Hindawi
Discrete Dynamics in Nature and Society
Volume 2022, Article ID 6779558, 11 pages
https://doi.org/10.1155/2022/6779558

Research Article

Study on Steel Content Estimation of Reinforced Concrete Rectangular Pool Wall

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Received 20 April 2022; Revised 24 May 2022; Accepted 20 June 2022; Published 7 July 2022

Academic Editor: Lele Qin

For water purification plants and sewage treatment plants, there is no reference optimal steel content for the wall of reinforced concrete water pool. Focusing on the reinforced concrete water pool, this paper explores the optimal wall thickness and optimal reinforcement area at different bending moments and identifies the optimal steel content. To solve the problem, the authors established the discrete distribution function for the engineering cost per unit length of pool wall and steel content. The theoretical model was verified by numerous data through Excel numerical simulation. The research results provide a reference optimal steel content for designers and help to save the engineering cost of pool wall.

1. Introduction

Most water plants or sewage treatment plants, either completed or under construction, adopt the rectangular reinforced concrete water pool, for the pool has various advantages. For instance, the pool adapts well to the field environment; the local materials can be directly used to build the pool; the reinforcement and supporting operations are very convenient; and the pool is durable and cheap to maintain [1, 2]. In traditional structural design, the designer usually determines the structural scheme through trial calculation, verification, and modification, according to the design requirements, his/her practical experience, and similar engineering designs. The scheme is rarely optimized through comparison due to time limit and excessive workload [3, 4].

During the expected construction boom of urban domestic wastewater treatment facilities, the key problem is the shortage of funds. In civil engineering cost, the material cost accounts for about 42%. Around 30% to 50% of the material cost is incurred by rebars [5]. How to estimate the steel content of each structure accurately and comprehensively is the focus and difficulty in cost analysis. In ACI 318-19 [6], GB 50010-2010 (2015 edition) [7], CECS138:2002 [8], and other codes, the reinforcement area and crack control of concrete are stipulated, but the structural design scheme is not optimized from the angle of cost reduction. In the past research on structural design optimization, researchers have studied the structural optimization design of residential buildings, complex buildings, commercial buildings, and single-storey industrial buildings [3, 4] and the reasonable steel content range of buildings by means of support vector machine method, genetic algorithm, statistical method, experimental and numerical study, etc. [9–20]. However, there is little report on the reasonable steel content for the minimal cost of water pools.

Based on the design specifications, and a thorough consideration of the feasibility of design and construction, this paper draws on the previous design experience and standard atlas and establishes a theoretical mathematical model that satisfies the force requirements and structural requirements. Through repeated data trials and verifications, the authors identified the optimal wall thickness and steel content that minimize the overall engineering cost of the wall of reinforced concrete water pool, when the pool wall's bending moment changes under external load. The research results provide a direct reference for designers to reduce the engineering cost of the water pool.

The remainder of this paper mainly covers four aspects: firstly, a mathematical model was established for the total engineering cost, wall thickness, and horizontal reinforcement area; next, the optimal steel content was verified through numerical simulation [10–14]; and finally, the optimal steel content was solved to minimize the engineering cost per unit area of the pool wall.

2. Mathematical Modeling

2.1. Objective Function and Variables. This research intends to find the optimal steel content that minimizes the total cost of pool wall under the premise of fixed bending moment (that is, assuming that the internal control length, width, and height of the pool, the water level in the pool, and the layout of the pool partition wall are all determined). The steel content refers to the rebar content per unit area, i.e., the proportion of reinforcement area in unit area of pool wall [5].

The total cost of the pool wall refers to the total construction cost of the wall, consisting of construction and installation fee, equipment and instrument fee, other fees of project construction, preparation fee, and the loan interest in the construction period. Among them, equipment and instrument fee, other fees of project construction, and preparation fee are not related to wall thickness and steel content. Therefore, wall thickness and steel content mainly influence the construction and installation fee in the total cost function of the pool wall.

According to the composition of cost, the construction and installation fee can be divided into five parts: subengineering fee, measure item fee, other item fee, compliance fee, and taxes [21]. By the calculation program of engineering cost, the other item fee was set to zero. The compliance fee and taxes are charged in accordance with the provisions in laws and regulations of China and related to the first three elements of engineering cost. Therefore, the authors did not consider the other item fee, compliance fee, and taxes, when they explored the cost variation induced by the changes of wall thickness and steel content. Then, the total cost of the pool wall mainly depends on two factors: subengineering fee and measure item fee.

2.1.1. Subengineering Fee. The subengineering fee contains the fee of concrete and rebars, as well as the variation in labor cost and machinery cost induced by the changes in the use volume of concrete and rebars (without considering the impact of management fee and profit).

2.1.2. Measure Item Fee. The measure item fee mainly consists of the cost of concrete formworks. When the pool has a fixed length, width, and thickness, the formworks on the two sides are of equal volume and independent of wall thickness. Besides, the unit price of concrete and rebars has nothing to do with the wall form. Thus, the total cost (C) of the pool wall is primarily affected by the amount of concrete and steel content.

For the reinforced concrete rectangular water pool, the reinforcement configuration of the wall mainly faces two constraints: the force requirement and the structural requirement. The volume of the pool wall concrete is equal to the length × height × thickness of pool wall. This study assumes that the internal control length, width, and height of the pool are certain, that is, the length and height of the pool wall are certain, so the thicker the wall, the greater the use volume of concrete, and the fewer the rebars required to meet the force requirement. Once the wall reaches a certain thickness, however, the rebar volume may increase rather than decrease, for it depends on the structural requirement. This paper temporarily ignores the truncation of horizontal rebars, and the regional configuration of horizontal rebars on the pool wall; that is, the vertical and horizontal rebars are assumed to be deployed across the height of the wall. The impacts of other factors were investigated after solving the optimal wall thickness.

In summary, the objective function of our model is the total cost of the pool wall, and the variables include wall thickness (i.e., concrete volume) and horizontal reinforcement area (i.e., rebar volume). For simplicity, a strip of the pool wall was taken as the research object (Figure 1), with the length of Ln, the height of 1 m, and the thickness of h. Then, the cost per unit length of pool wall can be converted into a function of wall thickness and reinforcement area using the following formula:

$$\begin{aligned} C &= C_1 + C_2 \\ &= \frac{y_1 \times h \times 10^{-3} \times Ln \times 1 + y_2 \times A_s \times 10^{-6} \times Ln \times \varepsilon}{Ln} \\ &= y_1 \times h \times 10^{-3} + y_2 \times A_s \times 10^{-6} \times \varepsilon. \end{aligned} \tag{1}$$

Steel content $\rho = (A_s/h \times 1)$.

Then,

$$\begin{aligned} C &= f(\rho, A_s) \\ &= f[\rho, g(\rho)], \end{aligned} \tag{2}$$

where C is the cost per unit length of the pool wall (yuan); C_1 and C_2 are the cost per unit length of concrete and the cost per unit length of rebar (yuan), respectively; y_1 is the sum of labor, material, and machinery costs per square meter of concrete (yuan); h is the wall thickness (mm); Ln is the wall length; y_2 is the sum of labor, material, and machinery costs per kg of wall rebars (yuan); A_s is the horizontal reinforcement area on the 1 m-long strip (mm^2); ε is the appearance density of rebars (7,850 kg/m^3); and ρ is the steel content of pool wall.

2.2. Constraints. In actual engineering, the model of the pool wall is constrained by three factors: the force requirements on rebars, the structural requirements on rebars, and the crack width requirements.

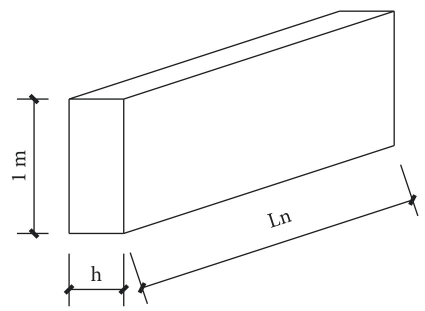

Figure 1: Research object of the model: 1 m-long strip of the pool wall.

2.2.1. Force Requirements on Rebars (Force Requirements under Strength Limit State). The wall of the reinforced concrete rectangular water pool is a bending component. Without considering prestressed rebars, this paper only takes account of the configuration of ordinary rebars. Referring to 6.2.10 of *Code for Design of Concrete Structures* (GB 50010-2010; 2015 version), the flexural capacity of the normal rectangular cross section (as show in Figure 2) must satisfy [7]:

$$M \le \alpha_1 f_c bx\left(h_0 - \frac{x}{2}\right) + f_y' A_s' \left(h_0 - a_s'\right), \tag{3}$$

$$\alpha_1 f_c bx = f_y A_s - f_y' A_S'. \tag{4}$$

Here, M is the bending moment; α_1 is the coefficient; f_c is the designed axial compressive strength of concrete; b is the width of rectangular section; x is the height of concrete compression zone; h_0 is the effective height of cross section; f_y' and f_y are the design value of tensile strength of steel bar in compression zone and the design value of tensile strength of steel bar in tensile zone; A_s' and A_s are the cross-sectional area of steel bar in compression zone and the cross-sectional area of steel bar in tensile zone; and a_s' is the unite efforts of longitudinal reinforcement in the compression zone.

That is, the load-bearing reinforcement area on the pool wall should satisfy formulas (3) and (4), when the bending moment M remains constant. Assuming that the bending component has only one rebar, it can be calculated that A_s' = 0. Then, formulas (3) and (4) can be simplified as formulas (5) and (6), respectively:

$$M \le \alpha_1 f_c bx\left(h_0 - \frac{x}{2}\right), \tag{5}$$

$$\alpha_1 f_c bx = f_y A_s, \tag{6}$$

$$\text{If } x < \varepsilon_b h_0, \text{ then } A_{s1} = \frac{\alpha_1 f_c bx}{f_y}. \tag{7}$$

2.2.2. Structural Requirements on Rebars (Configuration Requirements under Serviceability Limit State). According to 8.5.1 of *Code for Design of Concrete Structures* (GB 50010-2010; 2015 version), the reinforcement percentage of longitudinal load-bearing rebars in the bending components of reinforced concrete structure should not be lower than the larger value between the minimum reinforcement percentage $\rho_{\min} = 0.20$ and $45(f_t/f_y)$ [7]. Then, A_{s2} could be solved. Therefore, $A_s = \max\{A_{s1}, A_{s2}\}$.

The maximum reinforcement ratio stands for the reinforcement area when the longitudinal tensile rebars yield, and the concrete in the compressive zone fails. It can be calculated that $\varepsilon_b = 0.518$. When $x = \varepsilon_b h_0$, the maximum reinforcement ratio was 2.18%. The A_s must be controlled below the maximum reinforcement ratio.

2.2.3. Crack Width Requirements (Configuration Requirements under Serviceability Limit State). Referring to Appendix of the national standard CECS138:2002 [8], the crack width of large eccentricity tensile or compressive components must be smaller than or equal to the maximum crack width:

$$\begin{aligned}\omega_{max} &= 1.8\psi \frac{\sigma_{sq}}{E_s}\left(1.5c + 0.11\frac{d}{\rho_{te}}\right)(1 + a_1)v \le [\omega_{\max}] \\ &= 0.20mm,\end{aligned} \tag{8}$$

$$\psi = 1.1 - \frac{0.65 f_{tk}}{\rho_{te}\sigma_{sq}a_2}. \tag{9}$$

Under the permanent or standard combination of loads, the equivalent stress of the stress on the ordinary longitudinal rebars in the bending zone of reinforced concrete bending components can be calculated using the following formula:

$$\sigma_{\text{sq}} = \frac{M_q}{0.87 h_0 A_s}. \tag{10}$$

Combining formulas (8)–(10), the maximum crack width $\omega_{\max}$ of the pool wall can be solved. According to CECS138:2002 5.3.4 [8], the maximum crack width of the structural members of the reinforced concrete pool should not be greater than the following specified limit $\omega_{\max}$: for the clean water pool and the water purification treatment structure, $\omega_{\max} \le 0.25$mm; for sewage treatment structures, $\omega_{\max} \le 0.2$mm, so $\omega_{\max}$ must be smaller than $[\omega_{\max}] =$ 0.20 mm.

2.3. Theoretical Modeling. When M is fixed, $M = \alpha_1 f_c bx(h_0 - (x/2))$ can be derived from the limit value of formula (5). According to formula (6), it can be solved that $x = (f_y A_s/\alpha_1 f_c b)$. Then, $M = \alpha_1 f_c bx(h_0 - (x/2)) = f_y A_s (h_0 - (f_y A_s/2\alpha_1 f_c b)) = f(h_0, A_s)$. By the definition of *Code for Design of Concrete Structures* (GB 50010-2010; 2015 version), it can be obtained that h_0 = h-a_s' [7]. Since $\rho = (A_s/h \times 1)$, we have

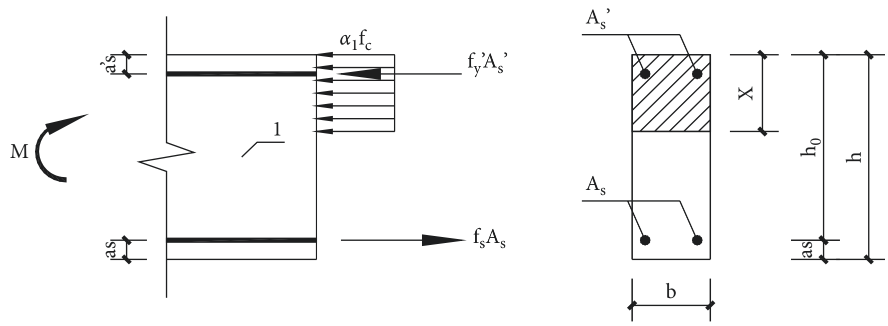

FIGURE 2: Calculation of flexural capacity of normal section of rectangular flexural members.

$$\begin{aligned} M &= f(h_0, A_s) \\ &= f(h, A_s) \\ &= f(\rho, A_s) \\ &= f[\rho, g(\rho)]. \end{aligned} \tag{11}$$

From formula (2), it can be learned that $C = f(\rho, A_s) = f[\rho, g(\rho)]$. Combining formulas (2) and (11), when M is constant, there exists an optimal steel content ρ that minimizes C. However, there are limited possibilities for the diameter and interval of rebars, i.e., A_s has a limited number of values. Thus, $C = f(\rho, A_s) = f[\rho, g(\rho)]$ is discrete. Next, the minimum C was searched for through numerical simulation.

3. Calculation of Optimal Steel Content through Numerical Simulation

Before formulating the verification grids for wall thickness and reinforcement area through numerical simulation (trial and error), it is necessary to preset the grid value and formula expression. Under a certain bending moment and wall thickness, the built-in formula of reinforcement area was calculated under model constraints. Next, the result of objective function (1), i.e., the total cost C, was solved, based on the combination between wall thickness and reinforcement area under a certain bending moment. Using the C value, the optimal steel content was queried, providing a reference for designers.

3.1. Calculation of Rebar Configuration

3.1.1. Calculation of Configuration and Structural Requirements on Load-Bearing Rebars. According to the normal force situation of the regular pool wall, the known conditions were set up in Excel (Table 1): the bending moment M of 250 kN·m; the wall thickness h of 400; the concrete grade of impervious C30; and the rebar grade of HRB400. The rebars were configured according to model constraints. Table 1 also lists the known data used to compute the reinforcement area of the pool wall.

According to formulas (5)–(7), and the known data in Table 1, $A_{s1} = 2047\,mm^2$ can be solved in Excel. Then, the reinforcement area table of plates was looked up in the rebar query software. The results show that, if φ20@150 rebars are used, the actual reinforcement area $A_{s1} = 2094\,mm^2$, and the reinforcement percentage ρ satisfies the requirement $\rho_{\min} = 0.2\% < \rho = 0.57\% < \rho_{\max} = 2.18\%$. Thus, the configuration of rebars φ20@150 meet the force and structural requirements on rebars.

3.1.2. Calculation of Maximum Crack Width. When rebars φ20@150 were deployed on the pool wall, the crack constraint was set up in Excel. The known conditions are presented in Table 2.

According to formulas (8)–(10), and the known data in Table 2, the maximum crack width can be solved as $\omega_{\max} = 0.332 > [\omega_{\max}] = 0.20\,mm$. The crack requirement was not satisfied, calling for expansion of rebar configuration.

The above calculations were repeated to verify whether the rebars on the wall satisfy the force and structural requirements, and whether the maximum crack width meets the crack requirement. In this way, four qualified reinforcement patterns were found for the pool wall: 20@100; φ22@125; φ25@150; and φ28@150.

The reinforcement pattern of φ22@125 was preferred because its reinforcement area was the smallest (3,040 mm^2). Then, the actual reinforcement area $A_{s1} = 3040\,mm^2$, and the reinforcement percentage ρ satisfies $\rho_{\min} = 0.2\% < \rho = 0.83\% < \rho_{\max} = 2.18\%$. The rebar configuration meets the force and structural requirements. In this case, the maximum crack width $\omega_{\max} = 0.180 < [\omega_{\max}] = 0.20$ mm meets the crack requirement. Hence, when the bending moment M is 250 kN·m, the wall thickness h is 400, the concrete grade is impervious C30, and the rebar grade is HRB400; the reinforcement pattern that meets model constraints and minimizes the actual reinforcement area is φ22@125, and $A_{s1} = 3040\,\text{mm}^2$.

3.1.3. Calculation of Wall Thickness and Rebar Configuration Meeting Model Constraints. By the above computing process, the rebar configuration meeting model constraints were solved for walls of different thicknesses, when the bending moment M of the wall was 250 kN·m. The results are displayed in Table 3.

With the bending moment of 250 kN·m, the above reinforcement patterns were compared, and the optimal one was selected by the principle of minimizing reinforcement area. The optimal results are displayed in Table 4.

Table 1: Known data used to compute the reinforcement area of the pool wall.

Symbol	f_c	α_1	f_y	ε_b	$\rho_{\min}$	$\rho_{\max}$	c	M	b	h	h_0
Meaning	Designed axial compressive strength of concrete	Coefficient	Designed tensile strength of rebars	Height of relative critical compressive zone	Minimum reinforcement ratio	Maximum reinforcement ratio	Thickness of protective layer	Bending moment	1 m-long strip	Wall thickness	Effective height of cross section
Known data	14.3	1.00	360	0.550	0.20%	2.18%	35	250	1000	400	365
Unit	N/mm^2	None	N/mm^2	None	None	None	mm	kN·m	mm	mm	mm

Table 2: Known data used to compute the maximum crack width.

Symbol	f_{tk}	E_s	$[\omega_{\max}]$	a_1	a_2	v	d
Meaning	Standard axial compressive strength of concrete	Elastic modulus of rebars	Maximum crack width	Coefficient	Coefficient	Surface characteristic coefficient of longitudinal tensile rebars	Rebar diameter
Known data	2.01	200000	0.20	0.0	1.0	0.7	20
Unit	N/mm^2	N/mm^2	mm	—	—	—	mm
Symbol	c	Mq	b	h		A_s	h_0
Meaning	Thickness of protective layer	Bending moment	1 m-long strip	Wall thickness		Actual reinforcement area	Effective height of cross section
Known data	35	196.85	1000	400		2094	365
Unit	Mm	kN m	mm	mm		mm^2	mm

Table 3: Rebar configurations of different wall thicknesses.

Wall thickness	250		300			350			
Actual rebar configuration	φ25@100	φ28@125	φ22@100	φ25@125	φ28@125	φ20@100	φ22@100	φ25@125	φ28@150
Actual reinforcement area	4910	4928	3800	3928	4928	3140	3800	3928	4107
Wall thickness	400					450			
Actual rebar configuration	φ20@100	φ22@125	φ25@150	φ28@150	φ18@100	φ20@125	φ22@125	φ25@150	φ28@200
Actual reinforcement area	3140	3040	3274	4107	2540	2512	3040	3274	3080
Wall thickness	500					550			
Actual rebar configuration	φ18@100	φ20@125	φ22@150	φ25@200	φ28@200	φ16@100	φ18@100	φ20@150	φ22@150
Actual reinforcement area	2540	2512	2534	2455	3080	2010	2540	2094	2534
Wall thickness	550		600			650			
Actual rebar configuration	φ25@200	φ14@100	φ16@100	φ18@125	φ20@150	φ22@200	φ25@200	φ28@200	φ14@100
Actual reinforcement area	2455	1540	2010	2032	2094	1900	2455	3080	1540
Wall thickness	650					700			
Actual rebar configuration	φ16@125	φ18@150	φ20@150	φ22@200	φ25@200	φ28@200	φ14@100	φ16@125	φ18@150
Actual reinforcement area	1608	1694	2094	1900	2455	3080	1540	1608	1694
Wall thickness	700					750			
Actual rebar configuration	φ20@200	φ22@200	φ25@200	φ28@200	φ14@100	φ16@125	φ18@150	φ20@200	φ22@200
Actual reinforcement area	1570	1900	2455	3080	1540	1608	1694	1570	1900
Wall thickness	750					800			
Actual rebar configuration	φ25@200	φ28@200	φ16@125	φ18@150	φ20@150	φ22@200	φ25@200	φ28@200	
Actual reinforcement area	2455	3080	1608	1694	2094	1900	2455	3080	

Table 4: Rebar configuration and steel content selected by the principle of minimizing reinforcement area.

Wall thickness	250	300	350	400	450	500	550	600	750	800
Actual rebar configuration	φ25@100	φ22@100	φ20@100	φ22@125	φ20@125	φ25@200	φ16@100	φ14@100	φ14@100	φ16@125
Actual reinforcement area	4910	3800	3140	3040	2512	2455	2010	1540		1608
Steel content	1.96%	1.27%	0.90%	0.76%	0.56%	0.49%	0.37%	0.26%	0.21%	0.20%

Then, the wall of reinforced concrete water pool was simulated with a bending moment of 50–600 kN·m. Then, the reinforcement patterns of different wall thicknesses and a fixed bending moment were compared, and the one corresponding to the minimum bending moment was selected. Table 5 displays the optimal wall thickness and optimal reinforcement situation at different bending moments.

4. Calculation of Wall Cost per Unit Area

4.1. Calculation of Unit Area of Pool Wall. The above calculation of rebar configuration shows that the optimal rebar configuration is φ22@125 for the bending moment M of 250 kN·m, the wall thickness h of 400, the concrete grade of impervious C30, and the rebar grade of HRB400. Referring to the quota of engineering consumption in municipal projects [22], and the engineering information prices of Shijiazhuang, the seat of northern China's Hebei Province in August, 2020 (data source: Glodon Cloud PRICING Platform GCCP6.0), the wall cost per unit area can be solved by formula (1) as $C = C_1 + C_2 = y1 \times h \times 10^{-3} + y2 \times \mathrm{As} \times 10^{-6} \times \rho = 387.14 \times 400 \times 10^{-3} + 4.96 \times 3040 \times 10^{-6} \times 7850 = 266.77$ yuan. According to the optimal rebar configuration in Table 4, the wall costs C per unit area of pool walls of different thicknesses can be solved (Table 6).

Table 5: Optimal wall thickness and optimal reinforcement situation at different bending moments.

Bending moment	Reinforcement situation	Wall thickness 250	300	350	400	450	500	550	600	650	700	750	800
Bending moment 50	Reinforcement area	904	904	754	904	904	904	1130	1232	1340	1540	1540	1608
	Reinforcement pattern	φ12@125	φ12@125	φ12@150	φ12@125	φ12@125	φ12@125	φ12@100	φ14@125	φ16@150	φ14@100	φ14@100	φ16@125
	Steel content	0.36%	0.30%	0.22%	0.23%	0.20%	0.18%	0.21%	0.21%	0.21%	0.22%	0.21%	0.20%
Bending moment 100	Reinforcement area	2032	1340	1130	1027	904	1005	1130	1232	1340	1540	1540	1608
	Reinforcement pattern	φ18@125	φ16@150	φ12@100	φ18@200	φ12@125	φ16@200	φ12@100	φ14@125	φ16@150	φ14@100	φ14@100	φ16@125
	Steel content	0.81%	0.45%	0.32%	0.26%	0.20%	0.20%	0.21%	0.21%	0.21%	0.22%	0.21%	0.20%
Bending moment 150	Reinforcement area	3040	2512	2032	1540	1130	1130	1130	1232	1340	1540	1540	1608
	Reinforcement pattern	φ22@125	φ20@125	φ18@125	φ14@100	φ12@100	φ12@100	φ12@100	φ14@125	φ16@150	φ14@100	φ14@100	φ16@125
	Steel content	1.22%	0.84%	0.58%	0.39%	0.25%	0.23%	0.21%	0.21%	0.21%	0.22%	0.21%	0.20%
Bending moment 200	Reinforcement area	3800	3140	2512	2512	2032	1540	1540	1232	1340	1540	1540	1608
	Reinforcement pattern	φ22@100	φ20@100	φ20@125	φ20@125	φ18@125	φ14@100	φ14@100	φ14@125	φ16@150	φ14@100	φ14@100	φ16@125
	Steel content	1.52%	1.05%	0.72%	0.63%	0.45%	0.31%	0.28%	0.21%	0.21%	0.22%	0.21%	0.20%
Bending moment 250	Reinforcement area	4910	3800	3140	3040	2512	2455	2010	1540	1540	1540	1540	1608
	Reinforcement pattern	φ25@100	φ22@100	φ20@100	φ22@125	φ20@125	φ25@200	φ16@100	φ14@100	φ14@100	φ14@100	φ14@100	φ16@125
	Steel content	1.96%	1.27%	0.90%	0.76%	0.56%	0.49%	0.37%	0.26%	0.24%	0.22%	0.21%	0.20%
Bending moment 300	Reinforcement area		4910	3800	3800	3040	2540	2512	2010	2010	2010	1540	1608
	Reinforcement pattern		φ25@100	φ22@100	φ22@100	φ22@125	φ18@100	φ20@125	φ16@100	φ16@100	φ16@100	φ14@100	φ16@125
	Steel content		1.64%	1.09%	0.95%	0.68%	0.51%	0.46%	0.34%	0.31%	0.29%	0.21%	0.20%
Bending moment 325	Reinforcement area		4910	4910	3800	3140	3040	2540	2512	2010	2010	2010	1608
	Reinforcement pattern		φ25@100	φ25@100	φ22@100	φ20@100	φ22@125	φ18@100	φ20@125	φ16@100	φ16@100	φ16@100	φ16@125
	Steel content		1.64%	1.40%	0.95%	0.70%	0.61%	0.46%	0.42%	0.31%	0.29%	0.27%	0.20%
Bending moment 350	Reinforcement area		6160	4910	3800	3800	3140	3040	2540	2512	2010	2010	2010
	Reinforcement pattern		φ28@100	φ25@100	φ22@100	φ22@100	φ20@100	φ22@125	φ18@100	φ20@125	φ16@100	φ16@100	φ16@100
	Steel content		2.05%	1.40%	0.95%	0.84%	0.63%	0.55%	0.42%	0.39%	0.29%	0.27%	0.25%
Bending moment 375	Reinforcement area		6160	4910	3800	3800	3800	3040	2540	2512	2512	2512	2010
	Reinforcement pattern		φ28@100	φ25@100	φ22@100	φ22@100	φ22@100	φ22@125	φ18@100	φ20@125	φ20@125	φ20@125	φ16@100
	Steel content		2.05%	1.40%	0.95%	0.84%	0.76%	0.55%	0.42%	0.39%	0.36%	0.33%	0.25%
Bending moment 400	Reinforcement area		6160	4910	3800	3800	3800	3140	3040	2540	2512	2512	2010
	Reinforcement pattern		φ28@100	φ25@100	φ22@100	φ22@100	φ22@100	φ20@100	φ22@125	φ18@100	φ20@125	φ20@125	φ16@100
	Steel content		2.05%	1.40%	0.95%	0.84%	0.76%	0.57%	0.51%	0.39%	0.36%	0.33%	0.25%
Bending moment 425	Reinforcement area			6160	4910	4910	3800	3800	3040	3040	2540	2512	2512
	Reinforcement pattern			φ28@100	φ25@100	φ25@100	φ22@100	φ22@100	φ22@125	φ22@125	φ18@100	φ20@125	φ20@125
	Steel content			1.76%	1.23%	1.09%	0.76%	0.69%	0.51%	0.47%	0.36%	0.33%	0.31%

Table 5: Continued.

Bending moment	Reinforcement situation	Wall thickness											
		250	300	350	400	450	500	550	600	650	700	750	800
Bending moment 450	Reinforcement area			6160	4910	4910	3800	3800	3040	3040	3040	2540	2540
	Reinforcement pattern			φ28@100	φ25@100	φ25@100	φ22@100	φ22@100	φ22@125	φ22@125	φ22@125	φ18@100	φ18@100
	Steel content			1.76%	1.23%	1.09%	0.76%	0.69%	0.51%	0.47%	0.43%	0.34%	0.32%
Bending moment 475	Reinforcement area			6160	6160	4910	4910	3800	3800	3140	3040	3040	2540
	Reinforcement pattern			φ28@100	φ28@100	φ25@100	φ25@100	φ22@100	φ22@100	φ20@100	φ22@125	φ22@125	φ18@100
	Steel content			1.76%	1.54%	1.09%	0.98%	0.69%	0.63%	0.48%	0.43%	0.41%	0.32%
Bending moment 500	Reinforcement area			6160	6160	4910	4910	4910	3800	3800	3140	3040	2540
	Reinforcement pattern			φ28@100	φ28@100	φ25@100	φ25@100	φ25@100	φ22@100	φ22@100	φ20@100	φ22@125	φ18@100
	Steel content			1.76%	1.54%	1.09%	0.98%	0.89%	0.63%	0.58%	0.45%	0.41%	0.32%
Bending moment 550	Reinforcement area				6160	4928	4910	4910	4910	3800	3800	3140	3040
	Reinforcement pattern				φ28@100	φ28@125	φ25@100	φ25@100	φ25@100	φ22@100	φ22@100	φ20@100	φ22@125
	Steel content				1.54%	1.10%	0.98%	0.89%	0.82%	0.58%	0.54%	0.42%	0.38%
Bending moment 600	Reinforcement area					6160	6160	4910	4910	4910	3800	3800	3040
	Reinforcement pattern					φ28@100	φ28@100	φ25@100	φ25@100	φ25@100	φ22@100	φ22@100	φ22@125
	Steel content					1.37%	1.23%	0.89%	0.82%	0.76%	0.54%	0.51%	0.38%

Table 6: Wall costs per unit area of pool walls with optimal rebar configuration (yuan).

Wall thickness	250	300	350	400	450	500	550	600	650	700	750	800
Actual rebar configuration	φ25@100	φ22@100	φ20@100	φ22@125	φ20@125	φ25@200	φ16@100	φ14@100				φ16@125
Actual reinforcement area	4910	3800	3140	3040	2512	2455	2010	1540				1608
Wall cost C per unit area	287.96	264.10	256.80	266.77	268.51	281.09	285.31	284.86	303.41	321.97	340.52	361.82

As shown in Table 6, when the bending moment M of the pool wall was 250 kN·m, the wall cost C per unit area was minimized at 256.80 yuan. Similarly, the optimal rebar configuration was φ20@100 for the wall thickness of 350.

By analogy, the minimum wall costs C per unit area were obtained through repeated data calculations, with the bending moment of the wall in 50–600 kN·m and the wall thickness changing over time. The results are presented in Table 7.

According to the wall costs per unit area at different bending moments in Table 7, as well as the reinforcement patterns, reinforcement areas, and steel contents in Table 5, the minimum wall costs per unit area, and the corresponding steel contents at different bending moments were solved (Table 8).

Table 7: Wall costs per unit area at different bending moments (yuan).

Bending moment	Cost C											
	Wall thickness											
	250	300	350	400	450	500	550	600	650	700	750	800
50	133.33	152.69	160.34	184.95	203.50	222.05	249.74	272.41	295.33	321.97	340.52	361.82
100	178.93	170.31	175.54	189.92	203.5	226.13	249.74	272.41	295.33	321.97	340.52	361.82
150	215.15	217.7	212	210.66	212.64	231.19	249.74	272.41	295.33	321.97	340.52	361.82
200	244.74	238.4	231.41	249.96	249.1	247.76	266.31	272.41	295.33	321.97	340.52	361.82
250	287.96	264.1	256.8	271.3	268.51	281.09	285.31	284.86	303.41	321.97	340.52	361.82
300		307.32	277.81	296.36	285.32	288.19	305.61	303.87	322.42	340.97	340.52	361.82
325		307.32	321.03	296.36	293.90	303.87	306.74	324.16	322.42	340.97	359.52	361.82
350		355.99	321.07	296.36	314.91	312.45	322.42	325.29	342.71	340.97	350.52	378.07
375		355.99	321.03	296.36	314.91	333.46	322.42	325.29	342.71	361.26	379.81	378.07
400		355.99	321.07	296.36	314.91	333.46	331	340.97	343.84	361.26	379.81	378.07
425			369.70	339.58	358.13	333.46	352.01	340.97	359.52	362.39	379.81	398.36
450			369.7	339.58	358.13	333.46	352.01	340.97	359.52	378.07	380.94	399.49
475			369.70	388.25	358.13	376.68	352.01	370.56	368.10	378.07	396.62	399.49
500			369.7	388.25	358.13	376.68	395.23	370.56	389.11	386.65	396.62	399.49
550				388.25	358.83	376.68	395.28	413.78	389.11	407.66	405.2	419.71
600					406.8	425.35	395.23	413.78	432.33	407.66	426.21	415.17

Table 8: Minimum wall costs per unit area (yuan) and the optimal steel contents.

Bending moment	Wall cost	Wall thickness	Reinforcement area	Steel content (%)
50	133.33	250	904	0.36
100	170.31	300	1340	0.45
150	210.66	400	1540	0.39
200	231.41	350	2512	0.72
250	256.8	350	3140	0.90
300	277.81	350	3800	1.09
325	293.9	450	3140	0.70
350	296.36	400	3800	0.95
375	296.36	400	3800	0.95
400	296.36	400	3800	0.95
425	333.46	500	3800	0.76
450	333.46	500	3800	0.76
475	352.01	550	3800	0.69
500	358.13	450	4910	1.09
550	358.83	450	4928	1.10
600	395.23	550	4910	0.89

5. Conclusions

This paper establishes a mathematical model for the wall cost of reinforced concrete water pool, the thickness of concrete pool wall (concrete volume), and horizontal reinforcement area (rebar volume) and sets up a direct function between pool cost and steel content, $C = f[\rho, g(\rho)]$, under model constraints. Since the function is discrete, repeated data calculations were performed through numerical simulation, and the optimal steel contents were identified to minimize the wall cost per unit length at different bending moments. According to minimum wall costs per unit area and the optimal steel contents in Table 8, when the bending moment is between 50 and 150, the thickness of the pool wall, the optimal steel content, and the cost of the pool wall gradually increase, and the cost of the pool wall increases greatly; when the bending moment is between 200 and 300, the thickness of the pool wall remains unchanged, the optimal steel content and the cost of the pool wall gradually increase, and the cost of the pool wall increases little; and when the bending moment is between 350 and 400, 425 and 450, and 500 and550, the thickness of the pool wall, the optimum steel content, and the cost of the pool wall are unchanged. According to the bending moment of the pool wall, the structural designer can directly select the thickness and reinforcement area of the pool wall from Table 8, which minimizes the total cost of the pool wall. This study provides a good reference for designers in actual project design and solves the problem that designers have no time to optimize the design scheme and saves the cost of the pool.

Appendix

Calculation of the Maximum Crack Width of Reinforced Concrete Rectangular Section under Bending and Large Eccentric Compression (Tension)

Width of maximal crack under bending, large eccentric tension, or compression members could be calculated by using the following equation:

$$\omega_{\max} = 1.8\psi \frac{\sigma_{sq}}{E_s}\left(1.5c + 0.11\frac{d}{\rho_{te}}\right)(1 + a_1)\upsilon, \quad (A.1)$$

$$\psi = 1.1 - \frac{0.65 f_{tk}}{\rho_{te}\sigma_{sq}a_2}, \quad (A.2)$$

where $\omega_{\max}$ is the maximum crack width(mm); ψ is the nonuniformity coefficient of strain of longitudinal tensile reinforcement among cracks; σ_{sq} is the stress of longitudinal tensile rebars section calculated by quasi-permanent combination of action effect; E_s is the elastic modulus of rebars; and c is the thickness of concrete protective layer of outermost longitudinal tensile reinforcement.

d is the diameter (mm) of longitudinal tensile steel rebars, when rebars with different diameters are used, $d = (4A_s/u)$, where u is the total circumference of longitudinal tensile rebars section (mm), and A_s is the cross-sectional area of tensile rebars (mm^2).

ρ_{te} is the ratio of reinforcement of longitudinal tensile rebars calculated by effective tensile concrete cross-sectional area: $\rho_{te} = (A_s/0.5bh)$, where b is the calculated width of the cross section, and h is the calculated height of the cross section.

a_1 is the coefficient, $a_1 = 0$ for bending and large eccentric compression members, and $a_1 = 0.28[1/1 + (2e_0/h_0)]$ for the large eccentric tension members, where e_0 is the eccentricity of longitudinal force to the center of gravity of section(mm), and h_0 is the effective height of cross section (mm).

υ is the surface characteristic coefficient of longitudinal tensile rebars, where $\upsilon = 1.0$ for smooth rebars; $\upsilon = 0.7$ for deformed rebars; f_{tk} is the standard axial compressive strength of concrete.

a_2 is the coefficient, $a_2 = 1.0$ for bending members, $a_2 = 1–0.2\ (h_0/e_0)$ for large eccentric compression members, and $a_2 = 1 + 0.35\ (h_0/e_0)$ for the large eccentric tension members.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

This paper was funded by the General Project of Hebei Provincial Natural Science Foundation (Grant No. E2016105062).

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