Analysis of floating effect of groundwater on built underground structure

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Abstract. With the continuous transformation of cities in China, urban land resources are becoming increasingly tense and traffic is becoming increasingly crowded. By building underground buildings such as subways, underground passages and underground shopping malls, we can not only make up for the shortage of existing space, but also rationally plan the urban layout. Therefore, it has become the first choice of urban construction in China. With the diversification of layout forms, the underground structure is increasingly developed in the depth direction, which highlights the anti-floating problem of underground structure. At present, the anti-floating design and construction of underground structures are not clearly defined by regulations in China, only the description of water buoyancy and requirements. In the actual underground structure engineering, the floating problem of underground structure is not uncommon. Therefore, how to design anti-floating measures is studied to ensure the reasonable application of anti-floating measures in the construction process.

Keywords: Groundwater, Underground structure, Flotation analysis

1. Research status of anti-floating design
The current code for checking the anti-floating of building foundation uses hydrostatic pressure \( P = \gamma h \) to calculate the groundwater pressure of basement and basement exterior wall. In which, \( p \) represents the calculated water pressure, \( \gamma \) represents the water weight, and \( h \) represents the depth of a certain calculated point to the water surface. \( P = \gamma H = \gamma (h, h_0) \) used to calculate the base anti-floating.[1-3] Among them, the water pressure at the base calculation point is expressed by \( P \), and the design head value of groundwater anti-floating is expressed by \( H \). In geotechnical engineering investigation report, the highest groundwater static water level elevation is expressed by \( h \), which can also be used to describe the building fortification water level elevation. Elevation of base calculation point is expressed by \( h_0 \). According to the measured data, the water pressure value usually obtained by the above formula is not equal to the actual water pressure value of the underground structure. Therefore, in the vertical direction, this formula cannot be used to calculate the groundwater pressure. As the depth increases, it increases linearly and is smaller than this value. Measures to deal with permanent anti-floating of underground structures are divided into counterweight method, anti-floating pile, anti-floating anchor rod and so on.[4-6]
2. Anti-floating calculation
When calculating the weight of the structural part, for example, the floor is calculated according to the whole floor area, and the hidden beam of the floor is calculated again, which results in repeated calculation. In view of the subsequent simulation calculation, the established non-solid model cannot be considered for repeated calculation, so the anti-floating calculation here is carried out according to the actual situation, and the repeated part is not considered during subsequent simulation calculation. The repeated calculated structural weight is shown in Table 1 below.

| Duplicate project name                  | Symbolic representation | Repeated weight (kN) |
|-----------------------------------------|-------------------------|---------------------|
| The pillars of 300 x 300 mm             | G29                     | 4.95                |
| The pillars of 400 x 400 mm             | G30                     | 8.80                |
| The pillars of 500 x 500 mm             | G31                     | 1646.56             |
| The pillars of 600 x 600 mm             | G32                     | 598.95              |
| Dl-1 reverse beam                       | G33                     | 936.87              |
| Dl-2 reverse beam                       | G34                     | 243.00              |
| Dl-3 reverse beam                       | G35                     | 19907.42            |
| Dl-4 reverse beam                       | G36                     | 11159.78            |
| Negative second floor dark beam         | G37                     | 25083.11            |
| Dark beams around the negative first floor | G38                 | 31114.66            |
| Dark beams on the roof of the hall      | G39                     | 45893.11            |
| Fine spacer wall                        | G40                     | 9347.98             |
| **Total**                               |                         | **145945.17**       |

When the overall anti-floating design of underground structure is completed and not used, the permanent load includes the weight of structure and the weight of backfill soil. Among them, G29 to G40 represent the weight of the repeated calculation structure. Therefore, Gs1 represents the total anti-floating weight of the structure, i.e.

\[ G_{s1} = \sum_{i=1}^{25} G_i - \sum_{i=29}^{40} G_i = 1536295.46 \text{kN} \]

The nominal height of the roof of the underground structure is 147.1m, and the thickness of the soil covered on the roof is 900mm. (1) according to the geological prospecting stable water level value of 146.27m in 2001, the calculated water level is as follows. F1 represents the supporting force of groundwater floating, so the calculation formula is as follows:

\[ F_1 = 1000 \times 9.8 \times (7.6 - (147.1 - 146.27)) \times (13600.3 + 12662.1) = 66346 \text{N/m} \times 26262.4 \text{m} \]
\[ = 1742405.19 \text{kN} \]

According to G > 1.05F formula for checking calculation

\[ G_{s1} = 1536295.46 \text{kN} < F_1 = 1.05 \times 1742405.19 = 1829525.45 \text{kN} \]

The buoyancy resistance is 293229.99 kN short.

(2) Calculate the water level according to the most unfavorable zero water level method. F2 represents the supporting force of groundwater floating, so the calculation formula is as follows:
The buoyancy resistance is short of $1.05 \times F_2 - Gs_1 = 760745.356 \text{ kN}$.

It can be seen from the above-mentioned checking calculation of overall anti-floating of the structure that the overall anti-floating calculated by the two methods is insufficient. Among them, the overall buoyancy calculated by the first method is still short of 293229.99 kN, with a deficiency rate of 17.03%. It shows that the whole anti-floating of underground structure, local anti-floating around and local anti-buoyancy of hall are not enough. There is a gap between the local buoyancy resistance of the hall and the local buoyancy resistance around it, resulting in insufficient permeability of the basement soil. When the groundwater level rises to a certain extent, the accident rate of anti-floating failure increases. In addition, the raft of the underground structure is cantilevered around and the soil is weighed. Therefore, the phenomena of floating up and raft reverse arch deformation will not occur.[7-10]

If the structural anti-floating failure accident occurs when the main structure is completed and unused, the problem should be attributed to the construction. To sum up, the potential causes and direct causes are: insufficient buoyancy resistance of underground structure design and failure to carry out detailed construction according to regulations.

3. Establishment of underground structure model and initial state analysis

Using MIDAS/GTS, the complex geometric model is visually and intuitively modeled. In GTS, the simplest geotechnical model is a linear elastic model in which stress is proportional to strain. The relationship between stress and strain is as follows:

$$
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{xy} \\
\tau_{xz} \\
\tau_{yz}
\end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix}
1-\nu & \nu & \nu \\
\nu & 1-\nu & \nu \\
\nu & \nu & 1-\nu
\end{bmatrix} \begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{xy} \\
\gamma_{xz} \\
\gamma_{yz}
\end{bmatrix}
$$

\(\tau_{yz} = \tau_{zx} = \gamma_{yz} = \gamma_{zx} = 0\) in 2d analysis, \(\varepsilon_z = 0\) in plane strain analysis.

Fig. 1 Elastic-complete plastic constitutive relation
The elastic-plastic model of GTS simulates the constitutive relation of elasticity and complete plasticity, and its typical stress-strain curve is shown in Figure 1. Before reaching the yield point, the stress is in direct proportion to the stress, and when the yield point is exceeded, the stress-strain relationship is horizontal.

Yield criterion: the elastic-plastic material models in MIDAS/GTS are Mohr-Coulomb, Tresca, von Mises, Drucker-Prager, Hawke-Brown Hoek-Brown models. The following mainly introduces Mohr-Coulomb criterion. According to Moore's (1900) criterion, failure is expressed by the following formula:

\[ |\tau| = f(\sigma) \]

The simplest Mohr failure envelope is a straight line, and the envelope equation of the straight line is:

\[ |\tau| = c + \sigma \tan \phi \]

Mohr-Coulomb is expressed by principal stress \( \sigma(\sigma_1 \geq \sigma_2 \geq \sigma_3) \), which can be obtained

\[ \frac{\sigma_1 (1 - \sin \phi)}{2c \cos \phi} - \frac{\sigma_3 (1 + \sin \phi)}{2c \cos \phi} = 1 \]

The stress invariants \( I_1, J_2 \) and \( \theta \) are expressed as follows:

\[
\begin{align*}
 f(I_1, J_2, \theta_0) &= -\frac{1}{3} I_1 \sin \phi + \sqrt{J_2} \sin \left( \theta_0 + \frac{\pi}{3} \right) - \frac{1}{\sqrt{3}} \sqrt{J_2} \cos \left( \theta_0 + \frac{\pi}{3} \right) \sin \phi - c \cos \phi \\
 &= -I_1 \sin \phi + \left[ \frac{3(1 + \sin \phi) \sin \theta_0 + \sqrt{3}(3 - \sin \phi) \cos \theta_0}{2} \right] \sqrt{J_2} - 3c \cos \phi \\
 &= 0
\end{align*}
\]

Commonly used formulas expressed by \( I_1, J_2 \) and \( \theta \) are:

\[
\begin{align*}
 f(I_1, J_2, \theta) &= -\frac{1}{3} I_1 \sin \phi + \sqrt{J_2} \left( \cos \theta + \frac{1}{\sqrt{3}} \sin \theta \sin \phi \right) - c \cos \phi \\
 &= \sqrt{J_2} - \frac{1}{3} I_1 \sin \phi + c \cos \phi_0 \\
 &= \frac{\cos \theta + \frac{1}{\sqrt{3}} \sin \theta \sin \phi}{\cos \theta_0 + \frac{1}{\sqrt{3}} \sin \theta_0 \sin \phi} \\
 &= 0
\end{align*}
\]

In Mohr-Coulomb criterion, the principal stress space is an irregular hexagonal cone, the meridian is a straight line, and the yield curve is an irregular hexagon on \( \pi \) plane \((\sigma_1 + \sigma_2 + \sigma_3) = 0\). Use the values of \( \rho_0 \) and \( \rho c_0 \) to draw the irregular hexagonal cone, and substitute \((\xi = 0, \rho = \rho c_0, \theta \alpha = 60)\), \((\xi = 0, \rho = \rho c_0, \theta \alpha = 60)\) into the following formula:

\[ \frac{\sigma_1 - \sigma_3}{2} = \frac{1}{\sqrt{3}} \sqrt{J_2} \left[ \cos \theta_0 - \cos \left( \theta_0 + \frac{2}{3} \pi \right) \right] \]

In Mohr-Coulomb failure plane, the geometric shapes of yield curves are similar in \( \pi \) plane. Therefore, the value of \( \rho/\rho c \) in any \( \pi \) plane (i.e. \( I_1 \) or different \( \xi \)) is constant.

Compare the maximum bending moment and bending bearing capacity of raft and foundation reverse beam of underground structure under its own weight, as shown in Table 2.
Table 2 Maximum bending moment of each part of raft and beam under dead weight

| Name                     | Maximum bending moment value (kN · m) | Limit of maximum bending moment (kN · m) | Whether meet the requirement |
|--------------------------|--------------------------------------|----------------------------------------|-----------------------------|
| Side raft (per meter)    | 46.28                                | 1625.24                                | YES                         |
| Hall raft (per meter)    | 120.58                               | 610.26                                 | YES                         |
| Di-1 reverse beam        | 829.67                               | 4360.83                                | YES                         |
| Di-2 reverse beam        | 505.2                                | 2681.97                                | YES                         |
| Di-3 reverse beam        | 543.52                               | 2681.97                                | YES                         |
| Di-4 reverse beam        | 1725.92                              | 8818.97                                | YES                         |

From the above calculation, it can be seen that the flexural bearing capacity of the raft in the hall, the surrounding raft and the reverse beam of the foundation can meet the requirements under the action of the dead weight of the structure and the soil above it, and the original design can meet the requirements for the design of the structure under normal working conditions.

Because of the large plane size of underground structure, the underground structure is extremely complex. The underground structure is surrounded by a two-story underground structure and a one-story underground structure in the middle. The rigidity and dead weight of the two parts are different, resulting in irregular layout of the underground structure. The shear wall of underground structure can strengthen the rigidity of the whole structure and make the displacement and bending moment of underground structure change greatly.

4. Conclusion

The fundamental reason for the failure of anti-floating of underground structure is that the buoyancy of water acting on the bottom plate of underground structure is greater than the load weight of the upper part of the structure. The floating of underground structures may be caused by design errors, construction paralysis and unexpected weather. After preliminary analysis, the main reasons for the failure of anti-floating of the underground structure studied in this topic are the insufficient anti-floating design of the underground structure, the illegal operation of the construction party and the sudden rise of the underground water level caused by unexpected weather.

With the continuous development of underground space, a large number of underground commercial streets and commercial squares have emerged. In order to ensure the stable construction and use of these buildings, it is necessary to focus on anti-floating design research. Therefore, it is necessary to establish relevant anti-floating design operation specifications and formulate design standards for anti-floating measures. Constantly improve anti-floating design specifications, formulate targeted anti-floating design requirements, and ensure reasonable and effective implementation of anti-floating measures during construction.

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