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Predicting of the Unit Grouting Quantity in Karst Curtain Grouting by the Water Permeability of Rock Strata

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Featured Application: This study can be used to predict the unit grouting quantity in karst curtain grouting, and has a certain reference value and guiding role in the design, construction and theoretical research of karst curtain grouting.

Abstract: The prediction of the unit grouting quantity is one of the key points in the design and construction of karst curtain grouting. Because of the concealment and complexity of the karst curtain grouting project, there is no reliable solution to this problem. In this paper, based on the calculation method of water permeability in water-pressure test in grouting engineering, Poiseuille flow equation in fluid mechanics, and cubic law, the relationship between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting is studied. It is found that there is a nonlinear positive correlation between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting, which is in the form of power function. At the same time, the comprehensive coefficient of karst curtain grouting (K) is introduced to describe the quantitative relationship between the unit grouting quantity and the water permeability of rock strata. K is comprehensively characterized by three controlling factors, namely, the characteristics of slurry fluid, the characteristics of grouted rock strata, and the technical factors of grouting in karst curtain grouting. Based on this theoretical relationship, a method for predicting the unit grouting quantity in karst curtain grouting by the water permeability of rock strata is proposed in this paper. Finally, based on the typical example of karst curtain grouting project, through the field grouting test and nonlinear function fitting, the comprehensive coefficient of karst curtain grouting (K) is 24.37 in the area of strong karst development, and it is 16.51 in the area of weak karst development. The proposed method is applied to the prediction of the unit grouting quantity in the main project of karst curtain grouting, and the results verify the rationality and applicability of the method. This study has a certain reference value and guiding role in the design, construction, and theoretical research of karst curtain grouting.

Keywords: karst curtain grouting; the unit grouting quantity; the water permeability of rock strata; prediction method; quantitative relationship

1. Introduction

Karstification geomorphology is widely distributed and large in Southwestern China [1,2]. In these areas where karst is developed, the seepage control of karst fissured strata is a common challenge [3–8]. Grouting method has been more and more widely used as an effective means to control water leakage disaster [9–12]. Karst curtain grouting is a reliable method to solve the problem of karst leakage in view of the special conditions in karstification areas [13]. In particular, with the successive use of many new materials and equipment, the effectiveness of grouting has been greatly improved. However, due to the nonuniformity and randomness of karat-crack distribution, the prediction of the unit grouting quantity in karst curtain grouting has always been one of the important problems in the design and construction of karst curtain grouting [14–16]. If the unit grouting quantity can be reasonably predicted in the design stage of karst curtain grouting, it can provide a reliable basis for the design of grouting materials. This avoids the fact that the curtain body cannot meet the anti-seepage standard of curtain grouting design due to the insufficient injection of grouting materials in the process of curtain grouting construction, and then affect the quality of karst curtain grouting and the effect of anti-seepage. Especially in the curtain grouting project of karstification mine, because of the particularity of the mine itself, the quality of curtain grouting and the effect of water shutoff must be successful at one time. The main criterion that can make such a judgment is the anti-seepage standard of mine curtain grouting [17]. Therefore, the prediction of the unit grouting quantity in karst curtain grouting is of great significance to the design and construction of karst curtain grouting.

At present, the prediction methods of the unit grouting quantity in karst curtain grouting can be divided into three categories. The first is the artificial experience prediction method, which is basically based on the engineering experience of technicians and relies on manual experience to predict the unit grouting quantity. Sohrabi-Bidar et al. [18] used the Bakhtiari dam site as a research case to establish an empirical estimation method of the unit grouting quantity. Gustafson et al. [19] established a prediction method of the unit grouting quantity in grouting construction based on empirical knowledge according to grouting characteristics and hydrogeological data. However, due to the roughness and difference of empirical estimation, the results can only be used as a reference for the design of grouting materials and cannot be used as a basis. The second is the traditional statistical prediction method, which mainly uses regression cluster analysis to establish the prediction model on the basis of collecting a large number of grouting data. Sadeghiyeh et al. [20] established a statistical prediction model of the unit grouting quantity based on the statistics of permeability and groutability of Ostur dam site rock mass. Song et al. [21] obtained a prediction model of the unit grouting quantity in the karst area by counting the curtain grouting data of Zhongguan iron mine for the past three years. However, the application effect of this kind of method is not very ideal, and it is not very good to use and popularize. The third is intelligent grouting prediction method, which applies artificial intelligence to grouting engineering of rock mass. Based on all kinds of prediction theory, the intelligent prediction model of the unit grouting quantity is established to realize the prediction of the unit grouting quantity. According to the prediction theory, this kind of method includes the prediction method of fuzzy theory, the prediction method of grey theory, and the prediction method of artificial neural network theory. Chen et al. [22] established a fuzzy comprehensive evaluation model for grouting scheme optimization to predict the unit grouting quantity. However, because the membership degree and the weight of the index of the prediction method of fuzzy theory are not easy to determine, and the evaluation results obtained by using different evaluation models are different, the prediction method of fuzzy theory has many shortcomings. It is not very practical in engineering practice. Li et al. [23] used the grey prediction model to predict the unit grouting quantity. However, the prediction method of grey theory is mainly based on a large number of grouting data, and it does not consider the grouting mechanism, so its science and feasibility have yet to be verified. Wang et al. [24] proposed and established the genetic neural network model of grouting quantity, and used the genetic neural network method to predict the unit grouting quantity. Hao et al. [25] introduced the back-propagation neural network and information diffusion method into grouting practice to predict the unit grouting quantity. However, the prediction method of artificial neural network theory lacks a unified mathematical basis. For its structure selection and the initial value setting of weight, it is necessary to rely on experience, and the model obtained is usually a local optimal solution rather than a global optimal solution, so its generalization ability is poor. At the same time, this method is a learning method based on large samples. Only enough learning samples can train the prediction model with high accuracy, but the actual situation is that there cannot be enough learning samples in the process of grouting test and construction. In most cases, it is faced with small sample data, and the learning speed of this method is slow and the efficiency is low, so the prediction method of artificial neural network theory also has many unreasonable points. From the above analysis, it can be seen that there are many irrationalities in the prediction methods of the unit grouting quantity in karst curtain grouting at present. The theoretical research in this aspect is lacking, and the grouting construction is lack of scientific guidance. Therefore, it is necessary to carry out the theoretical study on the prediction of the unit grouting quantity in karst curtain grouting and to find a reasonable and applicable method for predicting the unit grouting quantity.

In this paper, based on the study of the theoretical relationship between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting, a method of predicting the unit grouting quantity in karst curtain grouting, by using the water permeability of rock strata, is put forward. The characteristic of this method is that it is easy to extract experimental data from in situ test, and the data source is rich, reliable, and low in cost. it has strong engineering pertinence and obvious technical feasibility. The research of this paper is limited to the category of karst curtain grouting. Through the application in the case of typical karst curtain grouting engineering, the rationality and applicability of this method have been verified.

2. Study on the Relationship between the Unit Grouting Quantity and the Water Permeability of Rock Strata in Karst Curtain Grouting

2.1. Analysis of the Relationship between the Unit Grouting Quantity and the Water Permeability of Rock Strata

Some scholars [18,20,21] collated and summarized the grouting data of some typical karst curtain grouting areas and made a regression analysis of these grouting data by means of mathematical statistics. It is pointed out that there is no linear ratio between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting, but these two physical quantities are not two unrelated independent variables, and there is a certain correlation between them. This shows that there is a nonlinear relationship between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting.

In general, both the unit grouting quantity and the water permeability of rock strata can reflect the size of rock cracks. In fact, the permeable paths in rock mass are called water paths, and the water paths which slurry can pass through are called slurry paths. Different rock masses have their own unique water paths and slurry paths [26]. Therefore, there is the following quantitative relationship between water paths and slurry paths of rock mass:

$$M \geq m, \tag{1}$$

where M is the number of water paths of rock mass, and m is the number of slurry paths of rock mass.

In grouting engineering, the unit grouting quantity mainly depends on the condition of slurry paths of rock mass, and the water permeability of rock strata mainly depends on the condition of water paths of rock mass.

When the unit grouting quantity and the water permeability of rock strata are used to judge the development characteristics of cracks in the grouted rock strata, it is considered that there are two kinds of combination relationships: (i) The unit grouting quantity and the water permeability of rock strata are relatively small if the results show that the groutability and water permeability of rock strata are poor, indicating that the development of rock cracks is weak. (ii) The unit grouting quantity and the water permeability of rock strata are relatively large if the results show that the groutability and water permeability of rock strata are relatively good, indicating that cracks in rock strata are relatively well developed.

As far as karstification strata are concerned, they belong to strongly permeable strata, and their water paths and slurry paths are mainly wide karst fissures. In the combination relationship between the water permeability of rock strata and the unit grouting quantity, the combination of high water permeability of rock strata and large unit grouting quantity often appears, which is the reason why karstification strata must adopt grouting method to plug natural karst cracks in order to achieve the purpose of seepage control. In the area far away from the development of karst in the deep part of the rock strata, there will also be a combination of low water permeability of rock strata and small unit grouting quantity, indicating that the rock strata are slightly permeable, do not absorb slurry, and there is no need for grouting. It can be seen that the water permeability of rock strata is large, the unit grouting quantity is also large, the water permeability of rock strata is small, and the unit grouting quantity is also small. This shows that there is a positive correlation between the unit grouting quantity and the water permeability of rock strata.

The above analysis shows that there is a nonlinear positive correlation between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting. From a mathematical point of view, this dependency between the two physical quantities can be expressed by a certain functional relationship.

2.2. Establishment of Theoretical Relationship between the Unit Grouting Quantity and the Water Permeability of Rock Strata

The water permeability of rock strata is one of the most commonly used indexes in hydraulic anti-seepage design and construction. In the karst curtain grouting project, not only the permeability of the grouted rock strata is directly expressed by the water permeability of rock strata, but also it is regarded as an important index for the quality inspection and evaluation of the curtain grouting. The current regulations and codes for hydraulic design and construction in China [27,28] clearly stipulate that the anti-seepage standard of rock mass of dam foundation (or reservoir bank) of large reservoir dam is that the water permeability of single hole in the water-pressure test of inspection hole is less than 5 Lu.

The water permeability of rock strata is obtained directly by the water-pressure-test method, which is the main achievement index of the water-pressure test [13,18]. The water-pressure test is also known as the Lugeon test [13,29]. The current regulations and codes for hydraulic design and construction in China [27,28] specify that the international Lugeon test is adopted as the basic method for obtaining the water permeability of rock strata (Lugeon Value). It is widely used in grouting engineering. The basic definition of the water permeability of rock strata is the amount of water that is pressed into the rock strata by the grouting hole per meter, per unit time, under the full pressure acting on the grouting hole section. According to the Lugeon test, the water permeability of rock strata can be calculated directly by the following formula:

$$\omega = \frac{Q}{PL}, \tag{2}$$

where ω is the water permeability of rock strata (Lu or L/(min·m·MPa)); Q is the amount of water injected into the grouting hole section per unit time (L/min); P is the full pressure acting on the grouting hole section (MPa); and L is the length of the grouting hole section (m).

According to the formula, it can be seen that the pressure (P) and the length of the grouting hole section (L) are design parameters, which are fixed values, so the water permeability of rock strata (ω) mainly depends on the amount of water pressed into the grouting hole section per unit time (Q).

Because most of the karst fissures developed in the karstification strata have a large opening, the water injected in the water-pressure test basically flows in this kind of karst fissures. Here, the karst fissure of water diversion is assumed to be a karst pipeline, in which water can be considered to flow and form pipe flow, as shown in Figure 1.

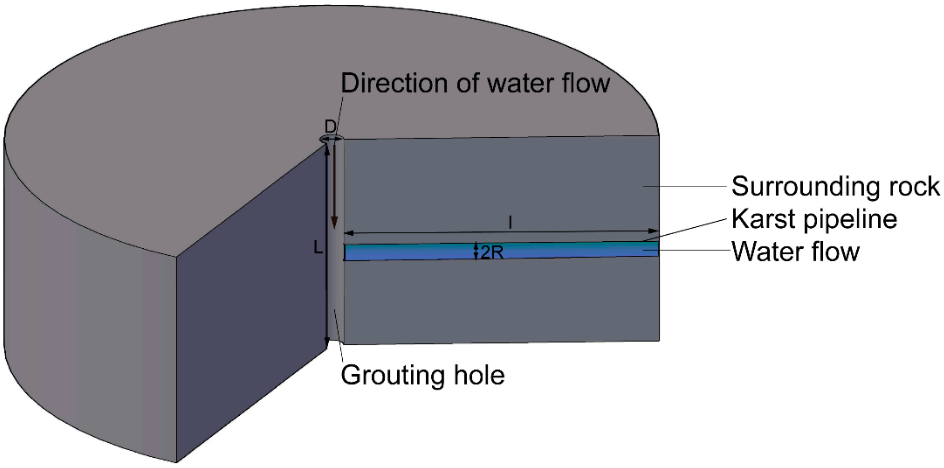


Figure 1. Schematic diagram of pipe-flow model.

According to the Poiseuille flow equation in fluid mechanics, when water flows in a circular pipeline, the water flow in the pipe is related to the radius of the pipeline, the viscosity of the water, the pressure difference between the two ends of the pipeline, and the length of the pipeline. This leads the following equation:

$$q = \frac{\pi R^4 \Delta p}{8\mu l}, \tag{3}$$

where q is the flow rate of water in the pipeline (m^3/s); R is the radius of the pipeline (m); μ is the dynamic viscosity of water (Pa·s); Δp is the pressure difference between the two ends of the pipeline (Pa); and l is the length of the pipeline (m).

The Poiseuille flow equation is suitable for the flow of Newtonian fluid in the pipeline, and water is a typical Newtonian fluid. Under the above assumptions, Equation (3) can be used to calculate the water flow in the karst pipeline.

The calculation formula of the water permeability of rock strata in the water-pressure test and the Poiseuille flow equation in fluid mechanics are compared. The corresponding physical quantities are the amount of water injected into the grouting hole section per unit time (Q) and the water flow rate in the pipeline (q), as well as the full pressure acting on the grouting hole section (P) and the pressure difference between the two ends of the pipeline (Δp), which have equivalent physical meaning. At the same time, taking into account the unit transformation between them, the equivalent replacement process between the above physical quantities is as follows:

$$Q = 6 \times 10^4 q \tag{4}$$

$$P = \frac{\Delta p}{10^6} \tag{5}$$

By substituting Equation (3) into Equation (4), the following equation can be obtained:

$$Q = \frac{3 \times 10^4 \pi R^4 \Delta p}{4\mu l}. \tag{6}$$

Equation (7) can be obtained by substituting Equations (5) and (6) into Equation (2).

$$\omega = \frac{3 \times 10^{10} \pi R^4}{4\mu l L}. \tag{7}$$

Assuming that there are karst fissures at a certain depth of the grouting hole section, the cracking area formed by these karst fissures along the horizontal direction of the grouting hole is the permeable area formed by the perimeter of the circular section of the grouting hole multiplied by the opening of the karst fissures. If it is equivalent to the cross-section area of permeable karst pipeline, there is a relationship of the following equation:

$$\pi Db = \pi R^2. \tag{8}$$

As a result, the following equation is obtained:

$$R = \sqrt{Db}, \tag{9}$$

where D is the diameter of grouting hole (m), and b is the opening of karst fracture (m).

When Equation (9) is substituted into Equation (7), the following expression of the water permeability of rock strata is obtained:

$$\omega = \frac{3 \times 10^{10} \pi D^2 \mathrm{b}^2}{4 \mu l L}. \tag{10}$$

The expression of the karst fracture opening is obtained from the transformation of Equation (10):

$$b = \frac{1}{5 \times 10^4 D} \sqrt{\frac{\mu l L \omega}{3\pi}}. \tag{11}$$

In the karst curtain grouting project, the scale of the karst crack structure is much larger than that of the roughness, and the viscosity time variation of the slurry is often ignored in the actual grouting process. Therefore, the cubic law can be directly used to describe the flow of slurry in karst fissures, without considering the influence of the roughness of karst fissures and the change of slurry viscosity. The expression is as follows:

$$Q_v = \frac{\rho g b^3 \mathrm{wh}}{12 \eta r}, \tag{12}$$

where Q_v is the flow rate of the slurry (m^3/s); ρ is the density of the slurry (kg/m^3); g is the acceleration of gravity (N/kg); w is the width of the karst fracture (m); h is the water head height converted by pressure (m); r is the diffusion distance of the slurry (m); and η is the dynamic viscosity of the slurry (Pa·s).

When Equation (11) is substituted into Equation (12), the flow model of slurry diffusion in karst fissures in karst curtain grouting is obtained:

$$Q_v = \frac{2\gamma h}{9 \times 10^{15} D^2 \eta r} \left(\frac{1}{3\pi} \right)^{\frac{1}{2}} (\mu l L \omega)^{\frac{3}{2}}, \tag{13}$$

where γ is the weight of the slurry (N/m^3).

Because the unit grouting quantity represents the quality of the slurry injected into the grouting hole per meter, the theoretical equation of the unit grouting quantity in karst curtain grouting is obtained by further transformation of Equation (13):

$$q_w = \frac{2\gamma \rho h \mathrm{t}}{9 \times 10^{15} D^2 \eta r} \left(\frac{L}{3\pi} \right)^{\frac{1}{2}} (\mu l \omega)^{\frac{3}{2}}, \tag{14}$$

where q_w is the unit grouting quantity (kg/m), and t is time used after grouting in grouting section (s).

In karst curtain grouting, the unit grouting quantity is affected by many factors, and the theoretical relationship equation between the unit grouting quantity and the water permeability of rock strata (Equation (14)) is more complicated. In order to simplify the form of the mathematical model, a new coefficient, K, is introduced. It is defined as the comprehensive coefficient of karst curtain grouting, so that its expression is as follows:

$$K = \frac{2\gamma\rho h t}{9 \times 10^{15} D^2 \eta r} \left(\frac{L}{3\pi}\right)^{\frac{1}{2}} (\mu l)^{\frac{3}{2}}. \tag{15}$$

It can be seen that the physical quantities contained in the comprehensive coefficient of karst curtain grouting defined in this paper basically reflect the three controlling factors of slurry diffusion, namely, the characteristics of slurry fluid, the characteristics of grouted rock strata, and the technical factors of grouting. Therefore, if the degree of karst development is different, K will be different values. In view of the fact that K is a complex coefficient, it is difficult to solve the value theoretically, so the field test and nonlinear function fitting are used to determine the value of K in this paper.

Therefore, the theoretical relationship between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting can be expressed by the following formula:

$$q_w = K\omega^{\frac{3}{2}}. \tag{16}$$

The theoretical relationship curve between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting can be expressed in the form of Figure 2.

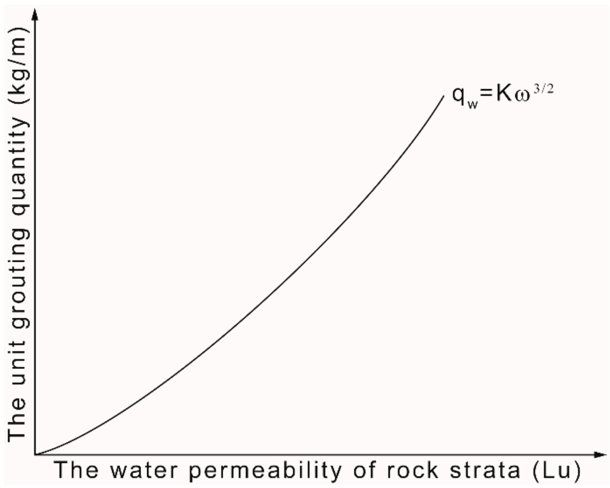


Figure 2. The graph showing the quantitative relationship between the unit grouting quantity and the water permeability of rock strata.

In engineering practice, the process of predicting the unit grouting quantity in karst curtain grouting is as follows: (i) According to the hydrogeological conditions of karst curtain grouting construction area, the suitable curtain grouting test section is selected for the field test. The unit grouting quantity and the water permeability of rock strata obtained in the test are recorded; (ii) using the test data and nonlinear function fitting, the comprehensive coefficient of karst curtain grouting is determined; (iii) Equation (16) is used to predict the unit grouting quantity by using the water permeability of rock strata obtained in the main project.

3. Application Verification of Typical Karst Curtain Grouting Project

3.1. Engineering Background

The typical case of karst curtain grouting project is the anti-seepage curtain grouting project of Panlong lead–zinc mine, a protective project in the reservoir area of Datengxia water control project in Guangxi, China. After the water storage of the Datengxia water control project, the return water level of the Qianjiang River section on the east side of the Panlong lead–zinc mine will exceed the normal water level of the reservoir, and the problem of reservoir leakage will affect the production safety of the Da-Ling section of Panlong lead–zinc mine. Therefore, an anti-seepage curtain is arranged on the east side of the mining area of Da-Ling section to prevent the influence of river uplift of Qianjiang River on mine production. The plane position diagram of the axis of the anti-seepage curtain is shown in Figure 3.

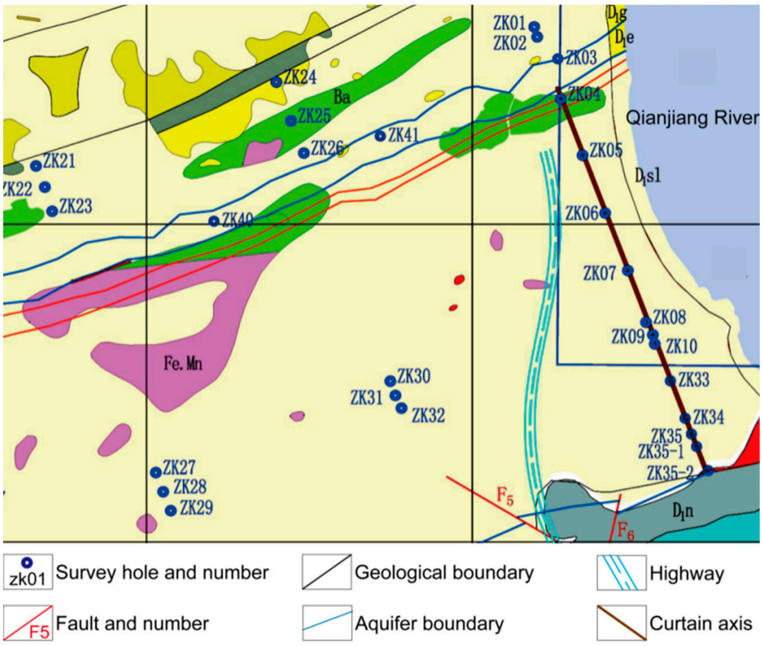


Figure 3. The plane position diagram of the axis of the curtain.

3.2. Hydrogeological Conditions of Working Area

3.2.1. Law of Karst Development in Working Area

According to the geological data of the field geological survey, the strata exposed by the surface and boreholes in the construction area are the Quaternary and the Shang-Lun formation in the Lower Devonian. The aquifer of the Shang-Lun formation in the Lower Devonian is the direct water-filled aquifer in the Da-Ling section of Panlong lead–zinc mine, which is the curtain protection area of the anti-seepage curtain project. The maximum depth level of strata exposure is −152.4 m. According to the statistical results of karst revealed by drilling (Figure 4), the karst encountered by boreholes accounts for 87.09% of the total karst above the elevation of −80 m, so this segment is a strong karst segment. In the elevation of −80 to −120 m, the karst encountered by boreholes accounts for 9.68% of the total karst, so this segment is a middle karst segment. Below the elevation of −120 m, the karst encountered by boreholes accounts for 3.23% of the total karst, so this segment is a weak karst segment. From the vertical development law of karst revealed by boreholes, it can be seen that there are differences and inhomogeneity in the development of karst, and the degree of karst decreases with the increase of the depth of strata, which is consistent with the research conclusions of many scholars [13,30–32].

3.2.2. Characteristics of the Water Permeability of Rock Strata in Working Area

The water-pressure test before grouting is carried out in the grouting hole used to expose the karst on the curtain line. The statistical results of the subsection and sublevel of the water-pressure test are shown in Figure 5. Figure 5 shows that, on the whole, the water permeability of rock strata is more than 100 Lu, which is mainly distributed above the elevation of −80 m, accounting for 100% of the same permeability range, and the water permeability of rock strata accounts for 76.19% of the same permeability range in 10–100 Lu segment. The water permeability of rock strata in 5–10 Lu segment accounts for 67.11% of the same permeability range. This shows that the segment above the elevation is strongly permeable. In the elevation of −80 to −120 m, the water permeability of rock strata accounts for 16.67% of the same permeability range in 10–100 Lu segment, and the water permeability of rock strata accounts for 18.42% of the same permeability range in 5–10 Lu segment. This shows that the segment is a medium permeability segment. In the elevation of −120 to −150 m, the water permeability of rock strata accounts for 7.14% of the same permeability range in 10–100 Lu segment, and the water permeability of rock strata accounts for 14.47% of the same permeability range in 5–10 Lu segment. This shows that the segment is weakly permeable. It can be seen that the water permeability of rock strata in the curtain protection area decreases with the increase of the depth of strata, mainly because the degree of development of karst decreases with the increase in the depth of strata, and the low density of karst cracks in the deep position of strata leads to the decrease of the water permeability of rock strata.

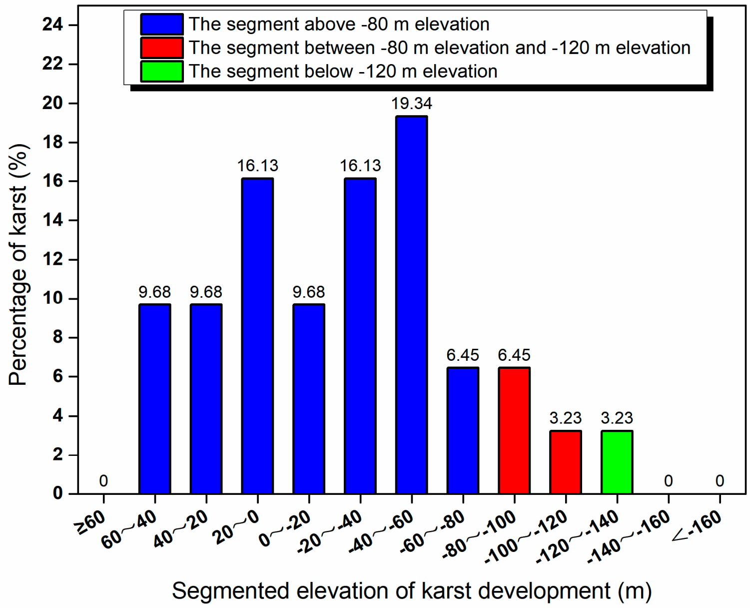


Figure 4. The statistical results of karst revealed by drilling.

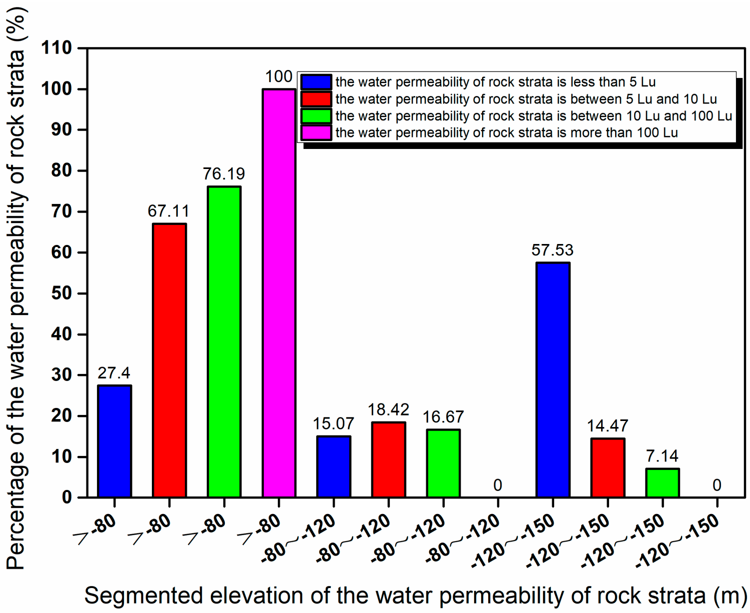


Figure 5. The statistical results of the subsegment and sub-elevation of the water-pressure test in Shang-Lun formation on curtain axis.

3.3. Engineering Application of Prediction Method of the Unit Grouting Quantity in Karst Curtain Grouting Based on the Water Permeability of Rock Strata

According to the characteristics of karst development, the curtain grouting project divides the construction area into two curtain grouting sections: the south and the north. Among them, the northern curtain grouting area is an area of strong karstification, while the southern curtain grouting area is an area of weak karstification.

The curtain grouting project mainly includes two parts: the curtain grouting test and the curtain grouting construction. The purpose of the field grouting test is to provide sample data for determining the comprehensive coefficient of karst curtain grouting (K) in the theoretical relationship equation between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting (Equation (16)). At the same time, it also provides relevant technical parameters for formal grouting design and construction.

The grouting technology and parameters adopted in the curtain grouting test are determined according to the actual conditions of the construction area and the practice of similar karst curtain grouting projects. In the grouting test section, double-row linear holes are used, and the row spacing is 3 m. First, a row of holes on the side of the mining area (west side) will be constructed, and then a row of holes on the side of the Qianjiang River (east side) will be constructed. Each row of holes is constructed in two sequences. First, the first sequence hole is constructed, and then the second sequence hole is constructed. In the grouting test, the top of the curtain body is this position, which is 2 m above the boundary between the rock and soil, and the elevation of the curtain bottom is −150 m. The opening diameter of grouting hole is not less than 110 mm, and the end diameter of grouting hole is not less than 75 mm. The length of grouting section is 3–40 m. The grouting method is a downward-segmented pure-pressure method. The grouting material is modified clay–cement paste. The assessment and evaluation index of curtain grouting quality is the anti-seepage standard of grouting curtain, that is, when the water permeability of a single hole is not greater than 5 Lu in the water-pressure test of the inspection hole, it is considered that the grouting quality is better and meets the quality acceptance standard.

3.3.1. Prediction of the Unit Grouting Quantity in Curtain Grouting in the Area of Strong Karst Development by Using the Water Permeability of Rock Strata

In the curtain grouting project, the northern curtain grouting area is an area of strong karst development. The purpose of this part is to verify the applicability of the proposed prediction method of the unit grouting quantity in the area of strong karst development. In the northern curtain grouting area, a typical section which can generally represent the characteristics of karst development in the grouting area is selected as the test section to carry out the field grouting test. Statistics are carried out on the data of the unit grouting quantity, and the water permeability of rock strata in the test section, and the correlation curve between the unit grouting quantity and the water permeability of rock strata is drawn by data fitting (as shown in Figure 6). As a result, the value of the comprehensive coefficient of karst curtain grouting (K) is 24.37, and the fitting equation between the unit grouting quantity and the water permeability of rock strata in the area of strong karst development is obtained:

$$q_w = 24.37\omega^{1.5} \qquad (R = 0.91). \tag{17}$$

According to Equation (17), the corresponding relationship between the water permeability of rock strata and the unit grouting quantity in the northern curtain grouting area can be obtained, as shown in Table 1.

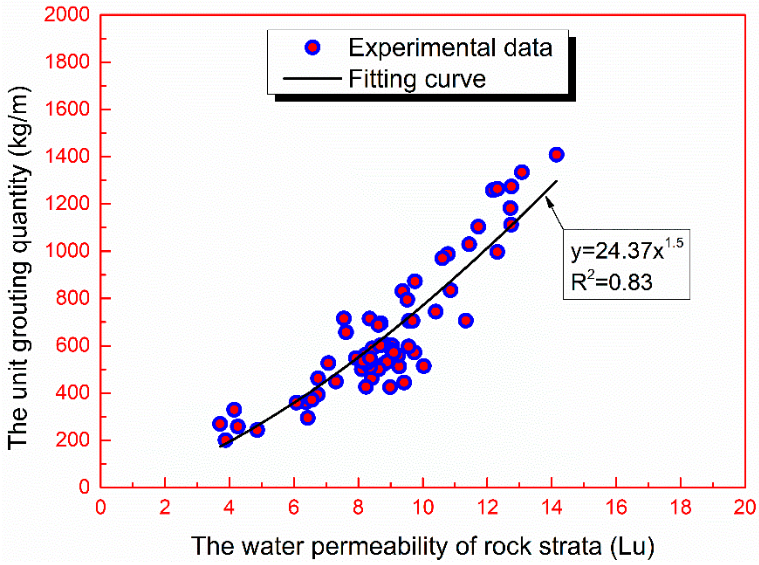
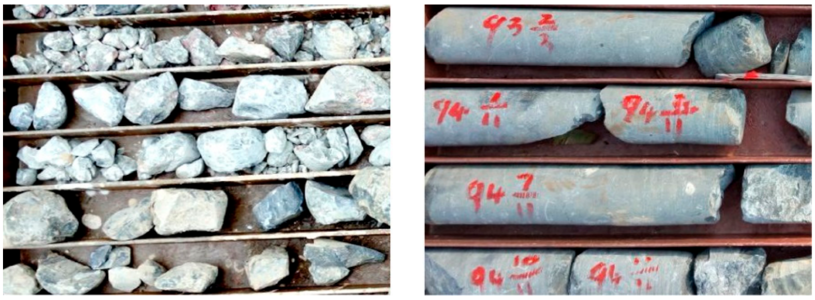


Figure 6. The relationship curve between the unit grouting quantity and the water permeability of rock strata before grouting in each grouting hole section in the northern grouting test section.

Table 1. The reference value of a certain water permeability of rock strata and corresponding unit grouting quantity in the northern curtain grouting area.

Water Permeability of Rock Strata (Lu)	Unit Grouting Quantity (kg/m)
1	24
2	69
3	127
4	195
5	272
6	358
7	451
8	551
9	658
10	771
11	889
12	1013
13	1142
14	1276
15	1416
16	1559
17	1708
18	1861
19	2018
20	2179

During the construction of the main project, the unit grouting quantity in the northern curtain grouting area is determined according to Table 1. After the construction of the karst curtain grouting project, the effect of the karst curtain grouting is tested and evaluated by means of grouting superposition effect analysis of each grouting hole, frequency curve analysis, variation curve analysis of the unit grouting quantity, and a water-pressure test in the inspection hole and drilling coring. The results show that an effective grouting curtain body is formed in the grouting area, according to the measured water permeability of rock strata before grouting in each grouting hole section at the construction site and selecting the corresponding unit grouting quantity from Table 1 for grouting construction. The effect of preventing seepage and blocking leakage is remarkable. The water permeability of rock strata measured by the water-pressure test in the inspection hole after grouting is less than 5 Lu, which meets the anti-seepage standard of grouting curtain required in the current regulations and codes for hydraulic design and construction in China [27,28]. Core samples of the drilling hole before and after grouting in the northern curtain grouting area are shown in Figure 7.



(**a**) (**b**)

Figure 7. Core samples before and after grouting in northern curtain grouting area. (**a**) Core samples before grouting; (**b**) core samples after grouting.

Therefore, based on Equation (17), the unit grouting quantity in curtain grouting in the area of strong karst development predicted by the water permeability of rock strata can ensure the construction quality of the project. It is shown that there is a quantitative relationship between the water permeability of rock strata and the unit grouting quantity expressed by Equation (17) in the area of strong karst development, and it is proved that the prediction method of the unit grouting quantity proposed in this paper has good applicability in the area of strong karst development.

3.3.2. Prediction of the Unit Grouting Quantity in Curtain Grouting in the Area of Weak Karst Development by Using the Water Permeability of Rock Strata

In the curtain grouting project, the southern curtain grouting area is an area of weak karst development. The purpose of this part is to verify the applicability of the proposed prediction method of the unit grouting quantity in the area of weak karst development. In the southern curtain grouting area, a typical section which can generally represent the characteristics of karst development in the grouting area is selected as the test section to carry out the field grouting test. Statistics are carried out on the data of the unit grouting quantity and the water permeability of rock strata in the test section, and the correlation curve between the unit grouting quantity and the water permeability of rock strata is drawn by data fitting (as shown in Figure 8). As a result, the value of the comprehensive coefficient of karst curtain grouting (K) is 16.51, and the fitting equation between the unit grouting quantity and the water permeability of rock strata in the area of weak karst development is obtained:

$$q_w = 16.51\omega^{1.5} \qquad (R = 0.90). \tag{18}$$

According to Equation (18), the corresponding relationship between the water permeability of rock strata and the unit grouting quantity in the southern curtain grouting area can be obtained, as shown in Table 2.

During the construction of the main project, the unit grouting quantity in the southern curtain grouting area is determined according to Table 2. After the construction of the karst curtain grouting project, the effect of the karst curtain grouting is tested and evaluated by means of grouting superposition effect analysis of each grouting hole, frequency curve analysis, variation curve analysis of the unit grouting quantity, water-pressure test in inspection hole, and drilling coring. The results show that an effective grouting curtain body is formed in the grouting area, according to the measured water permeability of rock strata before grouting in each grouting hole section at the construction site and selecting the corresponding unit grouting quantity from Table 2 for grouting construction. The effect of preventing seepage and blocking leakage is remarkable. The water permeability of rock strata measured by the water-pressure test in the inspection hole after grouting is less than 5 Lu, which meets the anti-seepage standard of grouting curtain required in the current regulations and codes for hydraulic design and construction in China [27,28]. Core samples of drilling hole before and after grouting in the southern curtain grouting area are shown in Figure 9.

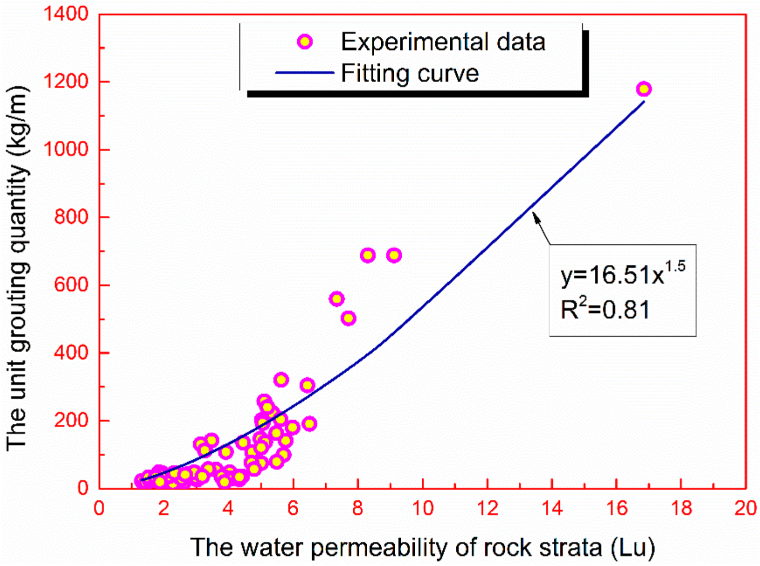


Figure 8. The relationship curve between the unit grouting quantity and the water permeability of rock strata before grouting in each grouting hole section in the southern grouting test section.

Table 2. The reference value of a certain water permeability of rock strata and corresponding unit grouting quantity in the southern curtain grouting area.

Water Permeability of Rock Strata (Lu)	Unit Grouting Quantity (kg/m)
1	17
2	47
3	86
4	132
5	185
6	243
7	306
8	374
9	446
10	522
11	602
12	686
13	774
14	865
15	959
16	1057
17	1157
18	1261
19	1368
20	1477

Therefore, based on Equation (18), the unit grouting quantity in curtain grouting in the area of weak karst development predicted by the water permeability of rock strata can ensure the construction quality of the project. It is shown that there is a quantitative relationship between the water permeability of rock strata and the unit grouting quantity expressed by Equation (18), in the area of weak karst development, and it is proved that the prediction method of the unit grouting quantity proposed in this paper has good applicability in the area of weak karst development.

(**a**) (**b**)

Figure 9. Core samples before and after grouting in southern curtain grouting area. (**a**) Core samples before grouting; (**b**) core samples after grouting.

4. Discussion

4.1. Parameter Analysis

In the theoretical relationship equation between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting, the comprehensive coefficient of karst curtain grouting (K) is introduced, which simplifies the form of the relationship equation.

The key to the success of the grouting prediction model is that it must reflect the main attributes and characteristics of the grouting project. The comprehensive coefficient of karst curtain grouting (K) is a complex coefficient, and the physical quantities it contains basically reflect the three controlling factors of slurry diffusion, namely, the characteristics of slurry fluid, the characteristics of grouted rock strata, and the technical factors of grouting, which theoretically ensure the rationality of the grouting prediction model proposed in this paper.

The comprehensive coefficient of karst curtain grouting (K) describes the quantitative relationship between the unit grouting quantity and the water permeability of rock strata. In the typical case of the karst curtain grouting project studied in this paper, the unit grouting quantity in the northern curtain grouting area is obviously larger than that in the southern curtain grouting area. The main reason for this difference is that the degree of karst development in the two curtain grouting areas is different. The northern curtain grouting area is an area of strong karst development, so the three controlling factors of slurry diffusion are more complex, and the comprehensive coefficient of karst curtain grouting (K) is larger. The southern curtain grouting area is an area of weak karst development, so the three controlling factors of slurry diffusion are relatively simple, and the comprehensive coefficient of karst curtain grouting (K) is smaller. The comprehensive coefficient of karst curtain grouting (K) reflects the sensitivity of the unit grouting quantity to the water permeability of rock strata in karst curtain grouting.

The unit grouting quantity in karst curtain grouting is affected by many factors, most of which have the uncertain characteristics of randomness and fuzziness, and many of them often influence each other. In the theoretical equation, the comprehensive coefficient of karst curtain grouting (K) is used to comprehensively reflect the influence of these factors on the unit grouting quantity, but it is difficult to solve its value theoretically. Therefore, how to simplify the influencing factors of the model in order to realize the theoretical solution of the coefficient is worthy of further study. In this paper, the field test and data fitting are used to determine the value of the comprehensive coefficient of karst curtain grouting (K), and the engineering application proves the feasibility of this parameter-determination method.

In the theoretical relationship equation between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting, the power of the water permeability of rock strata (ω) is 1.5, which is a constant. This constant is inferred on the basis of the existing theoretical formula.

In engineering application, the fitting equations (Equations (17) and (18)) suitable for different karst development conditions are obtained by field tests and data fitting. In the process of data fitting, both the parameter K and the power are free quantities. When the fitting converges, it is obtained that K is 24.37 and the power is 1.5 in the area of strong karst development, and K is 16.51 and the power is 1.5 in the area of weak karst development.

Whether it is deduced with the help of the existing theory, or fitted by the field-test data, the power of the water permeability of rock strata (ω) is 1.5 in the relationship equation between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting. This shows that the equation is reasonable in theory and applicable in engineering application.

4.2. Applicability and Limitation of the Prediction Method of the Unit Grouting Quantity in Karst Curtain Grouting Based on the Water Permeability of Rock Strata

The parameter value in the theoretical relationship equation between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting (Equation (16)) can be easily determined by extracting experimental data from field prototype test and using function fitting. Moreover, the required data sources are rich, reliable, and low in cost, and the method adopted has strong engineering pertinence and obvious technical feasibility, and the results obtained are relatively reasonable. Therefore, the prediction method of the unit grouting quantity proposed in this paper has good applicability to the karst curtain grouting project and can meet the needs of the design, construction, and theoretical research of karst curtain grouting, as well as provide an important theoretical basis for reference.

However, the theoretical relation equation is put forward on the basis of the assumption of the rock mass characteristics of karst fissures, which is different from the engineering practice and needs to be further improved in practice. In addition, although the prediction method of the unit grouting quantity in karst curtain grouting based on the water permeability of rock strata proposed in this paper can ensure the quality and anti-seepage effect of karst curtain grouting, the question of whether the prediction result of this method is the optimal solution needs to be further studied.

5. Conclusions

In order to overcome the lack of theoretical research on the prediction of the unit grouting quantity in karst curtain grouting and to seek a reasonable and applicable prediction method of the unit grouting quantity, in this paper, a theoretical study on the prediction of the unit grouting quantity in karst curtain grouting was carried out. On this basis, a prediction method of the unit grouting quantity in karst curtain grouting based on the water permeability of rock strata was proposed. The following main conclusions can be drawn:

(1) The theoretical relationship between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting can be expressed in the form of power function. The theoretical equation contains only the parameter K, which is the comprehensive characterization of the characteristics of slurry fluid, the characteristics of grouted rock strata, and the technical factors of grouting in karst curtain grouting, and its value is determined by field tests and data fitting.

(2) Based on the theoretical relationship between the unit grouting quantity and the water permeability of rock strata in karst curtain grouting, the proposed method can be used to reasonably predict the required unit grouting quantity in karst curtain grouting construction. The procedure is as follows: (i) According to the hydrogeological conditions of the construction area of karst curtain grouting, the suitable curtain grouting test section is selected to carry out the field test, and the data of the unit grouting quantity and the water permeability of rock strata obtained in the test are recorded. (ii) Using the test data and nonlinear function fitting, the comprehensive coefficient of karst curtain grouting is determined; and (iii) according to the theoretical relationship equation between the unit grouting quantity and the water permeability of rock strata in karst curtain

grouting, the required unit grouting quantity is predicted by using the water permeability of rock strata obtained in the main project.

(3) The relationship equation between the unit grouting quantity and the water permeability of rock strata in the karst curtain grouting obtained by theory (Equation (16)) is consistent with the fitting equation obtained in the typical case of karst curtain grouting project (Equations (17) and (18)), indicating that the theoretical equation can be effectively applied to predict the unit grouting quantity in the karst curtain grouting.

(4) In the engineering case, it is obtained that the comprehensive coefficient of karst curtain grouting is 24.37 in the area of strong karst development and 16.51 in the area of weak karst development. It can be applied respectively to predict the unit grouting quantity in the main project of karst curtain grouting in the area of strong karst development and the area of weak karst development.

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