Numerical simulation of consolidation settlement of the embankment of the Nansi Lake

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Abstract. The consolidation settlement of the lake embankment engineering under long-term load is very large. It makes the structure can’t work normally and even leads to severe damage. Therefore, it is very important to analyze the settlement of soft soil foundation for the stability and safety of the lake embankment. The mechanical parameters of soil in this area, based on the geological investigation report of the lake embankment, are used to analyze the engineering characteristics of lacustrine soil. The embankment of the Nansi Lake is selected as an object to analyze the consolidation deformation characteristics of the lake embankment. The consolidation settlement of the lake embankment is simulated by the finite element analysis software. The simulation data and analysis results are very important for studying local geological characteristics and hydraulic construction.

1. Introduction

The lake embankment is an important hydraulic facility made up of local earth and stone materials along the lake area to prevent flooding and resist soil erosion. However, the lake embankment projects in China lack effective supervision and maintenance for a long time. The damage caused by uneven settlement has caused great security risks to the economic development and people's safety. The consolidation settlement of the lake embankment in soft soil is studied and simulated by finite element software. Based on the simulation results, the settlement and cracking of the lake embankment structure are analyzed. This conclusion has very important engineering significance for the study of consolidation settlement of the lake embankment.

The settlement of soft soil foundation is a common problem in lake embankment engineering. It is important to reduce the consolidation settlement for the stability and safety of lake embankment[1]. Therefore, it is necessary to consider the consolidation settlement caused by the characteristics of lacustrine soil in construction. It is particularly important to analyze its mechanical properties and consolidation deformation characteristics.

2. Basic theory

2.1. Calculation of instantaneous settlement

The instantaneous settlement occurs during the untrained loading period of the soil. When the soil tends to be basically saturated, the deformation of soil particles is very small, which is considered negligible and its value tends to zero.

According to the requirements of Technical Guidelines for Design and Construction of Highway Embankment on Soft Ground, we use the following formula to calculate the instantaneous settlement:
\[ S_d = F \frac{PB}{E} \]  

(1)

Where \( P \) is defined as the maximum vertical load at midpoint of embankment bottom, \( E \) is taken as the average modulus of elasticity obtained from unconfined compression tests, \( F \) is taken as the midline settlement coefficient, and \( B \) is defined as the effective width of load. Instantaneous sedimentation under gradual loading conditions:

\[ S_d' = S_d \frac{P_t}{\sum \Delta p} \]  

(2)

Where \( S_d' \) is defined as the instantaneous settlement of cumulative load at time \( t \), \( P_t \) is taken as the cumulative load at time \( t \), and \( \sum \Delta p \) is taken as the total cumulative load.

There are limitations in calculating instantaneous settlement by the above formulas. It should be revised according to the actual project, so it can be better used in the actual project.

2.2. Calculation of main consolidation settlement

The main consolidation settlement refers to the settlement occurring when the load in soil is constant and the pore water is continuously discharged with the development of time. It begins at the time when the load is applied and ends when the pore water pressure produced by the applied load is completely dissipated. It is the main part of the soil settlement[2]. It is usually expressed by the following formula:

\[ S_c (t) = S_\infty \overline{U}_t \]  

(3)

Where \( S_c \) is defined as the final consolidation settlement of the stratum, \( \overline{U}_t \) is taken as the average consolidation degree of the stratum. The formula (3) shows that the consolidation settlement calculation includes the calculation of the final consolidation settlement and the upper body consolidation degree of the stratum. However, the above formula can’t apply to all soils, so it should be appropriately corrected according to local conditions in actual engineering.

3. Consolidation settlement analysis

3.1. Project overview

According to the geological data of engineering investigation, the physical and mechanical parameters of the Nansi Lake lacustrine soil are obtained, as shown in the table below. The range of mechanical parameters of soils varies greatly, especially the range of cohesion and internal friction angle. The natural void ratio \( e \) of lacustrine soil in the Nansi Lake is nearly equal to 1, it indicates that its void ratio is very large. The compression coefficient \( a_v \) ranges from 0.201 to 0.914, with an average value of 0.48. The compressive modulus \( E_s \) ranges from 2.6 to 8.7, with an average value of 4.8, indicating that the lacustrine soils in the Nansi Lake are medium-high compressive soils. The liquid limit is very small and most of the particles are between 34 and 50, because the content of powder particles is more than viscous particles. Only a few particles can reach 60. The water content in the plastic state is very small so this kind of soil has high water sensitivity. Saturation and water content can be used as the main parameters to control spring phenomenon in engineering.

| Statistical items | Water content \( \omega \) (%) | Bulk density \( \gamma \) (kN/m\(^3\)) | Void ratio \( e \) | Saturation \( S_t \) (%) | Liquid limit \( W_L \) (%) |
|-------------------|-----------------------------|---------------------|-----------------|-----------------|-------------------|
| Distribution      | 20.0–47.8                   | 18.1–19.4           | 0.61–1.50       | 90.6–99.0       | 34.3–60.4         |
| Average           | 29.4                        | 18.9                | 0.98            | 97.2            | 44.1              |
Table 2. Physical and mechanical parameters in the Nansi Lake area

| Statistical items | Plastic limit $W_P$ (%) | Compression coefficient $a_v$ (MPa$^{-1}$) | Compressive modulus $E_s$ (MPa) | Cohesion $C_q$ (KPa) | Internal friction angle $\phi_q$ (°) |
|-------------------|-------------------------|---------------------------------------------|--------------------------------|----------------------|----------------------------------|
| Distribution      | 20.6~27.7               | 0.201~0.914                                 | 2.6~9.2                        | 5.3~47.5             | 7.8~36.5                         |
| Average           | 23.1                    | 0.48                                        | 4.8                            | 26.6                 | 25                               |

3.2. Numerical simulation

3.2.1. Finite element model
The numerical simulation of consolidation settlement is carried out by taking a section of pile number 13+185. The height of the lake embankment is 4.94 m, the top width is 6 m, and the slope ratio of the designed lake embankment is 1:3. The two-dimensional plane model of the soil under uniform load is studied. In order to weaken the influence of the boundary of the model in the numerical simulation, the length of the horizontal direction of the model is 100 m. In order to improve the accuracy of calculation, the grid of the lake embankment and its underlying foundation is encrypted. 3240 cells and 5085 nodes are used for meshing, as shown in Figure 1.

![Figure 1. Finite element model](image)

3.2.2. External load and boundary conditions
Equivalent uniform distributed load on top of the lake embankment is 10.5 KPa, equivalent uniform distributed load on slope is 27 KPa, and hydrostatic pressure load in lake is 24.4 KPa. In order to reduce the complexity of the solution, this paper adopts the method of instantaneous imposition of permanent external load to simulate the actual force. The boundary condition is a one-sided undrained drainage mode with upper drainage and lower drainage. The vertical direction is free and the geometric model is constrained horizontally. That is to say, settlement occurs only in the vertical but not horizontal direction[3].

4. Analysis results
In the displacement nephogram, it can be seen that the settlement of the embankment body and its foundation is large, the settlement of both sides is small, and the settlement of the filling area is larger. In the pore pressure change nephogram and effective force change nephogram, it can be seen that the pore water pressure finally drops to zero, and the maximum effective stress is finally stable at 431.8KPa.
In order to study the settlement of the lake embankment, four points are taken in the vertical direction of the symmetrical axis of the lake embankment. They are node 2455 on the surface of the lake embankment, node 2536 at the depth of 3.4 m, node 1952 at the depth of 6.4 m and node 940 at the depth of 9.8 m. As shown in Figure 5.

4.1. Analysis of settlement calculation results

Figure 6 are the consolidation settlement curves at different depths on the center line of the lake embankment. The whole settlement process can be divided into three stages: initial stage, rapid stage and slow stage. The initial settlement stage refers to the period of construction, and the settlement increases rapidly and nearly linearly. In the stage of rapid settlement, the increase rate of settlement is slow and it is the main part of the whole consolidation settlement. In addition, the relationship between settlement and time is non-linear. The slow settlement stage is very long, and the velocity and amount of settlement are very small. This stage belongs to the settlement of secondary consolidation.

4.2. Analysis of calculation results of pore pressure

In Figure 7, it can be seen that the surface pore water pressure persists at zero and the abrupt change of pore water pressure after loading increases with the increase of depth. It can be seen that the pore pressure will sharply increase in a rapid release process, because pore water can't be eliminated instantaneously under the sudden loading. Therefore, the dissipation of pore water pressure in the
initial stage is the fastest under the action of soil self-weight and external load. When the pore water pressure dissipates to zero, the consolidation settlement completes finally.

4.3. The relationship between pore pressure and settlement with time

In Figure 8, the dissipation velocity of pore water pressure is very fast when the project is completed, and the settlement rate is relatively high at this time. In addition, the dissipation rate of pore water pressure becomes very small and even tends to zero. In this stage, the settlement velocity also slowly decreases, and finally tends to zero. In figure (a), the pore pressure at the depth of zero meters persists at zero, but the settlement is the largest in the whole vertical direction. It is the result of the accumulation of consolidation settlement of each soil layer. But the settlement trend in the whole depth direction is generally same, and they all go through the initial, rapid and slow settlement stage.

5. Conclusion

(1) Soil consolidation mainly occurs in the initial and rapid settlement stages. The settlement is very large and the speed is very fast. In the depth direction, the consolidation settlement of the upper joint is obviously larger, and the speed is also faster than that of the lower.

(2) The excess pore water pressure increases with improvement of soil depth in the depth direction. The excess pore water pressure dissipates slowly with time. During the whole consolidation process, the dissipation of excess pore water pressure appears corresponding to the consolidation settlement. As the depth increases, the initial pore water pressure increases after loading. The dissipation velocity of pore
water pressure increases with the improve of depth.

(3) Consolidation is actually a process of changing pore water pressure to effective stress. With the increase of depth, the pore water pressure and the load all increase. It causes effective stress to increase along the depth direction. The dissipation rate of pore water pressure increases along the depth direction, and the growth rate of effective stress also increases. When the dissipation of pore water pressure is zero, the effective stress reaches a stable value.

References
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