Height of Water-Conducting Fractured Zone with Coal Mining in Loess Covered Area

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Abstract: Loess covered areas in China are short of water resources, but yet contain abundant coal resources. Height of the Water-Conducting Fractured Zone (WCFZ) is an important index for protecting water resources and the ecological environment. Using the geological conditions of the Zhangjiamao coal mine, Yushen mining area, China, a series of in-situ testing methods were used to observe the height of WCFZ in coal mining face. Then, a physical simulation was conducted to determine the developing process of WCFZ. Finally, the single factor and multi factor statistical analysis of the height of WCFZ was performed based upon the collected data. The results show that height of WCFZ is mainly controlled by mining height, followed by bedrock and loess overlying the coal seam, which includes thick bedrock-thick loess type (I), thick bedrock-thin loess type (II), thin bedrock-thin loess type (III), and thin bedrock-thick loess type (IV). This study provides support for the sustainable development of coal mining in the loess covered area.

Keywords: water-preserved mining; Water-Conducting Fractured Zone (WCFZ); physical simulation; loess

1. Introduction
Currently, production of coal in Northwest China including Shaanxi, Shanxi, Inner Mongolia and Ningxia accounts for more than 70% of total production in China. But they are located in the ecologically fragile Loess Plateau and Maowusu Desert junction. In the early stage of large-scale coal mining in this region, there were many mine environmental geological problems, such as water inrush, ecological degradation, soil erosion, and reduction of the amount of water resources. All these problems are related to water.

In China, there have been adamant research on these mine environmental problems that commonly
occur throughout the early stage of mining in the loess covered area. Fan Limin et al. proposed "water-preserved mining" and generalized the environmental geological model of a mine covered with loess [1]. Wang Shuangming et al. proposed “water-preserved mining " based on the ecological water level to protect the surficial ecological environment [2]. Gu Dazhao proposed building underground reservoirs to store mine water used to solve the problem of water scarcity [3]. Li Tao studied the dynamic change of phreatic water with coal mining and proposed the method of protecting layer setting [4]. Ma Liqiang et al. proposed another water-preserved mining method [5]. With coal mining, protecting the ecological environment is a scientific issue for the sustainable development of the region.

The key to protecting the ecological water level in a loess covered area is to determine the controls of the height of WCFZ with coal mining. In different countries, a statistical formula is used to predict the height of the WCFZ. This formula indicates that the height of the WCFZ has many factors that affect the proper height of the WCFZ to various degrees under different mining geological conditions.

The Yushen mining area, the area of interest to this study, is one of the eight largest coal fields in the world. It has estimated coal reserves of 223.6 billion t, which accounts for one-third of the national proven reserves. This coal mining area contains a loess layer that varies in thickness from 0-200m, and the development of fractures with the coal mining loess further reduce the scarce water resources in the region. There are generally three methods for researching the height of a WCFZ, including simulation, in-situ observation, and statistical research [6-12]. This study uses a thick loess coal mine in the Yushen mining area as an example to perform physical simulation and in-situ observations, and then perform statistical research across the entire Yushen mining area. The study provides a technical basis for sustainable development of this area.

2. Study Area Descriptions
The loess layer (including Q4 Lishi loess and N3b Baode loess) under the aeolian sand is stable, with a thickness of 0-200m. The coal related strata (Regional strata as show in Figure 1) include J1f, J2y, J2z, J2a, K1l, N and Q. J2y is a rock series containing the mineable coal in study area. Q is the most important aquifer in the study area, and it is also the main protected strata. The underlying loess is the key water resisting layer for the Q aquifer. The development principles of WCFZ in loess layer are critical.

| No. | Thickness (m) | Main Lithology                  | Remarks             |
|-----|---------------|---------------------------------|---------------------|
| 1   | 0–150         | Aeolian sand (Q)                | Main aquifer        |
| 2   | 0–200         | Loess (Q3+ N3b)                 | Key aquiclude       |
| 3   | 0–340         | Medium coarse grained sandstone (K1) | Ofen weathering loss |
| 4   | 0–300         | mudstone (J)                    |                     |
| 5   | 0–240         | mudstone (J2z)                  |                     |
| 6   | 0–330         | Siltstone (J2y)                 | Coal measure strata |
| 7   | 0–150         | Quartz sandstone (J1f)          |                     |

*Figure 1. Location of the mine and lithology.*
3. Field Monitoring

3.1. Determination Methods
In drilling process, a series of methods were used to observe fractures in drilling. The observation methods include borehole TV observation, hydrological observation, core logging and MCI.

3.2. Results and Analysis
(1) Borehole television results and analysis
The top of the bedrock was detected at 59.9m within borehole Z1. In the bedrock section, the borehole television observed fractures throughout the entire unit, including a high angle fracture, horizontal fracture, block caving, and vertical fracture (Figure 2). This indicates that the overlying bedrock in coal mine is completely damaged.

(a) High angle fissure  (b) Horizontal fissure

Figure 2. Results of borehole television

(2) Borehole hydrologic results and analysis
The water levels and flushing fluid consumption during drilling of Z1 is showed in Figure 3. There are several fractures in the loess between 7.79-9.87m. There are also several fractures in the loess between 16.67-20.65m.

Figure 3. Variations in water levels and flushing fluid consumption at Z1.

(3) Core identification results and analysis
The results show that the borehole is full of fractures. The fractures in the medium grain sandstone were less compared to the other strata, indicating that the medium grain sandstone can form a
supporting structure. The bedrocks near the roof of the goaf are currently caving, and the bedrocks far from the roof of the goaf had more high-angle fractures.

(4) MCI results and analysis

In the Z1 borehole, four complete mining-induced fractures were scanned by MCI (Figure 4). There were two high-angle fractures in the 7.5-9m section, with a dip of 84° and strike direction of 155°. The other high-angle fractures were in the 17.5-23.2m section, with a dip of 82° and strike direction of 146°. The direction of all fractures was nearly perpendicular to the advancing direction of coal mining face (60°), similar to the fracture strike (149°) observed at the surface. The results of MCI are compared with the results of borehole hydrologic observation. The results of MCI are credible.

![Figure 4. Results of the micro resistivity by MCI.](image)

(5) Comprehensive results and analysis

The comprehensive study results of Z1 drilling show that the height of WCFZ is 165.9m with a 5.6m mining thickness. The ratio of WCFZ to mining height in this project is 29.63.

4. Physical Simulation

4.1. Physical Model

(1) Determination of the Model Simulation Scale

Based on similarity criteria including geometrical conditions, ambient conditions, boundary conditions, and initial conditions, and considering the geological conditions of the actual working face and size of the model supports, the geometric similarity ratio $Cl$ of the model was determined to be 120:1. The volume–weight similarity ratio $Cr$ of the model was determined to be 1.5:1. Calculations indicated that the stress similarity ratio $Cp = Cr \times Cl = 180:1$.

(2) Design of Model Parameters

The height, strength, and density for each rock stratum in the models were calculated based on the site test results of the actual lithology and principle of similarity. Rock physics similar materials consisted of sand, calcium carbonate, gypsum and water. Loess physics similar materials consisted of oil and loess.

4.2. Excavation Processes Results and Analysis

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When the coal mining face advanced to 36m, the immediate roof first collapsed. When the coal mining face advanced to 51.6m, the caving height increased to 12m and caused the first break of the base roof. When the coal mining face advanced to 61.2m, the main roof was periodically broken for the first time and the height of WCFZ increased to 26.4 m. When the coal mining face advanced to 124.8m, the main roof was periodically broken five times throughout the mining process and the height of WCFZ increased to 90 m. When the coal mining face advanced to 142.8m, the main roof periodically broke six separate times over the course of this mining advancement and the height of WCFZ increased to 105 m. When the coal mining face advanced to 240m, the loess layer broke and the WCFZ increased all the way to surface.

When the coal mining face advanced to 240m, Line D and E began to subside and the maximum subsidence dot was located in the middle of the goaf. The maximum subsidence was 4.128 m for Line D and 4.016m for Line E. The maximum subsidence of A, B, and C lines tended to be stable, and the maximum subsidence in the center of the goaf was 3.84m, and the surface subsidence coefficient was 0.69, which indicates that the WCFZ developed all the way to the surface(Figure 5).

![Diagram showing subsidence results](image)

**Figure 5. Observation results of subsidence while the coal mine face advanced to 240m**

### 5 Statistical Analysis of WCFZ

#### 5.1. Single Factor Analysis on the Relationship of WCFZ and Mining Height

Much of the current research results indicate that WCFZ is directly related to the height of coal mining. The relationship between mining thickness and WCFZ was analyzed by single factor statistics, and the result is shown in formula (1). Single factor analysis shows that the average ratio of WCFZ to mining height is 26.89, slightly smaller than the previously measured values. This shows that when only considering the coal mining thickness, there is a small error in the prediction of the height of WCFZ.

\[
H=23.58M+13.33, \quad R^2 = 0.707
\]

where $H$ is height of WCFZ, and $M$ is mining height.

#### 5.2. Multiple factors Analysis on the Relationship of WCFZ in Loess and Loess Thickness
In order to study the contribution of the loess to the height of the WCFZ, the relationship between the WCFZ in the loess (height of WCFZ minus the bedrock thickness) and the thickness of the loess was analyzed, and the results are shown in Figure 4.

(1) Thick bedrock-thick loess type (I)

In zone I, height of WCFZ in loess was less than 0, and the loess thickness is greater than 70m. There are only three type I locations in the area, which indicates that the situation is very rare in the study area. Also, the height of WCFZ is limited, and it will not be greater than the bedrock thickness.

(2) Thick bedrock-thin loess type (II)

In zone II, the height of WCFZ in loess is less than 0, and the loess thickness is less than 70m. The bedrock is thick in this zone, and the height of WCFZ increases rapidly with the increase of loess thickness. According to the key stratum theory, the key stratum in the bedrock has not yet been broken. Therefore, loess is the loading of the key stratum in zone II, and the thicker the loess, the greater the height of WCFZ. The average ratio of WCFZ to the mining height in II zone is 29.3. The coal face in the Zhangjiamao coal mine belongs to this zone, and the measured value is equivalent to the average value in this zone.

(3) Thin bedrock-thin loess type (III)

In zone III, height of WCFZ in loess is greater than 0, and the loess thickness is less than 70m. The bedrock in this area is thin, the bedrock is full of WCFZ and the key stratum in the bedrock is fractured due to mining. A thicker loess results in a higher WCFZ height, so the loess is still loading, but less than II zone. This indicates that the loess layer can restrain the development of the height of WCFZ. The average ratio of WCFZ to mining height in the zone III is 26.04, less than zone II.

(4) Thin bedrock-thick loess type (IV)

In zone IV, height of the WCFZ in loess is greater than 0, and the loess thickness is greater than 70m. The bedrock in this area is thin, the bedrock is full of WCFZ, and the key stratum in the bedrock is fractured. Even with an increase of loess thickness, the height of WCFZ in the loess essentially remains constant. The restraining effect of the loess layer is stronger than that of the loading effect in this zone. The average ratio of WCFZ to mining height in the zone IV is 25.33, less than II and III zones.

When the thickness of the loess layer is greater than 70m, the WCFZ is restrained by loess, and there is no WCFZ in part of the loess layer. The overlying groundwater of loess is protected from the mining process. From the trend line (Figure 6), when the loess is less than 70m, the height of WCFZ in the loess increases with the thickness of the loess, and when the loess layer is greater than 70m, the height of WCFZ in the loess becomes smaller as the thickness of the loess becomes greater.
Figure 6. Relationship of WCFZ in Loess with Loess Thickness.

6. Conclusions
The following conclusions have been reached based on the study of height of WCFZ in the loess covered area of the Yushen mining area, specifically the Zhangjiamao coal mine.

(1) In-situ observations showed that the WCFZ is 29.63 times that of the mining height in the Zhangjiamao mine. Physical simulation verified the development of WCFZ.

(2) The height of WCFZ is mainly controlled by mining height, followed by coal seam overlying bedrock and loess characteristics. When the thickness of the loess layer reaches 70m, the restraining effect is dominant.

Author Contributions: Data curation, T.L., and G.Y.; Investigation, T.L., G.Y., S.Y.Y., J.W. Y., A.R.M.; Writing—T.L.

Funding: This paper was funded by the Fund of Liupanshui Normal University High Level Talent Research Start-up (LPSSYJKJ201702), by Provincial Key Discipline of Mining Engineering (ZDKX[2015]9), by Guizhou Coal Green Development 2011 Collaborative Innovation Center([2016] 02), by Liupanshui Normal University Teaching Content and Course System Reform Project (LPSSYJg201813), by Natural Science Research Project of Guizhou Education Department (Qianjiaohe KY Zi[2018]376, Qianjiaohe KY Zi[2018]386, Qianjiaohe KY Zi[2018]029, Qianjiaohe KY Zi[2020]050, Qianjiaohe KY Zi[2020]119, Qianjiaohe XKTJ Zi[2020]23), by Key Subject Projects of Liupanshui Normal University (LPSSYZDKX201802), by Fund project of Liupanshui science and Technology Bureau (52020-2019-05-03), by Liupanshui Normal University Innovation Team Project (lpssykjtd201902).

Acknowledgments: We acknowledge the help of Feng hai and Xue Weifeng of Shaanxi Coal Industry Chemical Technology Research Institute Co., Ltd.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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