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Research Article

Study on Hydrodynamics Model of Total Tailings Filling Slurry Dehydration

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In order to ensure the dehydration effect of the whole tailings backfill, a dehydration model of the whole tailings backfill was established based on hydrodynamics on the basis of satisfying certain assumptions, and the theoretical solution was carried out. The control variable method is used to study the variation of dewatering capacity with dewatering depth and radius, and the applicability of the dewatering model is verified by experiments. The results show that the dewatering capacity increases with the increase of dewatering radius and decreases with the increase of dewatering depth by a quadratic polynomial. By comparing the experimental values with the theoretical ones, it is found that the variation law of the dewatering capacity with radius is the same and increases with the increase of dewatering depth. The reason is that the content of fine particles in the unclassified tailings is large and the filter hole on the branch pipe is blocked under the action of the hydrodynamic force. Therefore, the dewatering effect of the new root-like dehydration tube can be guaranteed by using the branch pipe arranged at the full height of main dewatering pipe. The dehydration model is modified by the test results to ensure the applicability.

1. Introduction

A safe, efficient, and low-cost dewatering technology is essential to ensure the filling effect. Under the current mining situation, if cemented filling is used in the large goaf formed in the mining process of low-grade deposits, the stability of the filling stope can be guaranteed, but the filling cost is high. If cementless filling is used, the dewatering effect cannot be guaranteed and the stability of the filling stope cannot be assured, leaving a serious potential safety hazard for mining [1–10]. How to solve the problem of rapid dewatering and shorten the filling period of filling stope has become the first important problem of efficient and stable operation of cementless filling system.

Experts and scholars all over the world have conducted a lot of research on the dewatering technology of fine tailings (see Table 1). The dewatering technology can be divided into two categories: external effect and no external effect.

Zhang et al. [23] improved the common dewatering pipe without considering the external effect, increasing the number of dewatering pipes, and shortening the spacing of dewatering pipes, designed a new root-like dewatering pipe based on bionics, and carried out dewatering tests of the new root-like dewatering pipe and the common dewatering pipe, respectively. It was concluded that the new root-like dewatering pipe can significantly improve the dewatering rate compared with the common dewatering pipe. Scholars have carried out research on the dynamic model [24–28], but there are few related research studies on the theoretical model of tailing filling slurry dehydration.

Therefore, on the basis of the existing research results, the authors construct the dewatering model of full tailings filling slurry based on hydrodynamics, analyze the variation law of the dewatering amount of full tailings filling slurry with the dewatering depth and dewatering radius, carry out the indoor dewatering test combined with the engineering example, compare the experimental value with the theoretical value, and verify the reliability of the dewatering model of full tailings filling slurry. The research results enrich the dewatering theory of noncemented filling slurry,

Table 1: Summary of research achievements in dewatering technology of whole tailings.

Type	Method	Pros and cons
External effect	Electro-osmosis [11–14] Negative pressure method [15] Forced air method [16] Chain dewatering method [17]	The above dehydration method has good dehydration effect, but the cost is high, the related supporting technology is complex, and there are potential safety hazards
No external effect	Setting dewatering closed wall and dewatering well [18] Increasing the spacing and diameter of dewatering pipe [19–21] Adding a certain amount of coarse particles to improve the particle size distribution [22]	This can improve the dehydration speed to a certain extent, but also lead to the increase of dehydration cost

so as to achieve the purpose of rapid dewatering of filling stope, shorten the filling period, and improve the dewatering effect of filling stope.

2. Dewatering Model of Full Tailings Filling Slurry Based on Hydrodynamics

2.1. Basic Assumptions.

(1) Assuming that the slurry is homogeneous and its concentration remains constant during dewatering, the unsaturated hydraulic conductivity of the slurry is constant.

(2) Assuming that the dewatering pipe is evenly distributed in its depth range, the water in the filling body flows to the dewatering pipe along different paths. The closer the dewatering pipe, the more obvious the streamline bending and the greater the hydraulic gradient. With the distance from the dewatering pipe, the streamline bending degree gradually decreases, as shown in Figure 1.

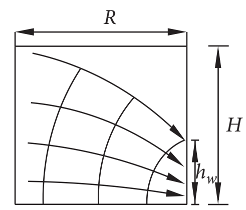

Figure 1: Schematic diagram of water flow in total tailing filling slurry.

On the right side of Figure 1 is the dewatering pipe, in which H is the effective dehydration depth of tailings filling slurry and h_w is the dehydration depth (height of the dewatering pipe).

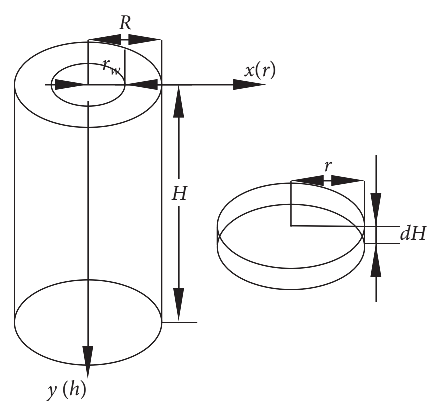

Figure 2: Schematic diagram of the dehydration model of total tailings filling slurry.

2.2. Construction of Dewatering Model for Full Tailings Filling Slurry

2.2.1. Single Stripper. In order to facilitate the theoretical calculation, it is assumed that the dehydration model of full tailings filling slurry is shown in Figure 2, and the micro-element is selected as the research object.

According to Darcy's law and Dupuit assumption, the flux of any infinitesimal element is as follows:

$$Q = \omega K J = 2\pi r H K \frac{dH}{dr}, \tag{1}$$

where Q is the amount of water removed, ml; ω is the surface of water removed; K is the unsaturated hydraulic conductivity, which can be measured by using the infiltration meter through the indoor test, cm/S; r is the radius of cylinder, *m*; H is the effective dehydration depth, *m*; and J is the gradient of plane radial flow.

The research method of reference [29, 30] is introduced, by introducing potential function $\varphi = 1/2KH^2$:

$$Q = 2\pi r \frac{d\left((1/2)KH^2\right)}{dr} = 2\pi r \frac{d(\varphi)}{dr}. \tag{2}$$

According to the axisymmetric condition and potential function, the transformation is carried out:

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\varphi}{dr}\right) = 0. \tag{3}$$

Assuming that the tailings filling slurry is homogeneous, the following formula holds:

$$\frac{\partial}{\partial x}\left(h\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\frac{\partial H}{\partial y}\right) = 0. \tag{4}$$

Let $h = H$, then

$$K\frac{\partial}{\partial x}\left(h\frac{\partial H}{\partial x}\right) = K\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) = \frac{\partial^2}{\partial x^2}\left(\frac{1}{2}KH^2\right) = \frac{\partial^2\varphi}{\partial x^2},$$
$$K\frac{\partial}{\partial y}\left(h\frac{\partial H}{\partial y}\right) = \frac{\partial^2\varphi}{\partial y^2},$$
$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} = 0. \tag{5}$$

The boundary conditions are as follows:

$$r = R, \varphi = \varphi_R = \frac{1}{2}KH^2,$$
$$r = r_w, \varphi = \varphi_{rw} = \frac{1}{2}Kh_w{}^2, \tag{6}$$

where R is the radius of influence, that is, the distance from the center of the main dehydration pipe to the edge of the influence range; h_w is the dehydration depth; and r_w is the dehydration radius.

In formula (2), the variables are separated and integrated under the above boundary conditions; it can be concluded that $\varphi = \int Q/2\pi r dr$, and the following formula can be obtained:

$$\varphi = \frac{Q}{2\pi}\ln r + C, \tag{7}$$

$$r = R, \varphi_R = \frac{Q}{2\pi}\ln R + C, \tag{8}$$

$$r = r_w, \varphi_{rw} = \frac{Q}{2\pi}\ln r_w + C. \tag{9}$$

By subtracting formulas (8) and (9) and eliminating C, we get the following results:

$$Q = \frac{2\pi(\varphi_R - \varphi_{rw})}{\ln R/r_w}. \tag{10}$$

By substituting the potential function into formula (10), the expression of dehydration model of full tailings filling slurry can be obtained:

$$Q = \frac{\pi K\left(H^2 - h^2{}_w\right)}{\ln R/r_w}. \tag{11}$$

According to formula (11), the unsaturated hydraulic conductivity K, effective dehydration depth H, and influence radius R are all constant on the basis of meeting the assumed conditions, and the dehydration depth h_w and dehydration radius r_w are the main factors affecting the dehydration of full tailings filling slurry.

2.2.2. Multiple Stripper. Two dehydration pipes are taken as an example to illustrate that, referring to the research method of single dehydration pipe, when two dehydration pipes are near, the dehydration potential of full tailings filling can be calculated according to the superposition principle, which is the following formula:

$$\varphi_D = \frac{1}{2\pi}\left(Q_1 \ln r_1 + Q_2 \ln r_2\right) + \left(C_1 + C_2\right). \tag{12}$$

In the formula, Q_1 and Q_2 are the dehydration amount of the whole tailings filling slurry corresponding to the two dehydration pipes, r_1 and r_2 are the dehydration radius corresponding to the two dehydration pipes, and C_1 and C_2 are constants.

Generally, the same type of dehydration pipe is used in the project, so the dehydration radius of the two dehydration pipes is the same, that is, $r_1 = r_2$. Assuming that the dehydration amount of the whole tailings filling slurry corresponding to the two dehydration pipes is the same, that is, $Q_1 = Q_2$, formula (12) can be transformed into

$$\varphi_D = \frac{Q}{\pi}\ln r + C. \tag{13}$$

Substituting formula (13) into formulas (8) and (9) and eliminating C, we get the following results:

$$Q_D = \frac{\pi(\varphi_{DR} - \varphi_{Drw})}{\ln R/r_w}. \tag{14}$$

By substituting the potential function into formula (14), we can get the expression of dehydration model of full tailings filling slurry with two dehydration pipes:

$$Q_D = \frac{2\pi K\left(H^2 - h^2{}_w\right)}{\ln R/r_w}. \tag{15}$$

3. Project Case Analysis

The above research shows that dehydration radius r_w and dehydration depth h_w are the main factors affecting the dehydration of tailings filling slurry. In order to deeply analyze the variation of dehydration with dehydration radius r_w and dehydration depth h_w, a new type of root dehydration tube and dehydration test device designed by reference [23] are used as test instruments. The whole tailings of an iron mine used to prepare noncemented filling slurry are selected as the test material, test steps are strictly in accordance with the requirements of reference [22], and reliability of the theoretical model is analyzed by comparing the test value with the theoretical value.

3.1. Variation of Dehydration Amount with Dehydration Radius. The unsaturated hydraulic conductivity K of a certain iron ore tailings filling slurry is 0.19 cm/s. The dehydration depth is proposed as 4 cm, and the dehydration radius is 4 cm, 5 cm, 6 cm, and 7 cm, respectively. The parameters are substituted into formula (11) to calculate the dehydration amount of tailings filling slurry, and the calculation results are presented in Figure 3.

It can be seen from the observation of Figure 3 that the dehydration amount of full tailings filling slurry increases with the increase of dehydration radius and shows a

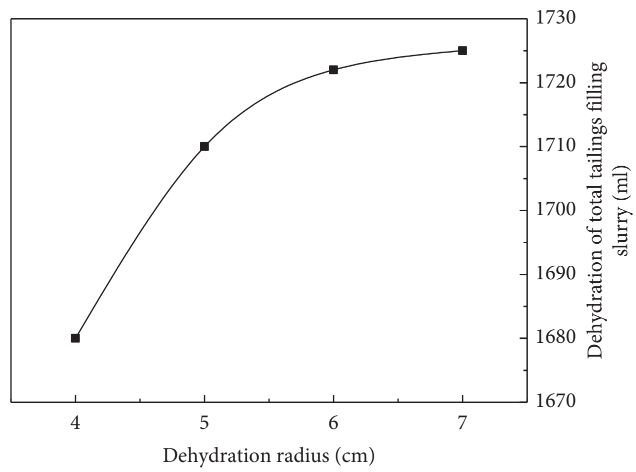

Figure 3: Variation of dehydration amount with dehydration radius.

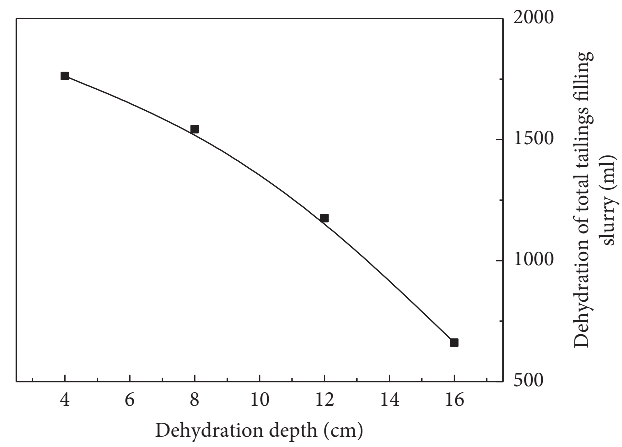

Figure 4: Variation of dehydration amount with dehydration depth.

binomial relationship. The dehydration radius reflects the length of the branch pipe of the new root-like dehydration pipe. The larger the dehydration radius is, the longer the branch pipe is and the greater the dehydration amount of the whole tailings filling slurry is. Therefore, increasing the dehydration radius of the whole tailings filling slurry can ensure the dehydration effect of the whole tailings filling slurry.

3.2. Variation of Dehydration Amount with Dehydration Depth. The dehydration radius is proposed as 4 cm, and the dehydration depth is 4 cm, 8 cm, 12 cm, and 16 cm, respectively. The above parameters are substituted into formula (11) to calculate the dehydration amount of full tailings filling slurry, and the calculation results are shown in Figure 4.

It can be seen from Figure 4 that the dehydration amount of full tailings filling slurry decreases with the increase of dehydration depth and the relationship is binomial. The dehydration depth can reflect the layout height of the branch pipe on the main dehydration pipe. The larger the dehydration depth is, the higher the layout height of the branch pipe on the main dehydration pipe is and the smaller the dehydration amount of the whole tailings filling slurry is. Therefore, the layout of the branch pipe at the bottom of the main dehydration pipe can achieve the purpose of improving the dehydration amount of the whole tailings filling slurry.

In conclusion, the effective way to improve the dehydration effect of tailings filling slurry is to lay the branch pipe at the bottom of the main dehydration pipe and increase the length of the branch pipe as much as possible.

3.3. Comparison of Theoretical and Experimental Values. In order to verify the reliability of the dehydration model of full tailings filling slurry, the dehydration test scheme of full tailings filling slurry is designed as shown in Table 2.

The experimental results are compared with the theoretical calculation results, as shown in Figures 5 and 6.

Table 2: Test plan of total tailings filling slurry dehydration.

Test group no.	Dehydration depth h_w (cm)	Dehydration radius r_w (cm)
Test group 1	16	4
	16	5
	16	6
	16	7
Test group 2	4	4
	8	4
	12	4
	16	4

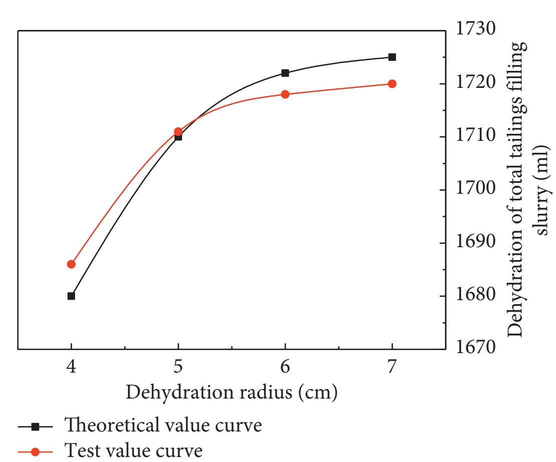

Figure 5: Comparison of the experimental values of the experimental group with the theoretical values.

It can be seen from Figure 5 that the experimental value curve is basically consistent with the theoretical value curve, which indicates that the theoretical formula can better reflect the dehydration state of full tailings filling slurry. When the dehydration radius is less than 5 cm, the experimental value is higher than the theoretical value, while when the dehydration radius is greater than 5 cm, the theoretical value is significantly higher than the experimental value. This is because the particle size composition of the whole tailings is

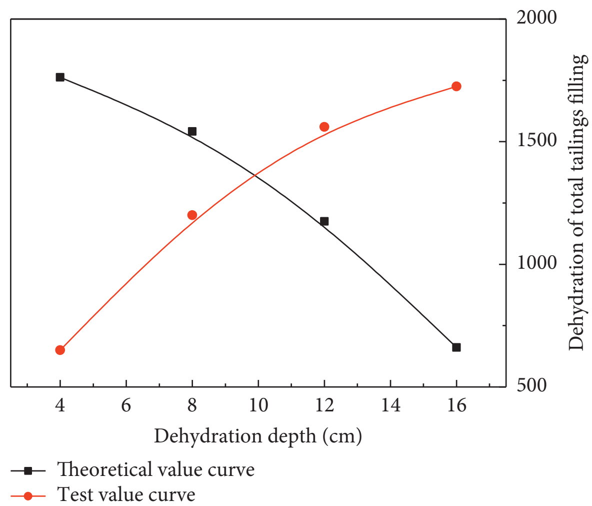

Figure 6: Comparison of the experimental values of the two groups with the theoretical values.

not considered in the theoretical formula. Because there are many fine particles in the whole tailings, the filter holes on the branch pipe will be blocked under the hydrodynamic effect, thus affecting the dehydration of the whole tailings filling slurry.

It can be seen from Figure 6 that the curve of experimental value is completely opposite to the curve of theoretical value, which indicates that the results calculated by the theoretical formula are not consistent with the experimental results. The main reason for this phenomenon is that there are many fine particles in the whole tailings, which continuously converge to the filter holes on the main dehydration pipe and branch pipe under the action of hydrodynamic force and finally block the filter holes on the main dehydration pipe and branch pipe.

At the end of the test, a new root-shaped dehydration pipe with a dehydration depth of 4 cm was taken out from the tailings filling slurry. It was found that a tightly wrapped mud layer with a thickness of about 2 mm was formed on the surface of the main dehydration pipe and the branch pipe. All the drainage holes on the main dehydration pipe and the branch pipe had been blocked by tailings particles. Although the dehydration amount was large in the early stage of the test, it could not be dehydrated in the later stage. The new root-shaped dehydration pipe is taken out from the tailings filling slurry, as shown in Figure 7. It can be seen that the blockage degree of the main dehydration pipe and the filter hole on the branch pipe with the dehydration depth of 16 cm gradually decreases from the bottom of the main dehydration pipe to the top, and a mud layer will be formed at a certain depth at the bottom. However, the test results show that the whole dehydration process is continuous dehydration. Therefore, the arrangement of branch pipes in the full height range of the main dehydration pipe can ensure the dehydration effect of the whole tailings filling slurry.

In order to make the theoretical formula in this paper accord with the actual dehydration situation of tailings filling slurry, formula (11) is modified according to the test results:

Figure 7: A new type of root-like dehydration tube used after the dehydration test.

$$Q = A\frac{\pi K h^2_{w}}{\ln R/r_{w}}, \tag{16}$$

where A is the correction factor, $A = 46.5{h_w}^{-1.24}$, and the other letters have the same meaning as before.

To sum up, the research shows that the change rule of dehydration radius of tailings filling slurry is consistent with that of theoretical value, while the change rule of dehydration depth is different from that of theoretical value. This is because the content of fine particles in tailings is high, the filter holes on the main dehydration pipe and branch pipe are blocked under hydrodynamic effect, and the thickness of 2 mm is formed on the surface of main dehydration pipe and branch pipe, the mud layer of the earth. Therefore, the theoretical formula is modified according to the test results to ensure the reliability of the theoretical model.

In practical engineering, because of the influence of pipe washing water and on-site filling process, it is difficult to ensure that the concentration of full tailings filling slurry does not change after it is filled into the filling stope. Therefore, the unsaturated water conductivity K in formula (16) is not a constant. In order to obtain accurate water removal, the concentration of uncemented backfill with total tailings must be monitored.

The process related to the backfilling of cementing filling body dehydration is to install new type root dehydration tube first and then fill the backfilling materials. Although the branch pipes are evenly distributed on the main dewatering pipe, it is difficult to guarantee during the filling process, and it will also affect the dehydration effect of the new root-like dehydration pipe. Therefore, we still need the new root-shaped dehydration branch pipe in the pipe material to carry out the relevant research.

4. Conclusions

(1) Under the premise of meeting certain assumptions, the dehydration model of full tailings filling slurry is established based on hydrodynamics, and the dehydration radius and depth are determined to be the two main factors affecting the dehydration effect of full tailings filling slurry. The results show that the dehydration capacity of tailings slurry increases with the increase of dehydration radius and decreases with the increase of dehydration depth.

(2) The results show that the variation law of the dehydration radius of the whole tailings filling slurry is consistent with the theoretical value, while the variation law of the dehydration depth is different from the theoretical value. It is found that there is a mud layer on the surface of the main dehydration pipe and branch pipe within a certain depth range of the bottom of the new root-shaped dehydration pipe, which is due to the high content of fine particles in the whole tailings and the low hydrodynamic pressure. Therefore, based on the test results, the theoretical model is modified to ensure the reliability.

(3) The dehydration model of full tailings filling slurry established in this paper does not consider the influence of pipe washing water, on-site filling process, and filling process, so there is a certain gap with the engineering practice. Further monitoring the unsaturated hydraulic conductivity of full tailings filling slurry and seeking new branch pipe materials are the key to ensure the dehydration effect of full tailings filling slurry.

Data Availability

The experimental results used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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