Effect of vibration frequency on settlement characteristic of reinforced embankment by geogrid with strengthened nodes using DEM simulation

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Abstract. Geogrid with strengthened nodes (GSN) is a new reinforcement system that is formed by attaching blocks of a certain thickness to the joints of the longitudinal and transverse ribs of an ordinary biaxial geogrid to form strengthened nodes. A series of discrete element method (DEM) simulations were performed to investigate the dynamic response of GSN-reinforced embankment at various vibration frequencies and compare the reinforcing effect of GSN with that of the ordinary geogrid. It was concluded that the settlement ratio of the loading platen at the top of the unreinforced and reinforced embankment decreases with the increase of the vibration frequency. As the frequency increases, the difference between the settlement ratios decreases, which is especially evident in the reinforced embankment. At the same frequency, GSN performs better in restricting the settlement ratio than the ordinary geogrid, and as the frequency increases, the reinforcing effects of both the ordinary geogrid and GSN decrease. The displacement fields of the simulated embankments were analyzed. It was found that the movement of soil particles below the loading platen is restricted due to the presence of the geogrid, resulting in less settlement of the loading platen and smaller lateral deformation of the embankment slope, compared with the unreinforced embankment. As for the GSN-reinforced embankment, the strengthened nodes provide resistance to soil particles, leading to a more effective reinforcing effect, so that the displacement vectors are even smaller.

1. Introduction
With the development of the earth-reinforcing technique, the reinforcement itself has evolved from metallic materials to polymer materials (i.e. the reinforcement used in the retaining wall develops from steel strips-to-steel mesh-to-geosynthetics [1]). Geosynthetics (such as geotextiles, geogrids, geocells, etc) are widely used in the construction of the roadbed, retaining walls, abutments, and other projects because of their low cost and good reinforcing effect. A large number of laboratory tests and numerical simulations using the finite element method (FEM) have been directed to identify the mechanical behaviors of the geosynthetics-soil system [2-7]. However, the continuum-based FEM simulation does not take into consideration particle rolling and sliding on the geosynthetics-reinforced structure. The discrete element method (DEM) has a distinct advantage in capturing the kinematic behavior of discontinuous media at a microscopic scale [8]. Considerable research on the geosynthetics-reinforced soil behavior has been performed based on DEM simulations [9-13].

In addition to the research on the conventional reinforcing materials, the researchers are actively
exploring the reinforcing effect of new materials and innovative reinforcement layout. Zhang et al. [14] proposed a new concept of soil reinforced with three-dimensional (3D) reinforcing elements, from which horizontal-vertical reinforcements and denti-strip reinforcements were derived [9-10,15]. Mosallanezhad et al [16,17] introduced a new reinforcement system named “Grid-Anchor”, which includes geogrids with anchors attached to them, and found that the anchors can effectively improve the pullout resistance of the geogrid. Horpibulsukt et al [18,19] studied the mechanism of a new reinforcement in the retaining wall, which is named “bearing reinforcement”, consisting of longitudinal reinforced bars and transverse barrier steel plates. Li et al [20] carried out model tests on the reinforced embankment of waste tires and found that the position of the first layer reinforcement had a great influence on the failure mode.

Geogrid with strengthened nodes (GSN) is a new reinforcement system by attaching blocks of a certain thickness to the joints of the longitudinal and transverse ribs of an ordinary biaxial geogrid to form strengthened nodes, which is also derived from the 3D reinforcement proposed by Zhang et al [14]. In this paper, a series of DEM simulations were performed to investigate the dynamic response of the GSN-reinforced embankment at various vibration frequencies and the displacement field was analyzed to explain the GSN-soil interaction at a microscopic level.

2. DEM modelling

2.1. Modelling procedure

![PFC2D model of GSN-reinforced embankment.](image)

The numerical model is established using the DEM software Particle Flow Code (PFC2D), based on a model test. The model test was conducted based on a secondary road by reducing the ratio of the geometric dimensions to 1:20. As the shape of the embankment was symmetric, only half of the embankment is simulated. PFC2D software provides two basic entities: balls and walls. To build the PFC2D model, firstly, four walls were generated to simulate the boundaries of the model box and a large number of ball particles were randomly generated within the boundaries according to the grading curve of soil particles. It is noted that the grading curve of soil particles in the model test has been modified and up-scaled by 3 times with the proved technique of “up-scaling”, which can reduce the number of particles to save the computational time [8,10,11]. Then, according to the thickness of the foundation, the angle of the slope and the height of the embankment, the excess particles were deleted to form the sloped embankment model. The calculation cycle stopped when the ratio of maximum unbalanced force to maximum contact force was $1 \times 10^{-6}$, indicating the standard of the equilibrium state was reached. After this, the ball particles at the place where the reinforcement should be placed were removed to set aside the position for the formation of the reinforcement. The reinforcement was modeled by some ball particles by assigning the parallel bond between particles to transmit both force and moment. The simulation model also was cycled until the ratio of maximum unbalanced force to maximum contact force reached $1 \times 10^{-6}$. Finally, a loading plate was generated at the center of the top
of the embankment using the clump function in PFC$^{2D}$. A clump is a group of slaved particles behaving as a rigid body and will not break apart [21]. The final PFC$^{2D}$ model is shown in figure 1. By controlling the force change on the clumped balls, the loading process can be successfully simulated. In this study, simplifying the traffic load into a half sinusoidal wave, dynamic loading was carried out by applying a half sinusoidal force to each ball in the loading plate at different frequencies (1, 5, 10 Hz). The amplitude value of the dynamic loading was 30 kPa.

2.2. Reinforcement simulation

The real reinforcement is a kind of biaxial polyester welded geogrid with an aperture size of 50 mm x 50 mm. Blocks of 6 mm × 6 mm × 6 mm were fixed at the joints of the longitudinal and transverse ribs of the geogrid to form a geogrid with strengthened nodes. As the real biaxial geogrid is a network structure, it should be simplified into a 2D model in PFC$^{2D}$. Because of the existence of the meshes, the joints of the longitudinal and transverse members of the geogrid are firmly designed. Since the 2D modelling cannot fully reflect the influence of the meshes, the characteristics of the solid joints should be grasped. The geogrid longitudinal member was simulated with one row of bonded ball particles and the joints were simulated by setting some balls into rigid bodies using the clump function. As for GSN, the strengthened nodes were also set into clumped balls according to the thickness of the nodes, as shown in figure 2.

![Figure 2. Geogrid with strengthened nodes: (a) real material, (b) simulation model](image)

2.3. Input parameters

The input parameters of the model have a great influence on the accuracy of the simulation results in PFC$^{2D}$. In this study, the Hertz-Mindlin model provided by PFC$^{2D}$ was used for the contact model of ball particles, as this model can better reflect the non-linear nature of soil under dynamic loading [22]. The parallel-bond model was also assigned to the ball particles of the simulated reinforcement to resist both forces and moments. Through repeated trial calculation and referring to the microscopic parameters of the horizontal-vertical reinforcement [10], the final input parameters of the soil particles, reinforcement and loading plate used are shown in table 1.

| Parameters                        | Soil Density $\rho$ (kg/m$^3$) | Reinforcement $G$ (Pa) | Loading platen $G$ (Pa) |
|-----------------------------------|---------------------------------|------------------------|------------------------|
| Particle radius $R$ (mm)          | 2~3                             | 3                      | 3                      |
| Shear modulus $G$ (Pa)            | $1 \times 10^{10}$              | $1 \times 10^{10}$     | $1 \times 10^{10}$     |
| Poisson’s ratio $\nu$             | 0.3                             | 0.2                    | —                      |
| Friction coefficient $f$          | 10                              | 20                     | 25                     |
| Parallel-bond radius multiplier pb_radius | 1                               | 1                      | —                      |
| Parallel-bond shear strength pb_sstrength (Pa) | $1 \times 10^5$              | $1 \times 10^5$        | —                      |
| Parallel-bond normal strength pb_nstrength (Pa) | $1 \times 10^5$              | $1 \times 10^5$        | —                      |
| Parallel-bond shear stiffness pb_ks (Pa/m) | $5 \times 10^6$              | $1 \times 10^5$        | —                      |
| Parallel-bond normal stiffness pb_kn (Pa/m) | $5 \times 10^6$              | $1 \times 10^5$        | —                      |
3. Simulation results

3.1. Effect of frequencies on the settlement

Figure 3 shows the settlement ratio $S/B$ (ratio of settlement $S$ to loading platen width $B$) at various frequencies for different cases versus the number of load cycles and table 2 summarizes the cumulative settlement ratio after 1000 cycles for different cases. For both unreinforced and reinforced cases, the settlement ratio developed rapidly in the early stage of vibration at each frequency, but with the increase of cycle number, the settlement ratio developed slowly and tended to be stable. For the same case, the settlement ratio of the small frequency ($f = 1$ Hz) was more significant, and with the increase of the frequency, the settlement ratio decreased. As the frequency increased ($f = 5, 10$ Hz), the difference between the settlement ratios became smaller, especially for the reinforced cases, as shown in figure 3(a)-3(c). This may be due to that when the frequency is small, the duration of the vibration period is long, and the soil deformation is sufficient in this period, which leads to a lower modulus of resilience and a larger cumulative deformation under the same cycle number.
Figure 3. Settlement ratio versus number of load cycles for different cases of (a) unreinforced embankment, embankments reinforced with (b) ordinary geogrid and (c) GSN at various frequencies of (d) 1Hz, (e) 5Hz and (f) 10Hz.

As shown in figure 3(d)-(3(f), at the same vibration frequency, the settlement ratio at the top of the embankment was effectively reduced by the geogrid reinforcement, and the effect of GSN was better than that of the ordinary geogrid in restricting settlement. For example, at the vibration frequency of \( f = 1 \) Hz, the settlement ratio of the unreinforced embankment was 73.75%, while that of the geogrid-reinforced embankment was 57%, 22.71% less than that of the unreinforced embankment. For GSN-reinforced embankment, the settlement ratio was 42.57%, 42.28% less than that of the unreinforced embankment and 25.32% less than that of the geogrid-reinforced embankment. However, as can be seen from table 2, the reinforcing effects of both geogrid reinforcement and GSN reinforcement decreased with the increase in vibration frequency. Besides, it can be observed that the settlement ratios of the unreinforced, geogrid-, and GSN-reinforced embankment are interlaced from 0 to 200 cycles, at the frequency of 5 and 10 Hz. On the one hand, this may be because when the frequency is large, the vibration time of each cycle is short, and the deformation of the soil is insufficient, which is not enough to mobilize the reinforcing effect of the reinforcement. On the other hand, it may be because the soil in the early stage of vibration is in the stage of vibration compaction, the settlement development is relatively fast, the reinforcement has not yet played a role, and the settlement ratios of the unreinforced and reinforced cases are not much different.

Table 2. Settlement ratios for different cases.

| Frequency/Hz | Settlement ratio/% | α/% | β/% | γ/% |
|--------------|-------------------|-----|-----|-----|
|              | Unreinforced      | Geogrid | GSN |     |
| 1            | 73.75             | 57.00 | 42.57| 22.71| 42.28| 25.32|
| 5            | 51.30             | 42.07 | 35.37| 18.00| 31.06| 15.93|
| 10           | 46.62             | 41.78 | 35.32| 10.37| 24.24| 15.48|

\(^{a}\) Refers to the reduction rate of the settlement ratio of geogrid-reinforced embankment compared with that of unreinforced embankment.  
\(^{b}\) Refers to the reduction rate of the settlement ratio of GSN-reinforced embankment compared with that of unreinforced embankment.  
\(^{c}\) Refers to the reduction rate of the settlement ratio of GSN-reinforced embankment compared with that of geogrid-reinforced embankment.
3.2. Displacement field

Figure 4. Displacement fields of the embankments after 1000 cycles at the frequency of 1 Hz: (a) unreinforced; (b) ordinary geogrid; (c) GSN.

In PFC$^{2D}$, the displacement field can be represented by the displacement vector of ball particles. The displacement vector is a line from the center of mass to the end of the arrow. The direction of the arrow indicates the direction in which the particle moves at a certain time step. The length of the line is proportional to the displacement magnitude. Figure 4 shows the displacement fields after 1000 cycles for three different cases at the frequency of 1 Hz. It can be seen that the displacement vectors inside the unreinforced embankment were very long, indicating large displacements. The settlement of the loading plate at the top of the unreinforced embankment was large, and the lateral deformation of the slope was obvious, especially the severe uplift in the slope crest. In the geogrid-reinforced
embankment, the displacement vectors were obviously smaller than that of the unreinforced embankment. The displacement of the particles right below the loading plate was larger, and the geogrid was bent under the push of the particles. For the presence of the reinforcement, the downward movement of the particles was restricted, resulting in a large reduction in the settlement of the loading platen and a small displacement within the embankment. As for the embankment reinforced with GSN, due to the strengthened nodes, the soil beneath the loading plate was further strengthened, the displacement of particles was reduced, and the degree of bending of the geogrid becomes smaller.

4. Conclusions
The settlement ratio develops rapidly in the initial stage of vibration, either in the unreinforced or reinforced embankment. With the increase of the vibration number, the settlement ratio develops slowly and tends to be stable. At a low frequency, the settlement ratio of the embankment is relatively large, and as the frequency increases, the settlement ratio decreases and the difference between the settlement ratios is getting smaller, which is particularly evident in the reinforced embankments. At the same frequency, the effect of GSN on restricting the settlement ratio is better than that of the ordinary geogrid, but as the frequency increases, the reinforcing effects of both GSN and ordinary geogrid are reduced. Through the displacement field analysis, it is found that the geogrid restricts the movement of the particles under the loading platen, resulting in smaller deformation than that of the unreinforced embankment. For the GSN-reinforced embankment, the strengthened nodes provide resistance to the soil particles, making the reinforcing effect more efficient.

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