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TECHNICAL COMMUNICATION

Mechanism and Remediation of Water and Sand Inrush Induced in an Inclined Shaft by Large-Tonnage Vehicles

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Abstract
In August 2016, multiple large-tonnage transport vehicles passed through the inclined shaft of the Jinjitian coal mine, Yulin, China, over a short period of time, resulting in fracturing of the floor, bearing capacity reduction, liquefaction of the underlying sand layer, and a serious water and sand inrush. The inrush and its sand content increased rapidly, with flows up to 72 m^3/h, with up to 16% sand. Fractures appeared in the walls of the shaft and nine subsidence pits formed on the ground surface. As the distance between the shaft roof and floor continued to shorten, the mine faced the risk of flooding. Four remedial measures were rapidly taken. First, where the roof and floor was seriously fractured, cribs were constructed to effectively stop the convergence of the roof and floor. Second, grouting was carried out on the periphery of the shaft sides to seal and block the inrush ducts, reducing the inrush by 52% and eliminating the sand content. Then, the cribs were replaced with arched steel supports for permanent support. Finally, the shaft wall behind the sand layer was reinforced with grout, which reduced the water inrush from 34.8 to 2.5 m^3/h. After adoption of these measures, the inclined shaft withstood the transport of large-tonnage coal-mining equipment for two work faces without an increase in water flow, floor fracturing, sand inrush, or other similar problems, indicating that the damaged shaft was well remediated. The measures taken provide a good reference for control of similar disasters.

Keywords Floor fracture · Ground subsidence · Crib · Grouting · U-shaped steel

Introduction

The shaft is often called the "throat" of a mine (Tu 2008; Zhang 2009, 2016). Water and sand inrushes in the mine shaft can seriously threaten the safety of the entire mine and can completely stop production. More than 10 coal mine shafts in China have experienced water and sand inrushes during the past 20 years (Fang and Tao 2014; Luan et al. 2000, 2001; Luan and Wang 2001; Ren 2014; Tao 2016; Wang et al. 2004; Xu 1983; Zhu 2006). The most serious of these have occurred in the sub-shafts of the Jinqiao and Liliadian mines.

On August 1999, a water and sand inrush occurred during grouting of the sub-shaft wall at a depth of 220 m in the Jinqiao coal mine, due to deviation of the grouting borehole position. Within 4 h, the mine was filled with about 50,000 m^3 of sand and water, resulting in a great economic loss. Later, the water and sand inrush was stopped by grouting (Luan et al. 2000, 2001; Luan and Wang 2001; Wang et al. 2004). On November 2013, a water and sand inrush occurred during grouting of the back wall at a depth of 272 m in the Liliangdian coal mine, with an initial inrush rate of about 20 m^3/h. Within 6 h, the inrush rate had increased to about 350 m^3/h, causing the sub-shaft wall and its surrounding surface to subside, which in turn damaged the sub-shaft and surface facilities, and caused high-speed trains 407 m away from the sub-shaft center (on the railway line from Beijing to Guangzhou) to decelerate from 310 to 120 km/h. The surface subsidence were effectively controlled using a temporary remedial measure that involved filling the shaft with a water and sand/gravel mixture. The accident caused a direct economic loss of 58.04 million

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Chinese yuan. The mine shaft has not yet been remediated (Ren 2014; Tao 2016).

In August 2016, a sub-shaft of the Jinjitian coal mine, in Yulin, Shaanxi Province, underwent a serious water and sand inrush disaster, with a maximum water inrush of 72 m^3/h containing up to 16% sand, and a maximum sand discharge per day of 276 m^3. Nine subsidence pits appeared above the mine. The water and sand inrush rapidly and continuously increased, and flooding of the entire mine was a distinct threat. In this paper, we describe the water and sand inrush that occurred there, analyze its mechanism, and describe the remediation process with the hope of providing a reference for preventing and managing similar disasters.

Water and Sand Inrush in the Sub-shaft of the Jinjitian Coal Mine

Sub-shaft Overview

The Jinjitian coal mine has an annual production capacity of 12 million metric tons (t) and its main mining seam is a ≈ 8.0 m thick Jurassic coal seam. The mine has the world record, with fully mechanized one-time mining of an 8.2 m thick coal seam (China Coal Network 2016). The mining machine components weigh up to 160 t, and the machine carrier weighs about 60 t.

The sub-shaft of the Jinjitian coal mine was completed and put into operation in July 2014. The first 60 m of the sand layer of the inclined shaft was constructed as an open trench, while the deeper (60–350 m) portion of the sand layer was developed using freezing. The sub-shaft had a 5° inclination. The cross section of the 60–350 m section was a straight, semi-circular arch, with a net width × net height of 6.0 m × 4.6 m (Fig. 1). Its roof and sides were supported using no.18 I-beam steel stands plus a hang net and 100 mm of shotcrete plus a single layer of 550 mm thick, reinforced C40 concrete. The floor was covered in turn with 500 mm of rubble mortar, 400 mm of single-layer reinforced concrete, and 300 mm of doubly reinforced C40 concrete. The continuous transportation of materials and equipment from the surface were realized using trackless rubber-tire vehicles. In addition, the sub-shaft was also used as an air inlet and safety exit.

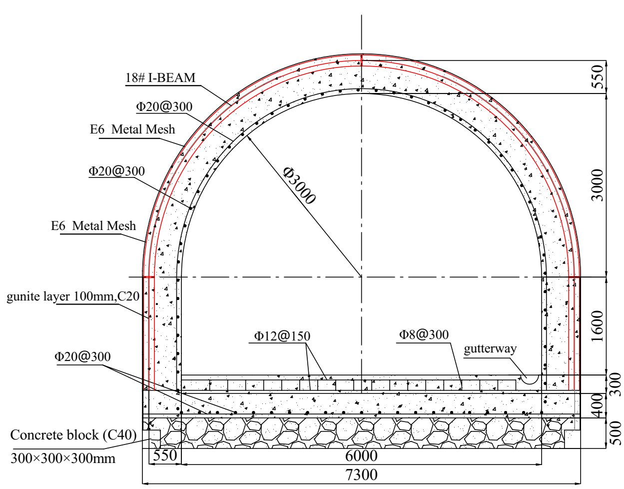

Fig. 1 Schematic of the 60–350 m section of the inclined subshaft

Water and Sand Inrush from the Inclined Subshaft

In the early August 2016, a water and sand inrush from the floor developed at the water trench along the 230–300 m section of the shaft as all of the coal-mining equipment was being transported to the working face. Both water inrush and the amount of sand increased over time (Fig. 2). Consequently, the floor developed cracks, the roof fractured, and a water–sand mixture flowed into the mine at rates up to 72 m^3/h, containing up to 16% sand and multiple fractures developed in the shaft wall. By August 17, nine subsidence pits, with a total volume of 650 m^3, had developed on the land surface above the 240–290 m section of the inclines shaft (Fig. 3) and the distance between the shaft roof and floor had decreased to 4.0 m.

The water and sand inrush sites were located over a wide area at multiple, dispersed sites, but mostly at floor water ditches and fractures. Field observations found that the 300 mm thick concrete bottom and 400 mm thick concrete top had separated, by as much as 50 mm at the ditch of the inclined floor.

Mechanism of Water and Sand Inrush from the Shaft

Water and sand inrush developed as multiple large-tonnage vehicles passed through the inclined subshaft in a short time. This suggests that the inrush was induced by the

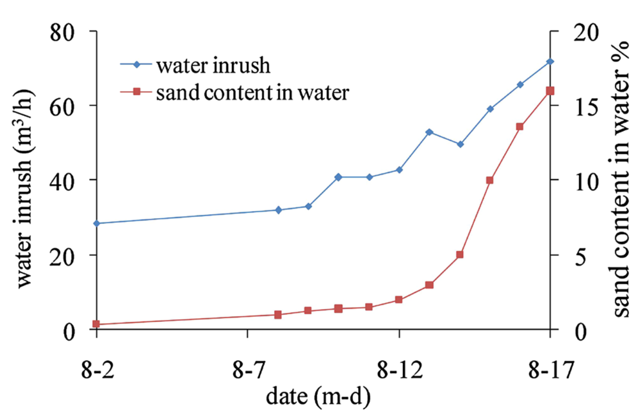

Fig. 2 Relationships of the measured water inrush and in-water sand-bearing volume to time in the inclined subshaft

Fig. 3 Site image of ground subsidence due to water and sand inrush from the inclined shaft

heavy vehicles, which apparently first caused the inclined floor to fracture, lowering its bearing capacity. As more vehicles passed through the shaft, the underlying sand floor began to lose stability; pore water pressure increased, causing the sand to layer to liquify. All of this led to sand-carrying groundwater to spurt first through the cracks in the floor, and then through the sides of the shaft and then the roof, eventually resulting in surface subsidence. Meanwhile, the cracks gradually widened, further increasing the amount of water and sand flowing into the mine. Figure 4 illustrates the mechanism.

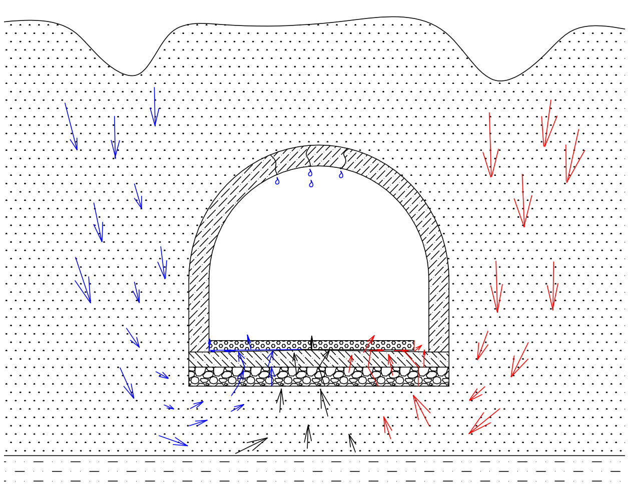

Fig. 4 Schematic of the mechanism of water and sand inrush from the inclined subshaft

Treatment of Water and Sand Inrush from the Inclined Subshaft

Overall Remediation Scheme

The overall remediation scheme involved internal support by wooden cribs plus grouting and flood-proof concrete wall casting. The cribbing was necessary to prevent wall collapse because the distance between the shaft roof and floor was decreasing, causing the shaft wall fractures to worsen. The wooden cribs were a temporary measure to reduce the rate of convergence. Grouting was initiated to seal and block the sites of water and sand inrush, which reduced the flow of water and eliminated the sand inrush. At the same time, a 12 m long concrete wall was prepared along the bedrock section of the shaft to prevent mine flooding.

Crib Construction

Pine timbers 300 mm wide and 300 mm thick were used to build cribs that were 2.5 m long and 2.5 m wide. The top of the stack were connected the roof of the shaft using wooden wedges (Fig. 5). Ten stacks were constructed on August 17–18, 2006 in the seriously fractured areas of the roof and floor, along the 220–300 m section. Figure 6 shows the measured closing distance of the shaft roof and floor over time at the 260 m section. The convergence of the shaft roof and floor obviously slowed down after completion of the cribbing, indicating that the stack provided good internal support.

Fig. 5 Image of the crib construction field

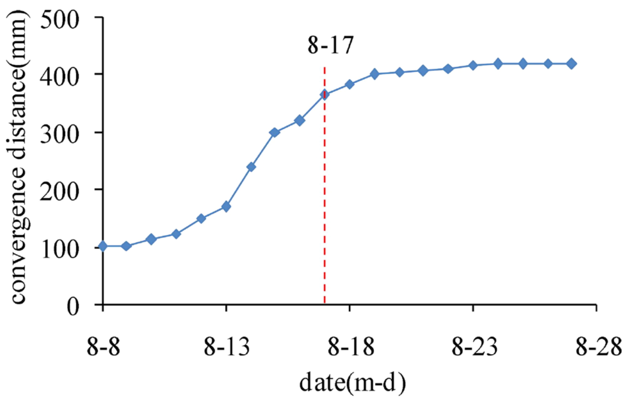

Fig. 6 Relationship of the measured convergence distance of roof and floor to time at 260 m of the inclined subshaft due to water and sand inrush

Grouting

Grouting in this study was done in two stages. First, a cement water glass (sodium metasilicate) slurry was injected into the floor on August 17. Then, a cement–water glass slurry and a urea formaldehyde resin slurry was injected into the sides of the inclined shaft from August 18 to 27.

The initial grouting was conducted into the shaft floor near the water and sand inrush sites, followed by the installation of orifice tubes deep into the 500 mm gravel and sand slurry layer. Because the grouting sites were very close to the water and sand inrush sites, the floor was seriously broken and had poor pressure-bearing capacity, resulting in a serious slurry return, obvious floor heave, poor sealing, and blocking of the water and sand inrush sites during grouting, along with newly-produced water and sand inrush sites near the grouting boreholes. Figure 7 shows a schematic of this grouting. During the 24 h of continuous grouting, a total of 20 grouting boreholes were drilled, consuming 36 t of cement and 12 t of water glass slurry. It soon became clear that water inrush and sand content had increased rather than being reduced, indicating that the floor grouting measure was not successful. In hindsight, this could have been predicted. In 2010, at the Yushujing coal mine, 180 km away from the Jinjitian mine, grouting of the floor to seal and block water and sand inrush sites in the main inclined shaft resulted in floor fractures, more water and sand inrush, and the shaft being made useless. Similarly, in 2014, at the Caojiatang coal mine, 15 km from the Jinjitian mine, grouting of the floor to block water inrush sites of its inclined shaft also led to increased floor fracturing and water flow.

Since the floor grouting method did not achieve the desired effect, a second grouting effort was initiated on August 18 at the sides of the inclined shaft in the 225–320 m section, with the boreholes 0.5 m away from the shaft floor and spaced every 2.0 m, with priority given to most severe water and sand inrush sites. Analysis of the water and sand inrush sites showed that water and sands coming through the floor originated from the sides and roof of the shaft. Thus, grouting through the wall into the sides of the shaft using instant hardening mortar could seal and block water and sand passageways. Figure 8 shows the schematic of grouting into the sides of the inclined shaft. A total of 194 grouting boreholes were drilled and a total of 700 t of cement, 180 t of water glass slurry, and 124 t of urea–formaldehyde resin slurry were consumed. Figure 9 shows how both the water inrush and the in-water sand content continuously decreased over time as a result. During the first day of grouting, water

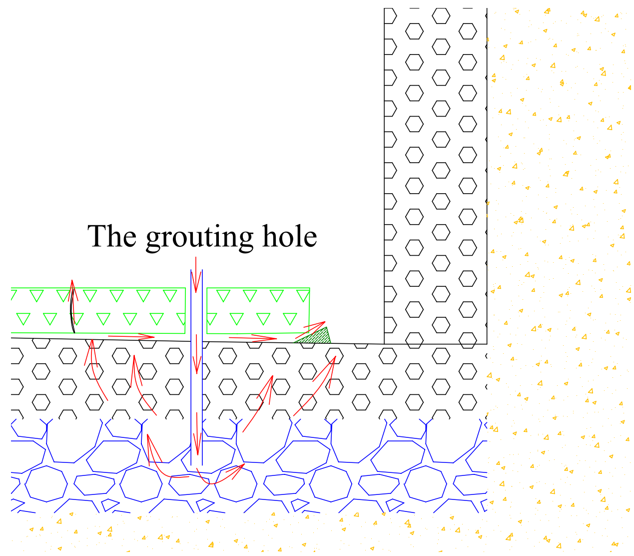

Fig. 7 Illustration of remediation of the inclined shaft floor

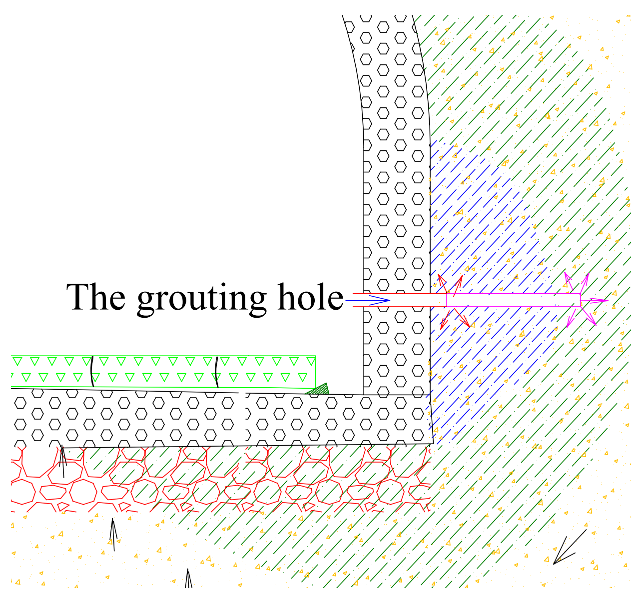

Fig. 8 Illustration of grouting the sides of the inclined shaft

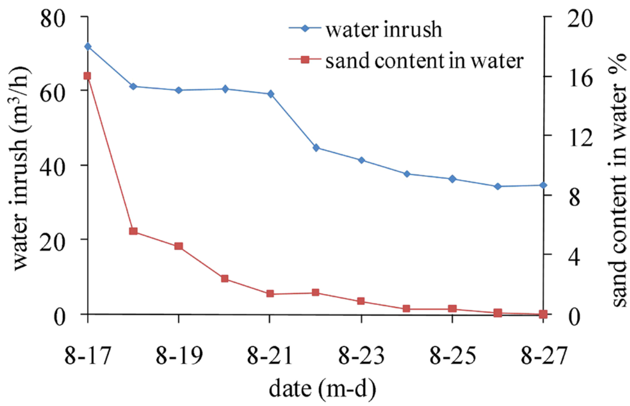

Fig. 9 Relationships of both water inrush and sand content to time in the inclined subshaft after side grouting

inrush was reduced by 10.5 m^3/h and the sand content fell from 16 to 5.6%. On August 27, the water inrush was 34.8 m^3/h, and the in-water sand content was undetectable. Because the grouting was so effective, construction of the concrete wall was not necessary.

Post-remediation Treatment

Permanent Reinforcement of U-Shaped Steel Supports

The wooden cribbing served as a temporary support and reinforcement. After the sand component of the inrush was stopped, 220 m long U-shaped steel supports, composed of leg, arch, and ground beams, were installed along the 130–350 m section of the shaft as a more permanent means of reinforcement. The leg and arch were made of no. 36 U-shaped steel with lengths of 4.0 and 5.2 m, respectively. The ground beam was made of no.12 U-shaped steel with length of 6.0 m. The U-shaped steel supports were emplaced every 0.7 m of roadway along the 130–240 m section and 300–350 m section of the subshaft, and every 0.5 m of roadway along the 240–300 m section. Figure 10 shows the in-field picture of the U-shaped steel supports after construction.

Grouting of Post-wall Sand Layer

The steel supports made it possible to safely seal and reinforce the floor in the 130–350 m section. Figure 11 shows the schematic of the post-wall sand layer grouting in this section. This phase of grouting work was finished January 2, 2017. A total of 572 boreholes were grouted in the construction section, consuming 3500 m^3 of cement–water glass slurry, 2265 t of cement, and 220 t of water glass

Fig. 10 Site image of the U-shaped steel supports after construction

slurry. Each borehole was grouted twice: first, when the drilling passed through the shaft wall and second, after the drilling had passed 2.0 m through the in-situ borehole into the post-wall sand layer, with the grouting pressure controlled within 1.0 MPa. No new shaft wall fractures were observed during or after grouting, and the water inrush volume dropped from the previous 34.8 to 2.5 m^3/h.

After grouting was completed, 14 detection boreholes were bored into the shaft walls and floor every 3 m along the grouted section and no sand inrush was observed. Furthermore, a borehole camera was used to videotape the interior of the boreholes. Figure 12 shows the hardened grayish vein-like cement slurry as well as the white vein-like urea–formaldehyde resin slurry.

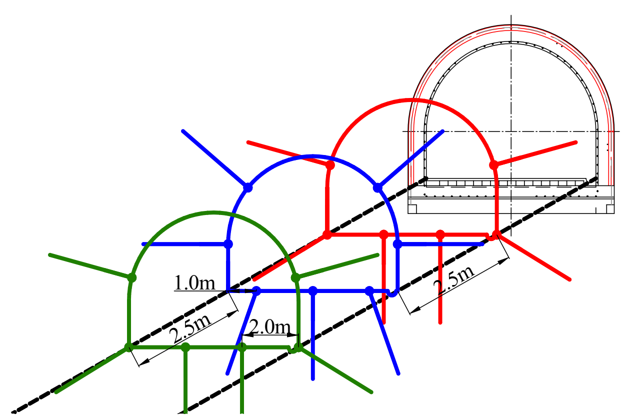

Fig. 11 Schematic of post-wall sand layer grouting hole

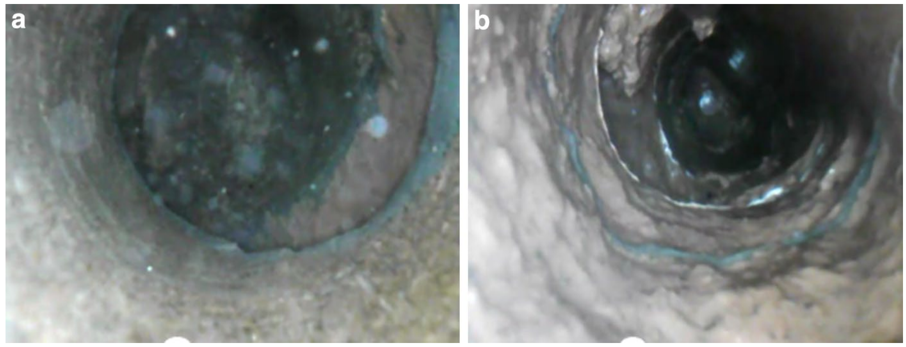

Fig. 12 Development of slurry veins at the shaft floor and wall at 240 m section of the shaft. **a** Image shot at the bottom of borehole into floor; **b** Image shot at the 2.5 m depth of borehole into the shaft wall

Post-remediation Vehicle Passage Through Inclined Shaft

After grouting reinforcement of the post-wall sand layer was completed, the mining equipment recovered from the mine's no. 123 face was transported through the remediated inclined subshaft to the ground for maintenance. Because it was the first use of the shaft for transportation of large tonnage equipment after the repair, the lighter weight equipment was transported before the heavy loads. Then, in April 15–25, 2017, the restored equipment was transported back through the shaft to re-equip working face 108. During both of these phases, personnel were dispatched along the repaired section of the shaft to watch for increased water inrush, floor fracturing, sand inrush, and other undesirable phenomena, and none were observed.

Summary and Conclusion

Serious water and sand inrush from the inclined subshaft of Jinjitian coal mine was caused by fracturing of the concrete floor and liquefaction of the underlying sand layer due to intensive passage of large tonnage vehicles through shaft in a short period of time. A mixture of sand and groundwater spurt out, widening the fractures and increasing in volume.

After an initial effort to seal the floor fractures with grout failed to solve the problem and in fact, appeared to worsen it, internal support with wooden cribbing combined with grouting into the walls of the shaft proved useful. The cribbing effectively lowered the closing speed between the shaft roof and floor and inhibited their deformation and failure, while the grouting effectively sealed and blocked the sources of water and sand and their inrush passageways, reduced water inrush from the shaft, and eliminated sand inrush.

Permanent arched steel supports subsequently replaced the temporary cribbing to internally reinforce the shaft. This was followed by post-wall grouting, which effectively reduced water inrush and effectively reinforced the sand layer behind the wall. After completion of this phase of the remediation, large tonnage vehicles carrying mining equipment for two working faces passed through the inclined shaft without causing any water inrush, floor fractures, sand inrush, or other undesirable phenomena, indicating that the shaft was well restored. This remediation effort could serve as a case study reference for management of any similar disaster in the future.

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References

China Coal Network (2016) Yanzhou coal industry has successfully developed the world's first set of 8.2 m super high variety technology and equipment. http://www.coalchina.org.cn/detail/16/06/24/00000016/content.html?path=16/06/24/00000016. Accessed 24 June 2016 **(in Chinese)**

Fang YM, Tao RM (2014) Ground freezing monitoring and control of mineshaft repair project. Mine Constr Technol 35(04):8–11 **(in Chinese, abstract in English)**

Luan YZ, Wang YZ (2001) A real time observation and catastrophe model of shaft damage for Jinqiao shaft deformation. J Jiaozuo Inst Technol (Nat Sci) 20(02):90–93 **(in Chinese, abstract in English)**

Luan YZ, Tong WL, Zhong SQ (2000) Discussion on monitoring technology of shaft deformation in Jinqiao coal mine. Mine Surv 20(04):13–15 **(in Chinese, abstract in English)**

Luan YZ, Zhao XH, Han LT (2001) Surface movement and deformation calculation caused by wellbore flooding. Nonferr Met 30(04):24–26 **(in Chinese, abstract in English)**

Ren YQ (2014) Case of water flooding in a coal mine. http://www.docin.com/p-1174127503.html. Accessed 24 June 2014

Tao WM (2016) Application of high density seismic exploration in exploration of influence range of permeable and sand inrush. Coal Technol 35(12):200–201 **(in Chinese, abstract in English)**

Tu XY (2008) Research on the treatment technology of the auxiliary shaft wall in Xinyi Mine. China University of Mining and Technology, Xuzhou, pp 30–50 **(in Chinese, abstract in English)**

Wang CT, Zhang SM, Zhou DP et al (2004) The technology of injection of injection perforation in the secondary well of jinqiao coal mine. Mine Constr Technol 25(01):1–3 **(in Chinese, abstract in English)**

Xu GJ (1983) Panyi coal mine shaft repair experience. Coal Sci Technol 10(09):7–10 **(in Chinese, abstract in English)**

Zhang P (2009) Study on characteristics and maintenance of shaft damage due to the extraction of industry square pillar. Henan Polytechnic University, Jiaozuo, pp 34–36 **(in Chinese, abstract in English)**

Zhang H (2016) Study on the deformation mechanism of shaft lining of Qianyingzi coal mine in Su-Nan mining area. China University of Mining and Technology, Xuzhou, pp 20–30 **(in Chinese, abstract in English)**

Zhu QK (2006) Study of the comprehensive government of grouting and sealing up by concrete curtain on caiyuan coal mine auxiliary shaft. Shandong University of Science and Technology, Qingdao, pp 34–44 **(in Chinese, abstract in English)**