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A Method for Determining the Safe Thickness of Concrete Retaining Walls Based on Slab Structure Theory

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Abstract: The safe thickness of concrete retaining walls for curtain grouting on tunnel faces is an essential factor related to tunnel safety and grouting effects. In this research, the concrete retaining wall was simplified into a standard rectangular slab structure. The Rankine active earth pressure theory and the plastic hinge theory were used to analyze the lateral force of the concrete retaining wall. By deriving the safety-thickness equation of the concrete retaining wall, a quantitative criterion that can display the mechanism of the concrete retaining wall was obtained. The traditional empirical formula and Kalmykov formula had a particular connection with the method in this paper in determining the safe thickness of the concrete retaining wall. This was negatively related to the compressive (tensile) strength of the concrete and the groundwater level and positively associated with the buried depth of the tunnel. The conversion relationship between the traditional empirical formula and the theoretical formula was established, and the exact solution formula for the value of safety coefficient K_0 was given. Finally, the rationality of the theoretical formula was verified by a field test, in novel work that provides a reference for similar projects.

Keywords: concrete retaining wall; Rankine active earth pressure; plate structure; plastic hinge theory; safety coefficient

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1. Introduction

A concrete retaining wall [1–7] is a preconstructed concrete structure in the roadway or tunnel, which can withstand the maximum grouting pressure, protect the stability of the face, and prevent slurry leakage from running into the roadway or tunnel. In the process of urban subway construction [8,9], weak and water-rich strata are often encountered, and the stability of the stratum is poor. The concrete retaining wall needs to withstand the maximum grouting pressure and the groundwater and formation pressures in front of the face. In practical engineering, the thickness of concrete retaining walls is mainly determined according to engineering experience, though various empirical formulas can be applied [1,10]. Still, there is a lack of deeper theoretical analysis. In concrete retaining wall design, it is necessary to consider the influences of grouting pressure, groundwater pressure, and formation pressure on the thickness of the concrete retaining wall, to determine a reasonably safe thickness.

The existing research focused on the flexural performance of concrete retaining walls, i.e., the variation law of parameters such as deformation and flexural stiffness for concrete walls with internal forces. There were few studies on concrete walls' bearing capacity and what classes as a reasonably safe thickness. A calculation method for the flexural bearing capacity and safe thickness of concrete retaining walls has not yet been proposed. The flexural bearing performance of concrete walls is essential for the safe construction of tunnels, and many scholars have carried out fruitful research. Lopez [11] conducted experiments to investigate the in-plane flexural performance of rectangular and T-shaped concrete walls. Al-Fakih [12] studied the flexural behavior of rubberized concrete interlocking masonry walls under out-of-plane loads. Scott [13] studied the effect of stay-in-place PVC formwork panel geometry on the flexural behavior of reinforced concrete walls. Polat [14] studied the flexural behavior of steel plate concrete. Lu [15] presented an experimental study on the mechanical behavior of non-uni-thickness walled rectangular concrete-filled steel tube beams subjected to pure bending. Numerous scholars studied the bending resistance of concrete walls. The deformation properties of concrete have significant safety implications. Yet, what is more important is the ultimate bearing capacity of the concrete wall and its safe thickness. There are few related studies in this regard. Ho [16] predicted the axial load capacity of concrete walls with openings restrained on three sides. Zhou [17] established the sectional load capacity of steel plate concrete walls under a predictable equalizing pressure and bending moment. However, the above results are difficult to directly apply to the design of concrete retaining walls during tunnel grouting. Therefore, this paper studied the ultimate bearing capacity and safe thickness of concrete walls, to provide theoretical guidance for the design of concrete retaining walls.

There are many calculation methods for concrete walls, and the ones commonly used are elastic mechanics analysis, plastic mechanics analysis, the difference method, finite element method, etc. The plastic hinge method is widely used in the plastic limit load analysis maneuver method. They were first proposed by Ingerslev and extensively promoted and improved by Johansen [18]. Recently, there have been many achievements in the research on plastic hinge theory. Andrea [19] studied the influence of the plastic hinge angle on the shear strength of reinforced continuous concrete beams. Mandeep [20] studied the plastic hinge behavior and rotation capacity of reinforced concrete flexural members. Ramin [21] studied the estimation of the bending moment redistribution and plastic hinge characteristics of two-span beams of high-performance fiber-reinforced cement-based composites. Yet, though the theory of plastic hinges has important theoretical significance for guiding engineering practice, there is no relevant application for calculating the safe thickness of concrete retaining walls.

To obtain the theoretical criterion of the safe thickness of the concrete retaining wall, this paper first uses the Rankine active earth pressure theory to analyze the lateral force of the concrete retaining wall. It applies plastic mechanics and the plastic hinge theory of the plate structure to study the concrete retaining wall's safe thickness, revealing its stress mechanism. The traditional empirical formula, the Kalmykov formula, and the theoretical formula derived in this paper are compared and analyzed through examples. A theoretical connection between the theoretical formula and the empirical formula in this paper is established, and the law of the parameter value of the empirical formula is analyzed. Finally, the rationality of the theoretical model is verified through field tests.

2. Theoretical Study on Safe Thickness of Grout-Concrete Retaining Wall

2.1. Model's Assumption

In actual projects, the concrete retaining walls have different shapes, though they are primarily elliptical structures based on the outline of the tunnel. To complete the theoretical analysis, this paper simplified the model of the concrete retaining wall and made the following approximate assumptions concerning the theoretical model of the wall:

(1) The concrete retaining wall is isotropic and made of homogeneous plain concrete, which meets the assumptions of elastic-plastic mechanics.
(2) The concrete retaining wall is a regular rectangular plate with four fixed sides and a flat surface, as shown in Figure 1.
(3) The grout acts uniformly on the concrete retaining wall, with the absolute pressure of the grouting placing additional pressure on the wall, and the influence of the grouting hole on the mechanical performance of the concrete retaining wall is ignored.

(4) The lateral force of the concrete retaining wall conforms to the Rankine active earth pressure theory. There is a weak, water-rich, and homogeneous single stratum, and a shallow buried tunnel.

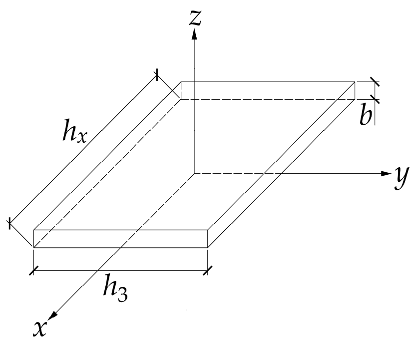

Figure 1. Concrete retaining wall simulation plate three-dimensional coordinate system.

2.2. Lateral Force Analysis

The longitudinal section of the concrete retaining wall is shown in Figure 2. Based on the Rankine active earth pressure theory [22–24], lateral force analysis of the concrete retaining wall was carried out.

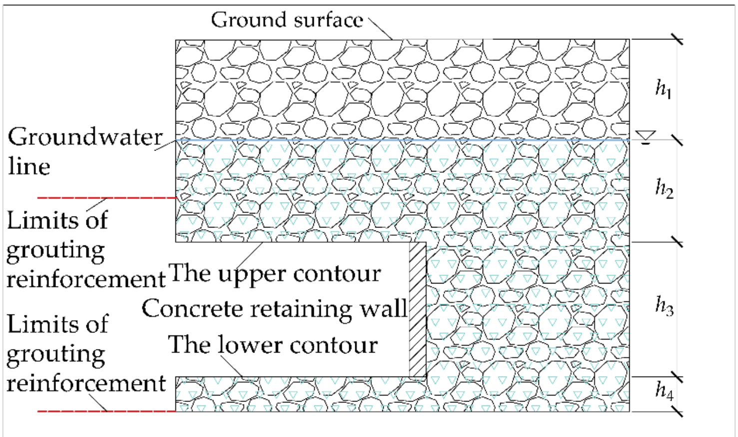

Figure 2. Diagram of the concrete retaining wall.

Taking a one-unit width of concrete retaining wall into account, according to Rankine active earth pressure theory, the sidewall of the concrete retaining wall is shown in Figure 3.

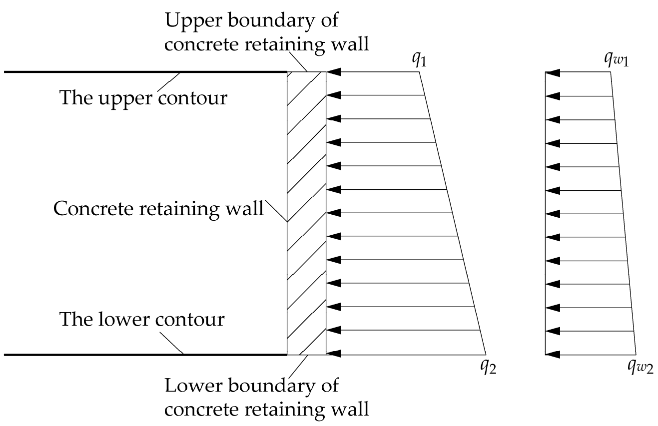

Figure 3. Pressure on the sidewall of the stopper wall.

The analysis and calculation from Figure 3 are as follows:

$$q_1 = \gamma h_1 K_a + \gamma\prime h_2 K_a - 2c\sqrt{K_a} \tag{1}$$

$$q_2 = \gamma h_1 K_a + \gamma\prime (h_2 + h_3) K_a - 2c\sqrt{K_a} \tag{2}$$

where γ is the bulk density of a homogeneous single stratum, γ' is the effective unit weight of the stratum, $K_a = \tan^2(45° - \varphi/2)$ is the Rankine active earth pressure coefficient, h_1 is the thickness of the strata above groundwater level, h_2 is the thickness from below the groundwater level to the boundary of the concrete retaining wall, h_3 is the net height of the concrete retaining wall, and q_1 and q_2 are the earth pressure at different positions of the concrete retaining wall.

$$q_{w1} = \gamma_w h_2 \tag{3}$$

$$q_{w2} = \gamma_w (h_2 + h_3) \tag{4}$$

where γ_w is the unit weight of the groundwater and q_{w1} and q_{w2} are the groundwater pressure at different positions of the concrete retaining wall.

Considering the slight difference between q_1 and q_2 and between q_{w1} and q_{w2}, and according to the principle of resultant force equivalence [25], this can be equivalent to Equation (5):

$$q = \frac{q_1 + q_2 + q_{w1} + q_{w2}}{2} \tag{5}$$

Then, Equations (1)–(4) are brought into Equation (5) to get:

$$q = \frac{2\gamma h_1 + (\gamma\prime + \gamma_w)(2h_2 + h_3)}{2} K_a - 2c\sqrt{K_a} \tag{6}$$

The static load and its equivalent load on the back of the concrete retaining wall are shown in Figure 4:

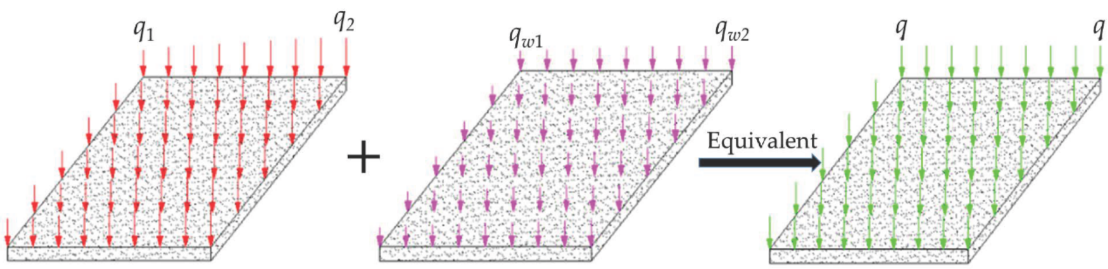

Figure 4. Equivalent force on the back of the concrete retaining wall.

Assuming that the single-hole grouting pressure is q_j because the concrete retaining wall has dozens of openings, the spread of the grout will form a grout crossing area on the entire surface. That is, there will be no blind grouting area. Therefore, the grouting uniform live load on the whole surface of the concrete retaining wall is q_j.

So, the uniform load on the whole face is:

$$q_u = q + q_j \tag{7}$$

According to plastic theory and the plate structure principle, plastic hinge theory [26–28] was used to analyze the ultimate bearing capacity of the concrete retaining wall.

The plastic hinge method studies the various possible failure patterns of the plate. It determines the possible maneuverable, allowable failure displacement mode by assuming a failure mechanism coordinated with the boundary conditions, and after the failure mechanism is given, the ultimate load is solved by establishing a virtual work equation.

When calculating the ultimate bearing capacity of the plate by the plastic hinge method, the assumptions are: (1) When the plate is about to fail, the plastic hinge line occurs at the maximum bending moment; (2) Under the action of a non-concentrated load, the plastic hinge line is straight; (3) The deformation of the plate is concentrated on the plastic hinge line, and each plate is rigid; (4) Among all the failure modes, there must be one that is the most dangerous, and its ultimate bearing capacity is the smallest.

The length of the rectangular concrete retaining wall bearing the uniformly distributed load is h_x, and the width is h_3. Assuming the limit state, the plastic hinge method is shown in Figure 5. Here, x is temporarily regarded as an unknown number. The deflection of line segment 5 is one.

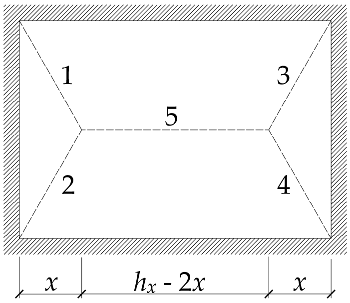

Figure 5. Distribution of plastic hinge lines when the concrete retaining wall is broken.

According to the plastic hinge theory, the concrete retaining wall is first destroyed at the plastic hinge line. However, the concrete retaining wall is still in equilibrium at the moment before destruction. Therefore, the principle of virtual work is used to solve it. The total virtual work T of the external force is equal to the volume of four slope crests in the plate structure multiplied by the uniform load q_u:

$$T = \frac{2}{3} q_u h_3 x + \frac{1}{2} h_3 (h_x - 2x) q_u \tag{8}$$

The internal force work is the sum of the work done by the five plastic hinge lines 1–5 and four plastic hinge lines formed by surrounding supporting edges. The internal work V done by the above five plastic hinge lines is:

$$V = 8(h_3/2x + h_x/h_3) M_0 \tag{9}$$

where M_0 is the plastic bending moment per unit length, $M_0 = S_t B^2/4$, B is the thickness of the concrete retaining wall, and S_t is the average tensile strength of the concrete retaining wall.

According to the principle of virtual work $T = V$:

$$q_u = \frac{24\left(h_3^2 + 2x h_x\right) M_0}{h_3^2 x (3h_x - 2x)} \tag{10}$$

Let $\mathrm{d}q_u/\mathrm{d}x = 0$, to get:

$$x = h_3 \left[-h_3/h_x + \sqrt{(h_3/h_x)^2 + 3} \right] / 2 \tag{11}$$

Then, combining (10) and (11), we can obtain:

$$B = \sqrt{\frac{q_u h_3^2 \left(\sqrt{h_3^2 + 3h_x^2} - h_3 \right)^2}{12 h_x^2 S_t}} \tag{12}$$

$$\text{Next, let } \alpha = \frac{h_3^2\left(\sqrt{h_3^2+3h_x^2}-h_3\right)^2}{12h_x^2} \tag{13}$$

Then, the theoretical formula for the safe thickness of the concrete retaining wall can be obtained as follows:

$$B = \sqrt{\frac{\alpha q_u}{S_t}} \tag{14}$$

3. Analysis of Mechanical Mechanism of Concrete Retaining Wall

To further study the mechanical mechanism of the concrete retaining wall, assumptions were made for the calculation parameters (Table 1), and the calculation examples were analyzed.Using the above basic parameters, the following research and analysis were carried out in turn.

Table 1. Calculation parameters of the example.

Tunnel Buried Depth/m	Groundwater Level/m	Concrete Retaining Wall Length/m	Concrete Retaining Wall Height/m	Concrete Tensile Strength/m	Concrete Compressive Strength/MPa
10	5	8	6	1.43	14.3
Groundwater bulk density/MPa	Stratum bulk density/kN/m^3	Floating bulk density/kN/m^3	Cohesion force/kPa	Internal friction angle of sand/°	-
9.8	18	9.5	0	30	-

3.1. Comparative Analysis of Safe Thickness of Concrete Retaining Wall

At present, in engineering practice, the traditional empirical formula [29] or Kalmykov formula [1] is generally adopted to determine the construction thickness of concrete retaining walls. The specific forms of the two methods are as follows:

(1) The traditional empirical formula is:

$$B = K_0\sqrt{\frac{Qh_x}{2h_3[\sigma]}} \tag{15}$$

where B is the thickness of the concrete retaining wall, K_0 is the safety coefficient (generally the value is 1~2), Q is the total load acting on the concrete retaining wall, $Q = P.S.$, P is the final grouting pressure, S is the area of concrete retaining wall, h is the width of the concrete retaining wall, and h_3 is the height of the concrete retaining wall.

(2) The Kalmykov formula is:

$$B = \frac{pr}{[\sigma]} + 0.3r \tag{16}$$

where B is the thickness of the concrete retaining wall, P is the final grouting pressure, $[\sigma]$ is the allowable compressive strength of the concrete, and r is the equivalent radius of the tunnel face.

The above two formulas were compared and analyzed with the theoretical formulas obtained in this article. According to the basic parameters of the calculation example, the relationship between the obtained final grouting pressure and the safe thickness of the concrete retaining wall is shown in Figure 6.

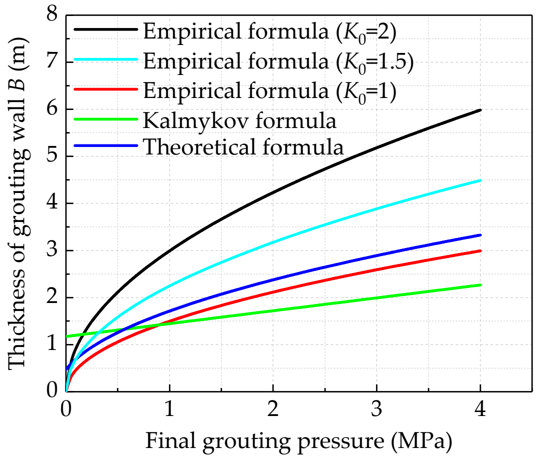

Figure 6. Relationship between the thickness of concrete retaining wall and grouting pressure.

(1) Due to the poor self-stabilization ability considered in this paper, the traditional empirical formula ignores the formation stress behind the concrete retaining wall and the groundwater pressure. Then, as can be seen on the graph, the curve starts from the origin, and when the safety coefficient K_0 is one or two, there is a big difference. Therefore, in actual engineering, the value of the safety coefficient is crucial. When the value is small, the effect cannot be achieved; the cost increases when the value is large.

(2) In the Kalmykov formula, there is a linear relationship between the final grouting pressure and the thickness of the concrete retaining wall. When the final grouting pressure is low, the thickness of the concrete retaining wall obtained by the Kalmykov formula is greater than that obtained by other formulas. With an increase of the final grouting pressure, the increase of the thickness of the concrete retaining wall is slight. The applicability of the Kalmykov formula is poor when the final grouting pressure is either small or large.

(3) The relationships between the final grouting pressure and the thickness of the concrete retaining wall obtained by the traditional empirical formula and the theoretical formula are similar in this paper. The curve forms show a trend that is first fast and then slow, and the curve of the final grouting pressure and the thickness of the concrete retaining wall in the theoretical formula obtained in this paper is sandwiched between the curves obtained when the safety coefficient K_0 of the traditional empirical formula is one or two. As such, there is a particular connection between the method in this paper and the traditional empirical formula.

3.2. Relationship between Thickness of Concrete Retaining Wall and Compressive (Tensile) Strength

The theoretical formula is related to the tensile strength of the concrete retaining wall, and the Kalmykov formula and the traditional theoretical formula are related to the compressive strength of the concrete retaining wall. From the literature [30], we can take $\sigma = 10S_t$.

Therefore, we propose combining the calculation examples and taking four working conditions (final grouting pressure P_j = 1, 2, 3, and 4 MPa) to analyze the curve relationships between the concrete tensile strength and the thickness of the concrete retaining wall, as shown in Figure 7.

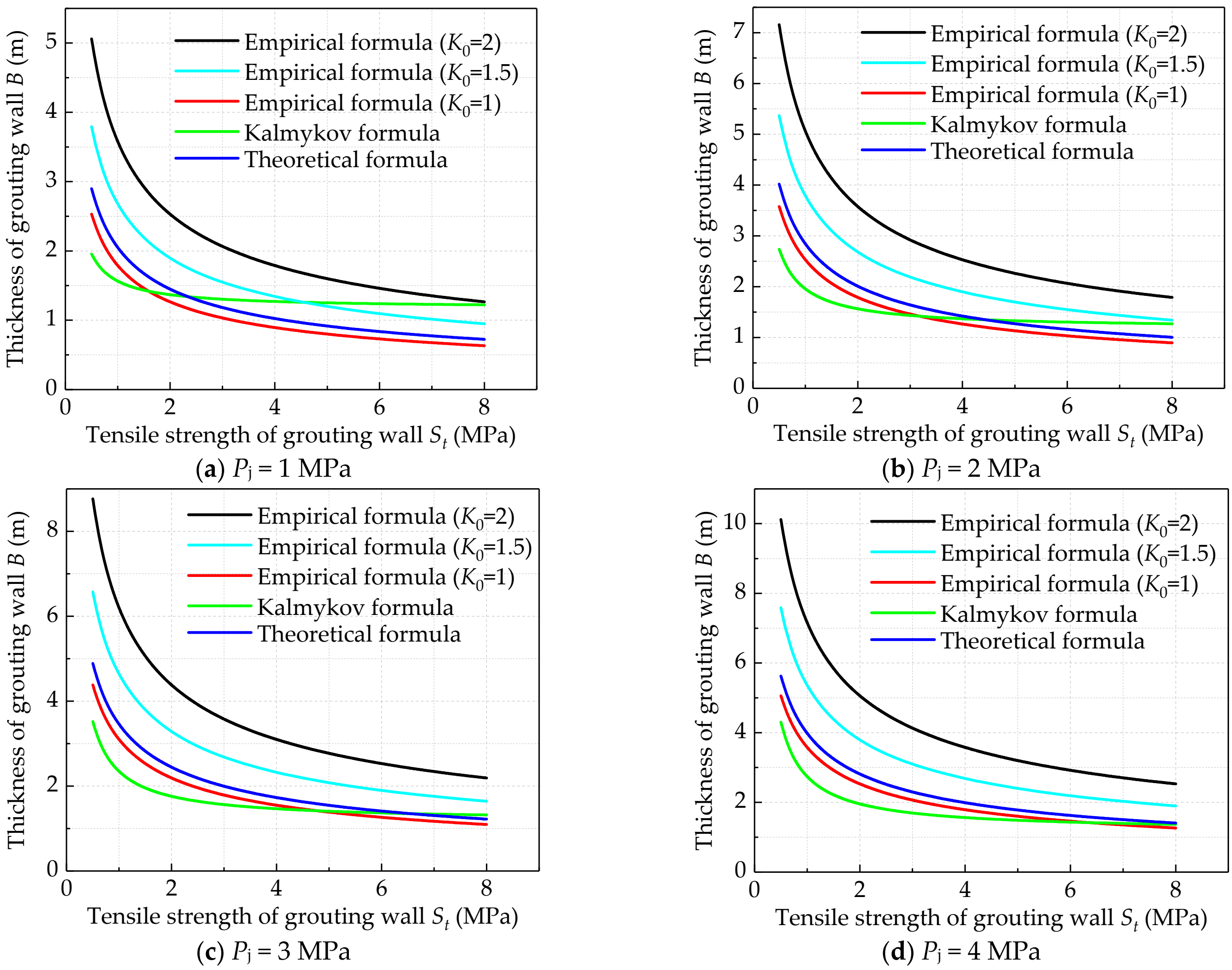

Figure 7. Relation between the thickness of concrete retaining wall and tensile strength.

By analyzing Figure 7, we can conclude that:

(1) When the final grouting pressure is constant, with an increase of the tensile strength of the concrete retaining wall, the required safe thickness of the concrete retaining wall gradually decreases. Under the same tensile strength, with the increase of final grouting pressure, the safe thickness of the concrete retaining wall increases slowly.

(2) The thickness of the concrete retaining wall obtained by the Kalmykov formula has little correlation with the tensile strength of the concrete and the final grouting pressure. The applicability is poor when the final grouting pressure is high and the tensile strength of the concrete is low.

(3) The variation trend of the concrete retaining wall thickness with the tensile strength is consistent between this paper's traditional empirical formula and the theoretical formula. Under the same conditions, with the improvement of the tensile strength of the concrete retaining wall, the thickness of the concrete retaining wall shows a trend of rapid decrease first and then slow decrease. The theoretical formula curve falls between the conventional empirical formula safety coefficients K_0 of one or two. As the final grouting pressure increases, the theoretical formula curve gradually approaches the traditional empirical formula curve when K_0 = 1.

3.3. Relationship between Thickness of Concrete Retaining Wall and Depth of Tunnel

We conducted further analysis of the relationship between the thickness of the concrete retaining wall and the buried depth of the tunnel in the theoretical formula, using the traditional empirical formula and the Kalmykov formula under different working conditions (P_j =2 MPa), and the results obtained are shown in Figure 8.

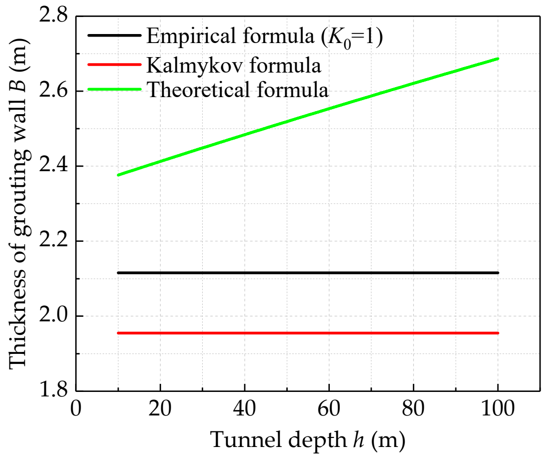

Figure 8. Relationship between concrete retaining wall's thickness and tunnel's buried depth.

By analyzing Figure 8, we can conclude that:

(1) Under the same final grouting pressure, the tunnel depth obtained by the theoretical formula is approximately positively correlated with the thickness of the concrete retaining wall. In the traditional empirical formula and Kalmykov formula, the influences of ground stress and groundwater pressure on the thickness of the concrete retaining wall are ignored, so the effect of the tunnel depth on the concrete retaining wall is not considered.

(2) The increase in the thickness of the concrete retaining wall with the buried depth of the tunnel is much smaller than the change in the thickness of the concrete retaining wall caused by the change of the final grouting pressure. This is because as the buried depth of the tunnel increases, the thickness of the stratum increases correspondingly, which translates into a relatively small force acting on the concrete retaining wall. For example, in this calculation example, the buried depth of the tunnel is increased to 100 m, and the uniform pressure is only increased by about 0.8 MPa.

3.4. Transformation Relationship between Empirical Formula and Theoretical Formula

From the above findings, it can be seen that there is a quantitative relationship between the traditional empirical formula and the theoretical formula, which is summarized as the safety coefficient K_0. By converting Equations (12) and (15), Equation (17) can be obtained.

$$K_0 = fi\sqrt{\frac{5(q_j+q)}{3q_j}} \tag{17}$$

where β is a parameter to be determined.

$$\beta = \frac{h_3\left(\sqrt{h_3^2 + 3h_x^2} - h_3\right)}{h_x^2} \tag{18}$$

According to the basic parameters of the above calculation example, we proposed adopting the following three working conditions (size of concrete retaining wall: 6 m × 4 m; 6 m × 6 m; 6 m × 8 m). The relationship between the safety coefficient K_0 and the final grouting pressure P was analyzed, as shown in Figure 9.

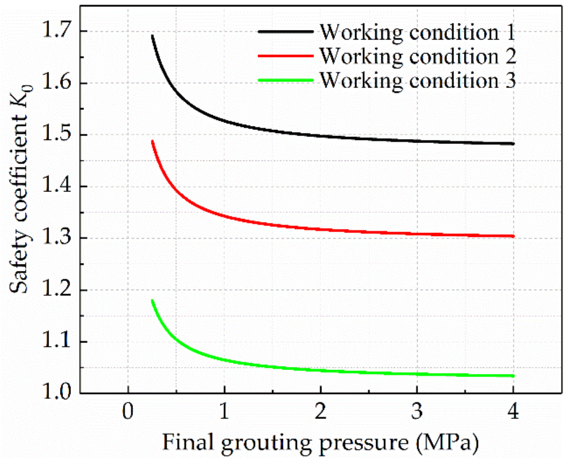

Figure 9. Relationship between final grouting pressure and safety coefficient.

By analyzing Figure 9, we can conclude that:

(1) When the size of the concrete retaining wall is determined, the safety coefficient K_0 is negatively correlated with the final grouting pressure, and the range of safety coefficient K_0 varies slightly with the final grouting pressure (about ± 0.3).

(2) The safety coefficient K_0 is highly correlated with the size of the concrete retaining wall. In tunnels with different sizes, as the size of the concrete retaining wall changes, the change of safety coefficient K_0 is noticeable.

(3) Combining this calculation example illustrates that, in shallow tunnels, the value of K_0 is relatively reasonable when between one and two. When the final grouting pressure $P < 1$ MPa, the value of the safety coefficient decreases rapidly with the increase of the final grouting pressure. When the final grouting pressure $P > 1$ MPa, the safety coefficient decreases slowly with the rise of the final grouting pressure. This is because when the final grouting pressure is small, the buried depth of the tunnel and the groundwater pressure significantly affect the thickness of the concrete retaining wall. The traditional empirical formula does not consider this effect in that regard, so the required safety coefficient is large. When the final grouting pressure is great, the influence of the tunnel depth and groundwater pressure on the concrete retaining wall can be ignored relative to the final grouting pressure, so the safety coefficient value will be smaller.

4. Field Test Findings

The Linghuang interval tunnel of Qingdao Metro Line R3 in Huangdao District mainly passes through a medium and coarse sand layer, silty clay layer, and moderately weathered breccia tuff layer, and the risk assessment is level II. In the interval section, YSK14+187-YSK14+342 on the right line; half of the tunnel face is made up of sand, silty clay, and other unfavorable geology, and the lower half comprises moderately weathered breccia tuff. The construction of the left line has reached ZSK14+267.5, and the surrounding rock conditions of the tunnel face have significantly changed. The tunnel face of the upper step is made up of sand, silt, silty clay, and other unfavorable geology, which is similar to the stratum exposed on the right line. The single hole of the tunnel has a width of 6 m and a clear height of 7.2 m. Part of the geological profile is shown in Figure 10.

A concrete retaining wall needs to be constructed in advance to better complete the grouting work and prevent accidents such as mortar running and tunnel face collapses during the grouting process. Accordingly, the tunnel condition could be used to verify whether the theoretical formula is reasonable. According to the geological profile, each stratum's average thickness and effective unit weight were determined through laboratory tests, as shown in Table 2.

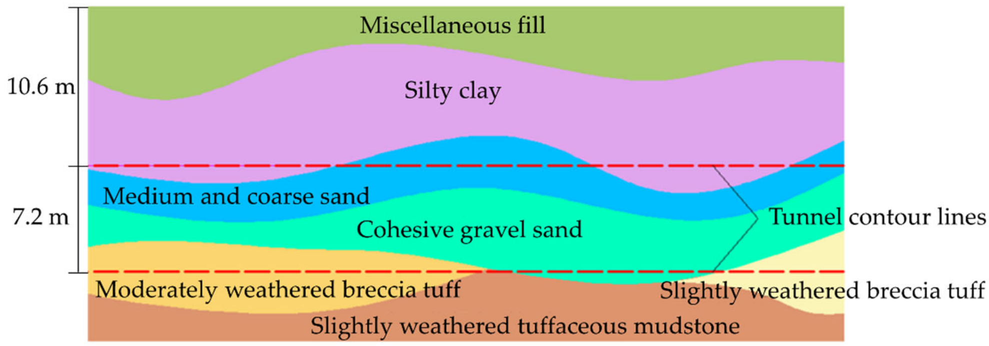

Figure 10. Geological profile.

Table 2. Classification table of different strata.

Stratigraphic Type	Cohesion Force/kPa	Internal Friction Angle of Sand/°	Average Depth/m	Density of Stratum/kN/m^3
Miscellaneous fill	5	5	0–5.1	17
Silty clay	10	10	5.1–10.6	19.5
Medium and coarse sand	4	25	10.6–14.2	14.7
Clay sand	30	30	14.2–17.8	12.3

The average groundwater level in this interval is −3.6 m. The different effective unit weights of each stratum could be determined by soil data and laboratory tests and calculated by Equation (19):

$$\gamma\prime = \frac{(G_s - 1)\gamma_w}{1+e} \tag{19}$$

where G_s is the specific gravity of the soil particles, γ' is the effective unit weight of the stratum, γ_w is the unit weight of the groundwater, and e is the particle void ratio. The results are shown in Table 3.

Table 3. Laboratory test results of different strata.

Stratigraphic Type	Specific Gravity/kg/m^3	Particle Void Ratio	Effective Unit Weight/kN/m^3
Miscellaneous fill	2.73	0.40	12.1
Silty clay	2.74	0.50	11.4
Medium and coarse sand	2.66	0.80	9.0
Clay sand	2.68	0.40	11.8

Using the theoretical formula in this paper to make the calculation, we determined that q = 0.16 MPa and α = 1.64. To verify the accuracy of the theoretical formula, field tests were carried out under the following conditions. The concrete specification used in these tests was C30, and the basic mechanical parameters were the same as those of the calculation example. The cement was P.O 32.5 cement produced by Shandong Shanshui Cement Group Co., Ltd. The fine aggregate was medium sand and the fineness modulus was 2.7. The coarse aggregate was granite gravel with a 5~20 mm continuous gradation.

Table 4 shows the empirical formula (K_0 = 1 or 2) and the calculated values of the theoretical formula in this paper, along with the experimental reference values. The final grouting pressures of the three working conditions were 0.6 MPa, 1 MPa, and 1.4 MPa, respectively.

Table 4. Calculation of thickness of concrete retaining wall and test selection.

Thickness /m	Condition 1 (P_j = 0.6 MPa)		Condition 2 (P_j = 1 MPa)		Condition 1 (P_j = 1.4 MPa)	
Empirical formula solution	0.52	1.04	0.67	1.34	0.80	1.60
Theoretical formula solution	0.93		1.15		1.33	
Experimental design	Left tunnel	0.50	Left tunnel	0.70	Left tunnel	0.80
	Right tunnel	0.90	Right tunnel	1.20	Right tunnel	1.30

The field test results show that:

(1) For the right tunnel, in the three working conditions, except for slight local deformation of the concrete retaining wall during a certain period of grouting, no water seepage, cracking, or other accidents occurred, which verifies the safety of the thickness of the concrete retaining wall obtained using the theoretical formula.
(2) The concrete retaining wall was damaged to varying degrees under the three working conditions for the left tunnel. To avoid accidents, grouting must be stopped to further strengthen the concrete retaining wall. Thus, the concrete retaining wall did not fulfill its purpose or meet its requirements. Yet, the rationality of the safe thickness of the concrete retaining wall obtained by the theoretical formula was indirectly verified.

In summary, the method for determining the safe thickness of the concrete retaining walls established in this paper is reasonable and has reference significance for similar projects.

5. Discussion

(1) Based on the Rankine active earth pressure theory, plastic mechanics, and plate structure theory, this paper offers a novel method for determining a safe thickness for a concrete retaining wall. However, the stratum in this paper had poor self-stability, and the formula deduced in this paper is conservative for strata with strong or complete self-stability, which means that related research needs to be further promoted.
(2) In actual construction, the grouting disc can be reserved in the follow-up cycle so the pouring thickness of the concrete retaining wall can be appropriately reduced. Currently, decisions on how to reduce the thickness are based solely on engineering experience and the advantages and disadvantages of the grouting effect. Thus, theoretical research must be further conducted.
(3) In actual grouting, borehole grouting is required and the grouting pressure decreases with the outward diffusion of the grouting hole. However, this paper ignored the weakness near the grouting hole and the lack of homogeneity of slurry pressure. Therefore, the distribution of actual grouting pressure and the weakness of the grouting hole require further study.

6. Conclusions

(1) The equivalent force on the back of the concrete retaining wall was calculated based on the Rankine earth pressure theory. The concrete retaining wall was regarded as a four-sided fixed support plate, and the ultimate load was solved by establishing the virtual work equation. A novel method for determining the safe thickness of the concrete retaining wall was proposed, and quantitative criteria for the safe thickness of concrete retaining wall were given.
(2) The theoretical formula derived in this paper was compared with the thickness of the concrete retaining wall obtained by the traditional empirical formula and the Kalmykov formula. The traditional empirical formula ignores the formation stress and groundwater pressure behind the concrete retaining wall. The Kalmykov formula has poor applicability when the final grouting pressure is small or large, and the influence of groundwater pressure is not considered. By considering the impacts of different working conditions on the concrete retaining wall, the rationale of the safe thickness of the concrete retaining wall obtained in this paper was further clarified.

(3) There is a connection between the method in this paper and the traditional empirical formula. The quantitative transformation relationship between the traditional empirical formula and the theoretical formula was established. In a shallow tunnel, the value of K_0 is relatively reasonable when between one and two. When the final grouting pressure is smaller, the safety factor should be larger. When the final grouting pressure is larger, the safety factor should be smaller.

(4) The safe thicknesses calculated by the traditional empirical formula with a K_0 of one and by the theoretical formula in this paper were analyzed through field tests to verify the rationale of the theoretical formula. The test results showed that the thickness of the concrete retaining wall designed according to the theoretical formula met the construction requirements. Under the traditional empirical formula (K_0 = 1) design, the concrete retaining wall failed to meet the construction requirements. We suggest that the theoretical formula established in this paper can be adopted in grouting engineering for shallow tunnels in weakly water-rich strata. If the traditional empirical formula is used, the value of K_0 needs to be solved theoretically.

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