Application of Bondwater Dynamics in prediction of Reservoir immersion problems in karst basin area

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Abstract: Since ground water supplies the basin margin area laterally in karst basin area, there is a certain confined head in the basin area. Generally, there’s a thicker layer of secondary red clay in the upper part of the basin. It belongs to the high liquid limit clay which has very low permeability. The bedrock is mainly dolostone, the upper of which exists discontinuous weathered sand. The weathered sand is a layer of strong permeability. And the lower bedrock has weak permeability. This paper takes the calculation of immersion problem in the protected zone of Changshou Ditch of Daton Gorge water control project’s reservoir area as target, and studies deeply about the characteristics of bondwater dynamics in cohesive soil in state of confined head. On the foundation of conventional Kaminski formula, we revise the formula based on the effect of bondwater dynamics. The predictions are more close to the actual working condition. And we provide measures to deal with this situation; it has referential meaning for similar projects.

1. Introduction
Predicting the reservoir immersion problems is one of the key points of the evaluation of survey which plays a key role in feasibility argumentation of the reservoir. It also concerns whether there would be environmental and geological hazard problems after the reservoir impoundment. On the foundation of the prediction method about dual structure provided by Geological Manual of Water Conservancy and Hydropower Engineering, this paper makes an immersion prediction for the basin protected zone of the reservoir by taking the characteristics of bondwater dynamics into consideration. Specifically, we can get a factual banked-up water level by revising the banked-up water level which we calculate with the conventional method. And then we can predict the immersion area. This paper also provides improved measures to deal with the immersion problems after the reservoir impoundment. Thus, we can optimize the governance cost eventually.

2. Project Overview[1]
Protected zone of Changshou Ditch of Daton Gorge water control project is in the middle part of the Wu Xuan basin. The plain of the left bank of QianJiang River is relatively flat. The plain comes from the residual peak, mound and most of the plain is occupied by sugar cane fields and paddy fields. The ground elevation is 59~65m. The low land almost in the middle of the plain. There are mainly twisty river ditches and fish ponds and the ground elevation is 55~58m. The elevation of
Changshou Ditch’s outlet is about 50m. The overburden of the protected zone is mainly residual red clay which is usually 7.8m~14.8m thick. Its clay content is 50%~80%. Its plasticity index is 30~40, and its liquid limit is between 50% and 90%. The average permeability coefficient, which is getting from the field water injection test, is $7.06 \times 10^{-5}$ cm/s. The average permeability coefficient, which is getting from the indoor test, is $5.27 \times 10^{-6}$ cm/s. Thus it belongs to the high liquid limit clay which has very low permeability. The bedrock is mainly Carboniferous dolostone of Tai Po group. The rock surface rolls, swells and its roof elevation is 54.2m~43.4m. The upper part of the bedrock is relatively fractured and it has medium permeability according to the results of packer permeability test. The lower bedrock is relatively complete and it has weak permeability that the average value is 2.19. However, local karst caves with strong permeability have been found. Karst is very developed in this area. RQD of the upper part of the bedrock is basically 0. And there’s always a layer of weathered sand upon the bedrock. It’s 0.9m~2.5m thick and local thickness reaches 7.6m. According to the drilling data of packer permeability test in reservoir area, the permeability coefficient is $K=6\times10^{-3}$ cm/s which is combined the fractured upper part of bedrock with the weathered sand. The normal water level elevation of the reservoir is 61m which is much higher than the discharge outlet’s elevation of ground water (30m~50m). The ground water’s elevation of QianJiang River in low water period is 34m~36m. The ground water level is below the bedrock’s roof in the front and middle of WuXuan basin. And the ground water level gradually exceeds the bedrock’s roof in the back of WuXuan basin. Part of the ground water is in pressure state. In the protected zone of Changshou Ditch, the confined head is relatively high and most of the drill holes found that the confined head level is above the roof of the aquifer. The ground water is mainly perched water and karst fissure water. The hydraulic slope is gentle, which is generally 3%~6%. And it discharges towards QianJiang River.

3. Theory of immersion prediction

The stratum of protected zone is a typical dual structure. The aquifer consists of rock’s two layers with different permeability properties. The aquiclude is the lower bedrock which is moderate weathered. We use the Kaminsky formula (Fig 1) to calculate the value of the ground water level backflow in this kind of stratum structure[2-3]:

$$K_1 M (h - h_1) + \frac{1}{2} K_2 (h - h_1) = K_1 M (y - y_1) + \frac{1}{2} K_2 (y^2 - y_1^2)$$

In the equation: $K_1$—permeability coefficient of the lower aquifer, m/d; $K_2$—permeability coefficient of the upper aquifer, m/d; $y$—reservoir water level, m; $y_1$—the banked-up water level of section1, m; $M$—thickness of the lower aquifer, m; $h$—original water level, m; $h_1$—original ground water level of section1, m.

![Fig. 1. A schematic of the kaminsky formula](image-url)
According to the formula, since $K_1$ (permeability coefficient of the lower permeable stratum) is 2 to 3 orders of magnitude larger than $K_2$ (permeability coefficient of the upper clay layer), then $K_2 \approx 0$, and we can simplify the formula to the following forms:

$$h - h_1 = y - y_1 \quad \text{or} \quad y_1 - h_1 = y - h$$

(1)

The above formula shows: Regardless of the bondwater’s effect of the upper soil layer, and the ground water rises synchronized as much as the reservoir water after the reservoir impoundment.

Since karst is developed in upper bedrock, the rock mass is fractured and a layer of weathered sand on the upper part. Its permeability is much larger than the overlying clay. If the actual ground water level in the clay layer under the pressure head of the aquifer, then a large percentage of the protected zone of Changshou Ditch is submerged. Thus, the key to the immersion evaluation is that, whether the actual ground water level of the clay layer is equal to the pressure head. Starting from the basic principle of bondwater dynamics [4], Professor Zhang Zhongyin illustrates that the ground water level of the clay layer under water pressure is unequal to the pressure head, but lower than the pressure head of the aquifer. The relationship of the water-bearing zone’s thickness $T$ in the clay layer and the pressure head $H_0$ is as follows:

$$T = \frac{H_0}{I_0 + 1} \quad (2)$$

If $I_0$ is known, we can use expression (2) to calculate the head of the return water and reduce the value of banked-up water level calculated by the expression (1). The top elevation of the zone of saturation is the actual value of the banked-up water level (pressure head) in the clay layer after the reservoir impoundment [5].

The calculation formula of the measuring point’s lifting height of the water head $H_y$ is:

$$H_y = \frac{H}{I_0 + 1} \quad (3)$$

In the equation: $I_0$—initial hydraulic slope;

In the formula, $H$ is the pressure head when the measuring point’s water level has lifted after the reservoir impoundment.

When the rising height $H_y$ of the measuring point’ water head is calculated, we can get the immersion range by adding the threshold value of the ground water level to it.

### 4. Immersion prediction of Changshou protected zone

Field observations indicate that the water level of clay layer is lower than pressure head, for example, in borehole CZK17 and CZK19, we measured the thickness of saturated clay separately. The results are 1.90m and 4.70m respectively. After drilling through the clay layer, the steady water level in the hole (the pressure head) rises to 3.30 m and 7.70 m, respectively above the roof of the aquifer. Combined with the local practical experience and the immersion evaluation, the critical and benchmark value of ground water depth is determined to be 1.5m.

During the survey, the water level of the QianJiang River is 41m. The elevation of the bedrock of QianJiang River and the protected zone is about 47m. Therefore, when the water level of the reservoir is raised to 47m and the bedrock is submerged, it will produce the artesian water and lift the ground water level of the protected zone. The initial calculated elevation of water level is 47m. When the reservoir water level is lower than 47m, the ground water level—$h$ is considered to be 0. We can calculate the ground water level’s lifting value of each section’s measuring points. Then we can use the formula (2) and formula (3) of bondwater dynamics to get the value of the rising height of the measuring point’ water head. And add it to the critical and threshold value of ground water depth; we can finally get the thickness and the roof elevation of the aquifer in protected zone after the reservoir impoundment.

In the investigation and exploration about immersion problems (see table 1), we use the data from drilling CZK17#–CZK27#. Since the $I_0$ is constant in the same lithology, when we calculate the elevation of the roof of the aquifer, there’re 2 cases as followed. In general, the gullies, marsh lands, paddy fields, and local swamps are below the 57m elevation. This area is basically saturated all year round. The water in the clay is mainly gravity water and has less bondwater, such as borehole CZK18,CZK20 and CZK25. So we take 0.05 as the value of the initial hydraulic slope $I_0$. In the other
case, the zone of saturation is deeper when the ground is above the 57m elevation. The water in the clay is mainly bondwater, such as borehole CZK17, CZK19 and CZK26. So we take 0.49 as the value of the initial hydraulic slope \( I_0 \). The karst in the bedrock of CZK21, CZK22, CZK23 and CZK27 is strong developed, and the complete bedrock is in a deeper depth. In addition, there is no phenomenon of artesian water. According to the operation and scheduling principle of the reservoir, from June to August, the water level of Datong Gorge reservoir is 44m~47.6m. In May and September, the running dynamic water level is 44m~53.6m and the limited water level is 59.6m. From October to March, the water level of the reservoir is 47.6m~59.6m and the limited water level is 61m. In April, the water level is 54.6m~57.6m and the limited water level is 59.6m. Therefore, the calculation conditions of water level of the reservoir are 47.6m, 53.6m, 57.6m, 59.6m and 61m respectively.

5. Analysis of Result

According to the operating and scheduling principle of Datong Gorge reservoir, it lasts about 6 months when the water level of reservoir is 44m to 53.6m. Taking the control flood function into consideration, it is only a short period of time when the water level of reservoir operates in the normal range. Since it takes a certain time for the underground water to overcome the resistance caused by the bound water and lifts up, consequently, we think that when the water level of reservoir is 59.6m, the influential range of producing banked-up water levels is the immersion area. When the water level of reservoir is 47.6m, it will cause no difference in the protected zone. When the water level of reservoir is 53.6m, the influential range of immersion is under 60.0 m. And the submerged area is 103.82×10^4 m^2. The area below 58m is 52.79×10^4 m^2 and the corresponding influential range of immersion is 51.03×10^4 m^2. Because there are mainly gullies, ponds, marshlands etc. below 58m elevation and the elevation of the Changshou Ditch control line is 58m, so we don’t need to consider the immersion effect below 58m elevation. It is suggested that the gullies should be dredged to insure that waterways are clear. On the other hand, within the influential range of immersion, most of the fields were paddy fields and sugarcane fields. And a small part of them were forests. After the immersion happened, due to the rise of the ground water, some water crops like paddies should be planted instead of sugarcanes. Furthermore, the monitoring of ground water level in influential range of immersion should be enhanced. Effective deposition should be implemented or not based on the actual situation. When the deposition is implemented, replacing of permeable bed is suggested. Meanwhile, within the influential area of immersion, one meter of planting soil from the upper layer should be dredged. Moreover, about 0.5 ~ 1.0m thickness of sand layer or other kinds of permeable stratum should be backfilled to export the banked-up underground water. Additionally, in order to complete the transformation, about 0.5 ~ 1.0m of original planting soil should also be backfilled.

| Borehole No. | Ground elevation | Initial water level | Steady water level | Bedrock elevation | \( I_0 \) | Water level of the reservoir |
|--------------|------------------|---------------------|-------------------|------------------|---------|---------------------------|
|              |                  |                     |                   |                  |         | 47.6m | 53.6m | 57.6m | 59.6m | 61m |
| CZK17        | 55.95            | 6.50                | 5.10              | 46.95            | 0.56    | 48.9 | 52.9 | 55.6 | 56.9 | 57.9 |
| CZK18        | 56.60            | 0.90                | 0.20              | 50.40            | 0.13    | 49.2 | 54.9 | 58.7 | 60.6 | 62.0 |
| CZK19        | 58.80            | 9.80                | 6.80              | 42.80            | 0.48    | 47.5 | 51.5 | 54.2 | 55.6 | 56.5 |
| CZK20        | 56.50            | 1.20                | 1.00              | 40.80            | 0.01    | 48.8 | 54.5 | 58.2 | 60.1 | 61.5 |
| CZK21        | 60.00            | 1.20                | 13.60             | 46.00            | (0.97)  | 48.6 | 52.6 | 55.3 | 56.6 | 57.6 |
| CZK22        | 58.00            | 1.60                | 5.30              | 34.70            | (0.17)  | 44.9 | 48.9 | 51.6 | 52.9 | 53.8 |
| CZK23        | 60.00            | 7.00                | 10.20             | 35.00            | (0.18)  | 45.0 | 49.0 | 51.7 | 53.0 | 53.9 |
| CZK24        | 59.30            | 8.00                | 4.80              | 49.80            | 2.13    | 49.8 | 53.9 | 56.5 | 57.9 | 58.8 |
| CZK25        | 56.00            | 1.50                | 1.20              | 33.70            | 0.01    | 48.4 | 54.1 | 57.9 | 59.8 | 61.1 |
| CZK26        | 61.00            | 8.00                | 5.10              | 46.20            | 0.43    | 48.6 | 52.7 | 55.4 | 56.7 | 57.6 |
| CZK27        | 64.30            | 1.10                | 2.00              | 47.10            | (0.06)  | 48.9 | 53.0 | 55.6 | 57.0 | 61.8 |
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