Optimization of 3D printed geocells based on numerical simulation and experimental investigation

Izidine Amurane, Mengxi Zhang, Tianyi Li, Haibo Jiang
Department of Civil Engineering, Shanghai University, Shanghai 200444, China
izidineamurane@hotmail.com

Abstract: In order to evaluate and increase the capacity of geocell that is widely used in ground improvement, the optimization research is conducted based on the node shapes and size of 3D printed geocells in this paper. Firstly, the finite element modelling is established and simulated by finite element analysis software CATIA and then comparison results of the simulation among stress distribution, mechanical characteristics and working conditions of nodes with different shapes and sizes are made. Furthermore, based on the lateral effect of geocell, the experiment on the optimized 3D printed geocell is carried out under variations of the numbers of holes, loading rates and different depths of soil deposits. It should be noted that the force characteristics and working conditions need to be considered while using or designing structure-optimized reinforced material to ensure the stability and strength of the structure. Finally, the simulation and experiment results show that the strength of the geocell is affected by different shapes and diameters of nodes, and the optimization can significantly enhance the performance of geocell.

1. Introduction
Geosynthetic materials are being extensively used in practice on foundations, road embankments, and soft soil in the past decades due to their performance, tensile resistance, durability, costs and ease of application in general for improvement of weak ground supporting variety constructions. In addition, geocell is a new geosynthetics which appeared in the early 1980s, a three-dimensional mesh structure made by ultrasonic welding of high dense polyethylene or polypropylene copolymer sheet. Compared with the general geosynthetics, geocells have the characteristics of higher overall strength, stable chemical properties and strong adaptability [1], and the lateral limit provided by the geocell can significantly improve the shear strength of coarse soil, and then increase its bearing capacity or prevent soil erosion as the strength of soil increases. Dash et al. [2], Sitharam et al. [3], conducted a model footing tests on geocell reinforced soil and found that interconnected geocells increases load carrying capacity and reduces settlement significantly through increased rigidity of geocell layer by confinement of foundation soils. Many case studies on use of geocell reinforced soil have also been reported by various researchers, Cowland and Wong [4], Hendricker et al. [5]. Construction of highway/railway embankments, containment dykes, flood protection levees etc. over soft clay are challenging for engineers as they cause very often bearing capacity failure and excessive settlement. Madhavi Latha et al. [6], Sitharam et al. [7], have reported that geocell reinforcement helps in improving overall performance by reducing deformations of the earth embankment over soft clay foundation. Research application of geocell reinforced soil has been paid more and more attention lately by researchers and engineering circles, and the engineering properties of soil reinforced by geocell have been studied a lot [8, 9].
Therefore, the study of the pore size of geogel is of great significance to the lateral limit of soil, and the optimization of the aperture of geocell can reduce the uplift displacement of soil, and more highlight the effect of lateral displacement of geocell. This paper highlights the findings of a series of simulations comparison between the force-distribution, mechanical characteristics and condition of node with different shape and size by CATIA, as well as the results of the geocell reinforced soil compression tests carried on the variation of soil pressure which would give to some extent an idea of improvement for the prototype material.

2. Optimal design and modelling of integral node shape

2.1. Monolithic node form
The 3D printed integral node shape adopts the structure of the sheet and the joint forming of the geocell. The integral node can guarantee the force uniformity of the geocell nodes in order to ensure the strength stability of the geocell, as shown in figure 1.

![Figure 1. 3D printed integral node of geocell](image)

2.2. Geocell modelling
The finite element model of the integral node of geocell is established by using CATIA software. Model nodes of different shapes are established as hexagonal, circular and rectangular shapes for numerical simulation analysis, as shown in figure 2. The length, width and sheet thickness dimensions adopted are 100mm, 50mm and 1.5mm respectively. Influence of the strength of the geocell is analysed according to the size of the node using the following sets of working conditions for modelling and calculation, as illustrated on table 1.

| Working conditions | Node shape | Node size (outer circle diameter) /mm) | Tension /kPa | Pull position |
|--------------------|------------|----------------------------------------|--------------|--------------|
| 1                  | Circular   | 3                                      | 100          | Adjacent     |
| 2                  | Circular   | 4.5                                    | 100          | Adjacent     |
| 3                  | Circular   | 4.5                                    | 100          | Relative     |
| 4                  | Circular   | 4.5                                    | 300          | Adjacent     |
| 5                  | Rectangular| 4.5                                    | 100          | Adjacent     |
| 6                  | Hexagon    | 4.5                                    | 100          | Adjacent     |
2.3. Material properties and mesh division
After the modelling of the geocell integral node is completed, it is assumed that the material used in the geocell is high density polyethylene (HDPE). Furthermore, the properties and the corresponding materials are established in the list of CATIA materials and then assigned to the sheet and node of the geocell. The mesh of the geocell is then divided to facilitate the calculation of the finite element model in later period, as shown in figure 3.

2.4. Force analysis of geocell integral node shape
According to comparison and analysis of geocell under different working conditions, each variable is used as a condition to compare and analyse the process and influence of the variables of each working condition on the integral node of the geocell qualitatively:
   • Analysis of integral shape nodes of different sizes
     The force analysis content of the internal nodes of the geocell is simulated as shown in figure 4, in the process is noted that in the middle part of the sheet material of the geocell is more stressed, while the stress change near the joint is more concentrated and obvious. The reason for this phenomenon is that the geocell force follows the positive direction of the sheet during the simulation process of the edge stretching while the HDPE material has a good elongation, therefore, when stretching the middle of the sheet will produce a large stress effect and will produce a large deformation.
Under the condition of integral node tensile simulation of the geocell, the diameter size of nodes of the same shape has an important influence on the geocell, as shown in figure 5. When the diameter of the joint is small, the change of the force at the node is more concentrated and more obvious. When the node diameter of the whole shape is large, the force change on the integral node is smaller. It is shown in the process of using the integral node that nodes with larger diameter can effectively share the tensile force produced by the sheet and can transfer the action of the force to the node.

- Analysis of integral shape nodes with different magnitude force

Under working conditions 2 and 4, different forces are applied to the two groups of geocells. The effect of force distribution on the nodes is observed under the action of different forces, as shown in Fig. 6.
By applying different tensile forces at the same integral node through stress analysis above, it is shown that under different tensile forces, the force produced on the node and sheet is different and the form and state of the force distribution as well as the distribution of force on the node are the same. Therefore, the integral node can ensure that the distribution forces around the nodes are in the same stress state and maintaining a stable stress state in the working process and won’t change under action of different forces.

**Shape effect analysis of integral node**

Through comparison analysis of numerical simulation results of working condition 2, Working condition 5 and working condition 6, the node shape is changed to analyse the joint effect on the stress distribution under same conditions. The shape of the integral node of the geocell is modelled in three shapes, namely, circular, rectangular and hexagonal respectively as shown in figure 7.

Through numerical stress simulation cloud diagram of integral nodes with different shapes, it can be found that the force distribution on circular nodes is more uniform, the stress around the nodes changes and the distribution is denser. The stress change around the rectangular node is also more uniform and obvious, but the change of stress distribution is different from the circular node. The force in the central area of the rectangular node is similar to the circular node, but the stress distribution on the four corners of the node is relatively small and the force is less in the middle part of the node. For the hexagonal node, the stress variation on both sides of the force is relatively large, while the two sides of the set displacement are relatively small and the overall force of the node is not uniform.
3. Geocell aperture optimization

3.1. Test device and materials properties

The test devices used in the experiment contains pressure device, model box and data acquisition device. The pressure device in the test adopts a CTM8050 universal microcomputer controlled electronic material testing machine which can produce pressure effect by controlling the compression speed. As shown in figure 8, the size of model box used in the test is 300 mm×300 mm×300 mm, both sides are made of plexiglass permitting the deformation of soil in the model box to be seen clearly. The displacement and soil pressure data acquisition instrument used is the DH5921 strain test system with maximum acquisition frequency reach of 1 kHz. The physical properties of sand with less water content used on the test in order to reduce the effect of moisture content are listed in table 2 and the grading curve of sand is shown in figure 9. The geocell used in the experiment is a rectangular monolithic geocell with a circular node made of 3D printing. Three types of geocell were used, with edge lengths of 15cm, 7.5cm and 5cm, as shown in figure 10. The shapes of the geocell used on the test are respectively, 1 hole, 4 holes and 9 holes.

![Test instruments setup](image)

![Particle grading curve of test sand](image)

Table 2. Physical characteristic parameters of sand soil

| Bulk density $G_s$ | Water content $w/%$ | uniformity coefficient $C_u$ | Curvature coefficient $C_c$ |
|-------------------|---------------------|------------------------------|-----------------------------|
| 2.62              | 0.08                | 2.07                         | 0.87                        |

![3D printed geocell](image)
3.2. Method principle
The test principle is based on the lateral limit effect of geocell on soil, as shown in figure 11. In work application of geocell, its net pocket side limit can effectively spread the overlying load and homogenization stress improving the bearing capacity of the soil, reducing the uneven settlement and improving the stability of the soil. In the experiment 9 test conditions were set up as shown in Table 3.

![Force analysis of geocell in reinforced Foundation](image)

Figure 11. Force analysis of geocell in reinforced Foundation

| Working conditions | Numbers of aperture | Load rate \( v \) (mm/min) | Buried depth of geocell \( h \) (mm) |
|--------------------|---------------------|-----------------------------|-----------------------------------|
| 1                  | 1                   | 1                           | 20                                |
| 2                  | 4                   | 1                           | 20                                |
| 3                  | 9                   | 1                           | 20                                |
| 4                  | 1                   | 5                           | 20                                |
| 5                  | 4                   | 5                           | 20                                |
| 6                  | 9                   | 5                           | 20                                |
| 7                  | 1                   | 1                           | 50                                |
| 8                  | 4                   | 1                           | 50                                |
| 9                  | 9                   | 1                           | 50                                |

In the course of the test, the sand is placed in the model box, layered and compacted to the corresponding compactness and filled up to 50 mm below the geocell. The loading devices are placed directly below the central positions 30 mm and 60 mm respectively as shown in figure 12. The soil is then filled, the geocell is placed and sand is again filled to the surface of the model box. The diameter of the loading device is 60 mm, the displacement meter is arranged at positions of 3 cm and 6 cm at the edge of the distance loading device in order to measure the surface uplift displacement of the soil.
3.3. Test results analysis

By sorting out the data obtained from the test, the uplift displacement of the soil surface at each distance away from the edge of loading device, the soil pressure data below the geocell and the earth pressure at each distance away from the centre of the loading position are obtained. Figure 13 and figure 14 show the data of the uplift displacement and soil pressure of the soil surface during different buried depths of geocell, while $v=1\text{mm/min}$ and $v=5\text{mm/min}$, respectively.

![Diagram of test programme](image)

Figure 12. Test programme

![Graphs showing results](images)

Figure 13. $v=1\text{mm/min}$ monitoring data
Through monitoring data from figure 13 and figure 14, the influence of large, medium and small pore size on uplift displacement of soil and soil pressure beneath the geocell under various test conditions were obtained. The following test results can be observed by data comparison and analysis:

- From figure 14 (a) and (b), the displacement of the uplift on the soil surface decreases with the increase of the distance of the loading device. With the decrease of the pore size of geocell, the uplift displacement difference of soil surface decreases correspondingly.
- From figure 15 (c) and (d), with the increase of the buried depth of the geocell, the soil pressure below the geocell decreases slightly, which indicates that the soil has diffusion effect on the force during the loading process.

4. Conclusion

This paper presents the optimization of the 3D printed geocell by numerical simulation and experimental investigation, main conclusions are as follows:

- Geocells using 3D printing technology have different effect on the diffusion of stress due to the good integrity and the displacement of the uplift of the soil around the loading range has a great influence on the stress diffusion of the soil under the geocell. The results show that the optimization
of the aperture of geocell can obviously control the uneven uplift displacement of soil surface and enhance the stability of soil structure.

- With the decrease of the aperture in the geocell, the difference of each soil pressure box decreases, which indicates that the optimization of the pore size of geocell can increase the diffusion effect of soil pressure so that the soil pressure in the upper concentration is diffused to the bottom of the geocell.
- In the selection of nodes according to the shape, circular nodes have better force effect allowing the force to be evenly distributed in all directions of the node. The force on rectangular nodes is less uniform and the material waste is caused by the small four corners on the edges of nodes. Good force effect on the hexagonal node is significant which allows the force distribution and increases the strength of nodes.

References

[1] Shadmand A, Ghazavi M, Ganjian N. Load-settlement characteristics of large scale square footing on sand reinforced with opening geocell reinforcement[J]. Geotextiles & Geomembranes, 2018, 46(3): 319-326
[2] Dash, S.K., Krishnaswamy, N.R., and Rajagopal, K., (2001a). “Bearing capacity of strip footings supported on geocell-reinforced sand.” Geotextiles and Geomembranes 19(4), 235–256.
[3] Sitharam, T.G, Sireesh, S., Dash, S.K. (2005). “Model studies of a circular footing supported on geocell-reinforced clay.” Canadian Geotechnical Journal, Vol. 42, (2), 693-703.
[4] Cowland, J.W., and Wong, S.C.K., 1993. “Performance of a road embankment on soft clay supported on a geocell mattress foundation.” Geotextiles and Geomembranes 12(8), 687–705.
[5] Hendricker, A.T., Fredranelli, K.H., Kavazanjian Jr, E., and Mckelvy III, J. A., (1998). “Reinforcement requirements at hazardous waste site.” Proc. of 6th International Conference on Geosynthetics, Atlanta, 1, pp. 465- 468.
[6] MadhaviLatha G., Rajagopal K., and Krishnaswamy, N.R., (2006). “Experimental and Theoretical Investigations on Geocell-Supported Embankments.” International Journal of Geomechanics, ASCE, Volume 6, No.1, January 1, 2006, pp. 30-35.
[7] Sitharam, T.G and A. Hegde (2013). “Design and construction of geocell foundation to support the embankment on settled red mud.” Geotextiles and Geomembranes, 41 pp. 55–63.
[8] Chen R H, Huang Y W, Huang F C. Confinement effect of geocells on sand samples under triaxial compression[J]. Geotextiles & Geomembranes, 2013, 37(3): 35-44.
[9] Hegde A M, Sitharam T G. Experimental and numerical studies on protection of buried pipelines and underground utilities using geocells[J]. Geotextiles & Geomembranes, 2015, 43(5): 372-381.