Study on Working Behavior of Cage-type Flexible Retaining Wall

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Abstract. Cage-type flexible retaining wall is a new type of anti-seepage structure with broad market prospects due to its low cost and convenient installation. In order to study the working behavior of flexible cage-type retaining wall in flood control during the flood season, a three-dimensional finite element model of the structure was established, and the stress and deformation characteristics of the structure were analyzed. The results show that the maximum tensile stress is 17.1MPa, the maximum compressive stress is 12.6MPa, and the maximum structural deformation is 0.35mm, which are less than the allowable value, meaning the stress and deformation of the structure can meet the requirements of engineering construction. The reliability of the structure is verified by the full-scale model water retaining test. The vertical flow frame on the backwater side is a relatively weak part of the structure. When designing the structure, the cross-sectional dimensions of the vertical flow frame on the upstream side and the downstream flow frame can be reduced appropriately, while the cross-sectional dimensions of the vertical flow frame on the backwater side can be increased appropriately, so as to give better play to the material characteristics and save project cost.

1. Introduction
Removable flood wall has been widely used in flood control projects such as river dikes, port terminals, railway tunnel portals, highway culvert portals, civil air defense portals, etc. due to the advantages of fast installation and disassembly, easy stacking and collection, strong water pressure resistance and wide application range, etc.[1] According to the different rigidity of the flood wall, the removable flood wall can be divided into rigid and flexible ones. Rigid removable flood walls are widely used abroad. For example, removable aluminum alloy removable flood walls have been installed in the Czech Prague riverbank, Koln of Germany and Hungary, etc. Meanwhile, removable rigid flood walls are also used in China, such as the removable flood wall built above the designed water level of Wuhan Han River estuary shoreline[2]. However, the high cost of rigid removable flood wall has limited its scope of use.

Compared with the rigid retaining wall, the new type of cage-type flexible retaining wall not only has the characteristics of fast installation, removability and small storage space as that of removable retaining wall, but also has a filling cage-type structure (an open cage structure consisting of square steel and wire mesh) which can use geomembrane to prevent permeation in the interior and on the upstream face. Geomembrane has been used in domestic water conservancy projects ever since 1980s and 1990s[3,4]. After 30 years of development, it has become a kind of low-cost and high-quality anti-seepage material widely used in the hydraulic seepage projects[5,6,7]. A built-in water bag made of geomembrane is laid in the cage-type flexible retaining wall, and water, soil or sediment is filled according to the site conditions to enhance the structural stability. Its cost is 30% lower than that of the...
rigid removable retaining wall. During the installation, fixed foundations are not required to be pre-casted on the shore, which further reduces the cost.

Many scholars have carried out relevant researches on the working behavior of removable rigid flood wall. Duan Yajuan[8] performed the water retaining test of rigid flood wall. The test results show that the midspan of baffle has the largest deflection and it is the weak part of the structure, so it is necessary to strengthen the reinforcement. Zhaxi Zhuoma[2] studied the failure mechanism and deformation characteristics of the baffle and columns of the IBS removable flood wall and pointed out that ENAW-6063T6 aluminum alloy material should be used, and the maximum span of its structure should not exceed 3m. Guo Lei et al.[9] studied the leakage characteristics of removable flood wall, which shows that the structure will leak when the water head exceeds 0.8m; the leakage will accelerate when the water head exceeds 1.70m. And during the actual application, the leakage of wall body and the installation accuracy of embedded parts are not high, which will aggravate the leakage of the system. Wu Junjun et al.[1] studied the working behavior of removable flood wall through field flood control water filling test and numerical simulation, and pointed out that the rigid flood wall of light aluminum alloy column could ensure the safety of flood control when the water filling height was not more than 3m. Zhao Gengrun et al.[10] calculated the current situation and long-term overflowing risk of flood wall in Shanghai Section of Huangpu River by using the Monte Carlo method on account of the overtopping risk of the flood wall in Shanghai Section of Huangpu River. The results show that the flood wall during the flood season has an insufficient elevation, which brings great hidden danger to flood control safety in urban area. At present, the research on the working behavior of cage-type flexible retaining wall has not been reported in the literature. Cage-type flexible retaining wall has broad application prospects due to its convenient construction, low cost, safety and reliability, and systematic research on its working behavior is required.

In terms of the cage-type flexible retaining wall, a new type of flood control structure, this paper uses ABAQUS finite element analysis software to establish a three-dimensional solid model, and studies and optimizes the stress and deformation law of the water retaining wall under different water retaining conditions, so as to provide theoretical support for the application of the cage-type flexible retaining wall.

2. Structural Style
The main structure of cage-type flexible retaining wall is composed of steel frame and steel wire mesh. The frame structure element can be made up of $1m \times 1m \times 1m$ or $1.5m \times 1.5m \times 1.5m$ square elements, and the frame element can be spliced along the horizontal, longitudinal and vertical directions. According to the needs of different water retaining heights, it can be spliced into different structural styles. Fixed connections are made between different elements by bolt pins, allowing a certain degree of deformation. The whole structure shows flexible characteristics and strong resistance to deformation.

Figure. 1 is the structural style and calculation model of the cage-type flexible retaining wall. Figure. 1.a shows a cross frame, consisting of steel frame, steel wire mesh and connecting framework. The square steel frame is welded with Q235 square steel, while the spacing of steel wire mesh is of 10cm and the diameter of steel wire is of 6mm. Figure 1.b shows an anti-seepage system, including inner water bags and waterproof cloth which use the geomembrane, a widely used anti-seepage material. Compared with rigid water retaining wall using metal plate (steel plate, aluminum alloy plate, etc.), it has good impermeability, strong deformation resistance, good durability and low cost, so it is a kind of excellent impermeable material. Figure. 1.c is the computational model diagram of this study, with bottom two floors in a $1.5m$ frame structure and the top one in a $1.0m$ frame structure. The overall layout is staircase piles, and its interior is filled with gravel and water, etc.
3. Three-dimensional Finite Element Analysis of Cage-type Retaining Wall

A three-dimensional mesh cage-type flood wall model is established by using finite element analysis software ABAQUS. The size of the frame element of the flood wall is $1 \times 1 \times 1$ m, and the whole flood wall is composed of 7 frame elements. The connection between the frame girder and the beam is made by welding during the test. Therefore, the frame girders can be set as rigid connections in numerical simulation. In the actual structure, the steel wire mesh structure is small in size and large in quantity. Thus, the direct modeling will lead to too large number of meshes, long calculation time, and stress concentration due to inaccurate geometry of the model, which will affect the accuracy of calculation. As a result, the equivalent homogeneous model is adopted in this calculation, which is equivalent by volume to the homogeneous solid model rigidly connected to the main frame structure. The stratum is divided into two layers: the first is loam and the second is bedrock. The calculated length, width and depth of the model take 31m, 37m and 30m respectively, and the calculation model is shown in Figure 2.

There are four boundary types in the calculation model: known head boundary, seepage boundary, anti-seepage boundary and fixed constraint: 1) the known head boundary includes upstream of flood wall as well as the horizontal contact surface between the anti-seepage cloth and water; 2) the seepage boundary is the downstream of flood wall area; 3) the anti-seepage boundary includes the boundary at both sides of flood wall and bottom interception boundary of upstream foundation. The fixed constraint includes the bottom of mode and soil body at two sides. The total number of finite element mesh nodes is 42,883, and the total number of elements is 38,880.

Considering that the main load is from the structural dead weight, external water pressure and internal water pressure, the stress deformation of the structure under normal operation of water retaining are calculated and analyzed. The main calculation parameters are shown in Table 1. According to the water retaining test, it can be known that the flood wall is stable as a whole. Therefore, the whole flood wall is rigidly connected to the foundation in the calculation, with the water retaining height of the flood wall of 1.0m and the downstream water level of 0.0m. The main calculation results are shown in Figure. 3-5.
Table 1. Model Calculation Parameters

| Material          | Density (kg/m$^3$) | Permeability coefficient (m/s) | Void ratio | Modulus of elasticity (GPa) | Poisson ratio |
|-------------------|--------------------|--------------------------------|------------|-----------------------------|---------------|
| Square steel      | 7800               | $1.0 \times 10^{-7}$          | 0.2        | 206                         | 0.26          |
| Wire mesh + Geomembrane | 7800               | $1.0 \times 10^{-6}$          | 0.20       | 216                         | 0.25          |
| Strata 1          | 1800               | $1.0 \times 10^{-7}$          | 0.19       | 0.05                        | 0.3           |
| Strata 2          | 1850               | $1.0 \times 10^{-8}$          | 0.18       | 0.1                         | 0.23          |

Figure 2. Diagram of Calculation Model

Figure 3. Nephogram for the Large Principal Stress of Main Frame
Figure 3 is the diagram for the large principal stress of the main frame of the cage-type flood wall. Figure 3.a is the upstream large principal stress of frame perpendicular to the water flow direction, Figure 3.b is the large principal stress of frame at the water flow direction, and Figure 3.c is the downstream large principal stress of frame perpendicular to the water flow direction. In ABAQUS, the tensile stress is taken as the positive stress, so the large principal stress corresponds to the tensile stress. It can be seen from the diagram that the upstream maximum tensile stress of frame perpendicular to the water flow direction appears at the top of the frame intersection, and the maximum tensile stress is 15.9MPa; the maximum tensile stress of frame along the water flow direction appears at the top intersection of frame near the upstream side, and the maximum tensile stress is 3.0MPa; the downstream maximum tensile stress of frame perpendicular to the water flow direction appears at the bottom intersection of the frame, and the maximum tensile stress is 17.1MPa. According to the distribution range of tensile stress over 14MPa, the largest frame in the tension zone of the structure is the downstream vertical flow frame, and the concentration location of tensile stress is located at the junction between the cross beam and the column at the bottom of the frame. The maximum tensile stress of the downstream frame is larger than that of the upstream and down-flow sides, which is because the water pressure inside and outside the upstream face as well as the water pressure on the left and right sides of the frame at the down-flow side are balanced, so this equals to the fact that the frame at the upstream face suffers no pressure. The frame along the down-flow direction only suffers the bottom anchoring force and internal downstream water pressure, while the downstream frame has no balance with the external water pressure, so the tensile area has a large scope and the structural stress form is similar with that of cantilever beam. The maximum tensile stress of the whole frame is 17.1MPa, which is less than the permissible value 215[MPa] of Q235 steel. The tensile strength of the cage-type flexible flood control wall meets the requirements.

Figure 4 is the diagram for the small principal stress of the main frame of the cage-type flood wall. In ABAQUS, the tensile stress is taken as the positive stress, while the compressive stress is taken as the negative one, so the large principal stress corresponds to the tensile stress. It can be seen from the diagram that the upstream maximum compressive stress of frame perpendicular to the water flow direction appears at the bottom of frame intersection, and the maximum compressive stress is 1.9MPa; the maximum compressive stress of frame at the down-flow direction appears at the frame bottom close to the downstream column, and the maximum compressive stress is 12.5MPa; the downstream maximum compressive stress of frame perpendicular to the water flow direction appears at the bottom of frame column, and the maximum compressive stress is 12.6MPa. According to the distribution range of compressive stress over 10MPa, the largest frame in the structural compression zone is the downstream frame c perpendicular to the water flow and the column bottom of frame b along the water flow, and the concentration part of compressive stress is located at the junction between the bottom cross beam and column of frame. The maximum compressive stress of the whole frame is 12.6MPa, which is less than the allowable value of the tensile stress 215MPa of Q235 steel. The compressive strength of the cage-type flexible flood wall meets the requirements.
Figure. 5 Diagram for the Deformation of Main Frame

Figure. 5 is the diagram for the deformation of the main frame of the cage-type flood wall. It can be seen from the diagram that the upstream frame a perpendicular to the water flow basically has no deformation, frame b close to the downstream column at the water flow direction has a certain degree of deformation, with the largest deformation of 0.24mm which occurs in the middle of the column. The maximum deformation of the downstream frame c perpendicular to the water flow appears in the middle of the central cross beam, with the maximum deformation of 0.34mm, and there is a certain degree of deformation to the left and right columns. According to the distribution scope of frame with deformation exceeding 0.1mm, the areas with large structural deformation are downstream frame c perpendicular to water flow and the frame b along the water flow direction.

Considering the tensile stress, compressive stress and deformation of the upstream frame a perpendicular to the water flow, frame b along the water flow direction and downstream frame c perpendicular to the water flow, it can be known that the downstream frame c perpendicular to the water flow is the relatively weak part of the structure, while the stress deformation of the upstream frame a perpendicular to the water flow is relatively small. Therefore, when designing the structure, the cross-sectional dimensions of the vertical flow frame on the upstream side and the downstream flow frame can be reduced appropriately, while the cross-sectional dimensions of the vertical flow frame on the backwater side can be increased appropriately, so as to give better play to the material characteristics and save project cost.

Figure. 6 Diagram for the Deformation of Cage-type Flood Wall Wire mesh

Figure. 6 is the diagram for the deformation of the main frame of the cage-type flood wall. It can be seen from the diagram that the deformation of the mesh mainly concentrates in the downstream middle part, and the maximum deformation is 0.35mm. The deformation of the wire mesh in the middle of the model is larger than that on both sides, which is due to the fixed restraints on both sides of the model itself. The overall structure of the cage-type is equivalent to the beam with fixed restraints at both ends, and the middle part has the largest deformation under the effect of the evenly distributed water pressure. Considering that the geomembrane has 50%-100% ductility, it is certain that the geomembrane will not come up with tensile failure caused by the structural deformation under this deformation condition. The reason why the downstream displacement is larger than the upstream displacement is the same as that of
the large principal stress, and it is also because the upstream internal and external water pressure counteracts each other. It can be seen from the deformation of the main frame that the overall deformation of the structure is small, which can meet the requirements of water retaining and flood control.

4. Model Test of Structural Stability and Impermeability

In order to verify the structural stability and impermeability of the new cage-type retaining wall and make sure that it can be used for flood control during the flood season, a full-scale water retaining test of the cage-type retaining wall as the Figure 7 is carried out. A 25 × 10 × 3.0m river course is selected as the test site, and the bottom of the river is a natural river bed without any treatment. After clearing the reeds in the river course, the flexible flood wall is installed. The bottom of the upstream wall is excavated into a slot with the depth of 50cm and width of 20cm. One end of the geomembrane is embedded in the slot, and the other is hung on the top of the cage. Soil bags are used to build bank slopes on both sides of the cage. Geomembrane is used to cover the geomembrane and upstream of the bank slopes to ensure that water will not seep from the junction of the two banks. In this test, 23 frames are set up, the length and height of water retaining is 23m, and the time of water retaining is 30d. The wire mesh is made of 5 × 7.5mm galvanized low carbon iron wire, the waterproof canvas has an area of 1m² and thickness of 3mm, and the steel frame is made of 2 × 3 cm galvanized steel tube frame.

![Figure 7 Water Retaining Test of The Cage-Type Flexible Retaining Wall](image)

In the course of the river course test, it is found that there is sludge at the bottom of the river course. On the one hand, the sludge reduces the friction coefficient between the bottom of the flood wall and the foundation of the river course due to its soft texture and high fluidity, which leads to the decrease of sliding resistance. On the other hand, the sludge leads to the untight connection between the bottom of water retaining wall and the foundation of river course because of the large permeability coefficient of sludge. At this time, the water in the river course infiltrates into the bottom of the tank body, which increases the uplift pressure of foundation bottom and influences the overall stability of the structure. In order to eliminate the influence of sludge layer below the wall stability, the geotechnical sand bag with its thickness of 3-5cm is laid under the retaining wall. Such sand bags are used to compact the sludge soil.
by their dead load, so as to increase the friction coefficient between the foundation and the retaining wall, and prevent the excessive uplift pressure of the foundation caused by the lack of close connection. After 30 days of water retaining, there is no obvious seepage behind the wall, which shows that the overall structure has a good anti-seepage effect. The structure remains stable as a whole, and the net cage structure hardly produces deformation, which is consistent with the results of numerical simulation, so the structure can be used for flood control during the flood season. Geotechnical sand bags have good effect in treating sludge foundation and are convenient for construction. It is suggested to adopt geotechnical sand bags according to the actual situation of the project in order to increase the overall stability of the structure.

5. Conclusion
Cage-type flexible retaining wall is a new type of flood control equipment with broad market prospects due to its low cost and convenient installation. In order to study the actual working behavior of cage-type flexible retaining wall during the flood season, a full-scale structural stability and impermeability model test is carried out as well as a three-dimensional finite element structural analysis. The following main conclusions are obtained:

(1) Based on the ABAQUS software, a three-dimensional finite element model of cage-type flood wall is established, and the structural stress deformation analysis under water retaining condition is carried out. The results show that the structural stress and deformation can meet the requirements, the maximum tensile stress is 17.1MPa, the maximum compressive stress is 12.6MPa, and the maximum structural deformation is 0.35mm, which are less than the allowable value and can meet the requirements of engineering construction.

(2) According to the tensile stress, compressive stress and deformation of the frame in different parts, it can be seen that the downstream frame perpendicular to the water flow is the relatively weak part of the structure, while the upstream frame a perpendicular to the water flow has a relatively small stress deformation. In structural design, the cross-sectional dimensions of the upstream frame perpendicular to water flow and the frame at the water flow direction can be reduced appropriately, while the cross-sectional dimension of downstream frame perpendicular to the water flow can be increased appropriately in order to give full play to material characteristics and save project cost.

(3) After 30 days of water retaining, there is no obvious seepage behind the wall, which shows that the overall anti-seepage effect of the structure is good. The overall stability of the structure is maintained, and the net cage structure hardly produces deformation, which indicates that the structure can be used for flood control during the flood season. In practical engineering application, it is suggested that 3-5cm thick sand bags should be used to treat the foundation of the flood wall with sludge, so as to increase the overall stability of the structure.

6. Reference
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