Mechanical characteristics analysis of two-stepped slope based on flow-solid coupled method

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Abstract. Atwo-stepped slope stress and displacement field characteristic is analyzed by the flow-solid coupled method in this study. The results of numerical simulation show that the maximum displacement of the coupled method appeared on the slope top and the value is larger than the results of uncoupled method. The results of stress show that the first principal stress of coupled method is larger, and this character is consistent with the coupled effect between groundwater seepage and stress, and then proved that the influence of groundwater seepage on stress is not neglect. The analysis method of this paper provides a reference for the stability of multi-stepped slope under complex conditions.

1. Introduction

The slope stability is an important factor on the safety of the underground engineering, and it is also a crucial monitoring object during the construction [1]. There are many factors affected the slope stability, one of the factors is the groundwater seepage that is a common factor to reduce the slope safety. Therefore, the stress distribution problem under the groundwater and soil coupled is must solved before the deep excavation [2-4].

The stress field of two-stepped slope is very complex, especially under this coupled condition. A simple stress is analyzed usually which to estimate the two-stepped slope stress, yet this method generally induced a computation error and accordingly affected the slope stability judgment. In early research, the groundwater seepage is only considered as a single factor to affect the stress field of soil, but the seepage and soil is an interaction in fact. Because of the change of soil stress is also affected the distribution of groundwater seepage, it required that considered the mutually mechanism in the numerical simulation to ensure the stress distribution integrality [5-7]. Therefore, this study focused on the two-way coupled interaction between the groundwater seepage and the soil stress, the stress and the displacement will compare with the results of uncoupled method. The characteristic of the two-stepped slope is analyzed and the research results will provide a reference for the slope stability in future.

2. Physical model and condition

The present geometric model is a two-stepped foundations pit, and the platform is settled in the middle of slope. The slope height is 14m, the bottom length is 32m, and the slope angle is 45°, and the water level is 0.5m [6]. The monitoring points are arranged along the slope, and the soil is divided
into three layers contained earth filling, silt clay and silt sandy. The model dimension can be seen Figure.1 and the soil physical parameters can be seen Table.1.

![Figure.1 Two-stepped slope geometrical model.](image.png)

| Soil type          | Weight (kN/m³) | Elastic modulus (kPa) | Poisson ratio | Friction angle (°) | Cohesion (kPa) | Permeability coefficient (m/s) |
|--------------------|----------------|-----------------------|---------------|-------------------|---------------|--------------------------------|
| Earth filling      | 16.0           | 700                   | 0.35          | 5                 | 5             | 2.24E-04                       |
| Silt clay          | 18.5           | 4000                  | 0.30          | 8.5               | 22.5          | 3.32E-06                       |
| Silt sandy         | 17.0           | 12000                 | 0.3           | 27.0              | 0             | 4.83E-05                       |

3. Computed method

The mechanical characteristics of slope are analyzed by finite element method in this computed process. A four-node isoparametric elements are used, and the average stress of four nodes is represented this element stress distribution. In order to ensure displacement and stress fields computed precision, the total element is 1184 and node is 1275. The boundary condition of slope bottom is all restrict and have no displacement. Two side boundary conditions of slope are no horizontal displacements and the slope boundary condition is freedom. The stress field convergence accompanied by the two-way coupled method between the soil and groundwater seepage, and the permeability coefficient as a transfer parameter is repeated iterative calculation used the self programming by FORTRAN computer language, and the stress and displacement accuracy is set as 10⁻⁵ to ensure the reliability of this method. The calculation process can be seen Figure.2.

![Figure.2 Calculation route of flow-solid coupled method](image.png)
4. Numerical results

Figure 3 is the pressure contours results of the soil mass computed by the flow-solid coupled method, the pressure zero position divided the soil to saturated zone and unsaturated zone, and these zero position are the phreatic lines. From this figure it can be seen that the most soil mass is in the unsaturated zone, but the foot of two-stepped slope appeared the saturated zone.

![Figure 3 Phreatic line position](image)

Figure 4 is the total displacement calculated by coupled method and uncoupled method. The law of displacement in these two methods is all same, but the value of coupled method is little larger than uncoupled results. The displacement at the top of the slope with the coupled method is 179.62mm, but the result of uncoupled method is 179.48mm, the displacement difference is only 0.14mm. It is worth noting that there is no significant difference in the total displacement from results.

![Figure 4 Displacement results of slope](image)

Figure 5 is the stress distribution of slope within two methods. Two methods results shape and size are all similarly, but the result of coupled method is larger slightly. The first principal stress computed by coupled method is 171.18kPa, and the result of uncoupled method is 169.01kPa. Although the stress difference is only 2.17kPa, but it is due to the change of permeability coefficient. The initial stress is affected by the groundwater seepage and then the soil stress field changed. Because of this effect is interactively, and then the groundwater seepage promoted the change of stress. The water level of example is only 0.5m, so the stress difference is 2.17kPa. However, when the water level is higher, the stress difference must be greater. Furthermore, stress concentration appears appreciably at the foot of slope.

![Figure 5 First principal stress results of slope](image)

The first principal stress and displacement results can be seen table 2. The monitoring points have different law along the slope, especially on the foot and platform, this distribution law is not same with the simple slope [6]. The stress field of two-stepped slope platform distributed complicatedly, this is...
not only affected by the soil consolidation, but also related to the two-stepped distribution type. Because the unsaturated silt clay distributed in the vicinity of platform, the permeability is lower and the external force action is not obvious, so the results of displacement are basically the same within two methods. But the results of stress on the foot of slope are different, these data prove the two-way coupled methods between soil stress and seepage field is correct, and it is accorded with the actual field results.

Table 2. Stress and displacement compared with two methods

| Monitor position | Total displacement (mm) | First principal stress (kPa) |
|------------------|------------------------|-----------------------------|
|                  | coupled                | uncoupled                   |
| Foot of slope    | 52.83                  | 52.79                       |
| Top of slope     | 179.62                 | 179.48                      |

5. Conclusion

The characteristics of stress and displacement on two-stepped slope are not identical compared the conventional slope, and it is the key to analyzing the stability of slope. From the foundation fit numerical results, it can be seen that the first principal stress on coupled method is larger, and this is consistent with the permeability coefficient as a variable function in the stress. Therefore, these data exactly explain the two-way coupled effects in these fields are obviously. The stress field of slope affected by many factors, and the groundwater seepage is only one of these factors. The results calculated by different numerical methods show that the coupled data are larger and are relatively close to the early research results [6], so that the influence of groundwater seepage on stress field is not ignored.

In the future study, the coupled analysis method of transient seepage field will be used to solve the soil stress distribution, and the results are compared with the test data to better determine the stress field and to provide a basis for the stability analysis in multi-stepped slope.

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