Centrifugal Modeling of Geo-synthetics Reinforced Roadbed under Cyclic Loading Condition

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Abstract. The cyclic load of overload vehicles will cause uneven deformation of the roadbed, leading to serious safety accidents. Geo-synthetics can effectively restrict the roadbed as a type of reinforcement. However, it is not clear how to arrange geo-synthetics for a good balance between the economic benefits and sufficient reinforcement. A series of centrifuge model tests of geo-synthetics reinforced roadbed are carried out under the cyclic loads. The deformation and reinforcement effect are investigated by considering the different geo-synthetics spacing. The results show that geo-synthetics effectively restricts the roadbed deformation. The reinforcement effect of geo-synthetics decreases with the increase of depth along the loading center. The geo-synthetics reinforcement effect is enhanced by decreasing the geo-synthetics spacing. The cyclic loads only induce deformation within a limited zone in the roadbed. As the geo-synthetics spacing decreases, the depth of the deformation zone decreases while the horizontal width increases.

1. Introduction
The cyclic load of overload vehicles often causes uneven deformation of the roadbed. How to control the deformation and settlement to a safety range is particularly important. Geo-synthetics can effectively restrict the roadbed as a type of reinforcement. Therefore, the study on the reinforcement effect and mechanism of geo-synthetics under cyclic loads can provide effective solutions to the uneven deformation of the roadbed. A series of studies have been conducted on the deformation characteristics of the roadbed by the field observation, numerical analysis and model tests (Jiang et al. 2009; Ishikawa et al. 2015) [1-2]. Geo-synthetics have been proven successful in improving the safety of soils (Abusharar et al. 2009; Viswanadham and König 2008; Wang et al. 2011) [3-5]. However, there are few researches on the deformation behaviors of the roadbed reinforced by the geo-synthetics under dynamic loading. Moreover, the reinforcement effect and mechanism of the geo-synthetics on uneven settlement of the roadbed are still unclear, which affects the application of the geo-synthetics.

In this paper, centrifuge model tests are carried out based on the current researches. The deformation characteristics of the roadbed reinforced by geo-synthetics under cyclic loads are analyzed.

2. Test description

2.1. Device
All the tests are carried out on the centrifuge at Tsinghua university. The effective radius of the centrifuge is 2 m, with a maximum acceleration of 250 g and a capacity of 50 g-ton. The model
container used in the tests is made of aluminum alloy with an internal size of 600 mm (length) ×200 mm (width) ×480 mm (height) (Fig. 1). The deformation of the container is negligible because of its large stiffness. One side of the model container is replaced by a 40 mm-thickness organic glass, through which the deformation of the roadbed can be observed during the test.

The hydraulic cylinder device installed at the top of the model container is used to provide vertical cyclic load through a rigid loading plate. The loading plate is 50 mm (long) ×200 mm (wide). The pressure can be obtained by dividing the vertical load by the area of the loading plate. A load sensor is equipped on the loading plate to measure the vertical load, the measurement range and accuracy of which are 10 kN and 0.3%. A displacement transducer is also installed for settlement measurement, with a measurement range of 50 mm to 350 mm and an accuracy of 0.1%.

The deformation process of the roadbed is recorded into a series of images by the image capture system during the test (Zhang et al. 2009) [6]. The real displacement vector of the roadbed can be determined by the image series with an accuracy of 0.03 mm. A single layer of tissue is laid on one side of the roadbed model and several pins with light color are inserted randomly for a significant grayscale in order to obtain more accurate measurement results (Fig. 2).

2.2. Model

All the results are presented with the model’s dimension. The length and the displacement can be transformed to the prototype’s dimension by multiplying the g level, 50 in this paper. The strain and stress are equivalent between model’s dimension and prototype’s dimension.

The height of the model is 300 mm, with a 40 mm-thickness soil layer at the bottom in order to reduce the influence of the container bottom on the roadbed. The silica gel is used to bond the organic glass and the container to reduce the friction between the roadbed model and the container. The loading plate is located above the middle of the model and has no contact with the roadbed before loading.

The maximum and minimum dry density of the sand used in all the tests are 1.8 g/cm³ and 1.5 g/cm³. The dry density of roadbed model is controlled to 1.65 g/cm³ by layering compaction. The soil thickness of each layer is selected as 50 mm with 6 layers considering the overall height of the model.

According to the modulus similarity criterion, the medical gauze is used to simulate the geo-synthetics. The average thickness of the single layer of the gauze is 0.14 mm, with the tensile strength of 3.15 kN/m and the elastic modulus of 39.7 kN/m. The geo-synthetics reinforcement is within 10 cm from the surface of the model with the different geo-synthetics spacing of 5 cm, 2 cm and 1 cm.
respectively. It should be noted that the length of gauze in all tests is the same as the length of the model container.

For further analysis, a rectangular plane coordinate system is established with the midpoint of the roadbed surface as the origin point. The positive direction of $x$-axis is going horizontally right and of $y$-axis is going vertically down (Fig. 1).

### 2.3. Test procedure

The roadbed model is fixed on the basket of the centrifuge. Centrifugal acceleration gradually increases to 50 g during the test. For each 10 g increase, the acceleration is maintained stable at this value for a period of time, waiting for the deformation of the model stable.

The vehicle loading is simplified as sinusoidal cyclic loads. The amplitude and frequency of sinusoidal cyclic load are maintained at 100 kPa and 1 Hz respectively, with an average of 200 kPa and a cyclic number of 2000 (Fig. 3). When the model deformation reaches stability at 50 g, the monotonic load is applied through the loading plate up to 200 kPa by step. And then, the load is the sum of the average value and the sinusoidal fluctuation of each period until the cyclic number reaches 2000.

![Loading process and Sinusoidal cyclic loads](image)

**Figure 3.** Loading condition on the roadbed. $p$, vertical load; $t$, time; $N$, cyclic number; $T$, period of vibration; $\Delta p$, peak-to-peak value.

### 3. Observation

#### 3.1. Displacement response

Fig. 4 shows the settlement of the top of the roadbed model under monotonic loads. It can be seen that the settlement increases with increasing monotonic loads. As the geo-synthetics spacing increases, the settlement increases with an increasing growth rate. This result suggests that reducing the geo-synthetics spacing can enhance the reinforcement effect.

![Settlement of the top of roadbed under monotonic loads](image)

**Figure 4.** Settlement of the top of roadbed under monotonic loads. $s$, settlement of the top of the slope; $p$, vertical load.

![Settlement of the top of roadbed under cyclic loads](image)

**Figure 5.** Settlement of the top of the roadbed under cyclic loads. $\Delta s$, settlement of the top of the slope; $N$, cyclic number.
The settlement of the top of the roadbed under cyclic loads is drawn in Fig. 5. It can be seen clearly that the growth of the settlement can be divided into two stages under cyclic loads. The settlement of the top of the roadbed grows rapidly when the cyclic loads is applied, indicating that great deformation occurs on the surface of the roadbed, which is defined as the rapid growth stage. It can be inferred that the cyclic loads have more significant effect on the roadbed than the monotonic loads. The growth rate in the rapid growth stage increases with decreasing geo-synthetics spacing. With the increase of the cyclic number, the settlement on the top of the roadbed continues to grow but the growth rate decreases, which can be defined as the slow rapid stage. It can be concluded that the geo-synthetics can effectively restrict the deformation of roadbed under monotonic or cyclic loads, and reinforcement effect is enhanced by decreasing the spacing of the geo-synthetics.

3.2. Deformation behaviors

Fig. 6 shows the displacement vectors under cyclic loads when the cyclic number reaches 2000. The direction and length of the arrow represent the direction and magnitude of the displacement in the roadbed model. It can be seen that the displacement becomes more obvious when the spacing of geo-synthetics increases. The displacement near the surface of the roadbed or close to the loading center is more distinct, while the displacement far away from the loading plate is almost zero, which is related to the direct application of the loading plate on the center of the roadbed surface.

As the most significant displacement occurs along loading center, the change of vertical displacement of roadbed with depth along the loading center when the cyclic number reaches 2000 is reflected in Fig. 7. It can be found that the reinforcement effect of geo-synthetics decreases with increasing depth. The depth when $\Delta s$ comes to zero is considered to be the maximum depth that the cyclic loads can affect. Some inflection points occur in the growth curve as the depth increases, which is related to the geo-synthetics laid at different depth in different tests.

![Figure 6. Vector diagram of displacement distribution under cyclic loads.](image)

![Figure 7. Vertical deformation of roadbed with depth along the loading center.](image)
4. Behavior analysis

4.1. Deformation development

As can be seen from Fig. 6, the cyclic loads can only induce deformation within a limited zone in the roadbed. The horizontal distributions of vertical displacement at different depth can be drawn in order to investigate the deformation development of different zones inside the reinforced roadbed. The horizontal distribution of vertical displacement at five different depth with the geo-synthetics spacing of 1 cm when the cyclic number reaches 2000 are drawn in Fig. 8. It can be seen that the settlement far away from the loading center is very small and close to zero. This result suggests that the cyclic loads have little influence on this zone. As it gets closer to the loading center, the settlement gradually increases, indicating that the cyclic loads start to have an effect on this zone. The vertical displacement at the same depth reaches the maximum near the loading center.

Fig. 9 shows the horizontal distribution of vertical displacement inside the roadbed with different geo-synthetics spacing at the same depth of 2 cm. It can be seen that the maximum of the vertical displacement decreases with decreasing geo-synthetics spacing, indicating that reducing the geo-synthetics spacing effectively restricts the deformation. As the geo-synthetics spacing reduces, the horizontal distribution gradient of the vertical displacement decreases, and the position of the inflection points where the settlement starts to grow gets far away from the loading center, suggesting that the maximum width that the cyclic loads can affect increases. That is to say, the roadbed model is changed by reducing geo-synthetics spacing, leading to the different distribution of displacement even under the same loads. The deformation inside the reinforced roadbed becomes more uniform, and thus, the reinforcement effect of the geo-synthetics is enhanced.

![Figure 8. Horizontal distributions of vertical displacement when the geo-synthetics spacing is 1 cm. v, vertical displacement.](image-url)
4.2. Behavior of the reinforced roadbed

A surface can be obtained by connecting the positions where the settlement starts to increase at different depth by a dotted line in Fig. 8. The area between this surface and the free surface of the roadbed is obviously affected by the cyclic loads, so this surface is termed influencing surface as shown in Fig. 10. This influencing surface divides the reinforced roadbed into two zones. The one enclosed by the influencing surface and the free surface of the roadbed can be called as the affected zone. The settlement in the other zone is almost zero and can be considered not affected by the cyclic loads.

It can be found that the affected zone is distributed symmetrically around the loading center. The different arrangement of geo-synthetics changes the shape of the affected zone. It is apparent that with the decrease of the geo-synthetics spacing, the horizontal width of the affected zone increases while the depth decreases. It proves that the deformation develops more uniform horizontally and the reinforcement effect is enhanced by reducing the geo-synthetics spacing.

5. Reinforcement Effect of Geo-synthetics

Fig. 11 shows the deformation of the geo-synthetics in the roadbed under cyclic loads with different geo-synthetics spacing. The dotted line represents the geo-synthetics before loading, and the solid line represents the shapes of geo-synthetics under cyclic loads when the cyclic number reaches 2000. It can be seen that each layer of geo-synthetics is in tension under cyclic loads, and deformation occurs in the affected zone. The deformation reaches largest near the loading center but hardly occurs far away from the loading center. It is obvious that for the geo-synthetics at the same depth, the deformation caused by tension gets smaller with the decreasing geo-synthetics spacing. It proves that reducing geo-synthetics spacing changes the roadbed model and the displacement distribution under the same loads. Therefore, the tension of geo-synthetics at the same depth is also changed.
Horizontal distribution of tensile strain of the geo-synthetics under cyclic loads when the geo-synthetics spacing is 5 cm is drawn in Fig. 12. It can be seen that the tensile strain decreases as far away from the loading center. The tension of geo-synthetics near the surface of the reinforced roadbed is more distinct. Considering the shapes of geo-synthetics under cyclic loads, it can be inferred that the deformation of the roadbed can be effectively restricted by geo-synthetics in two aspects. On the one hand, the effective reinforcement comes from the good friction between the geo-synthetics and the soil. On the other hand, the geo-synthetics limits the further development of the vertical displacement inside by its great tensile property.

Figure 12. Horizontal distribution of tensile strain of the geo-synthetics in the roadbed under cyclic loads when the geo-synthetics spacing is 5 cm. $\varepsilon$, the tensile strain of the geo-synthetics.

6. Conclusion
A series of centrifuge model tests were conducted to investigate the behavior of roadbed reinforced with geo-synthetics under monotonic and cyclic loads. Based on the observation results, the following issues were concluded:

1. The geo-synthetics effectively restricts the roadbed deformation. The reinforcement effect of geo-synthetics decreases with the increase of depth along the loading center.
2. The cyclic loads induce deformation in a limited zone. As the geo-synthetics spacing decreases, the depth of the affected zone decreases while the horizontal width increases.
3. Reducing the geo-synthetics spacing changes the roadbed model and significantly reduces the settlement. So that the distribution of displacement under the same loads develops differently and the tension of geo-synthetics at each layer is changed. The reinforcement effect can be greatly enhanced.
4. The geo-synthetics restricts the deformation by its tensile property under vertical cyclic loads.

References
[1] Jiang C.G., He Y., Peng J.G., Wang F.Q. (2009) Research on Subsidence Ageing of Soft Soil Roadbed Based on Original Position Monitor. Proceedings of the International Conference on Logistics, Engineering, Management and Computer Science.
[2] Ishikawa T., Miura S. (2015) Influence of moving wheel loads on mechanical behavior of submerged granular roadbed. Soils and Foundations 55(2).

[3] Abusharar S.W., Zheng J.J., Chen B.G., Yin J.H. (2009) A simplified method for analysis of a piled embankment reinforced with geo-synthetics. Geotextiles and Geomembranes 27(1):39-52.

[4] Viswanadham B.V.S., König D. (2008) Centrifuge modeling of geotextile-reinforced slopes subjected to differential settlements. Geotextiles and Geomembranes 27(2), 77-88.

[5] Wang L.P., Zhang G., Zhang J.M. (2011) Centrifuge model tests of geotextile reinforced soil embankments during an earthquake. Geotextiles and Geomembranes 29 (3), 222-232.

[6] Zhang G., Hu Y., and Zhang J.M. (2009) New image analysis-based displacement-measurement system for geotechnical centrifuge modeling tests. Measurement 42 (1), 87-96.