Research Article

On a Possible Mechanism of Hydrostatic Pressure on Mineshaft Linings in Western China

Lian-Fei Kuang,1 Qi-Yin Zhu,1 Jian-Zhou Wang,1 and Bo Wang2

1State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou 221008, China
2School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

Correspondence should be addressed to Jian-Zhou Wang; wjzh@cumt.edu.cn

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Reasonable determination of the water pressure on the shaft linings is the key to the optimization design of the vertical shaft of mining. The traditional water pressure calculation model is not suitable for the stratum conditions in western China. A new shaft-surrounding rock seepage model is proposed based on the coordinated seepage conditions of surrounding rock and shaft linings. In the model, the seepage within the shaft depth is assumed happening in a unit thickness confined aquifer. Thereby, the water pressure on the shaft linings is derived by the steady seepage theory, and the water pressure reduction coefficient is defined by normalizing the hydrostatic pressure. The influences of shaft diameter and shaft depth, the permeability coefficient of the surrounding rock, and the seepage flow on the water pressure reduction coefficient are analyzed. After that, the mechanism of reducing water pressure by grouting the surrounding rock is studied by considering the stratum conditions in western China. Finally, a practical equation, which only relating to the depth of the shaft, is fitted on account of the averaged water pressure reduction coefficient from the theoretical model. The effectiveness of the theoretical model and the fitted equation are verified by the measured data and data in the literature.

1. Introduction

The development and utilization of deep earth resources often require the construction of vertical shaft channels. The depth of some newly established vertical shafts in western China exceeds 1000 m. These shafts pass through the Cretaceous and Jurassic porous water-bearing rock layers. Accurately determination of the external water pressure on the shaft linings is one of the important contents in shaft designing [1, 2].

The shaft lining is generally made of high-strength and low permeability concrete, and the maximum water pressure is equal to the hydrostatic pressure corresponding to the water level line [3, 4]. However, due to the imperfect shaft construction technology and the groundwater erosion, there are often weak surfaces in the shaft linings, forming seepage channels and reducing water pressure [5–8]. It is found that the measured water pressure on the shaft linings is almost lower than the hydrostatic pressure at the corresponding depth. Thus, the reduction coefficient method is widely used to calculate water load on the shaft lining in the world [9]. For the hydrostatic pressure acting on the shaft lining, most studies believe that the ratio of permeability coefficient between the surrounding rock and shaft linings can be used to estimate the hydrostatic pressure reduction [9]. The existing kinds of literature contain relatively little information about the estimation of actual water pressure on the shaft linings. For water penetration in shield lining structures, a large number of theoretical and numerical analyses can be seen in the literature [10–12]. Kolymbas and Wagner [13] gave an analytical expression for the estimation of the steady-state groundwater ingress into a drained tunnel of the circular cross-section based on conformal mapping. Tan et al. [14] proposed a model to predict the hydraulic pressure and crack condition at the outer face of the lining based on measured water inflow rate and the crack condition.
at the inner face. Wang [15] proposed an equivalent depth of the water seepage model in the presence of the randomness and spatial correlation of the water seepage distribution. These mentioned water pressure calculation methods cannot be used to calculate water pressure on the shaft linings.

The goal of this study is to propose a practicable method for calculating shaft lining’s water pressure based on a new seepage flow model. The innovation of the model is that the proposed water pressure calculation method adopts water seepage flow as a variable for the first time.

2. Hydraulic Load Model of Shaft Lining

2.1. Characteristics of Surrounding Rock in Western China. Coal resources in western China are mainly distributed in Inner Mongolia, Ningxia, Shaanxi, and Xinjiang. The stratigraphic characteristics of mine crossing in these areas are obviously different from those in the Middle East. The strata are mainly Mesozoic Cretaceous and Jurassic strata. Among them, fractures in the Cretaceous strata are developed, which is the main source of water pressure of shaft lining. The porosity of the formation is greater than 20%, the density is between 2.1 and 2.4 g/cm$^3$, and the strength of core samples ranges from 1 to 55 MPa. Table 1 summarizes the permeability coefficient of Cretaceous strata, with the maximum value of 0.2 m/h, the minimum value of $1 \times 10^{-5}$ m/h, and the average value of 0.02 m/h, which is helpful for the modeling of shaft-surrounding rock seepage model.

| Minimum value (m/h) | Maximum value (m/h) | Average (m/h) | Sample variance | Sample number |
|---------------------|---------------------|--------------|-----------------|---------------|
| $1 \times 10^{-5}$  | 0.2                 | 0.02         | 0.8026          | 805           |

2.2. Shaft-Surrounding Rock Seepage Model. A large number of mines shaft are being built in western China for coal mining. To calculate the water inflow rate of a shaft lining, the shaft can be defined in a cylindrical coordinate system. The origin of the coordinate system is the center point of the shaft. The surrounding rock and linings of the shaft are permeable, and groundwater will penetrate the shaft to form a seepage field, as shown in Figure 1(a). In addition, it is assumed that the surrounding rock and the shaft lining are isotropic, uniform, and continuous materials.

Due to the problems of concrete construction connection and shaft linings damage, there are water leakage points in the shaft, which may occur anywhere within the depth of the shaft. Some places have large water leakage inflow, while others have small water leakage inflow. Then, shaft seepage does not conform to uniform seepage from the engineering practice. However, due to the total shaft seepage inflow being a key design parameter during shaft design, it is a good way to use it to associate with the water pressure acting on shaft linings. Therefore, it is necessary to make certain assumptions about shaft leakage. As the water leakage at depth $H$, the bottom of the shaft, has the greatest impact and is the most unfavorable working condition, this paper assumes that the shaft seepage only occurs in the confined aquifer with unit thickness at $H$, and the other parts of the shaft are in impermeable layers as shown in Figure 1(b). The thickness of the aquifer is constant and extends horizontally, in which the water seepage follows the steady flow, and its movement obeys Darcy’s law. The hydraulic coefficient of the shaft linings and the surrounding rock are defined as $k_c$ and $k_{sw}$, and the far-field distance is $R$. If the shaft total water seepage flow $Q$ is all inflow of aquifers, according to the theory of hydrodynamics, the relationship between $Q$ and the water pressure on the outer surface of the shaft linings can be analyzed.

2.3. Basic Equation. When the problem of shaft leakage is simplified to the action of confined water per unit thickness, the problem becomes theoretically solvable. According to the classical two-phase seepage theory, for permeable shaft linings under the water table, the radial flow head distribution satisfies the Laplace equation [16] expressing as

\[
\frac{1}{r} \frac{d}{dr} \left( r \frac{dp_{fc}}{dr} \right) = 0, \quad a \leq r \leq b, \tag{1}
\]

\[
\frac{1}{r} \frac{d}{dr} \left( r \frac{dp_{fw}}{dr} \right) = 0, \quad b \leq r \leq R, \tag{2}
\]

where $p_{fc}$ is the seepage pressure of the shaft lining, $p_{fw}$ is the seepage pressure of the surrounding rock, and $a$ and $b$ denote the inner and outer radius of the shaft, respectively.

2.4. Boundary Conditions. It is assumed that the flow rate at the junction of the surrounding rock and the shaft lining is continuous and the pressure is equal, and the hydrostatic pressure at the far-field $R$ is $P_R = \rho g H$. Then, the boundary conditions for the model shown in Figure 1 are as follows:

\[
Q_{rev} = Q, \tag{3}
\]

\[
\frac{k_c dp_{fw}}{dr} = \frac{k_{sw} dp_{fc}}{dr}, \tag{4}
\]

\[
p_{fc(r=b)} = p_{fw(r=b)} = p_b, \tag{5}
\]

\[
p_{fw(r=R)} = P_R, \tag{6}
\]

where $p_b$ denotes the water pressure at the outer of the shaft. Since the thickness of the shaft is rather small relative to the height of the groundwater head, the penetration force of the shaft can be simplified as the surface force acting on the outer surface of the shaft, which is the water pressure.

2.5. Model Solving. According to Equation (2), the seepage pressure on the surrounding rock can be expressed as

\[
dp_{fw} = \frac{1}{r} \frac{d}{dr} \left( r \frac{dp_{fw}}{dr} \right) = C \int_{r}^{R} \frac{1}{r} dr. \tag{7}
\]

Substituting the boundary conditions Equations (5) and
(6), thereby the derivative of \( P_{fw} \) over \( r \) can be expressed as

\[
\frac{\partial P_{fw}}{\partial r} = \frac{1}{r \ln (R/b)} \left( \frac{P_R - P_b}{r} \right).
\]  

(8)

According to the boundary equation (4), the water inflow at the interface between the shaft lining and the surrounding rock is equal, and we can get:

\[
\frac{\partial P_c}{\partial r} = \frac{k_w}{k_{cw}} \frac{P_R - P_b}{r \ln (R/b)}.
\]  

(9)

For a shaft, the total water seepage can be monitored, and its value can also be calculated by the seepage at the inside of the shaft

\[
Q = 2\pi a m k_w \frac{\partial P_{fw}}{\partial r}
\]

| (10)

where \( m \) is the thickness of the bedrock confined aquifer and unit thickness is assumed in this paper and \( y_w \) is the weight of water.

Substitute Equation (9) into Equation (10), the water pressure at the outer of the shaft can be obtained as

\[
P_b = P_R - \frac{Q y_w \ln (R/r_0)}{2\pi k_w}.
\]  

(11)

If the seepage of the shaft is not considered, the water pressure on the outer of the shaft linings \( P_R \) should be equal to \( P_b \). Under the presented seepage model, the value of \( P_b \) is smaller than \( P_R \), as shown in Equation (11). Thus, the water pressure \( P_b \) has a certain reduction effect. To study the influencing factors on reduction, a water pressure reduction coefficient \( \beta \) is defined, which is defined as

\[
\beta = \frac{P_b}{P_R} = 1 - \frac{Q \ln (R/b)}{2\pi H k_w}.
\]  

(12)

Equation (12) built the relationship between water pressure reduction coefficient and shaft seepage flow, which has never appeared in the previous literature.

3. Water Pressure Reduction Mechanism of the Shaft Lining

From Equations (11) and (12), the water pressure reduction of the shaft \( \Delta P \) and the water pressure reduction coefficient \( \beta \) related to the far-field hydrostatic pressure, \( P_R \) can be obtained:

\[
\Delta P = P_R - P_b = \frac{Q y_w \ln (R/b)}{2\pi k_w},
\]

\[
\beta = \frac{P_b}{P_R} = 1 - \frac{Q \ln (R/b)}{2\pi H k_w}.
\]  

(13)

The decrease of hydrostatic pressure on the outer of the shaft linings is related to the shaft water seepage inflow \( Q \) and the permeability of the surrounding rock \( k_w \). From Equation (13), some new understanding can be obtained as shown in Figure 2:

(i) When \( Q = 0, \Delta P = 0, P_b = P_w, \beta = 1 \), the water pressure on the shaft is not reduced.

(ii) As \( Q \) increases, \( \Delta P \) increases. Because \( P_b \) is a constant value, thus \( P_b \) and \( \beta \) decrease. When \( Q \) approaches \( 2\pi H k_w / \ln (R/b) \), \( P_b \) and \( \beta \) gradually approach to zero.

(iii) When the \( k_w \) is larger enough, \( Q \ln (R/b)/2\pi H k_w \) is close to zero, and \( \beta \) is close to 1. In this condition, the water pressure on the shaft tends to be completely discounted.

(iv) \( P_b \) and \( \beta \) decrease with the decreasing of \( k_w \). When \( k_w \) decreases to \( Q \ln (R/b)/2\pi H k_w \), \( P_b \) and \( \beta \) are approaching zero, which means the water pressure on the shaft tends to be completely discounted.

3.1. Basic Characteristics of Water Pressure Reduction Coefficient

Following with Equation (12), the characteristics of the relationship between the shaft lining water pressure reduction coefficient and various factors shown in Figure 3 can be obtained. The basic parameters in the analysis are \( R = 500 \text{ m}, H = 800 \text{ m}, b = 4.0 \text{ m}, Q = 3 \text{ m}^3/\text{h}, \) and \( k_w = 0.02 \text{ m}/\text{h} \).
Figure 3(a) shows the evolution of $\beta$ with the outer radius $b$. As $b$ increases, the water pressure reduction coefficient increases. However, within the engineering range of $b = 2.0 \sim 6.0$ m, $\beta$ only changes between 0.835 and 0.868, with a difference of 0.033, which is less than 4.0%. Therefore, the effect of shaft diameter on the water pressure reduction is rather small and can be ignored. Figure 3(b) presents the evolution of $\beta$ with depth $H$. As the depth of the shaft increases, $\beta$ increases nonlinearly. When $H$ is less than 400 m, $\beta$ is less than 0.71 and exceeds 0.90 when $H$ equals 1200 m. Therefore, the deeper the shaft, the more difficult it is to reduce the water pressure on the shaft lining.
Figure 3(c) shows the evolution of $\beta$ with the permeability of confined rock $k_w$. As $k_w$ increases, $\beta$ firstly increases sharply and then tends to level off. For $k_w$ larger than 0.01, $\beta$ changes from 0.71 to 0.95. Figure 3(b) presents the evolution of $\beta$ with seepage flow $Q$. With the increase of $Q$, $\beta$ linearly decreases. When $Q$ equals 3 m$^3$/h, $\beta$ equals 0.86. When $Q$ increases to 6 m$^3$/h, $\beta$ decreases to 0.71, which means a decrease of nearly 17%.

For a specific shaft engineering, its depth and diameter are fixed values. Then, the main factors that affect the water pressure on the shaft linings are the water seepage flow $Q$ and the permeability coefficient $k_w$ of the surrounding rock. Therefore, the effective methods to reduce the water pressure reduction coefficient are (1) properly control the water seepage flow of shaft and (2) minimize the permeability of surrounding rock.

According to the current code for acceptance of shaft sinking and drifting of the coal mine of China (GB50213-2010), the total water seepage flow of the shaft is $Q \leq 6.0$ m$^3$/h for the depth $H < 600$ m and $Q \leq 10.0$ m$^3$/h when $H$ varies from 600 to 1000 m. Thus, the variation of $Q$ in the analysis is 0.0 ~ 10.0 m$^3$/h.

Mine shafts in western China mainly pass through Cretaceous and Jurassic porous water-bearing rock layers. According to the relevant survey report analysis of the shaft construction project in western China, the natural permeability coefficient of the surrounding rock of the Lower Cretaceous Zhidan Group, which the shaft mainly crosses, is about 0.02 m/h as shown in Table 1. The natural seepage coefficient $k_w$ of surrounding rock in the Middle Jurassic Zhiluo formation and Yan’an formation is mainly between 0.001 and 0.006 m/h. Considering the variability and non-uniformity of permeability coefficient, this paper takes positive and negative 30% of the average permeability coefficient of Cretaceous surrounding rock of 0.02 m/h for the following analysis, which is 0.006~0.06 m/h.
3.2. Water Pressure Reduction Influenced by Seepage Flow.
The variation of water seepage defined above is used to discuss its influence on the water pressure reduction coefficient. Figure 4 shows the evolution of the water pressure reduction coefficient with seepage flow for several different shaft diameters, depths, and surrounding rock permeability coefficients. In the curve family, the change of factors at different levels does not change the general trend of the linear decrease of $\beta$ with $Q$, but only changes the position of the curves. Taking the shaft water seepage flow $Q = 4.0 \text{ m}^3/\text{h}$, for example, $\beta$ is reduced from 0.82 to 0.78 when $b$ is reduced from 6.0 m to 2.0 m as shown in Figure 4(a). Figure 4(b) shows $\beta$ decreases from 0.87 to 0.62 when $H$ is reduced from 1200 m to 400 m. Similarly, $\beta$ decreases from 0.94 to 0.36, while $k_w$ decreases from 0.006 m/h to 0.06 m/h as presented in Figure 4(c). Figure 4(d) summarizes the influences of three factors on the water reduction coefficient. For constant, $Q = 4 \text{ m}^3/\text{h}$. The three factors vary within the respective ranges of $k_w = 0.006-0.06 \text{ m}/\text{h}$, $H = 400-1200 \text{ m}$, and $b = 2.0 \sim 6.0 \text{ m}$ as defined above. The influence of the permeability coefficient of the surrounding rock is greater than the shaft depth, and the influence of the shaft diameter can be ignored. It can be concluded that the permeability coefficient of surrounding rock is the most sensitive parameter to the water pressure reduction coefficient. Thus, the water pressure on shaft lines can be adjusted by engineering measures to change the permeability coefficient of surrounding rock, for example, grouting.

If the shaft water seepage flow is artificially increased, such as controlling $Q = 10 \text{ m}^3/\text{h}$, the value of $\beta$ at $k_w = 0.02 \text{ m}^3/\text{h}$ will be reduced to 0.52, which is 35.7% lower than when $Q = 4 \text{ m}^3/\text{h}$. Thus, the water pressure reduction effect of the shaft is significantly enhanced. Therefore, based on ensuring the overall safety and stability of the shaft, the idea of “draining and depressurizing” can be adopted. New technologies such as arranging drain holes at specific locations...
on the shaft in the deep part of the shaft and installing intelligent water volume control devices can actively control the seepage of the shaft and greatly reduce the water pressure acting on the shaft.

3.3. Water Pressure Reduction Influenced by Surrounding Rock Permeability. Figures 5(a)–5(c) show a curve family of nonlinear changes between the water pressure reduction coefficient and the permeability coefficient of surrounding rock under different shaft diameters, shaft depths, and shaft water seepage flow. Similarly, changes in the three factors do not affect the trend of the relationship between the water pressure reduction coefficient and the permeability coefficient of the surrounding rock.

Taking the average permeability coefficient of surrounding rock $k_w = 0.02 \text{ m/h}$ to analyze, the influence of different shaft diameters on $\beta$ is only 0.033, which can be ignored. The influence of different depths and shaft water seepage flow on $\beta$ is 0.19 and 0.48, respectively. Figure 5(d) summarizes the influence of the three factors on the water pressure reduction coefficient for constant $k_w = 0.02 \text{ m/h}$. It can be seen that the impact of shaft depth and water seepage flow in the shaft is of an order of magnitude, and the impact of shaft diameter changes is minimal.

It can be seen from the above analysis that when the shaft depth is constant, changing the permeability of the surrounding rock $k_w$ can also change the water pressure reduction coefficient $\beta$. That is to say, the surrounding rock of the shaft can be grouted according to the idea of “water blocking and anti-seepage” to reduce its initial permeability coefficient and improve its integrity and impermeability, thereby reducing the water pressure acting on the shaft. Existing experimental studies have shown that the use of ultrafine cement grout to grouting pore and fissure sandstone can reduce significantly its permeability coefficient [17–21].

Grouting the surrounding rock of the shaft to improve its impermeability from the initial 0.0% to 60%, Figure 6 shows the relationship between the water pressure reduction coefficient of the shaft lining and the initial permeability coefficient of the surrounding rock for different grouting effects. After the surrounding rock is grouted, the water pressure reduction coefficient $\beta$ is still closely related to the initial permeability coefficient of the surrounding rock. For surrounding rock with a relatively small initial permeability coefficient, the effect of reducing the water pressure of the shaft after grouting is better. However, regardless of the initial permeability, as the grouting intensity of the surrounding rock increases, $\beta$ becomes smaller and smaller. The better the grouting effect of the surrounding rock, the impermeability increases greater, and the water pressure acts the lower on the shaft linings. Taking the average initial permeability coefficient of surrounding rock of 0.02 m/h as an example, $\beta$ is 0.82, 0.76, and 0.64, and the water pressure on the shaft is reduced by 18%, 24%, and 36% corresponding to the three cases of increasing the impermeability of surrounding rock by grouting by 20% (that is, 80% of the original permeability), 40%, and 60% as shown in Figure 6(b).

Similarly, Figure 7 compares the grouting effect on $\beta$ for the surrounding rock with different initial permeability coefficients. For the three cases of the surrounding rock with 0.015 m/h, 0.020 m/h, and 0.025 m/h permeability, $\beta$ becomes 0.59, 0.79, and 0.86 when the permeability of the surrounding rock decreases by 30% after grouting (that is, 70% of the original permeability). $\beta$ are 0.28, 0.64, and 0.76, respectively, when the permeability continues to decrease to 60%. Therefore, for surrounding rock with greater initial permeability, a better-effective surrounding rock grouting project is required to obtain the same water pressure reduction effect. Therefore, for a certain shaft project, the effect of surrounding rock grouting directly affects the water pressure on the shaft.

**Figure 6:** Relationship between water pressure reduction coefficient and the initial permeability: (a) effects of grouting; (b) enlargement of grouting effect.
3.4. Verification of Proposed Model. Once the shaft depth, shaft lining diameter, surrounding rock permeability, and shaft seepage flow are determined, the water pressure reduction factor can be directly calculated by Equation (12). According to the foregoing analysis, take the parameters $R = 500$ m, $b = 4.0$ m, and $k_w = 0.02$ m/h, and calculate the water pressure reduction coefficient $\beta$ under the permeability reduction of surrounding rock by 10%, 20%, 30%, and 40% after grouting. $Q = 3.0$, 4.5, 6.0, and 7.5 m$^3$/h, and $H = 600$, 800, 1000 m, and 1200 m. The calculated results are summarized in Table 2.

Figure 8 shows the variation of the water pressure reduction coefficient of the shaft in the depth of 600 m ~ 1200 m under the average value of $k_w$ equaling 0.02 m/h. As presented in Figure 8(a), the upper solid line indicates that permeability is reduced by 30% and water seepage flow is 4.5 m$^3$/h, and the dotted line below is that permeability is also reduced by 30%, and water seepage flow is 6.0 m$^3$/h. The middle line plots the average value of Table 2. $\beta$ shows a nonlinear change with the shaft depth, and its values are 0.54, 0.66, 0.72, and 0.77, respectively, corresponding to $H = 600$, 800, 1000, and 1200 m.

In engineering practice, it is difficult to evaluate quantitatively the grouting effect of surrounding rocks, and it is also difficult to accurately predict the amount of water seepage in the shaft design stage. For simplified analysis, Figure 8(b) presents the averaged $\beta$-$H$ relationship, and an approximate equation is fitted:

$$\beta = 0.0003H + 0.442. \quad (14)$$

For the fitting equation, the regression correlation coefficient $R^2 = 0.997$, which is highly correlated.

Figure 9 shows the measured maximum water pressure after the construction of coal mine shaft linings from western China and its comparison with the proposed Equation (14). The measured data in Figure 9 are measured from HuLuSu coal mine wild shaft by the first author. To increase contrast, the water pressure acting on the shaft lining of MenKeQing coal mine measured by Bo [1] is also selected. It can be seen that the measured maximum water pressures are all less than the predicted hydrostatic pressure by the proposed equation, and the method of no reduction is not applicable at all. The averaged theoretical value from Table 2 falls in the middle of the measured values. The predicted values by the fitted equation are greater than the measured value, which is also safe for shaft design. The proposed

| $H$ (m) | $Q$ (m$^3$/h) | 10% | 20% | 30% | 40% | Average |
|---|---|---|---|---|---|---|
| 600 | 3.0 | 0.79 | 0.76 | 0.73 | 0.68 | 0.74 | 0.54 |
|   | 4.5 | 0.68 | 0.64 | 0.59 | 0.52 | 0.61 |   |
|   | 6.0 | 0.57 | 0.52 | 0.45 | 0.36 | 0.48 |   |
|   | 7.5 | 0.47 | 0.40 | 0.31 | 0.20 | 0.34 |   |
|   | 3.0 | 0.84 | 0.82 | 0.80 | 0.76 | 0.80 |   |
| 800 | 4.5 | 0.76 | 0.73 | 0.69 | 0.64 | 0.71 | 0.66 |
|   | 6.0 | 0.68 | 0.64 | 0.59 | 0.52 | 0.61 |   |
|   | 7.5 | 0.60 | 0.55 | 0.49 | 0.40 | 0.51 |   |
|   | 3.0 | 0.87 | 0.86 | 0.84 | 0.81 | 0.84 | 0.67 |
| 1000 | 4.5 | 0.81 | 0.78 | 0.75 | 0.71 | 0.76 | 0.72 |
|   | 6.0 | 0.74 | 0.71 | 0.67 | 0.61 | 0.68 |   |
|   | 7.5 | 0.68 | 0.64 | 0.59 | 0.52 | 0.60 |   |
|   | 3.0 | 0.89 | 0.88 | 0.86 | 0.84 | 0.87 |   |
| 1200 | 4.5 | 0.84 | 0.82 | 0.79 | 0.76 | 0.80 | 0.77 |
|   | 6.0 | 0.79 | 0.76 | 0.73 | 0.68 | 0.74 |   |
|   | 7.5 | 0.73 | 0.70 | 0.66 | 0.60 | 0.67 |   |
equation can well reflect the water pressure acting on coal mine shaft linings in western China.

4. Conclusions

(1) A hydraulic load model of shaft lining was constructed, and a theoretical expression of the water pressure reduction coefficient was derived. The control parameter of the water pressure reduction is the permeability coefficient of the surrounding rock and the seepage flow. The influence of shaft diameter on the water pressure reduction is very small which can be ignored.

(2) The effective ways for reducing the water pressure reduction coefficient are controlling the water seepage flow of the shaft and minimizing the permeability of the surrounding rock. Therefore, it is feasible to actively adjust the permeability of the shaft and grouting the surrounding rock for reducing the water pressure coefficient.

(3) For the mine shaft with the depth range from 600 to 1200 m, considering that the permeability of the surrounding rock is reduced by 10%-40% after grouting, and the water seepage flow is 3.0-7.5 m³/h, the theoretical equation obtains the water pressure reduction coefficient to be 0.54-0.77. An approximate linear formula $\beta = 0.0003H + 0.442$ was fitted, which can well be used to calculate the water pressure reduction coefficient.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

No potential conflict of interest is reported by the authors.

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