Finite Element Analysis of Inverted Siphon During Operating Period

Wei He*
School of Civil Engineering and Communication, North China University of Water Resources and Electric Power, Zhengzhou, 450045, China
*Corresponding author(E-mail: hwyr123@sina.com)

Mengying Li
School of Civil Engineering and Communication, North China University of Water Resources and Electric Power, Zhengzhou, 450045, China

Hong Dong
School of Civil Engineering and Communication, North China University of Water Resources and Electric Power, Zhengzhou, 450045, China

Abstract
Inverted siphon project is a cross-river canal building, and is one of the important components of the South-to-North Water Transfer Project in China. The safety of the inverted siphon project has been a major problem during its operating period. Based on the ANSYS software, the inverted siphon is taken as the research object and established a three-dimensional finite element model. The stress and strain states of the inverted siphon at various water levels has been calculated under seven working conditions. And the influence of water level on the inverted siphon are analyzed. The results show that the calculated stress and strain distributions of the inverted siphon are agree well with actual engineering result, and the design of structure scheme is reasonable. The structure is safe under the action of gravity and water load during operation period.

Key words: Inverted Siphon, ANSYS, Stress and Strain, Reference Value.

1. INTRODUCTION

The inverted siphon structure is a thin-walled concrete structure, and the structural analysis has important engineering significance for the safety design of the inverted siphon structure (Xie, 2014). As a stressed water pipe, inverted siphon goes through a variety of channels, such as rivers, depressions and so on. Inverted siphon is low cost, easy construction, but high water-head loss, inconvenient operation and management compared with the aqueduct. The inverted siphon should be used when it is difficult to construct the aqueduct and the high filling or winding channel scheme is difficult; when the channel water level is close to the road elevation or river water level and using the aqueduct is inconvenient. Due to have a large flow and unprecedented scale, the inverted siphon is widely used in the middle of the South-to-North Water Transfer Project and its importance is self-evident (Zhang and Yao, 2013).

The inverted siphon project has always been a hot topic in the research of experts and scholars at home and abroad in the South-to-North Water Diversion Project, mainly in the construction of inverted siphon’s model experiment and numerical simulation. The stress and strain of the inverted siphon structure are not only an index of stiffness, but also a basis for identifying whether an inverted siphon structure is damaged or not (Liu and Yang, 2014). Ji took Liujia inverted siphon project as an example to provide a reference for its safe operation, taking into account the structural design and mechanical analysis theory (Ji, 2010); Li deduced the differential equation of water-filled process and obtained water-filled water level’s change rule for the scientific evaluation of actual engineering water-filling safety, through the establishment of inverted siphon calculation model (Li and Li, 2007). By using finite element software to simulate the calculation of precast inverted siphon, the stress and deformation distribution of inverted siphon are obtained under the most unfavorable conditions, which provides a beneficial reference value to the design and application for reinforced concrete precast inverted siphon project (Ji and Li, 2014).

The Canghe River canal inverted siphon is a large building through river, which the earth-cover of pipe roof is thick and water-head loss high, affecting the pipe body stress distribution. In recent years, scholars at home and abroad are mostly used numerical simulation method to calculate on these underground buildings such as inverted siphon. Taking the Canghe Canal inverted siphon project as the research object, the finite element model of the tube-foundation system was established by the large-scale software ANSYS. The stress
and strain states of the inverted siphon and the influence of the water level on the inverted siphon base were obtained at different water levels to analyze and access the most dangerous water level conditions. The results show that the Canghe Canal inverted siphon structure is economic and reasonable, and meet the requirement of stiffness, and can provide beneficial reference to the design and construction for other inverted siphons structure (Ji, 2013).

2. ENGINEERING SITUATION

The Canghe Canal inverted siphon project in the main canal of the Middle Route South-to-North Water Transfer Project is located in Henan Province, Weihui City, Andu Township, Ma Linzhuang NATO about 300m, and is the important cross-structure crossing the Canghe River. The main works of inverted siphon is the first-grade structure, with the flood control standard of 100-year event design and 300-year event check. The designed flood peak flow rate is 2780m$^3$/s, the corresponding water level 99.64 m. The checked peak flow is 3470m$^3$/s and the corresponding water level is 100.02m. The river is about 930m wide through cross-section of the project, and reaches of the existence of artificial sandbar upper cross-section. The total length of the building is 852m, channel design flow 250m$^3$/s, increased flow 300m$^3$/s, and channel's longitudinal slope 1/28000. The elastic modulus of concrete material is 30GPa, Poisson ratio 0.167, the density 2420kg/m$^3$. The elastic modulus of steel is 200GPa, Poisson ratio 0.3, the density 7800kg/m$^3$, elastic modulus 200GPa, Poisson ratio 0.3 (Gao and Zhang, 2012).

3. BASIC THEORY

3.1. The basic theory of finite element

Finite element method, with the development of the computer, gradually formed a solution method to solve complex problems of elastic mechanics. The original idea of the finite element method is to divide a large structure into small regions of finite elements. In each small region, the deformation and stress of the structure are assumed to be simple. The small regions of deformation and stress are easily solved by a computer, and then can get the whole structure of the deformation and stress. The finite element method can clearly show the stress behavior and development law of the structure under various external loads. It can reveal the whole process of internal force and deformation redistribution of structure and increase the reliability of the whole engineering structure.

An important feature of the finite element method is to use an approximation function in each element to fragmentally represent the unknown field function, which is to be solved over the whole solution domain. An approximation function in the element is usually represented by the value of an unknown field function or its derivative, which is on each node of the element and its interpolation. Therefore, in the finite element analysis of a problem, the unknown field function or its derivative on each node’s value becomes a new unknown quantity, so that a continuous infinite degree of freedom problem becomes a discrete finite degree of freedom problem. Once these unknown quantities are solved, the approximation of the field functions in each element can be calculated by the interpolation function, resulting in an approximation of the entire solution domain (Wu and Mo, 2006).

3.2. The strength checking theory

From the perspective of the performance of the force, the so-called reinforced concrete structure, before the structure is subjected to an external load, is no cracking or the degree of cracks’ development is small in the normal use, which is applied the artificial compressive stress in advance in the structure of the site which may be cracked, in order to reduce or offset the external stress caused by the load.

The vertical flexibility in serviceability limit state of the body should meet:

\[ f \leq \frac{L}{600} = \frac{24400}{600} = 40.667\text{mm} \] (1)

Formulas, \( f \) - The vertical maximum permissible deflection;
\( L \) - The calculation span of inverted siphon body.

The reinforced concrete flexural members should be checked the principal tensile stress and principal compressive stress of concrete section:

(1) The principal tensile stress of concrete:

The primary crack control grade links should meet the following requirements: \( \sigma_p \leq 0.85f_u \) (2)

The secondary crack control grade links should meet the following requirements: \( \sigma_p \leq 0.95f_u \) (3)

Formulas, \( f_u \) - The standard value of concrete for axial tensile strength;
\[ \sigma_p \] - The principal tensile stress of concrete.

(2) The principal compressive stress of concrete:
The primary and secondary crack control grade links should meet the following requirements:

\[ \sigma_p \leq 0.60 f_y \]  \hspace{1cm} (4)

Formulas, \( f_y \) - The standard value of concrete for axial compressive strength;
\[ \sigma_p \] - The principal compressive stress of concrete.

3.3. The cooling method to apply prestressing

There are two ways in analysis of the reinforced concrete in ANSYS: separation type and integral type. The separation type is to consider the concrete and reinforcement as different units, with the role of load to simulate the effect of prestressing, such as equivalent load method; the integral type is assumed to have a good bond between the reinforcement and the concrete, and the reinforced concrete structure is regarded as a continuous whole. The Link element is used to simulate the prestressing tendons, such as the cooling method and the initial strain method. The reinforcement deformed under the tension. Use the cooling method to apply prestressing for reinforcement here.

The Canghe River inverted siphon finite element model is used to simulate reinforcements by the integral type. Link8 element is used to simulate the reinforcement, and the distribution of reinforcements in the concrete are assumed to be uniform and there is no relative slip between the reinforcements and the concrete. The temperature dropped can be calculated according to the following formula:

\[ \Delta T = \frac{F}{(A \times E \times \alpha)} \]  \hspace{1cm} (5)

In the above formulas,
\( \Delta T \) - The temperature;
\( F \) - The tension of reinforcement;
\( A \) - The reinforcement area;
\( E \) - The elastic modulus of reinforcement;
\( \alpha \) - The linear expansion coefficient.

Check the relevant norms and take \( F/A = 735 \), \( E = 2.0 \times 10^{11} \) and \( \alpha = 1.2 \times 10^{-5} \). The calculated result is \( \Delta T = 306^\circ C \), and here is \( \Delta T = 300^\circ C \).

4. FINITE ELEMENT MODEL OF THE CANGHE RIVER INVERTED SIPHON

The three-dimensional finite element model of the Canghe River inverted siphon was established based on ANSYS software, as shown in Figure 1. The element types used were Solid 65 and Link 8. Solid 65 is used to simulate concrete elements, and Link 8 is used to simulate reinforcement elements. The Solid 65 can be used for 3D solid models with or without reinforcement, which possesses the ability to crack and crush (Lu and Jiang, 2003). The element has eight nodes, and each node has three degrees of freedom which are X, Y, Z line displacement in three directions. The Link 8 unit is mainly used to simulate the ordinary steel and prestressed steel, where uses cooling method to apply prestressing. After defining the material properties, the control unit precision is 0.4. The total number of elements divided is 61460 and the total number of nodes is 64851. The orientations of the overall model are specified: Yokogawa side along the cross flow is the X axis, the height direction along the inverted siphon the Y axis, along the river side along the river the Z axis. In this model, the ordinary reinforcement adopts integral type model, and the prestressed reinforcement adopts separation type model.

Taking into account the influence of foundation soil on the structure, a certain amount of foundation soil is taken as the part of calculation model. According to Saint-Venant's Principle and empirical calculation, take 10m depth following the pipe, and take 10m around pipe, and take the same length with the pipe 10m foundation soil involved in the calculation before and after. The role of backfill part to the foundation will transform into a linear load distribution. The deformation of the structure and foundation are assumed to be within the linear elastic range. In order to simplify the calculation, the influence of the soil in situ and the backfill on both sides of the inverted siphon pipe in serviceability limit state are replaced by the external load.

5. THREE-DIMENSIONAL FINITE ELEMENT STATIC ANALYSIS

During the operation of the Canghe River inverted siphon, the following conditions are mainly considered: condition 1: prestressed steel structure without self-weight; condition 2: prestressed steel structure + weight; condition 3: structure weight + single-box half-water level; condition 4: structure weight + single-box
full-water level; condition 5: structure weight + double-box half-water level; condition 6: structure weight + double-box full-water level; condition 7: structure weight + three-box empty-water level; condition 8: structure weight + three-box half-water level; condition 9: structure weight + three-box full-water level. (The first two conditions and the latter seven conditions were compared)

![Figure 1. The bottom’s path L1 selected](image1)

![Figure 2. The prestressed steel](image2)

As the condition 9 is the typical operating condition, Figure 3-Figure 10 show the stress and strain distributions of the Canghe River inverted siphon under the nine conditions during the operating. The results are shown as following: the model of gradient load, the total displacement nephogram, X-direction displacement nephogram, Y-direction displacement nephogram, Z-direction displacement nephogram, the principal tensile stress pattern of oblique section along the path L1, the normal stress pattern of normal section along the path L1, the principal compressive stress pattern of oblique section along the path L1 are shown in Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10.

![Figure 3. The model of gradient load](image3)

![Figure 4. The total displacement nephogram](image4)

![Figure 5. The X-direction displacement nephogram](image5)

![Figure 6. The Y-direction displacement nephogram](image6)
After neglecting the local stress concentration, the static results of the inverted siphon structure under the self-weight+ three-box full-water level are analyzed as following: it can be seen from Figure 3 that the maximum displacement of the inverted siphon is 2.34mm, which mainly occurs inverted siphon’s three-box roof middle position; the overall minimum displacement of inverted siphon is 0.52mm, mainly in inverted siphon’s bottom corner position. It can be seen from Figure 4 that the maximum displacement in the X-direction is 0.69mm, mainly in the position of the inverted siphon wall; the minimum displacement is 0.08mm, mainly in the down-chamfer position of the inverted siphon wall. It can be seen from Figure 5 that the maximum displacement in the Y-direction is 2.34mm, which mainly occurs in the roof position of the inverted siphon box; the minimum displacement is 0.5mm, mainly in the corner position of the inverted siphon floor. It can be seen from Figure 6 that the maximum displacement in the Z-direction is 0.123mm, mainly in the position of the inverted siphon floor; the minimum displacement is 0.014mm, mainly in the position of the inverted siphon roof. Figure 7 shows the main tensile stress of concrete oblique section is about 0.79MPa, and Figure 10 shows the main compressive stress of oblique section is 5.45MPa. The results show that the stress of the inverted siphon structure is less than the designed value of concrete C30, and the deformation displacement is smaller, which satisfies the safety requirements of structural specification.

**Table 1.** The maximum displacement of inverted siphon tube in all directions

<table>
<thead>
<tr>
<th>The operating conditions</th>
<th>X, mm</th>
<th>Y, mm</th>
<th>Z, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1: Prestressed steel structure without weight</td>
<td>0.538</td>
<td>-2.8</td>
<td>0.09</td>
</tr>
<tr>
<td>Condition 2: Prestressed steel structure+ self-weight</td>
<td>0.543</td>
<td>1.0</td>
<td>0.08</td>
</tr>
<tr>
<td>Condition 3: Structure weight+ single-box half-water level</td>
<td>-0.90</td>
<td>1.86</td>
<td>0.12</td>
</tr>
</tbody>
</table>
### Table 1. The result of inverted siphon structure

<table>
<thead>
<tr>
<th>Condition</th>
<th>Operating conditions</th>
<th>Single-box full-water level</th>
<th>Half-box full-water level</th>
<th>Separated half-box full-water level</th>
<th>Separated half-box empty-water level</th>
<th>Separated half-box water level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1</td>
<td>Structure weight + single-box full-water level</td>
<td>-0.91</td>
<td>2.08</td>
<td>0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 2</td>
<td>Adjacent double-box full-water level</td>
<td>-0.91</td>
<td>2.2</td>
<td>0.123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 3</td>
<td>Separated double-box full-water level</td>
<td>0.90</td>
<td>2.1</td>
<td>0.124</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 4</td>
<td>Adjacent double-box full-water level</td>
<td>-0.91</td>
<td>2.3</td>
<td>0.123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 5</td>
<td>Separated double-box full-water level</td>
<td>0.71</td>
<td>2.1</td>
<td>0.123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 6</td>
<td>Adjacent double-box half-water level</td>
<td>-0.91</td>
<td>2.2</td>
<td>0.123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 7</td>
<td>Separated double-box half-water level</td>
<td>0.89</td>
<td>1.8</td>
<td>0.114</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 8</td>
<td>Structure weight + three-box empty-water level</td>
<td>0.88</td>
<td>2.3</td>
<td>0.124</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 9</td>
<td>Structure weight + three-box full-water level</td>
<td>0.69</td>
<td>2.34</td>
<td>0.123</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It can be concluded from Table 1 that the structural displacements are smaller in the X and Z directions, but larger in the Y-direction. The maximum value lies in the inverted siphon’s roof. The overall displacement of the structure is the maximum under the condition 9; under the same load combination, the overall displacement of the structure is mainly dominated by the self-weight, and the water load has a regulatory effect; the displacement increases with the water level, and reaches the maximum value under the condition 9.

### Table 2. The stress results of inverted siphon structure

<table>
<thead>
<tr>
<th>The operating conditions</th>
<th>The tensile stress, MPa</th>
<th>The position appeared</th>
<th>The compressive stress, MPa</th>
<th>The position appeared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1</td>
<td>1.02</td>
<td>Roof edge in the wall</td>
<td>-2.85</td>
<td>Bottom angle of bottom plate</td>
</tr>
<tr>
<td>Condition 2</td>
<td>0.74</td>
<td>The middle of the bottom plate</td>
<td>-3.45</td>
<td>Three holes in the upper plate</td>
</tr>
<tr>
<td>Condition 3</td>
<td>0.85</td>
<td>Side wall chamfering</td>
<td>-5.33</td>
<td>Edge hole in the bottom plate</td>
</tr>
<tr>
<td>Condition 4</td>
<td>0.81</td>
<td>Side wall chamfering</td>
<td>-6.79</td>
<td>Edge hole in the bottom plate</td>
</tr>
<tr>
<td>Condition 5</td>
<td>0.81</td>
<td>Side wall chamfering</td>
<td>-5.95</td>
<td>Double hole in the bottom plate</td>
</tr>
<tr>
<td>Condition 6</td>
<td>0.73</td>
<td>Side wall chamfering</td>
<td>-5.77</td>
<td>Double hole in the bottom plate</td>
</tr>
<tr>
<td>Condition 7</td>
<td>0.80</td>
<td>Edge of the wall chamfer</td>
<td>-6.88</td>
<td>Double hole in the bottom plate</td>
</tr>
<tr>
<td>Condition 8</td>
<td>0.77</td>
<td>Edge of the wall chamfer</td>
<td>-6.84</td>
<td>Double hole in the bottom plate</td>
</tr>
<tr>
<td>Condition 9</td>
<td>0.79</td>
<td>Side wall chamfering</td>
<td>-5.45</td>
<td>Bottom angle of bottom plate</td>
</tr>
</tbody>
</table>

It can be concluded from Table 1 that the compressive stress is larger in X, Y and Z direction; the tensile stress is smaller in the Z direction and larger in the X and Y directions; the compressive stress is greater than the tensile stress in X, Y and Z direction. According to the results of finite element analysis of the inverted siphon body, it can be seen that the most unfavorable condition for the body is the condition 7, because the inverted siphon pipe has no water and the external is filled with the dual function of the backfill and groundwater. The tensile stress of the structure reaches the maximum under the condition 7: the first principal tensile stress is the largest, and there is large tensile stress in the middle and lower part and the inner part of the side wall. However, the remaining conditions are due to pipe filled with water, offsetting the part of external load of the pipe, so that the structure of the first principal tensile stress has been reduced.

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6. SUMMARY

1. The stress and strain distributions of the Canghe River inverted siphon are in accord with the stress characteristics of ordinary inverted siphon, and the design of structure scheme is reasonable under the action of gravity and water load during operation. Under the full-water lever conditions of inverted siphon, the tensile stress and compressive stress are not too large, meeting the requirements of the standard crack checking. So the inverted siphon pipe will not produce cracks during the operation. The tensile stress is relatively large in X, Y and Z direction under three-box empty-water level, but basically don’t exceed the standard tensile strength of concrete by the standard crack checking.

2. The stresses of the seven working conditions are less than the design value of the concrete tensile strength, and the deformation displacement are small, which meet the structural design safety requirements without considering the local stress concentration. However, the inner surface, which is the boundary between the side wall of the inverted siphon and the foundation, and the middle of the borehole bottom plate, are prone to stress concentration in the actual project. And the local stress concentration can be controlled or weakened by some appropriate construction measures.

ACKNOWLEDGEMENTS

This work was supported by Basic and Advanced Technology Research Project of Henan Province (No. 152300410241), China, Science and Technology Project of Zhengzhou (No.131PPTGG410-13), and Science and Technology Project of Education Department of Henan Province (No. 17B130001).

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