FEM Analysis of Stress Characteristics of Cut-off Wall in Rushan River Groundwater Reservoir

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Abstract. In order to evaluate the safety of stress intensity of the plastic concrete cut-off wall in Rushan River underground reservoir, the most dangerous section of the cut-off wall was selected, the stress distribution characteristics of the cut-off wall were analyzed by ABAQUS finite element analysis method, the safety strength was rechecked, and the calculation results are compared with the stress calculation results of the elastic foundation beam method. The following conclusions are drawn. The calculation results of the two methods show that the water level difference between the two sides of the cut-off wall has a great influence on the stress of the cut-off wall. The maximum compressive stress of cut-off wall is less than 3 Mpa and the maximum tensile stress is less than 0.65 Mpa, which meets the design strength of plastic concrete cut-off wall. ABAQUS finite element analysis method is feasible in the stress analysis of cut-off wall. Compared with the results of elastic foundation beam method, the finite element method can better reflect the stress distribution and displacement deformation on both sides of cut-off wall. ABAQUS finite element analysis method has certain advantages in stress analysis of cut-off wall.

1. Introduction
Cut-off wall is a diaphragm wall built in loose permeable layer or earth-rock dam (weir) to prevent seepage [1]. At present, plastic concrete cut-off wall is mostly used in engineering construction, which can adapt to various complicated geological conditions, can be constructed under the condition of reservoir storage, and it has a high reliability in anti-seepage [2]. The concrete cut-off wall is affected by complex external forces such as soil stress, water pressure, reinforcement load, and strong constraint in foundation. The stress and strain value of the wall will change with depth, the forced state becomes particularly complex, which brings difficulties to the physical and mechanical design index selection of the cut-off wall, the selection of construction materials, the structural arrangement of special parts, and the safety evaluation of the wall. In order to simulate the complex stress condition of cut-off wall in soil, some scholars have studied it [3-7]. The material of cut-off wall is plastic concrete, which has lower elastic modulus, and it is more suitable for uneven stress and corresponding deformation. If the conventional concrete is used, the elastic modulus of it is high, and the phenomenon of large deformation and stress concentration will appear under the action of water pressure. The tensile stress may cause cracks in the wall, and then affect the seepage control effect [8]. When simulating the stress-strain...
characteristics of the cut-off wall, the friction between the cut-off wall and the surrounding soil should be taken into account to ensure the accuracy of the stress of the cut-off wall [9].

In this paper, the plastic concrete cut-off wall engineering of Rushan River underground reservoir is taken as the research object, the most dangerous section is selected as the stress analysis section. The ABAQUS finite element analysis method is used to simulate the stress state of the cut-off wall, and the results are compared with those of elastic foundation beam method. The design strength of the two stress calculation methods is rechecked, which shows that the tensile stress and compressive stress of the cut-off wall meet the design strength requirements. The simulation results of ABAQUS well reflect the stress distribution of the cut-off wall, which can provide a reference for the reinforcement of the reservoir.

2. Engineering situation
Rushan River Groundwater Reservoir Project is located in the middle and lower reaches of Rushan River in Rushan City, Shandong Province, with a total storage capacity of 21.97 million cubic meter. The project is divided into upper reservoir and lower reservoir. In this paper, the dangerous section of plastic concrete cut-off wall of lower reservoir is taken as the research object. The length of cut-off wall of lower reservoir is 5.996 km. The top elevation of cut-off wall is 2.0 m, the bottom of the wall enters weathered rock (the embedment depth in rock is 1.5 m), and the maximum height of cut-off wall is 23.0 m. The cut-off wall is made of plastic concrete, which is mixed by marine cement, aggregate also takes into account the seawater environment. The connection section between the cut-off wall and embankment building, and the section across the high voltage wire are connected by High-pressure fixed spray cut-off wall.

Design index of plastic concrete cut-off wall: The thickness is not less than 0.15 m, the permeability coefficient is not more than \(2 \times 10^{-6}\) cm/s, the compressive stress is not more than 3.0 MPa, and the tensile stress is not more than 0.65 MPa.

3. Construction of calculation model

3.1. Calculation model
According to the actual situation of plastic concrete cut-off wall in Rushan River groundwater reservoir, the section with the stake number of 5+400 is selected. The ground elevation of cut-off wall is 2.76 m, the top elevation of cut-off wall is 2.0 m and the bottom elevation of it is -20.24 m. The water level in the inside of reservoir is -7 m and that in the outside of reservoir is 2.0 m. The soil layers on both sides of the cut-off wall are simplified and analyzed, from top to bottom are: mucky soil, medium-fine sand and gravelly coarse sand. The thickness of cut-off wall is 0.4 m and the length of soil layers on both sides are 40 m respectively. This section is selected as the object of stress analysis, and the geometric model is shown in Fig. 1. The calculation model is divided into 2576 elements and 2759 nodes. The elements of type CPE4 is used in the cut-off wall and the elements of type CPE4P is used in the soil layer.

![Fig. 1 Calculation model of cut-off wall](image)
3.2. Constitutive model and calculation parameters

In this study, the Mohr-Coulomb model of ABAQUS was used in the soil layer. The stress invariant \( p \) and the Mises equivalent stress \( q \) mentioned in ABAQUS are used to represent the yield function, and the Mohr-Coulomb yield function can be expressed as:

\[
F = R_{mc}(\Theta, \varphi) = \sqrt{3} \cos \varphi \sin \left( \Theta + \frac{\pi}{3} \right) + \frac{1}{3} \cos \left( \Theta + \frac{\pi}{3} \right) \tan \varphi
\]

(1)

Where \( c \) is the cohesion of the material, \( \varphi \) is the friction angle of the material, and \( R_{mc} \) is the deviatoric stress function:

\[
R_{mc}(\Theta, \varphi) = \frac{1}{\sqrt{3} \cos \varphi} \sin \left( \Theta + \frac{\pi}{3} \right) + \frac{1}{3} \cos \left( \Theta + \frac{\pi}{3} \right) \tan \varphi
\]

(2)

Where \( \Theta \) is the polar angle, \( I_1 \) is the first invariant of the stress tensor, and \( r \) is the third deviatoric stress invariant \( J_3 \).

ABAQUS adopts non-correlated flow rule, the plastic potential function \( G \) adopts continuous and smooth elliptic function. The hardening and softening of the constitutive model can be achieved by setting the relationship between cohesion and equivalent plastic strain.

The material of cut-off wall is plastic concrete, which adopts the linear elastic model. Its stress-strain relationship conforms to the generalized Hooke's law, and its expression is as follows:

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\gamma_{12} \\
\gamma_{13} \\
\gamma_{23}
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{E} & -\mu/E & -\mu/E & 0 & 0 & 0 \\
-\mu/E & \frac{1}{E} & -\mu/E & 0 & 0 & 0 \\
-\mu/E & -\mu/E & \frac{1}{E} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G}
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{13} \\
\sigma_{23}
\end{bmatrix}
\]

(3)

Where \( E \) is the elastic modulus, and \( \mu \) is the poisson ratio.

The main calculation parameters of the model are shown in Table 1. The data units in the model are processed uniformly before ABAQUS calculation. The soil in the actual reservoir is not homogeneous. The stress analysis is simplified and the soil is divided into three layers (Fig. 1).

| Material                | \( \rho_0 \) (kg/m\(^3\)) | E (kpa) | \( V \) | K (cm/s) | C (kpa) | \( \varphi \) (°) | \( e \) | \( \mu \) |
|-------------------------|-----------------------------|---------|---------|----------|---------|------------------|-------|--------|
| Cut-off wall            | 2400                        | 1200000 | 0.20    | 0.000002 | -       | 18               | -     | 1.25   |
| Mucky soil              | 1330                        | 13360   | 0.30    | 0.0001   | 18      | 5                | 1.25  | 0.194  |
| Medium-fine sand        | 1620                        | 19290   | 0.28    | 0.001    | 0       | 29               | 0.67  | 0.194  |
| Gravelly coarse sand    | 1650                        | 12040   | 0.25    | 0.01     | 0       | 32               | 0.73  | 0.194  |

3.3. Geo-stress Balance

The initial geo-stress needs to be balanced before the load is applied. The ODB import method is used to simulate the initial geo-stress. This method can use the results of the ODB file of the initial geo-stress calculated before. When defining the initial geo-stress, select the ODB file directly.

4. Analysis and Discussion

4.1. Stress analysis of cut-off wall

ABAQUS is used to calculate the stress distribution on both sides of the cut-off wall under normal operation conditions, as shown in Fig. 2 and Fig. 3. In these figures, the compressive stress is positive and the tensile stress is negative.

As is shown in Fig. 2 and Fig. 3, the stress difference between the two sides of the wall is caused by the different groundwater levels in the soil, which makes the plastic concrete cut-off wall incline to right
side of cut-off wall. The left side of the cut-off wall has larger vertical stress and deformation at the elevation of -14.11~ -18.20 m, and the maximum vertical compressive stress reaches 0.651 Mpa at the elevation of -16.15 m, meanwhile, the maximum vertical tensile stress appears at the bottom of the wall, which is 0.409 Mpa. The right side of the cut-off wall has larger vertical compressive stress at elevation of -17.17~ -20.24 m. The maximum compressive stress is 1.583 Mpa at the bottom of the wall, which has a great influence on the stress of the wall, meanwhile, the minimum vertical compressive stress appears at elevation 1 m, which is 0.020 Mpa (Fig. 2).

As is shown in Fig. 3, the maximum transverse compressive stress on the right side of the cut-off wall is 0.31 Mpa at elevation -17.15 m, while it on the left side of the cut-off wall is 0.54 Mpa at elevation -19.22 m, and the value of compressive stress at elevation -20.24 m is slightly reduced to 0.42 Mpa. There is no transverse tensile stress on the left side of the cut-off wall. Because there is no effect of consolidation settlement of soil on the stress of wall, under the action of horizontal load, the plastic concrete wall is in the state of bending and tension caused by horizontal thrust. The cut-off wall bends to the right side (Fig. 4), the deformation of the lower part of the cut-off wall is large, and the stress concentration occurs at the bottom of the wall (Fig. 5).
4.2. Verification

In order to further verify the reliability of the finite element calculation results, the elastic foundation beam method is used for comparative analysis in combination with the Rushan River groundwater reservoir project. The elastic foundation beam method uses the principle of trans-variable structural moment and side force primary distribution method to calculate the stress deformation of plastic concrete cut-off wall. The unit width of the cut-off wall is taken as the calculating diagram, and its cross-section changes along the height. The top of the wall is regarded as the free end and the bottom as articulated. It is assumed that the foundation coefficient varies linearly with depth and varies with different soil layers. The calculation diagram is shown in Fig. 6.

The cutoff wall divides soil layer into five layers according to different media, such as sandy clay layer, fine sand layer, medium sand layer and sandy gravel layer, etc. Because of the interaction of upstream and downstream water pressure, the upstream triangle load \( P_1 \) is 20 \( t/m^2 \), and the downstream triangle load \( P_2 \) is 9 \( t/m^2 \). In the structural calculation, the cut-off wall subjected to upstream and downstream loads is analyzed sequentially, and the internal force distribution of each section is finally obtained. When calculating the structure, the cut-off wall which subjected to upstream and downstream loads is analyzed sequentially, and the stress distribution of each section is finally obtained.

![Fig. 6 The calculation diagram of elastic foundation beam method](image1)

![Fig. 7 Vertical stress distribution of the cut-off wall](image2)

The stress calculation results of elastic foundation beam method are shown in Fig. 7. The results show that the stress is concentrated at the water level line on the right side of the cut-off wall. The maximum tensile stress on the left side of the cut-off wall occurs at the elevation -9.44 m, with a value of 0.622 MPa, and the maximum compressive stress on the right side of the cut-off wall occurs at the elevation -9.44 m, with a value of 1.281 MPa.

4.3. Comparative analysis

The error of the results obtained by the two methods is small, which shows that the two methods are consistent on the whole. In addition, the ABAQUS finite element analysis method is used to set fixed constraints at the contact area between plastic concrete cut-off wall and bedrock, the whole force and deformation of the cut-off wall make the bending moment of the lower and middle parts of the cut-off wall larger, and the direction of the bending moment changes, which indicates that the cut-off wall bears the horizontal load from the middle and lower parts to the right side of the wall. The vertical stress of the cut-off wall increases gradually along the depth of the wall, and produces the maximum tensile stress and compressive stress at the bottom of the wall. Therefore, the deformation near the bottom of the wall is large and the stress changes obviously.
The elastic foundation beam method is used to calculate the stress of the cut-off wall. The results show that the stress of the cut-off wall varies greatly at the water level line on the right side of the cut-off wall. Different water levels on both sides of the cut-off wall lead to different stresses. There is a large vertical tensile stress on the left side of the wall, and a large vertical compressive stress on the right side of the wall. At the elevation -9.44 m, maximum tensile stress and maximum compressive stress are generated on both sides of the cut-off wall, and a smaller vertical compressive stress occurs at the bottom of the cut-off wall.

The ABAQUS results show that the maximum compressive stress occurs at the bottom of the right side of the wall, which is 1.583 Mpa, and the maximum tensile stress occurs at the bottom of the left side of the wall, which is 0.409 Mpa. The elastic foundation beam method calculates the maximum tensile stress of the cut-off wall on the left side of the wall, which is 0.622 MPa, and the maximum compressive stress on the right side of the wall with a same elevation, with a value of 1.281 MPa. The maximum compressive stress of the plastic concrete cut-off wall of Rushan River groundwater reservoir is 1.583 Mpa, which is less than the design compressive strength of the plastic concrete of 3.00 Mpa (28d age); the maximum tensile stress of the cut-off wall is 0.622 Mpa, which is less than the design tensile strength of the plastic concrete of 0.65 Mpa. Therefore, the tension and compression stresses of the cut-off wall meet the design strength requirements.

5. Conclusion
The conclusions are based on the analysis mentioned above.

(1) The results show that the water level difference between the two sides of the cut-off wall has a great influence on the stress distribution. The cut-off wall inclines to the side of low water level, and the stress varies greatly at the water level line on the right side of the cut-off wall. The large vertical compressive stress occurs at the bottom of the right side of the wall, and a small vertical tensile stress occurs at the bottom of the left side of the cut-off wall.

(2) The elastic foundation beam method shows that the maximum tensile stress appears on the left side of the wall at the elevation of -9.44m, with the value of 0.622 MPa and the maximum compressive stress appears on the right side of the wall at the elevation of -9.44m, with the value of 1.281 MPa. Compared with elastic foundation beam method, ABAQUS finite element method has certain advantages. It can better show the stress distribution and displacement deformation on both sides of the cut-off wall. The calculated maximum compressive stress occurs at the bottom of the left side of the cut-off wall, which is 1.583 Mpa, and the minimum tensile stress occurs at the bottom of the right side of the wall, which is 0.409 Mpa.

(3) Both calculation methods show that the stress of plastic concrete cut-off wall meets the design strength requirements of maximum compressive stress less than 3 Mpa and maximum tensile stress less than 0.65 Mpa during the operation of groundwater reservoir, which indicates that the design strength of cut-off wall meets the stress calculation requirements.

Acknowledgments
This work was financially supported by the Shandong Provincial Natural Science Foundation, China (ZR2019MEE106).

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