Research on Stability of Gabion Slope on Seepage-stress Coupling

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Abstract. Based on an example of a basalt fiber gabion ecological slope protection project, this paper uses ABAQUS finite element software to conduct seepage-stress coupling modeling and calculation for the undisturbed slope and gabion protection under two conditions of low water level and design water level. Based on the theory of direct coupling method and strength reduction method, the slope instability evaluation criterion is based on the displacement mutation of the model and the formation of the plastic penetration zone of the soil. The safety factor of the coupled gabion protection is greater than that of the original slope. The results show that the overall stability of the slope after being supported by stone cages and grid protection pads is enhanced, which shows the feasibility and good application prospects of the engineering practice of stone cage slope protection. The research conclusions of this paper can provide reference for the study of seepage-stress coupling in water conservancy projects and provide reference for the stability analysis of similar engineering slopes.

1. Introduction

In the field of geotechnical engineering, there is interaction between fluid flow and deformation of rock and soil, and it is always in a complex dynamic change process [1]. The change of water head distribution in seepage field causes the change of seepage volume force acting on rock and soil media in slope, which makes the internal stress field and displacement field of slope change accordingly. With the change of slope stress field, the pore ratio and porosity of rock and soil media change, which changes the permeability coefficient of soil and finally leads to the change of seepage field in the whole slope. The coupling relationship between seepage field and stress field is bound to affect the stability of slope. Therefore, it is of theoretical and practical significance to study the coupling effect of seepage field and stress field for the stability and safety of slope.

Comparing the research status at home and abroad, it can be seen that there are two coupling methods: direct coupling and indirect coupling [2]. Indirect coupling is to get the pore water pressure needed for stress calculation through seepage calculation, and then transfer the pore water pressure into stress analysis, that is, seepage field and stress field are calculated separately and then coupled with each other. Direct coupling is to establish a mathematical model by spatially discretizing the corresponding force field and seepage field, and then obtain its analytical solution to achieve complete coupling.

In this paper, combined with a basalt fiber gabion ecological slope protection project, ABAQUS software is used for direct coupling, and a two-dimensional finite element seepage-stress coupling
calculation model is established. The elastic-plastic strength reduction method is used to solve the slope stability safety factor, and the protection effect of gabion is evaluated.

2. Basic Theory

Seepage-stress coupling model.

![Figure 1 Schematic diagram of seepage-stress coupling]

The ABAQUS finite element software is a commonly used software for studying fluid permeability and stress coupling analysis in rock and soil mechanics [3]. The finite element method can reflect the relationship between slope stability and rock-soil deformation without being limited by the irregular geometry and uneven material. In this paper, ABAQUS software is used to analyze the coupling effect of slope stress field and seepage field by direct coupling method. In the process of analysis and calculation, firstly, the node displacement of the corresponding force field and the pore water pressure of the seepage field are spatially discretized, and the time integral is introduced into the seepage equation. Then, the stress and seepage equations are transformed into matrix form, and Newton iteration is carried out on them, so as to obtain the governing equation of coupling action. At the same time, the initial boundary conditions and stress seepage conditions are established for the model, and then analyzed within the set time step, so that the coupling equation and its solving process meet the set conditions of the model, and finally realize the seepage-stress coupling in the true sense [4].

Mass conservation equation and mechanical control equation are as follows:

\[
\frac{\partial (\rho_w n S_r)}{\partial t} + \text{div}(\rho_w v_w) = 0
\]

\[
\frac{\partial}{\partial t} \left[ \rho_a n (1 - S_r + HS_r) \right] + \text{div}[\rho_a (v_a + H v_a)] = 0
\]

\[
\frac{\partial (\sigma_{jj} - \delta_{jj} u_a)}{\partial x_j} + \frac{\partial u_a}{\partial x_j} + b_j = 0
\]

(1)

In which \( \rho_w \) is pore water density, \( \rho_a \) is air density, \( S_r \) is saturation, \( n \) is soil porosity, \( v_w \) is soil volume, \( H \) is Henry coefficient, \( v_a \) is air volume, \( \sigma_{jj} \) is soil total stress, \( \delta_{jj} \) is Kroneck constant, \( u_a \) is soil pore air pressure, and \( b_j \) is physical strength. If the air density is neglected, the soil density \( \rho \) changes with the change of solid-liquid two-phase density and porosity \( n \):

\[
\rho = (1 - n) \rho_s + n S_r \rho_w
\]

(2)

Using Galerkin finite element scheme [5], the joint displacement and pore water pressure are discretized as joint degrees of freedom. Based on the mechanical seepage equation and continuity equation, the seepage-stress coupling governing equation is obtained:

\[
[K] \{\Delta \delta\} - [L] \{\Delta \rho\} = \{F\} - \{I\}
\]

\[-[B]^T \{\Delta \delta\} - \Delta t[D] \{\Delta \rho\} = \{R\}
\]

(3)
In which $[K]$ is stiffness matrix; $\{\Delta \delta\}$ is displacement increment; $[L]$ is the nodal force corresponding to the nodal pore water pressure; $\{\Delta p\}$ is pore water pressure increment; $\{F\}$ is the external load of the node; $\{I\}$ is the unbalanced force in the last incremental step in the incremental iteration process; $[B]$ is the change of fluid volume corresponding to node deformation; $[D]$ is the change of fluid volume corresponding to the change of pore water pressure; $\{R\}$ is the correction amount of fluid volume change; $\Delta t$ is the time step.

In the process of coupling solution of stress field and seepage field, within a time step $\Delta t$, the coupling governing equation forms the iterative basis [6]. If the seepage boundary conditions and displacement boundary conditions are met, when the element enters the plastic zone, it is only necessary to replace the elastic matrix with the elastic-plastic matrix and carry out plastic iterative calculation.

**Strength reduction method.** The basic principle of strength reduction method based on seepage-stress coupling is to give a group of original soil strength parameters $c$ and $\phi$, and reduce them according to a certain coefficient $k$, so as to obtain a new group of $c'$ and $\phi'$ values, and then take them as new material parameters into the slope model for a new round of calculation. This cycle is repeated and reduced continuously until the slope reaches the limit stable state. At this time, the corresponding reduction factor is the safety factor $k_s$. The formula of strength reduction method [7] based on Mohr-Coulomb constitutive relation is:

$$
\tan \phi' = \frac{\tan \phi}{k} 
$$

(4)

$$
\frac{c'}{k} = \frac{c}{k}
$$

The position of slip surface can be automatically obtained by ABAQUS finite element software; When the slope has other supports such as gabion, the interaction between the support and the slope soil can be simulated and analyzed, and the stress and displacement characteristics of the slope at various stages during excavation can also be analyzed. The boundary conditions of the model are not limited; The stress-strain relationship and displacement relationship can be calculated, and the position of the most dangerous sliding surface, i.e., plastic through zone, can be obtained, which truly reflects the slope instability and the development process of plastic zone.

When the finite element strength reduction method is used to solve the safety factor, it is necessary to clearly judge the standard of reaching the limit equilibrium of the slope, which is summarized as the following three aspects [8]:

1)Whether the finite element calculation converges or not. After the slope is unitized, a series of linear equations can be established and solved, and the equations are iterated for many times, so that the calculation results are close to the solutions of nonlinear equations. To specify the standard of iterative convergence is to determine the criterion of slope failure until the calculation fails to converge.

2)Displacement inflection point of feature point. The sudden change of displacement at a certain part of slope is the most prominent manifestation of slope instability. When the strength reduction method is used for calculation, different slope displacement states can be obtained by each reduction. When the displacement of the characteristic points taken by the slope changes significantly compared with the previous displacement, the slope will be in a state of failure at this time, and the corresponding reduction factor is the safety factor of the slope. Using cusp catastrophe theory to find displacement catastrophe point, the relationship curve between characteristic point displacement and reduction factor is drawn, and the inflection point of the curve is taken as the criterion of slope in critical sliding state.
3) Whether the plastic zone runs through the slope. When the through area from the top to the bottom of the slope appears in the nephogram, it means that the slope will lose stability along the plastic area, and the reduction factor corresponding to the through area is the safety factor of the slope.

In order to ensure the calculation accuracy of slope safety factor, this paper takes the sudden change of displacement of a characteristic point and the penetration of plastic strain zone as the instability criterion, and takes the non-convergence of calculation as the reference to obtain the safety factor and critical slip surface of slope. Considering the seepage-stress coupling, when analyzing the slope stability, the field variable function [9] in ABAQUS is used to reduce the soil strength parameters, so that the material can be automatically reduced along with the time step in the calculation process, until the calculation does not converge.

3. Slope Stability Analysis

Engineering survey. Gabion, also known as gabion structure, is a cage-like structure with stones, which is set up to prevent slope or other structures from being washed and unstable by water flow. As a new ecological grid structure with new technology and new materials, gabion embodies the effective combination of structural stability and ecological environment [10], and is the preferred structural type for landslide control and environmental protection.

![Figure 2 Schematic diagram of basalt fiber gabion and grille pad](image)

Basalt fiber reinforced cage (gabion cage)          Basalt fiber grille pad

Figure 2 Schematic diagram of basalt fiber gabion and grille pad

After sealing basalt fiber gabion and basalt fiber grille pad filled with stones, a slope is compacted and filled step by step, in order to improve the stability and safety of undisturbed slope [11]. See fig. 3 for ecological slope protection profile of gabion.

![Figure 3 Ecological slope protection profile of basalt fiber gabion](image)

Basalt fiber composite bars are used in gabion cages and grille pads, which is an innovative and environmentally-friendly high-performance fiber material with the advantages of high strength, high temperature resistance, corrosion resistance and degradability. The size of the gabion cage is...
2m×1m×1m, and the tensile strength and elongation at break of the composite rib material are ≥1000Mpa and ≥1.8% respectively. The size specification of grille cushion is 2m×1m×0.3m, the width of basalt fiber bundle is 8mm, the tensile strength of monofilament is ≥2000Mpa, and the elongation at break is ≥4%. The cages, pads, protective nets and gabions used in ecological slope protection all meet the material requirements of GB/T2973–91, GB/T1539–94 and GB/T228–87 standards.

Computational model. According to the cross-section type and size, the ecological slope protection with basalt fiber is simulated, and a two-dimensional finite element calculation model is established, including soil, 7 basalt fiber grid pads 2m×1m×0.3m and 1 basalt fiber composite reinforced gabion cage 2m×1m×1m. According to the actual operation situation, the safety factor of slope stability under two working conditions of low water level and design water level is solved, in which the low water level elevation is 141.75m and the design water level elevation is 144.25m. See fig. 3 for the positional relationship between gabion and slope. Calculation parameters of slope and gabion are mainly provided by geological survey data, as shown in Table 1.

| Category   | Density/(t·m⁻³) | Osmotic coefficient/(m·s⁻¹) | Shear strength parameters | Elastic modulus/(GPa) | Poisson’s ratio | Coefficient of friction with cage |
|------------|------------------|-----------------------------|---------------------------|----------------------|----------------|----------------------------------|
| Dry        | 1.48             | 1.78                        | 5×10⁻⁵                    | 14                   | 15             | 50                              | 0.30     | 0.55                           |
| Saturated  |                  |                             |                           |                      |                |                                  |          |
| Soil body  |                  |                             |                           |                      |                |                                  |          |
| Stone      | 2.65             | 1×10⁻¹                      | 60                        |                      | 0              | 56                              | 0.20     | \                             |
| Crib       | 2.06             |                             |                           |                      |                |                                  | 0.22     | 0.60                           |

The models of undisturbed slope and gabion slope protection adopt quadrilateral elements to divide grids, which is convenient for grid calculation of each element. The coordinate system takes the direction perpendicular to the slope height as the X axis, the direction pointing to the river bank as the positive direction, the direction along the slope height as the Y axis, and the direction pointing to the bottom of the slope as the negative. According to the ideas and methods introduced in 2.1 and 2.2, the top of the calculated area extends 15m to the right and the slope height is 15m, and the numerical calculation models of undisturbed slope and gabion slope protection as shown in Figures 4 and 5 are established. Horizontal displacement is constrained on both sides of the slope, while horizontal displacement and vertical displacement are constrained at the bottom. The pore water pressure of low water level and design water level is applied to the water-facing slope, and the pore water pressure of underground water level is applied to the far boundary. The height of underground water level is taken according to the elevation of river bottom.

![Figure 4 Schematic diagram of two-dimensional geometric model of undisturbed slope](image-url)
4. Analysis of Calculation Results

Low water level condition. Under the condition of low water level, the comparison of total head distribution and saturation line position between undisturbed slope and gabion slope protection is shown in Figures 6 and 7. It can be seen from the figure that for gabion slope protection, the maximum pore water pressure is slightly lower than that of undisturbed slope when considering seepage-stress coupling, and the saturation line is slightly lower, but there is little difference.

In the seepage-stress coupling analysis of gabion slope protection, firstly, the original slope stress should be balanced before slope protection construction to ensure that the settlement of slope soil before construction is zero, and gabion units should be added to simulate the slope protection construction process and retain the stress part of soil under seepage and dead weight.

As shown in fig. 8, after cutting the undisturbed slope and adding gabions and pads, the maximum horizontal displacement of the whole model of gabion slope protection appears at the top of gabion, with a maximum value of 1.3cm; The maximum settlement occurs at the bottom, with a value of 1.38cm.
Under the action of gabion load, the top of the slope has uplift phenomenon, and the maximum uplift is 1.29cm.

Fig. 8 Cloud picture of initial displacement of slope

Fig. 9 is a nephogram of displacement distribution of gabion and grille cushion. It can be seen from the figure that the displacement of gabion has little change. Under the load, the maximum horizontal displacement of gabion is 1.24cm, which occurs at the top of gabion. The maximum vertical settlement is 1.38cm, which occurs at the bottom of gabion. The settlement at the top of gabion is the smallest, which is 0.23cm.

Fig. 10 and fig. 11 show the horizontal displacement nephogram and vertical displacement nephogram of undisturbed slope and gabion slope protection under the seepage-stress coupling action, respectively. It can be concluded from the figure that: The maximum horizontal displacement of undisturbed slope is 9.7cm, and that of gabion slope protection is 1.23cm, which is slightly smaller. Because the critical failure is judged by the inflection point of horizontal displacement at the top of slope, the vertical displacement nephogram is only used as an auxiliary reference.
As shown in the cloud picture of plastic zone in Figure 12, by comparing the plastic zones of two kinds of slopes, it can be seen that after the gabion-grille pad supporting construction, the elevation of the lower end of the plastic penetration zone of the slope moves down obviously because of the protective effect of gabion on the slope soil.

![Figure 12 Cloud image of plastic zone](image)

The safety and stability of undisturbed slope and gabion slope protection under low water level are analyzed by strength reduction method. According to the results of finite element calculation, the relationship curve between the horizontal displacement of the slope characteristic point, that is, the peak of the slope facing water and the strength reduction factor is drawn, as shown in Figure 13.

![Figure 13 Horizontal displacement-reduction coefficient curve](image)

It can be seen from the figure that, with the inflection point of curve as the criterion, when the strength reduction factor increases to 1.31, the displacement at the top of the slope changes abruptly. According to fig. 12, the plastic zone has penetrated and has undergone great deformation. It can be judged that the overall stability safety factor of undisturbed slope under low water level is 1.31 under the coupling action of seepage and stress. Similarly, it can be judged that the overall stability safety factor of gabion slope protection under low water level is 1.33.

![Design water level condition](image)

By comparing the safety and stability of undisturbed slope and gabion slope protection under low water level, it can be concluded that when gabion slope protection is in critical instability state, the corresponding safety factor $K=1.33$, which is higher than that of undisturbed slope $K=1.31$. Comparing the plastic zones of the two slopes, it can be seen that with the continuous softening of soil materials, the plastic zones extend from the foot of the slope to the top of the slope until they are connected. After the gabion slope protection construction, the lower end of the plastic penetration zone of the slope moves down obviously due to the protective effect of the gabion on the slope soil. It shows that under the low water level condition, adopting gabion and grille pad protection from the left side of the toe to the slope can improve the overall stability of the slope.

**Design water level condition.** Under the design water level condition, the comparison diagrams of total head distribution and saturation line position of undisturbed slope and gabion slope protection are shown in Figures 14 and 15. It can be seen from the figure that for gabion slope protection, the maximum pore water pressure is slightly lower than that of undisturbed slope when considering seepage-stress coupling, and the saturation line is slightly lower, but the overall difference is not big.
Fig. 14 Total water head distribution map

(a) Original slope

Field-4

(b) Gabion slope protection

Figure 14 Total water head distribution map

(a) Original slope

POR

(b) Gabion slope protection

Figure 15 Location map of wetting line

Fig. 16 shows the initial displacement nephogram of gabion slope protection after adding gabion, cushion and other supports to the undisturbed slope under the design water level, considering seepage-stress coupling. As shown in the figure, the maximum horizontal displacement of the whole model appears at the top of the gabion, with the maximum value of 3.63cm; The maximum settlement occurs at the position of gabion near riverbed, with a value of 1.89cm. Under the action of design water level load, the top of slope has uplift phenomenon, with the maximum uplift of 8.60cm.

(a) Horizontal displacement nephogram  (b) Vertical displacement nephogram

Figure 16 Nephogram of initial displacement of slope

Fig. 17 is a nephogram of displacement distribution of gabion and grille cushion. It can be seen from the figure that the maximum horizontal displacement of gabion is 3.63cm at the design water level, which occurs at the top of gabion. The maximum vertical settlement is 1.89cm, which occurs at the bottom of the gabion, and the settlement at the top of the gabion appears uplift, which is 6.45cm.
Fig. 18 and fig. 19 show the horizontal displacement nephogram and vertical displacement nephogram of undisturbed slope and gabion slope protection under the condition of design water level under seepage-stress coupling and strength reduction analysis. It can be concluded from the figure that the horizontal displacement of gabion slope protection is slightly smaller than that of undisturbed slope. As the critical failure is judged by the inflection point of horizontal displacement at the top of slope, the vertical displacement nephogram is only used as an auxiliary reference.

Comparing the plastic zones of the two slopes in Figure 20, it can be seen that the sliding surface slides downward in an arc shape when losing stability. The lower end of plastic penetration zone of undisturbed slope moves down obviously after gabion support.

The strength reduction method is used to analyze the safety and stability of undisturbed slope and gabion slope protection under design water level conditions. According to the results of finite element calculation, the relationship curve between the horizontal displacement of the slope characteristic point,
that is, the peak of the slope facing water and the strength reduction factor is drawn, as shown in Figure 21.

It can be seen from the figure that, with the inflection point of curve as the criterion, when the strength reduction factor increases to 1.28, the displacement at the top of the slope changes abruptly. Combined with fig. 20, the plastic zone has penetrated and has undergone great deformation. It can be judged that the overall stability safety factor of undisturbed slope under the design water level condition is 1.28 under the coupling action of seepage and stress. Similarly, it can be judged that the overall stability safety factor of gabion slope protection under low water level is 1.37.

5. Summary

1) According to the nephogram of plastic zone of slope, the failure form and potential sliding surface of gabion slope protection calculated by seepage-stress coupling calculation are basically consistent with the actual failure form. It shows that the safety factor and potential sliding surface of gabion slope protection can be solved by using ABAQUS software and elastic-plastic strength reduction method.

2) At low water level, the stability safety factor of undisturbed slope and gabion slope protection is 1.31 and 1.33 respectively. At the design water level, the stability safety factor of undisturbed slope is 1.28, and that of gabion slope protection is 1.37. By comparing the safety factors of slope stability under two working conditions, it can be seen that the deformation of slope increases with the increase of water level; The safety factor decreases with the increase of water level. It shows that in the construction process, the groundwater level should be lowered as much as possible to improve the safety factor of the slope.

3) According to the strength reduction method, the stability coefficient of gabion slope protection at low water level and design water level is greater than the original slope stability coefficient, which shows that the stability of slope can be effectively improved by using gabion and grille pad.
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