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Geosynthetic reinforced piled embankment – large-scale model tests and numerical modelling

Chew, S.H. & Phoon, H.L.
National University of Singapore, Singapore

Le Hello, B. & Villard, P.
LIGIRM, Univeristé Joseph Fourrier, France

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ABSTRACT: The construction of road or railway embankment over soft soils and limestone formation has often encountered settlement problems that will cause failure to the structure. The use of piles coupled with geosynthetic reinforcement to support the embankment has gained popularity very recently due to its effectiveness and economical advantage. A series of large-scale model tests had been carried out to investigate the contributions of soil arching effect and geosynthetic's tensioned membrane effect in this geosynthetic reinforced piled embankment (GRPE) system. Four large-scale model tests were conducted to evaluate the effect of embankment fill height and geosynthetic's stiffness on the performance of GRPE system. In addition, a special new numerical modelling method that coupled finite elements with discrete elements has been developed to model this problem that involves the mechanism of collapse and rupture of the soil particles.

1 INTRODUCTION

In the Southeast Asia region, soft soils and limestone formation can be easily found. Soft soils are compressible and therefore result in large consolidation settlement. The construction of embankment over soft soils may lead to excessive settlement and subsequently cause failure to the structure. Sinkholes formation and surface settlement are the two common problems when embankments are constructed over limestone formation. Geosynthetic reinforced piled embankment (GRPE) has gained popularity very recently to overcome the above problems. The use of geosynthetic as basal reinforcement can increase the stability of the whole system and control the surface settlement of the embankment. A series of large-scale model tests had been carried out. The objectives of this series of tests were to have a better understanding of the complex mechanisms of GRPE system. This is a collaborative research between National University of Singapore and Univeristé Joseph Fourrier, France.

In addition, a new numerical modelling method using the coupled finite elements and discrete elements was developed. This method enables the modeling of the complex mechanisms of GRPE, which involves the mechanism of collapse and rupture of the soil particles.

2 LARGE-SCALE MODEL TESTS

The large-scale model tests were conducted at a test pit located in Selangor, Malaysia. The dimension of the test pit is 3 m (Width) × 4.75 m (Length) × 2 m (Depth) (Figure 1). The 3 sides of the pit were concreted, while the fourth side (front) was retained by a specially designed steel retaining wall. In addition, there are two "doors" specially located in the front wall to enable the removal of subsoil. Several H-steel piles were installed in triangular grid arrangement as end bearing piles with circular pile caps. The piles

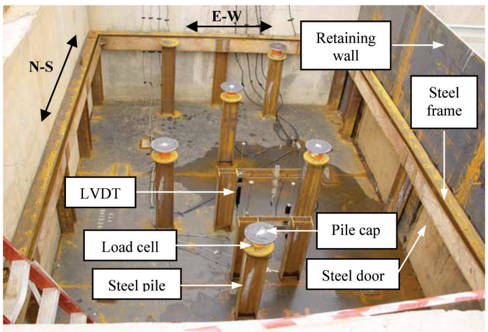

Figure 1. The instrumented large-scale model.

spacing in the N-S and E-W directions are 2.08 m and 1.2 m respectively. The diameter of the steel circular individual pile caps is 0.21 m. Granular fill was filled to the pile cap level as subsoil, followed by the laying of 2 layers of geosynthetics reinforcement on top of it. Sandy soil fill was then placed onto it layer by layer, with compaction similar to the site operation. After the stabilization achieved with the filling up of a predetermined height of fill material, all the soil underneath the geosynthetics reinforcement sheets (called sub-grade soil) was dug out from the front steel doors to simulate a subsidence.

Soil pressure cells (TPCs) and Linear Voltage Displacement Transducers (LVDTs) were installed at certain critical positions in the embankment fill to measure the vertical soil stresses and geotextile settlement respectively. Grid-liked fixed points were drawn on the surface of the embankment in order to measure the surface settlement.

Table 1 shows the details of the tests performed in this series. In the first two tests, two layers of mono-directional high tensile strength geotextile (Rock PEC75) were perpendicularly cross-laid to provide bi-directional reinforcements. The average ultimate tensile strength of this high strength geotextile in machine direction and cross machine direction are 75 kN/m (at 13% strain) and 14 kN/m (at 60% strain) respectively, which corresponds to stiffness of 577 kN/m in MD.

Table 1. Detail of the tests performed.

Test no.	Number of geosynthetic sheets	Fill height (m)	Surcharge after removal (m)	Reinforce-ment type
1	2	0.5	–	Geotextile
2	2	1.0	0.5	Geotextile
3	0	1.0	–	Nil
4	2	1.0	0.75	Microgrid

In Test 1 and Test 2, the embankment was filled up to a height of 0.5 m and 1.0 m respectively. Figure 2 shows the cross section of the large-scale model in Test 1. For comparison, a "no-geotextile" test, as designated as Test 3, had been conducted with 1.0 m fill height without any geosynthetics reinforcement. In Test 4, microgrid (MG100/100), a knitted polyester microgrid, with bi-directional tensile strength of 100 kN/m (at 11% strain) and aperture size of 5-7 mm was used as basal reinforcements. The stiffness of microgrid is 1818 kN/m in each reinforcement direction.

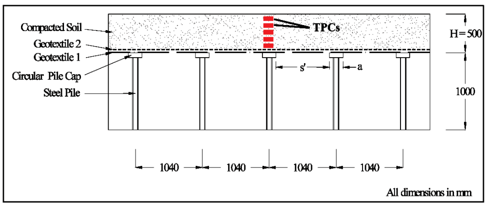

Figure 2. The cross section of the large-scale model in Test 1.

3 RESULTS AND DISCUSSIONS

3.1 *Surface settlement*

Surface settlement of about 5 to 15 cm was detected at the center of the model after the subsoil removing stage in Test 1 (Figure 3). The ratio of fill height to clear pile spacing (H/s') in the N-S and E-W directions are 0.27 and 0.51 respectively. Tensile cracks were observed on the embankment top surface due to shear failure.

Figure 3. Surface settlement in Test 1 to Test 4.

In Test 2, the ratio of fill height to clear spacing in the N-S and E-W directions were increased to 0.53 and 1.01 respectively, which were double the values in Test 1. It was observed that the soil arching effect could perform better in Test 2, which has 1.0 m soil fill. Hence, the surface settlement could be reduced slightly as compared to Test 1.

In Test 3, the sandy soil fill completely collapsed during the removal of subsoil and eventually a large sinkhole formed right through the top. This shows that the embankment with current configuration cannot achieve stability without the use of geosynthetics reinforcement. In Test 4, when stiffer geosynthetics reinforcements were used, the surface settlement was even smaller than that in Test 2.

Figure 4 shows the contour maps of surface settlement in Test 1, Test 2 and Test 4. It can be noticed that the surface settlement reduced slightly from Test 1 to Test 2, and reduced significantly from Test 2 to Test 4.

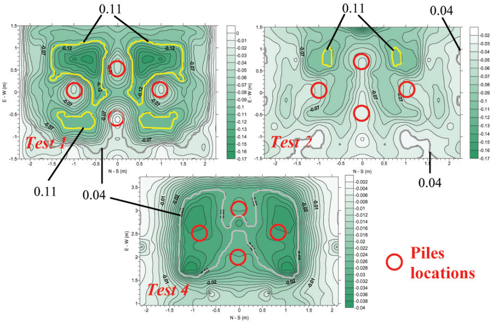

Figure 4. Contour maps of surface settlement - Tests 1, 2 and 4.

The results show that the percentage of volume that settled over total embankment volume reduced slightly from Test 1 (14.87%) to Test 2 (5.91%) due to the increase of fill height. Comparing Test 2 and Test 4, when about 3-time stiffer geosynthetics reinforcement was used in Test 4, the volume of settlement also reduced approximately 3 times.

3.2 *Soil arching formation*

During the removal of subsoil, a large differential settlement developed between the soil columns located directly above the pile caps and the soil in-between the pile caps. This promotes the development of soil arching effect.

Figure 5 shows the vertical soil stresses measured above the centre of 4 piles during the removal of subgrade in Test 4 (using microgrid as reinforcement). The results show that during the removal of subgrade, geosynthetics reinforcement will deform, and yielding of a portion of soil mass located directed above the geosynthetics reinforcement occurred. It is noted that the shape of the vertical stress profiles are similar to the soil pressure curve due to soil arching that was published by Terzaghi (1936).

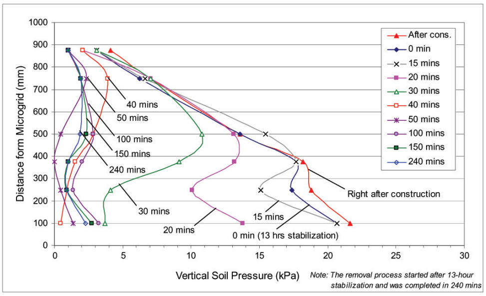

Figure 5. Vertical soil stresses measured above the center of 4 piles during the removal of subgrade in Test 4.

Figure 6 shows the vertical soil stresses measured by TPCs located in various depths at the center of 4 piles due to the placing of additional surcharge layer

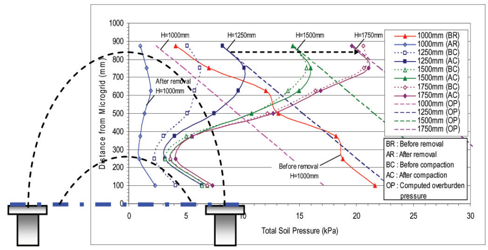

Figure 6. Vertical soil stresses measured above the center of 4 piles after placing additional surcharge layers in Test 4.

after the removal of subgrade in Test 4. The result shows that with the inclusion of geosynthetics reinforcement, the arch could remain stable when additional surcharge layer was placed and compacted. It was observed that the increase of vertical soil stresses was concentrated near the crown of the arch, which experienced the revised static overburden pressure. On the other hand, the soil beneath the crown of arch experienced a soil pressure that is lower than the static overburden pressure. The location of the "soil arch" was indicated by dotted arches in Figure 6, as deduced from these soil stress readings.

4 NUMERICAL MODELLING

The main numerical challenge linked to the modelling of embankment reinforced by piles and geosynthetic sheets results from the difficulties to take into account the membrane behaviour of the sheet, the transfer of load and the arching effect induced inside the granular material by the displacement of any grains.

To take into account these complex phenomena, a three dimensional software coupling finite element method (FEM) and discrete element method (DEM) was developed. The coupling between the two methods capitalizes the strength of both methods: using a continuous model defined by the macroscopic parameters to describe the fibrous nature of the geosynthetic sheet and its interaction with the soil, and using a discrete model to describe the arching effect, collapse, and failure of the soil.

The finite elements implemented in the three dimensional software are triangular finite elements developed specifically to take into account the fibrous nature of the geosynthetic sheet and to simulate its membrane behaviour (Villard et al. 1998). The discrete elements approach consists of modelling a structure by a group of particles interacting between them on their contact points. At any moment, the particles can be disassembled or be reassembled that make it possible to model fractured mediums or granular mediums in large deformations.

The interaction between finite and discrete elements is done at their contact points.

The mechanism of embankments reinforced by piles and geosynthetic was studied using this new numerical approach. The geometry of this numerical modelling is given in figure 7 (H = 1m, s = 1.5 m and a = 0.45 m). For reasons of symmetry and to reduce the time of calculation, only one part of the embankment will be modelled. The soil embankment is assumed to be a granular material modelled using 7260 spherical discrete elements (diameter ranging between 0.03 m and 0.09 m) positioned in space with a random distribution at porosity of 0.37. The geosynthetic sheet is modelled with 200 triangular finite elements reinforced in two orthogonal directions. The subsoil under the geosynthetic sheet is assumed to be very soft and was not considered in this numerical simulation.

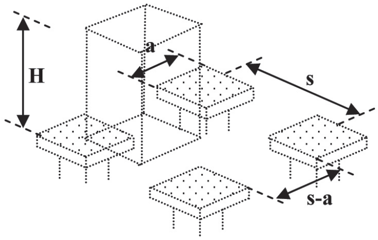

Figure 7. Geometry of model.

General view of the soil particles displacements is given in Figure 8. The displacements of the geosynthetic sheet are presented in Figures 9 and 10. The maximum vertical displacement fmax of the sheet in the centre of the square mesh is 0.183 m. Between the piles, the maximum vertical displacement of the sheet is 0.112 m.

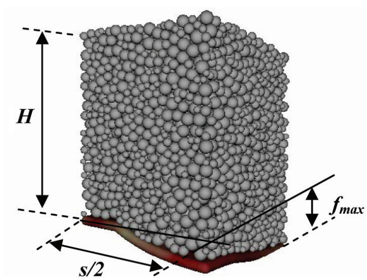

Figure 8. Displacements of the soil particles.

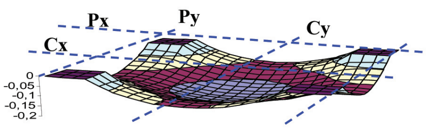

Figure 9. Vertical displacements of the sheet.

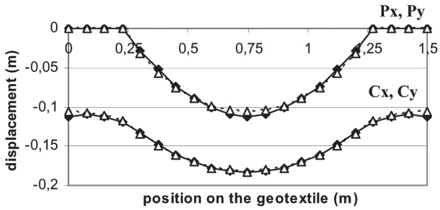

Figure 10. Vertical displacements of the sheet in cross sections C_X, C_Y, P_X and P_Y.

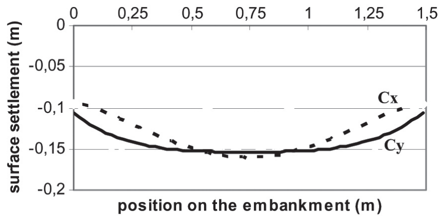

Figure 11. Surface settlement in cross section C_X and C_Y.

The surface settlements in the cross sections C_X and C_Y are shown in Figure 11. The maximum surface settlement obtained in the centre of the square mesh is around 0.15 m. This predicted soil and geotextile settlement patterns matched very well with the observed settlement from the physical model tests.

5 CONCLUSIONS

The results of this series of large-scale model tests on geosynthetics reinforced piled embankment show that both arching effect and geotextile's tensioned membrane effect contribute towards the stability of soil mass above a piled embankment. In addition, the embankment fill height has significant effect on arching formation that directly related to the surface settlement. This indicates that a minimum fill height is required to ensure that soil arching can develop before the soil subsidence takes place. The new three-dimensional numerical modeling method that coupled FEM/DEM show good promise to be able to capture the complex mechanism of geosynthetic reinforced piled embankment.

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