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Research on the Stability of the Geocell Protected Bank Slope under Rainfall

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Abstract. Based on the drainage project in the flight area of Beijing New Airport, the theoretical analysis, finite element simulations and laboratory model tests were carried out on the influence of the stability of the slope which was protected by geocell on its surface. In this paper, we studied the deformation laws of slope soil, the overall stability of slope soil and the erosion effect of slopes under different gradients in the cases where the slope surface was protected by geocell or not. The results show that after the geocell is installed, the pore water pressure of the slope soil is significantly reduced, and the cohesion and friction between the soil particles are indirectly increased. Besides, the restraining effect of the geocell on the topsoil can significantly reduce the maximum plastic deformation of the slope soil, reducing the maximum displacement of the slope soil by about one third. Lastly, the anti-erosion effect of geocell is more obvious after the slope gradient exceeds 1:1.5, and is most significant when it reaches 1:1.25. However, when the slope gradient reaches 1:1, this effect will decrease.

1. Introduction

In order to protect the ecological environment and avoid soil erosion, vegetation greening is very common in ditches and dam slopes. However, for the slope at the initial stage of construction, vegetation can not completely cover the slope and the root system of vegetation is not strong enough, the slope is most vulnerable to rain and water damage. To reduce the loss of slope soil and slope soil slip as much as possible, geocell can be used for constraint the topsoil. Geocell slope protection technology utilizes the restraint effect of geocell on the topsoil, and combines the vegetation root system on the slope surface to form the whole lateral connection and coverage of the slope soil, so as to realize the safety protection of the slope and the restoration of the original slope ecology.

In view of the application of geocell in slope engineering, experts and scholars at home and abroad have carried out some theoretical analysis and engineering practice research work in recent years[1-7], and put forward some suggestions for improvement. However, due to the differences of geological conditions and hydrological environment in different projects, serious soil loss often occurs in engineering practice. These problems are not only related to the engineering soil and geotechnical parameters, but also related to the design gradient, construction method, layout of geocell and so on. Therefore, it is necessary to select the proper design gradient and construction method according to the specific soil parameters according to the possible rain erosion degree in the initial stage of the project, so as to give full play to the protective effect of geocell on the slope soil and reduce the soil loss on the surface as far as possible.
2. Soil reinforcement effect of geocell on slope surface
The soil reinforcement effect of geocell is mainly manifested in the lateral restraint of the cell to the soil (as Figure 1), which includes the frictional effect of the cell sheet on the filled soil and the tightening effect of the three-dimensional space structure formed by the cell tension on the filled soil[8].

2.1 Frictional effect
In the flexible protective layer formed by the geocell and the inner soil, the elastic modulus of the geocell material is much larger than that of the soil because of the difference in material properties. Therefore, when the two materials are loaded together, they will produce a great deformation difference, and the relative movement trend caused by this large deformation difference is the main source of friction between the two on the contact surface. And the larger the relative deformation is, the stronger the friction effect will be.

2.2 Tightening effect
During the construction of geocell slope protection, the soil inside the geocell is usually leveled and compacted. The soil will expand around because of compaction, so that the side of geocell is subject to a certain tension force. And it will produce a tightening effect on the internal soil under the action of tension force, which restricts the lateral displacement of soil. Because of the great tensile strength and weld peeling strength of the cell material, the geocell structure can provide strong lateral restraint under the action of the upper load.

Table 1. Material parameters in finite element calculation

| Material Parameter                        | Soil | Geocell | Anchor |
|------------------------------------------|------|---------|--------|
| Internal friction angle / (°)            | 32.4 | —       | —      |
| Cohesion / (kPa)                         | 8.52 | —       | —      |
| Dilatancy angle / (°)                    | 0    | —       | —      |
| Elastic modulus / (MPa)                  | 30   | 500     | 20600  |
| Poisson ratio                            | 0.3  | 0.25    | 0.25   |
| Density / (kN/m³)                        | 19   | 10      | 78.5   |

Figure 1. Lateral confinement of geocell to its internal soil

3. Finite element analysis of slope protection law of geocell

3.1 Finite element calculation model and material parameters

Figure 2. Finite element calculation model
When modeling with ABAQUS finite element software, the whole slope model adopts 3D solid structure, and the rainfall intensity is $5 \times 10^{-6}$ m/s. In order to analyze the change of pore water pressure caused by rainfall infiltration, we adopted a hexahedral C3D8P element with pore pressure freedom for the soil, a S4R shell element for the geocell and a beam element for the anchor[9]. The calculation model and material parameters of finite element model are shown in Figure 2 and Table 1 respectively.

3.2 Analysis of finite element calculation results

3.2.1 Influence of geocell protection on pore water pressure of slope soil

![Figure 3. Pore water pressure distribution of unprotected slope](image)

![Figure 4. Pore water pressure distribution of geocell protected slope](image)

The results of Figure 3 show that the infiltration of rainwater makes the pore pressure accumulate along the depth of the slope. The pore pressure at the foot of the slope reaches 40 kPa, and the pore pressure difference between the top and the foot of the slope is as high as 40 kPa. This also increases the seepage velocity of water in the soil and is not conducive to the stability of the soil.

The results of Figure 4 show that the restraint effect of geocell on soil significantly alleviates the cumulative effect of seepage pressure, thus reducing the maximum pore pressure at the foot of slope to 14 kPa, and reducing the pore pressure difference between the top and the foot of slope to only 12 kPa. At the same time, the decrease of pore water pressure indirectly increases the cohesion and friction between soil particles, and also improves the stability of slope structure.

3.2.2 Influence of geocell protection on plastic strain of slope soil

![Figure 5. Plastic zone distribution of unprotected slope](image)

![Figure 6. Plastic zone distribution of geocell protected slope](image)

The results of Figure 5 show that the plastic deformation of topsoil of unprotected slope under the action of rain has a significant cumulative development trend, that is, the plastic deformation increases...
gradually from the top of slope to the foot of it, resulting in the plastic deformation at the foot of slope up to 9‰, thus increasing the risk of sliding instability at the foot of slope.

The results of Figure 6 show that the relative displacement of soil between adjacent compartments is limited after the geocell is set up, thus eliminating the accumulation of plastic deformation transferability between different compartments, making the plastic deformation of topsoil significantly reduce from the top of slope to the foot of it, and the distribution is more uniform, all below 2‰, thus benefiting the stability of topsoil. It is worth pointing out that the plastic deformation of the topsoil decreases remarkably after the geocell is set up, but the plastic deformation of the deeper soil near the top of the slope increases obviously. In order to avoid the risk caused by the excessive plastic deformation of the deep soil, it is necessary to take appropriate reinforcement measures for the deep soil at the top of the slope.

3.2.3 Influence of geocell protection on slope soil displacement

Under the action of continuous rain infiltration, besides the scouring phenomenon of soil on the slope, the tendency of soil sliding on the embankment slope will also increase. Based on the results of finite element analysis, the total displacement distribution of slope soil with or without geocell protection are shown in Figure 7 and Figure 8 respectively.

Figure 7 shows that the maximum total displacement of unprotected slope soil can reach 24 mm, and Figure 8 shows that it is only 16 mm after geocell protected. Obviously, the setting of geocell can reduce the displacement of slope soil by about one third, and improve the stability of slope soil remarkably.

4. Study on erosion experiment of geocell slope protection model

4.1 Experimental design

In order to verify the restraint effect of geocell on slope soil, simulated rainfall erosion experiments are carried out on slopes with or without geocell protection (as Figure 9). The experiments are carried out in a transparent toughened glass test box with a length of 2m, a width of 1m and a height of 1m, and the gradient of slope models are 1:1, 1:1.25, 1:1.5, 1:1.75 and 1:2. The soil samples were all collected from the flight area of Beijing New Airport. The scale change and erosion characteristics of the slope adjacent to the side wall of the test box were recorded every 10 minutes, and the rainfall lasts 60 minutes.
4.2 Experimental results and analysis

4.2.1 Slope erosion volume of simulated rainfall on different gradients
After 60 minutes continuous rainfall scouring, the slope erosion volume in different gradients and slope protection forms are calculated as shown in Table 2.

Table 2. 60 minute slope erosion volume under different slope protection forms and gradients

| Gradient | Protection status | Cumulative erosion volume (cm$^3$) | Erosion volume per unit area (cm$^3$/cm$^2$) |
|----------|-------------------|-------------------------------------|------------------------------------------|
| 1:2      | Unprotected       | 49965                               | 3.35                                    |
|          | Geocell protected | 41911                               | 2.81                                    |
| 1:1.75   | Unprotected       | 46090                               | 3.43                                    |
|          | Geocell protected | 40368                               | 2.81                                    |
| 1:1.5    | Unprotected       | 45689                               | 3.45                                    |
|          | Geocell protected | 41654                               | 3.47                                    |
| 1:1.25   | Unprotected       | 54276                               | 5.08                                    |
|          | Geocell protected | 37342                               | 3.49                                    |
| 1:1      | Unprotected       | 39940                               | 4.23                                    |
|          | Geocell protected | 32643                               | 3.46                                    |

4.2.2 Law of erosion change at different gradients
Based on the experimental results in Table 2, the variations of erosion per unit area in 60 minutes with different slope gradients and slope protection forms are shown in Figure 10.

As can be seen in Figure 10, whether the slope is protected or not, the degree of rain erosion will increase with the increase of gradient, and the geocell slope protection can significantly reduce its erosion volume. As far as the slope protection effect of geocell is concerned, it is more significant.
after the gradient exceeds 1:1.5, and is most significant when it reaches 1:1.25. Therefore, when the slope gradient exceeds 1:1.5, the effect of geocell slope protection is better. It is noteworthy that when the slope gradient reaches 1:1, the slope protection effect of geocell decreases, which may be related to the smaller actual rainfall intensity on per unit area of slope surface.

5. Conclusion
Taking the slope soil of Beijing New Airport drainage slope project as the research object, the deformation law of slope soil, the overall stability change law of slope and the effect of slope erosion under rainfall erosion with or without geocell protection are studied and analyzed. Based on the finite element simulation analysis and experimental results, the following conclusions are drawn.

Firstly, the finite element analysis results show that the confinement effect of geocell on slope soil can significantly reduce the maximum seepage pressure under rainwater infiltration, and the separation effect of geocell on soil can significantly reduce the pore water pressure of top soil, thus indirectly increasing the cohesion and friction between soil particles and improving the stability of slope structure.

Secondly, the local restraint effect of geocell can eliminate the accumulation of plastic deformation transfer between different cells under the action of rain erosion, significantly reduce the maximum plastic deformation of slope soil and reduce the displacement of slope soil by about one third, which is conducive to the stability of it. However, the maximum plastic deformation area will be transferred from the shallow layer near the slope foot to the deep layer near the slope top after the geocell is set up. In order to avoid the risk of excessive plastic deformation near the deep layer near the slope top, appropriate reinforcement measures should be taken to it.

Finally, the model experiment results show that the slope protection effect of geocell is more significant when the slope gradient exceeds 1:1.5, and the most significant when it reaches 1:1.25. Therefore, when the slope gradient is over 1:1.5, the effect of geocell slope protection is better, but when it exceeds 1:1, the slope protection effect will decrease.

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