Centrifugal and numerical analysis of geosynthetic-reinforced soil embankments

Etude par centrifugeuse et analyse numérique des remblais renforcés par géotextile

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ABSTRACT: Centrifuge models and numerical analysis of geosynthetic-reinforced and unreinforced soil embankments are presented. The results obtained from the centrifuge tests were compared with those from the numerical analysis. It is found that the filamentous fiber (polypropylene) is effective in constraining lateral displacement and reducing vertical settlement for the case of geosynthetic-reinforced soil embankments. Also, the distribution of stress in the geosynthetic-reinforced soil embankment is significantly ameliorated compared with the unreinforced. The presence of geosynthetic filamentous fibers in reticular structure provides the reinforced soil embankments strength to resist crack.

RÉSUMÉ : Dans cet article, les résultats de modèles de centrifugeuse et les analyses numérique des remblais renforcés par géotextile et non-renforcés sont présentés. Les résultats obtenus à l'aide de la centrifugeuse sont comparés avec ceux des analyses numériques. Les fibres filamenteux (polypropylène) sont efficaces pour restreindre les déplacements latérales et réduire les tassements verticaux dans le cas du remblais renforcé. De plus, la répartition des contraintes dans le remblai renforcé est améliorée de façon significative comparé avec celle du remblai non-renforcé. La présence des fibres dans une structure réticulaire dans le remblai renforcé donne une résistance contre la fissuration.

KEYWORDS: Embankment ; Geosynthetic-reinforcement ; Centrifuge test ; Numerical analysis

1 INTRODUCTION

The concept and design theory of reinforced soil were proposed by the French engineer Henri Vidal from model tests in the 1960s. The reinforcement materials include metal strips, concrete slabs, bamboo ribs and geosynthetic materials, etc. Now-a-days, geosynthetics was commonly used in reinforcing soil owing to its easy-controlled properties of structure type and size, strength, impermeability, acid dissolution and durability.

"Cohesion" of filamentous fiber reinforced soil comes from friction between soil and fibers, as well as the constraint force of the fiber network. The magnitudes of CBR and unconfined compressive strength(UCS) increase with augment of filamentous fibers linearly(Xiong Youyan 1989). Soil reinforced with continuous filamentous fibers is obviously effective in reducing the vertical deformation of sand under the vertical pressure; it is superior in reducing horizontal tension than geogrids(A.F.L.Hyde and M.Ismail 1988). In recent years, this technique has applied successfully by reinforcing the embankment using filamentous fibers in embankment projects, and datum are available from researches (Bao Chenggang and Ding Jinhua 2012). However, the interaction micro-mechanism of interface between soil and filamentous fibers is still unclear (Tang Chaosheng, Shi Bin and Gu Kai 2011, Jie Yuxin and Li Guangxin 1999).

In this paper, the behavior of geosynthetic-reinforced embankments has been explored using centrifugal and finite element modeling. The objectives of this paper include: (1) to probe the mechanism of filamentous fibers in improving the stability of the embankment, and (2) to examine the effectiveness of filamentous fiber reinforcement.

2 CENTRIFUGE TESTS

Centrifuge model testing, because of its ability to reproduce same stress levels, same deformation and same failure mechanism in an 1/ n scale model as in a full-scale prototype, is widely used in studying geotechnical problems. Jie Yuxin and Guang-Xin Li studied the stability of cohesive soil slope and fiber-reinforced soil slope with different densities through centrifugal model tests; Yang Xiwu and Ouyang Zhongchun obtained the deformation behavior of embankments which reinforced with various fiber styles. It should be pointed out that idealized conditions may be created in centrifuge models carefully to avoid problems caused by stress errors, boundary effects, particle scale effects and geometrical scale effects.

2.1 *Centrifuge tests—Equipment and procedure*

2.1.1 *Equipment*

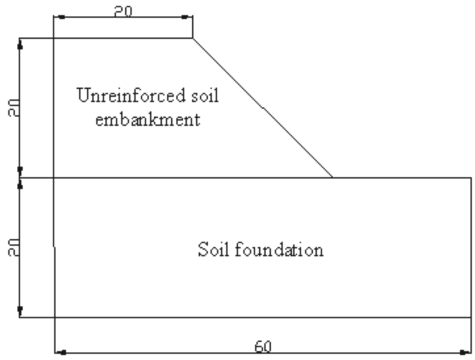
In the present study, centrifuge model tests were performed using the TLJ—60 centrifuge in Chongqing Jiaotong University. The main parameters of the centrifuge are indicated in Table 1.

Table 1. The main parameters of the centrifuge

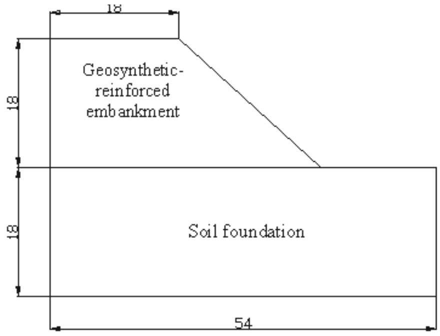
Characteristic	Value
Maximum volume weight	60g·t
Maximum load	600kg(100g)
	300kg(200g)
Effective radius	2.0m
Maximum acceleration	200g
Acceleration control accuracy	±0.5%F·S
Model box size	600mm×350mm ×500mm

2.1.2 *Model scale*

Due to the inherent symmetry of the embankment about its centerline, only one half of it was modeled. In order to simulate the actual project accurately and satisfy the boundary effects, 1:90 scale centrifuge model was constructed. Fig.1 shows the details of test model and its full-scale prototype.



(a) 1:90 scale centrifuge model (cm)



(b) Full-scale prototype (m)

Figure 1. Arrangement of model for centrifuge test and its prototype

2.1.3 *Parameters of soil and fiber*

（1）The physical parameters of the soil

Table 2 gives the parameters of the brown weathered shale that obtained from compaction test and liquid and plastic limit combined test.

Table 2. Brown weathered shale material properties

Optimm water content (%)	Maximm dry density (g/cm^3)	Liquid limit (%)	Plastic limit (%)	Plasticity index
8.9	2.15	26.928	20.193	6.735

Before the centrifuge test, soil sample was experienced airing and grinding, then sieved by 6mm sieve to remove impurities.

（2）The parameters of the fiber

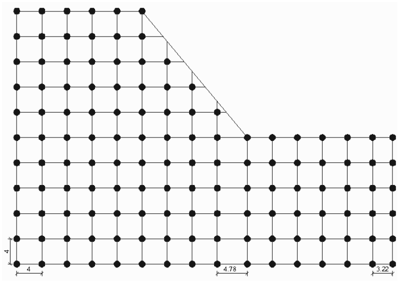
Polypropylene fiber with 19mm length was proposed to construct the fiber reinforced soil embankment model. Table 3 gives the triaxial test strength of the embankment soil with the fiber ratio of 1 ‰, 2 ‰ and 3 ‰ respectively.

Table 3. Embankment soil material parameters

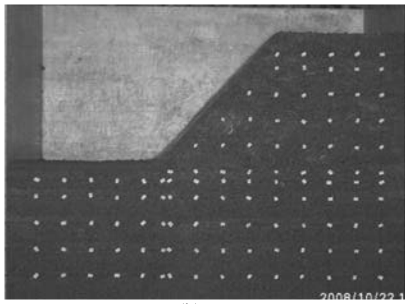
Embankment soil	Cohesion(kPa)	Friction angle(degrees)
Unreinforced soil	49.167	34.077
19mm-0.1%-Polypropylene-reinforced soil	94.005	35.717
19mm-0.2%-Polypropylene-reinforced soil	138.294	36.362
19mm-0.3%-Polypropylene-reinforced soil	228.356	35.951

2.1.4 *Deformation measuring*

An array of pins was installed on the front face of the embankment model as deformation marker. This was used for measuring the model vertical and horizontal displacement from coordinate difference between beginning of test and the end of test through the front perspex window. Fig.2 shows the details of the marked model.



(a)



(b)

Figure 2. The marked model

2.2 *Centrifuge tests—summary of results*

2.2.1 *Comparison analysis of deformation and displacement*

In this section, the results obtained from unreinforced embankment test are compared with the results obtained from reinforced embankment test. The deformation of unreinforced embankment was slightly larger than the deformation of reinforced embankment. The settlements under the shoulder of the unreinforced embankment and the slope gradient were considerably greater than those of reinforced embankment. Two cracks on the top of the unreinforced embankment and (heave) beyond the toe of the unreinforced embankment were observed at the end of the centrifuge tests. Fig.3 and Fig.4 show the displacement vectorgraph of unreinforced and reinforced embankment respectively. From the close comparison between unreinfroced and reinforced embankments, it is evident that fiber reinforcement reduced the displacement of embankment, and enhanced the embankment obviously.

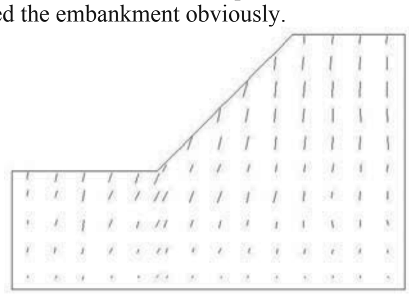


Figure 3. Deformation of the unreinforced model

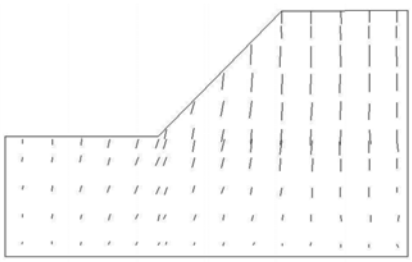


Figure 4. Deformation of geosynthetic-reinforced model

2.2.2 *Comparison analysis of settlement*

The maximum lateral displacement of unreinforced model was 72cm, which located in the distance of 8m from the toe of the embankment. The maximum settlement was 48.6cm, which located in the distance of 10.8m from the centerline; For reinforced case, the maximum lateral displacement emerged in the distance of 8.2m from the toe of the embankment with 35cm, and the maximum settlement was 41.2cm (located in the distance of 10.4m from the centerline). It is safely to conclude that the maximum displacement of both unreinforced and reinforced embankment approximately close to the same point, whereas the maximum lateral displacement of reinforced embankment is approximately equal to 48.6% of the maximum lateral displacement of unreinforced embankment and the maximum settlement of reinforced embankment is approximately equal to 84.8% of the maximum settlement of unreinforced embankment.

The comparison between computation analysis and centrifuge tests of the embankment discloses that fibers help to resist the lateral thrust and lateral deformation of the embankment effectively. This is due to the fact that fibers unified the overall redistribution of stress and reduced asymmetric settlement of embankment.

3 FINITE ELEMENT MODELLING

3.1 *Assumptions of computing*

In the analysis presented in this paper, the unreinforced and reinforced embankments are modeled using the Drucker-Prager constitutive model (D-P model).

Two-dimensional plane strain models were constructed with boundary conditions similar to those of centrifuge models. The modeling based on follow assumptions: (1) taking geotextile reinforced soil as homogeneously isotropic material, the parameters obtained from triaxial tests; (2) without considering the influence of temperature to embankment; (3) consolidation was completed under its gravity, and without considering the impact of pore pressure.

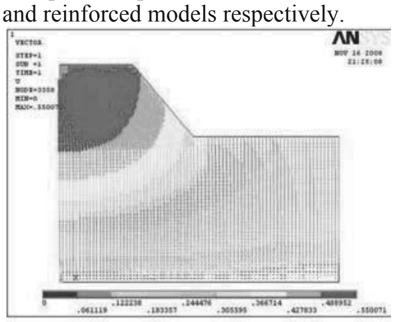
3.2 *Parameters*

Table 4. Material parameters specified for the finite element analysis

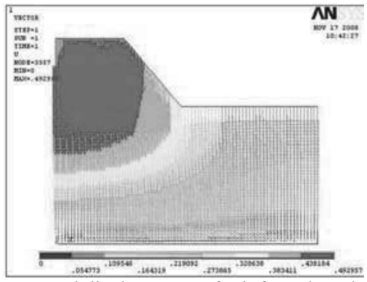
Characteristic	Unreinforced embankment	Polypropylene-reinforced embankment (19mm-0.1%)	Foundation
Density (kg/m^3)	2150	2180	2150
Cohesion (kPa)	49.167	94.005	49.167
Friction angle(degrees)	34.077	35.717	34.077
Poisson's ratio	0.27	0.23	0.27
Depth of embankment(m)	18	18	36

3.3 *Displacement comparison*

The computed results indicated that the values of deformation and stress as well as its fluctuation range were marginally less for reinforced embankment than for unreinforced embankment. The maximum lateral displacement of unreinforced model was 79.442cm (located in the distance of 11.4m from the toe of the embankment), and the maximum settlement was 51.498cm (located in the centerline); The maximum lateral displacement of reinforced model was 38.246cm (located in the distance of 11.4m from the toe of the embankment), and the maximum settlement was 48.318cm (located in the centerline). Fig.5 and Fig.6 present computed displacement and stress contours of the unreinforced and reinforced models respectively.

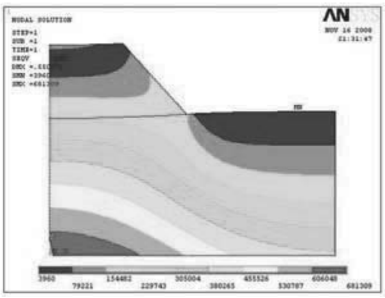


(a) computed displacement of unreinforced model

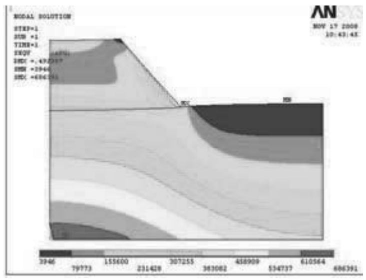


(b) computed displacement of reinforced model

Figure 5. Computed displacement of unreinforced and reinforced model



(a) stress contours of unreinforced model



(b) stress contours of reinforced model

Figure 6. Stress contours of unreinforced and reinforced model

4 RESULTS AND COMPARISIONS

Fig.7 shows the variation of lateral displacement and vertical displacement of unreinforced embankment from centrifuge tests. Superimposed on the measured variation are the variations computed by numerical modeling analysis. It can be seen from Fig.7 that there is a close agreement between the observed and computed displacements for centrifuge test and numerical analysis.

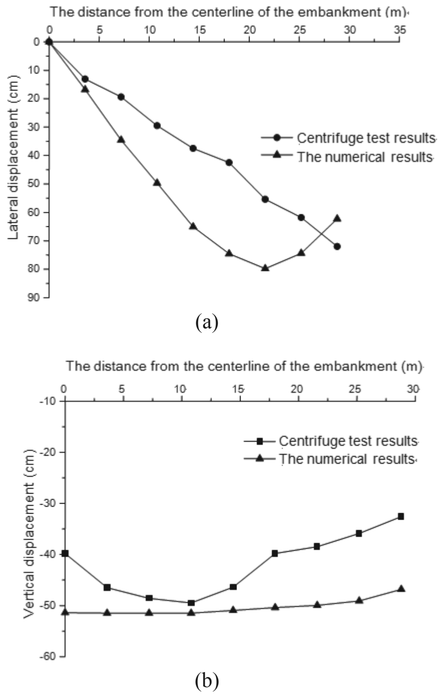


Figure 7. measured and computed displacement of unreinforced model

The comparison between the computed and observed displacement both in the horizontal direction and in the vertical direction for the reinforced embankment are shown in Fig.8. The computed displacement is quite close to the observed values for both lateral displacement and vertical displacement.

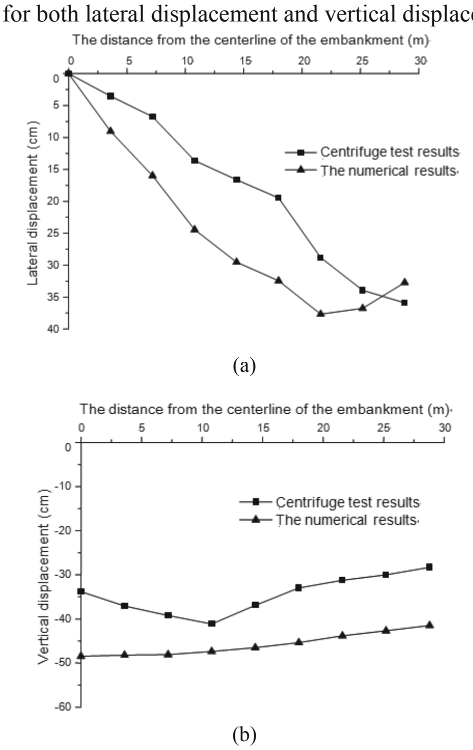


Figure 8. Measured and computed displacement of reinforced model

The behavior of reinforced embankment and unreinforced embankment was successfully investigated using centrifuge modeling and finite element analysis. The comparisons between the centrifuge tests and computed results indicated the utility of fibers can enhance overall stability of embankment. For the case of reinforced embankments with fibers, it was found that the deformation, the magnitude of stress, and their variation range was considerably less than those for unreinforced case. Also, the fiber reinforcement constrained the lateral displacement effectively, and the distribution of stress and deformation was harmonious comparing with the unreinforced.

When using geosynthetic fibers to reinforce embankment, it also shows two advantages: (1) reinforced embankment can resist cracks due to the network of intertwined fibers, and(2) the fiber reinforced soil is closer to a homogeneous, isotropic material than unreinforced soil.

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