STRESS AND DEFORMATION ANALYSIS OF A U-SHAPED THIN AQUEDUCT BASED ON SHELL ELEMENT

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ABSTRACT

To study the stress and deformation characteristics of Jigongzui U-shaped thin shell aqueduct structure, shell element in ANSYS is proposed to establish the three-dimensional finite element model of the aqueduct for numerical calculation, and the relevant mechanical parameters are obtained by detecting the depth of concrete carbonization. The simulated results show that: (1) The concrete carbonization depth of Jigongzui aqueduct reached 20mm, accounting for about 20% of the total thickness of the channel wall; (2) With the increase of aqueduct water level, the deformation and stress of the aqueduct body gradually increase. The maximum deflection in the middle of the span is 6.98mm, which is less than the limit value of the specification, but the tension in some areas at the bottom of the middle of the span is obvious, exceeding the allowable tensile strength. It is suggested to strengthen the aqueduct body by pasting high-performance fiber materials to improve the stress distribution of the aqueduct body; (3) Shell element has fast calculation speed and high efficiency when simulating similar U-shaped thin shell aqueduct, which can be popularized in simulating similar thin shell structures.

KEY WORDS

Thin aqueduct, Shell 181, Finite element method, Deflection, Tensile strength, Stress

INTRODUCTION

The reinforced concrete U-shaped thin shell aqueduct in Jigongzui aqueduct has been in operation for 53 years since its construction completed in 1968, exceeding the requirement of 50 years of reasonable service life specified in the code for design of reasonable service life and durability of water resources and hydropower projects (SL 654-2014) [1], and limited by the conditions of the time, the design standard is low and the construction quality is poor. After years of operation and natural aging, due to environmental erosion, natural disasters and other problems, concrete structures have different degrees of wear, aging, cracking and corrosion. Therefore, it is particularly important to evaluate the stress-strain characteristics of the aqueduct after many years of operation.

Liu Tao [2] carried out water filling test and bearing capacity safety evaluation of Kizi River rectangular aqueduct by using finite element method, and revealed the variation law of deflection and strain of aqueduct under various water loads; Liu Xiaojuan [3] established a typical U-shaped aqueduct of Xinnan main canal by using the solid element solid 65 of ANSYS, and studied the stress and deformation state of the U-shaped aqueduct structure under different operating conditions. The results accord with the general law; Huang Junbao [4] used three-dimensional laser scanning technology to copy the real scene of the aqueduct, established a three-dimensional point cloud model of the aqueduct, and evaluated the safety of the aqueduct as a whole; Xia

Fuzhou [5] put forward the index system and method of safety evaluation of beam aqueduct structure, and then formulated the safety grade scoring standard of aqueduct structure.

At present, the safety evaluation of the existing aqueduct structure is mainly based on on-site detection, theoretical calculation and finite element analysis. Among them, the aqueduct is often regarded as a simply supported beam structure in theoretical calculation, and the typical section is selected for analysis, so it is difficult to comprehensively study the stress and deformation characteristics of the aqueduct structure as a whole [6-8]. The finite element calculation can reconstruct the three-dimensional model, and objectively reflect the deformation and mechanical characteristics of each part of the aqueduct engineering structure by applying various external loads. It has certain advantages in the safety evaluation of the aqueduct structure. Based on the existing finite element analysis results of aqueduct, most studies use solid element modelling and meshing for numerical calculation. When the aqueduct span is long and the accuracy requirements are high, tens of thousands or even hundreds of thousands of meshes will be generated, which will greatly reduce the calculation efficiency.

In view of this, aiming at the characteristic attribute of thin wall of Jigongzui U-shaped thin shell aqueduct project, this paper proposes to use shell 181 shell element for modelling and carry out finite element simulation analysis and calculation, so as to reduce the number of grids and improve the calculation efficiency. At the same time, it explores the current health status of Jigongzui U-shaped thin shell aqueduct and puts forward corresponding reinforcement measures, The purpose is to ensure the safe operation of aqueduct structure engineering.

PROJECT OVERVIEW

Jigongzui aqueduct is located in Sanxing Town, Shuangliu District, Chengdu of China, with a design flow of 15.2m³/s. The corresponding water depth is 2.6m, the trough body type is reinforced concrete U-shaped thin shell, and the support form is reinforced concrete bent. The maximum span of the aqueduct body is 16m, and the gradient in the trough is 1/1200. It was built in 1968. Groove body depth: the measured groove depth is 280cm, the net width is 400cm, and the depth width ratio of groove body is 0.7. Typical cross-sectional structural dimensions of Jigongzui aqueduct: thickness of trough wall t is 0.1m, inner diameter of trough shell R0 is 2.00 m, height of straight section f is 0.80m, net spacing of tie rods 2m, height of tie rods H1 is 0.2m and width of tie rods b1 is 0.2m. Figure 1 shows the current situation of Jigongzui U-shaped thin shell aqueduct project of Dongfeng canal in Sichuan Province of China.

Fig.1 — Current situation of Jigongzui U-shaped thin shell aqueduct project

MATERIALS AND METHODS

As the Jigongzui aqueduct in this case is a thin shell aqueduct designed to save the amount of concrete, the thickness of the aqueduct body is only 0.1m, while the middle span of the aqueduct reaches 16m, which is a typical one-layer "thin shell" structure. Therefore, to improve the

calculation efficiency, shell element 181 in ANSYS finite element software is used for modelling, calculation and analysis.

Shell 181 element is suitable for analyzing thin to medium thickness shell structures. It is a 4-node element with 6 degrees of freedom per node: displacement degrees of freedom in the x, y, and z directions, and rotational degrees of freedom around the X, Y, and Z axes. (If the membrane option is applied, the unit will only have a degree of freedom of movement.). The degenerate triangle option is only used when meshing the cell as a filling cell. Shell element is also very suitable for linear, large rotation angle and large strain nonlinear applications. It supports complete and reduced integration methods in the element range. The coordinate system is shown in Figure 2 below. The element is defined by four nodes I, J, K and L. the expression of the element is through logarithmic strain and real stress. The thickness and other information can be defined through the definition of real constant or section. The real constant option is only used for single-layer shells [9-11].
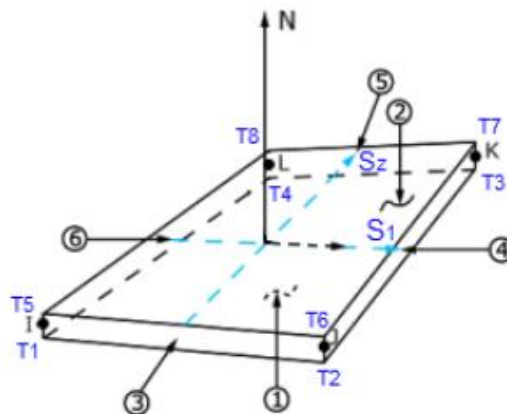

Fig. 2 — Geometric coordinate system of shell 181 shell element

Moreover, the change in shell thickness is to accommodate non-linear analysis. Within the application range of this element, both complete integration and reduced order integration are applicable. The Shell 181 element illustrates the effect of the following (load stiffness) distribution of pressure. The Shell 181 element can be applied to modelling materials of multi-layer structures, such as composite laminated shells or sandwich structures. In the modelling process of composite shells, the accuracy depends on the first shear deformation theory. Shell 181 uses the non-conforming mode method to improve the accuracy of the deflection governing problem, and its accuracy of calculating deformation has been verified in some cases through the Ansys tutorial.

Due to the problems of Jigongzui aqueduct after years of operation and natural aging, environmental erosion and natural disasters, the concrete structure has different degrees of wear, aging, cracking and corrosion. The carbonization depth detection of the body of Jigongzui aqueduct is carried out, as shown in Figure 3. The carbonation depth of concrete outside the tank body is basically more than 10mm, and the carbonation depth of concrete inside the tank body is between 5mm and 10mm. The total carbonation depth accounts for about 20% of the tank body thickness (0.1m). The calculated value of concrete strength grade meets the concrete C25 strength grade required by the specification. After inquiry, the reinforcement ratio of this project is about 5%, and the relevant parameters are shown in Table 1.

Fig. 3 — Detection of carbonization depth of Jigongzui aqueduct body

Tab.1 - Mechanical parameters of reinforced concrete for groove body and tie rod structure

Concrete strength grade	Density（kN/m3）	Standard value of axial tensile strength (N/mm2)	Standard value of axial compressive strength (N/mm2)	Elastic Modulus 104N/mm2	Poisson's ratio
C25	25	1.78	16.7	2.8	0.167
Strength grade of reinforcement	weight /m （kg, D is the diameter of reinforcement bar，mm）	Design value of tensile strength (N/mm2)	Design value of compressive strength (N/mm2)	Elastic Modulus 104N/mm2	Poisson's ratio
HPB235	0.00617D2	210	210	21	0.3

Equivalent treatment of aqueduct reinforced concrete: the aqueduct body structure is composed of materials with different material properties and different mechanical properties. The material properties of reinforcement bar and concrete are calculated as a whole, and the structures with different materials and heterogeneity are transformed into homogeneous model structures [12-14]. Then according to the longitudinal deformation coordination conditions:

$$A_{cs}E_{cs}=A_cE_c+A_sE_s \qquad (1)$$

Where E_{cs} and A_{cs} equivalent elastic modulus and equivalent area of reinforced concrete; E_c and A_c - elastic modulus and area of concrete; E_s and A_s - elastic modulus and area of reinforcement bar.

Since the carbonation depth of the aqueduct accounts for about 20% of the thickness of the aqueduct body, the parameters of the aqueduct are reduced by 20% in the analysis. After calculation, the current comprehensive elastic modulus of Jigongzui U-shaped aqueduct is E = 2.97 × 1010pa, Poisson's ratio is 0.2.

This paper focuses on the stress and deformation characteristics of the whole body of Jigongzui U-shaped thin shell aqueduct project. Therefore, ANSYS R19.0 is adopted to establish the aqueduct model by shell element is shown in Figure 4. The 9 horizontal tie rods at the upper part are simulated by beam188 element, with a length × Width (0.2m × 0.2m), and corresponding mechanical parameters are given at the same time. According to the aqueduct safety evaluation report, the mechanical effect in the midspan of the aqueduct is the most obvious. To facilitate the analysis of the stress-strain characteristics in the midspan under different working conditions, and the aqueduct is a left-right symmetrical structure, three points a, B and C at different heights on one side of the midspan cross section are selected as the monitoring points, and the node labels are 567, 2495 and 2168 respectively. The point distribution is shown in the figure below. To solve the linear contact problem between different elements, multipoint constraint (MPC) method is

selected to realize the degree of freedom coupling between contact node elements. The node elements at both ends of the aqueduct are subject to longitudinal (Z-direction) constraints, which can carry out transverse and vertical deformation. The structural elements at the bottom of both ends are fixed boundaries, which are constrained in X, Y and Z directions.
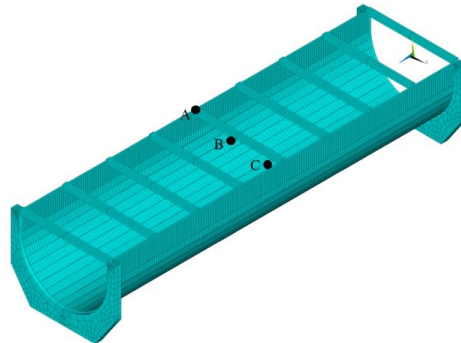

Fig. 4 — Three dimensional finite element model of Jigongzui aqueduct

The working conditions of calculation and analysis are defined as three categories: (1) Empty tank under gravity; (2) Water depth of the half trough under the action of gravity (water depth 1.4m); (3) Full tank depth under gravity (water depth 2.8m). Other external loads, such as crowd load and wind load, are not considered in this analysis. The water pressure inside the aqueduct is a triangular load perpendicular to the action surface. Sfgrad and SF are applied inside the aqueduct through the surface load pressure gradient APDL command, and the gravity acceleration g is 9.81N/kg.

RESULTS ANALYSIS

Deformation Analysis

When the aqueduct is empty without water, after long-term deformation, and the initial displacement of aqueduct will be reset to zero during water filling calculation. Then the water pressure gradient loads of half tank depth (water depth 1.4m) and full tank depth (water depth 2.8m) are applied to the model, and the displacement nephogram of the aqueduct structure under two different water depth conditions is obtained through numerical simulation calculation, as shown in Figure 5 and Figure 6, including horizontal transverse channel displacement Ux, vertical displacement Uy, longitudinal along channel displacement Uz and comprehensive displacement Usum.

The analysis shows that when the Jigongzui U-shaped aqueduct is in half tank water depth (water depth 1.4m), the transverse displacement Ux of the aqueduct is symmetrically distributed, and the wall shell of the aqueduct body tends to expand outward in the middle of the span, but the total transverse deformation is very small, and the maximum value is only 0.83mm. The vertical displacement Uy in the gravity direction shows that the main vertical deformation area is located at the bottom of the middle span of the aqueduct, the direction is vertical downward, decreases to the longitudinal ends gradually, and the maximum vertical displacement is 3.15mm. In the longitudinal direction of the aqueduct, the longitudinal displacement Uz is mainly distributed in the upper part of both ends of the aqueduct close to the pull rod, and the direction is deformed towards the middle of the span, but the total longitudinal deformation of the aqueduct is also very small, and the maximum value is only 0.86mm. The displacements in the three directions are synthesized into Usum. The comprehensive displacement nephogram is basically consistent with the vertical displacement uy. The obvious deformation area is located at the bottom of the mid span trough body and gradually decreases to both sides, with the maximum value of 3.15mm.
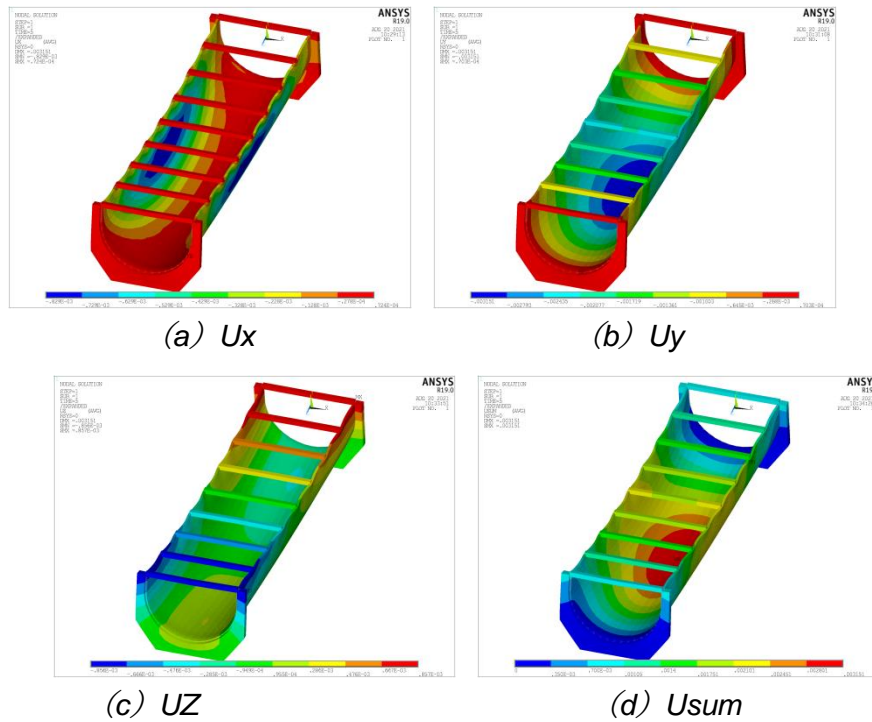
(a) Ux

(b) Uy

(c) UZ

(d) Usum

Fig. 5 — Displacement nephogram of Jigongzui aqueduct with water depth of 1.4m

(a) Ux

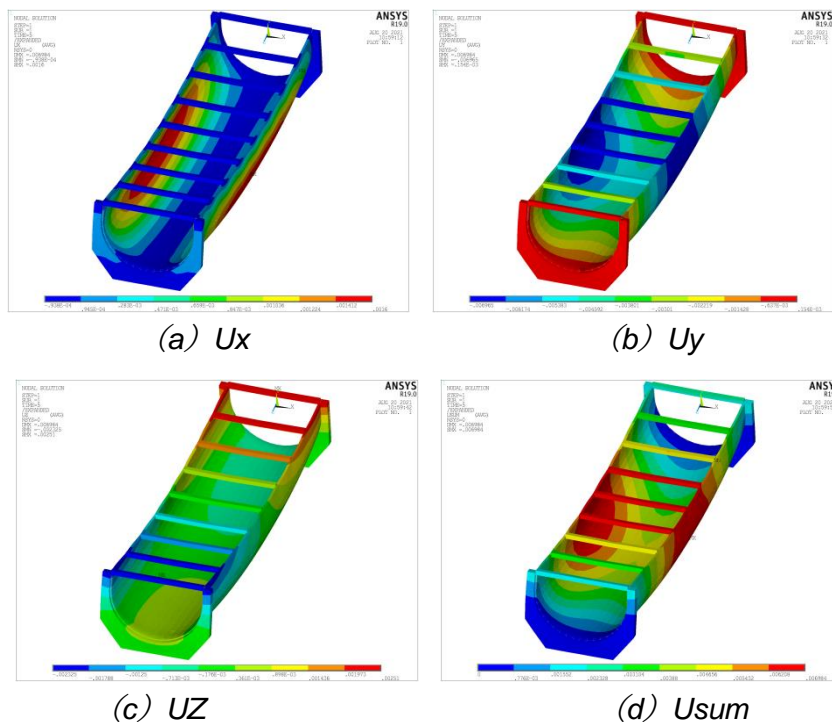
(b) Uy

(c) UZ

(d) Usum

Fig. 6 — Displacement nephogram of Jigongzui aqueduct with water depth of 2.8m

When the Jigongzui U-shaped aqueduct is filled with water to the full depth of 2.8m, the transverse displacement Ux of the aqueduct is symmetrically distributed, and the wall shell of the aqueduct body tends to expand further outward in the middle of the span. The total transverse deformation is slightly larger than that when the water depth is 1.4m, and the maximum value is 1.60mm. The vertical displacement Uy in the gravity direction shows that the main vertical deformation area is located on both sides of the middle span of the aqueduct. The direction is

vertical downward and gradually decreases to both longitudinal ends. The maximum vertical displacement is 6.97mm, which is more than twice that when the water depth is 1.4m (3.15mm); In the longitudinal direction of the aqueduct, the displacement Uz along the aqueduct is mainly distributed in the upper part of both ends of the aqueduct close to the pull rod, and the direction is towards the middle of the span and deformed. The total longitudinal deformation of the aqueduct increases compared with the water depth of 1.4m, and the maximum value reaches 2.51mm. The comprehensive displacement Usum cloud diagram is basically consistent with the vertical displacement Uy. The obvious deformation area is located on both sides of the mid span groove body, and decreases to both sides gradually, with the maximum value of 6.98mm, which is 121% higher than 3.15mm when the water depth is 1.4m. It shows that the vertical displacement in the middle of the span of Jigongzui U-shaped aqueduct is the most obvious after it is filled with water. According to the relevant provisions of article in the code for design of hydraulic concrete structures [15], when the calculated span is greater than 10m, the deflection limit value of flexural members shall not exceed l0/600. If the span of Jigongzui aqueduct is 16m, the deflection limit value is 26mm, and the deflection value does not exceed the limit value when it is full of water depth, and there is enough safety reserve. It is considered that the numerical calculation results of deflection meet the requirements of the specification.

Stress Analysis

Figure 7, 8 and 9 respectively show the stress distribution diagram under the three working conditions of empty groove, half groove water depth (water depth 1.4m) and full groove water depth (water depth 2.8m), including the first principal stress σ1, third principal stress σ3 and von Mises stress. With the first major principal stress σ1 as an example, when the slot is empty, the bottom of the middle span of the slot body is tensioned, and the maximum value at point C (node No. 2168) is 0.79MPa. When the water is filled to 1.4m, the first principal stress at point C increased to 1.89MPa and the aqueduct is filled with water to 2.8m, the first principal stress at point C increased to 4.98MPa, and the tensile area at the bottom of the middle span of the groove body is increased. It shows that when the tank is full of water depth, the tension at the bottom of the middle span of the tank body is obvious, and the local tensile stress exceeds the tensile strength of the concrete, which will lead to local tensile failure. The distribution range and variation trend of normal form equivalent stress are basically consistent with the first principal stress.
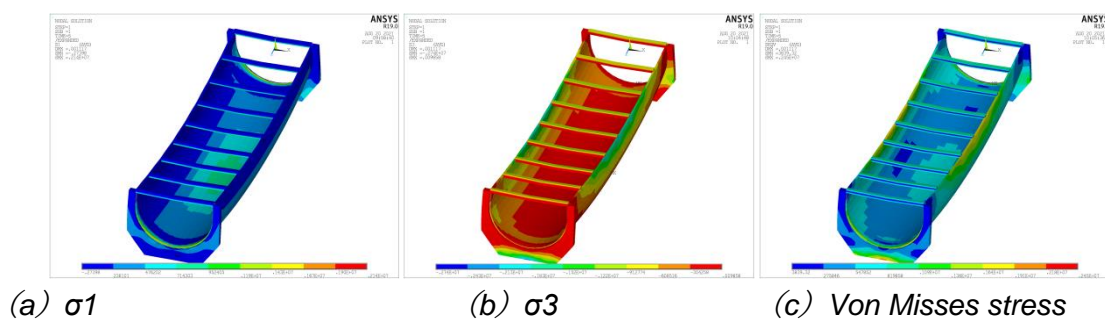

(a) σ1   (b) σ3   (c) Von Misses stress

Fig. 7 — Stress distribution of Jigongzui aqueduct in empty state

(a) σ1   (b) σ3   (c) Von Misses stress
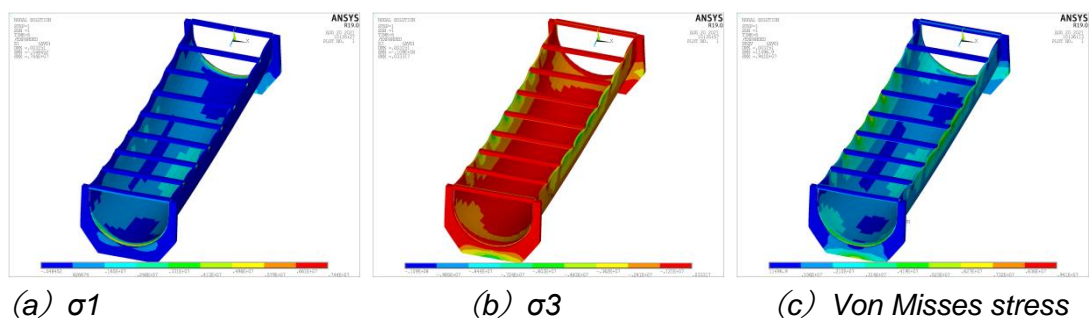
Fig. 8 — Stress distribution of 1.4m deep Jigongzui aqueduct (half trough depth)

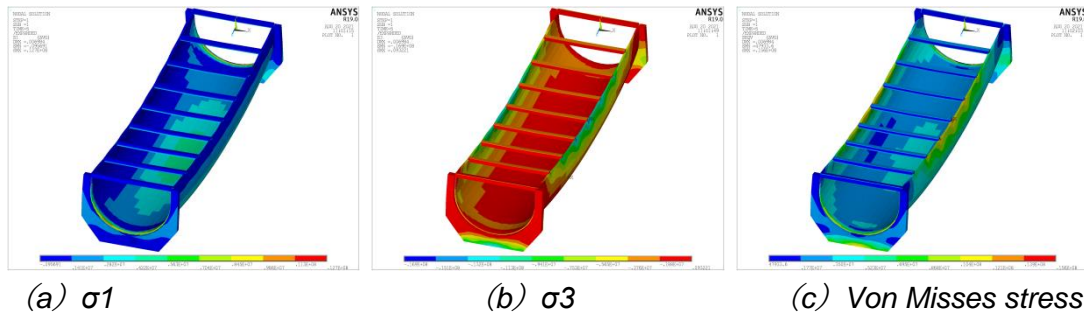| (a) σ1	(b) σ3	(c) Von Misses stress

Fig. 9 — Stress distribution of Jigongzui aqueduct with water depth of 2.8m (full water depth)

Von Mises stress diagram can clearly describe the distribution of stress in the whole model, so as to quickly determine the most dangerous area in the model. Figure 10 indicates the normal form equivalent stress of the three monitoring points in the cross section of the middle span of the structure of Jigongzui aqueduct. It is found that with the increase of the internal water depth of the aqueduct, the normal form equivalent stress values of the three monitoring points also gradually increase, and the value of point a is the largest. However, it can be seen from (c) in Figure 7 ~ Figure 9 that this is the stress concentration phenomenon between the tie rod and the trough wall, and the distribution range is very small. Point B in the middle increases from 0.47MPa to 3.09MPa, while point C at the bottom increases from 0.69MPa to 4.44MPa. Therefore, it can be determined that the most dangerous area after the aqueduct is filled with water is located at the bottom of the span. It is necessary to take corresponding reinforcement measures to improve the stress distribution at the bottom of the aqueduct, such as pasting high-performance fiber materials carbon fiber cloth and carbon fiber board at the corresponding positions, so as to improve the longitudinal bearing capacity of the aqueduct body and ensure the normal operation of the aqueduct engineering structure.
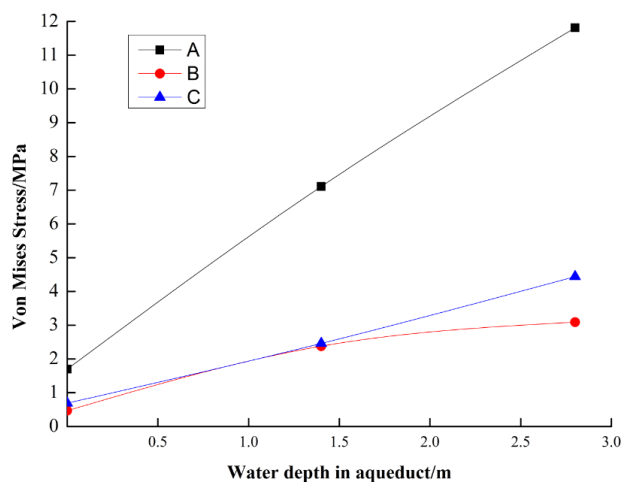

Fig. 10 — Von Mises stress at mid monitoring point of Jigongzui aqueduct under multiple working conditions

CONCLUSIONS

Taking the Jigongzui U-shaped thin shell aqueduct in Dujiangyan Irrigation Area in service as an example, the carbonation depth of the aqueduct is measured on site, and the shell element is proposed to establish the three-dimensional finite element model of the aqueduct engineering structure. The stress and deformation characteristics of the aqueduct under the three working conditions of empty slot, half slot water depth (water depth 1.4m) and full slot water depth (water depth 2.8m) are analyzed quantitatively. The following conclusions are obtained for reference.

(1)   The carbonation depth of concrete outside the tank body is basically more than 10mm, and the carbonation depth of concrete inside the tank body is between 5mm and 10mm. The total carbonation depth accounts for about 20% of the total thickness of the tank wall.

(2)   With the increase of aqueduct water level, the deformation of aqueduct body gradually increases, mainly vertical deformation. When the tank is full of water depth, the deflection value does not exceed the limit value, and the deflection calculation results meet the requirements of code for design of hydraulic concrete structures.

(3)   With the increase of aqueduct water level, the stress of aqueduct body increases gradually. When the groove is full of water depth, the tensile area at the bottom of the midspan tends to expand, and the tensile stress in some areas exceeds the tensile strength of concrete, so there is the possibility of tensile failure. It is necessary to take some reinforcement measures at the bottom of the aqueduct body to improve the longitudinal bearing capacity of the aqueduct body and ensure the normal operation of the aqueduct structure.

(4)   Compared with the traditional three-dimensional solid element structure, using shell element 181 to simulate U-shaped thin shell aqueduct has faster calculation speed and higher efficiency. It has certain advantages in the safety evaluation of similar thin shell aqueduct structures, and can be applied and popularized.

This paper only analyzes and discusses the current situation of Jigongzui U-shaped thin shell aqueduct. Combined with the safety evaluation report, it is found that there are certain potential safety hazards in the aqueduct engineering structure, and puts forward the way of pasting high-performance fiber materials for reinforcement. In the future work, the reinforcement effect of the modification scheme will be further studied.

ACKNOWLEDGMENTS

CONFLICTS OF INTEREST

Authors declare that they have no conflicts of interest.

REFERENCES

[1]   Ministry of water resources of the people's Republic of China Code for design of reasonable service life and durability of water conservancy and hydropower projects: SL 654-2014 [S] Beijing: China water resources and Hydropower Press, 2014.

[2]   Liu Tao, He Jianxin, Liu Liang, et al Water filling test and bearing capacity safety evaluation of Kizilsu river aqueduct [J] Hydropower energy science, 2021,39 (04): 100-104.

[3]   Liu Xiaojuan, Zhang Hongjun, Feng Sa. Three dimensional finite element analysis of stress and deformation of Xinnan main canal aqueduct structure [J] Engineering construction, 2021,53 (04): 32-37.

[4]   Huang Junbao, Deng Chengfa Performance safety evaluation of old aqueduct structure based on three-dimensional laser scanning [J] China rural water resources and hydropower, 2020 (03): 142-145.

[5]   Xia Fuzhou, Qian Liyun, Zhang Jun Study on structural safety and evaluation index system of large aqueduct [J] China Rural Water Conservancy and hydropower, 2011 (08): 121-123.

[6]   Ji richen, Su Xiaofeng, Yan Juan Study on the influence of water quality on the transverse seismic performance of large beam aqueduct [J] Journal of earthquake engineering, 2013,35 (3): 569-574.
[7]   Shang Feng, Zhu Yanzhi, Zheng Yongzhi Safety evaluation and disease treatment of in-service reinforced concrete aqueduct [J] Water conservancy and hydropower technology, 2018,49 (12): 208-214.
[8]   Huang Tao, Zhang Guoxin, Li Jiang, et al Causes of cracks in an aqueduct in cold area and influence of reinforcement corrosion on durability [J] Water conservancy and hydropower technology, 2019,50 (12): 120-129.
[9]   Shen Xiaoming, Huang Yong Study on Design of prestressed concrete U-beam aqueduct [J] China water transport, 2019,19 (11): 253-254.
[10]   Kate E. Porter, Stephanie E. Ordonez-Sanchez, Robynne E. Murray, et al. Flume testing of passively adaptive composite tidal turbine blades under combined wave and current loading[J]. Journal of Fluids and Structures, 2020, 93(1):11-15.
[11]   Holmlund P, Qvarlander S, Malm J, et al. Can pulsatile CSF flow across the cerebral aqueduct cause ventriculomegaly? A prospective study of patients with communicating hydrocephalus[J]. Fluids and barriers of the CNS, 2019, 16(1):40-41.
[12]   Deng Chengfa, Yu Junjun, Lai Sheng, et al Safety evaluation and analysis of datangkou open web double arch aqueduct [J] Hydropower and energy science, 2019,37 (7): 70-73.
[13]   Zhang Jianwei, Wen Jiaqi, Huang Jinlin, et al Determination of simulation parameters of aqueduct and its nonlinear contact wind-induced vibration analysis [J] Journal of North China University of water resources and hydropower (NATURAL SCIENCE EDITION), 2019,40 (2): 77-83.
[14]   Liu Shuai, Zhai juyun Stress and deformation monitoring and simulation analysis of large prestressed beam aqueduct [J] People's Yellow River, 2020,42 (1): 126-130.
[15]   Ministry of water resources of the people's Republic of China Code for design of hydraulic concrete structures: SL191-2008 [S] Beijing: China water resources and Hydropower Press, 2008.