CHEMICAL ENGINEERING TRANSACTIONS
VOL. 46, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Peiyu Ren, Yancang Li, Huiping Song

ISBN 978-88-95608-37-2; **ISSN** 2283-9216

DOI: 10.3303/CET1546114

Analysis of the Factors Causing Roof Water Inrush in Coal Seam Mining with Thin Bedrock

Kuikui Chen*[a], Xinyi Wang[b]

[a] School of Energy Science & Engineering, Henan Polytechnic University, Jiaozuo, 454000, China
[b] Institute of Resources & Environment, Henan Polytechnic University, Jiaozuo, 454000, China
ckk0606@hpu.edu.cn

To solve the problem of water inrush from overburdened bedrock aquifers during thin seam mining of thick loose layers, we analyzed the fourth Neogene strata structure and found that the bottom was a “clay-grit-clay” structure. The clay is semi-consolidated at low liquid limits and possesses a high level of impermeability and low mobility, preventing water and sand in the upper sand gravel aquifers from collapsing. By analyzing the roof structure and lithology of rock in secondary seams, we found that the clay layer in the roof is water impermeable, while the aquifer layer is low in water abundance, imposing minor effects upon the mining of the working face and causing minimal serious flooding. The aquifer can be dewatered simultaneously during mining. From the “two zone” pores on the construction ground, the height of the caving belt and water conducting fractured belt are 13.1 and 29.2 m, respectively. Lastly, the technical measures to prevent and control water in and surrounding mines are proposed.
Keywords: thin bedrock; roof water inrush; overlying rock structure; caving zone; water conducting fractured zone

1. Introduction

Currently, the theory regarding the mechanism underlying mine roof water inrush was primarily developed via the guidance of the “doctrine of overburden failure”, as proposed by Liu (Beijing Mining Institute and Coal Science Research Institute (1981)) in the 1980s. According to this doctrine, based on deformation characteristics and conducting properties of overlying strata in long wall mining, the overlying strata is divided into the “upper triple zones” of caving zone, fractured zone, and bending sinking zone. The water conducted via the fractured zone consists of caving and water flowing fractured zones. Researchers mainly consider the height of the conducting fractured zone using a published equation (National Coal Industrial Bureau (2000)), without condsideration of other factors worth study in the roof water inrush mechanism. The rock structural mechanics models should be classified as rupture, separation, bend, and loose impact layer zones, which further broadens an understanding of the mechanism of roof water inrush.
Some Chinese scholars have studied the roof water inrush problem in terms of mining, geological structure, and critical layer with good results (Xu (2009), Shi (2010), Zhou (2006), Ma (2013), Li (2011), Pu (2010), Liu (2006), Wu (2007), Zhang (2009) , Li (1999) , Jin(2002)). The Zhaogu mine zone of the Jiaozuo coal field is located in the east wing of the southern section of the anti-clinorium uplift belt of the Taihang Mountains. On the north part is the Taihang Mountains region where the natural water resources are up to 385.41 million m^3/a, and the mountainous limestone outcrop area is approximately 1395 km^2, widely accepting meteoric recharge. The Zhaogu mine zone comprises a typical thick loose thin bedrock structure with seven major aquifers in which the secondary coal roof sandstone aquifer imposes notable effects upon the roof. The aquifer consists of secondary large coal roof sandstone and charcoal sandstone, about 2.80~67.99 m (1~13layers) in thickness. The exposed 34 holes do not show rush or water leakage. The water impermeable layer beneath the aquifer consists of clay and sandy clay. Whether or not roof water inrush will occur is mainly dependent upon the following factors: the structural characteristics of the fourth loose Neogene rock layer; the structure of the overlying strata and water saturation; and the height of the “two zone” after mining. Therefore,

deep analysis of the problem is necessary in order to develop safe exploitation of the Zhaogu mine under the aquifer, as well as to develop an effective strategy for water management. Thus, we have investigated the water management technology of the Zhaogu mine zone and sought improved techniques for the sake of safe and efficient mine exploitation.

2. Influence of the fourth Neogene loose strata on the roof water inrush

The loose strata of the Zhaogu mine zone belong to the fourth Neogene strata. With no definitive depth classification, the strata cover the coal-bearing strata above the bedrock. According to the eight cylindrical drills on the first east panel of Zhaogu No. 1mine, the fourth Neogene loose strata in the first east panel is mainly composed of red, purple, gray, and mixed colored clay, sandy clay, conglomerate, and sandstone, which are all together approximately 427.49~518.85 m thick. According to the geologic report, the Zhaogu mine zone is roughly divided into two aquifers; i.e., the shallow quaternary gravel and deep Neogene gravel aquifers. The main features of the aquifers are as follows:

(1) Using the 6401 drill of the 11011 working face in the Zhaogu No.1 mine as an example, there are seven layers of clay with thicknesses of a single layer greater than 20m. The deepest buried depth is 295.35 m, with a clay thickness of 79.5 m, which can effectively prevent water in aquifers from penetrating.

(2) According to the structure of the aquifer and water impermeable layer and to the impact on mining, the loose layer is divided as follows: the first aquifer layer (group), or upper aquifer (group), is at a depth above 215.85m; and the aquifer is a quaternary gravel aquifer and is water-saturated. The first water insulation layer (group), located at 215.85~419.85 m in depth, consists of 6 layers of single clay thicker than 10m and a gravel aquifer with a thickness less than 5 m. The secondary aquifer (group), or lower aquifer (group), located at 419.85~437.35 in depth, consists of two layers of thick gravel aquifer. The water saturation of the gravel aquifers is from low to medium. At a depth of 437.358~518.85 m, the second water insulation layer (group) consists of 2 thick layers of clay and a medium/thick layer of gravel.

(3) The second impermeable layer (group) is a “sticky - grit - stick” structure; i.e., there is a medium/thick or thick layer of gravel or sand between the two thick layers of clay. According to published accounts (XU (2004)), safety production of coal mine beneath water entails that the bottom within 50m of the loose layers threatens the safety of mine production. In particular, the bedrock lithology and water enrichment of the bottom loose layer are dominated with base rock. Consequently, the main factor that hinders the safe exploitation of coal seam in the Zhaogu mining zone is the impermeability of the second impermeable layer (group).

The bottom of Neogene is a thick layer of clay which is the key layer that prevents the water collapse and sand collapse; the water barrier properties of clay and its engineering properties are closely related. To this end, overburden failure height observation wells (SD-01) and tests on soil samples are used. The name of the soil samples and drilling control group numbers are shown in Table 1, and the test results are shown in Table 2. As shown in Table 2, the basic soil plasticity index is greater than 17, and the liquid index is lower than 0.25. The clay is classified as a low liquid limit state and semi-solidified state, has a high level of impermeability, and poor mobility, which prevents sand and gravel aquifers water collapse and sand collapse.

Table 1: Name of Zhaogu soil samples and index of drilling groups

Name of soil sample	Drilling no.	Composition	Sampling depth/m
Zhaogu1	1	Aluminum Clay	478.05~482.22
Zhaogu 2	2	Aluminum Clay	483.30~484.92
Zhaogu 3	3	Clay	485.35~487.50
Zhaogu 4	4	Clay	497.50~499.80
Zhaogu 5	5	Clay	515.80~516.65

Table 2: Liquid limit and plastic limit parameters of Zhaogu soil samples

Name of soil sample	Liquid limit/%	Plastic limit/%	Plastic index/%	Classification of soil	Liquid parameters	Identification
Zhaogu1	38.0	15.0	23.0	Low liquid limit clay	-0.15	hard
Zhaogu 2	31.0	15.2	15.8	Low liquid limit clay	-0.23	hard
Zhaogu 3	27.4	15.4	12.0	Low liquid limit clay	-0.15	hard
Zhaogu 4	32.4	13.6	18.8	Low liquid limit clay	-0.18	hard
Zhaogu 5	31.2	12.6	18.6	Low liquid limit clay	-0.10	hard

3. Influence of the roof structure and water abundance on the roof water inrush

The main coal production in the Zhaogu mine is from the second coal seam, which is approximately 5.94 ~ 6.59 m thick. The coal seam is close to the Neogene strata. The thickness of the bedrock is 13.87 ~ 68.41 m, and the thickness ratio between the bedrock and seam is 2.21~10.67 m. This type of bedrock if highly influenced by the weathering band, and comprises native cleavage and well-developed fractures. The stratum is very unstable, with severe leakage and disturbed rock channels. Hence, the stratum is not a crucial structural layer. Due to the near-flat or slow steep coal seam and the thin bedrock, the proportion of exposed safety columns of the coal stratum columns. Cracks are well-developed in the actual production and represent unstable rock, display unstable rock roadway characteristics, and make it difficult to form a composition critical layer. Because a coal seam is nearly horizontal or gently inclined with thin bedrock, outcrop coal pillars play a large role in securing the structure. The bedrock of the Zhaogu mine coal seam roof consists of sandstone, sandy mudstone, and shale. Of the 0~20 m segment of the roof, approximately 66% is comprised of sandstone and 34% is mudstone. The layer in the 20 ~ 40 m segment of the roof, 36% is sandstone and 64% is mudstone. The layer in the 40~60 m segment of the roof, 46% is sandstone and 54% is mudstone. This type of layer is hard at the bottom, but soft on the top and is considered medium-hard strata. However, the strength of the strata was weakened due to the influence of the weathered band. There is an impermeable clay layer of variable thickness in the bedrock reducing the water inflow in the working face.

It has been established that the permeability coefficient of roof sandstone is a k <0.12 m/d, which indicates a low level of water-saturation in the aquifer. The pumping units inflow of examining well No.1 drill is 0.000736 L/s•m, the permeability coefficient is 0.00858 m/d, and the water level 了 is +84.51 m. The pumping unit inflow of the neighboring drill is 0.0159 L/s•m, indicating a low level of water-saturation in the aquifer. The hydrochemical make-up is of the HCO3-Ca Mg type, with salinity at 0.313 ~ 0.43 g / L, and a pH of 7.7-7.96. To further investigate the roof strata structure and water situation of the second coal seam, we performed a thorough analysis of its mining safety procedures and records. We constructed 18 examining drills on the roof of the second coal seam at positions corresponding to the two channel roofs on the 11011 working face of the East No.1 zone of the Zhaogu No.1 mine zone. The vertical depth of each drill was 37.8 ~ 58.8 m, which was sufficient to pass through the roof bedrock segment and penetrate the bottom clay layer of the fourth Neogene. The drills played an essential role in reaching a more comprehensive understanding of the bedrock lithology, water-saturation, and water insulation of the second coal seam.

(1) The vertical drills, 37.8 ~ 58.8 m in depth, penetrated through the bottom bedrock section of the second coal seam roof, and partially into the bottom clay segment of the fourth Neogene. This is clear proof of s the presencee of a thick clay layer on the bottom of the Neogene in the Zhaogu well fields.

(2) The vertical depth of the emerging water and water flow of roof drills indicated that the vertical depth of the spot where water was emerging is 25.06 ~ 48.79 m. Compared with the comprehensive histogram, there was no evident gushing from the sandstone aquifer of the second coal seam roof. The gushing occurred at the depth of the weathered sandstone of the second coal seam roof and the water inflow was 0.2 ~ 15 m^3/h, which was approximately 5 m^3/h. The maximum water inflow was approximately 15 m^3/h, and it occurred at the TC7-1 position at a vertical depth of 31.18 m.

It is therefore concluded that the aquifer in the second coal seam bears minimal water and poses little danger to the working face exploitation; i.e., the aquifer is not likely to induce severe flooding. Finally, the aquifer can be dewatered at the same time as exploitation continues as usual.

4. Determination of the damage height of the overlying rock after exploitation

Damage height of overburden rock and the number of the aquifer in the breakage band is one of the decisive factors affecting the amount of the roof water burst (Meng (2001), Wang (1999)). Therefore, the determination of damage height of overburden rock is one of the main parameters to determine whether the roof water burst can occur. At present, the methods of determining the damage height of overburden rock include empirical formula, theoretical calculation, numerical simulation and field measurement (Cheng (2011)). In consideration of the thickness of loose layer, thickness of bedrock, the observation of the collapse zone is the key point, and the ground is fit for drilling in Zhao Gu coal mine zone, the method of ground drilling hole is used in Zhao Gu coal mine to observe the damage height of overburden rock, especially the height of caving zone (Xu (2010) , Jia (2012)).

According to archived data and site conditions, two observation drillings were set for “two zones” on the 11011 working face, indexed as SD-01 and SD-02. The structure of the drillings, as shown in Figure 1, is as follows. ① SD-01 drilling: drilled 311 mm in diameter for the 0 ~ 250 m segment, installed with φ219 mm protection casing, and the diameter of drilling was 215 mm and 190 mm for the 250 ~ 469.88 m and 469.88 ~ 519.84 m segments, respectively; and ② SD-02 drilling: drilled 311 mm in diameter for the 0 ~ 11.99 m segment, installed withφ219 mm protection casing, for the 11.99 ~ 58.71 m segment the diameter of the aperture was 215 mm and it was installed with φ159 protection casing up to 500.20 m; for the 358.71 ~ 500.20 m segment the aperture diameter was 133 mm and not protected with casing.

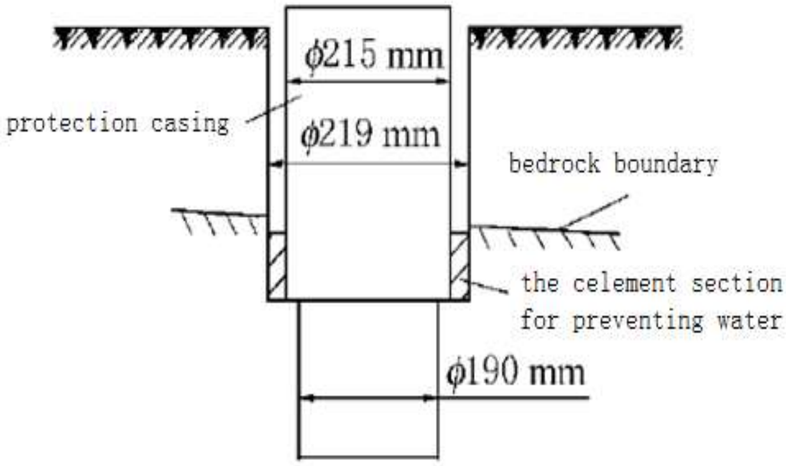

Figure 1: Scheme of drilling structure.

SD-01 drilling. In the original design, there are two casings inside the drilling. The first casing was installed in the fourth Neogene gravel aquifer, which is above 250 m in depth. The second casing was installed below the weathered bedrock. After closing the Neogene gravel aquifers and bedrock weathered zone aquifer, one can observe the water conducting fractured zone and height of the caving zone. But the collapsing and diameter narrowing of the borehole became evident, preventing drilling tools from drilling deeper. The 219 mm casing was damaged beyond repair due to the aforementioned conditions. Eventually, the drilling tool could only achieve a maximum depth of 170 m. Although many solutions were attempted, it remained impossible to find the original aperture and continue the construction. Hence, it was decided to move the drilling aperture about 5 m south to construct the SD-02 drilling.

SD-02 drilling. The No. 1 zone in the East mine No. 1 of Zhaogu is suitable for setting up sand proof coal pillars. The height of the caving zone is the key parameter in determining the thickness of the coal pillar. Because the water-conducting fractured zone extended into the bedrock weathering zone, it is difficult to observe the height of the caving zone through drilling apertures. Considering the lithology and deformation characteristics of the overlying strata, we decided to install a second casing, which would allow drilling through the bedrock in the thick clay layer on the bottom of the Negogene strata. In this way, we were able to observe the height of the caving zone through the SD-02 drilling aperture. For the bedrock segment, the quick non-coring drilling method was adopted. The height of the caving zone was estimated by drilling, dropping, or suction. During drilling, leakage of water occurred at a drilling depth of 494.16 m, with a leakage rate of approximately 51 m^3/h. Finally, we used 12,000 kg of sodium clay powder and 5 m^3 of sawdust to successfully block the leakage. In the bedrock section (530.00 ~ 547.35 m in depth), there were rig vibrations, noise, as well as blocking or dropping of drilling tools. Severe flooding occurred at a drilling depth of 547 m, with a leakage rate of approximately 51 m^3, After which we moved the drill. Because drill tests showed suction phenomena indicating for enterance into the caving zone, we terminated drilling.

When the SD-02 hole drilling was deeper than 547 m, the leakage of drilling fluid increased suddenly inside the drilling aperture. There was no anti-pulp, but stuck to and fell off of the drilling tools. The rock core was fragile sandstone. While lifting up the drilling tool, the ignite test indicated that there was a suction phenomenon within the aperture. Accordingly, the depth of the aperture at 547 m was determined to be at the top of the caving zone. The leveled height of the drilling inlet was more than 81.5m, and that of the coal seam bottom at the drilling aperture was less than 485 m. The height of the caving zone is defined as $H_k = H - M - h_k + W$; where H is the vertical depth of the bottom coal seam from the drilling inlet (set at 566.5 m), M is the thickness of the coal seam at drilling (set at 6.4 m), h_k is the vertical depth of the top of the caving zone from the inlet (set at 547 m), and W is the compression value of the fractured rock zone at the observing time (set at 0). The height of the caving zone, as calculated from the above formula, is 13.1 m.

The measured mining height is 3.37, 3.43, and 3.41 m (average = 3.40) at three drilling positions respectively during the advancement of the working face. The collapse production ratio is calculated to be 3.85.
As SD-01 and SD-02 drilling proceeded into the bedrock, a large amount of water leakage occurred due to the thin bedrock and the sandstone aquifer of the weathered zone. The fracture zone in drilling percolated into the aquifer. Hence, it was impossible to observe the highest point of the water-conducting fractured zone. The range of the water-conducting fractured zone could be deduced merely through the thickness of the rock pillar. The height of the water-conducting fractured zone is defined as $H_1 = H_D - H_S - M_F$; where H_D is the vertical depth of the top seam with respect to the orifice (set at 560.1 m), H_S is the drilling depth of the SD-02 loose layer (set at 517.10 m), and M_F is the thickness of SD - 02 drilling weathered sandstone (set at 13.08 m). Then, the height of the water-conducting fractured zone grew to about 29.2 m. Given the mining depth of the average 3.40 m, the height of the water-conducting fractured zone as calculated was greater than 29.2m, with a split-production ratio smaller than 8.59.

5. Prevention measures for water inrush

Based on the above analysis, a roof water inrush accident would rarely occur in the Zhaogu mine zone under normal conditions. Because the water saturation of the roof aquifer or the properties of the aquitard vary, water inrush or sand collapse accidents will occur. Hence, we propose preventive measures for water inrush, as follows.
(1) In case the working face is in thin bedrock and it is difficult to construct an anti-sand safety coal pillar, it is recommended to set an anti-collapse safety coal pillar if the thickness of the clay layer above the working face in the bottom of the fourth Neogene strata is greater than twice the mining height. In case the bedrock thickness of the working face cannot meet the size requirements of the safety coal seam pillar, or when the thickness of the clay layer above the working face in the bottom of the fourth Neogene strata is not as much as twice the coal thickness, an anti-sand coal pillar should be constructed.
(2) As for areas vulnerable to water inrush and in case the drilling encounters unanticipated geological structures and/or an intensely fractured zone, in order to reduce water pressure and conduct water in advance, anti-flooding projects should be set up, such as laying water conducting, monitoring orifice, water draining channel, and water releasing channel.
(3) During the mining process, the development of roof strata should be monitored. In the case that the structure or the lithology of the roof strata varies dramatically, the development height of the caving zone and water-conducting fractured zone shall be recalculated. If the damage height of the overlying strata increases, the effective height of the impermeable layer will decrease as a result, and the possibility of roof water inrush increases as a consequence.

6. Conclusions

After analyzing the factors causing roof water inrush in coal seam mines, the below conclusions have been drawn.
(1) The major causal factors in the occourance of roof water inrush of secondary coal mining in the Zhaogu mine zone are the structural features of the overlying strata, water saturation of the aquifer, water impermeability of the impermeable layer, and the damage height of the overlying strata after mining. The major reason is the thickness of the effective water impermeable layer and the secondary reason is the influence of mining and the water saturation of the aquifer.
(2) The work was performed in the “two zone” drilling on the floor for the 618 m thick loose layer, including the multiple aquifer and sandstone layers. The development height of the caving zone and water-conducting fractured zone is 13.1 m and greater than 29.2 m, respectively.
(3) In the case of the possibility of roof water inrush, we propose safety measures, such as setting up anti-sand, anti-water coal pillars on the segment with thin bedrock, to minimize water inrush accidents.

Acknowledgments

This research is supported by program of Science and Technology Innovation Team in University of Henan province (No. 15IRTSTHN027).

References

Beijing Mining Institute, Coal Science Research Institute, 1981, The Laws of Ground Movements and Overburden Failure in Coal Mines and Their Applications, Coal Science Research Institute.

Cheng F.P., Chen K., Zhang X.C., Wu Y.C., Zhu X.L.., 2011, Evaluation of the mining effects on ecological environment, Journal of Safety and Environment, 1, 113-117.

Jin D.W., 2002, Research status and outlook of water outburst from seam floor in China coal mines, Coal Science and Technology, 6, 1-4.

Jia M.K., 2012, The Study on the Deformation Process of Overlying Strata in the Deep and Thin Bedrock, Journal of China Coal Society, 2, 168-172.

Li S.C., Feng X.D., Li S.C., Li L.P., Yuan C., 2011, The normalization process of the muti-field information from a coal mine water-inrush model test, Journal of China Coal Society, 3, 447-451.

Liu W.Q., Gu Z.H., Wang B., Miao X.X., 2006, Coupling action of water-resisting roof layer and key strata, Journal of China University of Mining & Technology, 4, 427-430.

Li B.Y., 1998, “Down three zones” in the prediction of the water inrush from coal bed floor aquifer theory development and application, Journal of Shandong University of Scienceand Technology(Natural Science Edition), 4, 11-18.

Ma L.Q., Du X., Wang F., 2013, Water-preserved mining technology for shallow beried coal seam in ecologically-vulnerable coal field: a case stusy in the Shendong coal field of China, Disaster Advances, 5, 268-278.

Meng Z.P., Peng S.P., Li H., 2001, Influence of normal fault s on the physical and mechanical properties of coal and the dist ribution of underground pressure, Journal of China Coal Society, 6, 561-566.

National Coal Industrial Bureau, 2000, Rules for coal mining relating to building, water body, railway and main tunnel, Beijing.

Pu H., Zhang J., 2010, Numerical simulation of water inrush from coal roof affected by fault, Journal of Mining & Safety Engineering, 3, 421-424.

Shi L.Q., Yu X.G., Wei J.C., Guo J.B., Zhai P.B., Li J.F., Li G-Q., 2010, An analysis of factors affecting water-inrush from the number 4 coal-seam roof conglomerate in the Huafeng coal mine, Journal of China University of Mining & Technology, 1, 26-30.

Wang Y.J., Wang Y.M., 1999, The effect of surrounding rock stress of fault broken zones on the entry and its control, Coal Science, 2, 35-37.

Wu Q., Zhang Z.l., Ma J.F.,2007, A new practical methodology of the coal floor water bursting evaluating Ⅰ —— The master controlling index system construction, Journal of China Coal Society, 1, 42-47.

Xu J.L., Wang X.Z., 2009, Effects of primary key stratum location on height of water flowing fracture zone, Chinese Journal of Rock Mechanics and Engineering, 2, 380-385.

Xu Y.C., 2004, Mechanics characteristics of deep saturated clay, Journal of China Coal Society, 1, 26-30.

Xu Y.C., Li Z.H., Jia A.L., Ding X.P., Xu G.M.,2010, Site measurement and analysis on failure height of overburden strata under thick loose alluvium and thin bedrock, Coal Science and Technology, 7, 21-23.

Zhou X.L., Yang G.Y., Zheng S.S., 2006, Influencing factors on water burst in the roof of No.3 seam in Dongtan coal mine, Journal of Mining & Safety Engineering, 9, 281-284.

Zhang H.S., Xue G.W., Shi X.W., Liu H.F., Hu Y.Q., 2009, Prediction of water inrush from coal seam floor confined based on geo-information composite over lay analysis, Journal of China Coal Society, 8, 1100-1104.