Centrifuge modeling of reinforced and unreinforced embankments with lime-stabilized fill on soft ground

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ABSTRACT: In recent years, lime-stabilized soils have been used as a cost effective alternative to backfill highway embankments in China. Limited studies were conducted on the behavior of the embankments, especially the reinforced embankments, with lime-stabilized soil as backfill on soft clay. In this paper, two centrifuge tests were performed respectively on the reinforced and unreinforced embankments with lime-stabilized soil as backfill on soft clay installed with wick drains. Instrumentations were carried out to investigate the distributions of displacements, pore water pressures, and earth pressures in the foundations as well as tensile forces in the model geogrid.

1 INTRODUCTION

Lime-stabilized soils have been used in China as a cost-effective backfill material for the construction of highway embankments (Cao and Chen 2006). Soft clays with high liquid limit, salt content, and compressibility can be improved by mixing lime with these clays. The highway embankments along the Yangzi River in Jiangsu Province, China, were backfilled with naturally-dried soft clay mixed with 5 to 8% lime and they performed well during their construction and service (Xue and Chen 2004).

There have been a series of centrifuge tests conducted on scaled-down geosynthetics-reinforced embankments on soft clay to investigate their behaviors and reinforcement mechanisms (Bolton and Sharma 1994; Mandal and Joshi 1996; Ding and Bao 1999; Yu et al. 2005). However, there have been still limited studies conducted on the behavior of the reinforced embankments backfilled with lime-stabilized soil on soft clay. In this study, two centrifuge tests were conducted respectively on the reinforced and unreinforced embankments backfilled with lime-stabilized soil on soft clay installed with wick drains.

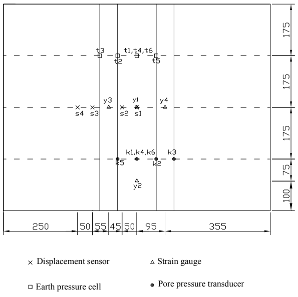
2 CENTRIFUGE MODELING

2.1 *Design of Model Tests*

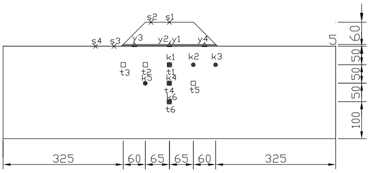
Two centrifuge tests were performed at the geotechnical centrifuge facility at Tongji University, Shanghai, China. This facility has a capacity of 150g•t and a 3 m radius arm.

The prototype reinforced embankment had a height of 6m, a base width of 25m, and a 1:1 side slope. A 50cm-thick sand cushion overlain by the embankment was placed over a 25m-thick soft subsoil installed with prefabricated vertical drains (PVDs) in triangular pattern at a center-to-center spacing of 2m. A sheet of biaxial plastic geogrid was placed in the middle of the sand cushion. The unreinforced embankment was the same as the reinforced embankment except for no reinforcement in the sand cushion.

The strongbox had internal dimensions of 900mm in length, 700mm in width, and 700mm in depth. The scale factor for these tests was 100. Figure 1 shows the dimensions of the 1/100 scaled down model.



(a) Plan view



(b) Cross view

Figure 1. Model dimensions and instrumental layout (unit: mm)

2.2 *Test Procedure*

(1) Double sheets of Teflon were glued to the inside vertical surfaces of the strongbox to reduce the friction between the strongbox and the soil.

(2) The foundation was made by controlling 5:3 of the mass ratio of air-dried soil to water. The soil was placed in 10 layers at a lift thickness of 30 mm each. Earth pressure cells and pore pressure transducers were installed during making foundation.

(3) In order to reach the similar stress level and degree of consolidation in the model foundation as those in the prototype, the model was subjected to an acceleration of 100 g for 2.5 hours, which is equivalent to the consolidation of the prototype for 3 years according to the centrifugal scaling law.

(4) After consolidation, the front Plexiglas window was removed and an array of markers was installed on the front face of the foundation. The model sand drains were installed using a thin shell steel tube with 5mm diameter. Then, 5mm thick, 250mm wide sand cushion, instrumented model geogrid, and a precast lime-stabilized embankment were placed successively over the surface. Displacement sensors were installed on a steel frame fixed on the strongbox.

(5) Three-staged construction of the embankment was simulated by increasing the acceleration as shown in Figure 2. In terms of the prototype, the three levels of accelerations at 33.3g, 66.7g, and 100g were equivalent to the construction heights of 2m, 4m, and 6m, respectively, and there was a month waiting period following each stage loading.

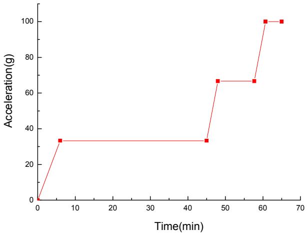


Figure 2. Relationship between acceleration and time

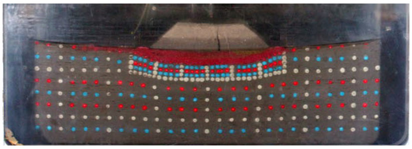
3 TEST RESULTS ADN ANALYSES

Table 1 presents the properties of the embankment and the after-consolidation foundation soils

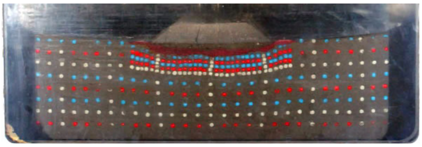
Table 1. Properties of the embankment and the after-consolidation foundation soils

	Unit weight γ(kN/m^3)	Water content w(%)	Initial void ratio e_0	Compression index C_c	Cohesion C_{cu}(kPa)	Friction angle ϕ_{cu}(°)
Embankment	19.1	20	0.43	--	109.0	35.0
Subsoil	17.3	44	0.58	0.29	8.0	23.0

Figure 3 shows the photographs taken in flight for reinforced and unreinforced embankments at 100g. Ruptures were observed in the reinforced and unreinforced embankments. This reason can be explained by the fact that the lime-stabilized soil exhibits brittle characteristics and has low tensile strength. Reinforcement in the lime-stabilized soil would improve the integrity and stability of the embankment.



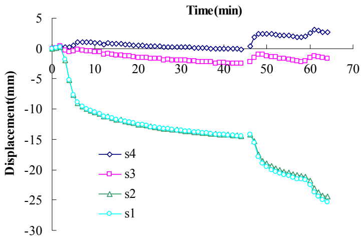
(a) reinforced



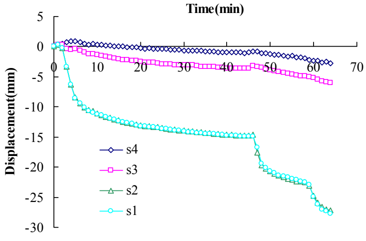
(b) unreinforced

Figure 3. Photographs taken in flight for reinforced and unreinforced embankments at 100g

Figure 4 shows displacement vs. time curves for reinforced and unreinforced embankments. It can be seen that reinforcement reduced settlement at central portion of the embankment. The settlement at the end of 100g at point s1 for the reinforced embankment was 2.35mm less than that for the unreinforced embankment, indicating that the reinforced embankment reduced approximately 8% of settlement as compared to the unreinforced embankment. The settlement at point s3 at a distance of 25mm beyond the toe of the reinforced embankment was 4.26mm less than that of the unreinforced embankment. An apparent heave was observed at point s4 at a distance of 200mm beyond the toe of the reinforced embankment while the unreinforced embankment exhibited settlement. It also can be seen from the displacement-time curve that the settlement increased apparently during waiting periods for both reinforced and unreinforced embankment. It should be noted that the subsoil was remolded and had weak structure, which exhibited the characteristics of apparent settlement.



(a) reinforced

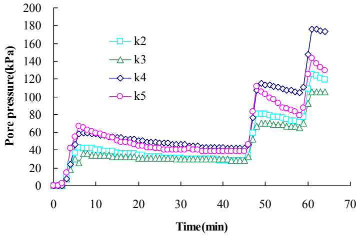


(b) unreinforced

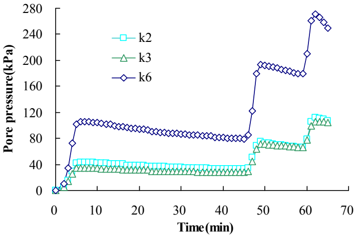
Figure 4. Displacement vs. time curves for the reinforced and unreinforced embankments

Figure 5 shows the pore pressures vs. time curves for the reinforced and unreinforced embankments. It should be noted that the pore pressure transducers at k1 and k6 for the reinforced embankment, and k1, k4, and k5 for the unreinforced embankment, did not work well. So the data from these malfunctioning transducers were not depicted in Figure 5. During each waiting period, the pore pressures in the foundations of the reinforced and unreinforced embankments dissipated apparently, which attributed to the model sand drains installed in the foundation.

Figure 6 shows earth pressures vs. time curves for the reinforced and unreinforced embankment. Earth pressures at t4 and t5 for the reinforced embankment were approximately 6 to 10% less than those for the unreinforced embankment while earth pressure at t3 for the reinforced embankment was approximately 40% higher than the unreinforced embankment. Furthermore, earth pressure at t4 was 20.2% less than that at t4 for the reinforced embankment whereas 49.1% for the unreinforced embankment. Note that t3, t4, and t5 were located under the embankments' toe, center, and shoulder, respectively, and t3 was 50mm above t4 and t5, as shown in Figure 1. These results indicate that the reinforcement spread the embankment loading apparently and made the stresses in the subsoil tend to be distributed uniformly.

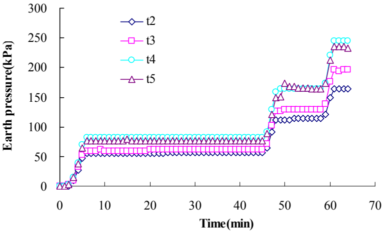


(a) reinforced

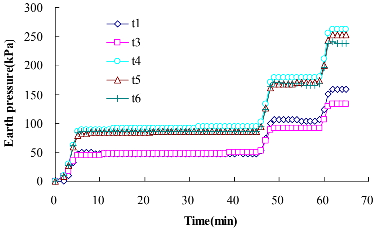


(b) unreinforced

Figure 5. Pore pressures vs. time curves for the reinforced and unreinforced embankments



(a) reinforced



(b) unreinforced

Figure 6. Earth pressures vs. time curves for the reinforced and unreinforced embankments

Figure 7 presents tensile forces in model geogrid vs. time curves for the reinforced embankment. The tensile forces were obtained from the strain gauges attached on the model geogrid. Note that the gauge of y1 was dysfunctional. As shown in Figure 7, the tensile forces increased with an increase of acceleration, which was in accordance with the variation of settlement with acceleration. The tensile forces at y3 and y4 were close since they were installed symmetrically at a distance of 95mm from the centerline. The tensile force at y2 installed at the centerline was slightly higher than that at y3 and y4 until an acceleration of 33g and then increased significantly when the acceleration exceeded 33g. The tensile force at y2 was approximately 1.5 time the average force at y3 and y4 at the end of the test.

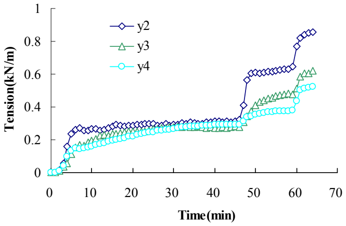


Figure 7. Tensile forces in model geogrid vs. time curves for the reinforced embankment

4 CONCLUSION

The findings were concluded as follows:

(1) Compared with the unreinforced embankment, the settlement of reinforced embankment was reduced approximately by 8%; and the heave of the reinforced embankment foundation was observed, whereas unreinforced embankment predominantly exhibited settlement;

(2) During each waiting period, the pore pressures in the foundations of the reinforced and unreinforced embankments dissipated apparently, which attributed to the model sand drains installed in the foundation;

(3) Earth pressures under embankment base were distributed uniformly due to geogrid reinforcement. Earth pressures under central part of the reinforced embankment were 6%～10% less than those of the unreinforced embankment, whereas earth pressures under the slope toes of the reinforced embankment were approximately 40% greater than that of the unreinforced embankment;

(4) The tensile forces increased with an increase of acceleration, which was in accordance with the variation of settlement. The tensile forces distributed uniformly until an acceleration of 33g and then the tensile force at the centerline increased significantly when the acceleration exceeded 33g;

(5) The lime-stabilized soil exhibits brittle characteristics and has low tensile strength. Reinforcement in the lime-stabilized soil would improve the integrity and stability of the embankment.

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