Particle flow analysis of basalt fiber gabion slope under conditions of rapid drawdown of water level

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Abstract: As a new green material, basalt fiber has the advantages of high strength and corrosion resistance, and is an ideal material for ecological protection technology. The rapid change of the hydraulic gradient within the slope caused by the sudden drop of river water level is an important factor inducing bank slope instability. Studying the stability of gabion slope protection under this condition is the key to evaluating the effect of gabion support. Taking a basalt fiber gabion slope protection project as an example, this paper carried out the stability study of the gabion slope protection under the condition of sudden drop in water level and compared it with the original slope. The stability was analyzed from the perspectives of deformation and stress, and revealed the deformation mechanism and the beneficial effects of the gabion structure during the instability failure process of the original slope. The results show that under the condition of a sudden drop in river water level, the use of gabion support from the left side of the slope to the slope surface can improve the stability of the slope, and there will be no continuous sliding surface in the slope, and the failure of gabion appears as partial dislocation and separation phenomenon. The research results provide important reference value for river gabion slope protection design and stability evaluation.

1. Introduction

The sudden drop of river water level will reduce the stability of bank slope. This is because the infiltration line in the slope and the water level outside the slope did not fall at the same time after the sudden drop of water level, and the pore water pressure could not dissipate quickly, which caused a downward trend to the slope under the action of seepage force, and even caused instability and damage [1]. Therefore, it is particularly important to analyze the stability of river bank slope under the condition of sudden drop of water level, discuss the movement process of bank slope instability, and select the appropriate support form according to the characteristics of bank slope instability under this condition. As a kind of flexible structure, gabion has the advantages of high strength, good water permeability and ecological environment protection. It has been widely used in retaining wall and bank slope support engineering and achieved good results. Compared with the traditional gabion mesh using steel wire as material, basalt fiber has good durability and corrosion resistance, and the binding effect of fiber can significantly improve the overall deformation coordination ability [3]. Basalt fiber gabion structure can well combine the advantages of the two, and has important practical value in river ecological control engineering.

The instability and failure movement of river bank slope is a complex process of sliding, translation and rotation of rock and soil mass, with macroscopic discontinuity and randomness of single block
movement [4]. Particle discrete element [5] adopts the disk and sphere particle model, which can analyze the meso-mechanism of slope failure. At present, the granular discrete element study of gabion support is mainly concentrated in the field of retaining wall. Chai Hejun [6] and others have studied the stability of gabion retaining wall by using discrete element method, which provides an important reference value for the practical engineering application of gabion retaining wall. Tian Qilin [7] established a variety of numerical models of gabion retaining wall by using particle flow, obtained the optimal design scheme of gabion retaining wall by comparison, and analyzed its mechanical properties. Zhang Bo [8] used PFC2D to simulate the displacement, deformation and failure mechanism of gabion retaining wall during pavement compaction. Meng Yunwei [9] established the particle flow model of the stepped gabion retaining wall at the back of the wall, and studied the mechanical behavior of the gabion retaining wall during construction. At present, there are relatively few studies on the basalt fiber gabion structure in river slope treatment projects, and the stability evaluation of the structure under the condition of sudden drop in water level is urgently needed. In this paper, combined with a basalt fiber gabion ecological slope protection project, the particle flow model of undisturbed slope and gabion slope protection is established, and the stability safety factor of undisturbed slope and gabion slope protection under the condition of sudden drop of water level is solved by particle flow strength reduction method, and its stability is analyzed from two aspects of deformation and stress.

2. Establishment of calculation model

2.1 Computation model

The elevation of the top of the undisturbed side slope of a river course is 148.25m, and the cross-sectional view of the ecological slope protection with basalt fiber gabion is shown in Figure 1. The design flood level of the river is 146.25m, and the low water level is 141.75m. The slope support plan is: place two grid protection pads on the left side of the slope foot, the size is 2m×1m×0.3m (length×width×height); place a stone cage net box at the slope foot position, the size is 1m×1m×1m; 10 gabion cages are placed on the slope surface with a setback table, the size is 1m×1m×0.5m. The stone cages are filled with boulders, and the main mechanical parameters of the slope are shown in Table 1.
2.2 Calibration of mesoscopic parameters of soil and Gabion monomer

In order to obtain the meso-parameters corresponding to the macro-parameters of soil, the micro-parameters of soil were calibrated by biaxial compression numerical test using PFC2D program, and the contact bonding model was adopted for soil particles [10]. The model can truly reflect the macroscopic mechanical properties of clay viscous materials.

According to the above test method, the model size of soil biaxial compression test is 3.0m×1.5m (length× width), and biaxial compression tests with confining pressures of 100kPa, 200kPa and 300kPa are carried out. See table 2 for the meso-parameters obtained after calibration according to geotechnical mechanical parameters of gabion slope protection.

**Table 2 Microscopic parameters of soil particles**

| Material name | Grain density kg·m⁻³ | Grain size d/m | Normal stiffness kN·m⁻¹ | Tangential stiffness kN·m⁻¹ | Normal bond force nb/N | Tangential adhesion ns/N | Friction coefficient |
|---------------|----------------------|----------------|-------------------------|---------------------------|------------------------|------------------------|---------------------|
| Soil body     | 1480                 | 0.04-0.06      | 1.5×10⁷                 | 1.5×10⁷                   | 5.67×10³              | 1.26×10³              | 0.2                 |

Considering that the gabion monomer is usually exposed on one side in the project, the uniaxial compression test is used to calibrate the meso-parameters of the gabion monomer. The block stone filled in the gabion cage is a typical loose body, and a linear model is used. The gabion steel bar adopts a parallel bonding model, which can transmit force and bending moment, and can simulate the tensile and bending characteristics of the steel bar. Since in the actual uniaxial compression test, the loading plate is in close contact with the steel bars and boulders, the contact between the loading plate and the steel bars also adopts a parallel bonding model.

At present, there are few researches on indoor and on-site gabion experiments, and there are few literatures using gabions of actual engineering size for experimental research. Therefore, taking the uniaxial compression test of the gabion monomer by Jiang Yang et al. [11] as a reference, the size of the gabion monomer is 1m×0.5m, and the mesoparameters of the gabion monomer are determined by the trial and error method in Table 3. Among them, B1 represents the contact between the rock, B2 represents the contact between the composite bar and the rock, and B3 represents the contact between the composite bar. Figure 2 shows the comparison between the stress-strain curve of the gabion uniaxial compression test under numerical simulation and the result of the indoor test C1 sample by Jiang Yang et al. [11].

**Table 3 Mesoscopic parameters of gabion monomer**

|       | Grain density kg·m⁻³ | Grain size d/m | Effective modulus E/Pa | Stiffness ratio | Friction coefficient | Tensile strength /Pa | Cohesion /Pa | Bond effective modulus E’/Pa | Bond stiffness ratio |
|-------|----------------------|----------------|------------------------|----------------|---------------------|---------------------|--------------|-----------------------------|--------------------|
| B1    | 2650                 | 0.08-0.10      | 5.6×10¹⁰              | 2.4            | 0.65                |                     |              |                             |                    |
| B2    | 2.8×10⁷              | 2.0            | 0.35                   |                |                     |                     |              |                             |                    |
| B3    | 2060                 | 0.005          | 5×10¹⁰                 | 1.0            | 0.45                | 5×10⁹              | 5×10¹⁰      | 5×10¹⁰                      | 1.0                |

Note: B1 refers to the contact between blocks, B2 refers to the contact between composite bars and blocks, and B3 refers to the contact between composite bars.
2.3 Construction of particle flow model for gabion revetment
According to the gabion ecological slope protection section, export the slope model drawn in AutoCAD in the dxf file format, use the geometry import command to import the dxf file into PFC2D, and use the wall import geometry command to generate the slope profile and wall, and use ball distribute Command to generate soil particles within a certain radius and delete excess particles outside the wall. The ratio of the maximum unbalanced force of the particles to the maximum contact force is less than $1.0 \times 10^{-5}$ as the balance condition. After the model reaches the equilibrium state, the velocity and displacement of the particles are cleared, and the meso-parameters in Table 2 are given to the soil particles. The FISH function is compiled to establish the gabion monomer model, and the meso-parameters in Table 3 are given to it. Linear contact model is adopted for the contact between soil and gabion (D1) and gabion monomer (D2), and its meso-parameters are shown in Table 4. The particle flow model of gabion slope protection finally established is shown in Figure 3. In the calculation area, the top of the slope extends 10m to the right, the upper and lower boundaries are 12m, and the total number of particles is 130,526. Among them, there are 117,600 soil particles, 878 stone particles and 12,048 steel bar particles. In order to better analyze the gabion slope protection, the particle flow model of undisturbed slope is established. As shown in Figure 4, there are 120,888 soil particles in total. In addition, in order to study the stress changes of soil in the slope, stress measurement circles with a radius of 1.0m were set at four different positions of the undisturbed slope and four different positions of the gabion slope protection to record the stress changes of soil in the sliding process of the slope at the corresponding positions.

| Table 4 Meso-parameters between the interface of gabion slope protection materials |
|-----------------------------------|----|----|-------|
|                                   | Effective modulus $E^\ast$/Pa | Stiffness ratio $k^\ast$ | Friction coefficient |
| D1                                | $2 \times 10^7$               | 1.0                      | 0.35                |
| D2                                | $5 \times 10^{10}$            | 1.0                      | 0.45                |

Note: D1 refers to the contact between soil and gabion, and D2 refers to the contact between gabion monomers.
3. Simulation of water acting on soil and stone particles

When the river water level drops suddenly, the water will have a great impact on the undisturbed slope and Gabion slope protection. When the water level drops to 141.75 m, the river water level is as high as the foot of the slope, the infiltration line in the slope is higher than the external water level, and the hydraulic gradient forms a large seepage force to the river side, which increases the sliding trend of soil along the seepage direction in the slope, which is not conducive to the stability of slope protection.

Because there is no built-in seepage calculation program in particle flow software PFC, finite element software is used to calculate the seepage field of undisturbed slope and gabion slope protection under the condition of sudden drop of river water level, and the river water level drops from 146.25m to 141.75m within 5 days. When the water level drops to 141.75m, the safety factor of undisturbed slope and gabion slope protection is the lowest. This water level is the most unfavorable water level in the process of sudden drop, so the stability of the slope is analyzed in combination with the seepage field at this time, and the flow chart of applying particle seepage force is shown in Figure 5.

![Figure 5 Particle penetration force application process](image)

The seepage field within 130m of the slope is calculated by finite element software, and the main calculation area of particle flow is selected for display. The total head distribution at the most unfavorable water level under the condition of sudden drop of river water level is shown in Figure 6(a) and (b). It can be seen from the figure that after using gabion support, the saturation line in the slope decreases, and the contour line of total head at the toe of slope becomes sparse. In order to simulate the buoyancy of water, the particles below the saturation line are calculated by buoyancy weight.
4. Stability analysis of gabion revetment

4.1 Calculation of stability safety factor by particle flow strength reduction method

Zhou Jian et al. [12] introduced the intensity reduction method into the particle discrete element. The basic idea is to reduce the contact bond strength and friction coefficient of particles continuously until the displacement of characteristic particles suddenly changes and reaches the critical displacement, which can be used as the basis for judging the failure of the model. The ratio of strength parameters before and after reduction becomes the strength reduction factor, and the strength reduction factor when the slope displacement changes suddenly is the stability safety factor of the slope.

According to the above method, under the condition of sudden drop of river water level, the contact bond strength and friction coefficient of slope model are reduced, and the initial reduction coefficient is set as 1.0, and the reduction coefficient is gradually increased. When the particle displacement field [13] reaches the critical displacement, the calculation is stopped. At this time, the stability safety factor of undisturbed slope is 1.25, and that of gabion slope protection is 1.50.

4.2 Deformation feature analysis

4.2.1 Original slope

According to the stability safety factor obtained by the particle flow strength reduction method, the meso-parameters of the undisturbed slope soil strength are reduced, and the failure process is simulated by applying gravity and osmotic force to the slope. See Figure 7 for landslide failure modes of undisturbed slope at different time steps.

From the simulation results, it can be seen that when the calculation runs to $10 \times 10^4$, because of the sudden drop of water level, the infiltration line in the slope is higher than the outer water level, the soil particles are subjected to the seepage force to the river side, and the hydraulic gradient at the foot of the slope is large. Moreover, under the action of gravity extrusion of overlying soil, the contact bond between particles at the foot of the slope and the middle of the slope began to break obviously, and the particles at the foot of the slope tended to extrude outward. At the time of $20 \times 10^4$ steps, the contact bonding of particles on the top of the slope breaks, forming a circular sliding surface, and the soil particles slide down along the sliding surface under the action of seepage force, resulting in many obvious tensile cracks in the middle of the slope. At $30 \times 10^4$ steps, with the increase of bond fracture between particles of slope soil, particles slip out of slope and start to accumulate at the foot of slope. At the same time, the contact bond between the deep soil particles at the foot of the slope and the middle of the slope breaks, and the particles at the left side of the foot of the slope tend to float outward. At $50 \times 10^4$ steps, the slope particles continuously slide down along the circular sliding surface and accumulate at the foot of the slope, resulting in obvious tensile cracks at the top of the slope. A circular bond contact failure zone with a certain thickness is formed in the deep part of the slope. Under the action of seepage force and driven by landslide particles on the upper layer, soil particles continuously slide out from the left side of the slope foot. At $70 \times 10^4$ steps, the particles on the left side of the slope foot continuously slide out, which is stabilized by the gravity of the upper soil, so the deformation rate is slow. At $100 \times 10^4$ steps, the movement of landslide stopped and the deformation tended to be stable.
4.2.2 Gabion slope protection

According to the obtained stability safety factor, the meso-scale parameters of soil strength of gabion slope protection are reduced, and the displacement nephogram of gabion slope protection under different steps is shown in Figure 8.

At $30 \times 10^4$ steps, under the action of gravity and outward seepage force, the whole slope produces downward displacement deformation, and under the joint action of stone particles and soil particles, the reinforcement in the middle of the pad produces bending deformation. At $50 \times 10^4$ steps, the displacement developed to the middle of the slope, and the position of the two grid pads was staggered due to the squeezing action of the surrounding soil particles. At $70 \times 10^4$ steps, the deformation developed to the top of the slope, and some gabion cages broke apart. At $100 \times 10^4$ steps, the displacement and deformation of the soil in the slope are basically stable, the displacement of the top of the slope is the largest, and some gabion units are separated, and the contact bonding of the soil particles in the slope does not form a through sliding surface, so the slope cannot be subjected to sliding failure. The failure of gabion slope protection is mainly characterized by dislocation and detachment of gabion monomer, and the reasons for the failure of slope body are as follows: (1) Because gabion monomer is used for support from the left side of slope foot to slope surface, the density of stone filled in gabion monomer is 1.79 times of that of soil. This is equivalent to adding a cover weight from the left side of the slope foot to the slope surface, which improves the integrity of the slope under the gravity of the gabion. (2) After adopting gabion support, the friction between block stone, block stone and steel bar, gabion monomer and gabion and soil. This makes the distribution of contact bond fracture of soil particles more uniform and unable to penetrate. Therefore, the gabion support can effectively prevent the soil in the slope from being damaged and sliding, which is of positive significance to the prevention and control of landslide.
4.3 Analysis of stress characteristics

4.3.1 Undisturbed slope

The stress changes in the process of slope failure are monitored by establishing a measuring circle, and the stress change curve of the measuring circle (with tension as positive) is shown in Figure 9. It can be seen from the figure that at the initial stage of slope failure, shear failure occurs at the foot of the slope, and the No.1 measuring circle located at the top of the slope is subjected to tensile stress caused by the deformation of the lower soil. As the soil particles at the top of the measuring circle slip downward due to tensile cracks, the stresses in X direction and Y direction in the circle become compressive stresses, and decrease with the continuous sliding of the particles at the top of the slope. The No.2 measuring circle is located in the middle of the slope, and the compressive stress in the X direction changes gently, while the compressive stress in the Y direction decreases gradually and then tends to be stable. Y-direction stress of No.3 measuring circle is mainly formed by the sliding and extrusion of overlying soil. With the continuous sliding of overlying soil particles, the Y-direction stress in the circle fluctuates continuously, and the change curve is similar to that of No.2 measuring circle. Due to the large hydraulic gradient at the foot of the slope, the compressive stress in X direction and Y direction in No.3 measuring circle is greater. The No.4 measuring circle is located at the foot of the slope. Because the slope gradient is gentle, the particles in the circle are squeezed more horizontally by the overlying soil, so the compressive stress in X direction is greater than that in Y direction. With the particles in landslide sliding down continuously and accumulating at the foot of slope, the stress in Y direction in the circle increases continuously, and finally the stress in both directions is close to equal.
4.3.2 Gabion slope protection

Figure 10 shows the stress change curve recorded during the failure process of the gabion slope protection. The soil particles have reached equilibrium when the gabion slope protection model is established, and the contact force tends to zero. Therefore, the stresses in the x-direction and y-direction of the four measuring circles are basically zero before the initial stage. The duration of zero stress from measuring circle No. 4 to measuring circle No. 1 gradually increases. This is because when the slope is deformed, first displacement occurs at the toe of the slope. As the deformation accumulates, it gradually develops toward the top of the slope. The entire deformation process takes a certain time. Therefore, the zero stress duration of the No. 4 measuring circle at the foot of the slope is the shortest. Due to the infiltration of the slope toward the river side, the soil particles tend to move outwards, but under the support of the slope gabion, the soil particles cannot move freely, and the contact bonding of the soil particles in the slope cannot be formed. Through the sliding surface, the particles become in close contact, and the x- and y-direction stresses in the measuring circle gradually increase.

Figure 9 Circular stress change curves of original slope measuring circles
5. Conclusion
In this paper, the stability of basalt fiber gabion slope protection under the condition of sudden drop of water level is analyzed by using two-dimensional particle flow method and strength reduction method, and compared with the original slope, the following conclusions are drawn:

(1) The soil in the slope is subjected to the river seepage force, which is the most unfavorable working condition of the project. The stability coefficient of gabion slope protection is 1.50, which is 20% higher than that of undisturbed slope.

(2) From the left side of the slope toe to the slope surface, gabion support can increase the slope cover weight, prevent the slope sliding deformation, and effectively improve the slope stability.

(3) Under the action of gabion support, the distribution of contact bond fracture of soil particles is more uniform, and no through sliding surface can be formed. In the process of failure, the gabion monomer is dislocated and detached. The use of gabion support can effectively prevent the destruction and sliding of the soil in the slope.

(4) The design flood level of the river should be considered in the layout of the gabion cage, and the composite reinforcement of the gabion cage at the foot of the slope should be reinforced. The gabion cage used in this paper exceeds the design flood level by 0.5m, which can effectively improve the stability coefficient under sudden drop of water level, and provide reference for similar projects.

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