Simulated Calculation of Temperature Control and Anti-crack during Construction of Inverted Siphon

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Abstract. Inverted siphon, such a thin-walled structure, tends to have large internal and external temperature differences during the early stage of pouring, resulting in a large tensile stress on the surface. Once surface or penetrating cracks appear, it will have a great influence on the integrity, safety, impermeability and durability of the structure and reduce the water transfer function. The temperature control simulation of the Liyanghe inverted siphon in the middle line of South-to-north Water Diversion project was designed to select the temperature control measures of inverted siphon concrete during different month construction. Temperature control measures can provide references for similar projects at home and abroad.

1. Introduction
Inverted siphon bottom plate, top plate, vertical wall and other components are thin-walled structures. Thin-walled structures tend to have large internal and external temperature differences in the early stage of pouring, resulting in greater tensile stress on the surface. Once a surface crack or a penetrating crack occurs, the structure will be greatly influenced in the integrity, safety, impermeability durability, and the water delivery function. Therefore, the temperature stress of the concrete must be taken to control during the construction period, so as to effectively prevent the occurrence of cracks and ensure the quality of the project.

In this paper, an inverted siphon is used for temperature control simulation calculation to select the temperature control measures for inverted siphon concrete during construction in different months. The calculation results are used for feedback design, guide construction, and achieve the purpose of crack prevention during construction.

2. Project overview and simulation model
Liyanghe inverted siphon as a large cross-drainage building is an important water-conveying structure in the Middle Route Project of South-to-North Water Transfer Project. The project is located 80m downstream of the junction of the two tributaries of Liyang River in the east of Shuangliu Village in the southwest of Neiqiu County. The total length is 513m. The design discharge is 220m³/s, and enlarged discharge is 240m³/s. The length of the inverted siphon tube is 352m, including the length of the imported inclined tube section is 60m, the length of the flat tube section is 224m, and the length of the exit oblique tube section is 68m. A 3-hole 6.5m*6.5m rectangular reinforced concrete structure is adopted. The thickness of the top plate, side walls and floor are 1.4m, and the thickness of the middle wall is 1.3m. The design dimension is shown in Figure 1. Li Yang River inverted siphon is located in
the warm temperate continental monsoon climate zone, winter is cold and dry, summer is hot and rainy. The annual average temperature is 12.8°C. In January, the average annual temperature is -3.5°C. In July, the average annual temperature is 26.6°C. The temperature changes significantly in a year.

Due to the symmetry structure, a quarter of a single inverted siphon was taken as the analysis object. The calculation model scale was 8m in the downstream direction, 12.45m in the vertical direction, and 9.3m vertically upwards, as shown in Figure 2. The calculation used 8-node hexahedral space units, which splits 5056 units and 6511 nodes.

In the calculation of the temperature field, the symmetry plane of the bottom surface of the inverted siphon and the model is used as an adiabatic surface, and the others are all the third boundary conditions. In the calculation of the stress field, the bottom plate of the calculation model is simply supported in the z-direction, and the symmetry plane of the middle hole is simply supported by the x-direction, and the symmetry plane of the middle section of the inverted siphon along the water flow direction is simply supported by the y-direction.

### 3. Basic information and calculation conditions

The construction conditions of a single-seat inverted siphon are as follows: There are three separate pouring steps. First, the bottom concrete shall be poured, including the floor and part of the vertical walls. The bottom concrete shall be poured to 60cm above the angle of the bottom of the vertical wall. After 10 days of interval, the vertical wall shall be poured to 60cm below the top angle; and the top plate pouring should be completed after another 10 days. The construction period of inverted siphon is from March to November of each year, and it is stopped from December to February.

The thermodynamic parameters of concrete in Liyanghe inverted siphon and allowable tensile strength of concrete of different ages are reported in the self-test report. The change curves of adiabatic temperature rise and elastic modulus are shown in Figure 3, and the allowable tensile strength at different ages is shown in Figure 4. Creep data can be seen in similar projects.

![Figure 1. Liyanghe inverted siphon section (in mm).](image1)
![Figure 2. Finite element grid (1/4 model).](image2)

![Figure 3. Adiabatic temperature rise and elastic modulus of concrete with age.](image3)
![Figure 4. Allowable tensile strength of concrete with age.](image4)

The simulation calculation period is 90 days after the start of construction. The temperature used during the calculation is the ten-day average temperature. Considering that the early hydration heat of concrete was faster, the calculation step changed with time. It was 0.2 days from the No. 0 day to 1
days and 0.5 days from 1th day to 10 days. The calculated step size increased to 1 day after 10 days. Since the inverted siphon can be constructed in any month from March to November, the simulation calculations are analyzed separately for each month of construction.

4. Simulation calculation analysis of inverted siphon concrete pouring
The construction period of the aqueduct is from March to November. The simulation analysis is carried out for every month of March ~ November to select the temperature control measures of inverted siphon concrete during different month construction.

If a single seat inverted siphon is poured in March, it is assumed that the soleplate will be poured on March 10th, poured to a height of 2.663 m, and the vertical wall concrete will be poured after 10 days of rest to 6.638 m height. After 10 days of rest, the roof shall be poured. The concrete pouring temperature is 12°C, and no temperature control measures are taken. This calculation plan is used as the solution 1.

The temperature and stress changes in the interior and surface of the typical vertical wall are shown in Figure 5. From the process of temperature and stress change of the vertical wall and middle vertical wall concrete, it can be seen that after one day of pouring, the concrete inside the vertical wall reaches a maximum temperature of about 31°C, and the concrete on the vertical wall surface reaches a maximum temperature of about 15°C. Vertical wall concrete temperature difference between inside and outside one day after pouring reaches a maximum of about 16°C. During this period, the internal concrete stress is under pressure with the increase of internal and external temperature difference, while the external concrete stress is in tensile state with the increase of internal and external temperature difference. When the internal and external temperature difference reaches the maximum, the internal concrete stress and external concrete tension are both When the maximum condition is reached and the external concrete stress exceeds the concrete's tensile strength, surface cracks "from the outside to the inside" may occur.

Later, as the temperature difference between inside and outside decreases, the surface concrete gradually changes to the pressure state, and the internal concrete becomes tensile. After 10 days of pouring, despite the summer, autumn, and winter seasons, the temperature inside and outside the stringer concrete is close to the outside temperature, and the temperature difference between the inside and outside of the concrete is basically within 1.0°C. The internal and surface stresses of the concrete basically do not change, but the interior pull the stress is maintained at about 3 MPa, the external compressive stress is maintained at about -3.0 MPa, and the internal stress of the concrete exceeds the standard, and temperature cracks “from the inside out” may appear. The change law of the temperature difference between the inside and outside of the floor and roof concrete is similar to the vertical wall. The specific characteristics can be seen in the Table 1.

Figure 5. The temperature and stress changes in the interior and surface of a typical vertical wall.

| Time (month/day) | 3/18 | 3/28 | 4/7  | 4/17 | 4/27 | 5/7  | 5/17 | 5/27 | 6/6  |
|-----------------|------|------|------|------|------|------|------|------|------|
| Stress (MPa)    |      |      |      |      |      |      |      |      |      |
| interior stress of vertical wall |      |      |      |      |      |      |      |      |      |
| external stress of vertical wall |      |      |      |      |      |      |      |      |      |
| temperature of interior concrete |      |      |      |      |      |      |      |      |      |
| temperature of external concrete |      |      |      |      |      |      |      |      |      |
| internal and external temperature difference |      |      |      |      |      |      |      |      |      |

Figure 6. Maximum first principal stress profile in scheme 2.
Table 1. Statistical Analysis of Characteristic Values of Typical Temperature and Stress of Concrete in Inverted Siphon Structures in scheme 1.

| Position      | Pouring temperature (℃) | Internal maximum temperature (℃) | Occurrence time of internal maximum temperature (days) | Occurrence time of external maximum temperature (days) | Maximum temperature difference between inside and outside (℃) | Occurrence time of the maximum temperature difference between inside and outside (days) | Time when temperature difference between inside and outside is less than 1.0°C (days) | Maximum internal stress (MPa) | Maximum surface stress (MPa) |
|---------------|--------------------------|----------------------------------|--------------------------------------------------------|-------------------------------------------------------|--------------------------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|--------------------------------|----------------------------|
| Floor         | 12                       | 30.93                            | 1.5                                                    | 13.44                                                 | 0.4                                                          | 18.55                                                                           | 1.5                                                                              | 12.5                           | 2.15                       |
| Limbic vertical wall | 12                       | 30.91                            | 1.5                                                    | 14.79                                                 | 0.8                                                          | 16.65                                                                           | 1.5                                                                              | 11.5                           | 2.98                       |
| Middle vertical wall | 12                       | 29.93                            | 1.5                                                    | 14.78                                                 | 0.8                                                          | 15.71                                                                           | 1.5                                                                              | 12                             | 3.01                       |
| Roof         | 12                       | 31.29                            | 1.5                                                    | 15.42                                                 | 2                                                            | 16.99                                                                           | 1.5                                                                              | 12                             | 2.02                       |
| Joint surface | 12                       | 30.25                            | 1.5                                                    | 15.03                                                 | 0.6                                                          | 16.06                                                                           | 1.5                                                                              | 12                             | 4.03                       |

From the simulation results of Scheme 1, it can be seen that the limbic vertical wall has a stress exceeding the standard, and surface cracks may appear in the early stage of pouring, and penetration cracks may appear after 10 days of pouring. Therefore, measures must be taken to reduce the temperature difference between the inside and outside of these thin-walled structures to control their temperature stress.

Scheme 2 is a simulation calculation based on scheme 1, and the difference between scheme 1 is that when the inverted siphon concrete is poured, the inner surface of the template is adhered to the inner surface of the template with 1.5 cm thick polystyrene board for early concrete surface thermal insulation. The aim was to reduce the temperature difference between the early concrete and the thermal stress. In addition, after the template is removed, the polystyrene board can remain on the concrete surface for later thermal insulation.

The following conclusions can be drawn from the calculation result of scheme 2: (1) After applying 1.5cm thick polyphenylene plate for surface heat preservation, the maximum temperature of the thin wall structure of inside and outside the limbic vertical wall concrete is increased (about 3℃), and the maximum temperature occurs more time Scheme 1 lags from 1 to 1.5 days, but the maximum internal and external temperature difference is about 10℃, which is lower than that of Option 1. (2) Due to the decrease of the internal and external temperature difference, the thermal stress of the interior and surface of the concrete of scheme 2 has been greatly reduced and is less than the tensile strength of the concrete, which can effectively prevent the cracks of the poured concrete in March. (3) After surface insulation is adopted, the late stress of the interior and surface of the concrete near the joint surface of the new and old concrete is in a tensile state, and the tensile strength of the concrete is not exceeded. However, the internal concrete temperature stress near the joint surface is close to allowable. Tensile strength, see Figure 6. Therefore, for a single seat inverted siphon poured in March, after applying a 1.5cm thick polystyrene board for internal heat preservation, it can meet the crack prevention requirements to prevent cracks from appearing.

5. Sensitivity analysis of effect of mold removal on temperature and stress of inverted siphon

The above simulation results show that, by using the polystyrene board attached the inner wall to insulate the concrete, after the formwork is removed, the polystyrene board remains on the concrete surface, and the purpose of effective temperature control and crack prevention can be achieved from March to November. The calculation of this scheme mainly considers the extreme situation that the inner thermal insulation plate falls off when the template is removed. In order to prevent the cracking safety, the temperature difference control index between the concrete surface temperature and the external environment temperature during the removal of the mold is proposed.

Taken a single-seat inverted siphon poured in October as an example, the temperature and stress changes of the concrete with 1.5cm thick polyphenylene plate for internal thermal insulation under different ambient temperatures (11.5℃, 16.0℃ and 18℃) were studied. Table 2 shows the statistics...
of characteristic values of inverted siphon concrete poured in October at different ambient temperatures in 7 days.

From the calculation results, it can be seen that, when the template is removed, assuming that the inner thermal insulation plate falls off, the surface temperature of the concrete rapidly decreases, the surface stress rapidly increases, and even the compressive stress before the removal of the mold changes to tensile stress. From the calculation results of the sidewalls, when the surface temperature of the concrete differs from the ambient temperature by 1°C, the surface stress increases by an average of about 0.1 MPa when the formwork and the insulation board are removed. It can be seen from the sensitivity analysis under different ambient temperature conditions during demolding that the difference between the surface temperature of the inverted siphon concrete and the external environment temperature when the template is removed should not exceed 15°C.

| Demolition surface temperature (°C) | Outside temperature (°C) | Temperature difference (°C) | Surface stress before demoulding (MPa) | Surface stress after demoulding (MPa) | Stress growth rate (MPa/°C) |
|------------------------------------|-------------------------|-----------------------------|---------------------------------------|--------------------------------------|---------------------------|
| 29.6                               | 11.5                    | 18.1                        | -0.05                                 | 2.06                                 | 0.11                      |
| 29.6                               | 13                      | 16.6                        | -0.05                                 | 1.87                                 | 0.11                      |
| 29.6                               | 15                      | 14.6                        | -0.05                                 | 1.6                                  | 0.11                      |

6. Conclusion and suggestion

For Liyanghe inverted siphon thin-walled concrete structures, the temperature difference between the inside and outside of the early stage of concrete placement plays a key role in the control of temperature stress. For this project, there are three main reasons for the temperature difference between interior and exterior: First, after the concrete has been poured, when the concrete temperature rises early, the internal temperature rises quickly and the surface temperature rises slowly, there is an internal and external temperature difference. During this period, the external surface of the structure is subjected to tensile stress, and the internal compressive stress is applied, and both the tensile stress and the compressive stress reach the highest value when the temperature difference between inside and outside reaches a maximum value. Second, when the temperature drops, the surface temperature dissipates quickly, and a larger temperature difference will be formed. Third, the surface stress increases rapidly after the internal insulation board is detached, and even the compressive stress before the mold is removed becomes the tensile stress.

It is recommended to reduce the temperature stress as much as possible by the following methods: ① Reducing the temperature of storage, including using the groundwater for aggregate cooling, using extended storage time for cement to ensure that the temperature of the tank is below 60°C, and the concrete adopting cooling water of 4~6°C Together. ② Reasonable choice of pouring time, make full use of the time of night pouring concrete.③ From March to November, 1.5 cm thick polystyrene insulation boards were pasted on the surface of concrete poured during the entire construction period to insulate the concrete. ④ During the construction process, the spray will increase the humidity of the environment, and the construction will finish the surface water conservation. ⑤ When the template is removed, the difference between the surface temperature of the inverted siphon concrete and the ambient temperature should not exceed 15°C. ⑥ During the shutdown period from December to February of the following year, plug the inverted siphon port to avoid cold wind entering the inverted siphon water transfer hole.

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References

[1] XIA SF, LU YH, LI XL, et al. Numerical Simulation of Temperature Control and Anti-cracking Measures for the Ming River Aqueduct of the South-to-North Water Diversion Project 2012 J. South-to-North Water Transfers and Water Science & Technology. 10(4):1-6 (in Chinese)

[2] WANG ZHH, ZHU YM, YU SP. Study on temperature control and crack prevention of thin-walled concrete structures during the construction period 2007 J. JOURNAL OF XI'AN UNIVERSITY OF ARCHITECTURE & TECHNOLOGY (NATURAL SCIENCE EDITION). 27(6):773-778 (in Chinese)

[3] ZHANG LF, YAO XH, YUE CHR, et al. Influences of Temperature Changes on Behaviors of Large Prestressed Concrete Inverted Siphon 2013 J. South-to-North Water Transfers and Water Science & Technology. 11(4):196-199 (in Chinese)

[4] SUN JCH, WANG LY, GUO L. Research on temperature control and crack prevention technology during inverted siphon construction 2012 J. LOW TEMPERATURE ARCHITECTURE TECHNOLOGY. 11:121-122 (in Chinese)

[5] LI XL, XIA SHF, SUN YL. Analysis on temperature control for the bottom outlet section of Chonghuier RCC Gravity Dam 2017 J. JOURNAL OF CHINA INSTITUTE OF WATER RESOURCES AND HYDROPOWER RESEARCH. 15(1):44-48 (in Chinese)

[6] LI XL, XIA SHF, LI R, et al. Feedback analysis on concrete thermal stress in a RCC gravity dam after upstream dam surface's insulation board falling off 2015 J. Dam & Safety. 6(6):48-50 (in Chinese)

[7] YANG JC, GUO L, HE DT, et al. Study on concrete's temperature control measures for the inverted siphon project in winter 2010 J. CONCRETE. (12):111-113 (in Chinese)

[8] LIANG RH. Culvert concrete temperature & crack control measures in Hutuohe inverted siphon project 2005 J. WATER SCIENCES AND ENGINEERING TECHNOLOGY. 5(5):34-36 (in Chinese)

[9] LU T. Analysis of Concrete Temperature Control Measures in Construction of Honghe Inverted Siphon at High Temperature Season 2009 J. Dam & Safety. (s1):99-100 (in Chinese)

[10] ZHU BF. M 2012 Thermal Stresses and Temperature Control of Mass Concrete second edition, (Beijing: Water & Power Press)