Optimisation design and structure analysis of large-scale prestressed rectangular aqueduct

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Abstract: In order to provide theoretical basis for the design of large-scale prestressed rectangular aqueduct, saving engineering investment, and ensuring the safety and reliability of aqueduct structure. This paper adopts mixed discrete variable optimisation design method to carry out optimisation design for Sha river aqueduct of the south-to-north water diversion project, the objective function of optimisation design is project cost. Calculated results show that, optimisation design scheme of rectangular aqueduct is economic and reasonable, aqueduct structure meets the strength condition and stiffness condition, wind load has little effect for stress and deformation distribution of aqueduct, but water pressure has great effect for stress and deformation distribution of aqueduct. When stress concentration phenomenon at the junction of the longitudinal beams and transverse ribs in the rectangular aqueduct occurs, local stress is higher.

Keywords: south-to-north water diversion project; aqueduct; optimisation design; finite element; force analysis; stress distribution.

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1 Preface

China is a country with uneven distribution of water resources, the distribution of water resources shows that the south has more than the north. In recent years, several cross-basin water diversion projects have been carried out in the country, the south-to-north water diversion project is implemented especially, and many large scale reinforced concrete aqueducts have appeared (Zhu et al., 2005, 2007; Connely and Perry, 1995). For example, in the middle route of the south-to-north water diversion project, Sha river aqueduct, Shuangji river aqueduct, Fuyang river aqueduct and Wu river aqueduct are implemented, these are large-scale prestressed reinforced concrete thin-walled beam aqueducts (Song and Gao, 2017; Ding, 2017; Chen, 2017). These aqueducts feature large span, large load and complicated force conditions, so it becomes an urgent problem to carry out force analysis of large scale reinforced concrete aqueducts, with important theoretical significance and application value (Hu, 2018; Liu and Lv, 2018).

Sha river is a major tributary of Shaying river system in the Huai river basin, Sha river originates from the stone mountain in Lushan county, it joins the Shaying river by the sand mouth and Ying river near Zhoukou City; the basin area is 3,713 km². There is Zhaopingtai reservoir upstream of Sha river aqueduct, and the downstream is Baiguishan reservoir, it is the main water source of industrial, agricultural and domestic water in Pingdingshan City. In recent years, scholars have conducted extensive research on aqueducts. These studies results are concentrated in the design and construction of aqueducts, however, the research results of aqueduct structure optimisation and prestressed reinforcement on the structure stress of aqueduct are relatively few.

2 The optimum design method of mixed discrete variable

2.1 The relative mixed sub-gradient vector

The sub-gradient of discrete variable function is calculated by approximate derivative on discrete points, discrete search direction is constructed by sub-gradient calculation, it is sub-gradient vector, the expression is shown in the following formula.

\[
\nabla F = \left[ \frac{\Delta F}{\Delta x_1}, \frac{\Delta F}{\Delta x_2}, \ldots, \frac{\Delta F}{\Delta x_{p+1}}, \ldots, \frac{\Delta F}{\Delta x_n} \right]^T
\]

In the expression

\[
\frac{\Delta F}{\Delta x_i} = \frac{F[X + \Delta_i \varepsilon_i] - F[X]}{\Delta_i} \quad i = 1, 2, \ldots, p
\]

\[
\frac{\Delta F}{\Delta x_j} = \frac{F[X + \varepsilon_i \varepsilon_j] - F[X]}{\varepsilon_i} \quad i = p+1, p+2, \ldots, n
\]

\[e_i\] is the unit vector of the \(i^{th}\) coordinate, \(\Delta_i\) is the incremental of the \(i^{th}\) discrete variable, \(\varepsilon_i\) is the proposed increment of the \(i^{th}\) continuous variable.
2.2 Subspace loop search

The search speed is faster along relative mixed sub-gradient vector direction in the beginning, but it is easy to cut off early in the constraint surface. In order to converge to the optimal solution as soon as possible, \( X^D \in R^D \) and \( X^C \in R^C \) can be searched alternately in different subspace sets, it is subspace loop search.

Set \( X \) is initial point, first search \( X^C \) along objective function negative gradient direction in \( R^C \) set, if getting a point which better than \( X \), and replace \( X \) point with this point. Otherwise, it will be returned to the original \( X \) point, discrete one-dimensional search of each component for \( X^D \) set is carried out by the order of objective function sensitivity from big to small. If a one-dimensional discrete search is successful, then we calculate the negative gradient of the objective function at this point with respect to \( X^C \), and then carrying out search for \( X^C \) in this direction, otherwise, this step is cancelled. So again and again, until the \( p^{th} \) component of \( X^D \) is done.

2.3 Check point in discrete unit neighbourhood

Discrete unit neighbourhood of point is shown in the following formula.

\[
UN(X) = \left\{ x \in \mathbb{X} : x_i + \Delta_i \leq x_i \leq x_i + \Delta_i^* \quad i = 1, 2, ..., p \\
x_i = \epsilon_i \leq x_i \leq x_i + \epsilon_i \quad i = p + 1, p + 2, ..., n \right\}
\]  \( (4) \)

If the subspace loop search is not better than the start point, and perturbation calculation of can be carried out along mixed sub-gradient vector direction. If we do not get a better point, this point is a pseudo-discrete optimal solution. At this time, we need to check the other points in \( UN(X) \) set, if getting a better point, the program get out from pseudo optimal point, ensure that the search continues, otherwise, \( X \) point is local discrete optimal point.

2.4 Optimise design idea

The basic idea of optimal design method of mixed discrete variables is as follows. First, starting from a feasible discrete point in the discrete variable range matrix \( Q \), the discrete one-dimensional search is carried out along mixed sub-gradient vector direction, so we get a new discrete point that reduces the objective function and satisfies the constraints. Then starting repeat the search from this point, until there is no such a new point, the loop search starts in the discrete subspace \( R^D \) and the continuous subspace \( R^C \), if a new feasible discrete point can be obtained after searching, then it returns the first step of the search process. Otherwise, it check points according to the established rules in the unit neighbourhood by the information, the information provided by the objective function and constraint function of this discrete point. If we find a new discrete point, then it returns the first step of the search process, otherwise, this point is tentatively determined as discrete optimal solution according to the basic property of optimal solution (Bai and Ma, 2015). According to the basic idea which is constructed by the above algorithm, the flow chart of logical structure is shown in Figure 1.
3 Optimisation design scheme of aqueduct structure

3.1 Project summary

Sha river aqueduct project is a composite building, it includes beam-supported aqueduct and ground-supported aqueduct across Sha river, Jiangxiang river and Dalang river, it also includes the aqueduct around Lu mountain. The main canal building that crosses Sha river and Dalang river adopts beam-supported aqueduct, the main canal building that crosses Jiangxiang river and low-lying areas adopts box foundation aqueduct, the main canal building around Lu mountain adopts ground-supported aqueduct. According to the terrain, channel morphology, geology and other factors, Sha river aqueduct is arranged as follows. Total length of the aqueduct is 7,590 m, it is composed of four parts: Sha river beam-supported aqueduct, the first ground-supported aqueduct, Dalang river beam-supported aqueduct and the second ground-supported aqueduct. The beam-supported aqueduct is double four aqueducts; the ground-supported aqueduct is box foundation double aqueduct.

3.2 Optimisation design model

In optimisation design of aqueduct, the control section of longitudinal calculation is one-half span cross section, structure size and longitudinal reinforcement are decided by one-half span cross section calculation. Therefore, if the size and reinforcement of the section are optimised, the optimal scheme of the whole structure of aqueduct can be obtained. Analytical method is adopted in the optimisation design of aqueduct. Beam
bending theory is applied for longitudinal calculation, curved beam theory is applied for lateral calculation, and shear effect is considered for structural calculation.

According to initial design scheme and experience, some sizes have little impact on the results of the optimisation design; it can be used as a design constant. Some sizes and quantities have great influence on optimisation results, it can be set to design variables.

There are 18 design constants, they are represented by $a_1 \sim a_{18}$. There are 16 design variables, geometric dimensions and structural shapes of the aqueduct are represented by $x_1 \sim x_7$, the number of prestressed reinforcement bars are represented by $x_8 \sim x_{16}$. In optimisation design of aqueduct, the optimisation goal is project cost, the objective function is expressed as follows.

$$ F(X) = C_C V_C + C_s W_s + C_p W_p $$

In the expression, $C_C$ is unit price of concrete (yuan/m$^3$), $V_C$ is dosage of concrete (m$^3$), $C_s$ is unit price of ordinary reinforced (yuan/t), $W_s$ is weight of ordinary reinforced (t), $C_p$ is unit price of prestressed reinforcement (yuan/t), $W_p$ is weight of prestressed reinforcement (t).

### 3.3 Optimisation design scheme

This paper adopts separately direct search and check points method of mixed discrete variable optimisation design, optimisation design of Sha river rectangular aqueduct is carried out. Direct search and check point’s method of mixed discrete variable optimisation design has a strong local search capability. But engineering structure optimisation design usually is non convex programming problems, the optimisation result of the method may be a local optimal solution. In practice, multiple initial points are considered, it starts from different initial points, in order to get different optimisation results. Then compare the results, we select a minimum value as the global optimal solution for the problem. In spite of this, sometimes we ca not get the global optimal solution for the problem. Genetic algorithm has a strong global search capability, the objective function of optimisation design is calculated in evolutionary computation, its calculation process is stable, and it is very likely to get the global optimal solution (Bai et al., 2005).

In optimisation design of aqueduct, considering the construction and other requirements, the design variables are limited to the following.

Wall thickness $x_3$ is not less than 40 cm, wall thickness $x_4$ is not less than 60 cm, wall thickness $x_5$ is not less than 80 cm. Prestressed reinforcement’s quantity of side wall’s top $x_{10} \geq 1$, prestressed reinforcement’s quantity of middle wall’s top $x_{10} \geq 2$, prestressed reinforcement’s quantity of side wall’s waist $x_{12} \geq 6$, prestressed reinforcement’s quantity of middle wall’s waist $x_{13} \geq 12$.

The geometric dimensions and prestressed reinforcement’s layout of optimisation design scheme are given by optimisation calculation. The design constants are as follows: $a_1 = 0.8$ m, $a_2 = 0.8$ m, $a_3 = 0.8$ m, $a_4 = 0.8$ m, $a_5 = 0.2$ m, $a_6 = 0.5$ m, $a_7 = 1.0$ m, $a_8 = 0.15$ m, $a_9 = 1.0$ m, $a_{10} = 0.15$ m, $a_{11} = 0.3$ m, $a_{12} = 0.2$ m, $a_{13} = 0.4$ m, $a_{14} = 2.0$ m, $a_{15} = 2.2$ m, $a_{16} = 0.5$ m, $a_{17} = 1.0$ m, $a_{18} = 1.2$ m.

From the project cost, two slots of rectangular aqueduct are 4.395 million Yuan per span, four slots of rectangular aqueduct are 4.138 million Yuan per span. But considering the overall force of the aqueduct, four slots of rectangular aqueduct are recommended.
4 Force analysis of the aqueduct structure

4.1 Calculation model

4.1.1 Element division

In order to carry out the force analysis on the optimisation scheme of Sha river aqueduct, three-dimensional block element are used, the SOLID45 element is used to simulate rectangular aqueduct, aqueduct pier and foundation. The LINK8 element is used to simulate prestressed reinforcement, the beam and the support. The SHELL63 element is used to simulate anchor plate (Belytschko et al., 2011). The finite element model of rectangular aqueduct is shown in Figure 2.

Figure 2  The element division of rectangular aqueduct, aqueduct pier, pile and soil body
(see online version for colours)

4.1.2 Prestressed reinforcement simulation

According to the position of prestressed reinforcement, longitudinal straight-line prestressed reinforcement is simulated by elastic rod element (Wang, 2003). It is the tensile and compressive element in the direction of the shaft, each node has three degrees of freedom, they are translational degrees of freedom along the node coordinates x, y, and z. When the longitudinal prestressed reinforcement, transverse prestressed reinforcement
and vertical prestressed reinforcement are simulated from the tensioning end to the anchor end, considering the loss of prestress is relatively small, in order to simplify the calculation model, the prestress simulation adopts element initial strain method. Tension control stress of prestressed reinforcement is $\sigma_{\text{con}} = 0.7 f_{\text{ptk}}$. The prestress loss includes two batches by calculation, the first batch prestress loss of the rectilinear reinforced is 5%, the first batch prestress loss of the curved reinforced is 15%. The second batch prestress loss of the rectilinear reinforced is 10%, the second batch prestress loss of the curved reinforced is 10%. Total prestress loss of the rectilinear reinforced is 15%, total prestress loss of the curved reinforced is 25%. The calculation model of rectangular aqueduct and prestressed reinforcement is shown in Figure 3.

4.1.3 Calculation case

According to the calculation requirement, the force analysis of rectangular aqueduct considers 22 calculation cases in construction process and operating process. For the simulation analysis of the aqueduct in construction process, there are many kinds of calculation cases, this paper mainly considers routine construction sequence. The construction of rectangular aqueduct mainly considers the sequence of self-weight, tensioning longitudinal prestressed reinforcement, then tensioning transverse prestressed reinforcement, and final tensioning vertical prestressed reinforcement, the process includes four cases. The calculation and analysis of the aqueduct considers load capacity limit state and normal use limit state in operating process. Two limit states consider 18 calculation cases, they include self-weight, prestressed, different water level, wind load, crowd load, temperature load and seismic load.

4.2 Force analysis

4.2.1 Stress analysis

In order to analyse the stress distribution of aqueduct structure under different cases, stress distribution of the aqueduct is shown from Figures 4 to 9 under case 9 and case 17. The transverse stress of the aqueduct is between $-21.2$ MPa and $6.25$ MPa under case 9, the maximum tensile stress appears on the end of the beam, most of the aqueduct’s transverse stress is between $-7$ MPa and $1$ MPa, the transverse stress on the bottom plate is mostly compressive stress, tensile stress appears only in the corner and end of the aqueduct, the maximum tensile stress is $1.62$ MPa. The transverse stress of the bottom beam is between $-18.3$ MPa and $0.63$ MPa, the tensile stress only exists within a very small range. The longitudinal stress of the aqueduct is between $-16.6$ MPa and $1.77$ MPa under case 9, the maximum tensile stress appears on the end of the aqueduct, most of the aqueduct’s longitudinal stress is between $-10$ MPa and $-1$ MPa. In addition to side wall and middle wall of the aqueduct appear tensile stress, other parts are compressive stress, most longitudinal stress is compressive stresses on the bottom plate, tensile stress only appears on the end of the aqueduct, and the maximum tensile stress is $1.11$ MPa. The vertical stress of the aqueduct is between $-21.2$ MPa and $1.46$ MPa under case 9, the maximum tensile stress appears on the top flange of the aqueduct, most of the aqueduct’s vertical stress is between $-8.5$ MPa and $0.5$ MPa. The vertical stress of side wall only appears local tensile stress in the corner of the aqueduct; the maximum tensile stress is $1.0$ MPa. The vertical stress of middle wall only appears local tensile stress in the corner and end of the aqueduct, the maximum tensile stress is $0.56$ MPa.
Figure 4  The aqueduct’s transverse stress under case 9 (Pa) (see online version for colours)

Figure 5  The aqueduct’s longitudinal stress under case 9 (Pa) (see online version for colours)

Figure 6  The aqueduct’s vertical stress under case 9 (Pa) (see online version for colours)
Figure 7  The aqueduct’s transverse stress under case 17 (Pa) (see online version for colours)

Figure 8  The aqueduct’s longitudinal stress under case 17 (Pa) (see online version for colours)

Figure 9  The aqueduct’s vertical stress under case 17 (Pa) (see online version for colours)
The transverse stress of the aqueduct is between –21.9 MPa and 5.33 MPa under case 17, the maximum tensile stress appears on the end of the beam, most of the aqueduct’s transverse stress is between –10 MPa and 0 MPa, the transverse stress on the bottom plate is mostly compressive stress, tensile stress appears only in the corner and end of the aqueduct, the maximum tensile stress is 1.1 MPa. The transverse stress of the bottom beam is between –19.8 MPa and –0.17 MPa, the tensile stress only exists within a very small range. The longitudinal stress of the aqueduct is between –25 MPa and 1.64 MPa under case 17, the maximum tensile stress appears on the end of the aqueduct, most of the aqueduct’s longitudinal stress is between –10 MPa and 0.4 MPa. In addition to side wall and middle wall of the aqueduct appear tensile stress, other parts are compressive stress, tensile stress only appears on the end of the aqueduct, the maximum tensile stress is 1.51 MPa. The vertical stress of the aqueduct is between –18.2 MPa and 1.6 MPa under case 17, the maximum tensile stress appears on the top flange of the side wall, most of the aqueduct’s vertical stress is between –11.6 MPa and 0.8 MPa. The vertical stress of side wall only appears local tensile stress in the corner of the aqueduct, the maximum tensile stress is 0.936 MPa. The vertical stress of middle wall only appears local tensile stress in the corner of the aqueduct, the maximum tensile stress is 0.233 MPa.

The circumferential stress and longitudinal stress of aqueduct’s inner surface is shown from Figures 10 to 15 under case 17.

**Figure 10** The circumferential stress of aqueduct’s one-half span cross section’s inner surface under case 17 (MPa) (see online version for colours)

**Figure 11** The longitudinal stress of aqueduct’s one-half span cross section’s inner surface under case 17 (MPa) (see online version for colours)
Figure 12  The circumferential stress of aqueduct’s quarter span cross section’s inner surface under case 17 (MPa) (see online version for colours)

Figure 13  The longitudinal stress of aqueduct’s quarter span cross section’s inner surface under case 17 (MPa) (see online version for colours)

Figure 14  The circumferential stress of aqueduct’s eighth span cross section’s inner surface under case 17 (MPa) (see online version for colours)
Figure 15  The longitudinal stress of aqueduct’s eighth span cross section’s inner surface under case 17 (MPa) (see online version for colours)

We can see from Figures 10 to 15, under design water level, the circumferential stress and longitudinal stress of aqueduct’s inner surface is basically compressive stress. Vertical compressive stress of middle wall is smaller, vertical compressive stress of side wall is larger, this is mainly due to symmetry arrangement for the vertical prestressed reinforcement of the middle wall, the inner surface of the middle wall produces less compressive stress; but the vertical prestressed reinforcement of the side wall is arranged on the inside surface, so the inner surface of the side wall produces large compressive stress. Vertical compressive stress of side wall’s inner surface gradually increases from the middle section to the end section, but the stress change is small. Longitudinal compressive stress of aqueduct’s inner surface is larger on the top of the aqueduct, the stress is smaller on the bottom of the aqueduct, and maximum compressive stress appears top flange of aqueduct’s one-half span cross section, the compressive stress is smaller on the bottom of aqueduct’s one-half span cross section. The longitudinal compressive stress difference is small on the end section of the aqueduct, the longitudinal stress distribution is consistent with the stress variation of the beam aqueduct.

In order to analyse the stress distribution of rectangular aqueduct structure along particular path, the longitudinal path shown in Figure 16 is defined.

Figure 16  The longitudinal path’s position sketch of rectangular aqueduct

The stress of aqueduct change curve along longitudinal path is shown from Figures 17 to 20 under various cases.
We can see from Figures 17 to 20, under capacity limit state and normal use limit state, longitudinal stress of the path 1 is compressive stress, the longitudinal stress changes gently, and with the increase of water depth, the longitudinal compressive stress decreases. Longitudinal stress of the path 2 is compressive stress, and the stress shows regular fluctuations, this is mainly because that the bottom beam of aqueduct has the effect for longitudinal stress of the bottom plate’s inner surface. Longitudinal stress of the path 3 is compressive stress, the longitudinal stress changes gently, and with the increase of water depth, the longitudinal compressive stress increases, this is mainly due to the increase of water load, the stress on the upper edge of the aqueduct increases gradually.

Figure 17  The longitudinal stress change curve of path 2 under various cases (case 5–14) (see online version for colours)

Figure 18  The longitudinal stress change curve of path 2 under various cases (case 15–22) (see online version for colours)

Figure 19  The longitudinal stress change curve of path 3 under various cases (case 5–14) (see online version for colours)
4.2.2 Deformation analysis

The whole displacement of the aqueduct is downwards under the self-weight, the maximum displacement is 9.886 mm, it includes the whole rigid body displacement caused by foundation settlement. The maximum transverse displacement of the aqueduct is 0.242 mm, it appears in the middle of the aqueduct side wall, the maximum vertical displacement is 3.977 mm, it appears one-half span cross section of the aqueduct. The top of the aqueduct was squeezed, the deformation moves inward along the longitudinal direction, the bottom of the aqueduct is stretched, the deformation is elongated along the longitudinal direction, the maximum displacement is 3.318 mm, it appears on the top of the aqueduct. The aqueduct appears inverted arch under longitudinal prestress, the vertical displacement of aqueduct has changed obviously, the maximum vertical displacement is 1.879 mm, it appears one-half span cross section of the aqueduct, the direction of the displacement is upward. The maximum longitudinal displacement is 9.373 mm, it appears on the bottom of the aqueduct. The transverse deformation moves inward on the bottom of the aqueduct under transverse prestress, the maximum transverse displacement is 1.344 mm, it appears on the support. The inverted arch of aqueduct is more obvious under vertical prestress; the maximum upward displacement is 3.576 mm on the one-half span cross section of the aqueduct.

Under case 5, the maximum displacement of aqueduct is 8.8 mm, the maximum transverse displacement of aqueduct is 2.609 mm, it appears on the side support. The maximum longitudinal displacement of aqueduct is 4.836 mm, it appears on the support. Vertical displacement is 5.35 mm on the one-half span cross section of the aqueduct, it includes the integral rigid body downward displacement, the rigid body is caused by foundation settlement. The aqueduct appears inverted arch without the water load under prestress. The maximum vertical displacement of aqueduct is 3.679 mm under case 6. The maximum vertical displacement of aqueduct is 11.915 mm under case 7, the maximum vertical displacement of aqueduct is 10.747 mm under case 8, the maximum vertical displacement of aqueduct is 16.044 mm under case 9, the maximum vertical displacement of aqueduct is 14.412 mm under case 10, the maximum vertical displacement of aqueduct is 18.189 mm under case 11, the maximum vertical displacement of aqueduct is 16.057 mm under case 12, the maximum vertical displacement of aqueduct is 15.387 mm under case 13, and the maximum transverse
displacement of aqueduct is 15.177 mm on the top of aqueduct. The maximum vertical displacement of aqueduct is 13.917 mm under case 14, the maximum transverse displacement of aqueduct is 15.139 mm on the top of aqueduct.

The vertical displacement is 5.683 mm on the one-half span cross section of the aqueduct under case 15, it includes the integral rigid body downward displacement, the rigid body is caused by foundation settlement. The aqueduct appears inverted arch without the water load under prestress. The maximum vertical displacement of aqueduct is 3.955 mm under case 16, the maximum vertical displacement of aqueduct is 15.100 mm under case 17, the maximum vertical displacement of aqueduct is 13.018 mm under case 18, the maximum vertical displacement of aqueduct is 16.679 mm under case 19, the maximum vertical displacement of aqueduct is 14.030 mm under case 20, the maximum vertical displacement of aqueduct is 16.770 mm under case 21, and the maximum transverse displacement of aqueduct is 17.373 mm on the top of aqueduct. The maximum vertical displacement of aqueduct is 15.967 mm under case 22, and the maximum transverse displacement of aqueduct is 17.279 mm on the top of aqueduct.

5 Conclusions

Calculated results show that, the optimisation scheme of rectangular aqueduct is economic and reasonable, under capacity limit state and normal use limit state, the aqueduct meets the strength condition and stiffness condition in construction process and operating process. Direct search and check points method of mixed discrete variable is an effective method of optimise design, the method has obtained good design effect. The stiffness of rectangular aqueduct is large enough, wind load has little effect for stress and deformation distribution of aqueduct, but water pressure has great effect for stress and deformation distribution of aqueduct. Rectangular aqueduct has longitudinal beams and transverse ribs on the bottom of the aqueduct, stress concentration appears at the junction of the longitudinal beams and transverse ribs, local stress is higher. Therefore, in the aqueduct design, it should be as smooth as possible to avoid the appearance of stress concentration; this ensures that there is no crack in the aqueduct.

References


