

Article

Mining Stability Criterion of Weakly Cemented Aquiclude and Its Application

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Abstract: The effective discrimination of aquiclude mining stability is one of the important indexes for the feasibility judgment of water-conserved mining. Based on the mining-induced deformation characteristics of weakly cemented aquiclude and the water level change of weakly cemented aquifer in northwest China, a mechanical model of mining stability of weakly cemented aquiclude is established, and the mining instability criterion of weakly cemented aquiclude and its influencing factors are analyzed. The results show that the weakly cemented aquiclude has strong plastic deformation ability and mainly undergoes bending deformation during coal mining. Considering the mining-induced bending deformation of weakly cemented aquiclude and the groundwater pressure variation of the weakly cemented aquifer, the expressions of the deflection, stress components, and strain components of weakly cemented aquiclude are derived. Furthermore, the stress instability and strain instability criteria of the weakly cemented aquiclude are proposed. The influences of aquiclude thickness, elastic modulus, Poisson's ratio, groundwater level, coalface length, and longwall panel length on the mining stability of weakly cemented aquiclude are analyzed. The research results are applied to the feasibility judgment of water-conserved mining in Xinjiang Ehuobulake Coal Mine, and the validity of the mining stability criterion of weakly cemented aquiclude is verified.



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1. Introduction

Jurassic and Cretaceous weakly cemented strata are widespread in coal-rich areas of Northwest China, such as Xinjiang, Inner Mongolia, Gansu, etc. This kind of rock mass is characterized by late diagenetic time, low strength, poor cementation, easy expansion, and argillization in water [1]. The mining stability of weakly cemented strata is more sensitive to the disturbance of underground coal mining [2,3]. Furthermore, northwest China is a mostly arid and semi-arid climate with scarce water resources and a fragile ecological environment. The weakly cemented aquiclude is an important barrier to the protection of shallow water resources, which is essential to the ecological stability of the mining area [4,5]. The contradiction between underground coal mining and water resources protection has been one of the main issues restricting coal mine production in northwest China [6]. Due to the influence of mining disturbances, the weakly cemented aquiclude will move and deform inevitably, which affects its own water-resistance properties and overlying water resources [3,7,8]. How to realize the effective judgement of mining stability of weakly cemented aquiclude is of great significance to the determination of water-conserved mining.

For the study of aquiclude mining stability, the previous focus was mainly on the roof clay aquiclude or floor non-weakly cemented aquiclude [9–11]. Huang and Fan

et al. discovered that the loess and clay layers had good water-resistance properties and considered that their water swelling characteristics were the main factors for the crack closure of the aquiclude [12,13]. Yu and Ma believed that the roadway backfill mining method could effectively control the deformation and subsidence of the loess aquiclude so that the aquiclude maintained good water-resistance stability [14]. Zhang and Sun et al. analyzed the mechanism of clay aquiclude instability and groundwater leakage induced by backfill mining; they also noted that reconstructing the key aquiclude would protect regional water resources and analyzed the physical, mechanical, and permeability characteristics of the key aquiclude [15,16]. Feng, Fu, and Wang et al. believed that structural stability and permeability stability were the main factors affecting the water-resistance property of non-weakly cemented floor aquiclude and analyzed the influence of rock properties, aquiclude thickness, and groundwater pressure on the mining stability of the floor aquiclude [17–19]. Liu et al. found that the water-conducting collapse column could reduce the effective water-resistance thickness of the non-weakly cemented floor aquiclude directly, thereby increasing the risk of floor water inrush [20]. Previous studies have obtained the general law of mining stability change of roof clay aquiclude and floor non-weakly cemented aquiclude, and some scholars have established mechanical models for the mining stability of clay aquiclude [21,22]. However, there are few studies on the evolution law of mining stability and instability criterion of weakly cemented aquiclude.

In this paper, on the basis of previous studies, the weakly cemented aquiclude in northwest China is taken as the research object. Based on the mining-induced deformation characteristics of weakly cemented aquiclude and the water level variation characteristics of the aquifer, a mechanical model of mining stability of weakly cemented aquiclude is established, and the mining instability criterion of weakly cemented aquiclude is proposed. Furthermore, the influence of different geological factors and coalface mining factors on the mining stability of weakly cemented aquiclude is analyzed. Finally, according to the obtained mining stability criterion of aquiclude, the water-conserved mining under the condition of weakly cemented strata is guided, and the validity of the instability criterion is tested.

2. Characteristics of Aquiclude Deformation and Water Level Change

A similar physical simulation shows that the weakly cemented aquiclude mainly undergoes bending deformation during the retreat process and exhibits good plastic deformation ability by taking Xinjiang's weakly cemented mudstone as an example. The physically similar model is 290 cm in length, 150 cm in width, and 115 cm in height, which is geometrically 1:100. A 30 cm wide section unmined is leaved on each lateral to eliminate potential impacts of boundaries. Based on the results of the three-dimensional physical simulation results of solid-liquid coupling in weakly cemented strata, the weakly cemented aquiclude has good overall continuity and forms concave subsidence above the goaf after the retreat process, as shown in Figure 1 [23]. Furthermore, during the retreat process, the aquifer water level in the middle of the model shows a trend of first decreasing and then increasing. After the end of the retreat, the aquifer water level in the middle of the model increased by 0.2 m compared with the original water level, as shown in Figure 2. This indicates that the aquifer water flows to the middle of the subsidence basin after mining, causing the water level to rise.

X-ray diffraction result shows that the weakly cemented aquiclude is rich in clay minerals such as montmorillonite, illite, and kaolinite. The content of clay minerals even accounts for more than 60% of the total content of rock minerals. In particular, montmorillonite and kaolinite have significant water swelling and argillization, which may be one of the reasons for the good plastic deformation ability of the weakly cemented aquiclude. The X-ray diffraction pattern of weakly cemented aquiclude mudstone is shown in Figure 3.

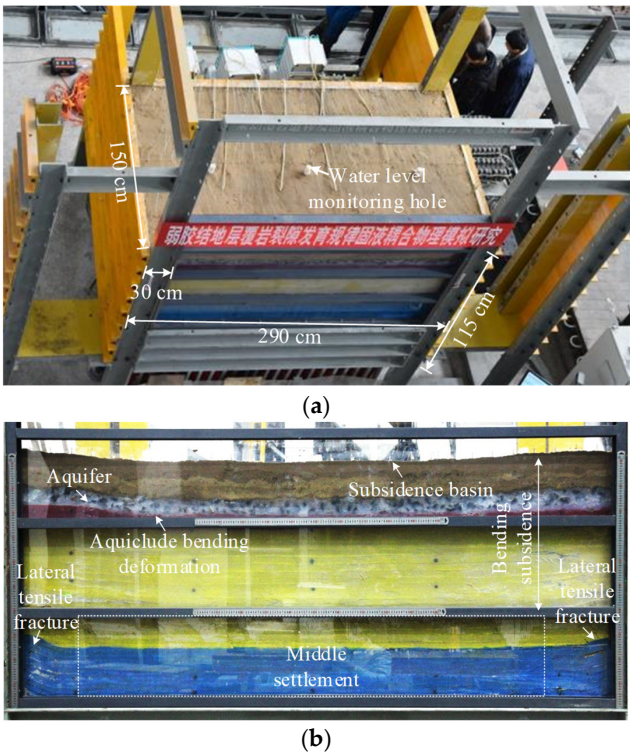


Figure 1. Physical similarity simulation of solid-liquid coupling: (a) three-dimensional physical similarity model; (b) mining-induced deformation characteristics of weakly cemented aquiclude.

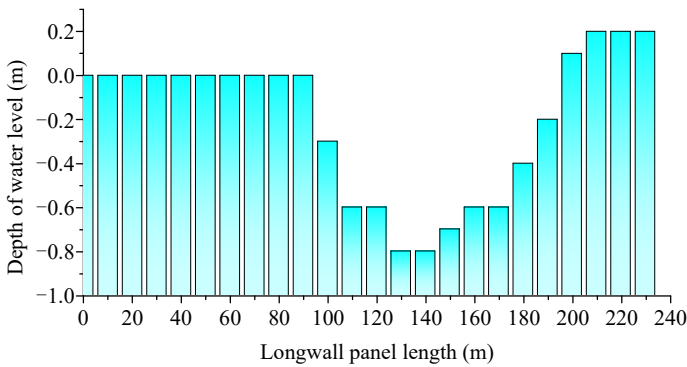


Figure 2. Variation characteristics of aquifer water level.

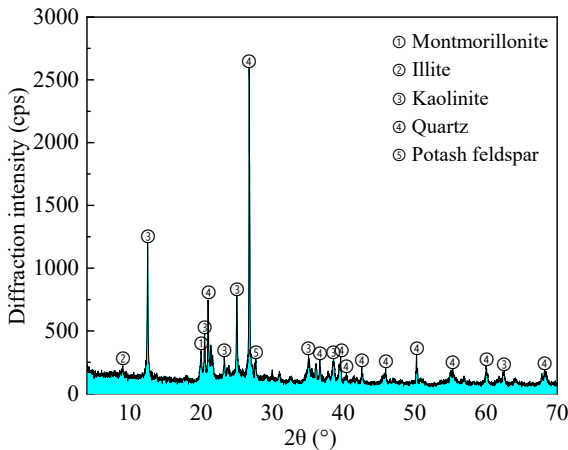


Figure 3. X-ray diffraction pattern of weakly cemented mudstone.

3. Instability Criterion of Weakly Cemented Aquiclude

3.1. Mechanics Modeling

Although the weakly cemented aquiclude has plastic deformation characteristics, it also has elastic characteristics as a natural rock mass according to previous studies [24–27]. In order to obtain the general law of mining stability variation and the quantitative criterion for the mining instability of the weakly cemented aquiclude accurately, the aquiclude is assumed as elastomer before coalface mining. According to the elastic thin plate theory, the thickness of the overlying aquiclude is generally much smaller than the other two dimensions; thus, the aquiclude can be regarded as an elastic thin plate. In addition, the strata below the aquiclude can be regarded as the elastic foundation, and the aquiclude can be regarded as the elastic thin plate located on the elastic foundation. Before coalface mining, the aquiclude is balanced under the overburden pressure, groundwater pressure, self-gravity, and foundation reaction force. Under the influence of coalface mining, the aquiclude bends and deforms, and the water in the upper aquifer flows to the middle of the subsidence basin, which changes the groundwater pressure on the aquiclude. Regarding the aquiclude as an elastic thin plate with four sides fixed, a mechanical model of horizontal or near-horizontal aquiclude is established based on the Winkler elastic foundation assumption. Considering the groundwater fluidity and the change of water pressure after aquiclude bending deformation under sufficient recharge conditions, the mechanical model of horizontal or near-horizontal aquiclude is established as shown in Figure 4.

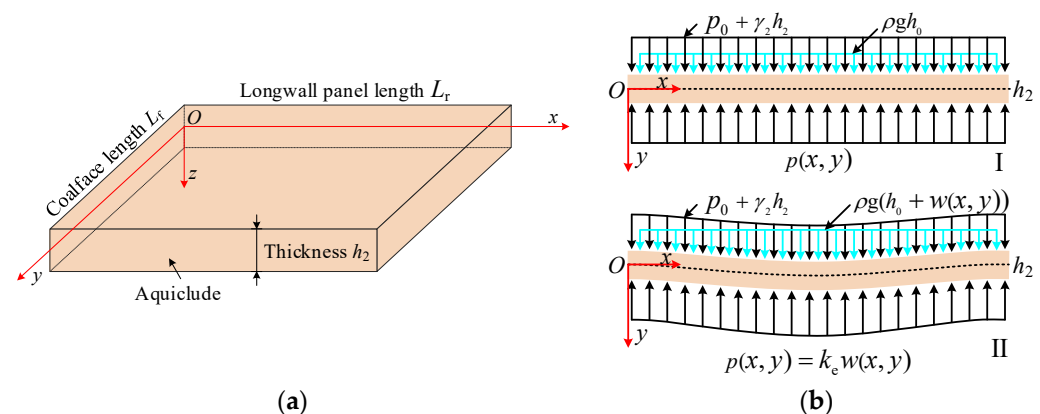


Figure 4. Mechanical model of aquiclude: (a) aquiclude plate; (b) stress conditions.

Taking the aquiclude above the coalface as the study object, the simplified model of aquiclude is shown in Figure 4a, in which the coalface length is L_c , the longwall panel length is L_r , and aquiclude thickness is h_2 . A vertical section is made along the retreat direction, and the stress distribution of aquiclude before coalface mining is shown as a state I in Figure 4b. Affected by coalface mining, the aquiclude undergoes bending deformation, and its stress distribution is shown as state II in Figure 4b. After the bending deformation of the aquiclude, the force at its upper boundary is expressed as follows:

$$q(x, y) = p_0 + \gamma_2 h_2 + \rho g (h_0 + w(x, y)) \quad (1)$$

where p_0 is the overburden pressure of aquiclude, MPa; γ_2 is the bulk density of aquiclude, N/m^3 ; h_2 and h_0 are the aquiclude thickness and the groundwater level, respectively, m; ρ is the groundwater density, kg/m^3 ; g is the gravity coefficient; N/kg ; w is the aquiclude deflection, m.

The force at the lower boundary of the aquiclude is expressed as follows:

$$p(x, y) = k_e w(x, y) \quad (2)$$

where k_e is the coefficient of elastic foundation.

Based on the double trigonometric series solution method, the deflection function can be expressed as follows:

$$w(x, y) = \sum_{m'=1}^{\infty} \sum_{n'=1}^{\infty} A_{m'n'} \sin^2\left(\frac{m'\pi}{L_r}x\right) \sin^2\left(\frac{n'\pi}{L_f}y\right) \quad (3)$$

where m' and n' is any positive integer; $A_{m'n'}$ is the coefficient of the deflection function.

For the convenience of calculation, only one coefficient A_{11} is taken in Equation (3), so there is $m' = n' = 1$ [28]. Equation (3) can be simplified as follows:

$$w(x, y) = A_{11} \sin^2\left(\frac{\pi}{L_r}x\right) \sin^2\left(\frac{\pi}{L_f}y\right) \quad (4)$$

According to the principle of minimum potential energy, while ignoring the aquiclude deformation components ε_z , γ_{yz} and γ_{xz} , the total potential energy Π generated after aquiclude bending deformation is equal to the sum of the aquiclude strain energy V and the external force potential energy W_c , as expressed in Equation (5).

$$\Pi = V + W_c \quad (5)$$

where Π is the total potential energy of the aquiclude; V is the strain energy of the aquiclude; W_c is the external potential energy of the aquiclude under external load.

According to the mechanics model, it follows that:

$$\begin{cases} V = \frac{D_c}{2} \iint \left\{ \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right)^2 - 2(1-\mu) \left[\frac{\partial^2 w}{\partial x^2} \frac{\partial^2 w}{\partial y^2} - \left(\frac{\partial^2 w}{\partial xy} \right)^2 \right] \right\} dx dy \\ W_c = - \iint (p_0 + \gamma_2 h_2 + \rho g(h_0 + w) - kw) \cdot w dx dy \end{cases} \quad (6)$$

where μ is the Poisson's ratio of aquiclude; D_c is the flexural stiffness of aquiclude, and $D_c = \frac{Eh_2^3}{12(1-\mu^2)}$, where E is the elastic modulus of aquiclude.

Combining Equations (5) and (6):

$$\begin{aligned} \Pi = & D_c \pi^4 A_{11}^2 \left[\frac{(9-6\mu)L_r}{8L_f^3} + \frac{3L_f}{8L_r^3} + \frac{\mu}{4L_r L_f} \right] - \frac{9L_r L_f}{32} A_{11}^2 (\rho g - k) \\ & - \frac{L_r L_f}{4} A_{11} (p_0 + \gamma_2 h_2 + \rho g h_0) \end{aligned} \quad (7)$$

Calculate the first derivative of the coefficient A of the deflection function in Equation (7) and let $\partial \Pi / \partial A = 0$, Equation (8) is obtained:

$$A_{11} = \frac{12(p_0 + \gamma_2 h_2 + \rho g h_0)}{\frac{\pi^4 E h_2^3}{(1-\mu^2)} \left[\frac{(9-6\mu)}{L_f^4} + \frac{3}{L_r^4} + \frac{2\mu}{L_r^2 L_f^2} \right] - \left(\frac{27(\rho g - k)}{2} \right)} \quad (8)$$

Substituting Equation (8) into Equation (4), the deflection expression at any point of aquiclude can be obtained as follows:

$$w(x, y) = \frac{12(p_0 + \gamma_2 h_2 + \rho g h_0)}{\frac{\pi^4 E h_2^3}{(1-\mu^2)} \left[\frac{(9-6\mu)}{L_f^4} + \frac{3}{L_r^4} + \frac{2\mu}{L_r^2 L_f^2} \right] - \left(\frac{27(\rho g - k)}{2} \right)} \sin^2\left(\frac{\pi}{L_r}x\right) \sin^2\left(\frac{\pi}{L_f}y\right) \quad (9)$$

Based on the deflection equation of any point of the aquiclude and Hooke's law, the stress components σ_x and σ_y of aquiclude in the x and y directions can be expressed:

$$\left\{ \begin{array}{l} \sigma_x = -\frac{Ez}{1-\mu^2} \left(\frac{\partial^2 w}{\partial x^2} + \mu \frac{\partial^2 w}{\partial y^2} \right) = -\frac{24\pi^2 z(p_0 + \gamma_2 h_2 + \rho g h_0)}{\pi^4 h_2^3 \left[\frac{(9-6\mu)}{L_f^4} + \frac{3}{L_f^4} + \frac{2\mu}{L_f^2 L_r^2} \right] - \left(\frac{27(1-\mu^2)(\rho g - k)}{2E} \right)} \\ \quad \cdot \left(\frac{1}{L_r^2} \sin^2 \left(\frac{\pi}{L_f} y \right) \cos \left(\frac{2\pi}{L_r} x \right) + \frac{\mu}{L_f^2} \sin^2 \left(\frac{\pi}{L_r} x \right) \cos \left(\frac{2\pi}{L_f} y \right) \right) \\ \sigma_y = -\frac{Ez}{1-\mu^2} \left(\frac{\partial^2 w}{\partial y^2} + \mu \frac{\partial^2 w}{\partial x^2} \right) = -\frac{24\pi^2 z(p_0 + \gamma_2 h_2 + \rho g h_0)}{\pi^4 h_2^3 \left[\frac{(9-6\mu)}{L_f^4} + \frac{3}{L_f^4} + \frac{2\mu}{L_f^2 L_r^2} \right] - \left(\frac{27(1-\mu^2)(\rho g - k)}{2E} \right)} \\ \quad \cdot \left(\frac{\mu}{L_r^2} \sin^2 \left(\frac{\pi}{L_f} y \right) \cos \left(\frac{2\pi}{L_r} x \right) + \frac{1}{L_f^2} \sin^2 \left(\frac{\pi}{L_r} x \right) \cos \left(\frac{2\pi}{L_f} y \right) \right) \end{array} \right. \quad (10)$$

Similarly, the strain components ε_x and ε_y of aquiclude in the x direction and y direction can be expressed as:

$$\left\{ \begin{array}{l} \varepsilon_x = -z \frac{\partial^2 w}{\partial x^2} = -\frac{24\pi^2 z(p_0 + \gamma_2 h_2 + \rho g h_0)}{\frac{\pi^4 E h_2^3}{(1-\mu^2)} \left[\frac{(9-6\mu)L_f^2}{L_f^4} + \frac{3}{L_f^4} + \frac{2\mu}{L_f^2} \right] - \left(\frac{27(\rho g - k)}{2} \right)} \sin^2 \left(\frac{\pi}{L_f} y \right) \cos \left(\frac{2\pi}{L_r} x \right) \\ \varepsilon_y = -z \frac{\partial^2 w}{\partial y^2} = -\frac{24\pi^2 z(p_0 + \gamma_2 h_2 + \rho g h_0)}{\frac{\pi^4 E h_2^3}{(1-\mu^2)} \left[\frac{(9-6\mu)}{L_f^4} + \frac{3L_f^2}{L_f^4} + \frac{2\mu}{L_f^2} \right] - \left(\frac{27(\rho g - k)}{2} \right)} \sin^2 \left(\frac{\pi}{L_r} x \right) \cos \left(\frac{2\pi}{L_f} y \right) \end{array} \right. \quad (11)$$

3.2. Instability Conditions of Aquiclude

The internal stress state of aquiclude changes and bending deformation occurs affected by mining disturbance. The mining stability of aquiclude is directly related to its stress state and deformation variables. When the internal stress of the aquiclude exceeds the ultimate stress it can withstand, or when the deformation of the aquiclude exceeds its allowable ultimate deformation, the aquiclude will become unstable. Therefore, the instability conditions of the aquiclude should be analyzed in terms of stress instability and strain instability, respectively.

3.2.1. Stress Instability Criterion of Aquiclude

According to the physical similar simulation, the upper boundary of aquiclude above the set-up and stopping line and the bottom boundary of aquiclude in the middle of goaf are mainly subjected to tensile action; the stress state is mainly tensile stress. The bottom boundary of the aquiclude above the set-up and stopping line and the upper boundary of the aquiclude in the middle of goaf are squeezed. The stress state is mainly compressive stress. As the tensile strength of aquiclude is generally much smaller than its compressive strength, the ultimate tensile strength of aquiclude is used as the measurement index, and the stress condition for the aquiclude instability is obtained. That is the maximum tensile stress of aquiclude $\sigma_t^{\max}$ is greater than or equal to its ultimate tensile strength $[\sigma_t]$.

$$\sigma_t^{\max} \geq [\sigma_t] \quad (12)$$

where $\sigma_t^{\max}$ is the maximum tensile stress of aquiclude, MPa; $[\sigma_t]$ is the ultimate tensile strength of aquiclude, MPa.

According to Equation (10), when $x = L_r/2$ and $y = L_f/2$, the maximum tensile stresses $\sigma_x^{\max}$ and $\sigma_y^{\max}$ appear at the bottom boundary of aquiclude along the retreat direction (direction x) and the coalface layout direction (direction y), which can be expressed as:

$$\left\{ \begin{array}{l} \sigma_x^{\max} = \frac{12\pi^2 h_2(p_0 + \gamma_2 h_2 + \rho g h_0)}{\pi^4 h_2^3 \left[\frac{(9-6\mu)}{L_f^4} + \frac{3}{L_f^4} + \frac{2\mu}{L_f^2 L_r^2} \right] - \left(\frac{27(1-\mu^2)(\rho g - k)}{2E} \right)} \left(\frac{1}{L_r^2} + \frac{\mu}{L_f^2} \right) \\ \sigma_y^{\max} = \frac{12\pi^2 h_2(p_0 + \gamma_2 h_2 + \rho g h_0)}{\pi^4 h_2^3 \left[\frac{(9-6\mu)}{L_f^4} + \frac{3}{L_f^4} + \frac{2\mu}{L_f^2 L_r^2} \right] - \left(\frac{27(1-\mu^2)(\rho g - k)}{2E} \right)} \left(\frac{1}{L_f^2} + \frac{\mu}{L_r^2} \right) \end{array} \right. \quad (13)$$

The longwall panel length L_r is generally longer than the coalface length L_f , and the Poisson's ratio of weakly cemented aquiclude is $0 < \mu < 0.5$. It can be seen from Equation (13) that the maximum tensile stress at the bottom boundary of aquiclude $\sigma_x^{\max} < \sigma_y^{\max}$. Therefore, the maximum tensile stress of weakly cemented aquiclude is:

$$\sigma_t^{\max} = \sigma_y^{\max} = \frac{12\pi^2 h_2 (p_0 + \gamma_2 h_2 + \rho g h_0)}{\pi^4 h_2^3 \left[\frac{(9-6\mu)}{L_f^4} + \frac{3}{L_r^4} + \frac{2\mu}{L_r^2 L_f^2} \right] - \left(\frac{27(1-\mu^2)(\rho g - k)}{2E} \right)} \left(\frac{1}{L_f^2} + \frac{\mu}{L_r^2} \right) \quad (14)$$

Then the stress instability criterion of weakly cemented aquiclude is:

$$\sigma_t^{\max} = \frac{12\pi^2 h_2 (p_0 + \gamma_2 h_2 + \rho g h_0)}{\pi^4 h_2^3 \left[\frac{(9-6\mu)}{L_f^4} + \frac{3}{L_r^4} + \frac{2\mu}{L_r^2 L_f^2} \right] - \left(\frac{27(1-\mu^2)(\rho g - k)}{2E} \right)} \left(\frac{1}{L_f^2} + \frac{\mu}{L_r^2} \right) \geq [\sigma_t] \quad (15)$$

3.2.2. Strain Instability Criterion of Aquiclude

The upper boundary of aquiclude above the set-up and stopping line and the bottom boundary of the aquiclude in the middle of mining area are mainly subject to tensile strain during coalface mining. The bottom boundary of the aquiclude above the set-up and stopping line and the upper boundary of the aquiclude in the middle of the mining area are subjected to compression. Under the action of tensile strain, the aquiclude is easy to produce tension cracks. When the tension cracks develop gradually and penetrate the aquiclude, the water-resistance capacity of aquiclude is lost. On the contrary, the compressive strain is conducive to the closure of internal fractures of aquiclude, which is not easy to cause mining instability of aquiclude. Therefore, taking the ultimate tensile strain of aquiclude as a measurement index, the strain condition for the aquiclude instability is the maximum tensile strain of aquiclude $\varepsilon_t^{\max}$ must be greater than or equal to its ultimate tensile strain $[\varepsilon_t]$.

$$\varepsilon_t^{\max} \geq [\varepsilon_t] \quad (16)$$

where $\varepsilon_t^{\max}$ is the maximum tensile strain of aquiclude; $[\varepsilon_t]$ is the ultimate tensile strain of aquiclude.

According to Equation (10), when $x = L_r/2$ and $y = 0$, the maximum tensile strain $\varepsilon_x^{\max}$ occurs at the lower boundary of aquiclude along the retreat direction (direction x); When $x = 0$ and $y = L_f/2$, the maximum tensile strain $\varepsilon_y^{\max}$ occurs at the lower boundary of the coalface layout direction (direction y). $\varepsilon_x^{\max}$ and $\varepsilon_y^{\max}$ can be expressed as Equation (17):

$$\begin{cases} \varepsilon_x^{\max} = \frac{12\pi^2 h_2 (p_0 + \gamma_2 h_2 + \rho g h_0)}{\frac{\pi^4 E h_2^3}{(1-\mu^2)} \left[\frac{(9-6\mu)}{L_f^4} + \frac{3L_f^2}{L_r^4} + \frac{2\mu}{L_r^2} \right] - \left(\frac{27(\rho g - k)}{2} \right)} \\ \varepsilon_y^{\max} = \frac{12\pi^2 h_2 (p_0 + \gamma_2 h_2 + \rho g h_0)}{\frac{\pi^4 E h_2^3}{(1-\mu^2)} \left[\frac{(9-6\mu)L_r^2}{L_f^4} + \frac{3}{L_r^2} + \frac{2\mu}{L_f^2} \right] - \left(\frac{27(\rho g - k)}{2} \right)} \end{cases} \quad (17)$$

Similarly, the longwall panel length L_r is generally longer than the coalface length L_f , $\varepsilon_x^{\max} < \varepsilon_y^{\max}$ in Equation (17). The maximum tensile strain of aquiclude is:

$$\varepsilon_t^{\max} = \varepsilon_y^{\max} = \frac{12\pi^2 h_2 (p_0 + \gamma_2 h_2 + \rho g h_0)}{\frac{\pi^4 E h_2^3}{(1-\mu^2)} \left[\frac{(9-6\mu)L_r^2}{L_f^4} + \frac{3}{L_r^2} + \frac{2\mu}{L_f^2} \right] - \left(\frac{27(\rho g - k)}{2} \right)} \quad (18)$$

Then the strain instability criterion of aquiclude is:

$$\varepsilon_t^{\max} = \frac{12\pi^2 h_2 (p_0 + \gamma_2 h_2 + \rho g h_0)}{\frac{\pi^4 E h_2^3}{(1-\mu^2)} \left[\frac{(9-6\mu)L_r^2}{L_f^4} + \frac{3}{L_r^2} + \frac{2\mu}{L_f^2} \right] - \left(\frac{27(\rho g - k)}{2} \right)} \geq [\varepsilon_t] \quad (19)$$

4. Influencing Factors Analysis of Aquiclude Stability

In addition to its own thickness, elastic modulus, Poisson's ratio, etc., the mining stability of the aquiclude is also related to the groundwater level, coalface length, longwall panel length, etc. In order to study the influence of different factors on the mining stability of weakly cemented aquiclude, the maximum tensile stress of aquiclude is used as the measurement index. Based on the weakly cemented geological conditions in Xinjiang and the control variable method, hydrogeological factors, such as the aquiclude thickness, groundwater level, and elastic modulus and mining factors, such as the coalface length and longwall panel length, influence the mining stability of aquiclude. According to indoor testing and consulting the actual geology and mining data, the initial calculation parameters affecting the mining stability of aquiclude are determined as shown in Table 1.

Table 1. Initial calculation parameters of aquiclude.

Aquiclude Thickness h_2 (m)	5	Water Density ρ (kg/m ³)	1×10^3
Groundwater level h_0 (m)	25	Coalface length L_f (m)	250
Overburden pressure p_0 (Pa)	5.4×10^5	Longwall panel length L_r (m)	800
Poisson's ratio μ	0.27	Bulk density of aquiclude γ_2 (N/m ³)	2.2×10^4
Elastic modulus E (GPa)	1.0	Gravity coefficient g (N/kg)	9.8

4.1. Elastic Modulus and Poisson's Ratio

Elastic modulus is a basic physical quantity to describe rock properties [29–32], which has an important influence on the mining stability of aquiclude. The research shows that the elastic modulus of weakly cemented aquiclude is low, generally within 0–2 GPa, and Poisson's ratio of aquiclude is generally between 0.1 and 0.3 [33]. Combining the initial calculation parameters of the weakly cemented strata in Table 1, keeping other parameters constant and changing the elastic modulus E and Poisson's ratio μ of weakly cemented aquiclude only, the influence of elastic modulus and Poisson's ratio on the mining stability of aquiclude is obtained in Figure 5.

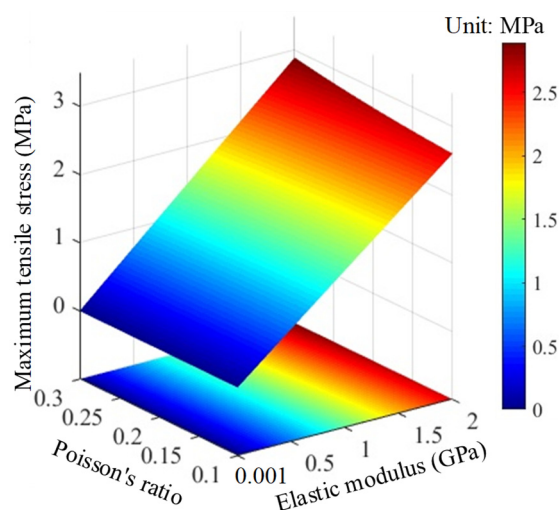


Figure 5. Influence of elastic modulus and Poisson's ratio on the mining stability of aquiclude.

As shown in Figure 5, the maximum tensile stress of weakly cemented aquiclude increases rapidly with the increase in the elastic modulus in the range of 0–2 GPa. This indicates that the larger the elastic modulus, the more prone to stress instability is the aquiclude. When the elastic modulus of aquiclude is low (<1.5 GPa), the influence of Poisson's ratio on the maximum tensile stress of aquiclude is small. While when the elastic

modulus of aquiclude is high (>1.5 GPa), the maximum tensile stress of the aquiclude increases significantly with the increase in Poisson's ratio.

4.2. Aquiclude Thickness and Groundwater Level

Keeping other parameters constant and changing the aquiclude thickness h_2 and groundwater level h_0 only, the influence of aquiclude thickness and groundwater level on the mining stability of aquiclude are obtained in Figure 6.

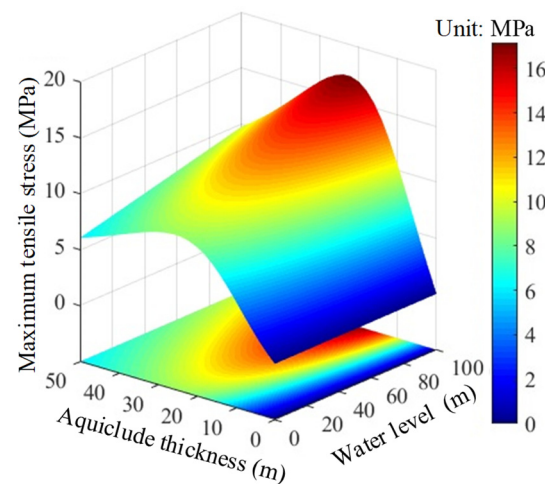


Figure 6. Influence of aquiclude thickness and groundwater level on the mining stability of aquiclude.

As shown in Figure 6, the maximum tensile stress of aquiclude changes in a parabola with the increase in the aquiclude thickness in the range of 0–50 m, showing a trend of increasing first and then decreasing. When the aquiclude thickness is about 20 m, the maximum tensile stress of the aquiclude reaches the maximum. In the range of 0–100 m, the maximum tensile stress of aquiclude increases continuously with the increase in groundwater level. It shows that the higher the groundwater pressure in the aquifer, the lower the mining stability of the aquiclude.

4.3. Coalface Length and Longwall Panel Length

Keeping other parameters constant and changing the working face length L_f and longwall panel length L_r only, the influence of coalface length and longwall panel length on the mining stability of aquiclude is obtained in Figure 7.

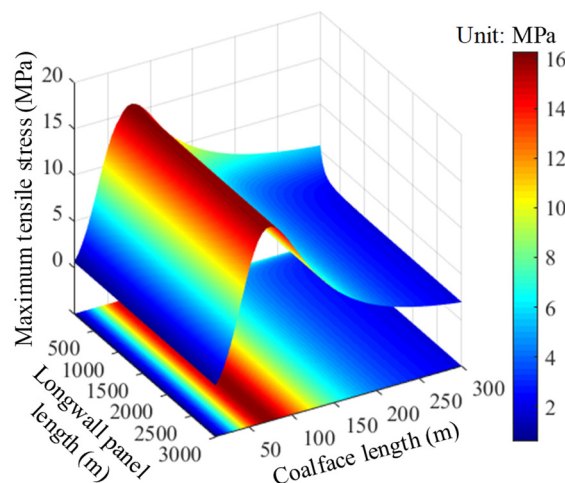


Figure 7. Influence of coalface length and longwall panel length on the mining stability of aquiclude.

As shown in Figure 7, the maximum tensile stress of aquiclude exhibits a trend of sharp increase followed by a slow decrease with the increase in the coalface length in the range of 0–300 m. When the coalface length is 50–100 m, it has the largest influence on the maximum tensile stress of aquiclude. When the coalface length is longer than 200 m, its influence on the maximum tensile stress of aquiclude is smaller and remains unchanged. When the longwall panel length is longer than 500 m, its influence on the maximum tensile stress of aquiclude is not obvious. However, when the longwall panel length is less than 500 m, its influence on the maximum tensile stress of aquiclude is more significant, and the smaller the coalface length, the larger the maximum tensile stress of aquiclude.

5. Engineering Applications

In order to verify the effectiveness of the instability criterion of weakly cemented aquiclude, the actual geology and mining conditions of the 1404 coalface in Xinjiang Ehuobulake Coal Mine are used as the case to determine the feasibility of water-conserved mining, and the water-inflow of the coalface is monitored during the mining process.

5.1. Determination of Aquiclude Mining Stability

The 1404 coalface of the Ehuobulake coal mine in Xinjiang adopts longwall mining. The coalface length is 278 m, the longwall panel length is 3980 m, and the coal seam thickness is 3.3 m. According to the actual hydrogeological data of the Ehuobulake coal mine, the main shallow aquifers in the mining area are the Quaternary loose aquifer and the lower Jurassic pore fissure aquifer. The relative aquiclude is argillaceous sandstone with a thickness of 17.8 m, buried depth of 98.4 m, and tensile strength of 1.2 MPa. The comprehensive column of the 1404 coalface is shown in Figure 8.

Column	Lithology	Thickness (m)	Remark
	Glutenite	32.0	Aquifer
	Sandstone	66.4	Aquifer
	Argillaceous Sandstone	17.8	Aquiclude
	Silty fine sandstone	6.5	
	Coarse sandstone	26.0	
	Mudstone	0.4	
	1# coal seam	3.3	

Note: # is the meaning of coal seam number

Figure 8. The comprehensive column of the 1404 coalface.

According to Equation (14), the maximum tensile stress of aquiclude in 1404 coalface under current mining conditions is:

$$\sigma_t^{\max} = \sigma_y^{\max} = 0.85 \text{ MPa} < [\sigma_t] = 1.2 \text{ MPa} \quad (20)$$

Therefore, it can be predicted that the retreat mining of the 1404 coalface will not cause the instability failure of the overlying argillaceous sandstone aquiclude, which means that the 1404 coalface can achieve water-conserved mining.

5.2. Variation of Coalface Water Inflow

In order to verify the accuracy of the feasibility determination of water-conserved mining in 1404 coalface, the water inflow of the coalface is monitored, and the changes of water inflow during the mining process of 1404 coalface are recorded as shown in Figure 9.

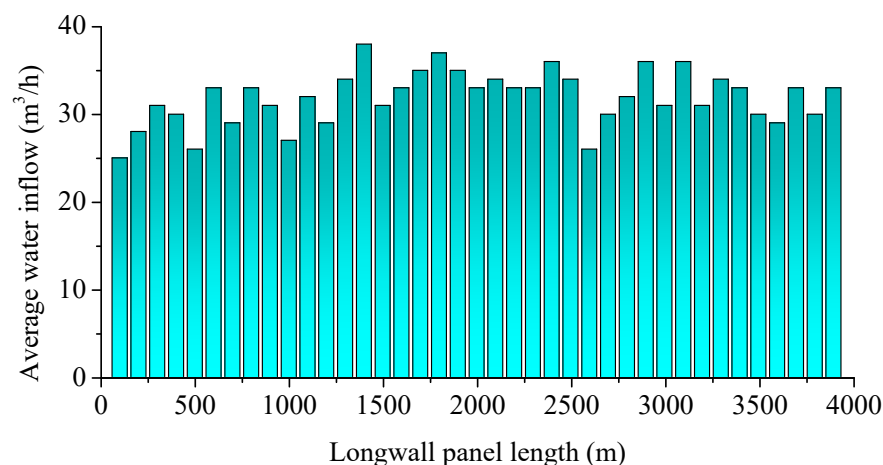


Figure 9. Water inflow variation of 1404 coalface.

As shown in Figure 9, the water-inflow of the 1404 coalface is small during the retreat mining. The maximum water inflow is $38 \text{ m}^3/\text{h}$, the minimum water inflow is $25 \text{ m}^3/\text{h}$ and the average water inflow is $31.9 \text{ m}^3/\text{h}$. It is considered that the source of water-inflow of the coalface is the sandstone water in the main roof. The retreat process does not cause the loss of water resources in shallow aquifers. The water-resistance ability of the aquiclude is good, and there is no mining instability damage in the aquiclude. It indicates that the mining instability criterion of the weakly cemented aquiclude proposed in this paper can effectively determine the feasibility of water-conserved mining in weakly cemented strata.

6. Discussion

In the previous research, more attention is paid to the stress state of the rock stratum and less to the change of the water pressure on the aquiclude caused by coalface mining. In this paper, a mechanical model of the weakly cemented aquiclude is established considering the stress and hydraulic pressure according to the concave subsidence characteristic and the water pressure change of the weakly cemented aquiclude. Furthermore, the quantitative criteria for the mining instability of the weakly cemented aquiclude are obtained. This is the originality of this work.

Based on the previous studies and elastic thin plate theory [34–37], the general law of mining stability variation and the quantitative solution of instability criterion of weakly cemented aquiclude is obtained. However, it is obviously insufficient to assume the weakly cemented aquiclude is an elastomer according to the similarity simulation. In future research, the elastoplastic or plastic model should be further studied to express the deformation characteristics of the weakly cemented aquiclude accurately.

As this work focuses on the mining stability criterion of the weakly cemented aquiclude, the degree of influence of different factors (such as aquiclude thickness, groundwater level, elastic modulus, Poisson's ratio, et al.) on the aquiclude stability has not been analyzed. The influence of different factors on the mining stability of the weakly cemented aquiclude should be different. At the same time, it is of positive significance to master the most critical factors of the aquiclude instability. This will be one of our future works. In addition, humidity is an important factor affecting rock properties. More attention should be paid to the change of rock properties with the increase in humidity in future research.

7. Conclusions

Due to the clay minerals such as kaolinite and montmorillonite, the weakly cemented aquiclude mainly produces bending deformation during underground coal mining, showing a good plastic deformation ability. The water above the aquiclude flows to the middle of the subsidence basin, causing the aquifer water level in the middle of the goaf to decrease first and then increase after the end of mining.

Considering the bending deformation of the weakly cemented aquiclude and the change of groundwater pressure in the aquifer, the stress instability and strain instability criteria of the weakly cemented aquiclude are derived based on the elastic thin plate theory. The influence of the aquiclude thickness, elastic modulus, Poisson's ratio, groundwater level, coalface length, and longwall panel length on the mining stability of the weakly cemented aquiclude is analyzed.

The aquiclude mining-induced instability criterion is applied to the feasibility determination of water-conserved mining in the weakly cemented strata of the Ehuobulake Coal Mine in Xinjiang. The maximum tensile stress of the aquiclude is less than its ultimate tensile strength. It is considered that water-conserved mining can be realized in the coalface. The on-site monitoring of water inflow in the coalface verifies the effectiveness of the mining stability criterion of the weakly cemented aquiclude.

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