Optimal height of the main beam of radial gate considering the cooperative work of members

Jiliang Liu[1*], Yong Yang[1], Shouyi Li[1] and Chunlong Zhao[2]

[1] College of Water Resources and Hydropower Engineering, Xi'an University of Technology, Shaanxi, Xi'an 710048, China
[2] Northwest Engineering Corporation Limited, Power China, Shaanxi, Xi'an 710065, China

*Corresponding author's e-mail: 857635569@qq.com

Abstract. The height of the main beam of the radial gate is an important design parameter. This paper defines the dimensionless expression of beam height, and the beam height of the double cantilevered main beam of the radial gate is studied. Considering the cooperative work of panels, partitions, and other members with the main beam, the finite element method is used for calculation and analysis. The results show that it is necessary to consider the spatial cooperation between the main beam and other members of radial gates. There is an optimal beam height between the minimum beam height and the economic beam height, and the ratio of the optimal beam height to the economic beam height is about 0.868, which can minimize the stress of the main beam.

Keywords: Radial gate; optimal beam height; cooperative work; finite element method

1 Introduction

The radial gate is an important structure in the hydraulic complex, and the force transmission path of the radial gate is very complicated. Water pressure is first applied to the panel which transmits to the horizontal secondary beams, the main beam, the vertical secondary beam, the support arm, the hinge, and finally to the pier. The main beam is one of the main load-bearing members of a radial gate, and a reasonable design of the main beam can ensure the safe operation of the gate.

The optimal beam height of the radial gate affects the safety and economy of the structure. Many scholars have studied the height problem of the main beam. According to the structural optimization theory, Azad, Vachajitpan and Rockey put forward formula for computing economic beam height of simply supported double axisymmetric I-shaped beam [1-2]. Considering the effect of panel and partitions on the height of the main beam, Dou took the strength, stiffness, and stability as the constraints of design requirements and took the total steel consumption of the main beam itself and vertical members related to its height as the objective function, and obtained the theoretical formula of the optimal height of the main beam of the steel gate [3-5]. He proposed a fitted formula of the optimal beam height of the simply supported I-

D. Li et al. (eds.), *Proceedings of the 2023 9th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2023)*, Advances in Engineering Research 228,
https://doi.org/10.2991/978-94-6463-336-8_78

beam with uniaxial symmetry from the data of 196 gates [6]. Wang and Cui proposed a theoretical formula for the optimal beam height of double cantilevered single axisymmetric beam [7-8]. According to the current design specification for steel gates, Zhang took the strength, stiffness, stability, and geometry as constraints, and took the minimum total steel consumption of the main beam and vertical partition as the objective function, established a optimization model of the height of double cantilevered main beam with uniaxial and biaxial cross sections [9]. Using the finite element method, Yang et al. investigated the optimal beam height of a simply supported main beam with the consideration of the cooperative work of the main beam, the panel, and the vertical partition, and it was obtained that the optimal exists between the minimum beam height and the economic beam height, and the ratio of optimal beam height to the minimum beam height is about 1.038 [10]. Using the similar approach, we studied the optimal height of the double cantilevered main beam of the radial gate.

2 Several beam height

The main beam of the radial gate generally adopts I-shaped or box-shaped cross section. Figure1 shows the schematic diagram of double cantilevered main beam of radial gate.

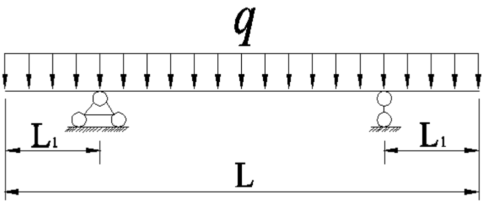

Fig. 1. Schematic diagram of double cantilevered main beam of radial gate

where L is the total span of the main beam, L_1 is the cantilever length, and q is the unit load. According to the specification, it is recommended that the cantilever length L_1 is 0.2 times the total span L [11], and the bending moment M=0.025qL^2.

2.1 Minimum beam height

The stiffness condition determines the minimum beam height; that is, the relative deflection $w/L \leq [w/L]$, and the limit value of the relative deflection of the beam $[w/L]$ can be found in the specification. According to the deflection calculation formula, the maximum deflection of the beam can be obtained by integration as follows:

$$w = 1.565 \times 10^{-3} \frac{qL^4}{2EI} \quad (1)$$

where w and q are the deflection of the beam and the unit load, respectively, and EI is the flexural rigidity of the beam.

The calculation flow of minimum beam height can be calculated as follows:

$$\sigma = \frac{M}{W} = \frac{0.025qL^2}{W} \tag{2}$$

where σ is the bending stress, and W is the section modulus.

For symmetrical section,

$$W = \frac{I}{(h/2)}$$

$$\frac{w}{L} = \frac{1.565\times10^{-3}qL^4}{2EIL} = \frac{1.565\times10^{-3}L}{Eh}\frac{qL^2}{W} = \frac{1.565\times10^{-3}L}{0.025Eh}\frac{M}{W} = 0.063\frac{\sigma L}{Eh}$$

where h is the beam height.

Thus the minimum beam height of the double cantilevered main beam of radial gate can be computed as:

$$h_{min} = 0.063\frac{[\sigma]L}{E[w/L]} \tag{3}$$

where h_{min} is the minimum height of beam, and $[\sigma]$ is the allowable stress.

2.2 Economic beam height

The economic beam height usually makes the beam's own weight the lightest, and does not consider the beam height's effect on the weight of the whole structure. To consider this effect, it must be solved by optimization design, so this paper only discusses the economic beam height with the lightest beam weight. The weight per unit length of the beam is the sum of the weight of the upper and lower flanges and the weight of the web, including the weight of stiffening ribs.

The moment of inertia of box-shaped beam can be obtained by:

$$I = W\frac{h}{2} = 2A\left(\frac{h_1}{2}\right)^2 + 2\frac{1}{12}t_w h_0^3 \tag{4}$$

where I is the moment of inertia of box-shaped beam, h_1 is the flange height, h_0 is the web height, and t_w is the web thickness.

Considering $h \approx h_0 \approx h_1$, the cross-sectional area of each flange can be obtained as follows:

$$A \approx \frac{W}{h} - \frac{1}{3} t_w h \tag{5}$$

Under the condition that the section modulus W of the beam is known, the economic beam height can be obtained according to the relationship between the beam height h and beam weight g, and the calculation flow is as follows:

$$g = 2\gamma \varphi_w t_w h + 2\gamma \varphi_f \left(\frac{W}{h} - \frac{1}{3} t_w h \right) \tag{6}$$

where φ_w is the structural coefficient of web weight, usually $\varphi_w = 1.1 \sim 1.2$; φ_f is the structural coefficient of flange weight, $\varphi_f = 1.0$ for beams with equal cross section and $\varphi_f = 0.8$ for beams with variable flange.

According to the empirical formula, the web thickness can be expressed with respect to the beam height h as the following formula:

$$t_w = \frac{\sqrt{h}}{11} \tag{7}$$

Substituting equation 7 into equation 6 and letting $\varphi_w = 1.2$, and $\varphi_f = 1.0$, yields:

$$\mathrm{g} = \gamma \left(2\frac{W}{h} + 0.1576 h^{\frac{3}{2}} \right) \tag{8}$$

Letting dg/dh = 0, the economic beam height of box-shaped beam h_{ec} with minimum beam weight g can be obtained as follows:

$$h_{ec} = 2.35 W^{\frac{2}{5}} \tag{9}$$

2.3 Dimensionless beam height

In general, stiffness condition does not play a controlling role while strength condition and economic condition do (economic beam height). There is no a clear recommended value of beam height in the design specification of steel gate, but the upper and lower limits of beam height are given. To study the effect of the beam height of the main beam on the mechanical performance of each component of the main beam, the dimensionless beam height Z is defined as:

$$Z = \frac{h}{h_{ec}} \quad Z \in \left[\frac{h}{h_{\min}} \quad 1 \right] \tag{10}$$

3 Calculation scheme and the optimal height

According to the defined dimensionless beam height Z in equation 10, eight calculation schemes are drawn up in the range where Z belongs, as shown in table 1.

Table 1. Calculation schemes

Schemes	1	2	3	4	5	6	7	8
h	90	93	96	99	102	105	108	111
h_{ec}	114	114	114	114	114	114	114	114
Z	0.789	0.815	0.842	0.868	0.895	0.921	0.947	0.973

Based on the given schemes, eight three-dimensional finite element models for the radial gate which can reflect the cooperative work of gate members were established and one of which is depicted in figure 2.

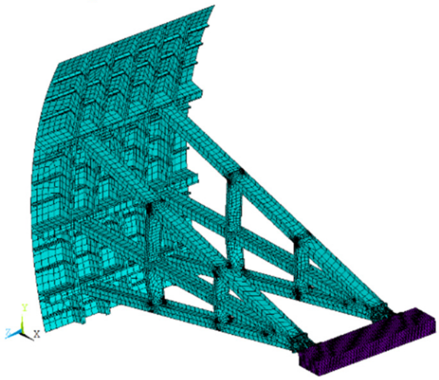

Fig. 2. Finite element model

From the calculation result of finite element model, we can summarize the variation law of stresses of the flanges and the web of the main beam of the eight schemes. After comparison, the stresses of the upper flange, the lower flange, and the web of the main beam calculated scheme 4 is the smallest, and the corresponding beam height is about 0.868 times the economic beam height thus can be treated as the optimal height.

4 Conclusions

The optimal height of the main beam of radial gate was studied by using the three-dimensional finite element analysis method and the following conclusions are obtained: (1) It is necessary to consider the spatial cooperation work between the main beam and other components, which can more truly reflect the stress characteristics of the gate. (2) There is an optimal beam height between the minimum beam height and the economic beam height, and the ratio of the beam height to the minimum beam height is about 0.868. (3) The main beam of the radial gate is the primary stress component, and the reasonable selection of the beam height is directly related to the economy and safety of the gate. The optimal beam height obtained in this paper can provide a reference for engineering design.

Acknowledgments

This study was supported by China Postdoctoral Science Foundation (2019M663787), Natural Science Basic Research Program of Shaanxi Province (2018JQ5102), and Scientific Research Program Funded by Shaanxi Provincial Education Department (20JK0792).

References

1. Vachajitpan, P., Rockey, K.C. (1978) Design method for optimum unstiffened girders. Journal of the Structural Division, 104: 141–155.
2. Azad, A. K. (1978) Economic Design of homogeneous I-beams. Journal of the Structural Division, 104: 637–648.
3. Dou, G.Z. (1979) The economic height of main beam of hydraulic steel gate. Port & Waterway Engineering, 36:1–8.
4. Dou, G.Z. (1991) The formula of optimal beam height of Steel gates. Journal of Hydroelectric Engineering, 10:35–45.
5. Dou, G.Z. (1994) The economic height of main beam of the oblique arm radial gate. Water Power, 61:34–38.
6. He, Y.L. (1992) Optimal depth of unequal-flanged steel girders in steel gates. Journal of Hydroelectric Engineering, 11:39–51.
7. Wang, Z.Z. (1993) The optimal height of main beam of curved double cantilever. In: The theory and Applications of Hydraulic Structure Engineering. Dalian. pp. 109–115.
8. Cui, L.P. (2011) Optimized design of the main frame beam height of steel gate. Journal of Hydroelectric Engineering, 30:175–178.
9. Zhang, X.C., Wang, Z.Z., Meng, M., Li, L.M. (2016) Optimal height of the main beam on hydraulic steel gate. Journal of Yangtze River Scientific Research Institute, 33:127–131.
10. Yang, Y., Li, S.Y., Liu, J.L., Xiao, Y., Li, L., Yang, G. (2019) Research on optimal beam height of main girder of plane steel gate based on component cooperative work. Journal of Water Resources & Water Engineering, 30: 194–198.
11. The Ministry of Water Resources of the People's Republic of China. (2019) Design specification for gates of water and hydropower projects: SL 74-2019. China Water & Power Press, Beijing.