradual (Fig. 9a) except in local regions near the groundwater level (Fig. 9b).

The sand basin on the ground surface

Because the sand near the ground surface does not contain water, it does not behave in the same manner as the mixed flow of water and sand. The surface sand particles should obey the law of dry sand and form a sand basin. Assuming that the surface subsidence area is an inverted cone and that the natural repose angle of the aeolian sand is θ, the angle between the time-dependent generatrix and the ground surface is then θ, as shown in Fig. 10. The total volume of the water and sand in the accident is equal to the volume of the inverted cone. Assuming that the flow of the water inrush and quicksand movement is constant, the corresponding relationship can be depicted as Eq. (10):

$$\frac{1}{3}\pi H^3(t)\cot^2\theta = qt \tag{10}$$

Combined with Eq. (8), the relationship between the basin depth $H(t)$ and time can be depicted as Eq. (11):

$$H(t) = \sqrt[3]{\frac{3D^2\sqrt{2gh}}{4\cot^2\theta}t} \tag{11}$$

The relationship between the radius of influence $R(t)$ of the sand basin and time can be depicted as Eq. (12):

$$R(t) = \sqrt[3]{\frac{3D^2\cot\theta\sqrt{2gh}}{4}t} \tag{12}$$

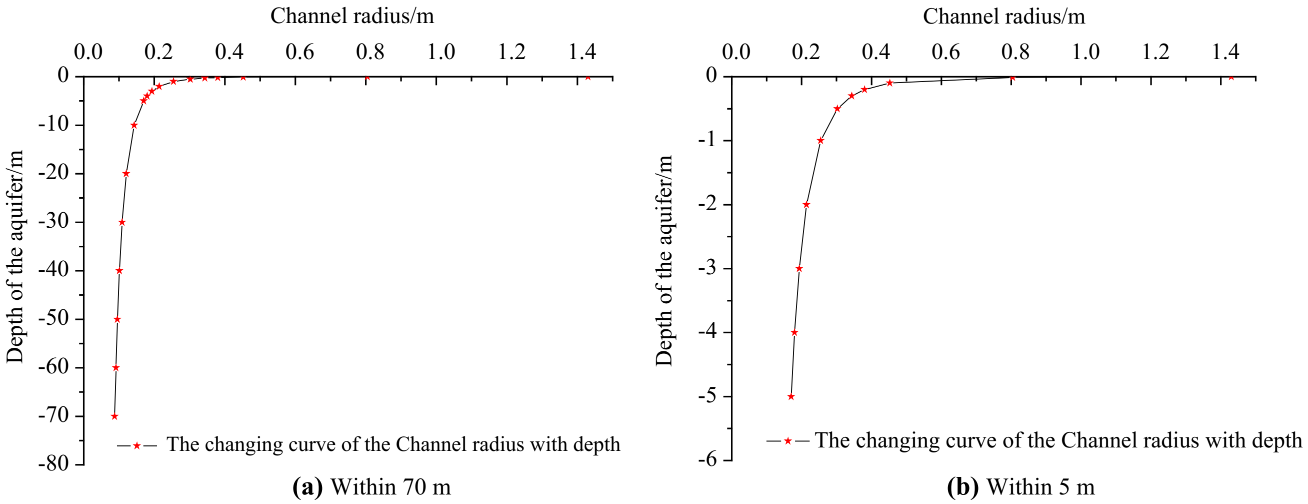
As shown in Eqs. (11) and (12), both the basin depth $H(t)$ and radius of influence $R(t)$ are proportional to the borehole diameter D to the power of 3/2, and the basin depth (the aquifer thickness h) to the power of 1/6. Assuming that the repose angle of the aeolian sand is 45°, the depth of the basin and the radius of influence of the surface subsidence over time are shown in Fig. 11. From this figure, the central subsidence value of the surface and the radius of influence increase over time, but the acceleration gradually decreases. When the accident happened, over a period of just 10 minutes the basin depth $H(t)$ reached 6.86 m and the radius of influence $R(t)$ was 9.45 m. This suggests that the initial zone of influence of the accident was very small but that it increased rapidly.

Table 2 Relationship between the channel diameter of the water inrush/quicksand movement and depth

Depth/m	Channel diameter/m	Channel radius/m
−0.001	2.860	1.430
−0.01	1.608	0.804
−0.1	0.904	0.452
−1	0.904	0.452
−5	0.340	0.170
−10	0.286	0.143
−20	0.241	0.120
−30	0.217	0.109
−40	0.202	0.101
−50	0.191	0.096
−60	0.183	0.091
−70	0.176	0.088

Prevention and remediation measures

As depicted in Eq. (8), the flow q is directly proportional to the square root of the aquifer thickness h but to the



(a) Within 70 m **(b)** Within 5 m

Fig. 9 Flow channel shape of the water inrush/quicksand movement with depth

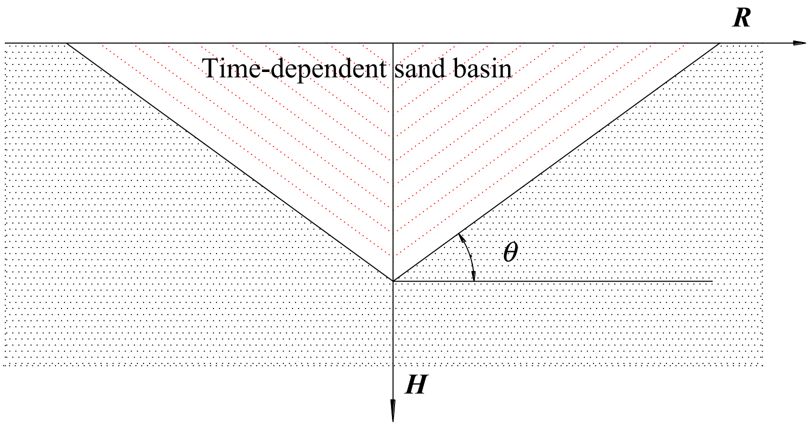


Fig. 10 Time-dependent sand basin on the ground surface

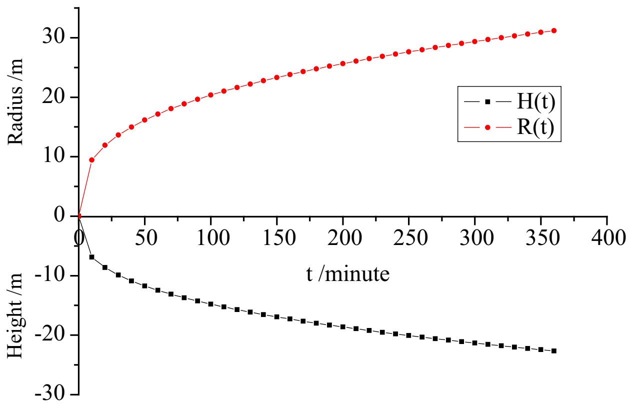


Fig. 11 Basin depth $H(t)$ and radius of influence $R(t)$ at the surface over time

square of the borehole diameter D. The aquifer thickness h and borehole diameter D are therefore the two primary factors affecting the flow of the water inrush and quicksand movement. Thus three effective treatments for the quicksand and water inrush can be recommended: (1) reducing the aquifer thickness h, (2) installing a casing in the borehole, and (3) grouting and plugging the borehole. However, it is not possible to reduce the aquifer thickness using drainage measures or to install a casing in the borehole within a reasonable length of time, as the method is costly and the technique is complex. Therefore, a reasonable measure is to reduce or plug the channel of the water and quicksand inrush, namely the borehole.

Prevention measures

We propose the prevention method, “Prior to mining development, borehole should be investigated and plugged for prevention.“ The specific measures include:

1. On the surface, any poorly sealed boreholes should be opened and then sealed perfectly.
2. For poorly sealed boreholes that cannot be opened, leave a coal pillar to avoid water inrush resulting from drilling.
3. For boreholes that are well-sealed, the hydrologic characteristics should be investigated using geophysical prospecting. Based on the exploration results, the relevant methodology should be adopted, as follows: if the strata are rich in water—namely, the overlying aquifers are saturated, and there are ample water resources that can supply sufficient water in the event that water inrush and quicksand movement occurs—the underground grouting and plugging should be adopted as a prevention and treatment method; if they are not rich in water, no further processing is needed.

Remediation measures

For mines that suffer from water inrush and quicksand accidents, neither the opening and sealing of the borehole nor the change of the coal pillar can be accomplished in a timely and convenient manner, as the poorly sealed boreholes are around the working face and may cause further hazards. At the same time, it is not possible to reduce the aquifer thickness using drainage measures in a limited amount of time. Therefore, a remediation method is proposed: “Firstly, change the pipeline flow into fracture flow; secondly, change the fracture flow into pore flow; finally, grout and plug.” The specific measures include:

1. First, change the pipeline flow into fracture flow. A huge quantity of large stones should be cast simultaneously into the sand funnel; the larger the size of the stones, the better the results will be. At a minimum, they must be larger than the diameter of the borehole.

Fig. 12 Remediation for the Longde mine accident (Yulin.hxfz.org 2012)

Conceptually, stones can achieve this purpose only if they large enough.

2. Second, change the fracture flow into pore flow. Medium-size stones or detritus should be cast successively into the sand funnel.
3. Finally, grout and plug with cement.

The accident at Longde Coal Mine was controlled successfully using the above-referenced method, as shown in Fig. 12, suggesting that these remediation measures are reasonable and feasible under the above-stated conditions.

Conclusions

The water inrush and quicksand movement that took place at Longde Coal Mine was used as an example to investigate the mechanism, prevention, and remediation of water and quicksand inrush induced by an open borehole. Two sand funnel models and a water inrush outlet model were introduced as methods to calculate the flow of the water and quicksand. The aquifer channel shape and the surface time-dependent subsidence were determined. Finally, prevention and remediation measures were proposed. The main conclusions are as follows:

1. Compared to that of the sand funnel model, the flow predicted by the water inrush outlet model is consistent with the inferred results of the Longde Coal Mine accident, suggesting that the model can better simulate or explain the mechanism of water inrush and quicksand movement. Based on the water inrush outlet model, the aquifer thickness and borehole diameter are the two key factors influencing the bursting flow.
2. The channel of the water and quicksand inrush in the aquifer is inferred as tubular, with its diameter gradually decreasing from the surface to underground. Based on the time-dependent surface subsidence model constructed, the central subsidence value of the surface sand inrush funnel and the radius of influence increased over time, but the acceleration gradually decreased.
3. We developed a prevention method, "Prior to mining development, boreholes should be investigated and plugged for prevention," and proposed a remediation method, "First, changing the pipeline flow into fracture flow, followed by changing the fracture flow into pore flow, and finally grouting and plugging."

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