Experimental study on the macro-meso properties of geosynthetic-reinforced granular material under plain strain condition

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Abstract: Geosynthetics have been widely used in the construction of reinforced soil structures, however, the reinforcement mechanism has not been fully understood. To investigate the macro-meso properties of geosyntheitc-reinforced soils, biaxial compression tests of reinforced soils were conducted in this study. Geomembrane was used as reinforcement element and aluminum rods as backfill material. A free image analysis module, GeoPIV-RG, was applied to reveal the distribution of horizontal and vertical displacements of the specimens under vertical load and lateral confining pressure. The results indicated that reinforcement-soil interaction was closely related with the stiffness and spacing of reinforcements, which had a strong effect on the global volumetric strain, and the reinforcement spacing played more important role in controlling the properties of geosynthetic-reinforced granular material than reinforcement stiffness. The reinforcing effects of geosynthetics with weak stiffness cannot develop quite well until its tensile stress was mobilized substantially. Reinforcements also were capable of controlling the distribution of vertical settlements and restraining its development along the height of the specimen when reinforced with closely-spaced reinforcements particularly.

Keywords: Geosynthetics; Plain strain condition; Macro-meso properties; Strength and stiffness; Reinforcement-soil interaction; Digital image analysis

1 INTRODUCTION

Geosynthetics are now gaining popularity and have been used very widely in the construction of geosynthetic-reinforced soil (GRS) structures (e.g., retaining walls, slopes, embankments, abutments, etc.), because they can provide enhanced confinement to the soil by increasing its strength and stiffness.

Reinforcement-soil interaction is the key issue to interpret the reinforcing mechanisms of geosynthetics and has been studied using pull-out tests and direct shear tests by many researchers (Palmeira, 2009; Sadat Taghavi and Mosallanezhad, 2017). Reinforcements are directly subjected to horizontal load in pull-out tests, and then the load will transfer to adjacent soil through friction and bearing resistance of any tensile members, while it is an opposite process (the load is applied to the soil firstly) in most applications of reinforced soil structures. Though the reinforcements are fixed in direct shear tests, the relative displacements between reinforcement and soil which affect the behavior of adjacent soil particularly are not identical between experiments and practical engineering. This has been interpreted clearly by Liang and Xu (2017).

Many model tests have been conducted to analyze the behavior of GRS structures in a plain-strain situation (Ketchart and Wu, 2002; Kongkitkul et al., 2007; Bathurst, 2014), because they can be simplified as two-dimensional problems in such an assumed condition. Biaxial compression tests, which could reproduce the stress-strain state of GRS structures, have been applied to study the behaviors of geogrid-reinforced soil by Jacobs and Ziegler (2015). However, a series of factors would influence the interaction mechanisms between geosynthetics and backfill, the reinforcement mechanism needs further exploration to be fully recognized.

In this study, biaxial compression tests were employed to investigate the macroscopic and mesoscopic properties of geosynthetic-reinforced granular material, and three influencing factors were considered, including reinforcement spacing, reinforcement stiffness and gradation of backfill. In addition, the method of digital image analysis was used to reveal the distribution of horizontal and vertical displacements under vertical loading in mesoscopic aspects.

2 DESCRIPTION OF THE TESTS

2.1 *General description*

A unit cell specimen, part of GRS structures, was chosen as the object in this experimental study. A strong box with inside dimensions of 893 mm long by 50 mm wide by 430 mm high was used to contain it. One of the sidewalls of the box was replaced with transparent organic glass to enable visualization of the specimen and take photos during testing. The unit cell specimens were built to a height of 380 mm and with a width of 693 mm. Their configurations were shown in Fig.1. Two plastic bags, made of polyvinyl chloride material, were used to provide lateral confining pressure with full of pure water during testing. The maximum and minimum confining pressure were 4.2 kPa and 0 kPa, respectively, and the pressure increased linearly from top to bottom of the plastic bag. The water surface was exposed to the air to avoid siphoning induced by the difference between inside pressure and outside pressure of the plastic bag, and its elevation was kept the same height as that of rigid box. To maintain the confining pressure, the elevation of water surface was kept unchanged during loading. Redundant water, generated due to the lateral deformation of the specimen, was discharged by aqueducts and was used to calculate the global volumetric strain with a measured cup. Vaseline was used outside surface of the plastic bag to minimize the friction between the bag and sidewalls of rigid box. The weight loading method was used to provide vertical loads by iron plate with dimensions of 600 mm long by 50 mm wide by 20 mm high. Each iron plate weighs about 45.3 N.

2.2 *Materials and methods*

2.2.1 *Backfill*

Aluminum rods with circular cross section were used to construct the testing specimens and have been demonstrated that they can simulate the properties of backfill soil very well (Oda et al., 1982; Shahin et al., 2004; Zhang et al., 2011). Two different kinds of gradation of aluminum rods, gradation-1 and gradation-2, were considered in this study to evaluate their effects on the performance of geosynthetic-reinforced granular material, as shown in Fig.2. Gradation-1 consisted of four different diameters, including 5, 8, 12 and 15 mm, and mixed in a ratio of 6:2:1:1 in weight. Gradation-2 consisted of five different diameters, including 5, 8, 12, 15 and 18 mm, and mixed in a ratio of 6:10:7:5:2 in weight. They were used to simulate the behavior of coarse granular soil without fines. Aluminum rods were all 50 mm in length, and its unit weight was 26.5 kN/m^3.

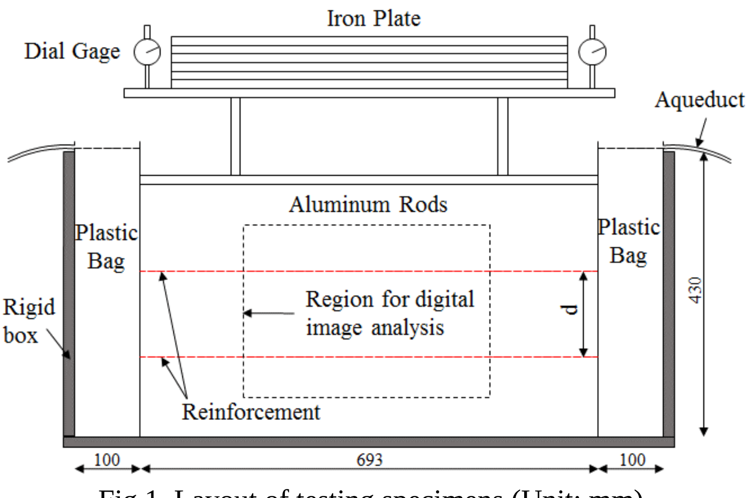

Fig.1. Layout of testing specimens (Unit: mm)

2.2.2 *Reinforcements*

Two types of geomembranes, made of high-density polyethylene (HDPE) and polyvinyl chloride (PVC), respectively, were used as reinforcement materials in the tests. Wide-width tensile tests were performed in accordance to ASTM D4885-01 (2011) to quantify the relationship between load and deformation of geomembranes, and the results were shown in Fig.3. The secant modulus of HDPE-Geomembrane is about one half times that of PVC-Geomembrane when the tensile strain is 2 %. The unconfined ultimate tensile strength of HDPE-Geomembrane is 1.98 kN/m when the strain is 23.5 %, while the unit tension of PVC-Geomembrane increases with the increase of tensile strain. Furthermore, the two load-curves of tensile tests intersect with each other when the strain reaches 100 %.

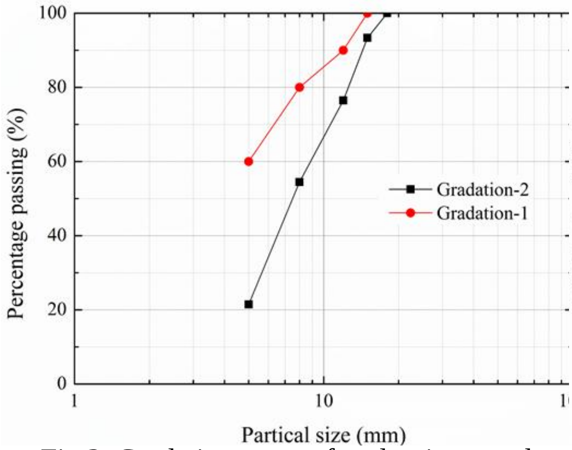

Fig.2. Gradation curves for aluminum rods

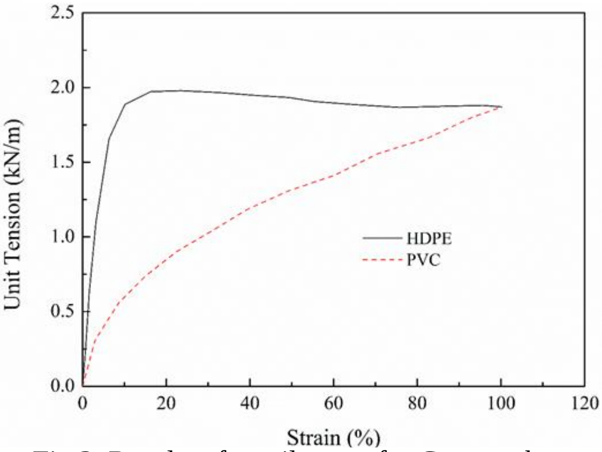

Fig.3. Results of tensile tests for Geomembranes

2.3 *Testing program*

In the experimental studies, the testing program are summarized in Table 1. All tests were constructed and conducted using the layout shown in Fig.1 except the arrangement of reinforcement. The unreinforced specimens were tested for comparison (baseline test). Geomembranes were located at the middle and trisection position of the specimen when the reinforcement spacing was 0.19 m and 0.127 m, respectively.

Table 1. Summary of the tests

Tests	Gradation	Reinforcement Spacing d (m)	Geomembrane
T1	1	Unreinforced	/
T2		0.19	HDPE
T3			PVC
T4		0.127	HDPE
T5			PVC
T6	2	Unreinforced	/
T7		0.19	PVC
T8		0.127	PVC

2.4 *Construction and Instrumentation*

Plastic bags were covered by two rectangular wooden cases which have enough strength and stiffness to prevent lateral deformation of aluminum rods during construction. Firstly, the aluminum rods were mixed uniformly based on the requirements described in backfill section, then the testing specimens were built carefully layer by layer from bottom to top. During preparation of the last layer of each testing specimen, special attention was paid to achieve a uniform surface to avoid stress concentration under vertical load. After finishing the construction, the two wooden cases were removed.

Two dial gages were used to measure the vertical settlements at the top of the specimen during testing. Each iron plate was not added until the deformation was stable under existing pressure, and the settlements were recorded before the next stage loading. The maximum pressure was limited to 16.8 kPa for each test, which was appropriate and sufficient for the following researches. In addition, photos were taken in front of the specimen automatically every 20 seconds for the next digital image analysis and two light-emitting diode lights were used on both side of the specimen to provide external lighting during loading.

3 TEST RESULTS

3.1 *Macroscopic properties*

3.1.1 *Settlement*

Fig.4 shows the settlements under vertical pressure, which were calculated based on the average value of the results measured using two dial gages at top of the specimen as previously mentioned. Fig.4(a) shows the settlements of the specimen with Gradation-1 by considering the effects of reinforcement spacing and reinforcement stiffness. The unreinforced specimen had the weakest strength and failed when the applied pressure was 16.8 kPa. However, the specimen reinforced with two layers of HDPE-Geomembrane had the strongest strength among the five tests, and it deformed almost linearly within the vertical load of 16.8 kPa. The stiffness of soil reinforced with one layer of PVC-Geomembrane increased slowly at initial stage of loading compared with unreinforced one, and it indicated that reinforcing effects of geosynthetics with weak stiffness cannot develop well until its tensile stress was mobilized substantially. The settlements of the specimen reinforced with HDPE-Geomembrane were smaller than that of the specimen reinforced with PVC-Geomembrane when the reinforcement spacing was 0.19 m or 0.127 m. Meanwhile, the settlements of the specimen reinforced with two layers of PVC-Geomembrane were less than those of the specimen reinforced with one layer of HDPE-Geomembrane. The performance of the two specimens were improved by closer spacing and stiffer reinforcement at the same magnitude (one half times). It means that decreasing reinforcement spacing and increasing reinforcement stiffness result in promotion of reinforcement-soil interaction and increase of strength and stiffness of reinforced soil by providing stronger confining pressure with same strain for backfill soil and reinforcement spacing plays much more important role in controlling the properties of geosynthetic-reinforced granular material than reinforcement stiffness. These results were also confirmed by the numerical simulations and model tests of geosynthetic-reinforced soil structures which were conducted by Xu et al. (2017) and Wu and Pham (2013), respectively.

Similar patterns can also be found in Fig.4(b) which shows the settlements by considering the effects of gradation and reinforcement spacing. PVC-Geomembrane was used as reinforcement in these tests. The stiffness and strength of the specimen with gradation-2 were larger than that of the specimen with gradation-1. This is because aluminum rods with diameter of 18 mm in gradation-2 increased the strength of backfill. Moreover, improvement of stiffness and strength of the specimen with two layers of PVC-Geomembrane was much more significant than that of the specimen with one layer of PVC-Geomembrane compared with unreinforced ones.

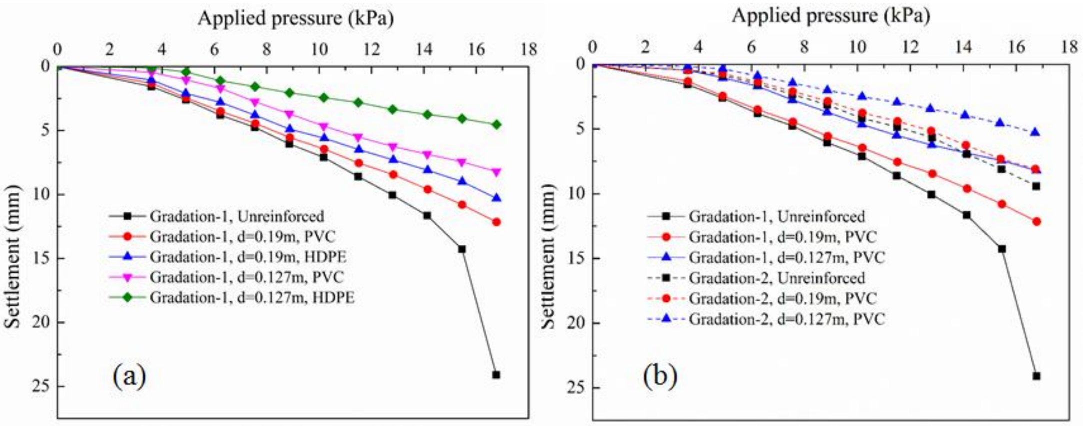

Fig.4. Settlements at top of the specimen under vertical load. (a) The effects of reinforcement spacing and reinforcement stiffness. (b) The effects of gradation and reinforcement spacing.

In the actual engineering practice of geosynthetic-reinforced bridge abutment, the tolerable limited vertical strain, which was calculated by dividing the vertical settlements to the height of the wall, should be less than 0.5 percent as stated by FHWA (2011). To study the varying pattern of bearing capacity of the specimen under different working conditions, the pressure which was applied at the top of specimen with Gradation-1 was shown in Fig.5 when the vertical settlements were all equal to 2 mm (0.5 percent). The applied pressure for the specimen reinforced with two layers of HDPE-Geomembrane was almost two times of that for the specimen reinforced with one layer of HDPE-Geomembrane, while the increment was smaller in PVC-Geomembrane reinforced specimen when the reinforcement spacing decreased from 0.19 m to 0.127 m. This is consistent with the results previously described.

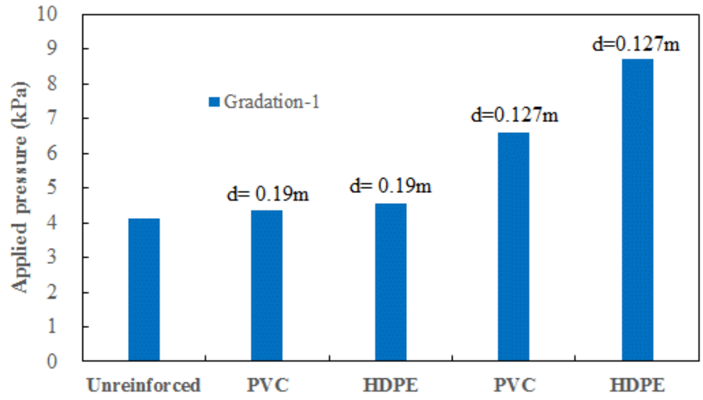

Fig.5. The pressure applied at top of the specimen with Gradation-1 when the settlements were 2 mm

3.1.2 *Volume change*

Global volumetric strain of the specimens was calculated based on the vertical and horizontal deformation, because the tests were conducted under plain strain conditions. Then, their changing patterns were investigated at small vertical strain, as shown in Fig.6. It is seen that volumetric strain was less than zero. The dilatancy of backfill soil can be determined by the relationship between volumetric strain and vertical strain of the specimen, and it was suppressed by reinforcement in this study and this tendency was enhanced by higher reinforcement stiffness and smaller reinforcement spacing based on the experimental results. This phenomenon was regarded as another reinforcing mechanism besides the mechanisms of apparent confining pressure and apparent cohesion and demonstrated by Wu et al (2014). Moreover, the specimen built with Gradation-2 and reinforced with two layers of PVC-Geomembrane behaved almost the same (Volumetric strain and vertical strain) with the specimen built with Gradation-1 and reinforced with two layers of HDPE-Geomembrane. This indicated that the reinforced soil with larger particle diameters (e.g., reinforced coarse-grained soil) was more in favor of contraction when subjected to external load at initial stage, which can result in higher strength and stiffness.

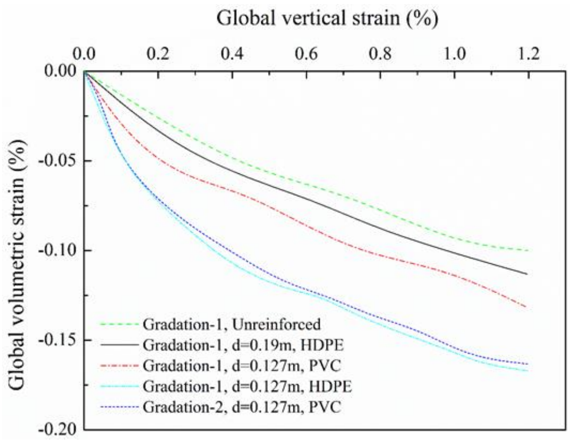

Fig.6. Volume change of the specimens

3.2 *Mesoscopic properties*

The mesoscopic properties of the specimen were analyzed by utilizing the program GeoPIV-RG to deal with the photos taken during testing. GeoPIV-RG is a free image analysis module designed for geotechnical and structural engineering research applications. It is capable of sub-pixel measurement resolution for problems involving large displacements and deformations. This program was developed by Stanier et al. (2016) and has been applied successfully in centrifugal tests to identify the soil deformation under vertical strip load. In this study, contour maps of horizontal displacements and vertical settlements of the specimens under three different vertical loads (4.9, 10.2 and 15.4 kPa) were used to illustrate their properties from mesoscopic aspects by considering the effects of reinforcement spacing, because constraining the lateral and vertical deformation of soil is the main reinforcing effects of geosynthetics. The region for digital image analysis of mesoscopic properties of the specimen was shown in Fig.1.

3.2.1 *Distribution of horizontal displacements*

Fig.7 shows the typical contour maps of horizontal displacements of the specimens built with Gradation-1. Lateral deformation of the specimen was greatly reduced by two layers of reinforcements, which was coincident with the results of macroscopic properties presented previously. The unreinforced soil failed in shear failure mode with the increase of vertical load, shown in Fig.7(a), but this mode was changed in reinforced ones. The horizontal displacements of reinforced specimen with two-layer reinforcements were mainly generated between reinforcement layers, as shown in Fig.7(b). This is because reinforcements have changed the state of stress-strain of the soil through reinforcement-soil interaction, and the results were consistent with the results of what Wang et al. (2017) got when studying the influence of geogrid transverse members on deformation behavior of reinforced granular soil.

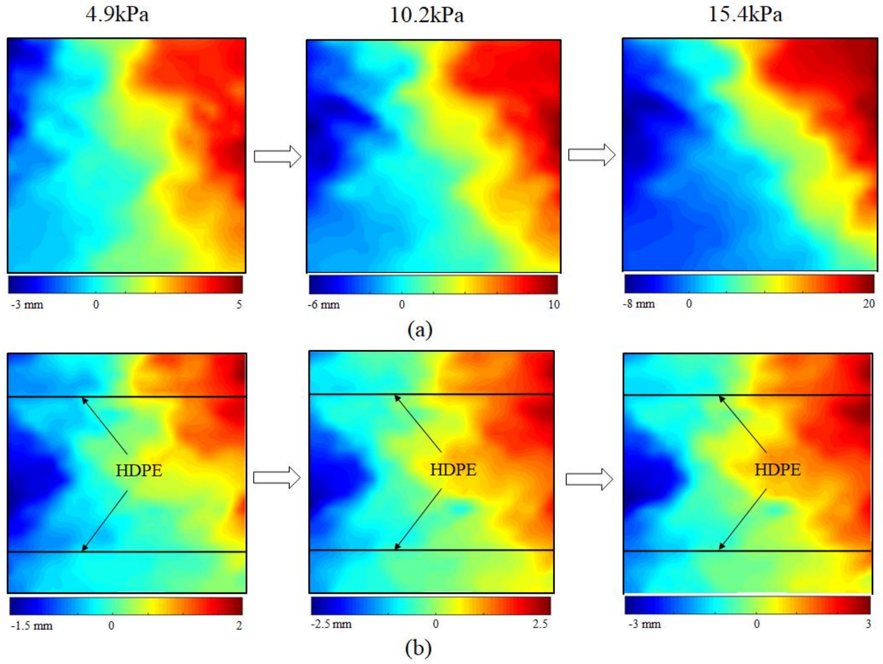

Fig.7. Contour maps of horizontal displacements of the specimens built with Gradation-1 under three different applied pressure: 4.9, 10.2 and 15.4 kPa. (a) Unreinforced specimen. (b) Reinforced specimen with two layers of HDPE-Geomembrane.

3.2.2 *Distribution of vertical settlements*

Fig.8 shows the typical contour maps of vertical settlements of the specimens built with Gradation-1. The distributions of vertical settlements were similar to those of horizontal displacements for unreinforced specimen when the vertical pressure was 15.4 kPa, as shown in Fig.7(a), and a shear band appeared due to the unreinforced specimen failed in shear failure mode. Fig.8(b) shows the development of vertical settlements when the reinforcement spacing was 0.19 m, and it can be found that the displacements were transferred from top to bottom of specimens gradually with increase of vertical load. However, the transfer process of vertical settlements was delayed when the reinforcement spacing reduced to 0.127 m, as shown in Fig.8(c). Besides, it was noted from Fig.8(c) that geosynthetics resisted the development of vertical settlements and controlled its distribution along the height of the specimen. This indicated that geosynthetics were capable of restraining the settlements of specimen, which was particularly reinforced with closely spaced reinforcements.

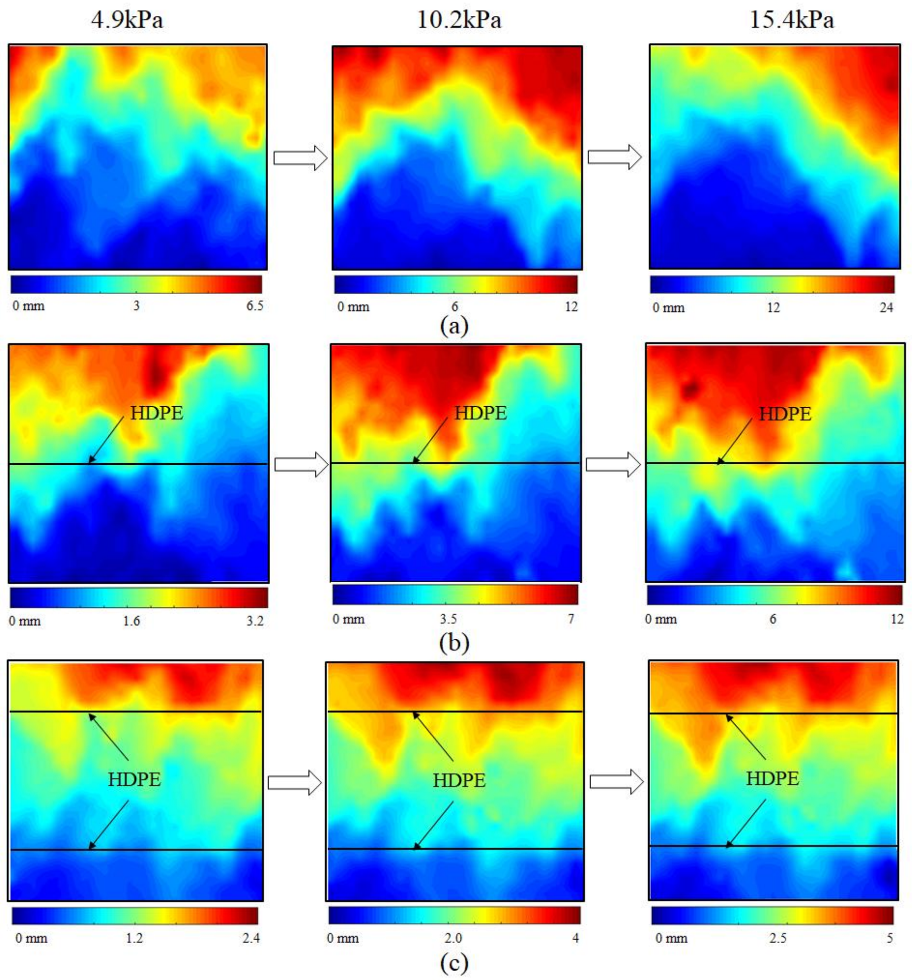

Fig.8. Contour maps of vertical settlements of the specimens built with Gradation-1 under three different applied pressure: 4.9, 10.2 and 15.4 kPa. (a) Unreinforced specimen. (b) Reinforced specimen with one layer of HDPE-Geomembrane. (c) Reinforced specimen with two layers of HDPE-Geomembrane.

4 CONCLUSIONS

Biaxial compression tests were conducted to investigate the properties of geosynthetic-reinforced granular material. The effects of reinforcement spacing, reinforcement stiffness and gradation of backfill were analyzed in this study both from macroscopic and mesoscopic views. The following conclusions could be drawn from this study.

- The strength and stiffness of reinforced granular material increased with the decrease of reinforcement spacing and the increase of reinforcement stiffness. And reinforcement spacing played more important role in controlling the properties of geosynthetic-reinforced granular material than reinforcement stiffness.
- The reinforcing effects of geosynthetics with weak stiffness developed weakly until its tensile stress was mobilized substantially.
- The dilatancy of backfill soil was suppressed by geosynthetic reinforcement, and this restriction could be enhanced by higher reinforcement stiffness and smaller reinforcement spacing.
- The unreinforced soil failed in shear failure mode with increase of vertical load, while the shear band didn’t develop fully in reinforced ones and horizontal displacements were mainly generated between reinforcement layers.
- Geosynthetics were capable of controlling the distribution of vertical settlements and restraining its development along the height of the specimen, which was especially reinforced with closely spaced reinforcements.

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