Optimization analysis of giant spiral case with combined embedding method

Yongfeng Qi1*, Qin Chen1, Yaqi Gong1 and Zhiqiang Xie1

1 Department of Materials and Structures, Changjiang Scientific Research Institute, Wuhan, Hubei, 430010, China
2 China Research Center on Water Safety and Disaster Prevention of Ministry of Water Resources, Wuhan, Hubei, 430010, China
*Corresponding author’s e-mail: qiyf@mail.crsri.cn

Abstract: For selecting reasonable embedding method of the giant spiral case, contact nonlinear finite element analysis is used to obtain optimal range of cushion laying for the combination embedding method of direct embedding and cushion in Wudongde hydropower station, comparing concrete stress, non-uniform uplifting displacement of baseplates, the bearing ratio of concrete, etc. The optimization results show that the combination scheme with cushion laying to 270° section can meet the control standards of strength, stiffness and displacement for structure, which is the best embedding method for this hydropower station.

1. Introduction
At present, the spiral case are usually embedded directly, cushioned and filled with water and pressure. With the development of the large-scale spiral case of hydropower station, a new embedding type has been developed, that is, the combination embedding method of partial direct embedding and partial cushion[1]. The combined embedding type has the advantages of both direct embedding and cushion embedding, which can ensure the increase of overall stiffness and reduce the excessive load-bearing ratio and uneven uplift of concrete structure in the direct embedding method[2], which has great application prospect.

The spiral case of Wudongde hydropower station is huge, which belongs to giant spiral case. The diameter of inlet is 11.5m. The water pressure is high, the center elevation of the unit is 803m, the water hammer pressure is 2.46MPa at load rejection, and the HD value is 2820m². The combination type will be applied in Wudongde hydropower station, that is, the straight section of spiral case is adopted by embedding directly, and the other areas are adopted by cushion. In order to find the best combination of cushion and direct embedding, the reasonable laying range of cushion is very important.

Based on the engineering practice of Wudongde hydropower station, contact non-linear finite element analysis of spiral case and surrounding concrete structure with rock. Through the comparative analysis of stress characteristics, non-uniform uplifting displacement of baseplates and bearing ratio of concrete, a reasonable laying range for cushion is obtained, so that the bearing capacity of steel spiral case can be fully exerted and the purpose of safe operation for the powerhouse is satisfied, which can accumulate experience for the popularization and application of the combined embedding type of the giant spiral case.
2. Contact simulation of runner structure
The force transmission characteristics between steel spiral case and surrounding concrete are very complex. How to simulate reasonably the contact characteristics between steel spiral case and surrounding concrete has been one of the difficulties in finite element calculation for hydropower station, and the relative sliding friction between steel spiral case and surrounding concrete and cushion cannot be ignored.

The Stick-slip model based on a slightly modified step function can be used to simulate true stick-slip behavior between steel spiral case and surrounding concrete and cushion[3]. In this model, each node in contact gets a friction status, being either stick or slip. Depending on this status, different constraints are applied and after each iteration in the iterative solution process, the correctness of friction status is checked and if necessary adapted.

The typical parameters used (shown as Figure 1) are the friction coefficient multiplier \( \alpha \), the slip to stick transition region \( \beta \) and the friction force tolerance \( \varepsilon \). Where \( f_t \) is the tangential friction force, and \( f_n \) is the normal force, and \( \Delta u_n \) is tangential relative incremental displacement.

![Figure 1. Stick-slip Step Function Friction Model](image)

3. Computation condition

3.1 Computation model
Taking the standard unit section and surrounding rock as the research object, simulation range of the height direction is 785.625m to 823.2m, that is, from the bottom of draft tube to the generator layer. The typical section diagram of workshop and spiral case is shown in Figure 2.

The finite element calculation model is shown in Figure 3. There are 109 517 elements and 93736 nodes, of which 67969 are concrete elements. Concrete, stay ring and stay vane adopt 8-node hexahedron element. Spiral case and tongue plate adopt 4-node plate element, simulating according to actual thickness. The bedrock extends 70 m to upstream and downstream, whose top is simulated to 823.2 m.

![Figure 2. Typical section](image)

![Figure 3. Computation model](image)

3.2 Material parameters
Material parameters are shown in Table 1.
Table 1. Parameters of computation model

| Material     | Density (kN·m⁻³) | Elastic modulus (MPa) | Poisson ratio |
|--------------|------------------|-----------------------|---------------|
| Concrete     | 24.5             | 28000                 | 0.167         |
| Steel        | 78.5             | 210000                | 0.3           |
| Cushion      | 2                | 2                     | 0.01          |
| Bedrock      | -                | 11500                 | 0.27          |

The cushion is simulated by orthotropic model, only considering its normal stiffness[4]. The cushion layer is laid at the upper half circle to 1 m below the waist of outside spiral case. Generally, the thickness of cushion is 3 cm, and the thickness is 1 cm at the end. In order to ensure the insertion effect of the structure on the spiral case and the stay ring, no cushion is laid within 2.0 m from the turbine pit. The self-weight of bedrock is not considered, too.

3.3 Load of computation model
The control load case is load rejection including hammer pressure of water, and the loads are as follows: (1) self-weight of structure. (2) The internal water pressure of the spiral case is 2.46 MPa at 803 m of center elevation for the unit; (3) the unit load on the floor of the turbine is 0.02 MPa; (4) the unit load acts on the position of the baseplates, and the load on each stator foundation is 598 kN; the load on each lower bracket foundation is 1842 kN; There are 18 stator foundations and 16 lower bracket foundations in total. (5) the force transmitted from the top cover of the turbine to the annular plate on the stay ring is 1260 kN.

3.4 Computation scheme
According to the laying range of cushion along water direction, the computation scheme is as follows. (1) 135° cushion combination scheme: cushion laying along water direction to 45° section of spiral case. (2) 180° cushion combination scheme: the cushion is laid along the flow direction to 180° section of spiral case. (3) 280° cushion combination scheme: the cushion is laid along the flow direction to 180° section of spiral case.

4. Result analysis

4.1 Displacement of Spiral Case and surrounding Concrete
Under the action of water load, the concrete structure expands outward, and the vertical displacement of the concrete above the central elevation is upward. The displacement of spiral case is mainly radial displacement. In the area laying cushion, the expansion outward of spiral case is large, and the area without cushion is small.

The schematic diagram of 0° section deformation of scheme 1 for spiral case is shown in Fig.3. The maximum displacement of each scheme is shown in Table 2. The maximum displacement occurs at about 1.5m above the waist of spiral case (804.5m elevation), about 12.8mm to 13.8mm.

4.2 Uplift displacement of baseplates
Under water load, the foundation of the lower bracket produces uplift displacement. In order to ensure the safe operation of the unit, the relative uplift displacement of maximum diagonal for the lower bracket foundation should be controlled within a reasonable range. According to the engineering practice of three kinds of spiral case embedding methods adopted in Three Gorges Project, the relative uplift displacement standard of Wudongde Hydropower Station should be controlled by less than 1.2 mm.

The uplift of stator and lower bracket baseplates caused by water load (excluding the effect of self-weight) is shown in Figure 4 and Figure 5. The maximum displacement of uplift and relative uplift are shown in Table 2. The numbering of the baseplates starts from 0° section of spiral case and is sequentially numbered clockwise. Relative uplift is the relative uplift of the two ends of foundation.
slab at 180°.

![Graph showing uplift displacement of stator and lower bracket baseplates](image1)

Table 2. Maximum uplift and maximum relative uplift displacement of baseplates  
unit: mm

| Scheme | Stator baseplates | Lower bracket baseplates |
|--------|-------------------|--------------------------|
|        | absolute uplift   | relative uplift          | absolute uplift   | relative uplift          |
| 1      | 0.91              | 0.44                     | 1.05              | 0.54                     |
| 2      | 0.93              | 0.31                     | 1.08              | 0.40                     |
| 3      | 0.96              | 0.35                     | 1.14              | 0.45                     |

The absolute uplift displacement of lower bracket baseplates is larger than that of stator baseplates. The uplift displacement of baseplates is larger at the end of spiral case from 0°section to 90°section in scheme 1, while the uplift displacement of scheme 2 and scheme 3 is larger at the end of spiral case from 0°section and 180°section. The uplift displacement of the lower bracket baseplates of scheme 2 and 3 in the area without cushion is obviously larger than that of scheme 1.

Relative uplift displacement is the largest between 90°section and 270°section of spiral case, which all meets the control standard.

4.3 Stress of concrete

According to strength criterion of concrete, the possible location of cracks are preliminarily judged from the tensile stress or the average stress of the section. When the maximum principal stress of concrete reaches the tensile strength, it is considered that the concrete will crack. The standard value of the tensile strength of C25 concrete is taken as the criterion, which is 1.78MPa.

The maximum principal stresses of typical sections under different embedding scheme are listed in Table 3.

For the scheme 1, the overall tensile stress of concrete is not large, mostly less than the standard value of tensile strength of C25 concrete. The larger tensile stress mainly occurs in the 280°section to the end of the spiral case. In the section with cushion, the tensile stress of concrete is less than 1.78 MPa.

Compared with scheme 1, there is little difference in tensile stress in the area with cushion for scheme 2 and scheme 3. In the region without cushion, the tensile stress of concrete increases obviously, and the tensile stress exceeds the standard value of the tensile strength of concrete in most regions, which may cause penetrating cracks. For example, the stress at the top and waist of 180° section is greater than 2.0 MPa in scheme 2 and 3, and less than 1.0 MPa in scheme 1.

Table 3. Maximum principal stresses under different embedding scheme  
unit: MPa

| Scheme  | Position | Straight section | 135° section | 180° section | 270° section |
|---------|----------|------------------|--------------|--------------|--------------|
| scheme1 | Top      | 1.53             | 0.81         | 0.84         | 0.20         |
|         | Waist    | 1.58             | 0.50         | 0.77         | 1.41         |
4.4 The bearing ratio of concrete

Basing on the circumferential stress of typical section steel spiral case, The bearing ratio of concrete can be calculated according to the following formula [5].

\[
\eta = 1 - \frac{\delta \cdot \sigma_0}{r \cdot \rho}
\]  

(1)

Where \( \eta \) is percentage of water pressure borne by concrete to the total internal water pressure for design, referring to as load-bearing ratio, \( \sigma_0 \) is the circumferential stress of typical section steel spiral case, and \( \delta \) is the thickness of steel spiral case at typical section, and \( r \) is radius of steel volute at typical section, and \( \rho \) is internal water pressure of steel spiral case for design, which is 2.46 MPa.

For the scheme 1 in the area with cushion, the load-bearing ratio is 19%-25% at the top, 27%-35% at the waist, 36%-48% at the bottom, and 84%-92% in the area without cushion. But for Schemes 2 and 3 in the area with cushion, the bearing ratio of concrete is the same as scheme 1, and in the area without cushion, the bearing ratio of concrete is 84%-92%.

4.5 Stress of Steel Spiral Case

The equivalent stress of each scheme is less than the allowable stress of steel 203MPa. In the area with cushion, the steel spiral case bears more water load and greater stress. Over the waist, the tensile stress is generally 140 MPa to 195 MPa, but the bottom of the spiral case is not laid cushion, so the tensile stress is generally less than 140 MPa.

5. Conclusion

According to the structural control standard, the relative uplift displacement of baseplates and the stress of the spiral case can meet the control standard. However, tensile stress for the concrete of in the 180°section and 270°section without cushion is large and the penetrating cracks are easy to occur, which cannot meet the control standard.

It is recommended that the cushion be laid along the flow direction to the 280°section of the spiral case. Under these conditions, tensile stress of concrete is mostly less than the standard value of concrete tensile strength, only there is larger tensile stress in local region; the concrete bearing ratio in a reasonable range can effectively play the combined bearing role of steel liner reinforced concrete structure. The stress of steel spiral case and seat ring are less than the design strength.

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