Three-dimensional stability analysis of a deep excavation with seepage in Karst deposit

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Abstract. Groundwater seepage is an important factor threatening the safety of excavation. In order to reduce the threatening, a simulation of excavation and the seepage process in Guilin city is carried out by FLAC³D. The paper establishes a three-dimensional numerical model through spline interpolation method. The model built by the system of CAD can show the scope of an ancient collapse and the topological relationship among the soil layers in small scale. After that, the fluid-solid coupling technology is used to the pore pressure calculation, which adjusts the parameter by comparing the model simulation results and the site observation results. The regular pore pressure in the excavation is obtained. The results show that the pore pressure fluctuates greatly in excavation area nearby the ancient collapse during the excavation process, the local upward seepage can be driven and flow up under the reverse hydraulic power. It provides suggestions for the excavation construction and as a reference for analyzing stable seepage of groundwater in deep excavation.

1. Introduction

Groundwater seepage is not only an important factor in engineering design, construction and safety, but also a great concern in evaluating the social, economical and environmental benefits of the project [1-3]. The complex geological phenomena of Karst deposit, such as Karst clints, pinch-out or Karst collapse, have become the challenge for engineers to analyze the groundwater seepage stability in past decades [4,5]. Some scholars have finished a lot of major works in building the model to realize the three-dimensional visualization of the groundwater seepage [6,7]. In recent years, some software such as FLAC³D, which make us capable of modeling complex strata from the point of three-dimensional view. The simulation results can also be compared with the measured data, which makes the excavation project more safety and reliability [8,9]. Therefore, on the basis of complex three-dimensional stratum modelling, the application of FLAC³D to simulate groundwater seepage in excavation engineering is of great research significance.

2. Construction of a three-dimensional Karst deposit

2.1. Engineering background

The construction site is located in the geomorphic unit of the first terrace of Lijiang River, Guilin, China, where the Karst is the strong development. It is proposed to build an underground parking lot with an irregular plane of the excavation area of 142.2 m long, 85.3 m wide and roughly 11486 m².
The depth of the excavation is about 12.8 m including two ground floors: the first is 7.8 m depth and the second 5.0 m. According to the construction procedure, each floor was divided into five excavation areas (also called excavation phases), labeled A1, A2, B, D, and C (figure 1). The reversed construction method was adopted for the whole building. The cement mixing pile as the structure for supporting the slope of foundation pit and as the waterproof curtains has been finished before the excavation. In order to avoid the danger of seepage deformation, the early warning scheme has been preset for insuring the smooth excavation process in which the water level in monitoring points do not change greatly. However, when excavating the B area in the first floor, a water inrush incident once happens nearby the ancient collapse in the year of 2017.

![Figure 1. The sketch of excavation area, ancient collapse scope and labeled areas in the consequence of construction.](image)

Revealed by the No. 7 and the No. 17 boreholes, the pebble layer is missing and replaced by a thick clay layer in the soft-plastic state (figure 2). It could presumably be an ancient collapse site filled by the mud of clay. The soil layers mainly include: the alluvial clay, the silt, the fine sand, the pebble (Q₄ₜₗ) and the alluvial-diluvial silty clay pebble (Q₃ₜₗₚ). The underlying bedrock is the upper Devonian Rongxian Formation limestone (D₃₉). The groundwater flow through the Karst channels or caves with the potential hydraulic power are apt to enlarge soil caves and cause surface collapse, especially in the case of the large variation of groundwater.

Groundwater is locally affected by the surface water, i.e. Guihu Lake and Ronghu Lake. So the lateral supply of water source is abundant while the sand and pebble layers are strong permeable layers. The water level varies with season, and the annual variation of water level is 2.0 ~ 3.0 m. The style of groundwater is porous groundwater mainly stored in the pebble beds. In the dry season, the initial water table depth is 6.30 ~ 7.47 m, the static water table depth is 5.17 ~ 6.23 m, meaning the water level of 145.96 ~ 147.30 m elevation. According to the engineering experience in the Guilin area, the karst underground water in-site is confined.

In order to seepage stability during excavation, the early warning scheme has been set out that is (1) the variation rate of water level in monitoring points up to a specified value or in 3 consecutive days exceeding 70% of the specified value; (2) the cumulative settlement of surrounding buildings more than 15.0 mm or the settlement rate overtaken 2.0 mm/d in a day; (3) the cumulative inclination of surrounding buildings up to the value of 2/1000 m or in 3 consecutive days the inclining rate more than 0.001 H/d, where the character H represents the height of the bearing structure of the building.
2.2. Construction of three-dimension model and parameter setting

The results of three-dimensional models of complex strata are different by different spatial interpolation methods. There are two kinds of spatial interpolation method: one is the deterministic method based on spline function by various CAD software, the other is non-deterministic method represented by the geostatistics model in many GIS software.

By comparing the two kinds of method, it could be found that the modeling system of CAD has a better effect on the small-scale three-dimensional modeling (figure 3), especially in reflecting the ancient collapse. In figure 4, the topological and spatial relationship between the various soil layers are shown clearly by extruding the space distance, meanwhile, the ancient collapse is also shown distinctly.
Figure 4. Fitting chart of simulated monitoring water level and actual monitoring water level are selected. The fitting effect is evaluated by two indexes of mean square error (MSE) and root means the square error (RMSE).

To control the deformation and reduce the risk of safety, the method of block excavation was adopted along with the main structure constructed at the same time, i.e. called top-down or reverse construction. In order to simulate the excavation and construction process, calculation was also divided into several groups based on the actual excavation planning. According to the data of the previous in-site investigation and the laboratory test, the parameters, such as the density, the permeability, the porosity, the modulus and so on, for every soil are determined. The soil parameters for simulation are summarized in table 1.

Table 1. Soil parameters for simulation.

| Simulation Parameters | Clay layer | Fine sand layer | Silty clay pebble layer | Limestone layer | Soil layer in subsidence area |
|-----------------------|------------|-----------------|------------------------|-----------------|-----------------------------|
| Permeability (m²/Pa·sec) | 6e-10      | 5e-7            | 5e-10                  | 6e-17           | 5e-8                        |
| Bulk modulus (MPa)     | 5.89e6     | 4.24e6          | 1.68e5                 | 14.49e6         | 2e4                         |
| Shear modulus (MPa)    | 2.72e6     | 2.3e6           | 6.91e5                 | 7.87e6          | 1.5e3                       |
| Porosity (%)           | 0.5        | 0.5             | 0.5                    | 0.5             | 0.5                         |
| Density (g/cm²)        | 1.9        | 1.9             | 1.9                    | 1.9             | 1.9                         |
| Cohesion (Pa)          | 4e7        | 1.49e7          | 1.5e7                  | 0               | 1.5e4                       |
| Friction (°)           | 10.3       | 18.8            | 25                     | 33              | —                           |

3. Model verification and results analysis

3.1. Model verification

The numerical simulation of the model is carried out based on the fluid-solid coupling calculation. By establishing simulation monitoring point in the FLAC³D model, the history of groundwater variation can be observed during simulation. A direct comparison of the simulating water level with the actual monitoring water level shows a better fitness (figure 4) in which six representative results.

The results show that the MSE is almost less than 0.05, and the RMSE is less than 0.2. Conventionally, the simulation data below 0.05 is considered as a small probability event in statistic. That is to say this simulation model is reality and validity.
3.2. Analysis of seepage stability

When the hydrodynamic pressure produced by seepage reaches a certain critical value, some fine particles will be carried and transported away from the soil by the seepage flow, therefore, causing potential erosion and infiltration damage. Judgement of whether or not seepage stability in the process of excavation is an important issue for a geological engineering. Critical hydraulic gradient as a key index used to judge the seepage stability has been proposed by Terzaghi (1932).

\[
I_{cr} = (\rho_s - 1)(1 - n)
\]

(1)

where \(I_{cr}\) is the critical hydraulic gradient; \(\rho_s\) is the density of soil particles; \(n\) is the porosity of the soil.

The permitted hydraulic gradient \(I_{pe}\), the result of the critical gradient divided by a coefficient \(m\) ranging from 2.5 to 4.0 to keep a safety reserve, is often be used in engineering. If the actual hydraulic gradient in-situ \(I_{ac}\) is larger than the permitted gradient, the seepage of the flow will lead to instability of the excavation.

Figure 5 illustrates several of key monitoring points set inside of the ancient collapse body. They are labeled as 1B, 4B, 7B and 8B with elevation of 139.8 m, 119.0 m, 140.0 m and 135.4 m, respectively. Meanwhile, two actual monitoring points in the field are also shown in the figure 5, labeled as S4 and S8, respectively.

![Figure 5. Location of monitoring points for ancient collapse.](image)

The trend of pore pressure at actual and simulated monitoring points under different excavation phases are shown in figure 6. It can be seen that the pore pressure at all simulated points demonstrates a kind of fluctuation states in the phase of A11, then tending to a stable states in subsequent phases.

![Figure 6. Pore pressure variation at the monitoring points set inside of ancient collapse body in different simulation phase: (a) simulated results at two actual monitoring points; (b) simulated results at four simulated monitoring points in comparison with the in-situ observed results in the S8.](image)
But there are obvious fluctuations at the points of S8 and S4 in the phase of C (figure 6(a)). These phenomena were also observed in the in-situ results at the S8 shown in figure 6(b). This manifests that there is a great effect on the pore pressure when excavation in the area nearby the ancient collapse body. Local upward seepage can occur due to the reversed hydraulic power, which drives the water flow up by upward hydraulic gradient. The table 2 shows the hydraulic gradients between both of monitoring points in accordance with the simulation results. And the evaluation of seepage stability is also given out by comparing the actual hydraulic gradient with the permitted one.

Table 2. Evaluation of seepage stability between monitoring points according to simulation results.

| Seepage flow     | Dh (m) | Dl (m) | Iac | \( \rho_s \) (g/cm²) | n   | \( I_c \) | m   | \( I_{pc} \) | Stability |
|------------------|--------|--------|-----|----------------------|-----|---------|-----|------------|-----------|
| 4B→7B            | 0.62   | 26.53  | 0.023 | 2.65                | 52.0 | 0.792   | 4.0 | 0.198      | Yes       |
| 8B→7B            | 5.49   | 10.28  | 0.534 |                     |      |         |     |            | No        |
| 1B→S4            | 2.5    | 24.38  | 0.102 |                     |      |         |     |            | Yes       |
| 8B→S4            | 1.3    | 31     | 0.042 |                     |      |         |     |            | Yes       |

4. Discussion on seepage stability of the excavation
According to the above results, it could be found that the pore pressure in the body of ancient collapse is easily affected by excavation with great fluctuation. Therefore, the excavation area nearby the ancient collapse becomes a field prone to water inrush. The simulation results are in good agreement with the water inrush event occurred in 2017. The cement mixing pile used as both functions of foundation pit supports and waterproof curtains does not fall on the bedrock could be the reason for water inrush presumably. And the comparative experiment is really in progress.

Guilin city is located in the area with developed karst landscape. It is easy to induce ground subsidence there under the influence of human engineering activity. It is a potential threaten to the underground engineering safety. It is suggested that the pile body should be placed deeply in the bedrock within such karst developed area. Its advantages are not only to obtain greater bearing capacity, but also to proof completely the excavation from the water. Grouting along the boundary of the ancient collapse area also can be used to isolate the water from the surrounding environment.

5. Conclusion
• Based on the spline interpolation method, the complex strata model, such as an ancient collapse, can be built up efficiently in small scale through the system of CAD.
• Importing the model to the FLAC3D, a numerical simulation model can calculate the pore pressure with the process of deep excavation and be verified through fitting with the in-situ observed results.
• The results of simulation show that the pore pressure within the ancient collapse body is affected greatly during excavation. There are the tendency of local upward seepage driven by the reverse hydraulic power and the possibility of water flow inrush leading to the foundation pit instability.
• The occurrence of water inrush incident is because the body of cement mixing piles fails to fall on the limestone bedrock and to take the role of the waterproof curtains. It is suggested that the scheme of pile body falling on bedrock or local grouting should be adopted in the Karst area.

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