A groundwater flow model for excavation of coastal earthen sites: case study Jintoushan site, China

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ABSTRACT

Most of the earthen sites in coastal areas of South China are rescue excavations. According to the statistics, the main environmental geological hazards of the protection of original earthen sites is the water seepage caused by groundwater damages, especially during typhoon season (Jun.-Sep.). The article takes the Jingtoushan site of Zhejiang province, China as an example to establish a hydrogeological model, which was formally started excavation on June 3, 2018. The average depth of Neolithic remains in this site is 7m and the scheme is to design a rectangular foundation pit with row pile supporting structure. By collecting and analyzing the local meteorological data (precipitation, evaporation, etc.) and geological conditions of the site, the study simulates Jingtoushan site using the finite difference code of Visual MODFLOW to calculate the distribution of original groundwater and the variation law of seepage field in site area during construction period. The models are calibrated and verified through survey data using permeability and seepage model. The new numerical simulation method can be used to guide the excavation and construction of other earthen sites.

Keywords: earthen site, groundwater damages, permeability, seepage, hydrogeological model

1 INTRODUCTION

The conservation of earthen sites poses challenging questions regarding conservation methods and historic preservation (Charnov, A. 2011). Many scholars hold the view that incorporating preventative measures in a collaborative multidisciplinary approach creates the foundation for extending the useable life of a site and its values (Jane Henderson 2018, David Gregory et al.2012). For archaeological remains in wetland environment, the key of the conservation measure is to control the water. Numerical means are increasingly applied to estimate rationality of the conservation scheme. Koo’s (2001) numerical simulations showed that the major seepage source is the downward flow of water in the unsaturated zone through cracks in the protective layer above the Muryong Royal Tomb. Liu (2008) established a hydrogeological model of the mausoleum site of Yue Kingdom and proposed water control plan. Wang (2010) established a saturated unsaturated rainfall infiltration model to analyse the distribution characteristics of the seepage field in the soil cliff during a relatively complete rainfall infiltration process.

Jintoushan site is a typical shell mound lying in eastern Zhejiang province suffering from a long rainy season (Fig. 1). The burial depth of the cultural remains is - 6.8~ - 11.0 m under the thick marine clay layer. It’s important to figure out the variation law of seepage field in site area during construction period.

Fig. 1. Geomorphologic map of the area around the Jintoushan site.
In this paper, Visual MODFLOW is used as numerical tool to simulate ground-water flow in a three dimensional heterogeneous and anisotropic medium (Harbaugh. 1996, 2000). Using the finite-difference method, the domain in which flow is to be simulated is divided into a rectilinear mesh of rows, columns, and layers. The advantage lies in the ability to describe mean value, unequal thickness and complex hydrogeological conditions to improve the reliability of numerical simulation results, which is rarely used in the construction of archaeological excavation.

The overall goal of this study is to assess the impact of influence of the excavation works on the groundwater distribution of the site by numerical models and gives a quantitative analysis thought simultaneously.

2 AN OVERVIEW OF GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

2.1 Regional situation and geomorphological features

The Jintoushan site belongs to the early culture of Hemudu and is the only prehistoric shell mound found so far in Zhejiang province. The Jintoushan site (30°01'30"N, 121°21'36"E) is located at west side of Guanqiao Village, Sanqi Town, Yuyao City, which is part of Ningbo-Shaoxing Plain, south of Hangzhou Bay. Fig. 1 shows that it lies on the northern flank of the Yuyao River Basin and on the southern slope of the Cinan Mountain. There are two completed sites with shelters nearby. The Hemudu site is about 7.1 km away to the southwest and the Tianluoshan site is about 2.2 km away to the east (Fig. 1).

The annual average temperature in the past three years is 18.0 °C, the annual sunshine is about 1700 hours. Continuous precipitation occurred in May to June during the rainy period while heavy rainstorms (6.0mm/h) and super rainstorms (13.0mm/h) occur mainly during typhoon period from June to September. There remains serious problems of water accumulation in pits during rainy season in the completed Hemudu and Tianluoshan sites around.

2.2 Site conditions

The accumulative shape of the cultural remains of the site is approximately elliptical in the North-South direction. It is about 83 meters long in the south and 48 meters wide in the east and west. The total area is about 7000 square meters, and the maximum accumulation thickness in the middle is about 1 meter, which is obviously inclined from northwest to southeast. As Fig.2 shows, the burial depth of the cultural remains at Jintoushan site is - 6.8~ - 11.0 m. The original landform is farmland, the upper part of which has been backfilled with pond dregs 1~1.3 meters thick, which is mainly composed of gravel, gravel, sand and a small amount of clay.

According to the results of indoor geotechnical tests and field data of exploration holes (including the results of in-situ test of drilling sample holes & drilling holes and heavy dynamic penetration), the proposed site can be divided into seven layers within the 19 m exploration depth of ZK11 point according to the distribution of foundation soil, burial depth, soil properties and its physical and mechanical properties. They are listed in Table 1 below.

On the west side of the site, there is a north-south river, and on the West side, there is a north-south river. It is about 50 meters away from the archaeological excavation area, about 7~8 meters wide, about 1.00~2.00 meters deep, and about 0.40 meters thick of floating mud. The rise and fall of river water level is mainly controlled by atmospheric precipitation. There is a certain hydraulic relationship between river water level and shallow groundwater in the site. The adverse influence of river water rising and seepage on foundation pit excavation should be paid attention to during construction in this area.

Fig. 2. Survey section details of the Jintoushan site (east-west direction).
Shallow pore phreatic water in the upper part of the site occurs in the surface and subsurface miscellaneous fills and clay layers. The miscellaneous fills have more water content during loose and continuous rainy days, good permeability, poor permeability and poor water content in clay layers. Shallow pore phreatic water is mainly recharged from atmospheric precipitation, mostly discharged by evaporation. The high water level generally occurs in June to September, and the low water level occurs in December to February of the next year. The annual variation range of groundwater level in the proposed site is generally about 1.00 meters. In April 2018, after 24 hours of the final hole, the buried depth of the stable water level was 0.50m~0.71 m (a.s.l.) and the elevation of the water level was 1.08m~1.54 m (a.s.l.). Weak confined water exists in the sixth layer of gravel sand with silty clay. The height of the aquifer roof is -7.39m to ~17.81m (a.s.l.). The water permeability is general and has a certain amount of water. The borehole reveals that the stable water level of the fourth layer is -3.5 m (a.s.l.), and the variation range of confined water head is about 1.0m (a.s.l.). Hydraulic parameters of the soil layer and rock are shown in Table 1.

| Layer | Main Components              | Layer height (m) | Gravity (kN/m3) | Cohesion (kPa) | Internal friction angle (°) | Effective porosity | Permeability coefficient |
|-------|------------------------------|------------------|-----------------|----------------|----------------------------|-------------------|--------------------------|
| 1     | Miscellaneous fill           | 1.10             | 18.0            | 10.0           | 8.00                       | 0.397             | 8.30e-3                  |
| 2     | Clay                         | 0.90             | 18.6            | 25.0           | 10.9                       | 0.442             | 7.00e-6                  |
| 3     | Peat soil                    | 0.40             | 12.6            | 4.80           | 3.70                       | 0.420             | 1.00e-5                  |
| 4     | Silt soil                    | 9.40             | 16.3            | 7.30           | 6.20                       | 0.460             | 1.50e-7                  |
| 5     | Marine ooze                  | 2.50             | 19.3            |                |                            | 0.442             | 6.00e-6                  |
| 6     | Gravel sand with silty clay  | 2.70             | 20.5            |                |                            | 0.350             | 1.20e-5                  |
| 7     | Weathered tuff bedrock       | 2.00             | 19.0            |                |                            | 1.2e-8            | <1.2e-9                  |

3. SIMULATION AND CALCULATION

3.1 Establishment of three-dimensional numerical model

The excavation area is 70 meters long and 35 meters wide in east-west direction. There is a river to the west, 23.5 meters away. The foundation pit of Jintoushan Site is 40 meters long and 5 meters wide, located in the center of the excavation area (Fig. 3). During the excavation, a drainage ditch with a section of 300×400mm is set around the excavation area, and a centralized drainage well is set every 20 meters. Longitudinal slope of drainage ditch is 0.15% (Fig. 3).

1) Setting of observation well

Six water level measuring points are arranged around the foundation pit of the site. In Figure 3, it is marked as SWO1–6. Water level monitoring uses MIK-P260 input level gauge sensor and external light column type digital display meter. When the sensor touches the water surface, the digital display displays the values. When simulated in Visual MODFLOW software, the positions of observation wells are set at the coordinates of actual water level monitoring points for comparison.
2) Boundary conditions

About 200m away from the center of the foundation pit, the north side is a mountain with bedrock fissure water, which is regarded as a constant head boundary. There is a north-south river. It is about 50 meters away from the study area. The water volume of the river is large and the annual water level changes little. It is set as the river boundary with fixed water level. In Visual MODFLOW Software, river module could be set directly. The upper boundary of the study area is mainly supplied by precipitation. It can be converted according to the infiltration coefficient and rainfall in the study area. It is known that it is set as water exchange boundary. Rainfall data is based on 30-year average monthly rainfall of Yuyao City. The bottom is taken to the bedrock and regarded as the water separation boundary. At the same time, the vertical and horizontal permeability coefficients in the same stratum are set to the same value in the model.

3) 3D numerical model

According to the existing soil geology, hydrogeology and mapping data, the model of the study area is established by using the grid center node of the finite difference method. The study area is 180 m long, 150 m wide, divided into 3000 units, each 3 m long. The maximum value of Z in the vertical direction is 20m. As shown in Figure 4, seven soil layers model and six observation wells are established.

![3D numerical model of the Jintoushan site](image)

**Fig. 4. 3D numerical model of the Jintoushan site.**

3.2 Simulation of initial water level in natural state

Information available suggests:

1) Groundwater in natural state receives river recharge in the west and discharges eastward through the site;

2) The large linear density of surface water level on the west side of the site indicates the boundary of groundwater head in this area. The planar network is divided into 3 m ×3 m cells (Fig. 5).

![Grading dissecting plot of the numerical model](image)

**Fig. 5. The grading dissecting plot of the numerical model.**

Table 2 and Fig. 6 reflect the fitting degree of groundwater gradient is high. The model truly reflects the actual situation of groundwater aquifer in the study area. The operation of the model is stable and reliable, which can be used for prediction and analysis.

![Map of contrasting the simulated with the surveyed](image)

**Fig. 6. Map of contrasting the simulated with the surveyed.**

| Observation Point | SWO1  | SWO2  | SWO3  | SWO4  | SWO5  | SWO6  |
|-------------------|-------|-------|-------|-------|-------|-------|
| **Simulated Value** | -70.9 | -85.1 | -54.4 | -86.4 | -57.5 | -96.3 |
| **Measured Value**  | -73.1 | -89.5 | -58.5 | -86.5 | -59.1 | -93.0 |
3.3 Simulation of water level during the construction period

The groundwater in the site area is discharged by seepage, pumping and evaporation, among which pumping is the main way. MODFLOW uses the recharge package (RCH) to handle groundwater recharge. The recharge package is used to simulate groundwater recharge from the atmosphere. In most cases, the atmospheric recharge is the result of precipitation infiltration into groundwater system. In this paper, the upper boundary of the model is a supply boundary, which allocates monthly mean precipitation to the model according to the simulated pit, the simulation time is one year, from June 2018 to June 2019. The precipitation is shown in the figure below.

![Fig. 7. Average monthly precipitation of Yuyao City in 30 years Data sources: Yuyao Municipal People’s government website.](image)

During the one-year construction period, due to technical problems, it had been shut down from November 2018 to March 2019. In this paper, data of continuous construction from September 11th to October 16th, 2018 are adopted. During this period, the pump operates stably, which is easier to simplify the model.

Fig. 8 and Table 3 shown that the simulated value is very close to the measured value. Fig.8 displays the detailed values, simulated value in 11/9/2018, 18/9/2018 and 16/10/2018 are chosen typically to compare with the measured value.

![Fig. 8. Comparison between Simulated Value and Measured Value](image)

Table 3. Comparison between Simulated Value and Measured Value of water level in 6 observation wells from 11/9/2018 to 16/10/2018.

|   | SWO1 | SWO2 | SWO3 | SWO4 | SWO5 | SWO6 |
|---|------|------|------|------|------|------|
| B | 0.996| 1.006| 0.958| 1.025| 1.019| 0.978|
| 9.11 | 1.120| 1.183| 1.117| 1.663| 1.163| 1.268|
| 9.25 | 1.012| 0.945| 0.978| 0.964| 0.953| 1.002|
| 10.2 | 1.024| 0.975| 0.995| 0.963| 0.918| 0.985|
| 10.9 | 1.075| 1.152| 1.254| 1.184| 1.212| 1.128|
| 10.16 | 1.075| 0.944| 1.062| 1.012| 0.960| 0.978|

B is the simulated value divided by the measured value.

![Fig. 8 and Table 3 shown that the simulated value is very close to the measured value.](image)

Obviously, simulated value in September 11th and September 18th are overlarge on the whole compared with measured value. Simulation value from SWO4 is up to 1.66 times of the measured value. For other four groups of data represented by the data of October 16th, the simulated value is in good agreement with the measured value. After analysis, the error is thought to be caused by the use of data. As mentioned above, average monthly precipitation of Yuyao City in 30 years has been chosen to put in the MODFLOW as the upper boundary of the model. While the distribution of precipitation has been changed strongly during the construction (Fig. 9). Meanwhile there has been seven typhoons and tropical storms occurred. Influenced by the circumfluence of Super Typhoon Mangkhut and Super Typhoon Kong-rey, there was a heavy rain in the east of Yuyao where the site is located, maximum rainfall of the former is reach 80 mm per hour.

![Fig. 8 and Table 3 shown that the simulated value is very close to the measured value.](image)

Obviously, the instantaneous heavy rain caused by

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typhoon will affect the short-term simulation results.

Fig. 10. Distribution of original seepage field in site area.

Fig. 11. Distribution of seepage field in site area during construction period (October 16th).

After the excavation of the site and the layout of the drainage ditch, the groundwater around the site area converges to the site point. Due to the small permeability coefficient of the soil, the contour line near the drainage ditch is very dense, and the shape of the water level chart is similar to that of the drainage ditch, and gradually becomes elliptical outwards; the head value of the contour line gradually increases outwards from the location of the drainage ditch to the state of natural water level.

4 CONCLUSIONS

1) Using Visual MODFLOW 3D groundwater flow simulation software to simulate and predict the groundwater level change caused by the actual archaeological foundation pit dewatering, which has achieved good results. It provided a new idea and working method for the analysis of similar and related engineering groundwater problems.

2) In Visual MODFLOW, when rainfall related modules are set, it's better to use the data of the past three years as a reference. It is necessary to raise the relevant parameters according to the situation of rainstorm, especially in typhoon season.

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