Analysis and research on the bearing capacity of geocell reinforced cushion subgrade in liyu expressway

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Abstract. This paper takes the filling roadbed of the Lipu-Yulin Expressway (Liyu Expressway) project in the Guangxi Zhuang Autonomous Region as the backup project. Numerical simulation research is conducted by employing the general finite-element analysis software ABAQUS. The three-dimensional numerical models of the unreinforced soil embankment and reinforced embankment are formulated and the subgrade's ultimate bearing capacity is calculated and solved by the elastoplastic finite element method. Effects of planar and three-dimensional reinforcement, i.e., geotextile and geocell, on the ultimate bearing capacity of the foundation are calculated and analysed. Simultaneously, the strength and deformation characteristics of geocells and geotextiles under embankment loads are studied. Research results show that the enhanced bearing capacity of geocell-reinforced foundation in this paper is increased by about 30%, which is greater than that of the planar reinforced material. This research results in this paper provide reference and theoretical basis for designing and analysing geocell-reinforced embankment in actual engineering practices.

1. Introduction

Soft soil foundations in highway construction are inevitable. Building embankments on soft foundations are usually prone to excessive post-construction settlement and uneven settlement due to large compressibility, poor permeability, high sensitivity and low soft soil strength, which will cause major damage to pavement structure. To reduce these hazards, reinforcement methods are often used to treat soft roadbeds. Reinforcement mainly uses anchoring force, interlocking force, and interfacial friction resistance between geosynthetic material's tensile strength and soil to connect structure and fill. It's the international geotechnical community's new structure development in recent decades.

In the 1970s, using geosynthetics as soil reinforcement was unpopular. It was quickly promoted after entering the 1980s with the geosynthetics industry's development [1]. Many types of geosynthetics can be used for reinforcement, mostly planar materials such as geotextiles, geogrids, and three-dimensional materials such as geocells. There have been many research results on the improvement of roadbed stability via reinforcement.

Xu Bo [2] (2002) conducted an indoor model test under instantaneous load on a square, geogrid-reinforced foundation. Model test results show that the geogrid reduces foundation settlement and settlement reduction factors are related to the foundation's reinforcement depth. Yang Xiaohua et al. [3] conducted a static load test on the geocell structure's anti-deformation performance and showed that the cell can effectively limit structure deformation; Yu Zhongquan [4] analyzed the mechanism of geotextile foundation reinforcement through geotechnical centrifugal model tests. The analysis concludes that the
application of geotextile sand cushion composite material to reinforce the embankment is effective, which not only reduces the vertical displacement of the embankment centre, but also prevents the lateral displacement of the foundation soil by simultaneously ensuring the stability of the embankment.

Liu Feiyu [5] (2007) used ABAQUS universal finite-element software to compare and analyze soft foundation reinforced and unreinforced roads under traffic loads. The results show that reinforcement can restrain the horizontal deformation of the soil, reduce overall road settlement, and reduce uneven road settlement. Mao Linfeng [6] used the finite element method to analyze the influence of reinforcement on the soft foundation's stress field and displacement field, comparing the soft foundation of the natural embankment with the soft foundation of the reinforced embankment. The results of finite element analysis show that reinforcement of geosynthetics can greatly constrain lateral displacement, reduce uneven settlement, make foundation deformation uniform, reduce uplift outside the embankment, homogenize stress, reduce plastic zone development and improve foundation stability. In the ABAQUS software, Luo Changing [7] conducted a finite-element analysis on soft soil foundation strengthened by geotextiles. The results show that reinforced soft soil foundation can reduce foundation settlement deformation due to higher stress diffusion.

There are many studies and achievements on the lateral deformation and reinforcement stability of the embankment, but few studies on reinforcing the embankment's bearing capacity can be found. There is not much research on comparative analysis of reinforced materials, the specific increase in the bearing capacity of the embankment structure and the difference.

This paper takes the geocell-reinforced embankment on soft soil in the Lipu-Yulin highway project in the Guangxi Zhuang Autonomous Region as a prototype. The general finite-element analysis software ABAQUS is employed to formulate the geotextile and geocell reinforced embankments. Simulation and discussion of variation in bearing capacity of different structures provide reference and theoretical basis for the construction of geocell-reinforced embankments on soft foundations.

2. Project overview

2.1. Project Introduction
The Lipu-Yulin Expressway is a component of the Guangxi Expressway Network Planning "the Second Vertical" Lipu-Tieshangang Expressway and an important part of the G59 Guangxi section of the national expressway network. The project is the first contract section for the survey and design of the Lipu-Yulin Expressway in the Guangxi Zhuang Autonomous Region. The mileage is K0+000 ~ K71+198.221 and the route is about 71.2km long.

This project's route is located in the counties of Lipu, Mengshan, and Tengxian. The starting point is near Mengcun in Lipu County's northeast, and is connected to the Jianyangshuo-Lipu Expressway. Beginning point is K0+000. The route's general direction runs from north to south, passing through Licheng Town, Xinping Town, and Dumo Town in Lipu County; Xinxu Town, Mengshan Town, Wenxu Town, Xiayi Township in Mengshan County; Dali Town, Teng County; located 130m east of Fudou Village, Dali Town, Teng County. The terminal station is K71+198.221, connected to the second contract design starting point. Total route length is about 71.2km.

2.2. Engineering Geology
The first contract section of the Guangxi Zhuang Autonomous Region's Lipu-Yulin Expressway Engineering Survey and Design Section is about 19 high-filled embankment sections with a cumulative length of about 3.95km and a maximum filling height of about 32m. The deep excavation cuts are about 65 sections, with a maximum slope height of about 69m. Bad geology includes landslides, collapses, karsts, etc. Among them, landslides and collapses are relatively small, having little effect on the route. Karst sections are predominantly distributed in K6+000 ~ K14+000 sections. Additionally, the cumulative length of the soft soil roadbed in the main line section is about 28.87km, accounting for about 40 percent of the total route length.
This section's route mainly spreads in hilly landforms and quasi-plains, and weak soils generally develop along the route. Soft soil is distributed in depression, valley and paddy fields. Silty clay and saturated clay dominate. It is generally soft to plastic, partially flow-plastic, and generally between 0.5-4m thick. There is a wide range of paddy fields in the quasi-plain landform area, and the continuous distribution length can reach several kilometres, and the soft soil road section is relatively long. The results of the exploration show that the area is dominated by seasonal soft soil, the surface layer is soaked and soft, the lower soil has good properties and the bearing capacity basically meets the requirements of the general subgrade bearing layer; the soft soil along the line is relatively developed, with continuous, large dense distribution characteristics, development thickness is generally thin and appropriate treatment design needs to be done.

The reinforcement method is mainly suitable for road sections with small soft soil thickness and wide distribution range (>100m). The thickness of the soft soil in this project's section K32+400~K49+700 is less than 3m, and the underlying layer is hard plastic clay or high-bearing capacity bedrock, or hard shell layers are distributed in the open alluvium in terraces or denuded quasi-plains, the topography is relatively small, so it can be treated with reinforcement.

The advantage of the reinforcement method is to control the embankment settlement uniformly, improve the foundation's bearing capacity, avoid large-scale soft foundation replacement, reduce software replacement thickness and benefit environmental protection. Figure 1 shows the design drawing of the geocell-reinforced embankment of Liyu Expressway section K32+400~K49+700. Figure 2 shows the geocell layout. Cell height is 75mm, and side length of the geocell pocket is 40cm.

3. Model Calculation and calculation plan

3.1. Computational constitutive model

3.1.1. Constitutive relationship of soil
Soil is a mixture of viscous, elastic and plastic deformation, and soil stress-strain relationship is nonlinear. There are currently four main constitutive soil theories: elastic nonlinear model, elastic-plastic nonlinear model, viscoelastic-plastic nonlinear model and modified Cambridge model. Duncan-
Prager model and Drucker-Prager (DP) model are widely used in China's engineering community. The Duncan-Prager model belongs to the elastic nonlinear constitutive relationship and the DP model belongs to the constitutive elastic-plastic relationship \[8\]. The Drucker-Prager ideal elastoplastic constitutive model is used in this paper to simulate subgrade fill and foundation soil. Figure 3 shows the linear Drucker-Prager model of yield surface. The function is to:

\[ F = t - p\tan\beta - d = 0 \]  

(1)

Where,

\[ t = \frac{q}{2} \left[ 1 + \frac{1}{k} - \left( \frac{1}{k} \right)^3 \right] \]  

(2)

\[ \beta \] is the inclination angle of de-negation in the p-t stress space, which is related to the friction angle \( \phi \).

\( K \) is the ratio of tensile strength to compressive strength in the triaxial test, reflecting the influence of intermediate principal stress on the yield surface.

\[ d = (1 - \frac{1}{3}\tan\beta)\sigma_c, \] defined according to uniaxial compressive strength \( \sigma_c \);

\[ d = (1 - \frac{1}{3}\tan\beta)\sigma_t, \] defined according to uniaxial compressive strength \( \sigma_t \);

\[ d = \frac{\sqrt{2}}{2} \tau \left( 1 + \frac{1}{k} \right), \] defined according to the shear strength \( \tau \)

In the plane strain condition, the relationship between the parameters of Drucker-Prager and Mohr-Coulomb models are as follows if the associated flow rule is assumed:

\[ \tan\beta = \frac{\sqrt{3}\sin\varphi}{\sqrt{1 + \frac{\sin^2\varphi}{3}}} \]  

(3)

\[ \frac{d}{c} = \frac{\sqrt{3}\cos\varphi}{\sqrt{1 + \frac{1}{3}\sin^2\varphi}} \]  

(4)

3.1.2. Constitutive relationship of reinforcement material

Many research and calculation results show that the tensile force of the reinforced body in soil is much smaller than its tensile strength, and the stress and strain of the geotextile are all within the elastic range, so this paper simplifies it to linear elastic material. In the analysis, the reinforced body is considered pure elastic and the membrane element is used to simulate the reinforced body. Membrane element thickness is 1.2mm. Geocell's schematic diagrams are in Figure 4; geocell height is 75mm.
3.2. Model Size Calculation
A simplified calculation model is established for the K32+400~K49+700 road embankment project of the first contract section of the Lipu-Yulin Highway Engineering Survey and Design in the Guangxi Zhuang Autonomous Region, which is illustrated in Fig. 5. Considering the symmetry of the embankment, a calculation model is established by taking half of the embankment and the foundation. The thickness of model is taken as 1.13m perpendicular to the direction of cross-section. The embankment top width is 10.4m, embankment side slope is 1:1.5, and height is 6.6m. The subgrade filling layer is 3m-thick soft soil, and between the filling layer and the soft soil layer, a 0.6m thick crushed stone cushion is laid. Example 1 is a model without reinforcement, and Example 2 is an embankment reinforced via geotextiles. The geotextile has a 575mm spacing in three layers. In Example 3, reinforcement is a three-layer geocell, 75 mm cell height and 500 mm cell spacing on each layer.

3.3. Determination of calculation parameters
The parameters of the subgrade structure's numerical simulation model are shown in Table 1. Table 2 shows the parameters of the reinforcement material.

| Subgrade structure | Bulk density (kN/m³) | Cohesion (kPa) | Internal friction angle (°) | Elastic Modulus (MPa) | Poisson's ratio (µ) |
|--------------------|----------------------|----------------|-----------------------------|-----------------------|--------------------|
| Fill soil          | 20                   | 8              | 35                          | 50                    | 0.33               |
| Cushion            | 21                   | 1              | 43                          | 20                    | 0.25               |
| Clay               | 18                   | 20             | 10                          | 20                    | 0.33               |
| Foundation         | 20                   | 50             | 35                          | 80                    | 0.33               |

| Material            | Bulk density (kN/m³) | Elastic Modulus (MPa) | Poisson's ratio (µ) | Longitudinal tensile strength (kN/m) | Transverse tensile strength (kN/m) |
|---------------------|----------------------|-----------------------|---------------------|--------------------------------------|-----------------------------------|
| Geotextile/Geocell  | 9.5                  | 113.6                 | 0.32                | 120                                  | 12                                |

3.4. Establishing model calculation
The three-dimensional embankment model for soft foundations based on the simplified schematic diagram of the embankment model shown in Figure 5. In ABAQUS, the reinforcement (geotextile and geocell) is simulated. Geo-reinforcing can only bear tensile force by setting the option No compression. Embedded element technology in ABAQUS is used to simulate contact and interaction between reinforcement and fill, and reinforcement material (Embedded region) is embedded in the fill behind the wall (the shell is embedded in the solid type). The reinforcement is embedded as the embedded region
in the embankment, and the embankment is the host region. The embedded element technique is suitable for simulating a collection of reinforced membrane elements, shell elements and surface elements (i.e. slave elements) built into a solid continuum three-dimensional element (i.e., master). If the embedded element is a shell element and beam element, it cannot restrict embedded nodes' rotational freedom. The definition of geometric tolerance and the embedded node position adjustment can be set by default values. Setting up the contact relationship can not only satisfy the actual project conditions, but also help calculate the convergence of finite element analysis.

The soft foundation embankment model calculation model is based on the Linear Drucker-Prager plastic potential surface using ABAQUS finite element software. The embankment adopts 3D solid unit C3D8 grid unit and divides the stiffener by M3D4 membrane unit. Membrane is a surface element which can only transmit in-plane force and cannot transmit bending moment (that is, no bending stiffness). It can be used to simulate a thin surface in space that only bears force but not bending moment (such as a thin rubber plate). Forming a balloon and reinforcing thin members in a solid structure (such as a reinforced layer in a continuum), which is understood as a thin layer of reinforcing characteristics, so that the membrane component is suitable for simulating reinforced soil material. Both adopts structured division technology and the finite element mesh obtained is shown in Figure 6.

4. Results and numerical simulation analysis

4.1. Displacement-load curve

On top of the embankment, the uniformly distributed loads are increased step by step until the iteration diverges. The characteristic points on the calculation model are selected and shown in Figure 5. After the calculation was completed, the load-displacement curves of different cases at the same point are compared and the ultimate load carrying capacity of each cases are analysed and determined. The corresponding load level is the reinforced embankment model's ultimate bearing capacity when calculation is completed.

Figure 7 and 8 show the vertical displacement-load and horizontal displacement-load curves of different calculation examples at the same analysis point. Herein the ultimate bearing capacity of the subgrade is the solution when the failure criterion is adopted as that the finite element calculation does not converge. Under the condition of large deformation, displacement has no practical meaning, and the ultimate bearing capacity is primarily solved. Analysis shows that 181.3kpa is the unreinforced embankment bearing capacity, and the embankment's bearing capacity is enhanced after reinforcement. The geotextile enhanced embankment's ultimate bearing capacity is 222.1kpa, which is about 22.5% higher than the unreinforced soil embankment. The ultimate bearing capacity of the geocell reinforced embankment is 235.4kpa, about 29.8% higher than that of the unreinforced soil embankment.
4.2. Tensile stress of stiffened body

Figure 9 is a cloud diagram of the transverse tensile stress S11 distribution of the reinforcement. Figure 10 is the X-direction distribution curve of the transverse tensile stress. It can be seen from the figure that whether geotextile and geocell reinforced embankment, the reinforced body's tensile stress shows a small distribution in the middle and two sides along the X direction, showing an upward convex shape; tensile stress is mainly distributed in 8-18m. Within the range, the maximum value appears at 13m from the surface of the slope, where the most critical slip surface of the embankment slope may cut through, which helps to assess the critical slip surface position during slope stability analysis.

The two working conditions are similar regarding the distribution shape, but the two are quite different in terms of quantity. The maximum stress of the geocell is about 252.Mkpa, and the maximum value of the geotextile stress is about 26.8Mpa. The maximum stress of geocells is about 9 times that of geotextiles, which shows that geocells have a significant confinement effect on the infill soil compared to geotextiles and other planar-reinforced materials due to their special three-dimensional mesh structure. After destroying the cloth-reinforced embankment, the geocell-reinforced embankment remains intact and the cell's force is exerted more fully. From previous paragraph 4.1, it is known that the geocell's ultimate bearing capacity is greater than the geotextile's. The three-dimensional reinforced geocell can mobilize the reinforcement tensile resistance more significantly than the geotextile of the plane-reinforced material and enhance the embankment's bearing capacity.
4.3. Tensile Strain of stiffened body

The transverse strain $E_{11}$ distribution curve along X direction is shown in Fig.11, from which it can be observed that, in terms of the distribution shape, the distribution curves of the reinforcement strain $E_{11}$ is similar to the distribution curve of the stress $S_{11}$ for both geotextile and geocell-reinforced embankment. The tensile strain is small in the middle and on both sides, showing an upward convex shape; the main distribution range of the strain $E_{11}$ is also approximately the same and the location of the maximum value is similar.

Regarding the magnitude, the geocell's maximum strain $E_{11}$ is 0.475, and geotextile's maximum strain $E_{11}$ is 0.075. This shows that, compared to planar-reinforced materials such as geotextiles, the deformation of 3D reinforced materials such as geocells is more fully developed and has a stronger reinforcement effect. Geocell's maximum stress is about 6 times the geotextile's. Comparing geocell and geotextile stress and strain, it can be seen that the geocell force is 9 times that of geotextile, but the deformation is about 6 times that of geotextile.

5. Conclusion

In this paper, the actual engineering case of geocell-reinforced embankment in Liyu expressway was taken as a prototype and the numerical model was formulated using the software ABAQUS. Through the numerical simulation, the bearing capacities of three cases, i.e., the unreinforced soil embankment, the geotextile reinforced embankment and the geocell reinforced embankment, were compared and analyzed. The following conclusions can be primarily drawn.

- The ultimate bearing capacities of the unreinforced embankment, that reinforced via geotextile and that reinforced via geocell were 181.3kPa, 222.1kPa, and 235.4kPa. The load-bearing capacity was increased by about 22.5% via geotextile, and about 29.8% via geocell. When the length and spacing...
of the reinforcement remain the same, the reinforcement effect of the geocell is about 7.3 percent greater than that of the geotextile.

- The distribution of tensile stress $S_{11}$ and strain $E_{11}$ along geotextile and geocell-reinforced material reinforcement direction (X direction) is similar, showing a convex form on both sides and the maximum value appears at the location about 13m away from the slope surface. The maximum tensile stresses of the geocell and the geotextile are 248Mpa and 26.8 Mpa, respectively. While the maximum tensile strain of the geocell and the geotextile are 0.475 and 0.075, respectively. By comparing the mechanical behavior of the three-dimensional reinforcement material with the planar reinforcement material, it can be found that the tensile strength of geocell can be sufficiently mobilized and thus the bearing capacity of the roadbed can be significantly enhanced.

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