Effects of Reinforcement Stiffness on Deformation of Reinforced Soil Structures under Sustained and Cyclic Loading

Uchimura, T. and Tatsuoka, F.
Department of Civil Engineering, University of Tokyo
uchimura@geot.t.u-tokyo.ac.jp

Hirakawa, D.
Department of Civil Engineering, Tokyo University of Science

Shibata, Y.
Ministry of Land, Infrastructure and Transport Government of Japan

ABSTRACT: The stiffness and residual deformation of geosynthetic-reinforced soil structure subjected to sustained concentrated vertical loading and a long-term vertical cyclic loading history was evaluated by performing small-scale model tests in the laboratory. Within the examined limit of reinforcement stiffness, the effects of reinforcement stiffness were utterly insignificant on the behaviour during unloading and reloading. When the vertical spacing was smaller than some limit, the deformation of backfill did not decrease noticeably with a decrease in the vertical spacing of reinforcement layers. These results suggest that it is not necessary to use metal reinforcement and the reinforced backfill property could be more important.

1 INTRODUCTION

To construct geosynthetic-reinforced soil structures allowing small instantaneous and residual deformations, such as bridge abutments, it is necessary to restrain the deformation of the backfill to a small value. It is generally considered that the reinforcement materials can be classified to “extensible” reinforcements (e.g. geosynthetics) and “inextensible” reinforcements (e.g. steel bars and strips), and soil structures reinforced with “extensible” materials have low stiffness and strength. However, this popular belief should be carefully examined by experimental facts. The stiffness of reinforcement materials could be less essential to the stiffness of reinforced soil structures, because ordinary “extensible” geosynthetics have much higher stiffness than the backfill geomaterials.

The stiffness and residual deformation of geosynthetic-reinforced soil structures were evaluated by performing small-scale model tests in the laboratory. Sustained concentrated vertical loading and a long-term vertical cyclic loading history were applied. The backfill soil was a well-graded gravel (D_{max} = 5mm, D_{50} = 2.52mm, U_{c} = 5.41, Dr = 90 %) compacted to a dry density of 1.79 g/cm$^3$. Two types of reinforcement were used: a polyester geogrid and a phosphor bronze grid (Figure 2). The polyester geogrid had nominal rapture strength of 39.2 kN/m and the maximum extensive strain of 22 % and stiffness of 507 kN/m, at a strain rate of 1 %/min. Each strand was 1 mm-wide and the ce-
center-to-center spacing was 9 mm. The phosphor bronze grid consisted of 34 phosphor bronze strips (3.5 mm-wide, 0.2 mm-thick and 350 mm-long) for each direction having the center-to-center spacing of 20 mm. The stiffness was 5580 kN/m, which is 11 times larger than that of the polyester grid. Fine sand particles were glued to surface of the phosphor bronze grid to make the friction angle with the backfill material to be nearly the same as that of the polyester grid, around 40 degrees.

The vertical spacing between the reinforcement layers, 5 cm, was much smaller than that of real reinforced soil structures. However, as the particle size of the backfill materials and the aperture of the grids were also scaled, the dimensions may geometrically reasonably simulate typical prototype structures.

The pier models were vertically compressed in a strain control condition by using a gear system. The vertical compressive strains of the model were precisely measured by means of LDTs (local displacement transducers) set on the side surfaces. The horizontal strains were measured at the middle height of the model in two directions orthogonal to each other by using laser displacement transducers with targets connected to the backfill just behind the sandbags.

Figure 1. Configurations of models.

Figure 2. Configurations of reinforcements.

2.2 Results and discussions

Figures 3 and 4 show the results from two tests on models with reinforcement of polyester and phosphor bronze, which were loaded with the same procedures. At loading stage denoted as “a” to “s” in the figures, the vertical strain rate were variously changed step by step, within a range of 0.00472 %/min to 0.472 %/min, in order to observe the strain-rate dependency on the stress-strain behaviours, which is however out of scope of this paper. At sustained loading stage denoted as “s” to “y”, a constant vertical stress of 250 kPa was applied for around 40 hours, while 100 cycles of unload/reload were applied with several stress amplitudes of 6.2, 12.4, 24.8, and 49.6 kPa. At several stages of unloading, denoted as “y” to “hh”, 100 cycles of cyclic load with amplitude of 12.4 kPa were applied.
Figure 3. Loading test results on a model pier reinforced with a polyester geogrid.
(a) vertical compressive strain vs. vertical stress; (b) time history of vertical stress; (c) time history of vertical and horizontal strain; (d) time history of vertical strain increment at each sustained or cyclic loading stage; (e) vertical compressive strain vs. horizontal strain; (f) vertical strain vs. vertical stress at cyclic loading stages during unloading.
Figure 4. Loading test results on a model pier reinforced with a phosphor bronze grid.
(a) vertical compressive strain vs. vertical stress;  
(b) time history of vertical stress;  
(c) time history of vertical and horizontal strain;  
(d) time history of vertical strain increment at each sustained or cyclic loading stage;  
(e) vertical compressive strain vs. horizontal strain;  
(f) vertical strain vs. vertical stress at cyclic loading stages during unloading.
The followings can be found from these results:

1) Clear viscous deformation due to sustained load and residual deformation due to cyclic loading were observed, even though the backfill material was a non-cohesive well-graded gravel.
2) The relationships between the vertical stress and the vertical strain for the model reinforced with an “extensible” polyester geogrid was similar to the one reinforced with an “inextensible” phosphor bronze grid (e.g. compare Figures 3a and 4a).
3) The viscous and residual deformations for the model with a polyester geogrid were similar to those reinforced with a phosphor bronze grid (e.g. compare Figures 3d and 4d).
4) The stiffness (average Young’s modulus) of the model structure measured by applying small-amplitude cyclic stresses at several stress levels during otherwise global unloading were similar for the models reinforced with polyester geogrid and phosphor bronze grid (e.g. compare Figures 3f and 4f).
5) However, the horizontal strains for the model reinforced with a polymer grid was nearly twice as large as that for the model reinforced with a phosphor bronze grid (e.g. compare Figures 3e and 4e), while the vertical strains were nearly the same as each other.

It can be concluded from these results that the stiffness of the reinforcement was not essential to restrain the deformation of reinforced soil structures within the examined range, even though the stiffness of the reinforcement was different by a factor more than 10 times. The corresponding horizontal strain was however noticeably different.

3 EFFECTS OF VERTICAL SPACING BETWEEN REINFORCEMENT LAYERS

3.1 Test methods

In order to investigate the effects of the total stiffness of the reinforcement, four models of reinforced soil pier with a vertical spacing of 5 cm (single reinforcement layer) or 2.5 cm (double layers) between the reinforcement layers (Figure 5) were tested. The backfill and the reinforcement were the same as the model reinforced with polyester geogrid mentioned before. Two types of loading procedures were employed as shown in Figure 6. In the PLPS (preloading and prestressing) loading tests, the pier was preloaded to the 250 kPa, and it was sustained for 56 hours, then unloaded to 100 kPa, and finally 100 times of cyclic loads were applied between 100 and 150 kPa. In the case without PLPS loading, the pier was loaded to 50 kPa, and 100 times of cyclic loads were applied between 50 and 100 kPa. These loading procedures simulated the estimated stress history of actual cases of a PLPS reinforced soil pier and a non-PLPS reinforced soil abutment, which were constructed for a railway bridge (Uchimura et. al. 2003b). In these tests, small cyclic stresses with amplitude of 5 kPa were applied at several stress levels in order to measure the average Young’s modulus of the structure. The strain rate was kept constant, 0.004 %/min, except for the sustained loading stages. The tensile strains in the reinforcement were measured by means of strain gages pasted at the center of the grid at the middle height in two directions orthogonal to each other.
3.2 Results and discussions

Figure 7 shows the relationships between the vertical compressive stress and strain from the four tests. Some scatter seen in these results (e.g. a model with single reinforcement layer showed higher stiffness than a model with double layers for non-PLPS loading) is probably due to a variation among the models. It seems that the difference in the behaviour between the models with single and double layers is within the range of the scatter. The secant modulus obtained from the cyclic loading states is as follows:

- PLPS loading with single layer : 355 kPa
- PLPS loading with double layers : 345 kPa
- non-PLPS loading with single layer : 251 kPa
- non-PLPS loading with double layers : 234 kPa

Figure 8 shows the average Young’s modulus of the structure measured by the small-amplitude cyclic loadings plotted against the vertical stress. It is clear that the Young’s modulus increased with an increase in the current vertical stress, and the vertical spacing of reinforcement layers had no effects on it.

Figure 9 shows the time histories of the vertical strain from the four tests. The residual strains caused by the cyclic loading were not affected by the difference in the vertical spacing of reinforcement layers. On the other hand, the horizontal strain (measured as the extension of geogrid) for the model with a single layer was almost twice as large as that with double layers in the case with PLPS loading (Figure 10a). The differences between the strains in the principal and transversal directions of the geogrid were due to a difference in the stiffness of strand in each direction. In the case without PLPS loading, such trends were not clear probably due to a variation among the models (Figure 10b).

These results suggest that the vertical spacing of reinforcement layers is not essential to the vertical compressive stiffness of the reinforced soil structures within the examined range, while it affects the corresponding horizontal strains.
4 CONCLUSIONS

It is usually considered that the effects of reinforcement stiffness could be significant on the deformation of reinforced backfill during primary loading and sustained loading applied during otherwise primary loading. However, within the examined limit of reinforcement stiffness, the effects of reinforcement stiffness were utterly insignificant on the behaviours. This result suggests that it is not necessary to use metal reinforcement, in particular when the reinforced backfill is preloaded and prestressed.

The vertical spacing between reinforcement layers should be small enough so that sufficiently large load could be applied to the backfill without damaging the backfill. However, when the vertical spacing is smaller than some limit, the deformation of backfill does not decrease noticeably with a decrease in the vertical spacing of reinforcement layers.

These results suggest that the total stiffness of the reinforcement larger than some limit may not be essential to the vertical compressive stiffness of the reinforced soil structures. It could be more effective to ensure better deformation characteristics of the backfill by selecting high quality backfill materials, controlling the compaction quality, and if possible, improving the stiffness of the backfill by applying preload and prestress as proposed by Tatsuoka et. al. (1997) and Uchimura et. al. (2003a and b).

REFERENCES


